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Chapter 1

Introduction

IMITATOR is a free, open source software tool to perform automated parameter synthesis for concurrent timed systems [And21]. IMITATOR takes as input a network of IMITATOR parametric timed automata (NIPTA): NIPTA are an extension of parametric timed automata [AHV93], a well-known formalism to specify and verify models of systems where timing constants can be replaced with parameters, i.e., unknown constants.

IMITATOR addresses several variants of the following problem: “given a concurrent timed system, what are the values of the timing constants that guarantee that the model of the system satisfies some property?” Among other algorithms, IMITATOR implements parametric safety and reachability analysis [AHV93; JLR15], parametric liveness synthesis (with Büchi conditions) [NPV18; And+21], parametric deadlock-freeness synthesis [And16], robustness analysis (also known as the inverse method) [And+09; ALM20], the behavioral cartography [AF10], and parametric reachability preservation [And+15]. Some algorithms can also run distributed on a cluster. Numerous analysis options are available.

IMITATOR is a command-line only tool, but that can output results in graphical form.

IMITATOR was able to verify numerous case studies from the literature and from the industry, such as communication protocols, hardware asynchronous circuits, schedulability problems and various other systems such as models of coffee machines (probably the most critical systems from a researcher point of view). Numerous benchmarks are available at IMITATOR Web page [IMI-Web]. An official benchmarks library is available at [AMP21].

In this document, we present the input syntax, we formally define the input model of IMITATOR, and we explain how to perform various analyses using the numerous options.

Keywords: formal verification, model checking, software verification, parametric timed automata, parameter synthesis
Chapter 2

A brief introduction to the syntax

We first briefly introduce the syntax using a simple example for readers familiar with parametric timed automata, and not interested in subtle details (such as the synchronization model). A formal (and nearly exhaustive) definition of IMITATOR parametric timed automata (NIPTA) can be found in Chapter 3. The complete syntax is given in Chapter 9.

2.1 Generalities

IMITATOR performs parametric verification of models specified using networks of IMITATOR parametric timed automata (hereafter NIPTA). An IMITATOR parametric timed automaton (hereafter IPTA) is a variant of parametric automata (as introduced in [AHV93]). IPTA and NIPTA are formalized in Section 3.1.

The input syntax of IMITATOR is originally based on the syntax of HYTECH [HHW95], with several improvements. Still nowadays, the syntax of HYTECH (and PHAVerLite, reusing itself in part the HYTECH) models is remarkably close to IMITATOR.

Comments are OCaml-like comments starting with (* and ending with *). As in OCaml, comments can be nested.

The Fischer mutual exclusion protocol We use as a motivating example one timed version of the Fischer mutual exclusion protocol, coming from the PAT model checker [Sun+09]. This version of the protocol is neither the most complete, nor the most simple; we just use it here to introduce various aspects of the IMITATOR input syntax.

Fischer mutual exclusion protocol is a protocol that guarantees the mutual exclusion of several processes (here two) that want to access a shared resource (called the critical section).

2.2 Model syntax

We give below this model using the IMITATOR syntax. This model is given in graphical form in Fig. 2.1.\(^1\)

\(^1\)This \LaTeX\ representation, that makes use of the \LaTeX\ TikZ library, was automatically output by IMITATOR, using option -imi2TikZ, followed by some manual positioning optimization.
IMITATOR user manual

*IMITATOR MODEL*

* Fischer’s mutual exclusion protocol*

* Description : Fischer’s mutual exclusion protocol with 2 processes
* Correctness : Not 2 processes together in the critical section (location obs_violation unreachable)
* Source : PAT library of benchmarks
* Author : ?
* Input by : Étienne André
* Created : 2012/10/08
* Last modified : 2021/10/14
* IMITATOR version : 3.2

-----------------------------------------------

```
var
  x1, (* proc1’s clock *)
  x2, (* proc2’s clock *)
  : clock;

  turn,
  counter
  : int;

  delta,
  gamma
  : parameter;

IDLE = -1
  : int;

 Automaton proc1
------------------------------

Synclabs: access_1, enter_1, exit_1, no_access_1, try_1, update_1;

loc idle1: invariant True
  when turn = IDLE sync try_1 do {x1 := 0} goto active1;

loc active1: invariant x1 <= delta
  when True sync update_1 do {turn := 1, x1 := 0} goto check1;

loc check1: invariant True
  when x1 >= gamma & turn = 1 sync access_1 do {x1 := 0} goto access1;
  when x1 >= gamma & turn <> 1 sync no_access_1 do {x1 := 0} goto idle1;

loc access1: invariant True
  when True sync enter_1 do {counter := counter + 1} goto CS1;

loc CS1: invariant True
  when True sync exit_1 do {counter := counter - 1, turn := IDLE, x1 := 0} goto idle1;
```

-----------------------------------------------
end (* proc1 *)

(* ******************************************************)
automaton proc2
(* ******************************************************)
synclabs: access_2, enter_2, exit_2, no_access_2, try_2, update_2;

loc idle2: invariant True
  when turn = IDLE sync try_2 do {x2 := 0} goto active2;

loc active2: invariant x2 <= delta
  when True sync update_2 do {turn := 2, x2 := 0} goto check2;

loc check2: invariant True
  when x2 >= gamma & turn = 2 sync access_2 do {x2 := 0} goto access2;
  when x2 >= gamma & turn <> 2 sync no_access_2 do {x2 := 0} goto idle2;

loc access2: invariant True
  when True sync enter_2 do {counter := counter + 1} goto CS2;

loc CS2: invariant True
  when True sync exit_2 do {counter := counter - 1, turn := IDLE, x2 := 0} goto idle2;

end (* proc2 *)

(* ******************************************************)
automaton observer
(* ******************************************************)
synclabs: enter_1, enter_2, exit_1, exit_2;

loc obs_waiting: invariant True
  when True sync enter_1 goto obs_1;
  when True sync enter_2 goto obs_2;

loc obs_1: invariant True
  when True sync exit_1 goto obs_waiting;
  when True sync enter_2 goto obs_violation;

loc obs_2: invariant True
  when True sync exit_2 goto obs_waiting;
  when True sync enter_1 goto obs_violation;

(* NOTE: no outgoing action to reduce state space *)
loc obs_violation: invariant True

end (* observer *)

(* ******************************************************)
(* Initial state *)
(* ******************************************************)

init := {

**Header**  Let us comment this case model by starting with the header. First, text in comments gives generalities about the model (author, date, description, etc.). The form is not normalized, but it could be in the future, so it is strongly advised to follow this form.²

**Variable declarations**  The variable declarations starts with keyword `var`.

This model contains two clocks: `x1` is process 1’s clock, and `x2` is process 2’s clock.

This model contains two parameters: `delta` is the parametric duration specifying how long a process is idle at most, whereas `gamma` is the parametric duration specifying the minimum duration between the time a process checks for the availability of the critical section and the time the same process indeed enters the critical section (if it is still available).

²An empty model template with all these comments ready to be filled out (containing also a sample IPTA and its initial definitions) is available at: https://github.com/imitator-model-checker/imitator/blob/master/benchmarks/template.imi
Two integer-valued variables \textit{(i.e., global, discrete variables, see Section 3.1.2)} are used: \texttt{turn} checks which process is attempting to enter the critical section; \texttt{counter} records how many processes are in the critical section (this variable will not be used for the verification, but was used in the original PAT model, and we choose to keep it).

Finally, a global constant \texttt{IDLE} is set to -1 (just as in the original PAT model), and encodes that no process is attempting to enter the critical section.

\textbf{Automata} \hspace{1em} This model contains three IPTA: the first and second ones (\texttt{proc1} and \texttt{proc2}) model the first and second process, respectively. The third one (\texttt{observer}) is an observer, \textit{i.e.,} an IPTA that checks the system behavior without modifying it.

\textbf{The first process} \hspace{1em} Let us first describe the IPTA \texttt{proc1} (a graphical representation is given in Fig. 2.1a). This IPTA uses six actions, given in the \texttt{synclabs} declaration.

\texttt{proc1} is initially in location \texttt{idle1}, with no invariant (depicted by \texttt{invariant True}). At any time, when the discrete variable \texttt{turn} is equal to \texttt{IDLE}, then this IPTA may synchronize on action \texttt{try_1}, reset its clock \texttt{x1}, and enter location \texttt{active1}.

The invariant of this location is \texttt{x1 <= delta}, \textit{i.e.,} \texttt{proc1} can only remain in \texttt{active1} as long as the value of \texttt{x1} does not exceed \texttt{delta}. At any time, this IPTA may synchronize on action \texttt{update_1}, reset its clock \texttt{x1} and set the global variable \texttt{turn} to 1, and enter location \texttt{check1}.

In location \texttt{check1}, the process wait at least \texttt{gamma} time units (modeled by the inequality \texttt{x1 >= gamma}, in all outgoing transitions). If \texttt{turn} is still equal to 1 (that is, no other process attempted in the meanwhile to enter the critical section), then process 1 is indeed ready to enter the critical section, by synchronizing \texttt{access_1} and resetting \texttt{x1}. If \texttt{turn} is different from 1 (that is, another process attempted in the meanwhile to enter the critical section, and it is not safe for process 1 to enter), then process 1 returns to its idle location, by synchronizing \texttt{no_access_1} and resetting \texttt{x1}.

In location \texttt{access1}, process 1 can remain any time, and eventually enters the critical section by synchronizing \texttt{enter_1} and incrementing the global variable \texttt{counter} by 1.

In location \texttt{CS1}, process 1 can remain any time, and eventually leaves it, by decrementing the global variable \texttt{counter} by 1, and setting the global variable \texttt{turn} to its initial value \texttt{IDLE}.

\textbf{The second process} \hspace{1em} Process 2 is identical to process 1, except that \texttt{x1} is replaced with \texttt{x2}, and that the value of \texttt{turn} becomes 2.

\textbf{The observer} \hspace{1em} The observer is in charge to check that no more than one process is in critical section at the same time.\footnote{This observer is not really necessary to check the correctness of this protocol; instead of adding this observer and checking \texttt{unreachable loc[observer] = obs_violation}, one could just check either \texttt{counter > 1} or \texttt{loc[proc1] = CS1 & loc[proc2] = CS2}. However, this example comes from an earlier version of IMITATOR (that did not support checking global variables or more that one location in the \texttt{unreachable} property — which has been fixed since version 2.7); furthermore, introducing an observer is also useful, as it is often used for the verification of more complex properties \textit{(see, e.g., [ABL98; Ace+98]).}} This observer will detect that this situation happens if an action \texttt{enter_1} is followed by an action \texttt{enter_2} without an action \texttt{exit_1} in between (or symmetrically if an action \texttt{enter_2} is followed by an action \texttt{enter_1} without an action \texttt{exit_2} in
Figure 2.1: Fischer mutual exclusion protocol (graphical NITPA)
between). Note that the observer simply observes the system state, and synchronizes on the actions used by proc1 and proc2; it does not use any clock nor variable.

A graphical representation of the IPTA observer is given in Fig. 2.1b.

**Initial state definition** The initial state is defined by the part of the file following init :=.

Since IMITATOR 3.1, the initial definition section is split between the discrete initialization and the continuous initialization (the latter being given in the form of a set of constraints).

The discrete initialization (introduced by the discrete keyword) assigns an initial value to each discrete (global) variable, and sets the initial location for each automaton. Note that the assignment operator := is used (in contrast with unification operator = used for constraints). For example, loc[proc1] := idle1 states that proc1 is initially in location idle1. The initial definition should assign a constant value to each discrete variable: here turn is initially assigned to IDLE, and counter is initially assigned to 0.

The continuous initialization (introduced by the continuous keyword) defines the initial constraints over clocks and parameters (possibly also using discrete variables). The initial definition may (only may, see Section 3.3) give an initial value to the clocks, for example requiring them to be equal to some constant (typically 0). In our example, clocks are only bound to be greater or equal to 0. Finally, in this example, parameters are bound to be non-negative as well. Note that the initial definition can introduce more complex constraints over clocks, parameters and discrete variables; see Section 3.3 for details.

### 2.3 Property syntax

**Property specification** For this model, the correctness property is that two processes cannot be in the critical section at the same time; as explained above, this is equivalent to the fact that the obs_violation location of the observer IPTA is unreachable. This is input in the property as follows:

```
property := #synth AGnot(loc[observer] = obs_violation);
```

Here, AGnot stands for safety. More elaborate properties are detailed in Section 4.7.

We give below the whole property file:

```
(* *******************************************************
  IMITATOR MODEL
  *
  * Fischer's mutual exclusion protocol
  *
  * Description : Fischer's mutual exclusion protocol with 2 processes
  * Correctness : Not 2 processes together in the critical section (location
    obs_violation unreachable)
  * Source : PAT library of benchmarks
  * Author : ?
  * Input by : Étienne André
  *
  * Created : 2012/10/08
  * Last modified : 2020/04/03
  *
  * IMITATOR version: 3
  *******************************************************)
```
Parameter synthesis  Finally, let us run IMPITATOR on this case study. Quite naturally, what we would be interested in is knowing for which parameter valuations this protocol is correct, i.e., no more than one process can be present in the critical section at one time. Assuming this model is input in file fischer.imi and the property is in file fischer.imiprop, the command calling IMPITATOR is as follows:

```iml
imitator fischer.imi fischer.imiprop
```

The result of the call to IMPITATOR is

```
Final positive constraint guaranteeing safety:
delta >= 0
& gamma > delta
This positive constraint is exact (sound and complete)
```

That is, the system is safe if $0 \leq \delta < \gamma$, which is the well-known constraint ensuring mutual exclusion for this protocol.
Chapter 3

IMITATOR Parametric Timed Automata

This chapter formally introduces the input model ofIMITATOR.

3.1 Formal definition

IMITATOR performs parametric verification of models specified using networks ofIMITATOR parametric timed automata (hereafter NIPTA).

AnIMITATOR parametric timed automaton (hereafter IPTA) is a variant of parametric automata (as introduced in [AHV93]). IPTA augment the expressiveness of PTA from [AHV93] with several features such as invariants, discrete (rational) variables, complex guards and invariants (i.e., not only comparing a single clock to a single parameter), stopwatches (i.e., the ability to stop some clocks in some locations), multi-rate clocks (i.e., the speed of a clock is not necessarily 1, and can be defined to any rational) and arbitrary clock updates (i.e., not necessarily to 0, but also to rationals, other clock valuations or even parameters).

3.1.1 Clocks, parameters

Clocks are real-valued variables. A set of clocks is \(X = \{x_1, \ldots, x_H\}\); a clock valuation is \(w : X \rightarrow \mathbb{R}_{\geq 0}\). By default, all clocks are evolving at the same rate (1), but this rate can be defined to any rational value inIMITATOR. Clocks can also be stopped inIMITATOR, i.e., their rate can be null.

Parameters are rational-valued variables, that act as unknown constants. A set of parameters is \(P = \{p_1, \ldots, p_M\}\); a parameter valuation is a function \(v : P \rightarrow \mathbb{R}\). We will often identify a valuation \(v\) with the point \((v(p_1), \ldots, v(p_M))\).

3.1.2 Discrete variables

IMITATOR features discrete variables. Discrete variables\(^1\) are global variables. Their value is global, in the sense that they are shared by all IPTA of the model. They can be seen as syntactic sugar to represent a possibly unbounded number of locations.

\(^1\)The name “discrete variable” comes from HYTECH.
Discrete variables must be initialized to a single constant value in the \texttt{init} definition; if they are not, a warning is issued, and they are arbitrarily set to a standard value (e.g., 0 for numerical variables, or \texttt{false} for Boolean variables; see Section 3.3 for the actual value).

Discrete variables can be tested in guards, and updated along transitions.

IMITATOR currently supports four types of discrete variables:

1. rational-valued variables
2. “int”-valued variables (over 32 bits)
3. Boolean variables
4. binary word variables, allowing to use bitwise binary operations.

### 3.1.2.1 Rational-valued variables

\textit{Rational variables} are rational-valued variables.

In IMITATOR, rationals are exact and unbounded, just as in maths (i.e., they are \textit{not} represented using a limited number of bits, such as 32 or 64 bits). Rational variables are encoded in IMITATOR as \textit{exact rational arithmetics}, thanks to the GNU Multiple Precision Arithmetic (GMP) library. Therefore, neither floating-point approximation, nor overflow, can occur; and the representation of the constraints is always exact. Note that floating-point numbers (“float”) are totally absent from the IMITATOR implementation (except for the generation of graphical outputs).

In the following, we define the set of rational variables as $R = \{r_1, \ldots, r_J\}$; a rational variable valuation is a function $\rho : R \rightarrow \mathbb{Q}$.

### 3.1.2.2 “Int”-valued variables

\textit{Int variables} are bounded signed integer-valued variables encoded on 32 bits (which is architecture independent).

Int variables are encoded in IMITATOR using the \texttt{int} type of OCaml.

\textit{Warning 1 (int encoding).} All arithmetic operations over the “int” variables are taken modulo $2^{32}$. Overflow can therefore occur.

For critical models, it is highly advised to use \textit{rational} variables instead (the computation using rational variables may be significantly slower but always exact).

Formally, the set of integer variables is $I = \{i_1, \ldots, i_K\}$; an integer variable valuation is a function $\iota : I \rightarrow \mathbb{Z} \cap [-2,147,483,648, +2,147,483,647]$.

### 3.1.2.3 Boolean variables

IMITATOR also features \textit{Boolean-valued variables}. The set of Boolean variables is $B = \{b_1, \ldots, b_L\}$; a Boolean variable valuation is a function $\beta : B \rightarrow \mathbb{B}$, where $\mathbb{B} = \{\text{true, false}\}$. 
3.1.2.4 Binary word variables

Binary word variables are sequences of bits of fixed length—the maximum size of a binary word is $2^{16}$. Bitwise operations can be defined on these variables (on same length).

For example, defining two binary words $bw_1$ and $bw_2$ both of size 4 (type : binary(4)), such that initially $bw_1 := 0b1010$ and $bw_2 := 0b1011$, we can use a guard $\text{logor}(bw_1, bw_2) <> bw_1$ that checks whether the result of the bitwise (logical) “or” operation on both variables differs from $bw_1$. Then, if this check is true, one may want to shift the bits of $b1$ by 2 positions, and set $bw_2$ to the result of the bitwise “and” operation on $bw_1$ and $bw_2$. A transition featuring such a guard and such updates would be written as follows in IMITATOR syntax:

```plaintext
when logor(bw1, bw2) <> bw1 sync a do {bw1 := shift_left(bw1, 2), bw2 := logand(bw1, bw2)} goto l1;
```

Note that binary words are of fixed length, and operations can only be applied to words of the same length.

We denote by $W$ the set of binary word variables.

3.1.2.5 Built-in functions over discrete variables

IMITATOR 3.1 and higher comes with some built-in functions over discrete variables:

**Arithmetic functions**

- $\text{pow}(x : \text{'a}, e : \text{int}) : \text{'a}$ with $\text{'a} : \{\text{rational} | \text{int}\}$: compute the power of a number

**Conversion functions**

- $\text{rational_of_int}(x : \text{int}) : \text{rational}$: convert an int number to a rational one

**Binary word functions**

- $\text{shift_left}(b : \text{binary_word(l)}, i : \text{int}) : \text{binary_word(l)}$: shift a binary word of length $l$ to left
- $\text{shift_right}(b : \text{binary_word(l)}, i : \text{int}) : \text{binary_word(l)}$: shift a binary word of length $l$ to right
- $\text{fill_left}(b : \text{binary_word(l)}, i : \text{const int}) : \text{binary_word(l + i)}$: shift a binary word of length $l$ to left (non destructive)
- $\text{fill_right}(b : \text{binary_word(l)}, i : \text{const int}) : \text{binary_word(l + i)}$: shift a binary word of length $l$ to right (non destructive)
- $\text{logand}(b1 : \text{binary_word(l)}, b2 : \text{binary_word(l)}) : \text{binary_word(l)}$: apply AND bitwise operation to two binary words of length $l$
• logor(b1 : binary_word(1), b2 : binary_word(1)) : binary_word(1): apply OR bitwise operation to two binary words of length 1
• logxor(b1 : binary_word(1), b2 : binary_word(1)) : binary_word(1): apply XOR bitwise operation to two binary words of length 1
• lognot(b : binary_word(1)) : binary_word(1): apply NOT bitwise operation to a binary word of length 1

Example 3.1. To illustrate the binary words operations, note that all the following guards in the model fragment below will evaluate to true:

<table>
<thead>
<tr>
<th>Guard</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>when shift_left(0b010110 . 3) = 0b110000 goto 11;</td>
<td></td>
</tr>
<tr>
<td>when shift_right(0b010110 . 3) = 0b000010 goto 11;</td>
<td></td>
</tr>
<tr>
<td>when fill_left(0b010110 . 3) = 0b01011000 goto 11;</td>
<td></td>
</tr>
<tr>
<td>when fill_right(0b010110 . 3) = 0b000010110 goto 11;</td>
<td></td>
</tr>
<tr>
<td>when logand(0b010110 . 0b101010 ) = 0b000010 goto 11;</td>
<td></td>
</tr>
<tr>
<td>when logor(0b010110 . 0b101010 ) = 0b111110 goto 11;</td>
<td></td>
</tr>
<tr>
<td>when logxor(0b010110 . 0b101010 ) = 0b111100 goto 11;</td>
<td></td>
</tr>
<tr>
<td>when lognot(0b010110 ) = 0b101001 goto 11;</td>
<td></td>
</tr>
</tbody>
</table>

3.1.2.6 Discrete variables definition

The set of discrete variables is \( D = R \cup I \cup B \cup W \).

3.1.3 Linear constraints

Let us formalize the set of linear constraints allowed in IMITATOR. Given a set of variables \( Var = \{z_1, \ldots, z_N\} \) (in the following, this set will be instantiated with \( X \) and/or \( P \) and/or \( R \)), a linear term over \( Var \) is an expression of the form

\[
\sum_{1 \leq i \leq n} a_i z_i + d
\]

for some \( n \in \mathbb{N} \), where \( z_i \in Var \), \( a_i \in \mathbb{Q} \), for \( 1 \leq i \leq n \), and \( d \in \mathbb{Q} \).

An atomic constraint over \( Var \) is an expression of the form \( lt \sigma 0 \) where \( lt \) is a linear term over \( Var \), and \( \sigma \in \{<, \leq, =, \geq, >\} \).

A constraint over \( Var \) is a conjunction of atomic constraints. We denote by \( LT(Var) \) the set of linear terms over \( Var \), and by \( LE(Var) \) the set of constraints over \( Var \). In IMITATOR, we will consider constraints belonging to sets such as \( LE(X \cup P) \) (i.e., the set of constraints over clocks and parameters), or \( LE(X \cup P \cup R) \) (i.e., the set of constraints over clocks, parameters and discrete rational-valued variables).

3.1.4 Arithmetic expressions

Let \( AE(R) \) denote the set of arithmetic expressions over the numerical discrete rational variables, \( i.e., \) made of addition, subtraction, multiplication, and division over rational (or integer) constants and discrete numerical variables.
3.1.5 IMITATOR Parametric Timed Automata

We can now give a formal definition of IPTA.

**Remark 3.1.** In the subsequent formal definition, we rule out int-valued variables, Boolean variables and binary words, for sake of simplicity. They can be used in a straightforward manner. That is, guards (and invariants) can also include operations on such variables. See the grammar in Chapter 9 for the exact behavior allowed by IMITATOR.

Let $\epsilon$ denote the unobservable action.

**Definition 3.1 (IPTA).** An IMITATOR parametric timed automaton (IPTA) is a tuple $\mathcal{A} = \langle \Sigma, L, \ell_{\text{init}}, D, X, P, I, \text{flow}, \rightarrow \rangle$, where:

- $\Sigma$ is a finite set of actions;
- $L$ is a finite set of locations;
- $\ell_{\text{init}} \in L$ is the initial location;
- $D$ is a set of rational-valued variables;
- $X$ is a set of clocks;
- $P$ is a set of parameters;
- $I : L \rightarrow \mathcal{L}^\mathcal{C}(X \cup P \cup R)$ assigns to every location $\ell$ a constraint over all variables, called the invariant of $\ell$;
- $\text{flow} : L \times X \rightarrow \mathbb{Q}$ assigns to a every location and clock a given flow (or speed), i.e., a rational number;
- $\rightarrow$ is a set of edges $(\ell, g, a, X_{\text{up}}, D_{\text{up}}, \ell')$, where $\ell, \ell' \in L$ are the source and destination locations, $g \in \mathcal{L}^\mathcal{C}(X \cup P \cup R)$ is a constraint over all variables (called guard of the transition), $a \in \Sigma \cup \{\epsilon\}$ is the action associated with the transition, $X_{\text{up}} : X \rightarrow \mathcal{L}^\mathcal{T}(X \cup P \cup R)$ is the (possibly partial) update function for clocks, and $D_{\text{up}} : R \rightarrow \mathcal{A}^\mathcal{C}(R)$ is the (possibly partial) update function for discrete rational variables.

In the following, we explain this definition.

**Guards and invariants** Guards and invariants in IMITATOR are linear constraints over all variables. For example, the following expression can be used in a guard or an invariant:

\[
\begin{align*}
\mathbf{r}_1 + .5 \mathbf{x}_1 + 3 \mathbf{x}_2 &\geq 2 \mathbf{p}_1 - \mathbf{r}_2 &\& \mathbf{p}_2 < 1/3 
\end{align*}
\]

where $\mathbf{r}_1$, $\mathbf{r}_2$ are discrete rational variables, $\mathbf{x}_1$, $\mathbf{x}_2$ are clocks and $\mathbf{p}_1$, $\mathbf{p}_2$ are parameters. This syntax includes in particular diagonal constraints (e.g., $\mathbf{x}_1 - \mathbf{x}_2 \leq 2$), not always supported in other model-checking tools.
**Actions**  Transitions can be synchronized on an action in $\Sigma$, or have no synchronized action ("$\epsilon$"), which is often referred to in the literature as a silent transition, or an $\epsilon$-transition. For the semantics of the synchronization model between various IPTA, refer to Section 3.4. A non-silent transition is said to be observable, and it can be synchronized with other automata.

**Clock updates**  Observe that clocks can be updated to any value, i.e., a clock can be assigned not only to 0, but to any linear term over the other clocks, the parameters and the discrete rational variables. This considerably extends the traditional syntax of PTAs defined in [AHV93]. In fact, the IMITATOR includes (more than just) the updatable timed automata of [Bou+04], as well as the reset-to-parameter (parametric) timed automata of [ALR18b]. If clocks are always reset to constants (i.e., not assigned to more complex linear terms), IMITATOR will apply some optimizations that (may) increase the analysis speed.

**Discrete updates**  Discrete variables can be assigned to expressions compatible with their type. Notably, rational variables can be assigned to rational arithmetic expressions over $R$. On the one hand, this is more restrictive than clock updates, because discrete rational variables cannot be assigned to a clock or to a parameter. On the other hand, arithmetic expressions are richer than linear constraints, as they allow multiplication or division of rational variables with each other.

Since version 2.12, if-then-else conditions are allowed in discrete updates.

**Flows and stopwatches**  By default, all clocks evolve at the same rate in all locations, and this rate is 1. That is, by default, $\forall \ell \in L, \forall x \in X : \text{flow}(\ell, x) = 1$.

However, one can explicitly define an alternative (constant, rational-valued) flow using two methods:

**Using stopwatches**  A stopwatch is a clock whose elapsing is stopped in some locations, i.e., $\text{flow}(\ell, x) = 0$. There is no distinction between clocks and stopwatches. That is, any clock can potentially be stopped in some location. IMITATOR will detect whether a model has or not stopwatches; if there is no stopwatch in the model, IMITATOR will apply some optimizations that (may) increase the analysis speed.

Clocks can be stopped in locations, thanks to the optional **stop** \{ ... \} keyword (see grammar in Section 9.2). A clock is stopped in a location if it belongs to the list of clocks in **stop** \{ ... \}. It is resumed when leaving the location—unless the target location again stops this clock.

**Using explicit flows**  IMITATOR also support constant flows, i.e., multi-rate (parametric) timed automata [Alu+95]. That is, it is possible to specify the speed of a clock in a location. This value is an arbitrary rational number, including 0 (in which case it is equivalent to a stopwatch) or a negative number. This can be specified using a syntax of the following form: \text{flow} \{x' = 2\}. A clock for which no flow is explicitly defined has of course flow 1. A stopwatch has flow 0.
Remark 3.2. It is possible to defined ill-formed models where contradictory flows are defined for a given clock. For example, in

\[ \text{stop \{ x \} flow \{ x' = 2, y' = 0 \} } \]

\( x \) is assigned both flow 0 (because it is defined as a stopped clock) and 2 (in the explicit flow definition).

Alternatively, in an NIPTA, it is possible to be in a global location such that, in one location of one of the automata a given clock is assigned a given flow, and in another location of another automata in parallel, the same clock is assigned another flow.

In the case of such contradictory flows, IMITATOR will trigger a warning on-the-fly, and the result of the analysis is unspecified.

**Urgent locations**  A location can be defined as urgent, using the keyword urgent (see grammar in Section 9.2). In an urgent location, time cannot elapse, i.e., it must be left in 0-time. Note however that “in 0-time” does not necessarily mean immediately: that is, several actions may be performed (in 0-time) before the location is left.

### 3.1.6 Networks of IMITATOR Parametric Timed Automata

**Definition 3.2** (NIPTA). Given a set of IPTA \( \mathcal{A}_i = \langle \Sigma_i, L_i, (\ell_{\text{init}})_i, D_i, X_i, P_i, I_i, \text{flow}_i, \rightarrow_i \rangle \), \( 1 \leq i \leq N \) for some \( N \in \mathbb{N} \), a network of IPTA (NIPTA) is a tuple \( \langle \Sigma, D, X, P, \{ \mathcal{A}_i \mid 1 \leq i \leq N \}, C_{\text{init}} \rangle \), where:

- \( \Sigma = \bigcup_{1 \leq i \leq N} \Sigma_i \) is the set of all actions;
- \( D = \bigcup_{1 \leq i \leq N} D_i \) is the set of all discrete variables;
- \( X = \bigcup_{1 \leq i \leq N} X_i \) is the set of all clocks;
- \( P = \bigcup_{1 \leq i \leq N} P_i \) is the set of all parameters;
- \( C_{\text{init}} \in \mathcal{L}[X \cup P \cup R] \) is the initial constraint over \( R, X \) and \( P \).

Observe that each set of actions, discrete variables, clocks and parameters is not disjoint between all IPTA. That is, actions, discrete variables, clocks and parameters may be shared between different IPTA. If a variable is required to be local to an IPTA, then it should just not be used in any other IPTA of the model.

Different from many tools for (parametric) timed automata, clocks are not necessarily initially equal to 0 (this is similar to HyTech [HHW95] but different from UPPAAL [LPY97]). The initial value of the clocks is defined by \( C_{\text{init}} \) (see Section 3.3). If nothing is defined in \( C_{\text{init}} \), then their value is supposed to be arbitrary (any real value).

In an NIPTA, a clock \( x \) is stopped in a location \( (\ell_1, \ldots, \ell_N) \) if it stopped in at least one of the locations \( \ell_i \), i.e., \( x \in \text{flow}_i(\ell_i) = 0 \) for some \( i \in \{1, \ldots, N\} \).

Note that parameters are not assumed to be positive; however, the behavior of IMITATOR has not been tested for negative parameters, and it is strongly advised to constrain them to be non-negative in \( C_{\text{init}} \) (if it is not the case, a warning is issued by IMITATOR).
Finally, note that the number of IPTA, locations, variables and actions that can be defined in a model is bounded in IMITATOR by some very large number (most probably $2^{32}$); but, well, you don’t seriously plan to build such a large model, do you?

IMITATOR may use the determinism in (yet to come) algorithms; and the deterministic nature of an NIPTA is detected by IMITATOR. In our setting, the strong determinism denotes at most one transition going out from a location and labeled with a given observable (i.e., non-silent) transition. Let us precisely define what it means:

**Definition 3.3** (strong determinism). Let $\mathcal{A}$ be an NIPTA made of $N$ IPTA $\mathcal{A}_i = (\Sigma_i, L_i, (\ell_{in_i}), D_i, X_i, P_i, I_i, flow_i, -i), 1 \leq i \leq N$ for some $N \in \mathbb{N}$.

$\mathcal{A}$ is strongly-deterministic if for all automaton $\mathcal{A}_i$, for all location $\ell_i \in L_i$, for all observable action $a \in \Sigma_i$, there exists at most one transition from $\ell_i$ labeled with $a$.

### 3.2 Discrete variables updates

Discrete variables are first tested, then updated. If two IPTA in parallel update the same variable on the same synchronized transition (e.g., an IPTA performs $i := 2$ while another one performs $i := 3$), then a warning is issued, and the behavior of the NIPTA becomes unspecified (i.e., IMITATOR will choose one or the other assignment in an unspecified manner). If a division by zero is encountered (e.g., in an update $i := 2 / i$, when the current value of $i$ is 0), an exception is raised and IMITATOR terminates with an error.

### 3.3 Initial state and initialization of variables

For each IPTA, a unique initial location must be defined.

For variables, the definition of the initial value is very permissive in IMITATOR. Clocks are not necessarily equal to 0, and parameters are not even necessarily positive.

Parameters and clocks can be initially bound by any linear constraint over parameters, clocks, and discrete variables. That is, we can define initial constraints such as:

$$x_1 + x_2 \leq 2 \cdot p_1 + 0.5 \cdot p_2 - i$$

However, discrete variables must be initialized to a constant compatible with their type. Given a discrete variable $i$, if the definition of the initial state does not contain an equality of the form $i := \ldots$, followed by a constant (or a linear term over $\mathbb{F}(R)$, for rational variables), then IMITATOR will assume that $i$ is initially set to a default value, and will issue a warning.

This initial default value is as follows, depending on the variable type:

- Rational: 0
- Integer: 0
- Boolean: false
- Binary words: 0b0
### 3.4 Synchronization model

By default, all IPTA of an IMITATOR model declare their set of actions.\(^2\)

The IMITATOR synchronization model is such that all IPTA declaring an action must synchronize together on this action. This can be seen as a *strong broadcast*. That is, for a transition labeled with action \(a\) to be executed, all IPTA declaring \(a\) must be ready to execute \(a\) locally. Otherwise, this transition cannot be taken (yet).

If an IPTA declares an action \(a\) that is never used in this IPTA, then action \(a\) will never be executed in the entire model.\(^3\)

### 3.5 Global constants

IMITATOR supports global constants, *i.e.*, a variable the value of which is known once for all. The syntax is the following one:

\[
c = 1 : \text{constant};
\]

Then, any occurrence of \(c\) in the model is replaced with \(1\).

By default, constants are (unbounded, exact) rationals. It is possible to define constants of another type by making their type explicit:

\[
c = 1 : \text{int};
\]

In this case, \(c\) is a constant of type \text{int}.

Limited linear expressions over rationals can be used in the definition of a (rational) constant; however no other constant can be used in a definition, *i.e.*, one cannot (yet) write \(c1 = c2 + 1 : \text{constant};\).

**Hint 3.1.** In fact, a variable (*e.g.*, a parameter) can be turned to a constant as follows in the definition of the parameters:

\[
p = 2 : \text{parameter};
\]

This is equivalent to replacing \(p\) with \(2\) everywhere in the model; this is particularly useful when some parameters should be instantiated. In contrast, if the parameter is instantiated in the initial definition, IMITATOR still counts it as a parameter, which makes all constraints suffer from an additional dimension.

---

\(^2\)An alternative is an automatic recognition of the actions used, see option –\texttt{sync-auto-detect} in Chapter 8.

\(^3\)In this case, IMITATOR will detect this situation and will entirely delete this action from the model, while issuing a warning.
Chapter 4

Parameter synthesis using IMITATOR

We give here the commands corresponding to the main analysis features of IMITATOR. We only give the most useful options. For more detailed commands, and a complete list of options, see Chapter 8.

4.1 Synthesis and emptiness

**Main command**  The standard IMITATOR command for all algorithms is:

```
imitator model.imi property.imiprop
```

**Synthesis and emptiness**  IMITATOR features two modes for properties:

- synthesis (#synth): synthesizing all valuations such that a property holds;
- witness (#exhibit or #witness, both equivalent): find (at least) one valuation such that a property holds.

While the “witness” mode is close to (the contrary of) emptiness-checking, the “witness” mode is not strictly speaking an emptiness check: rather, the algorithm stops as soon as it finds some valuations, but there may be more than one, so the result can still be symbolic. For example, in the case of reachability-checking, IMITATOR would output the parameter valuations associated with the first target symbolic state found.

While all properties implement synthesis, not all of them implement emptiness; a warning would then be raised.

In the following, we now describe the algorithms implemented in IMITATOR.

4.2 Reachability

A main problem in parametric timed automata is to compute the set of parameter valuations for which some location (for instance, an error location) is reachable.
The property syntax is as follows:

\[
\text{property} := \#\text{synth EF(state\_predicate)};
\]

where \text{state\_predicate} is a state predicate, for example of the form \text{loc[AUTOMATON] = LOCATION}, where AUTOMATON is an automaton name, and LOCATION is a location name. State predicates allow conjunction, disjunction and the use of global discrete variables (see Section 9.3 for details).

The algorithm EFsynth implemented in IMITATOR is a basic breadth-first procedure, close to the one described in [JLR15]. Of course, the EF-emptiness problem being undecidable [AHV93], the analysis is not guaranteed to terminate.

One obtains a result in an external text file (\text{model.res}) formatted using a standardized manner (see Chapter 5), and therefore easier to parse using an external tool than the terminal output.

The options \text{-merge} and \text{-comparison inclusion} are implicitly activated for this algorithm, as they usually greatly increase the analysis efficiency and the termination. You may want to use \text{-no-merge} and \text{-comparison none} to disable them. The options \text{-dynamic-elimination} (not activated by default) and \text{-comparison doubleinclusion} can also be used to (try to) reduce the state space.

IMITATOR can also output the state space in a graphical form (option \text{-draw-statespace}), output the constraint synthesized in a graphical form in two dimensions (option \text{-draw-cart}), or output the text description of all states (option \text{-states-description}).

\textbf{Remark 4.1.} For all reachability/safety algorithms (including cycle synthesis), one can also use the \text{accepting} keyword in the model (in front of a location, see grammar in Section 9.2). In that case, one can use the \text{accepting} predicate inside the property state predicate. That is, one can define properties of the form:

\[
\text{property} := \#\text{witness EF(accepting)};
\]

or even:

\[
\text{property} := \#\text{synth EF(loc[pta] = l1 | (accepting & loc[pta] <> l2))};
\]

The semantics of the acceptance of a state is as follows: “at least one of the locations is accepting (as specified by the \text{accepting} keyword in the model).”

\section{Safety}

Often, we are rather interested in safety synthesis, \textit{i.e.}, the set of valuations for which the target location is unreachable.

The property syntax is as follows:

\[
\text{property} := \#\text{synth AGnot(state\_predicate)};
\]

\footnote{IMITATOR uses the TCTL syntax, where EF notably denotes reachability.}
Internally, this algorithm works exactly the same as the reachability-synthesis, and at the end the obtained constraint is *negated* (with parameters being constrained to be included in the initial state valuations).

### 4.4 EF-minimization

This algorithm synthesizes the minimum valuation for a given parameter for which a given location is reachable. This algorithm is briefly mentioned in [And+19].

The property syntax is as follows:

```plaintext
property : = #synth EFpmin(state_predicate, p);
```

where \( p \) is the parameter the value of which must be minimized.

### 4.5 EF-maximization

This algorithm is the dual of EF-minimization (see Section 4.4).

The property syntax is as follows:

```plaintext
property : = #synth EFpmax(state_predicate, p);
```

### 4.6 EF with minimal time reachability

This algorithm synthesizes the parameter valuations for which a given location is reachable in minimal time [And+19].

Our algorithm uses a priority queue, with priority to the earliest successor for the selection of the next state.

The property syntax is as follows:

```plaintext
property : = #synth EFtmin(state_predicate);
```

*The maximum time reachability is currently not implemented.*

### 4.7 Parameter synthesis using patterns

IMITATOR basically only supports bad state reachability synthesis on the one hand, and algorithms such as the inverse method and the cartography on the other hand. However, many correctness properties can reduce to reachability using *observers* (see [ABL98; Ace+98; Ace+03; And13b]).

Encoding observers can be done manually (using *ad-hoc* IPTA), or using predefined correctness property patterns commonly met in the literature.

**Warning 2.** These properties assume *time-progress*, i.e., if the model is stuck in a *time-lock*, these properties may give incorrect results.

If using a predefined property pattern, the property pattern must be specified as follows:
```plaintext
property := #synth_pattern(<PROP>);
```

where `<PROP>` must follow the syntax of the following patterns, where `a, a1, a2` are actions, and the deadline `d` is a (possibly parametric) linear expression:

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

The semantics of these properties is detailed in [And13b]. IMITATOR then translates the selected pattern into an additional observer automaton, and performs some safety or reachability synthesis.

### 4.8 Parametric deadlock-freeness checking

Given an NIPTA, PDFC synthesizes a parameter constraint such that, for any parameter valuation in that constraint, the system is deadlock-free [And16].

The property syntax is as follows:

```plaintext
property := #synth_DeadlockFree;
```

As usual, IMITATOR can also output the state space in a graphical form (option `-draw-statespace`) or output the constraint synthesized in a graphical form in two dimensions (option `-draw-cart`).

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4.9 Parametric cycle synthesis

4.9.1 Accepting cycle synthesis

Given an NIPTA, IMITATOR synthesizes a parameter constraint such that, for any parameter valuation in that constraint, the system contains at least one accepting cycle, i.e., an infinite run passing infinitely often by location matching an accepting condition. Such accepting conditions are given in the form of a state predicate, i.e., a conjunction or disjunction of locations and values for discrete variables. This can be seen as a liveness property, or more precisely Büchi acceptance condition.

IMITATOR implements two algorithms to this goal:

1. a basic BFS algorithm using a variant of Tarjan's strongly connected components algorithm [And+21] (Section 4.9.1.1); and
2. an NDFS algorithm with several options [NPV18; And+21] (Section 4.9.1.2).

In both cases, the property syntax is as follows:

\[
\text{property} \,:= \, \#\text{synth CycleThrough(state\_predicate)};
\]

Syntax freedom 1. IMITATOR accepts LoopThrough as an equivalent keyword for CycleThrough.

The second algorithm (Section 4.9.1.2) is the default in IMITATOR. As usual, IMITATOR can also output the state space in a graphical form (option -draw-statespace) or output the constraint synthesized in a graphical form in two dimensions (option -draw-cart).

4.9.1.1 Accepting cycle (BFS + Tarjan)

This (non-default) algorithm can be called using the following option syntax:

- cycle-algo BFS

4.9.1.2 Accepting cycle (NDFS)

This (default) algorithm can be called using the following option syntax:

- cycle-algo NDFS

It is also called when no -cycle-algo is specified.

Two additional options can be specified (a third one, -pending-order, is explained later):

1. -layer (or -no-layer) to enable (or disable) layered NDFS [NPV18];
2. -subsumption (or -no-subsumption) to enable (or disable) subsumption [NPV18].
By default, `-layer` is disabled, and `-subsumption` is enabled, as experiments showed this is the most efficient setting [NPV18].

All combinations of options yield an exact result.

At each cycle found, IMITATOR outputs its number (when using the synthesis) and the node at which the cycle was detected. When it terminates the complete parameter constraint is displayed.

When using the `-depth-limit` option, the depth-first search stops exploring the current branch and backtracks when this depth is reached.

**Exploration with layers**  The exploration with layers considers different ordering policies for its pending list via the `-pending-order` option:

- `-pending-order none` : the states are added to the pending list without specific policy (default option);
- `-pending-order accepting` : the accepting states are added at the head of the pending list, the others at the tail;
- `-pending-order param` : the states are added to the list on the basis of a largest projection of zone on parameters first;
- `-pending-order zone` : the states are added to the list on the basis of a largest zone first.

**Accepting cycle (NDFS) with iterative deepening** The NDFS algorithm described above with all its options can also be applied in an iterative manner, based on depth limits. Each iteration explores a deeper state space, taking advantage of the previous computation. The iterations are applied until either the exact constraint is found or a limit is reached. This iterative analysis uses the following options:

- `-depth-init` allows for starting this iterative computing by indicating the initial depth limit to be used;
- `-depth-limit` is the maximal depth at which the last iteration will be run.
- `-depth-step` indicates the step between the depths of two iterations;

The results obtained at each iteration are displayed, thus giving valuable information to the user.

As usual, IMITATOR can also output the state space in a graphical form (option `-draw-statespace`) or output the constraint synthesized in a graphical form in two dimensions (option `-output-cart`).

### 4.9.2 Accepting cycle with generalized acceptance condition (BFS)

Generalized Büchi conditions are supported by IMITATOR. The property syntax is as follows:

```plaintext
property := #synth_CycleThrough(state_predicate_1, . . . , state_predicate_n);
```

The semantics is that each of the $n$ conditions must hold on at least one state of the same cycle, in order for this cycle to be accepting.
Remark 4.2. Only BFS (see Section 4.9.1.1) is available for these generalized conditions.

Example 4.1. Assume the following condition:

```plaintext
property := #synth CycleThrough(loc[pta1] = l1, loc[pta1] = l2 and loc[pta2] = l2, accepting, i = 2 or i = 3);
```

A cycle is accepting if it contains:

- a state in which `pta1` is in location `l1`; and
- another state in which `pta1` is in location `l2` and at the same time `pta2` is in location `l2`; and
- another state syntactically labeled as `accepting` in the model; and
- another state in which either `i` is equal to 2, or `i` is equal to 3.

4.9.3 Any cycle synthesis

Given an NIPTA, IMITATOR synthesizes a parameter constraint such that, for any parameter valuation in that constraint, the system contains at least one cycle, i.e., an infinite run.

The property syntax is as follows:

```plaintext
property := #synth Cycle;
```

This is syntactic sugar for the following property:

```plaintext
property := #synth CycleThrough(True);
```

**Syntax freedom 2.** IMITATOR accepts the `Loop` keyword as an equivalent for `Cycle`.

4.10 Parametric non-Zeno cycle synthesis

Given an NIPTA, IMITATOR synthesizes a parameter constraint such that, for any parameter valuation in that constraint, the system contains at least one cycle, under the non-Zeno assumption [And+17]. That is, only parameter valuations yielding at least one non-Zeno cycle are synthesized. Parameter valuations yielding only Zeno-cycles or no cycles are ignored.

The method implemented in IMITATOR is based on CUB-IPTA, a syntactic subclass of PTA based on the CUB-TA proposed in [Wan+15]. The precise algorithm we use, including the transformation of an arbitrary PTA into a CUB-PTA, is described in [And+17].

The property syntax is:

```plaintext
property := #synth NZCycle;
```

Two options are possible in IMITATOR:
1. a partial method (but slightly faster), that first detects whether the input NIPTA is already a CUB-PTA; if so, it applies non-Zeno checking on this CUB-PTA; otherwise, the returned constraint will be false.

Use `-nz-method check`.

2. a complete method (though of course without guarantee of termination), that transforms the NIPTA into a network of CUB-PTAs, and applies non-Zeno checking on the transformed CUB-PTA.

Use `-nz-method transform`.

Use `-nz-method already`.

**Warning 3 (restrictions).** In contrast to most other algorithms of IMITATOR, these two algorithms work on a slightly restricted syntax:

- in a guard or invariant, each clock must be used at most once;
- invariants should not contain discrete inequalities (i.e., inequalities over discrete variables only);
- the use of discrete variables was not tested (and may not be always working);
- the conditional updates (new since version 2.12) are not supported;
- the use of coefficients on parameters (different from 0 or 1) was not tested;
- the use of stopwatches or multi-rate was not tested.

Overall, this part of IMITATOR has been less tested and is probably less stable than the rest of the tool.

As usual, IMITATOR can also output the state space in a graphical form (option `--draw-statespace`) or output the constraint synthesized in a graphical form in two dimensions (option `--draw-cart`).

**Remark 4.3.** The accepting cycles are not (yet?) supported for non-Zeno synthesis.

### 4.11 Inverse method: Trace preservation and robustness

Given an NIPTA and a reference parameter valuation, the inverse method IM synthesizes a parameter constraint such that, for any parameter valuation in that constraint, the set of traces is the same as for the reference valuation [And+09]. This problem is known as the trace-preservation synthesis, and formalized in [ALM20]. The trace-preservation emptiness problem being undecidable [ALM20], the analysis is not guaranteed to terminate (although it often does in practice).

The property syntax is of the following form:
property := #synth IM(parameter_valuation);

where parameter_valuation is a reference valuation of the form \( p_1 = 1 \) & \( p_2 = 2 \) & ... (see Section 9.3 for details).

**Syntax freedom 3.** IMITATOR accepts the following equivalent keywords for IM:
- \texttt{InverseMethod}
- \texttt{TracePreservation}

IMITATOR can also output the state space in a graphical form (option -draw-statespace) or output the constraint synthesized in a graphical form in two dimensions (option -draw-cart).

Recall that IMITATOR generates a result in an external text file (\texttt{model.res}) and formatted using a standardized manner (see Chapter 5).

IMITATOR also offers two similar algorithms: IMK and IMunion return similar but slightly different results (see [AS11]).

### 4.12 Behavioral cartography

Given an NIPTA and a bounded parameter domain, the behavioral cartography BC synthesizes tiles, i.e., parameter domains such that for any parameter valuation in that domain, the set of traces is the same [AF10]. The corresponding problem being undecidable, the analysis is not guaranteed to terminate; when it terminates, it may also leave “holes”, i.e., parameter domains not covered by any tile.

The property syntax is of the following form:

\[
\text{property := #synth BC\text{\small\texttt{cover}}(hyper\_rectangle);}\
\]

where \( \text{hyper\_rectangle} \) is a reference hyper-rectangle of the form \( p_1 = 1..5 \) & \( p_2 = 2..4 \) & ... (see Section 9.3 for details).

IMITATOR can also output all state spaces in a graphical form (option -draw-statespace), or output the constraints synthesized in a graphical form in two dimensions (option -draw-cart).

When using the following syntax with an optional second argument:

\[
\text{property := #synth BC\text{\small\texttt{cover}}(hyper\_rectangle, step=2/3);}\
\]

one can specify the interval between any two points of which the coverage is checked (see [AF10]), here \( 2/3 \). By default, it is 1; setting \( \frac{1}{3} \) often leads to full coverage when 1 was not enough. Any strictly positive rational (or integer) is allowed.

**Warning 4.** This optional argument is syntactically accepted for other cartography-like algorithms, but may not always be considered by the algorithm, nor was fully tested.

In addition, state spaces and separate graphical cartographies for each tile can also be generated by adding option -tiles-files.
**Behavioral cartography with random coverage**

An alternative to the behavioral cartography is a random coverage \[\text{AF10}\]; it can be seen as a kind of sampling.

The property syntax is of the following form:

```plaintext
property := #synth BCrando\(\text{m}(\text{hyper\_rectangle} , \text{nb});
```

where \(\text{nb}\) is the number of times an integer point is randomly selected within the domain defined. If this point is already covered by one of the tiles, the inverse method is not called, another point is selected. Note that \(\text{nb}\) represents the number of integer points randomly selected; the number of calls to the inverse method can be significantly smaller.

A second algorithm is \(\text{BCrandomseq}\) \[\text{ACE14}\], which first selects random point selections, and then enumerates all integer points to make sure they are actually covered. This algorithm is mostly interesting when distributed (see \[\text{ACE14;} \text{ACN15}\]).

**Behavioral cartography with shuffle enumeration**

A second alternative to the behavioral cartography is an enumeration of all integer points in a random fashion. That is, all integer points in the reference parameter domain are generated in a data structure (an array), and then are shuffled. Then the points are enumerated \[\text{ACN15}\]. It differs from the random cartography in the sense that the random cartography randomly samples points without guarantee of full coverage, whereas the shuffle enumeration guarantees the coverage of all integer points.

The property syntax is:

```plaintext
property := #synth BCshuf\(\text{fle}(\text{hyper\_rectangle});
```

4.13 Parametric reachability preservation

\text{IMITATOR} implements an algorithm solving the following problem: “given a reference parameter valuation \(\nu\) and some location \(\ell\), synthesize other valuations that preserve the reachability of \(\ell\).” By preserving the reachability, we mean that \(\ell\) is reachable for the other valuations iff \(\ell\) is reachable for \(\nu\).

This algorithm \text{PRP}, that somehow combines \text{EFsynth} and \text{IM} (see \[\text{And+15}\] for details), is called using the following property syntax:

```plaintext
property := #synth PRP(state\_predicate , parameter\_valuation);
```

**Parametric reachability preservation cartography**

An extension of \text{PRP} to the cartography (named \text{PRPC}) is also available: \text{PRPC} synthesizes parameter constraints in which the (non-)reachability of \(\ell\) is uniform. \text{PRPC} was showed in \[\text{And+15}\] to be a suitable alternative to \text{EFsynth}, especially when distributed (see option \text{-distributed}).

The property syntax for this algorithm \text{PRPC} is as follows:

```plaintext
property := #synth PRPC(state\_predicate , hyper\_rectangle);
```
4.14 Summary

We summarize algorithms in Table 4.1, recalling the basic syntax, and specifying whether they support the \texttt{#witness} mode that stops as soon as (at least) one parameter valuation is witnessed.

Table 4.1: Summary of the algorithms syntax

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Syntax</th>
<th>Synth</th>
<th>Witness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reachability</td>
<td>\texttt{EF(state_predicate)}</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Safety</td>
<td>\texttt{AGnot(state_predicate)}</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Parameter minimization</td>
<td>\texttt{EFpmin(state_predicate, p)}</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Parameter maximization</td>
<td>\texttt{EFpmax(state_predicate, p)}</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Minimal-time</td>
<td>\texttt{EFtmin(state_predicate)}</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cycle</td>
<td>\texttt{Cycle}</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Accepting cycle</td>
<td>\texttt{CycleThrough(state_predicate)}</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Non-Zeno cycles</td>
<td>\texttt{NZCycle}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Deadlock-freeness</td>
<td>\texttt{DeadlockFree}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Inverse method</td>
<td>\texttt{IM(parameter_valuation)}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Inverse method</td>
<td>\texttt{IMK(parameter_valuation)}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Inverse method</td>
<td>\texttt{IMunion(parameter_valuation)}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Cartography</td>
<td>\texttt{BCcover(hyper_rectangle)}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Cartography</td>
<td>\texttt{BCrandom(hyper_rectangle, nb)}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Cartography</td>
<td>\texttt{BCrandomseq(hyper_rectangle, nb)}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Cartography</td>
<td>\texttt{BCshuffle(hyper_rectangle)}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>PRP</td>
<td>\texttt{PRP(state_pred, parameter_val)}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>PRPC</td>
<td>\texttt{PRPC(state_pred, hyper_rect)}</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Patterns</td>
<td>\texttt{pattern(&lt;pattern&gt;)}</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

4.15 Symbolic state space computation

Finally, instead of synthesizing parameter valuations or checking for emptiness, IMITATOR can also compute the entire symbolic state space (“parametric zone graph”). Of course, the state space may be infinite, and this analysis is not guaranteed to terminate.

The standard command is:

\begin{verbatim}
imitor model.imi -mode statespace -states-description
\end{verbatim}

The option \texttt{-states-description} generates a file with a textual description of all states (without this option, IMITATOR will not output anything). Each state is represented with its discrete part (location and values of the discrete variables), the clock and parameter constraints, and below their projection onto the parameters.

IMITATOR can also output the state space in a graphical form using option \texttt{-draw-statespace}.
Table 4.2: Summary of the algorithms default options

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Syntax</th>
<th>-merge</th>
<th>-comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>State space computation</td>
<td>N/A</td>
<td></td>
<td>equality</td>
</tr>
<tr>
<td>Reachability</td>
<td>EF(state_predicate)</td>
<td>✓</td>
<td>inclusion</td>
</tr>
<tr>
<td>Safety</td>
<td>AGnot(state_predicate)</td>
<td>✓</td>
<td>inclusion</td>
</tr>
<tr>
<td>Parameter minimization</td>
<td>EFpmin(state_predicate, p)</td>
<td>✓</td>
<td>inclusion</td>
</tr>
<tr>
<td>Parameter maximization</td>
<td>EFpmax(state_predicate, p)</td>
<td>✓</td>
<td>inclusion</td>
</tr>
<tr>
<td>Minimal-time</td>
<td>EFtmin(state_predicate)</td>
<td>✓</td>
<td>inclusion</td>
</tr>
<tr>
<td>Cycle</td>
<td>Cycle</td>
<td></td>
<td>equality</td>
</tr>
<tr>
<td>Accepting cycle</td>
<td>CycleThrough(state_predicate)</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>Accepting cycle</td>
<td>CycleThrough(state_predicates)</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>Non-Zeno cycles</td>
<td>NZCycle</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>Deadlock-freeness</td>
<td>DeadlockFree</td>
<td></td>
<td>inclusion</td>
</tr>
<tr>
<td>Inverse method</td>
<td>IM(parameter_valuation)</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>Inverse method</td>
<td>IMK(parameter_valuation)</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>Inverse method</td>
<td>IMunion(parameter_valuation)</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>Cartography</td>
<td>BCcover(hyper_rectangle)</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>Cartography</td>
<td>BCrandom(hyper_rectangle, nb)</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>Cartography</td>
<td>BCrandomseq(hyper_rectangle, nb)</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>Cartography</td>
<td>BCshuffle(hyper_rectangle)</td>
<td>×</td>
<td>equality</td>
</tr>
<tr>
<td>PRP</td>
<td>PRP(state_pred, parameter_val)</td>
<td>✓</td>
<td>inclusion</td>
</tr>
<tr>
<td>PRPC</td>
<td>PRPC(state_pred, hyper_rect)</td>
<td>✓</td>
<td>inclusion</td>
</tr>
<tr>
<td>Patterns</td>
<td>pattern(&lt;pattern&gt;)</td>
<td>✓</td>
<td>inclusion</td>
</tr>
</tbody>
</table>
Chapter 5

Understanding the IMITATOR result

IMITATOR generates a file `model.res`. This file has a standardized format, and can therefore be parsed using an external tool.

To disable the creation of this file, please use `-no-output-result` (see Chapter 8).

We do not give a formal grammar for this file (yet), but it can be easily inferred from example outputs.

5.1 Header

The file header recalls the exact version of IMITATOR used to run the analysis, including the build number, the git branch and the git SHA hash. It also recalls the model name, the exact command used, and the time when the file was generated (which may slightly differ from the time the analysis was run, if the analysis was significantly long).

Then, the header recalls global information on the model (number of IPTA, of clocks, of parameters, whether the model contains clocks with a rate $\neq 1$, etc.).

5.2 The resulting constraint

The main result of a single synthesis (i.e., EFsynth, PDFC, IM and its variants, PRP... ) is a constraint. This result is clearly delimited by delimiters `BEGIN CONSTRAINT` and `END CONSTRAINT`.

The result can be a convex or a non-convex constraint. In some cases, the result is made of two (convex or non-convex) constraints: a good constraint (characterizing good parameter valuations), and a bad constraint (characterizing bad parameter valuations). Both parts of the results are then separated using the keyword `<good | bad>` (of course the good constraint comes left of this separator, and the bad constraint comes right).

The resulting constraint comes with two other information:

- its nature, i.e., whether it attempts to characterize a good set of valuations, a bad set of valuations, or both a good set and a bad of valuations. “Good” and “bad” must be understood to the property that is being checked (non-reachability of some states, deadlock-freeness, etc.). The constraint nature is only an attempt, as the constraint may not always be sound (see below).
• its soundness, i.e., whether the constraint is exact (IMITATOR returned exactly the set of parameter valuations solution to the analysis requested), a possible under-approximation of that result, a possible over-approximation of that result (in some rare cases), or a possibly invalid constraint (in which case the result output by IMITATOR shall not be used).

Note that in almost all analyses, IMITATOR returns an exact or an under-approximated constraint. A possibly invalid constraint can be synthesized when some options are used: for example, computing the result of IM with the merging enabled (-merge) yields a possibly invalid constraint, as it was shown that the merging optimization does not preserve the validity of the result of IM [AFS13].

Finally, the result also comes with an evaluation of the termination: the termination can be regular (the analysis went to its end without interruption) or an early termination, with some states unexplored (e.g., if a maximum analysis time (-time-limit), a maximum exploration depth (-depth-limit), etc., was set).

5.3 The cartography result

The behavioral cartography does not strictly speaking generate a result, but a list of tiles: each of them is made of the reference valuation that yielded that tile, the associated constraint again with its nature, its soundness, and the analysis termination. In addition, each tile comes with its associated number of states and transitions, and its computation time.

5.4 General statistics

The result file finally contains general statistics such as the global computation time (excluding the generation of graphics, or the result file), an estimation of the memory used, the number of states and transitions computed, etc. Finally, some statistics on specific operations (model parsing, graphics drawing, etc.) are given. More statistics are obtained with higher levels of verbosity, or with the -statistics option.

5.5 Projection onto some parameters

The result can be projected onto selected parameters, by using the following syntax at the end of the property file:

```
projectresult(param1, .... paramn);
```

In that case, all parameters not in that set are eliminated using variable elimination, and the result in the result file only contains the selected parameters.

This projection is also added to the states description (see option -states-description) and to the graphical state space output (see option -draw-statespace full).
Chapter 6

Graphical output and translation

Again, we only give the most useful options. For more detailed commands, and a complete list of options, see Chapter 8.

6.1 State space

To generate the (discretized) state space of a given computation in a graphical form, use:

```
iminator model.imi [property.improp] [options] -draw-statespace
```

IMITATOR will generate a file `model-statespace.pdf`. States are made of two parts: the left-hand number (e.g., \(s_0\)) is the number of the symbolic state, which comes from IMITATOR internal representation (\(s_0\) is the first one to be generated, and so on); the right-hand part displays all the discrete part of the symbolic state vertically, that is the current location in each of the NIPTA in parallel, and the value of possible discrete variables (if any). Consider state \(s_1\) in Fig. 6.1b (and originating from the example in Chapter 2): the current location of IPTA proc_1 is active1, the current location of IPTA proc_2 is idle2, while the current location of IPTA observer is obs_waiting. In addition, the current value of variable turn is \(-1\) while the current value of counter is 0. The color is chosen according to IMITATOR internal choice: however, two symbolic states with the same color have the same discrete part (location and values of the discrete variables). For example, this is the case of \(s_4\) and \(s_5\) in Fig. 6.1b.

Note that, beyond about 1,000 states or 1,000 transitions, the dot utility (responsible to generate the state space) may crash.

Using `--draw-statespace undetailed` makes a more compact representation, but is also less informative as only the state number and the transition labels are shown.

Conversely, `--draw-statespace full` makes a more detailed representation, by also adding to the state space all constraints: the clock and parameter constraints, and below their projection onto the parameters. This option is mostly suitable for small state spaces.

Example 6.1. An example of state space with no details (output using `--draw-statespace undetailed`), with normal details (using `--draw-statespace normal`).
normal), and in verbose mode (using -draw-statespace full) are given in Figs. 6.1a to 6.1c.

These graphics were generated using the example in Chapter 2 with the following command:

```
iminator fischer.imi fischer.imiprop -depth-limit 4 -draw-statespace normal
```

(where normal should be replaced with undetailed or full, respectively)

### 6.2 Visualizing the synthesized constraint in 2D

To visualize the constraint generated by IMITATOR using a 2-dimensional plot (thanks to the external plot utility), use:

```
imitor model.imi property.imiprop [options] -draw-cart
```

This will generate file model_cart.png.

The two dimensions chosen for the plot are the first two (non-constant) parameter dimension in the model.

Additional useful options are -draw-cart-x-min, -draw-cart-x-max, -draw-cart-y-min, -draw-cart-y-max to tune the values of the axes, and -graphics-source to keep the plot source.

### 6.3 Translation to UPPAAL

Since version 2.11, IMITATOR supports a translation of the model to the UPPAAL syntax [LPY97]. To generate an equivalent UPPAAL model without performing any analysis, use:

```
imitor model.imi -imi2Upaad
```

IMITATOR will generate a file model-uppaal.xml. Note that the translation of properties is not supported.

Due to the different semantics and features between IMITATOR and UPPAAL, the translation is done in a “best effort” manner, but the semantics may differ. We review some points in the following.

**Parameters** A fundamental difference IMITATOR and UPPAAL is that UPPAAL does not support timing parameters. Parameters are therefore translated to constants, the value of which can be manually changed by the user.

**Form of the constraints** IMITATOR allows a much wider form of constraints than UPPAAL. In particular, IMITATOR allows any conjunction of linear constraints (see Section 3.1.3) while UPPAAL mainly allows clocks to be compared to integers. In addition, UPPAAL only allows invariants of the form $x \leq c$ or $x < c$, which is not a restriction in IMITATOR. No checks are made when translating, and therefore UPPAAL may not accept models translated from IMITATOR input models using these features.
Figure 6.1: Examples of graphical state space
Rational variables  Rational variables in IMITATOR are rational-valued with an exact value. In UPPAAL, they are interpreted as (bounded) integers: overflows may occur and, if their value becomes non-integer, it seems UPPAAL will just round them to the nearest integer, thus creating a difference in semantics.

Binary variables

Warning 5. Binary words translation into UPPAAL formalism is experimental. Binary words are translated and encoded into 32-bit integer variables in UPPAAL (with dedicated functions). For this reason, translating binary words of length greater than 31 bits or shifting a binary word of an arbitrary length can lead to unexpected behaviors and results.

Strong broadcast synchronization  IMITATOR uses a single communication model: strong broadcast (see Section 3.4), while UPPAAL uses both channel binary synchronization, and broadcast synchronization. None of them match IMITATOR’s semantics. Our translation tries to preserve IMITATOR semantics, using the following scheme:

- Unnamed actions (necessarily used in a single IPTA) remain unnamed in UPPAAL.
- An action $a$ used in a single IPTA is implemented in UPPAAL using a broadcast action $a!$.
- An action $a$ used in exactly two IPTA is implemented in UPPAAL using a binary action $a$, where the first ($i.e.$, declared first in the IMITATOR file) uses $a!$ while the second uses $a?$.
- An action $a$ used in $n$ IPTA with $n \geq 3$ is implemented in UPPAAL using a broadcast action $a$ and an additional variable $\text{nb}_{--}a$ initially set to $n$, and that will be responsible to check that all automata can indeed synchronize, as follows:
  - all invariants contain $\text{nb}_{--}a = n$
  - the first automaton ($i.e.$, declared first in the IMITATOR file) involved in the synchronization synchronizes on $a!$ and performs $\text{nb}_{--}a := 1$;
  - all other automata involved in the synchronization perform $\text{nb}_{--}a := \text{nb}_{--}a + 1$.

From the UPPAAL official semantics, the discrete variables are updated by first executing the update label given on the $a!$ transition, and then the update labels given on the $a?$ for increasing, which guarantees the correctness of this construction. (This construction was suggested by Jiří Srba.)

However, a major difference (which may prevent UPPAAL to interpret the translated models) is that UPPAAL forbids guard on receiving actions (of the form $a?$). Therefore, translating an IMITATOR model where an action $a$ is used in two automata (or more) with guards on more than one transition will lead UPPAAL to not accept the model. A manual editing will be needed.
**Initial constraint** The initial constraint is *not* translated, except for the initial value of the discrete variables. Notably, the clocks are initially 0 in UPPAAL, which is not necessarily the case in IMITATOR.

**Properties** Properties are so far not translated to UPPAAL.

### 6.4 Translation to HYTech

Since version 2.8, IMITATOR supports a translation of the model to the HYTech syntax [HHW95] (that is quite close to that of IMITATOR anyway). To generate an equivalent HYTech model without performing any analysis, use:

```bash
imitator model.imi -imi2HyTech
```

IMITATOR will generate a file `model.hy`.

The syntax going beyond that of HYTech (typically, Booleans, binary words...) is obviously not translated.

In addition, the translation of properties is not supported.

### 6.5 Translation to JANI

Since version 3.1, IMITATOR supports a translation of the model to the JANI specification [Bud+17]. To generate an equivalent JANI model without performing any analysis, use:

```bash
imitator model.imi -imi2Jani
```

IMITATOR will generate a file `model.jani`. Note that the translation of properties is not supported.

Due to the different semantics and features between IMITATOR and JANI, the translation is done in a “best effort” manner, but the semantics may differ. We review some points in the following.

**Updates** IMITATOR and JANI do not have exactly the same semantics in the case of `if-then-else` updates. In order to provide a similar behavior, the translation is performed as follow:

```plaintext
if (x=1) then (x:=2, y:=3) else (x:=4)
```

is transformed (and, subsequently, written in JANI format) into

```plaintext
x := (if (x=1) then 2 else x);
y := (if (x=1) then 3 else y);
x := (if (x=1) then x else 4);
```
Stopwatches and multi-rate clocks  If no clock of the input model has a rate different from 1, then all of them are declared in the output JANI model with the clock type.

Otherwise, if at least one rate uses a non-1 rate in the IMITATOR model, then all of the clocks (including non multi-rate clocks) are declared with the continuous type and the corresponding derivative (1, if non specified in the IMITATOR input model) is explicitly specified in each location of the output model.

Synchronization  JANI synchronization semantics is more permissive than the IMITATOR one, therefore the exact meaning can be kept. It is done by listing synchronization vectors in the syncs entry.

Binary words  Binary words are somehow supported by our translation to JANI, but not the built-in functions.

Properties  Properties are so far not translated to JANI. The corresponding input in the JANI file exists but remains empty.

6.6 Export to graphics

To generate a graphic representation of the NIPTA model without performing any analysis, use:

```
imitor model.imi -imi2JP
nimitor model.imi -imi2PDF
nimitor model.imi -imi2PNG
```

IMITATOR will generate a file model-pta.jpg, model-pta.pdf and model-pta.png respectively (using the dot utility).

Colored transitions are synchronized transitions (i.e., shared by at least two IPTA), black transitions are local transitions, while dotted transitions are unnamed local transitions (often referred to as \( \epsilon \)-transitions in the literature).

Example 6.2. Consider again the case study given in Chapter 2 (and of which a TikZ export was given in Fig. 2.1). Then the result of the -imi2PDF command is given in Fig. 6.2.

6.7 Export to \LaTeX

To generate a \LaTeX representation of the NIPTA model (using the \texttt{tikz} package) without performing any analysis, use:

```
imitor model.imi -imi2TikZ
```
IMITATOR will generate a file `model.tex`. This file is a standalone \LaTeX{} file containing a single figure, which contains the different IPTA in “subfigure” environments. The node positioning is not yet supported (locations are depicted vertically), so you may need to manually position all nodes, and bend some transitions if needed.

**Example 6.3.** Consider again the case study given in Chapter 2: a TikZ export was given in Fig. 2.1, with some manual positioning.
Chapter 7

Inside the box

7.1 Language and libraries

In short, IMITATOR is written in OCaml, and contains about 26,000 lines of code. IMITATOR makes use of the following external libraries:

- The OCaml ExtLib library (Extended Standard Library for Objective Caml);
- The GNU Multiple Precision Arithmetic Library (GMP);
- The Parma Polyhedra Library (PPL) [BHZ08], used to compute operations on polyhedra.

7.2 Symbolic states

Verification of timed systems (and specially parametric timed systems) is necessarily done in a symbolic manner, in the sense that the timing information is abstracted by clock constraints. However, IMITATOR does not perform what is referred to as symbolic model checking; in other words, the representation of locations in IMITATOR is explicit (and not symbolic using, e.g., binary decision diagrams).

In short, a symbolic state in IMITATOR is made of the following elements:

- the current location (index) of each IPTA;
- the current value of the discrete variables;
- a constraint on $X \cup P$ representing the continuous information.

In IMITATOR, all rationals (i.e., the value of the rational-valued discrete variables and the coefficients used in the constraints) are unbounded rationals (implemented using GMP). Integers over 32 bits are used to encode int variables. No floating-point approximations (float) are used, except for the generation of graphics.
7.3 Type system

Since version 3.1 IMITATOR supports several types of discrete variables. Common primitive types as integer, rational and Booleans are available. They can be declared with the following keywords:

- Rational: rational (or discrete for backward-compatibility)
- Integer (32 bits): int
- Boolean: bool
- Binary word: binary(l) with l the length of the word

These types are divided into three categories: numerical (for rational and int), Booleans (for bool) and Binary (for binary(l)). IMITATOR models are statically typed, in the sense of their variables and expressions types are resolved prior to the algorithms execution.

7.3.1 Type checking

In order to verify the model type consistency, a step called type checking is applied—during the semantic analysis prior to the start of the verification or synthesis algorithm—on all expressions of the model: declarations, assignments, updates, conditions (if-then-else), guards and invariants. Type checking does the following:

- It checks type consistency within the expressions;
- It resolves the types of the expressions;
- It applies a numerical type to literal numbers according to the numerical type held by their outer expression;
- It checks consistency between an expression type and variable type, in case of assignment;
- It checks consistency between an expression type and its grammar rule.

7.3.2 Expression type solving

The expression tree is traversed (depth-first search) in order to deduce its type. As soon as a variable, constant or literal is found, the expression takes its type. If the expression only contains numbers (e.g., 2 + 3 * 4), the inferred type will be a rational arithmetic expression (and not the int type).

IMITATOR does not support implicit conversion. In other words, r + i + 3, where r is a rational and i is an int, is not allowed. Neither is allowed r := i.

If an expression mixes different types, a type error is risen before the start of the algorithm.
7.3.3 Literal number type inference

The types of literal numbers are automatically resolved during the semantic analysis and more precisely during the type checking step. Once an expression type is resolved, all literal numbers within are automatically typed as the numerical type holding by the expression.

For example, in the following update expression $b := \text{True} \& i < 3 + 1$ with $i : \text{int}$, literal numbers $3$ and $1$ will be automatically typed as a $\text{int}$.

7.3.4 Type conversion

As said previously, there is no implicit conversion of variables, constants or literals from one type to another type. All expressions are holding exactly one type and cannot mix different types. However, it is possible to convert an expression to another type using built-in conversion functions:

- $\text{rational_of_int}$: converts an $\text{int}$ expression to a rational one.

7.4 Installation

This document does not aim at explaining how to install IMITATOR. See the installation information available on the website for the most up-to-date information.

Binaries and source code packages are available on IMITATOR's Web page [IMI-Web]. Several standalone binaries are provided for Linux systems, that require no installation.
Chapter 8

List of options

The options available for IMITATOR are explained in the following.

Note that some more options are available in the current implementation of IMITATOR. If these options are not listed here, they are experimental (or deprecated). If needed, more information can be obtained by contacting the IMITATOR team.

- **acyclic** *(default: disabled)*  Does not test if a new state was already encountered. Without this option, 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-tiles-limit <limit>** *(default: none)*  In cartography algorithm, set up a maximum of tiles to be generated by the algorithm.

- **cart-time-limit <limit>** *(default: none)*  In cartography algorithm, set up a global time limit to the algorithm. In contrast, **-time-limit** is applied to each call to the inverse method.

- **comparison** *(default: depending on the algorithm)*  This option specifies how to compare the constraint of a newly computed symbolic state with the constraints of the formerly computed symbolic states. Possible values are:

  - **none**: Does not test if a new state was already encountered. To be set to this value *only* if the state space is a tree with all states being different (otherwise analysis may enter an infinite loop and never terminate).
equality Test the equality of the constraints.

inclusion Consider an inclusion of parametric zone instead of the equality when computing the successors of a set of states. In other terms, when encountering a new state, IMITATOR checks whether an old state shares the same discrete part (location and value of the discrete variables) and is such that the new state constraint is included into (i.e., is smaller than or equal to) the old state constraint; if so, IMITATOR discards this “new” state.

including When encountering a new state, IMITATOR checks whether an old state shares the same discrete part (location and value of the discrete variables) and is such that the new state constraint includes (i.e., is larger than or equal to) the old state constraint; if so, IMITATOR replaces the old state with the new state, and explores it further.

doubleinclusion Consider a bidirectional inclusion of parametric zones when computing the successors of a set of states. When this value is enabled, it suffices that a previous state with the same location and a constraint greater than or equal to (resp. smaller or equal to) the constraint of the new state has been encountered to discard the new state (resp. the old state, which is replaced by the new one).

It seems that, although less states are computed, this value is less efficient than -comparison inclusion (in part due to the extra inclusion checks required by -comparison doubleinclusion). This explains why this option, while preserving the correctness, is not default for reachability algorithms.

In reachability algorithms (Sections 4.2 to 4.7 and 4.13), -comparison inclusion is usually enabled by default; however, for loop synthesis algorithms (Sections 4.9 and 4.10), -comparison equality is used, as inclusion may introduce spurious cycles. See Table 4.2 for the default behavior of algorithms w.r.t. this option.

-contributors Print the list of contributors and exits.

-cycle-algo (default: NDFS) For cycle synthesis algorithms (Section 4.9), call either BFS (breadth-first search) or NDFS (nested depth-first search), with some additional options in the latter case. See -layer, -subsumption, -pending-order, -depth-init, -depth-limit, -depth-step for possible additional options.

-depth-init <initial_depth> (default: none) For the cycle detection using NDFS (Section 4.9.1.2), setting -depth-init allows for running iteratively NDFS, starting with depth limit <initial_depth> and increasing this limit at each iteration.

-depth-limit <limit> (default: none) Limits the depth of the exploration of the state space. In the cartography mode, this option gives a limit to each call to the inverse method. Setting -depth-limit guarantees the termination of any execution of IMITATOR, but not necessarily the correctness of the algorithms.
-depth-step (default: 1) For the cycle detection using NDFS (Section 4.9.1.2), -depth-step is used for iterative NDFS: it indicates the step between two iterations.

-distributed <mode> (default: not distributed) Distributed version of the behavioral cartography. Various distribution modes are possible:

no Non-distributed mode (default)

static Static domain decomposition [ACN15];

sequential Master-worker scheme with sequential point distribution [ACE14]

randomXX Master-worker scheme with random point distribution (e.g., random5 or random10); after XX successive unsuccessful attempts (where the generated point is already covered), the algorithm will switch to an exhaustive sequential iteration [ACE14]

shuffle Master-worker scheme with shuffle point distribution [ACN15]

dynamic Master-worker dynamic subdomain decomposition [ACN15]

-draw-cart (default: off) After execution of the behavioral cartography or EFsynth, plots the generated zones as a .png file. This will generate file model_cart.png. If the model contains more than two parameters, then -draw-cart will plot the projection of the generated zones on the first two parameters of the model (or on the two varying parameters in the case of BC).

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 current directory, unless option -output-prefix is used.

Additional useful options are -draw-cart-x-min, -draw-cart-x-max, -draw-cart-y-min, -draw-cart-y-max to tune the values of the axes, and -graphics-source to keep the plot source.

-draw-cart-x-min (default: off) Set minimum value for the x axis when plotting the cartography (not entirely functional in all situations yet).

-draw-cart-x-max (default: off) Set maximum value for the x axis when plotting the cartography (not entirely functional in all situations yet).

-draw-cart-y-min (default: off) Set minimum value for the y axis when plotting the cartography (not entirely functional in all situations yet).

-draw-cart-y-max (default: off) Set maximum value for the y axis when plotting the cartography (not entirely functional in all situations yet).
**-draw-statespace (default: none)**  Graphical output using dot. In this case, IMITATOR outputs a file `<input_file>.pdf`, which is a graphical output in the PDF format, generated using dot, corresponding to the state space.

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

Three values for this option are allowed:

- Use value **undetailed** for the structure only (no location names): does not provide detailed information on the local locations of the composed IPTA, and instead only outputs the state id. Enabling the option with this value instead of **-draw-statespace normal** may yield a smaller graph, which is useful when generating relatively large state spaces.

- Use value **normal** for location names.

- Use value **full** for location names and constraints. This provides very detailed information, by adding to the right of the local locations of the composed IPTA the associated constraint as well. In addition, the parametric constraint is printed too. Enabling the option with this value instead of **-draw-statespace normal** will yield a very large graph, and it is useful (and readable) mostly for very small state spaces.

**-dynamic-elimination (default: disabled)**  Dynamic elimination of clocks that are known to not be used in the future of the current state [And13a]. That is, IMITATOR deletes from the symbolic states all clocks that will not be used in a guard or an invariant until their next reset. This technique uses some basic static analysis of the IPTA composing the NIPTA.

**-expl-order**  Exploration orders are considered for standard reachability analysis (and counterexample analysis, using #witness), and are documented in [ANP17].

- **-expl-order layerBFS**: layer-based breadth-first search (default);
- **-expl-order queueBFS**: queue-based breadth-first search;
- **-expl-order queueBFSRS**: queue-based breadth-first search with ranking system
- **-expl-order queueBFSPRIOR**: priority-based BFS with ranking system

This framework remains relatively experimental.

**-graphics-source (default: disabled)**  Keep file(s) used for generating graphical output (e.g., state space, cartography); these files are otherwise deleted after the generation of the graphics.

**-imi2HyTech (default: disabled)**  Translates the input model to a HyTech model, and exits. See Section 6.4 for details.

**-imi2IMI (default: disabled)**  Regenerates the model into an IMITATOR model, and exits.
-**imi2JPG** *(default: disabled)* Translates the input model to a graphical, human-readable form (in .jpg format), and exits.

-**imi2PDF** *(default: disabled)* Translates the input model to a graphical, human-readable form (in .pdf format), and exits.

-**imi2PNG** *(default: disabled)* Translates the input model to a graphical, human-readable form (in .png format), and exits.

-**imi2TikZ** *(default: disabled)* Translates the input model to a \LaTeX representation of the model (using the \texttt{tikz} package) without performing any analysis, and exits. Note that node positioning is not (much) supported, so may want to edit manually some positions.

-**imi2Uppaal** *(default: disabled)* Translates the input model to a UPPAAL model, and exits. See Section 6.3 for details.

-**layer** *(default: disabled)* For the cycle detection using NDFS (Section 4.9.1.2), consider layered NDFS [NPV18].

-**no-layer** *(default: disabled)* For the cycle detection using NDFS (Section 4.9.1.2), do not consider layered NDFS [NPV18].

-**merge** *(default: depending on the algorithm)* Use the merging technique of [AFS13]. This option is safe (and used by default) for the EFsynth algorithm, and similar algorithms. However, not all the properties of the inverse method are preserved when using merging (see [AFS13] for details). See Table 4.2 for the default behavior of algorithms w.r.t. this option.

-**no-merge** *(default: depending on the algorithm)* Force disabling merging, even if the selected algorithm normally requires it.

-**mode** *(default: none)* When executing IMITATOR without a property, \textit{i.e.}, in a special mode.

  - **checksyntax** Simple syntax check and no analysis.
  - **statespace** Generation of the entire parametric state space (see Section 4.15)

-**no-acceptfirst** *(default: disabled)* For the cycle detection using NDFS (Section 4.9.1.2), do not put accepting states at the head of the successors list.

-**no-cumulative-pruning** *(default: disabled)* In EFsynth and BFS-based (accepting) loop synthesis, no inclusion test of the new states parameter constraints in the already synthesized constraint is performed when this option is enabled. Otherwise, by default, the algorithm
checks whether a new state parameter constraint is included into the already computed parameter constraint and, if so, cuts the branch. This can save time by cutting branches, but can also slow down the analysis for very complex constraints with dozens or hundreds of disjunctions. This option was designed when using IMITATOR for monitoring or parametric timed pattern matching, when constraints can contain up to thousands of disjunctions [AHW18].

-no-lookahead (default: disabled)  For the cycle detection using NDFS (Section 4.9.1.2), do not perform a lookahead for finding successors closing an accepting cycle.

-no-random (default: disabled)  In the inverse method, no random selection of the \( \pi_0 \)-incompatible inequality (select the first found). By default, select an inequality in a random manner.

-no-var-autoremove (default: disabled)  Usually, IMITATOR automatically removes from the analysis the variables declared in the header, but used nowhere in the IPTAs nor in the correctness property. Note that a variable updated (to 0 or to any other value) is not considered used, as long as it is not used elsewhere (i.e., in a guard, an invariant, a value to be updated to, a property...). Using -no-var-autoremove prevents IMITATOR from automatically remove these variables.

-nz-method (default: transform)  For non-Zeno cycle synthesis (Section 4.10), choose to either:

- synthesize valuations only for the subset of valuations for which the NIPTA already satisfies the CUB assumption (-nz-method check), or
- transform the NIPTA into an equivalent CUB-NIPTA (-nz-method transform).

-output-float (default: disabled)  Convert (exact-valued) discrete rational variables into (possibly approximated) floats in all outputs.

-output-prefix (default: <input_file>)  Set the path prefix for all generated files. The path can be either relative (to the path to the ./imitator binary) or absolute, and must be followed by the file name.

Examples:

- -output-prefix log
- -output-prefix ./log
- -output-prefix /home/imitator/outputs

By default, the path prefix is the current directory, i.e., where the user is (therefore not necessarily the model directory).

-no-output-result (default: enabled)  Does not write the result of the analysis to a file. By default, a file named <input_file> .res is created using a normalized syntax, that can be easily parsed, e.g., using an external script.
-pending-order (default: none)  For the cycle detection using NDFS (Section 4.9.1.2), defines the ordering strategy used for the pending list in NDFS exploration with layers. The possible values are:

- none  the states are added to the pending list without specific policy (default option).
- accepting  the accepting states are added at the head of the pending list, the others at the tail.
- param  the states are added to the list on the basis of a largest projection of zone on parameters first.
- zone  the states are added to the list on the basis of a largest zone first.

-recompute-green (default: disabled)  For the cycle detection using NDFS (Section 4.9.1.2) with iterative deepening, force re-exploration of green states when encountered on a shorter path.

-states-description (default: disabled)  Generates a file `<input_file>.states` describing the reachable states in plain text (value of the location, of the discrete variables, associated constraint, and its projection onto the parameters).

-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 (i.e., the exploration of the state space at the current depth) before stopping.

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

-subsumption (default: enabled for NDFS)  For the cycle detection using NDFS (Section 4.9.1.2), use subsumption [NPV18].

-no-subsumption (default: enabled for NDFS)  For the cycle detection using NDFS (Section 4.9.1.2), do not use subsumption [NPV18].

-sync-auto-detect (default: disabled)  IMITATOR considers that all the IPTA declaring a given action must be able to synchronize all together, so that the synchronization can happen. By default, IMITATOR considers that the actions declared in an IPTA are those declared in the synclabs section. Therefore, if an action is declared but never used in (at least) one IPTA, this label will never be synchronized in the execution.\(^1\)

The option --sync-auto-detect allows to detect automatically the actions in each IPTA: the actions declared in the synclabs section are ignored, and IMITATOR considers as declared actions only the actions really used in this IPTA.

\(^1\)In such a case, action label is actually completely removed before the execution, in order to optimize the execution, and the user is warned of this removal.
-tiles-files (default: disabled)  In cartography, generates the required files for each tile (i.e., the .res files, as well as the graphical cartography files whenever -draw-cart is enabled).

-time-elapsing-after (default: disabled)  When computing a new symbolic state, compute the time elapsing before taking the transition instead of after.

-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 the exploration of the state space at the current depth). In the cartography mode, this option represents a global time limit, not a limit for each call to the inverse method.

-timed (default: disabled)  Add a timing information to each shell 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:

  - mute  No output (the result is still output to an external file)
  - warnings  Prints only warnings
  - standard  Give little information (number of steps, computation time)
  - experiments  Give some additional information, typically enough for experiments
  - low  Give some additional information on what happens internally
  - medium  Give quite a lot of information
  - high  Give much information
  - total  Give really too much information

-version  Prints IMITATOR header including the version number and exits.
Chapter 9

Grammar

We give in this chapter the complete grammar of input models and properties for IMITATOR.

9.1 Variable names

A variable name (represented by \texttt{name} in the grammar below) is a string starting with a letter (small or capital), and followed by a set of letters, digits and underscores ("_"). By letter we mean the 26 letters of the Latin alphabet, without any diacritic mark.

The set of clock names, parameter names and discrete variable names must (quite naturally) be disjoint. However, the sets of IPTA names, location names, action names, and variable names are not required to be disjoint. That is, the same name can be given to a clock, an automaton, an action and a location.

Furthermore, the names of the sets of locations of various IPTA are not-necessarily disjoint either: that is, a same name can be given to two different locations in two different IPTA (and they still represent two different things).

9.2 Grammar of the model

The IMITATOR input model is described by the following grammar. Non-terminals appear \textit{within chevrons}. 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 \texttt{typewriter} font. The meta symbol \( \epsilon \) denotes the empty string.

\[
\langle \text{imitator_input} \rangle ::=
\langle \text{automata_descriptions} \rangle \langle \text{init} \rangle
\]

We define each of those two components below.

9.2.1 Automata descriptions

\[
\langle \text{include_file_list} \rangle ::=
\langle \text{include_file} \rangle \langle \text{include_file_list} \rangle
| \epsilon
\]
(include_file) ::
# include"<path>";

(automata_descriptions) ::
 (include_file) (declarations) (automata)

(declarations) ::
 var (var_lists)
 | e

(var_lists) ::
 (var_list) : (var_type); (var_lists)
 | e

(var_list) ::
 <name>
 | <name> = (global_expression)
 | <name>, (var_list)
 | <name> = (global_expression), (var_list)

(var_type) ::
 | binary (pos_integer)
 | bool
 | clock
 | constant
 | discrete
 | int
 | parameter
 | rational

(automata) ::
 (automaton) (automata)
 | (include_file) (automata)
 | e

(automaton) ::
 automaton <name> (prolog) (locations) end

(prolog) ::
 | (sync_labels)
 | e

(sync_labels) ::
 synclabs: (name_list);

(name_list) ::
 (name_nonempty_list)
 | e
\langle name\_nonempty\_list \rangle :: \\
\quad <name>, \langle name\_nonempty\_list \rangle \\
\quad | \quad <name> \\

\langle locations \rangle :: \\
\quad \langle location \rangle \langle locations \rangle \\
\quad | \quad \epsilon \\

\langle location\_attribute \rangle :: \\
\quad | \quad \epsilon \\
\quad | \quad urgent \\
\quad | \quad accepting \\
\quad | \quad accepting urgent \\
\quad | \quad urgent accepting \\

\langle location \rangle :: \\
\quad \langle location\_attribute \rangle \text{loc} <name> : invariant \langle nonlinear\_convex\_predicate \rangle \\
\quad \langle stopw\_and\_flow\_opt \rangle \langle transitions \rangle \\

\langle stopw\_and\_flow\_opt \rangle :: \\
\quad \langle stopwatches \rangle \langle flow \rangle \\
\quad | \quad \langle flow \rangle \langle stopwatches \rangle \\
\quad | \quad \langle flow \rangle \\
\quad | \quad \langle stopwatches \rangle \\
\quad | \quad \epsilon \\

\langle flow \rangle :: \\
\quad \text{flow} \{ \langle flow\_list \rangle \}$

\langle flow\_list \rangle :: \\
\quad \langle flow\_nonempty\_list \rangle \\
\quad | \quad \epsilon \\

\langle flow\_nonempty\_list \rangle :: \\
\quad \langle single\_flow \rangle, \langle flow\_nonempty\_list \rangle \\
\quad | \quad \langle single\_flow \rangle \langle comma\_opt \rangle \\

\langle single\_flow \rangle :: \\
\quad <name>' = \langle constant\_arithmetic\_expr \rangle \\

\langle stopwatches \rangle :: \\
\quad \text{stop}\{ \langle name\_list \rangle \}$

\langle transitions \rangle :: \\
\quad \langle transition \rangle \langle transitions \rangle \\
\quad | \quad \epsilon \\

\langle transition \rangle :: \\
\quad \text{when} \langle nonlinear\_convex\_predicate \rangle \langle update\_synchronization \rangle \text{goto} <name> ;
\[\text{(update synchronization)} :: \]
\[\quad \text{(updates)} \]
\[\quad | \quad \text{(syn_label)} \]
\[\quad | \quad \text{(updates)} \text{(syn_label)} \]
\[\quad | \quad \text{(syn_label)} \text{(updates)} \]
\[\quad | \quad \epsilon \]
\[\text{(updates)} :: \]
\[\quad \text{do} \{ \text{(update_list) } \} \]
\[\text{(update_list)} :: \]
\[\quad \text{(update_nonempty_list)} \]
\[\quad | \quad \epsilon \]
\[\text{(update_nonempty_list)} :: \]
\[\quad \text{(update)} , \text{(update_list)} \]
\[\quad | \quad \text{(condition_update)} , \text{(update_list)} \]
\[\quad | \quad \text{(update)} \]
\[\quad | \quad \text{(condition_update)} \]
\[\text{(update)} :: \]
\[\quad <\text{name}> := \text{(global_expression)} \]
\[\text{(normal_update_list)} :: \]
\[\quad \text{(update)} , \text{(normal_update_list)} \]
\[\quad | \quad \text{(update)} \]
\[\quad | \quad \epsilon \]
\[\text{(condition_update)} :: \]
\[\quad \text{if} (\text{(boolean_expression)}) \text{then} \text{(normal_update_list)} \text{end} \]
\[\quad | \quad \text{if} (\text{(boolean_expression)}) \text{then} \text{(normal_update_list)} \text{else} \text{(normal_update_list)} \text{end} \]
\[\text{(syn_label)} :: \]
\[\quad \text{sync} <\text{name}> \]
\[\text{(global_expression)} :: \]
\[\quad \text{(arithmetic_expression)} \]
\[\quad | \quad \text{(binary_word_expression)} \]
\[\quad | \quad \text{(boolean_expression)} \]
\[\text{(binary_word_expression)} :: \]
\[\quad \text{shift_left} (\text{(binary_word_expression)} , \text{(arithmetic_expression)}) \]
\[\quad \text{shift_right} (\text{(binary_word_expression)} , \text{(arithmetic_expression)}) \]
\[\quad \text{fill_left} (\text{(binary_word_expression)} , \text{(arithmetic_expression)}) \]
\[\quad \text{fill_right} (\text{(binary_word_expression)} , \text{(arithmetic_expression)}) \]
\[\quad \text{log_and} (\text{(binary_word_expression)} , \text{(binary_word_expression)}) \]
\[\quad \text{log_or} (\text{(binary_word_expression)} , \text{(binary_word_expression)}) \]
\[\quad \text{logxor} (\text{(binary_word_expression)} , \text{(binary_word_expression)}) \]
\[\quad \text{log_not} (\text{(binary_word_expression)}) \]
\[\quad | \quad <\text{binary_word}> \]
(boolean_expression) ::
   True
   | False
   | (boolean_expression) & (boolean_expression)
   | (boolean_expression) | (boolean_expression)
   | (arithmetic_expression) | (relop) | (arithmetic_expression)
   | (discrete_boolean_expression)

(discrete_boolean_expression) ::
   (arithmetic_expression) | (relop) | (arithmetic_expression)
   | (arithmetic_expression) in [ (arithmetic_expression) , (arithmetic_expression) ]
   | ( (boolean_expression) )
   | not ( (boolean_expression) )

(arithmetic_expression) ::
   (arithmetic_term)
   | (arithmetic_expression) + (arithmetic_term)
   | (arithmetic_expression) - (arithmetic_term)

(arithmetic_term) ::
   (arithmetic_factor)
   | (rational) <name>
   | (arithmetic_term) * (arithmetic_factor)
   | (arithmetic_term) / (arithmetic_factor)
   | - (arithmetic_term)

(arithmetic_factor) ::
   (rational)
   | <name>
   | ( (arithmetic_expression) )
   | pow( (arithmetic_expression) , (arithmetic_expression) )
   | rational_of_int( (arithmetic_expression) )

(convex_predicate) ::
   & (convex_predicate_fol)
   | (convex_predicate_fol)

(convex_predicate_fol) ::
   (linear_constraint) & (convex_predicate)
   | (linear_constraint)

(nonlinear_convex_predicate) ::
   & (nonlinear_convex_predicate_fol)
   | (nonlinear_convex_predicate_fol)

(nonlinear_convex_predicate_fol) ::
   (nonlinear_constraint) & (nonlinear_convex_predicate)
   | (nonlinear_constraint)
\( \langle \text{linear_constraint} \rangle :: \\
\langle \text{linear_expression} \rangle \ \langle \text{relop} \rangle \ \langle \text{linear_expression} \rangle \\
| \ \text{True} \\
| \ \text{False} \\
\)

\( \langle \text{nonlinear_constraint} \rangle :: \\
\langle \text{discrete_boolean_expression} \rangle \\
| \ \text{True} \\
| \ \text{False} \\
\)

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

\( \langle \text{linear_expression} \rangle :: \\
\langle \text{linear_term} \rangle \\
| \ \langle \text{linear_expression} \rangle + \langle \text{linear_term} \rangle \\
| \ \langle \text{linear_expression} \rangle - \langle \text{linear_term} \rangle \\
\)

\( \langle \text{linear_term} \rangle :: \\
\langle \text{rational} \rangle \\
| \ \langle \text{rational} \rangle \ <\text{name}> \\
| \ \langle \text{rational} \rangle \ * \ <\text{name}> \\
| \ - \ <\text{name}> \\
| \ <\text{name}> \\
| \ ( \ \langle \text{linear_term} \rangle \\) \\
\)

\( \langle \text{rational} \rangle :: \\
\langle \text{integer} \rangle \\
| \ \langle \text{float} \rangle \\
| \ \langle \text{integer} \rangle \ / \ \langle \text{pos_integer} \rangle \\
\)

\( \langle \text{integer} \rangle :: \\
\langle \text{pos_integer} \rangle \\
| \ - \ \langle \text{pos_integer} \rangle \\
\)

\( \langle \text{pos_integer} \rangle :: \\
\langle \text{int} \rangle \\
\)

\( \langle \text{float} \rangle :: \\
\langle \text{pos_float} \rangle \\
| \ - \ \langle \text{pos_float} \rangle \\
\)

\( \langle \text{pos_float} \rangle :: \\
\langle \text{float} \rangle \\
\)
9.2.2 Initial state

\( (\text{init}) :: \\
\quad \text{init} := \{ (\text{init\_discrete\_continuous\_definition}) \} \)

\( (\text{init\_discrete\_continuous\_definition}) :: \\
\quad (\text{init\_discrete\_definition}) (\text{init\_continuous\_definition}) \\
\quad | (\text{init\_continuous\_definition}) (\text{init\_discrete\_definition}) \)

\( (\text{init\_discrete\_definition}) :: \\
\quad \text{discrete} = (\text{init\_discrete\_expression}) ; \\
\quad | \epsilon \)

\( (\text{init\_discrete\_expression}) :: \\
\quad , (\text{init\_discrete\_expression\_nonempty\_list}) \\
\quad | (\text{init\_discrete\_expression\_nonempty\_list}) \\
\quad | \epsilon \)

\( (\text{init\_discrete\_expression\_nonempty\_list}) :: \\
\quad (\text{init\_discrete\_state\_predicate}), (\text{init\_discrete\_expression\_nonempty\_list}) \\
\quad | (\text{init\_discrete\_state\_predicate}) \\
\quad | (\text{init\_discrete\_state\_predicate}), \)

\( (\text{init\_discrete\_state\_predicate}) :: \\
\quad <\text{name}> := (\text{global\_expression}) \\
\quad | (\text{init\_discrete\_loc\_predicate}) \\
\quad | ( (\text{init\_discrete\_state\_predicate}) ) \)

\( (\text{init\_discrete\_loc\_predicate}) :: \\
\quad \text{loc}[<\text{name}>] := <\text{name}> \\
\quad | <\text{name}> \text{ is in } <\text{name}> \)

\( (\text{init\_continuous\_definition}) :: \\
\quad \text{continuous} = (\text{region\_expression}) ; \\
\quad | \epsilon \)

\( (\text{region\_expression}) :: \\
\quad \& (\text{region\_expression\_fol}) \\
\quad | (\text{region\_expression\_fol}) \)

\( (\text{region\_expression\_fol}) :: \\
\quad (\text{linear\_constraint}) \\
\quad | ( (\text{region\_expression\_fol}) ) \\
\quad | (\text{region\_expression\_fol}) \& (\text{region\_expression\_fol}) \)
9.3 Grammar of the property file

\[
\langle \text{property definition} \rangle ::
\quad \langle \text{property kw opt} \rangle \langle \text{quantified property} \rangle
\]

\[
\langle \text{property kw opt} \rangle ::
\quad \text{property} :=
\quad \epsilon
\]

\[
\langle \text{quantified property} \rangle ::
\quad \text{#synth (property)} \langle \text{semicolon opt} \rangle \langle \text{projection definition opt} \rangle
\quad \text{#exhibit (property)} \langle \text{semicolon opt} \rangle \langle \text{projection definition opt} \rangle
\quad \text{#witness (property)} \langle \text{semicolon opt} \rangle \langle \text{projection definition opt} \rangle
\]

\[
\langle \text{property} \rangle ::
\quad \text{EF} \langle \text{state predicate} \rangle
\quad \text{AGnot} \langle \text{state predicate} \rangle
\quad \text{EFpmin} \langle \text{state predicate} \rangle , <\text{name}> \rangle
\quad \text{EFpmax} \langle \text{state predicate} \rangle , <\text{name}> \rangle
\quad \text{EFtmin} \langle \text{state predicate} \rangle
\quad \text{Cycle}
\quad \text{Loop} /* alias for Cycle */
\quad \text{CycleThrough} \langle \text{state predicate list} \rangle
\quad \text{LoopThrough} \langle \text{state predicate list} \rangle /* alias for CycleThrough */
\quad \text{NZCycle}
\quad \text{DeadlockFree}
\quad \text{IM} \langle \text{parameter valuation} \rangle
\quad \text{InverseMethod} \langle \text{parameter valuation} \rangle /* alias for IM */
\quad \text{TracePreservation} \langle \text{parameter valuation} \rangle /* alias for IM */
\quad \text{IMconvex} \langle \text{parameter valuation} \rangle
\quad \text{IMK} \langle \text{parameter valuation} \rangle
\quad \text{IMunion} \langle \text{parameter valuation} \rangle
\quad \text{PRP} \langle \text{parameter valuation} \rangle
\quad \text{BCcover} \langle \text{hyper rectangle} \rangle \langle \text{step opt} \rangle
\quad \text{B_shuffle} \langle \text{hyper rectangle} \rangle \langle \text{step opt} \rangle
\quad \text{B_Crandom} \langle \text{hyper rectangle} \rangle , <\text{pos integer}> \langle \text{step opt} \rangle
\quad \text{B_Crandomseq} \langle \text{hyper rectangle} \rangle , <\text{pos integer}> \langle \text{step opt} \rangle
\quad \text{PRPC} \langle \text{state predicate} \rangle , \langle \text{hyper rectangle} \rangle \langle \text{step opt} \rangle
\quad \text{pattern} \langle \text{pattern} \rangle
\]
| if <name> then <name> has happened before
| everytime <name> then <name> has happened before
| everytime <name> then <name> has happened once before
| <name> within \(\langle \text{linear_expression}\rangle\)
| if <name> then <name> has happened within \(\langle \text{linear_expression}\rangle\) before
| everytime <name> then <name> has happened within \(\langle \text{linear_expression}\rangle\) before
| everytime <name> then <name> has happened once within \(\langle \text{linear_expression}\rangle\) before
| if <name> then eventually <name> within \(\langle \text{linear_expression}\rangle\) before
| everytime <name> then eventually <name> within \(\langle \text{linear_expression}\rangle\) before
| everytime <name> then eventually <name> within \(\langle \text{linear_expression}\rangle\) once before next
| sequence \(\langle \text{var_list}\rangle\)
| sequence \(\langle \text{var_list}\rangle\)
| always sequence \(\langle \text{var_list}\rangle\)
| always sequence \(\langle \text{var_list}\rangle\)

\(\langle \text{state_predicate_list}\rangle\) ::
| \(\langle \text{non_empty_state_predicate_list}\rangle\)
| \(\epsilon\)

\(\langle \text{non_empty_state_predicate_list}\rangle\) ::
| \(\langle \text{state_predicate}\rangle, \langle \text{non_empty_state_predicate_list}\rangle\)
| \(\langle \text{state_predicate}\rangle \langle \text{comma_opt}\rangle\)

\(\langle \text{state_predicate}\rangle\) ::
| \(\langle \text{state_predicate}\rangle || \langle \text{state_predicate}\rangle\)
| \(\langle \text{state_predicate_term}\rangle\)
| True
| False
| accepting
| \(\epsilon\)

\(\langle \text{state_predicate_term}\rangle\) ::
| \(\langle \text{state_predicate_term}\rangle \& \langle \text{state_predicate_term}\rangle\)
| \(\langle \text{state_predicate_factor}\rangle\)

\(\langle \text{state_predicate_factor}\rangle\) ::
| \(\langle \text{simple_predicate}\rangle\)
| \(\text{not} \langle \text{state_predicate_factor}\rangle\)
| \(\langle \text{state_predicate}\rangle \rangle\)

\(\langle \text{simple_predicate}\rangle\) ::
| \(\langle \text{discrete_boolean_predicate}\rangle\)
| \(\langle \text{loc_predicate}\rangle\)

\(\langle \text{loc_predicate}\rangle\) ::
| loc[<name>] = <name>
| <name> is in <name>
| loc[<name>] <> <name>
| <name> is not in <name>
\( \text{discrete_boolean_predicate} :: 
\begin{align*}
& \text{discrete_expression} \ \text{op_bool} \ \text{discrete_expression} \\
\mid & \text{discrete_expression} \ \text{in} \ [\text{discrete_expression}, \text{discrete_expression}] \\
\mid & \text{discrete_expression} \ \text{in} \ [\text{discrete_expression}..\text{discrete_expression}] 
\end{align*} \\
\( \text{discrete_expression} :: 
\begin{align*}
& \text{discrete_expression} + \text{discrete_term} \\
\mid & \text{discrete_expression} - \text{discrete_term} \\
\mid & \text{discrete_term} 
\end{align*} \\
\( \text{discrete_term} :: 
\begin{align*}
& \text{discrete_term} \times \text{discrete_factor} \\
\mid & \text{discrete_term} / \text{discrete_factor} \\
\mid & \text{discrete_factor} 
\end{align*} \\
\( \text{discrete_factor} :: 
\begin{align*}
& \text{name} \\
\mid & \text{positive_rational} \\
\mid & (\text{discrete_expression}) \\
\mid & -\text{discrete_factor} 
\end{align*} \\
\( \text{op_bool} :: 
\begin{align*}
& < \\
\mid & \leq \\
\mid & = \\
\mid & \neq \\
\mid & \geq \\
\mid & > 
\end{align*} \\
\( \text{positive_rational} :: 
\begin{align*}
& \text{pos_integer} \\
\mid & \text{pos_float} 
\end{align*} \\
\( \text{projection_definition_opt} :: 
\begin{align*}
& \text{projectresult}(\text{name_nonempty_list}) \ \text{semicolon_opt} \\
\mid & \epsilon 
\end{align*} \\
\( \text{parameter_valuation} :: 
\begin{align*}
& \text{parameter_assignments} \ \text{semicolon_opt} 
\end{align*} \\
\( \text{parameter_assignments} :: 
\begin{align*}
& \text{parameter_assignment} \ \text{parameter_assignments} \\
\mid & \epsilon 
\end{align*} \\
\( \text{parameter_assignment} :: 
\begin{align*}
& \text{and_opt} \ \text{name} = \text{constant_arithmetic_expr} \ \text{comma_opt} 
\end{align*} \\
\( \text{hyper_rectangle} :: 
\begin{align*}
& \text{rectangle_parameter_assignments} \ \text{semicolon_opt} 
\end{align*}
Remark 9.1. In the parameter valuation definition (\langle parameter\_valuation \rangle), all parameters of the model must be given a valuation; but the definition of the parameter valuation may also use names that do not appear in the model (a warning will just be issued).
Remark 9.2. In the hyper-rectangle definition (\((\text{hyper_rectangle})\)), all parameters of the model must be given an interval (possibly punctual); again, the definition of the hyper-rectangle may also use names that do not appear in the model (a warning will just be issued).

9.4 Reserved words

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

#exhibit, #include, #synth, #witness, accepting, always, and, automatically_generated_observer, automatically_generated_x_obs, automaton, before, binary, clock, constant, discrete, do, else, end, eventually, everytime, False, fill_left, fill_right, flow, goto, happened, has, if, in, init, initially, invariant, is, loc, logand, lognot, logor, logxor, next, nosync_obs, not, once, or, parameter, pow, projectresult, property, rational_of_int, sequence, shift_left, shift_right, special_0_clock, step, stop, sync, synclabs, then, True, urgent, var, wait, when, while, within
Chapter 10

Missing features

Although we try to make IMITATOR as complete as possible, it misses some features, not implemented due to lack of time (contributors are welcome!) or due to complexity, or to keep the tool consistent. We enumerate in the following what seems to us to be the “most missing” features and, when applicable, we give hints to overcome these limitations.

10.1 ASAP transitions

ASAP (as soon as possible) transitions are transitions that can be taken as soon as all IPTA synchronizing with this transition can execute their local transition. This is different from urgent transitions, that must be taken in 0 time. Here, time can elapse, but not after all IPTA are ready to execute their local transition.

This is not supported by IMITATOR.

10.2 Parameterized models

Parameterized models are understood here as models with an arbitrary number of components (e.g., Fischer's mutual exclusion protocol with \( n \) processes), that would be instantiated (e.g., \( n = 15 \)) before performing the analysis. IMITATOR does not currently support such parameterized models, and one should use copy/paste utilities to instantiate \( n \) models. For complicated models with many processes, we usually write short scripts to generate the model (a script `CSMACDgenerator.py` to model the varying part of parameterized models for the CSMA/CD case study is available on the IMITATOR project on GitHub).

10.3 Other synchronization models

One-to-one synchronization could possibly be simulated by using as many transitions as pairs of IPTA in the model, although this may make the model rather complex.

Broadcast synchronization (“only the IPTA ready to execute a given transition execute it”) is not supported. Once more, it could possibly be simulated by using as many transitions as subsets of IPTA in the model, although this will make the model definitely complex.
Message passing is not supported. This can be easily simulated using dedicated discrete
variables, that would be read / written in the transition.

10.4 Initial intervals for discrete variables

Discrete variables must be set to a constant rational in the init definition (e.g., \( i = 0 \)). Setting
a variable to an arbitrarily value (e.g., \( i \in [0 .. 10] \)) is currently not supported. This
can be simulated using an initialization IPTA that nondeterministically sets \( i \) to any of the
values, in \( 0 \) time so as to not disturb the model.

10.5 Complex updates for discrete variables

So far, discrete variables can only be set to arithmetic expressions in \( \mathcal{A}(R) \); hence, assigning
a discrete variable to a clock, or to a parameter, or to any more complex expression, is not
allowed. A reason for this restriction is that the value of the discrete variables would not
anymore be constant (recall that discrete variables are syntactic sugar for locations).

However, this can be (partially) simulated with stopwatches: we can replace a discrete
variable with a clock that is stopped in all locations (i.e., it does not evolve with time), and
that is updated to the desired value (recall from Definition 3.1 that the clock updates allow
assignments to linear expressions over clocks, discrete variables and parameters). However,
in this latter case, the non-linear power of arithmetic expressions (multiplications and divi-
sions between variables) cannot be used anymore.

10.6 Synthesis for L/U-PTA

IMITATOR does not implement specific algorithms for lower-bound / upper-bound PTA
(L/U-PTA). This subclass of PTA, introduced in [Hun+02], constrains parameters to appear ei-
ther always as upper-bounds in inequalities comparing them with clocks, or always as lower-
bounds. L/U-PTA benefit from some decidability results (see e.g., [Hun+02; BL09; JLR15;
AL17; ALM20]); however, exact synthesis seems to be intractable in practice [JLR15; ALR16].
Still, some subclasses for which exact synthesis can be performed were proposed [BL09;
ALR18a].

However, IMITATOR does detect whether an input model is an L/U-PTA, in which case a
message is printed with the list of lower-bounds parameters and upper-bounds parameters.

Remark 10.1. Note that our definition of L/U-PTAs is consistent with that of, e.g., [BL09];
however, we do not consider the constraint of the initial state while checking for the L/U
nature of the model. That is, we refer to as L/U-PTAs even for the constrained L/U-PTAs
of [BL09].
Chapter 11

Acknowledgments

Étienne André initiated the development of IMITATOR in 2008, and keeps developing it. Emmanuelle Encrenaz and Laurent Fribourg have been great supporters of IMITATOR, on a theoretical point of view, and to find applications both from the literature and real case studies. Abdelrezzak Bara provided several examples from the hardware literature. Jeremy Sproston provided examples from the probabilistic community. Bertrand Jeannet has been of great help on the linking with Apron [JM09] in a previous version of IMITATOR. Ulrich Kühne made several important improvements to IMITATOR, and linked the tool to PPL. Daphne Dussaud implemented the graphical output of the behavioral cartography. Romain Soulat implemented in part the merging technique [AFS13], and brought several case studies. Giuseppe Lipari and Sun Youcheng provided examples from the real-time systems community, and collaborated on several algorithms. Camille Coti, Sami Evangelista and Nguyễn Hoàng Gia worked on the distributed version of IMITATOR. Nguyễn Hoàng Gia worked on the non-Zeno synthesis algorithms. Laure Petrucci and Jaco van de Pol implemented an NDFS algorithm. Stéphan Rosse improved a script for comparing results and speeds of various versions of IMITATOR. Vincent Bloemen implemented the optimal-time reachability synthesis. Jaime Arias simplified a lot the source code management and implemented new features. Jiří Srba suggested the translation of IMITATOR’s strong broadcast into UPPAAL. Benjamin Loillier enhanced the syntax, notably allowing Boolean and int types. Dylan Marinho reformatted the library of benchmarks [AMP21] and implemented the translation to JANI.

We acknowledge the help of the PPL [BHZ08] developers for their help with solving several issues over the years, and more generally for making this very useful library available.
Chapter 12

Licensing and credits

IMITATOR license

IMITATOR is free software available under the GNU GPL license.

Contributors

The following people contributed to the development ofIMITATOR.

Étienne André 2008 –
Jaime Arias 2018 –
Vincent Bloemen 2018
Camille Coti 2014
Daphne Dussaud 2010
Sami Evangelista 2014
Ulrich Kühne 2010 – 2011
Benjamin Loïllier 2021 –
Dylan Marinho 2021 –
Nguyễn Hoàng Gia 2014 – 2018
Laure Petrucci 2019 –
Jaco van de Pol 2019 –
Romain Soulat 2010 – 2013

The following people contributed to the compiling, testing and packaging facilities.
Corentin Guillevic 2015
Sarah Hadbi 2015
Fabrice Kordon 2015
Alban Linard 2014 – 2015
Stéphane Rosse 2016 – 2017
User manual

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Graphics credits

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References


