UPPAAL2k: Small Tutorial

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1 Introduction

This document is intended to be used by new comers to UPPAAL and verification. Students or engineers with little background in formal methods should be able to use UPPAAL for practical purposes after this tutorial.

Section two describes UPPAAL and section three is the tutorial itself.

2 UPPAAL

UPPAAL is a tool box for validation (via graphical simulation) and verification (via automatic model-checking) of real-time systems. It consists of two main parts: a graphical user interface and a model-checker engine.

The idea is to model a system using timed-automata, simulate it and then verify properties on it. Timed-automata are finite state machines with time. A system consists of a network of processes that are composed of locations. Transitions between these locations define how the system behaves. The simulation step consists of running interactively the system to check that it works as intended. Then we can ask the verifier to check reachability properties, i.e. if a certain state is reachable or not. This is called model-checking and it is basically an exhaustive search that covers all possible dynamic behaviours of the system.

More precisely, the engine uses on-the-fly verification combined with a *symbolic* technique reducing the verification problem to that of solving simple *constraint systems* [YPD94, LPY95]. The verifier checks for simple invariants and reachability properties for efficiency reasons. Other properties may be checked by using testing automata [JLS96] or the decorated system with debugging information [LPY97].

3 Learning UPPAAL

UPPAAL is based on timed automata, that is finite state machine with clocks. The clocks are the way to use time in UPPAAL. Time is continuous and the clocks measure time progress. It is allowed to test the value of a clock or to reset it, but time will progress globally at the same pace for the whole system.

A system in UPPAAL is composed of concurrent processes, each of them modeled as an automaton. The automaton has a set of locations. Transitions are used to change location. To control how to fire these transitions, it is possible to have a guard and a synchronization. A guard is a condition on the variables and the clocks saying when the transition is enabled. The synchronization mechanism in UPPAAL is a hand-shaking synchronization: two processes take a transition at the same time, one will have a `a!` and the other a `a?`, `a` being the synchronization channel. When taking a transition actions are possible: assignment of variables or reset of clocks.

The following examples will make you familiar with this short description.

3.1 Overview

UPPAAL main window (figure 1) has two main parts: the menu and the tabs.

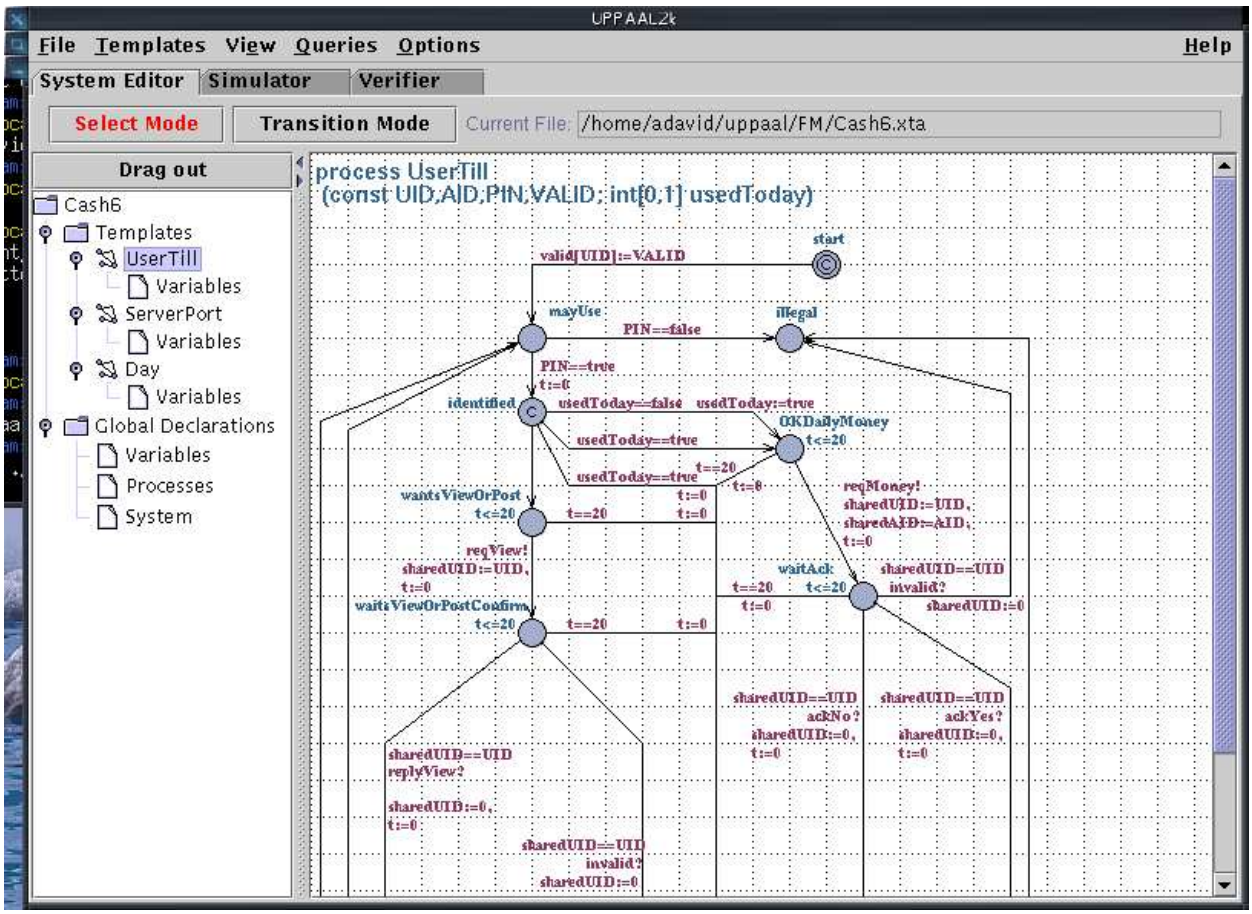

Figure 1: Overview of UPPAAL.

The menu is described in the integrated help, accessible though the `help` menu. This menu describes the GUI in details, so this document will rather focus on how to use it. The three give access to the three components of UPPAAL that are the *editor*, the *simulator* and the *verifier*.

Figure 1 shows the editor view. The idea is to define a bunch of templates (like in C++) that are instanciated to have a complete system. The templates can have symbolic variables and constants as parameters and they may have local variables as well.

To get a first contact with UPPAAL, *double click* in the drawing area to get a location, repeat this, you have two. Double click on these locations to rename them to `start` and `end`. Click on the `Transition Mode`, click on the start location and on the end location. You have your first automaton ready, as depicted in figure 2.

Click on the `Simulator` tab to start the simulator, click on the `yes` button that will popup and you are ready to run your first system.

Figure 3 shows the simulator view. On the left you will find the control part where you can choose the transitions (upper part) and replay/save/load a trace (lower part). In the middle are the variables and on the right the system itself.

The goal of the rest of this document is to explore some key points of UPPAAL though examples.

Figure 2: Your first automaton.

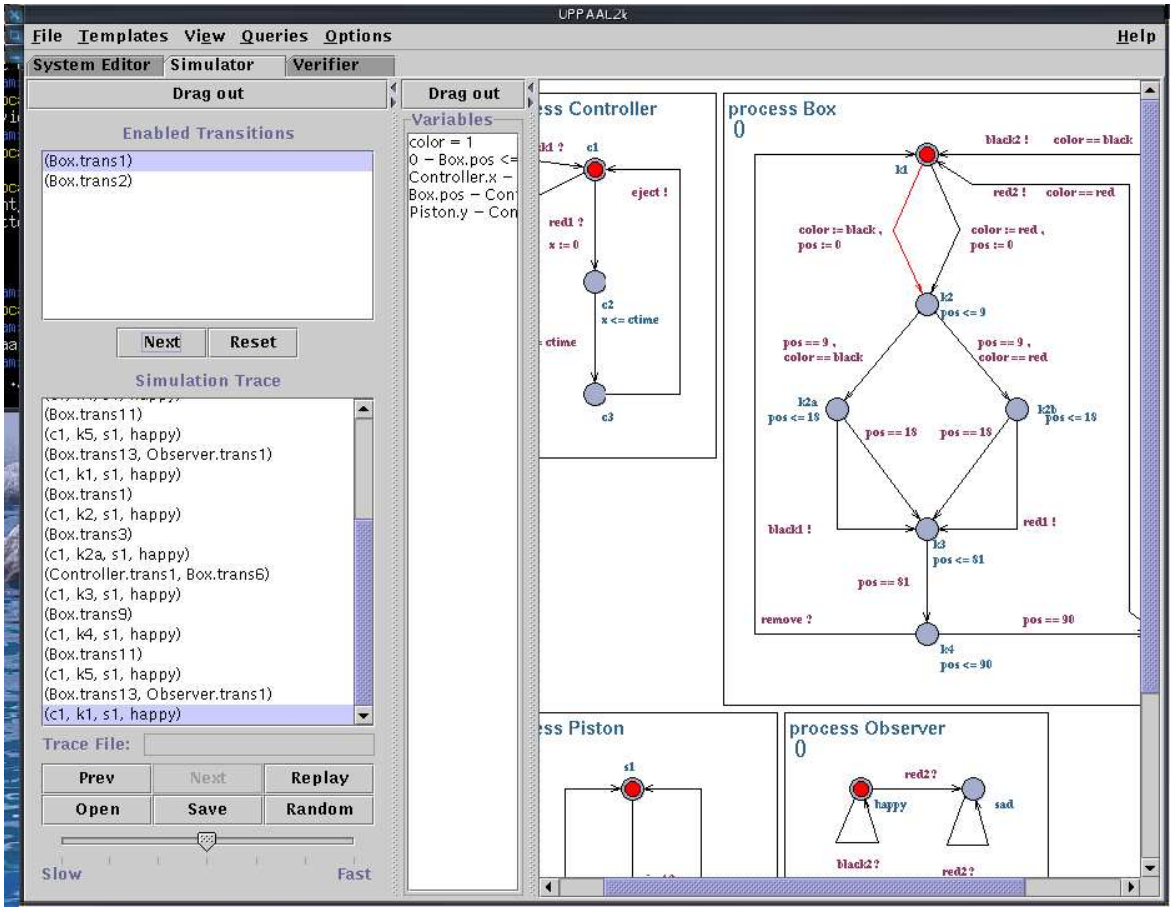

Figure 3: A snapshot of the graphical simulator.

3.2 Mutual Exclusion Algorithm

We will study now the known Petterson's mutual exclusion algorithm to see how from a program/algorigthm we can derive its automaton and check properties related to it.

The algorithm is as follows for two processes, in C:

Process 1	Process 2
`req1=1;`	`req2=1;`
`turn=2;`	`turn=1;`
`while(turn!=1 && req2!=0);`	`while(turn!=2 && req1!=0);`
//critical section	//critical section
`job1();`	`job2();`
`req1=0;`	`req2=0;`

You will construct the corresponding automata. Notice that the protocol is symmetric, so you will use the *template* of UPPAAL. First reset the system (`New system`) to clear the "Hello World" example. Rename the default template `P` to `mutex`.

We will abstract the actual work in the critical section since it has no interest here. The protocol has four states that come directly from the described algorithm, similar to goto labels:

Process 1

idle:
`req1=1;`
want:
`turn=2;`
wait:
`while(turn!=1 && req2!=0);`
CS:
//critical section
`job1();`
//and return to idle `req1=0;`

Draw the automaton as depicted in figure 4.

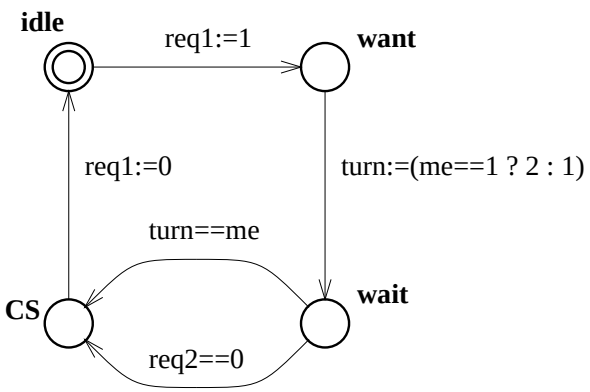

Figure 4: Mutex template

Now you will define it as a template: double click on the parenthesis below the template name. There you can define the template parameters. Type `int[0,1] req1,req2 ; const me` which

means that you define three variables for instanciation of type integer, bounded between 0 and 1, boolean in fact. The last parameter will be a constant. As you guess now from your drawing, two instances of the type `P1:=mutex(req1,req2,1);` and `P2:=mutex(req2,req1,2);` will do the job. Examine how the expression (like C syntax) `turn:=(me==1 ? 2 : 1)` will evaluate. Well, open the `Global Declaration` sub-tree. Click on the `Processes` label and type the declarations above.

Something is still missing: the variables, they have to be declared. Click on the `Variable` label and declare: `int[0,1] req1,req2,turn;` We have to define the system now: click on the `System` label and define there `system P1,P2;`.

Now you have defined your template, instanciated them, used the instanciations in the system and declared proper variables. As you noticed the variables in the global declaration sub-tree are global! This is used for `turn` that is common. The scope of the name declaration are local first and then global: you notice this on the parameters of the templates and the name of the global variables. This is on purpose to show how it works. Now click on the `Simulator` tab and examine how the two automata were instanciated. Look particularly at the names of the two automata that are symmetric. You can simulate your system by choosing interactively the transitions. Try to reach the critical section in both processes at the same time ... well you cannot, a better idea is to use the verifier to be sure of this.

Click on the `Verifier` tab, click on the `Insert` button, click in the `Query` text area and write your property: `A[] not (P1.CS and P2.CS)`. Press the `Model Check` button and you are done. There should be a green button lighted on, which means that the property was verified. If the button were red it would mean that the property was not verified. The property `A[]` is a safety property: you check that `not (P1.CS and P2.CS)` is always true. Another type of property, the `E<>` may be used for simple reachability properties. Try `E<> P1.CS`, check on the the trace in the `Options` menu and press the `Model Check` button. You will get a dialog window asking to save the trace, say yes and return to the simulator. You can go through the found trace, press `Replay` for this.

3.3 The Time in UPPAAL

This sub-section intends to explain intuitively the concept of time in UPPAAL.

The time model in UPPAAL is continuous time. Technically, it is implemented as regions and the states are thus symbolic, which means that at a state we do not have any concrete value for the time, but rather differences. To grasp how the time is handled in UPPAAL we will study a simple example. We will use an *observer* to show the differences. Normally an observer is an add-on automaton in charge of detecting events without pertubing the observed system. In our case the reset of the clock (`x:=0`) is delegated to the observer to make it work, the original behaviour with the reset directly on the transition `loop` to itself is not changed actually.

Figure 5 shows the first model with its observer. Time is used through *clocks*. In the example `x` is a clock declared as `clock x;` in the global declarations (`Variables` label). A channel is used for synchronization with the observer. The channel synchronization is a hand-shaking between `reset!` and `reset?` in our example. So in this example the clock may be reset after 2 time units. The observer detects this and actually performs the reset.

Draw the model, name the automata P1 and Obs, define them in the system. Notice that the state `taken` of the observer is of type `commit`. If you simulate the system you will not see much. To train to interpret what you see we will use queries and modify the system progressively. The expected behaviour of our system is depicted in figure 6.

Try these properties to exhibit this behaviour:

- `A[] Obs.taken imply x>=2` : all fall-down of the clock value (see curve) are above 2. This questions means: for all states, being in the location `Obs.taken` implies that `x>=2`.
- `E<> Obs.idle and x>3` : this is for the waiting period, you can try values like 30000 and

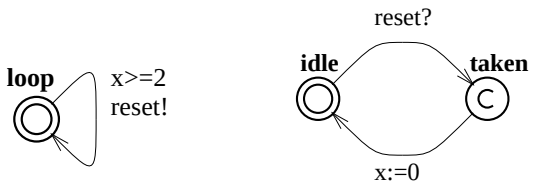

Figure 5: First example with the observer.

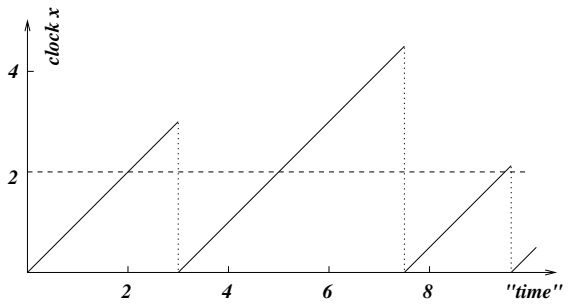

Figure 6: Time behaviour of the first example: this is one possible run.

you will get the same result. This question means: is it possible to reach a state where `Obs` is in the location `idle` and `x>3`.

Add now an invariant to the `loop` state as shown in figure 7.

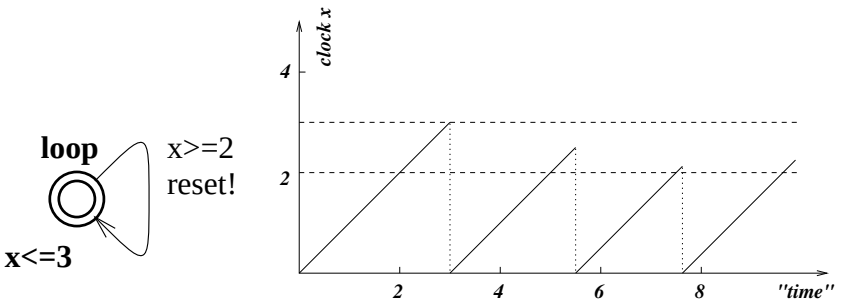

Figure 7: Adding an invariant: the new behaviour.

The invariant is a progress condition: the system is not allowed to stay in the state more than 3 time units, so the transition has to be taken and the clock reset in our example.

To see the difference, try the properties:

- `A[] Obs.taken imply (x>=2 and x<=3)` to show that the transition is taken when in the interval 2-3.
- `E<> Obs.idle and x>2` : it is possible to take the transition in the interval 2-3.
- `A[] Obs.idle imply x<=3` : to show that the upper bound is respected.

The former property `E<> Obs.idle and x>3` no longer holds.

Remove the invariant and change the guard to `x>=2,x<=3`. You may think that it is the same as before but it is not! The system has no progress condition, just a new condition on the guard now. Figure 8 shows the new system.

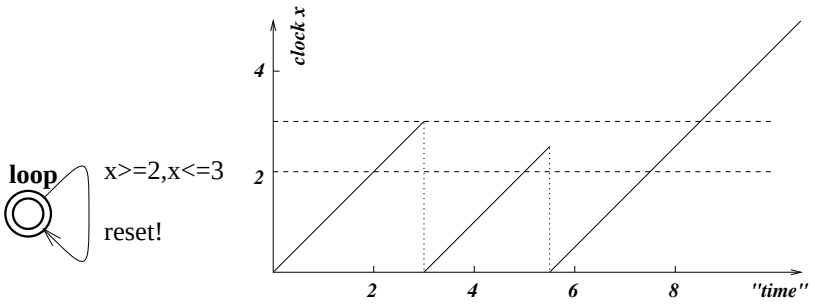

Figure 8: No invariant and a new guard: the new behaviour.

As you can see the system may take the same transitions as before, but there is now a deadlock: the system may be stuck if it does not take the transition after 3 time units. To see what happens

Retry the same properties, the last one does not hold now. Actually you can see the deadlock with the following property: `A[] x>3 imply not Obs.taken`, that is after 3 time units the transition is not taken any more.

3.4 Urgent/Committed Locations

We will now look at the different kind of locations of UPPAAL. You already saw the type `commit` in the previous example. There are three different types of locations in UPPAAL that are normal locations with or without invariants (the `x<=3`), urgent locations and committed locations. Draw the automata depicted in figure 9. Define the clocks locally to try this feature: open the sub-tree of the automata, you will see a `Variables` label under the template. Click on it and define `clock x;`.

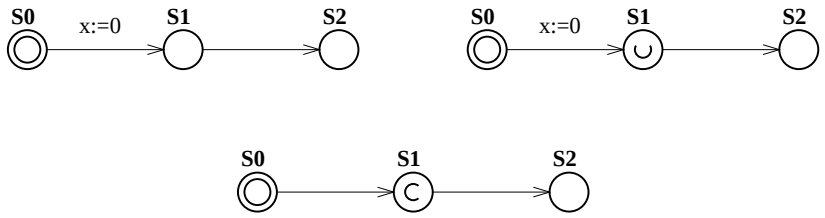

Figure 9: Automata with normal, urgent and commit states.

Name the automata P0, P1 and P2 respectively. The state marked U is urgent and the one marked C is committed. Try them in the simulator and notice that when in the commit state, the only possible transition is always the one going out of the commit state. The commit state has to be left immediately. To see the difference between normal and urgent state, go to the verifier and try the properties:

- `E<> P0.S1 and P0.x>0` : it is possible to wait in `S1`.

- `A[] P1.S1 imply P1.x==0` : it is not possible to wait in `S1`.

Time may not pass in an urgent state, but interleavings with normal states are allowed as you can see in the simulator.

3.5 Some Modeling Tricks

UPPAAL offers *urgent channels* that are synchronization that must be taken when the transition is enabled, *without* delay. Clock conditions on these transitions are not allowed. It is possible to encode "urgent transitions" with a guard on a variable, i.e. busy wait on a variable, by using urgent channels. Use a dummy process with one state looping with one transition `read!`. The urgent transition will be `x>0 read?` for example.

There is no value passing though the channels but this is easily encoded by shared variable: define globally a variable x, and use it to write and read it. Notice that it is not clean to do `read! x:=3;` and `read? y:=x;` but it is better to use a commit state: `read?` commit state and `y:=x;`.

There is no broadcast communication: synchronization is only by pairs. To get broadcast use a serie of commit states. The sequence will be typically: `go1!` commit `go2!` commit `go3!` and three automata having the corresponding `go1?, go2?` and `go3?`. Several solutions are possible.

Arrays of integers may be useful, declare them as `int a[3];` to have an array indexable from 0 to 2. The index can be an other variable `i` typically `int[0,2] i;` to be clean.

To keep a model manageable, one has to pay attention to some points:

- The number of clocks has an important impact on the complexity.
- The use of committed locations can reduce significantly the state space, but one has to be careful with this feature because it can possibly take away relevant states.
- The number of variables plays an important role as well and more importantly their range. One should be careful that the integer will not use all the values from -32000 to 32000 for example.

References

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