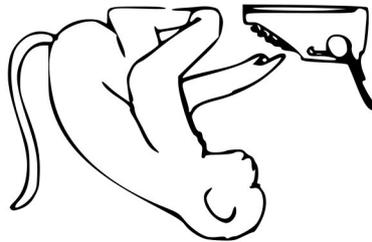


# IMITATOR User Manual

Version 2.6.0

March 7, 2013



## Abstract

IMITATOR is a tool for parameter synthesis in timed automata with stopwatches [5]. It is based on the inverse method: given a reference valuation of the parameters, it generates a constraint such that the system behaves the same as under the reference valuation in terms of traces, i.e., alternating sequences of locations and actions. Besides the inverse method, IMITATOR also implements the “behavioral cartography algorithm”, allowing to solve the following good parameters problem: find a set of valuations within a given rectangle for which the system behaves well. We give here the installation requirements and the launching commands of IMITATOR, as well as the source code of a toy example.

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# 1 Introduction

IMITATOR [5] (for *Inverse Method for Inferring Time Abstract behavior*) is a tool for parameter synthesis in the framework of real-time systems based on the inverse method *IM* for Parametric Timed Automata (PTAs) augmented with stopwatches [3, 1]. Different from CEGAR-based methods (see [9]), this algorithm for parameter synthesis makes use of a “good” parameter valuation  $\pi_0$  instead of a set of “bad” states [7].

When executing the inverse method, IMITATOR takes as input a network of PTAs with stopwatches and a reference valuation  $\pi_0$ ; it synthesizes a constraint  $K$  on the parameters such that (1)  $\pi_0 \models K$  and (2) for all parameter valuation  $\pi$  satisfying  $K$ , the trace set (i.e., the discrete behavior) of  $\mathcal{A}$  under  $\pi$  is the same as for  $\mathcal{A}$  under  $\pi_0$ . This provides the system with a criterion of *robustness* (see, e.g., [12]) around  $\pi_0$ .



Figure 1: Functional view of IMITATOR

## 2 Installing IMITATOR

Sources, binaries for Linux platforms, and installation instructions are available on IMITATOR’s Web page [11].

## 3 General Structure and Implementation

### 3.1 Inputs and Outputs

The input syntax of IMITATOR to describe the network of PTAs modeling the system is originally based on the HYTECH syntax, with several improvements. Actually, all standard HYTECH files describing only PTAs (and not more general systems like linear hybrid automata[2]) can be analyzed directly by IMITATOR with very minor changes.

**Inverse Method.** When calling IMITATOR to apply the inverse method algorithm, the tool takes as input two files, one describing the network of PTAs modeling the system, and the other describing the reference valuation. As depicted in Figure 2, it synthesizes a constraint on the parameters solving the inverse problem, as well as optionally the corresponding trace set under

a graphical form. The description of all the parametric reachable states can also be optionally output.



Figure 2: IMITATOR inputs and outputs in inverse method mode

**Behavioral Cartography Algorithm.** When calling IMITATOR to apply the behavioral cartography algorithm, the tool takes as an input two files, one describing the network of PTAs modeling the system, and the other describing the reference rectangle, i.e., the bounds to consider for each parameter. As depicted in Figure 3, it synthesizes a list of tiles, as well as optionally the trace set corresponding to each tile under a graphical form. The description of all the parametric reachable states for each tile may also optionally be output.



Figure 3: IMITATOR inputs and outputs in behavioral cartography mode

### 3.2 Features

IMITATOR (version 2.6.0) includes the following features:

- Analysis of a network of parametric timed automata augmented with stopwatches and discrete rational-valued variables;
- Reachability analysis: given a PTA  $\mathcal{A}$ , compute the set of all the reachable states (as it is done in tools such as, e.g., HyTECH and PHAVer);
- Inverse method algorithm: given a PTA  $\mathcal{A}$  and a reference valuation  $\pi_0$ , synthesize a constraint guaranteeing the same trace set as for  $\mathcal{A}[\pi_0]$ ;

- Behavioral cartography algorithm: given a PTA  $\mathcal{A}$  and a rectangular parameter domain  $V_0$ , compute a list of tiles. Two different modes can be considered: (1) cover all the integer points of  $V_0$  or, (2) call a given number of times the inverse method on an integer point selected randomly within  $V_0$  (which is interesting for rectangles containing a very big number of integer points but few different tiles);
- Automatic generation of the trace sets, for the reachability analysis and for both algorithms *IM* and *BC*;
- Graphical output of the trace sets;
- Graphical output of the behavioral cartography;
- Optional use of the merging technique of [6].

See Section 4.3.4 for the list of options available when calling *IMITATOR*.

## 4 How to Use *Imitator*

### 4.1 Installation

See the installation files available on the website for the most up-to-date information.

In short, *IMITATOR* is written in OCaml, and makes use of the following libraries:

- The OCaml ExtLib library (Extended Standard Library for Objective Caml)
- The Parma Polyhedra Library (PPL) [8]
- The GNU Multiple Precision Arithmetic Library (GMP)

Binaries and source code packages are available on *IMITATOR*'s Web page [11].

### 4.2 The *Imitator* Input File

Examples of input files can be found on *IMITATOR*'s Web page [11]. A complete example is given in Appendix A. A tentative grammar is given in Appendix B.

#### 4.2.1 Variables

Discrete variables, clocks and parameters variable names must be disjoint.

The synchronization label names may be identical to other names (automata or variables). The automata names may be identical to other names (variables synchronization labels).

## 4.2.2 Parametric Timed Automata

See Appendix B.

## 4.2.3 Initial region and $\pi_0$

See Appendix B.

## 4.3 Calling Imitator

IMITATOR can be used with three different modes:

1. Reachability analysis: given a PTA  $\mathcal{A}$ , compute the whole set of reachable states from a given initial state.
2. Inverse Method: given a PTA  $\mathcal{A}$  and a valuation  $\pi_0$  of the parameters, compute a constraint on the parameters guaranteeing the same behavior as under  $\pi_0$  [7].
3. Behavioral Cartography Algorithm: given a PTA  $\mathcal{A}$  and a rectangle  $V_0$  (bounded interval of values for each parameter), compute a cartography of the system [4].

We detail those three modes below.

### 4.3.1 Reachability Analysis

Given a PTA  $\mathcal{A}$ , the reachability analysis computes the whole set of reachable states from a given initial state. The syntax in this case is the following one:

```
IMITATOR <input_file> -mode reachability [options]
```

Note that there is no need to provide a  $\pi_0$  or  $V_0$  file in this case (if one is provided, it will be ignored).

### 4.3.2 Inverse Method

Given a PTA  $\mathcal{A}$  and a valuation  $\pi_0$  of the parameters, the inverse method compute a constraint  $K_0$  on the parameters guaranteeing that, for any  $\pi \models K_0$ , the trace sets of  $\mathcal{A}[\pi]$  and  $\mathcal{A}[\pi_0]$  are the same [7]. The syntax in this case is the following one:

```
IMITATOR <input_file> <pi0_file> [-mode inversemethod] [options]
```

Note that the `-mode inversemethod` option is not necessary, since the default value for `-mode` is precisely `inversemethod`.

Note that, unlike the algorithm given in [7], at a given iteration, the  $\pi_0$ -incompatible state is selected deterministically, for efficiency reasons. However, the  $\pi_0$ -incompatible inequality within a  $\pi_0$ -incompatible state is selected randomly, unless the `-no-random` option is activated.

In this case, IMITATOR outputs the resulting constraint  $K_0$  on the standard output.

### 4.3.3 Cartography

Given a PTA  $\mathcal{A}$  and a rectangle  $V_0$  (bounded interval of values for each parameter), the Behavioral Cartography Algorithm computes a cartography of the system [4]. Two possible variants of the algorithm can be used:

1. The standard variant covers all the integer points within  $V_0$ . The syntax in this case is the following one:  
`IMITATOR <input_file> <V0_file> [-mode cover] [options]`
2. The alternative variant calls the inverse method a certain number of times on a random point  $V_0$ . The syntax in this case is the following one:  
`IMITATOR <input_file> <V0_file> [-mode randomX] [options]`  
 where X represents the number of random points to consider. If a point has already been generated before, the inverse method is not called. If a point belongs to one of the tiles computed before, the inverse method is not called neither. Therefore, in practice, the number of tiles generated is smaller than X.

When in behavioral cartography mode, one can generate the cartography in a graphical form (for 2 dimensions) using option `-cart` (see below). In that case, an image will be output.

It is also possible to automatically color this cartography (in green and red) according to a property to be verified. The property must be defined at the end of the `.imi` model file, using the following syntax:

```
property := [PROP]
```

[PROP] must conform to one of the following patterns, where AUTOMATON is an automaton name, LOCATION is a location name, a, a1, a2 are actions, and the deadline d is a (possibly parametric) linear expression:

- `property := unreachable loc[AUTOMATON] = LOCATION`
- `property := if a2 then a1 has happened before`
- `property := everytime a2 then a1 has happened before`
- `property := everytime a2 then a1 has happened once before`
- `property := if a1 then eventually a2`
- `property := everytime a1 then eventually a2`
- `property := everytime a1 then eventually a2 once before next`

- `property := a within d`
- `property := if a2 then a1 has happened within d before`
- `property := everytime a2 then a1 has happened within d before`
- `property := everytime a2 then a1 has happened once within d before`
- `property := if a1 then eventually a2 within d`
- `property := everytime a1 then eventually a2 within d`
- `property := if a1 then eventually a2 within d once before next`
- `property := sequence a1, ..., an`
- `property := always sequence a1, ..., an`

#### 4.3.4 Options

The options available for IMITATOR are explained in the following.

`-acyclic (default: false)` Does not test if a new state was already encountered. In a normal use, when IMITATOR encounters a new state, it checks if it has been encountered before. This test may be time consuming for systems with a high number of reachable states. For acyclic systems, all traces pass only once by a given location. As a consequence, there are no cycles, so there should be no need to check if a given state has been encountered before. This is the main purpose of this option.

However, be aware that, even for acyclic systems, several (different) traces can pass by the same state. In such a case, if the `-acyclic` option is activated, IMITATOR will compute *twice* the states after the state common to the two traces. As a consequence, it is all but sure that activating this option will lead to an increase of speed.

Note also that activating this option for non-acyclic systems may lead to an infinite loop in IMITATOR.

`-cart (default: off)` After execution of the behavioral cartography, plots the generated zones as a *PostScript* file. This option takes an integer which limits the number of generated plots, where each plot represents the projection of the parametric zones on two parameters. If the considered rectangle  $v_0$  is spanned by two parameters only, then `-cart 1` will plot the projection of the generated zones on these two parameters.

This option makes use of the external utility `graph`, which is part of the *GNU plotting utils*, available on most Linux platforms. The generated files will be located in the same directory as the source files, unless option `-log-prefix` is used.

**-depth-limit <limit> (default: none)** Limits the number of iterations in the *Post* exploration, i.e., the depth of the traces. In the cartography mode, this option gives a limit to *each* call to the inverse method.

**-fancy (default: false)** In the graphical output of the reachable states (see option **-with-dot**), provide detailed information on the local states of the composed automata.

**-fromGrML (default: false)** Does not use the standard input syntax described here, but a GrML input syntax. This is used when interfacing IMITATOR with the CosyVerif platform. Note that, in that case, not all syntactic features of IMITATOR are supported.

**-IMK (default: false)** Uses a variant of the inverse method that returns a constraint such that no  $\pi_0$ -compatible state is reached; it does not guarantee however that any “good” state will be reached (see [7]).

**-IMunion (default: false)** Uses a variant of the inverse method that returns the union of the constraints associated to the last state of each path (see [7]).

**-incl (default: false)** Consider an inclusion of region instead of the equality when performing the *Post* operation. In other terms, when encountering a new state, IMITATOR checks if the same state (same location and same constraint) has been encountered before and, if yes, does not consider this “new” state. However, when the **-inclusion** option is activated, it suffices that a previous state with the same location and a constraint *greater or equal* to the constraint of the new state has been encountered to stop the analysis. This option corresponds to the way that, e.g., HYTECH works, and suffices when one wants to check the *non-reachability* of a given bad state.

**-log-prefix (default: <input\_file>)** Set the prefix for log (.states) and graphical (.jpg) files.

**-merge (default: false)** Use the merging technique of [6]. Note that, in that case, not all the properties of the inverse method are preserved.

**-mode (default: inversemethod)** The mode for IMITATOR.

<code>reachability</code>	Parametric reachability analysis (see Section 4.3.1)
<code>inversemethod</code>	Inverse method (see Section 4.3.2)
<code>cover</code>	Behavioral Cartography Algorithm with full coverage (see Section 4.3.3)
<code>randomXX</code>	Behavioral Cartography Algorithm with <code>XX</code> iterations (see Section 4.3.3)

`-no-random (default: false)` No random selection of the  $\pi_0$ -incompatible inequality (select the first found). By default, select an inequality in a random manner.

`-PTA2GrML (default: false)` Translates the input model to a GrML format, and exits.

`-PTA2JPG (default: false)` Translates the input model to a graphical, human-readable form (in `.jpg` format), and exits.

`-states-limit (default: none)` Will try to stop after reaching this number of states. Warning: the program may have to first finish computing the current iteration before stopping.

`-statistics (default: false)` Print info on number of calls to PPL, and other statistics about memory and time. Warning: enabling this option may slow down the analysis, and will certainly induce some extra computational time at the end.

`-step (default: 1)` Step for the behavioral cartography.

`-sync-auto-detect (default: false)` IMITATOR considers that all the automata declaring a given synchronization label must be able to synchronize all together, so that the synchronization can happen. By default, IMITATOR considers that the synchronization labels declared in an automaton are those declared in the `syncclabs` section. Therefore, if a synchronization label is declared but never used in (at least) one automaton, this label will never be synchronized in the execution<sup>1</sup>.

The option `-sync-auto-detect` allows to detect automatically the synchronization labels in each automaton: the labels declared in the `syncclabs` section are ignored, and the IMITATOR considers that only the labels really used in an automaton are those considered to be declared.

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<sup>1</sup>In such a case, the synchronization label is actually completely removed before the execution, in order to optimize the execution, and the user is warned of this removal.

**-time-limit <limit> (default: none)** Try to limit the execution time (the value <limit> is given in seconds). Note that, in the current version of IMITATOR, the test of time limit is performed at the end of an iteration only (i.e., at the end of a given *Post* iteration). In the cartography mode, this option represents a *global* time limit, not a limit for each call to the inverse method.

**-timed (default: false)** Add a timing information to each output of the program.

**-verbose (default: standard)** Give some debugging information, that may also be useful to have more details on the way IMITATOR works. The admissible values for **-verbose** are given below:

<b>nodebug</b>	Give only the resulting constraint
<b>standard</b>	Give little information (number of steps, computation time)
<b>low</b>	Give little additional information
<b>medium</b>	Give quite a lot of information
<b>high</b>	Give much information
<b>total</b>	Give really too much information

**-with-dot (default: false)** Graphical output using DOT. In this case, IMITATOR outputs a file <input\_file>.jpg, which is a graphical output in the jpg format, generated using DOT, corresponding to the trace set.

Note that the location and the name of those two files can be changed using the **-log-prefix** option.

**-with-graphics-source (default: false)** Keep file(s) generated for the graphical outputs.

**-with-log (default: false)** Generation of the files describing the reachable states. In this case, IMITATOR outputs a file <input\_file>.states containing the set of all the reachable states, with their names and the associated constraint on the clocks and parameters. If one wants to generate also the constraint on the parameters only, use the **-with-parametric-log** option. This file also contains the source for the generation of the graphical file, using the DOT syntax.

**-with-parametric-log (default: false)** For any constraint on the clocks and the parameters in the description of the states in the log files, add the constraint on the parameters only (i.e., eliminate clock variables).

### 4.3.5 Examples of Calls

`IMITATOR flipflop.imi -mode reachability` Computes a reachability analysis on the automata described in file `flipflop.imi`.

`IMITATOR flipflop.imi -mode reachability -with-dot -with-log` Computes a reachability analysis on the automata described in file `flipflop.imi`. Will generate files `flipflop.imi.states`, containing the description of the reachable states, and `flipflop.imi.jpg` depicting the reachability graph.

`IMITATOR flipflop.imi flipflop.pi0` Calls the inverse method on the automata described in file `flipflop.imi`, and the reference valuation  $\pi_0$  given in file `flipflop.pi0`. The resulting constraint  $K_0$  will be given on the standard output.

`IMITATOR flipflop.imi flipflop.pi0 -with-log -with-parametric-log` Calls the inverse method on the automata described in file `flipflop.imi`, and the reference valuation  $\pi_0$  given in file `flipflop.pi0`. The resulting constraint  $K_0$  will be given on the standard output. and `IMITATOR` will generate the file `flipflop.imi.states`, containing the description of the (parametric) states reachable under  $K_0$ . Moreover, for any state in this file, both the constraint on the clocks and the parameters, and the constraint on the parameters will be given.

`IMITATOR SRLatch.imi SRLatch.v0 -mode cover` Calls the behavioral cartography algorithm on the automata described in file `flipflop.imi`, and the rectangle  $V_0$  given in file `SRLatch.v0`. The algorithm will cover (at least) all the integer points within  $V_0$ . The resulting set of tiles will be given on the standard output.

`IMITATOR SRLatch.imi SRLatch.v0 -mode cover -with-dot -with-log` Calls the behavioral cartography algorithm on the automata described in file `flipflop.imi`, and the rectangle  $V_0$  given in file `SRLatch.v0`. The algorithm will cover (at least) all the integer points within  $V_0$ . The resulting set of tiles will be given on the standard output. Given  $n$  the number of generated tiles (i.e., the number of calls to the inverse method algorithm), the program will generate  $n$  files of the form `SRLatch.imi.i.states` (resp.  $n$  files of the form `SRLatch.imi.i.jpg`) giving the description of the states (resp. the reachability graph) of tile  $i$ , for  $i = 1, \dots, n$ .

`IMITATOR SRLatch.imi SRLatch.v0 -mode random100 -with-dot` Calls the behavioral cartography algorithm on the automata described in file

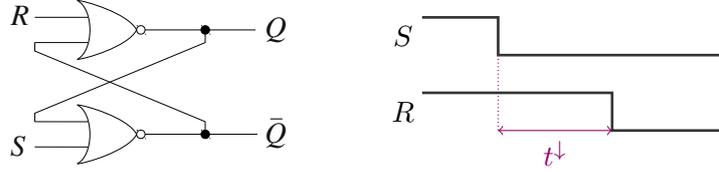


Figure 4: SR latch (left) and environment (right)

`flipflop.imi`, and the rectangle  $V_0$  given in file `SRlatch.v0`. The program will call the inverse method on 100 points randomly selected within  $V_0$ . Since some points may be generated several times, or some points may belong to previously generated tiles (see Section 4.3.3), the number  $n$  of tiles generated will be such that  $n \leq 100$ . The program will generate  $n$  files of the form `SRlatch.imi_i.jpg` giving the reachability graph of tile  $i$ , for  $i = 1, \dots, n$ .

## 5 Example: SR-latch

We consider a SR-latch described in, e.g., [10], and depicted on Figure 4 left. The possible configurations of the latch are the following ones:

$S$	$R$	$Q$	$\bar{Q}$
0	0	latch	latch
0	1	0	1
1	0	1	0
1	1	0	0

We consider an initial configuration with  $R = S = 1$  and  $Q = \bar{Q} = 0$ . As depicted in Figure 4, the signal  $S$  first goes down. Then, the signal  $R$  goes down after a time  $t^\downarrow$ .

We consider that the gate  $Nor_1$  (resp.  $Nor_2$ ) has a punctual parametric delay  $\delta_1$  (resp.  $\delta_2$ ). Moreover, the parameter  $t^\downarrow$  corresponds to the time duration between the fall of  $S$  and the fall of  $R$ .

### 5.1 Parametric Reachability Analysis

We first perform a reachability analysis. The launch command for IMITATOR is the following one:

```
IMITATOR SRlatch.imi -mode reachability
```

Considering this environment, the trace set of this system is given in Figure 5, where the states  $q_i$ ,  $i = 0, \dots, 6$  correspond to the following values for each signal:

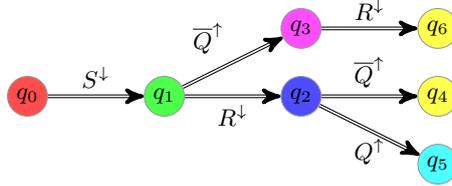


Figure 5: Parametric reachability analysis of the SR latch

State	$S$	$R$	$Q$	$\overline{Q}$
$q_0$	1	1	0	0
$q_1$	0	1	0	0
$q_2$	0	0	0	0
$q_3$	0	1	0	1
$q_4$	0	0	0	1
$q_5$	0	0	1	0
$q_6$	0	0	0	1

## 5.2 Behavioral Cartography Algorithm

Using IMITATOR, we now perform a behavioral cartography of this system. We consider the following rectangle  $V_0$  for the parameters:

$$\begin{aligned} t^\downarrow &\in [0, 10] \\ \delta_1 &\in [0, 10] \\ \delta_2 &\in [0, 10] \end{aligned}$$

The launch command for IMITATOR is the following one:

```
IMITATOR SRLatch.imi SRLatch.v0 -mode cover
```

We get the following six behavioral tiles. Note that the graphical outputs, automatically generated in the `jpg` format by IMITATOR using the `-with-dot` option, were rewritten in  $\text{\LaTeX}$  in this document.

**Tile 1.** This tile corresponds to the values of the parameters verifying the following constraint:

$$t^\downarrow = \delta_2 \quad \wedge \quad \delta_1 = 0$$

The trace set of this tile is given in Figure 6.

Since  $t^\downarrow = \delta_2$ ,  $R^\downarrow$  and  $\overline{Q}^\uparrow$  will occur at the same time. Thus, the order of those two events is unspecified, which explains the choice between going to  $q_2$  or  $q_3$ . When in state  $q_2$ , either  $Q^\uparrow$  can occur (since  $\delta_1 = 0$ ), in which case the system is stable, or  $\overline{Q}^\uparrow$  can occur, which also leads to stability.

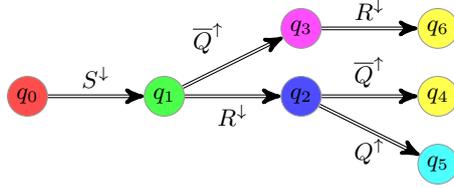


Figure 6: Trace set of tile 1 for the SR latch

**Tile 2.** This tile corresponds to the values of the parameters verifying the following constraint:

$$t^\downarrow = \delta_2 \quad \wedge \quad \delta_1 > 0$$

The trace set of this tile is given in Figure 7.

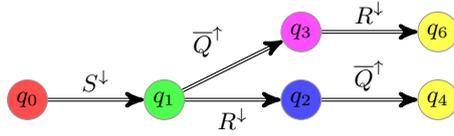


Figure 7: Trace set of tile 2 for the SR latch

Since  $t^\downarrow = \delta_2$ ,  $R^\downarrow$  and  $\overline{Q}^\uparrow$  will occur at the same time. Thus, the order of those two events is unspecified, which explains the choice between going to  $q_2$  or  $q_3$ . When in state  $q_2$ ,  $Q^\uparrow$  can not occur (since  $\delta_1 > 0$ ), so  $\overline{Q}^\uparrow$  occurs immediately after  $R^\downarrow$ , which leads to stability.

**Tile 3.** This tile corresponds to the values of the parameters verifying the following constraint:

$$\delta_2 > t^\downarrow + \delta_1$$

The trace set of this tile is given in Figure 8.

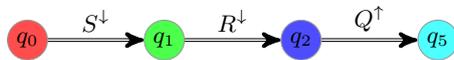


Figure 8: Trace set of tile 3 for the SR latch

In this case, since  $\delta_2 > t^\downarrow + \delta_1$ ,  $S^\downarrow$  will occur before the gate  $Nor_2$  has the time to change. For the same reason,  $Q^\uparrow$  will change before  $Nor_1$  has the time to change. With  $Q = 1$ , the system is now stable:  $Nor_1$  does not change.

**Tile 4.** This tile corresponds to the values of the parameters verifying the following constraint:

$$t^\downarrow + \delta_1 = \delta_2 \quad \wedge \quad \delta_2 \geq \delta_1 \quad \wedge \quad \delta_1 > 0$$

The trace set of this tile is given in Figure 9.

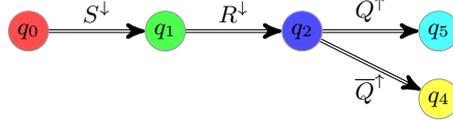


Figure 9: Trace set of tile 4 for the SR latch

Since  $t^\downarrow + \delta_1 = \delta_2$ , both  $Q^\uparrow$  or  $\overline{Q}^\uparrow$  can occur. Once one of them occurred, the system gets stable, and no other change occurs.

**Tile 5.** This tile corresponds to the values of the parameters verifying the following constraint:

$$\delta_2 > t^\downarrow \quad \wedge \quad t^\downarrow + \delta_1 > \delta_2$$

The trace set of this tile is given in Figure 10.

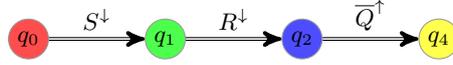


Figure 10: Trace set of tile 5 for the SR latch

Since  $\delta_2 > t^\downarrow$ , the gate  $Nor_2$  can not change before  $R^\downarrow$  occurs. However, since  $t^\downarrow + \delta_1 > \delta_2$ , the gate  $Nor_2$  changes before  $Q^\uparrow$  can occur, thus leading to event  $\overline{Q}^\uparrow$ .

**Tile 6.** This tile corresponds to the values of the parameters verifying the following constraint:

$$t^\downarrow > \delta_2$$

The trace set of this tile is given in Figure 11.

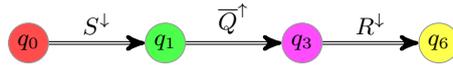


Figure 11: Trace set of tile 6 for the SR latch

Since  $t^\downarrow > \delta_2$ ,  $\overline{Q}^\uparrow$  occurs before  $S^\downarrow$ . The system is then stable.

**Cartography.** We give in Figure 12 the cartography of the SR latch example. For the sake of simplicity of representation, we consider only parameters  $\delta_1$  and  $\delta_2$ . Therefore, we set  $t^\dagger = 1$ .

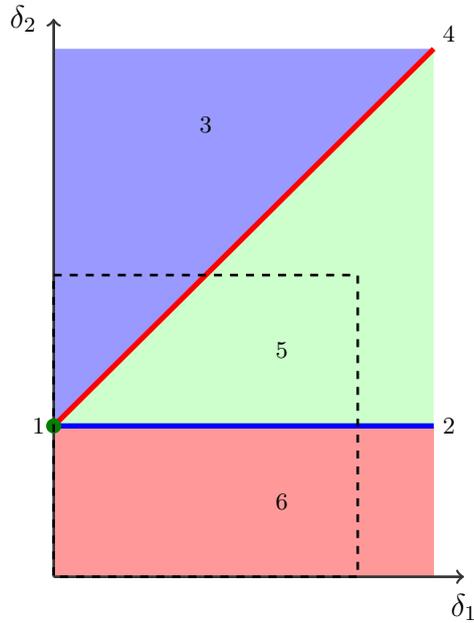


Figure 12: Behavioral cartography of the SR latch according to  $\delta_1$  and  $\delta_2$

Note that tile 1 corresponds to a point, and tiles 2 and 4 correspond to lines.

The rectangle  $V_0$  has been represented with dashed lines. Note that all tiles (except tile 1) are unbounded, so that they cover, not only  $V_0$ , but all the positive real-valued plan.

The source code of this example is available in [Appendix A](#).

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IMITATOR's logo comes from KaterBegemot's `Typing monkey.svg` (Licence: Creative Commons Attribution-Share Alike 3.0 Unported).

## References

- [1] Y. Adbeddaïm and O. Maler. Preemptive job-shop scheduling using stopwatch automata. In J.-P. Katoen and P. Stevens, editors, *Proceedings of the 8th International Conference on Tools and Algorithms for Construction and Analysis of Systems (TACAS'02)*, volume 2280 of *Lecture Notes in Computer Science*, pages 113–126. Springer-Verlag, Apr. 2002. [3](#)
- [2] R. Alur, C. Courcoubetis, T. A. Henzinger, and P.-H. Ho. Hybrid automata: An algorithmic approach to the specification and verification of hybrid systems. In R. L. Grossman, A. Nerode, A. P. Ravn, and H. Rischel, editors, *Hybrid Systems 1992*, volume 736 of *Lecture Notes in Computer Science*, pages 209–229. Springer, 1993. [3](#)
- [3] R. Alur, T. A. Henzinger, and M. Y. Vardi. Parametric real-time reasoning. In *Proceedings of the twenty-fifth annual ACM symposium on Theory of computing*, STOC'93, pages 592–601, New York, NY, USA, 1993. ACM. [3](#)
- [4] É. André and L. Fribourg. Behavioral cartography of timed automata. In A. Kučera and I. Potapov, editors, *Proceedings of the 4th Workshop on Reachability Problems in Computational Models (RP'10)*, volume 6227 of *Lecture Notes in Computer Science*, pages 76–90, Brno, Czech Republic, Aug. 2010. Springer. [6](#), [7](#)
- [5] É. André, L. Fribourg, U. Kühne, and R. Soulat. IMITATOR 2.5: A tool for analyzing robustness in scheduling problems. In D. Giannakopoulou and D. Méry, editors, *Proceedings of the 18th International Symposium on Formal Methods (FM'12)*, volume 7436 of *Lecture Notes in Computer Science*, pages 33–36, Paris, France, Aug. 2012. Springer. [1](#), [3](#)
- [6] É. André, L. Fribourg, and R. Soulat. Enhancing the inverse method with state merging. In A. Goodloe and S. Person, editors, *Proceedings of the 4th NASA Formal Methods Symposium (NFM'12)*, volume 7226 of *Lecture Notes in Computer Science*, pages 100–105, Norfolk, Virginia, USA, Apr. 2012. Springer. [5](#), [9](#)
- [7] É. André and R. Soulat. *The Inverse Method*. ISTE Ltd and John Wiley & Sons Inc., 2013. 176 pages. [3](#), [6](#), [9](#)
- [8] R. Bagnara, P. M. Hill, and E. Zaffanella. The Parma Polyhedra Library: Toward a complete set of numerical abstractions for the analysis and verification of hardware and software systems. *Science of Computer Programming*, 72(1–2):3–21, 2008. [5](#)

- [9] E. M. Clarke, O. Grumberg, S. Jha, Y. Lu, and H. Veith. Counterexample-guided abstraction refinement. In *CAV'00*, pages 154–169. Springer-Verlag, 2000. [3](#)
- [10] D. Harris and S. Harris. *Digital Design and Computer Architecture*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 2007. [13](#)
- [11] IMITATOR Team. IMITATOR Web page, 2013. [3](#), [5](#)
- [12] N. Markey. Robustness in real-time systems. In *Proceedings of the 6th IEEE International Symposium on Industrial Embedded Systems (SIES'11)*, pages 28–34, Västerås, Sweden, June 2011. IEEE Computer Society Press. [3](#)

## A Source Code of the Example

### A.1 Main Input File

```
1  ---***** ---
2  ---***** ---
3  ---  Laboratoire Specification et Verification
4  ---
5  ---  Race on a digital circuit (SR Latch)
6  ---
7  ---  Etienne ANDRE
8  ---
9  ---  Created:          2010/03/19
10 ---  Last modified : 2013/03/07
11 ---***** ---
12 ---***** ---
13
14 var      ckNor1, ckNor2, s
15           : clock;
16
17           dNor1_l, dNor1_u,
18           dNor2_l, dNor2_u,
19           t_down
20
21
22
23 ---***** ---
24 automaton norGate1
25 ---***** ---
26 synclabs: R_Up, R_Down, overQ_Up, overQ_Down,
27           Q_Up, Q_Down;
28
29 --- UNSTABLE
30 loc Nor1_000: while ckNor1 <= dNor1_u wait {}
31           when True sync R_Up do {} goto Nor1_100;
32           when True sync overQ_Up do {} goto Nor1_010;
33           when ckNor1 >= dNor1_l sync Q_Up do {} goto
34           Nor1_001;
35 --- STABLE
36 loc Nor1_001: while True wait {}
37           when True sync R_Up do {ckNor1' = 0} goto
38           Nor1_101;
39           when True sync overQ_Up do {ckNor1' = 0} goto
```

```

Nor1_011;
39
40 — STABLE
41 loc Nor1_010: while True wait {}
42     when True sync R_Up do {} goto Nor1_110;
43     when True sync overQ_Down do {ckNor1' = 0}
         goto Nor1_000;
44
45 — UNSTABLE
46 loc Nor1_011: while ckNor1 <= dNor1_u wait {}
47     when True sync R_Up do {ckNor1' = 0} goto
         Nor1_111;
48     when True sync overQ_Down do {} goto Nor1_001;
49     when ckNor1 >= dNor1_l sync Q_Down do {} goto
         Nor1_010;
50
51 — STABLE
52 loc Nor1_100: while True wait {}
53     when True sync R_Down do {ckNor1' = 0} goto
         Nor1_000;
54     when True sync overQ_Up do {} goto Nor1_110;
55
56 — UNSTABLE
57 loc Nor1_101: while ckNor1 <= dNor1_u wait {}
58     when True sync R_Down do {} goto Nor1_001;
59     when True sync overQ_Up do {ckNor1' = 0} goto
         Nor1_111;
60     when ckNor1 >= dNor1_l sync Q_Down do {} goto
         Nor1_100;
61
62 — STABLE
63 loc Nor1_110: while True wait {}
64     when True sync R_Down do {} goto Nor1_010;
65     when True sync overQ_Down do {} goto Nor1_100;
66
67 — UNSTABLE
68 loc Nor1_111: while ckNor1 <= dNor1_u wait {}
69     when True sync R_Down do {ckNor1' = 0} goto
         Nor1_011;
70     when True sync overQ_Down do {ckNor1' = 0}
         goto Nor1_101;
71     when ckNor1 >= dNor1_l sync Q_Down do {} goto
         Nor1_110;
72

```

```

73 end — norGate1
74
75
76 —***** —
77 automaton norGate2
78 —***** —
79 synclabs: Q_Up, Q_Down, S_Up, S_Down,
80 overQ_Up, overQ_Down;
81 — initially Nor2_110;
82
83 — UNSTABLE
84 loc Nor2_000: while ckNor2 <= dNor2_u wait {}
85 when True sync Q_Up do {} goto Nor2_100;
86 when True sync S_Up do {} goto Nor2_010;
87 when ckNor2 >= dNor2_l sync overQ_Up do {}
goto Nor2_001;
88
89 — STABLE
90 loc Nor2_001: while True wait {}
91 when True sync Q_Up do {ckNor2' = 0} goto
Nor2_101;
92 when True sync S_Up do {ckNor2' = 0} goto
Nor2_011;
93
94 — STABLE
95 loc Nor2_010: while True wait {}
96 when True sync Q_Up do {} goto Nor2_110;
97 when True sync S_Down do {ckNor2' = 0} goto
Nor2_000;
98
99 — UNSTABLE
100 loc Nor2_011: while ckNor2 <= dNor2_u wait {}
101 when True sync Q_Up do {ckNor2' = 0} goto
Nor2_111;
102 when True sync S_Down do {} goto Nor2_001;
103 when ckNor2 >= dNor2_l sync overQ_Down do {}
goto Nor2_010;
104
105 — STABLE
106 loc Nor2_100: while True wait {}
107 when True sync Q_Down do {ckNor2' = 0} goto
Nor2_000;
108 when True sync S_Up do {} goto Nor2_110;
109

```

```

110 -- UNSTABLE
111 loc Nor2_101: while ckNor2 <= dNor2_u wait {}
112     when True sync Q_Down do {} goto Nor2_001;
113     when True sync S_Up do {ckNor2' = 0} goto
        Nor2_111;
114     when ckNor2 >= dNor2_l sync overQ_Down do {}
        goto Nor2_100;

115
116 -- STABLE
117 loc Nor2_110: while True wait {}
118     when True sync Q_Down do {} goto Nor2_010;
119     when True sync S_Down do {} goto Nor2_100;

120
121 -- UNSTABLE
122 loc Nor2_111: while ckNor2 <= dNor2_u wait {}
123     when True sync Q_Down do {ckNor2' = 0} goto
        Nor2_011;
124     when True sync S_Down do {ckNor2' = 0} goto
        Nor2_101;
125     when ckNor2 >= dNor2_l sync overQ_Down do {}
        goto Nor2_110;

126
127 end -- norGate2
128
129
130 -----
131     automaton env
132 -----
133 synclabs: R_Down, R_Up, S_Down, S_Up;
134
135 -- ENVIRONMENT : first S then R at constant time
136 loc env_11: while True wait {}
137     when True sync S_Down do {s' = 0} goto env_10;
138
139 loc env_10: while s <= t_down wait {}
140     when s = t_down sync R_Down do {} goto
        env_final;

141
142 loc env_final: while True wait {}
143
144 end -- env
145
146 -----
147 -- ANALYSIS

```



## B Complete Grammar

### B.1 Grammar of the Input File

IMITATOR input is described by the following grammar. Non-terminals appear within angled parentheses. A non-terminal followed by two colons is defined by the list of immediately following non-blank lines, each of which represents a legal expansion. Input characters of terminals appear in typewriter font. The meta symbol  $\epsilon$  denotes the empty string.

The text **in green** is not taken into account by IMITATOR, but is allowed (or sometimes necessary) in order to allow the compatibility with HYTECH files.

```
<imitator_input> ::  
  <automata_descriptions> <init>
```

We define each of those two components below.

#### B.1.1 Automata Descriptions

```
<automata_descriptions> ::  
  <declarations> <automata>
```

```
<declarations> ::  
  var <var_lists>
```

```
<var_lists> ::  
  <var_list> : <var_type> ; <var_lists>  
  |  $\epsilon$ 
```

```
<var_list> ::  
  <name>  
  | <name> , <var_list>
```

```
<var_type> ::  
  clock  
  | discrete  
  | parameter
```

```
<automata> ::  
  <automaton> <automata>  
  |  $\epsilon$ 
```

```
<automaton> ::  
  automaton <name> <prolog> <locations> end
```

```

⟨prolog⟩ ::
    ⟨initialization⟩ ⟨sync_labels⟩
  | ⟨sync_labels⟩ ⟨initialization⟩
  | ⟨sync_labels⟩

⟨initialization⟩ ::
    initially <name> ⟨state_initialization⟩ ;

⟨state_initialization⟩ ::
    & ⟨convex_predicate⟩
  | ε

⟨sync_labels⟩ ::
    syncclabs : ⟨sync_var_list⟩ ;

⟨sync_var_list⟩ ::
    ⟨sync_var_nonempty_list⟩
  | ε

⟨sync_var_nonempty_list⟩ ::
    <name> , ⟨sync_var_nonempty_list⟩
  | <name>

⟨locations⟩ ::
    ⟨location⟩ ⟨locations⟩
  | ε

⟨locations⟩ ::
    loc <name> : while ⟨convex_predicate⟩ ⟨stop_opt⟩ ⟨wait_opt⟩ ⟨transitions⟩

⟨wait_opt⟩ ::
    wait()
  | wait
  | ε

⟨stop_opt⟩ ::
    stop{ ⟨var_list⟩ }
  | ε

⟨transitions⟩ ::
    ⟨transition⟩ ⟨transitions⟩
  | ε

⟨transition⟩ ::
    when ⟨convex_predicate⟩ ⟨update_synchronization⟩ goto <name> ;

```

$\langle \text{update\_synchronization} \rangle ::$   
 $\langle \text{updates} \rangle$   
 $| \langle \text{syn\_label} \rangle$   
 $| \langle \text{updates} \rangle \langle \text{syn\_label} \rangle$   
 $| \langle \text{syn\_label} \rangle \langle \text{updates} \rangle$   
 $| \epsilon$

$\langle \text{updates} \rangle ::$   
 $\text{do} ( \langle \text{update\_list} \rangle )$

$\langle \text{update\_list} \rangle ::$   
 $\langle \text{update\_nonempty\_list} \rangle$   
 $| \epsilon$

$\langle \text{update\_nonempty\_list} \rangle ::$   
 $\langle \text{update} \rangle , \langle \text{update\_nonempty\_list} \rangle$   
 $| \langle \text{update} \rangle$

$\langle \text{update} \rangle ::$   
 $\langle \text{name} \rangle ' = \langle \text{linear\_expression} \rangle$

$\langle \text{syn\_label} \rangle ::$   
 $\text{sync} \langle \text{name} \rangle$

$\langle \text{convex\_predicate} \rangle ::$   
 $\langle \text{linear\_constraint} \rangle \& \langle \text{convex\_predicate} \rangle$   
 $| \langle \text{linear\_constraint} \rangle$

$\langle \text{linear\_constraint} \rangle ::$   
 $\langle \text{linear\_expression} \rangle \langle \text{relop} \rangle \langle \text{linear\_expression} \rangle$   
 $| \text{True}$   
 $| \text{False}$

$\langle \text{relop} \rangle ::$   
 $<$   
 $| <=$   
 $| =$   
 $| >=$   
 $| >$   
 $| <>$

$\langle \text{linear\_expression} \rangle ::$   
 $\langle \text{linear\_term} \rangle$   
 $| \langle \text{linear\_expression} \rangle + \langle \text{linear\_term} \rangle$   
 $| \langle \text{linear\_expression} \rangle - \langle \text{linear\_term} \rangle$

```

⟨linear_term⟩ ::
  ⟨rational⟩
  | ⟨rational⟩ <name>
  | ⟨rational⟩ * <name>
  | <name>
  | ( ⟨linear_term⟩ )

⟨rational⟩ ::
  ⟨integer⟩
  | ⟨float⟩
  | ⟨integer⟩ / ⟨pos_integer⟩

⟨integer⟩ ::
  ⟨pos_integer⟩
  | - ⟨pos_integer⟩

⟨pos_integer⟩ ::
  <int>

⟨float⟩ ::
  ⟨pos_float⟩
  | - ⟨pos_float⟩

⟨pos_float⟩ ::
  <float>

```

### B.1.2 Initial State

```

⟨init⟩ ::
  ⟨init_declaration⟩ ⟨init_definition⟩ ⟨property_definition⟩ ⟨reach_command⟩

⟨init_declaration⟩ ::
  var init : region ;
  | ε

⟨reach_command⟩ ::
  print ( reach forward from init endreach ) ;
  | ε

⟨init_definition⟩ ::
  init := ⟨region_expression⟩ ;

⟨region_expression⟩ ::
  ⟨state_predicate⟩
  | ( ⟨region_expression⟩ )
  | ⟨region_expression⟩ & ⟨region_expression⟩

```

```

<state_predicate> ::
    loc [ <name> ] = <name>
    | <linear_constraint>

<property_definition> ::
    property := <pattern> ;
    | ε

<pattern> ::
    unreachable <loc_predicate>
    | if <name> then <name> has happened before
    | everytime <name> then <name> has happened before
    | everytime <name> then <name> has happened once before
    | if <name> then eventually <name>
    | everytime <name> then eventually <name>
    | everytime <name> then eventually <name> once before next
    | <name> within <linear_expression>
    | if <name> then <name> happened within <linear_expression> before
    | everytime <name> then <name> happened within <linear_expression> before
    | everytime <name> then <name> happened once within <linear_expression> before
    | if <name> then eventually <name> within <linear_expression>
    | everytime <name> then eventually <name> within <linear_expression>
    | everytime <name> then eventually <name> within <linear_expression> once before next
    | sequence <var_list>
    | sequence always <var_list>

<loc_expression> ::
    <loc_predicate>
    | <loc_predicate> & <loc_expression>
    | <loc_predicate> <loc_expression>

<loc_predicate> ::
    loc [ <name> ] = <name>

```

## B.2 Reserved Words

The following words are keywords and cannot be used as names for automata, variables, synchronization labels or locations.

always, and, automaton, bad, before, carto, clock, discrete, do, end, eventually, everytime, False, goto, happened, has, if, init, initially, loc, locations, next, not, once, or, parameter, property, region, sequence, stop, sync, synclabs, then, True, unreachable, var, wait, when, while, within