Formal Methods Technical Report

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Abstract. The Calculus of Communicating Systems (CCS) is a young branch in process calculus introduced by Robin Milner. CCS's theory has promising results in the field of modeling and analysing of reactive systems. Despite CCS's success, there are only few computer tools that are available for modeling and analysis of CCS's theory. This paper is a technical report of an effort to build a tool that is able to parse CCS's expressions, build LTSs (Labelled Transition Systems) from CCS and can calculate if two LTS are strongly or weakly bisimilar by using naive method or by using Fernandez's method. The tool is simple, but it has the functionality needed to perform modeling, specification and verification. TODO: Revise the abstract as a short summary of the report.

Keywords: Reactive Systems, CCS, Formal Methods, Process Algebra

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1 Introduction

In this paper we presnt a tool for modeling, manipulation and analysis of concurrent systems based on CCS process language and LTS as its semantic model. The tool is implented in java using Graphical User Interface (GUI) making it unique amongst tools with similar functionalities. the tool can check for weak and strong bisimilarity TUKA DOPOLNETE.

(The tool is a Java executable jar library with very simple user interface...)

TODO: Rewrite the introduction to represent a longer summary of the report.

1.1 Related work

In the past two decades different tools for modeling, specification and verification of concurrent reactive systems

The Edinburgh Concurrency Workbench (CWB) is a tool for analysis of cuncurrent systems. CWB allows for equivalence, preorder and model checking using a variety of different process semantics. It also allows defining of behaviours in an extended version of CCS and perform various analysis of these behaviours, such as checking various semantic equivalences for examples checking if two processes (agents in CWB) are strongly or weakly bisimilar [CWB]. Although CWB covers much of the functionality of our tool and more, CWB has a command interpreter interface that is more difficult to work with, unlike our tool that has a Graphical User Interface (GUI), and is very intuitive. As far as we know the CWB does not have the functionality for exporting LTS graphs in Aldebaran format, that our tool has. We have used the CWB many times while testing our tool, for checking CCS validity and also testing algorithms for strong and weak bisimularity of LTS graphs.

The micro Common Representation Language 2 (mCRL2), successor of CRL, is a formal specification language that can be used to specify and analyse the behaviour of distrubuted systems and protocols. Its accompanying toolset contains extensive collection of tools to automatically translate any mCRL2 specification to a linear process, manipulate and simulate linear processes, generate the state space associated with a linear process, manipulate and visualize state spaces, generate a PBES from a formula and a linear process, generate a BES from PBES and manipulate and solve (P)BESs [mCRL2]. All mCRL2 tools can be used from the command line, but mCRL2 has an enhanced Graphical User Interface (GUI) as well which makes it very user-friendly and easy and to use. However, to our knowledge, mCRL2 does not provide the possibility to define systems' behaviour in the CCS process language nor to specify systems' properties using HML logic, functionalities that are implemented in the very initial version of our tool. Also, even though mCRL2 supports minimization modulo strong and weak bisimulation equivalence, it does not output the computed bisimulation, feature that we have implemented in our tool.

1.2 Outline

The contributions of this paper are organized as follows. In the next section we give introduction to some of the basic terminology used throughout the report. The third section is devoted to the implementation of the CCS process language and generation of Labelled Transition Systems as a semantic model of process expressions, and it also discusses some of the choices made during the implementation. Section four describes the process of reducing the size of the state space of an LTS as well as checking the equivalence between two LTSs with respect to behavioural relations such as strong bisimilarity and observational equivalence (weak bisimilarity). It includes implementation details of two algorithms for computing strong bisimulation equivalence, the naive algorithm and the advanced algorithm due to Fernandez, as well as description of the saturation technique together with a respective algorithm for saturating an LTS with which the problem of computing weak bisimilarity is reduced to computing strong bisimilarity over the saturated systems. Section five explains how the implementation of Hennesy-Milner Logic (HML) works and gives implementation details for the U_w and U_s operators. Next we illustrate the application of the tool for modeling, specification and verification of some classical examples. These classical examples include the Alternating Bit Protocol and Peterson's mutual exclusion algorithm. Finally, we give some conclusions and some directions for future development of the tool. We also include four appendixes. The first appendix contains the experimental results we got with analysis of the running times of our implementations of the two algorithms for computing bisimulation equivalence. The second one shows the syntax diagram for the grammar that recognizes CCS expressions . And the last appendix includes some visual illustration of the tool's usage via screenshots of the graphical application.

2 CCS parsing and LTS generation

Given a set of action names, the set of CCS processes is defined by the following BNF grammar:

$$P ::= \emptyset \mid a.P_1 \mid A \mid P_1 + P_2 \mid P_1|P_2 \mid P_1[b/a] \mid P_1\backslash a \tag{1}$$

Two choices were considered for the problem of building a parser. The first choice was to build a new parser, which required much more resources and the second choice was to define a grammar and to use a parser generator (compiler-compiler, compiler generator) software to generate the parser source code. In formal language theory, a context-free grammar (CFG) is a grammar in which every production rule has the form:

$$V \rightarrow w$$

where V e is a nonterminal symbol, and w is a string of terminal and/or nonterminal symbols (w can be empty). Obviously, the defined BNF grammar for describing the CCS process is a CFG. Deterministic context-free grammars (DCFGs)

are grammars that can be recognized by a deterministic pushdown automaton or equivalently, grammars that can be recognized by a LR (left to right) parser. DCFGs are a proper subset of the context-free grammar family. Although, the defined grammar is a non-deterministic context-free grammar, modern parsers have a look ahead feature, which means that the parser will not make a parsing decision until it reads ahead several tokens. This feature alows us to use a parser generator software, that will generate LR or LL parser which is able to recognize the non-deterministic grammar.

2.1 Generating the parser

ANTLR (ANother Tool for Language Recognition) [Par07] is a parser generator that was used to generate the parser for the CCS grammar. ANTLR uses LL(*) parsing and also allows generating parsers, lexers, tree parsers and combined lexer parsers. It also automatically generates abstract syntax trees (AST), by providing operators and rewrite rules to guide the tree construction, which can be further processed with a tree parser, to build an abstract model of the AST using some programming language. A language is specified by using a context-free grammar which is expressed using Extended Backus Naur Form (EBNF). In short, an LL parser is a top-down parser which parses the input from left to right and constructs a Leftmost derivation of the sentence. An LL parser is called an LL(*) parser if it is not restricted to a finite k tokens of lookahead, but can make parsing decisions by recognizing whether the following tokens belong to a regular language. This is achieved by building temporary deterministic finite automaton, which are maintained and used until the parser makes a decision. This feature and some more optimization for the LL parser were published in recent years which made this kind of parser generators popular and favorable.

ANTLR was used to generate lexer, parser and a well defined AST which represents a tree representation of the abstract syntactic structure of the parsed sentence. The term abstract is used in a sense that the tree does not represent every single detail that exists in the language syntax, for example, parentheses are implicit in the tree structure. From a development point of view it is much easier to work with trees than with a list of recognized tokens. One example of an AST is shown in Fig. 1 which is the result of parsing the expression:

$$A = (b.B \mid c.D \ + \ d.D) \backslash \{b, \ c\} \tag{2}$$

2.2 CCS domain model and LTS graph generation

Although working directly with ASTs and performing all algorithms on them is possible, it causes a limitation in future changes, where even a small change in the grammar and/or in the structure of the generated ASTs causes a change in the implemented algorithms. Because of this, a specific domain model is built along with a domain builder algorithm, which has corresponding abstractions for all CCS operators, processes and actions. The input of the domain builder algorithm

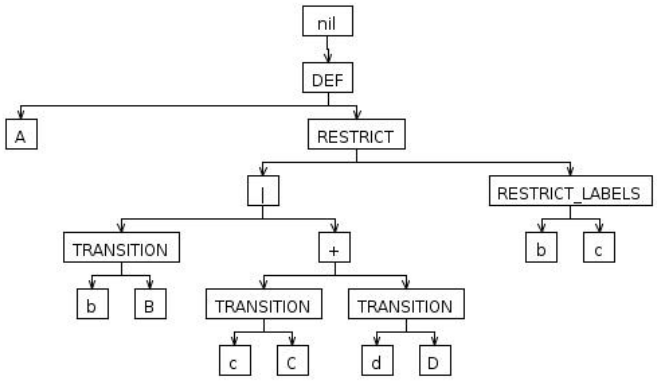

Fig. 1. AST Example

is an AST, and the output is a fully built domain model. The algorithms for constructing an LTS graph are implemented on the domain model because it is not expected for the domain model structure to change much in the future. The domain model is also a tree-like structure, so it is as easy to work with, as with the AST.

The LTS generation algorithm is a recursive algorithm which traverses the tree structure of objects in the domain model and performs SOS rule every time it reaches an operation. In this fashion all SOS transformation are performed on the domain and as result a new graph structure is created which represents the LTS which can be easily exported to a file in Aldebaran format.

2.3 Workflow of operations

In Fig. 2 the workflow of all operations that are executed for constructing an LTS graph from a CCS expression are shown. Every operation is done as a standalone algorithm independent from the other operations, that has input and output shown in the Figure. The modular design is deliberately chosen in order to help achieve better testing and maintenance of the source code.

3 Saturation and weak bisimulation equivalence

Def: Let P and Q be CCS processes or, more generally, states in a labeled transition system. For each action a, we shall write $P \stackrel{a}{\Rightarrow} Q$ iff:

- Either $a \neq \tau$ and there are processes P' and Q' such that $P \left(\stackrel{\tau}{\rightarrow}\right)^* P' \stackrel{a}{\rightarrow} Q' \left(\stackrel{\tau}{\rightarrow}\right)^* Q$,
- Or $a = \tau$ and $P \left(\stackrel{\tau}{\rightarrow}\right)^* Q$,

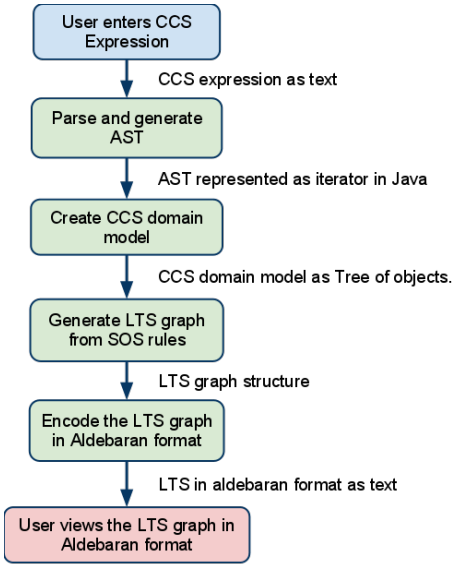

Fig. 2. Workflow of all operations for producing an LTS graph from a CCS expression

where we write $\left(\xrightarrow{\tau}\right)^*$ for he reflexive and transitive closure of the relation $\xrightarrow{\tau}$.

Def: (weak bisimulation and observational equivalence) A binary relation R over the set of states of an LTS is a weak bisimulation iff, whenever $s_1 R s_2$ and a is an action (including τ):

- If $s_1 \xrightarrow{a} s_1'$ then there is a transition $s_2 \stackrel{a}{\Rightarrow} s_2'$ such that $s_1' R s_2'$;
- If $s_2 \xrightarrow{a} s_2'$ then there is a transition $s_1 \stackrel{a}{\Rightarrow} s_1'$ such that $s_1' R s_2'$;

Two states s and s' are observationally equivalent (or weakly bisimilar), written $s \approx s'$, iff there is a weak bisimulation equivalence that relates them.

Def: Let $T \subseteq S \times Act \times S$ be an LTS. We shall say that $T^* = \left\{(p,a,q)\,|p \stackrel{a}{\Rightarrow} q\right\} = T \cup \left(\xrightarrow{a}\right)^* \cup \left\{(p,a,q)\,|a \neq \tau \wedge (\exists p', q' \in A)\, p \left(\xrightarrow{\tau}\right)^* p' \xrightarrow{a} q' \left(\xrightarrow{\tau}\right)^* q\right\}$ is a saturation of T.

Proposition: Two LTSs are weakly bisimilar iff their saturated LTSs are strongly bisimilar.

Proof: Let T and U be two LTSs for which their saturated LTSs are strongly bisimilar by the relation R. Since the strong bisimulation is also a weak bisimulation it follows that T and U are weakly bisimular, since they are weakly bisimular to their respective saturated LTSs. Let T and U be two LTSs that are weakly bisimilar. Let $u \approx t$, $u' \approx t'$. If $t \xrightarrow{a} t' \in T^*$, that means $t \stackrel{a}{\Rightarrow} t'$, or that there exist states t_i, t_j' such that: $t \xrightarrow{\tau} t_1 \xrightarrow{\tau} ... \xrightarrow{\tau} t_k \xrightarrow{a} t_1' \xrightarrow{\tau} ... \xrightarrow{\tau} t_m' \xrightarrow{\tau} t'$. Let $u_i \approx t_i$,...,$u_j' \approx t_j'$,.... It follows that $u \stackrel{\tau}{\Rightarrow} u_1 \stackrel{\tau}{\Rightarrow} ... \stackrel{\tau}{\Rightarrow} u_k \stackrel{a}{\Rightarrow} u_1' \stackrel{\tau}{\Rightarrow} ... \stackrel{\tau}{\Rightarrow} u'$, or that there exist states u'', u''' in U such that $u \left(\xrightarrow{\tau}\right)^* u_k \left(\xrightarrow{\tau}\right)^* u'' \xrightarrow{a} u''' \left(\xrightarrow{\tau}\right)^* u_1' \left(\xrightarrow{\tau}\right)^* u'$

which means $u \stackrel{a}{\Rightarrow} u'$. Since U^* is a saturation of U, it follows that $u \stackrel{a}{\rightarrow} u' \in U^*$. Similarly, for every transition $u \stackrel{a}{\rightarrow} u' \in U^*$, there is a transition in $t \stackrel{a}{\rightarrow} t' \in T^*$, such that $u \approx t$, $u' \approx t'$. Therefore, the weak bisimulation relation $\approx$ for T and U is a strong bisimulation relation for T^* and U^*.

3.1 The algorithm for saturation.

The set of triples R can be partitioned in $2n$ sets with:
$T_{\tau p} = \{(p, \tau, q) \,|\, (p, \tau, q) \in T\}$, and
$T_{ap} = \{(p, \tau, q) \,|\, a \neq \tau \wedge (p, \tau, q) \in T\}$ for every $p \in S$.

By the definition of $T_{\tau p}$ and T_{ap} it can be seen that $\bigcup_{p \in S} (T_{\tau p} \cup T_{ap}) = T$, and also, their pairwise intersection is empty.

The family of sets $T^*_{\tau p}$ can be iteratively constructed with:
$T^0_{\tau p} = T_{\tau p} \cup \{(p, \tau, p)\}$,
$T^i_{\tau p} = T^{i-1}_{\tau p} \cup \left\{(p, \tau, r) \,|\, (\exists q \in S)\, (p, \tau, q) \in T^{i-1}_{\tau p} \wedge (q, \tau, r) \in T_{\tau q}\right\}$ and
$T^*_{\tau p} = T^n_{\tau p}$

(Note: $\left|T^*_{\tau p}\right| \leq |S| = n$; when for some $k < n$, $T^k_{\tau p} = T^{k+1}_{\tau p}$, then $T^*_{\tau p} = T^k_{\tau p} = T^n_{\tau p}$)

With this step a reflexive, transitive closure was constructed: $T^*_\tau = \bigcup_{p \in A} T^*_{\tau p} = \left\{(p, \tau, q) \,|p \left(\stackrel{\tau}{\rightarrow}\right)^* q\right\}$.

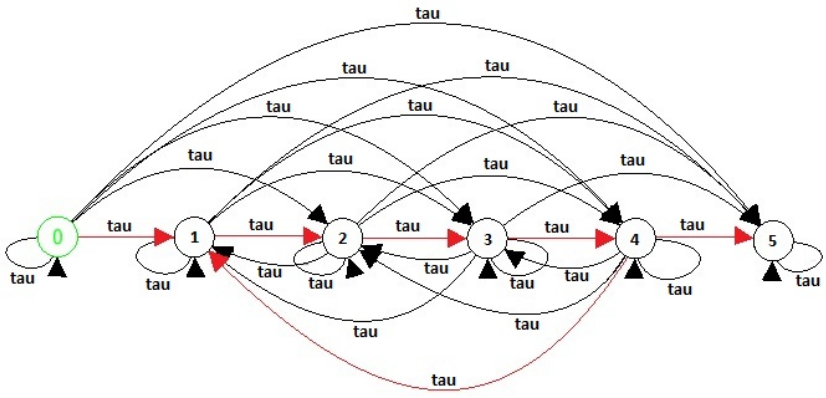

Fig. 3. Reflexive, transitive closure of τ. The original graph is depicted with red lines

The next step is to construct $T'_{ap} = \bigcup_{p \in A} T'_{ap} = \left\{(p, a, q) \,|\, (\exists q' \in S)\, (p, a, q') \in T \wedge q' \left(\stackrel{\tau}{\rightarrow}\right)^* q\right\}$:
$T^0_{ap} = T_{ap'}$,
$T^i_{ap} = T^{i-1}_{ap} \cup \left\{(p, a, r) \,|\, (\exists q \in S)\, (p, a, q) \in T^{i-1}_{ap} \wedge (q, \tau, r) \in T^{i-1}_{\tau q}\right\}$ and
$T'_{ap} = T^{n|Act|}_{ap}$

(Note: $|T'_{ap}| \leq |S||Act| = n|Act|$, when for some $k < n|Act|$, $T^k_{ap} = T^{k+1}_{ap}$, then $T'_{ap} = T^k_{ap} = T^{n|Act|}_{ap}$)

For the third step, $T' = \bigcup_{p \in S} \left(T^*_{\tau p} \cup T'_{ap}\right)$ needs to be partitioned again, defined by the destination in the triple:
$T_{\tau q} = \{(p, \tau, q) \,|\, (p, \tau, q) \in T'\}$ and $T_{bq} = \{(p, a, q) \,|\, a \neq \tau \wedge (p, a, q) \in T'\}$ for every $p \in S$,
and then construct:
$T^0_{bq} = T_{bq}$,
$T^i_{bq} = T^{i-1}_{bq} \cup \left\{(p', a, q) \,|\, (\exists p \in S)\, (p, a, q) \in T^{i-1}_{bq} \wedge (p', \tau, p) \in T^*_{\tau p}\right\}$ and
$T^*_{bq} = T^{n|Act|}_{bq}$

Finally the saturated LTS is:
$T^* = \bigcup_{p \in S} \left(T^*_{\tau p} \cup T^*_{bp}\right) = \left(\xrightarrow{\tau}\right)^* \cup \left\{(p, a, q) \,|\, a \neq \tau \wedge (\exists p', q' \in A)\, p \left(\xrightarrow{\tau}\right)^* p' \xrightarrow{a} q' \left(\xrightarrow{\tau}\right)^* q\right\}$

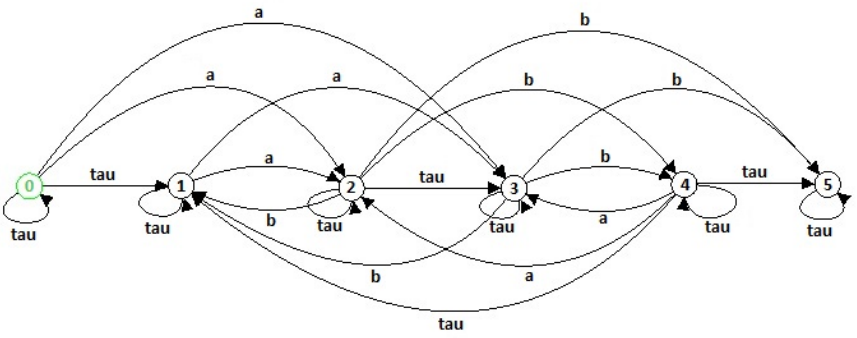

Fig. 4. Example saturated LTS

4 Alternating Bit Protocol - Modelling, Specification and Verification

The alternating bit protocol is a simple yet effective protocol (usually used as a test case), designed to ensure reliable communication through unreliable transmission mediums, and it is used for managing the retransmission of lost messages [AILS07c][Kul94].

The representation of Alternating Bit Protocol (hereby abbreviated as ABP) is shown bellow, and it consists of a *Sender* S, a *Receiver* R and two channels $Transport$ T and *Acknowledge* A.

All of the transitions in the ABP are internal synchronization and the only visible transitions are deliver and accept, which can occur only sequentially.

The specication of ABP is that it should act as a simple buffer, as follows:
$ABP = \overline{deliver}.accept.ABP$

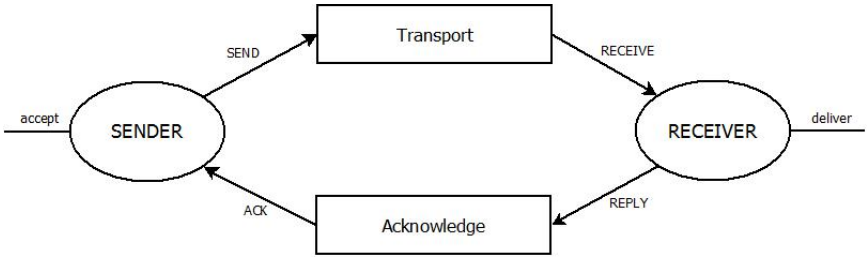

Fig. 5. Alternating bit protocol

Messages are sent from a sender S to a receiver R. Channel from S to R is initialized and there are no messages in transit. There is no direct communication between the sender S and the receiver R, and all messages must travel trough the medium (transport and acknowledge channel). The ABP works like this:

1. Each message sent by S contains the protocol bit, 0 or 1.
   Here is the implementation:
   $Imp \stackrel{def}{=} (S|T|R|A) \setminus L$,
   where $L = (send0, send1, receive0, receive1, reply0, reply1, ack0, ack1)$ is the set of restricted actions.
2. When a sender S sends a message, it sends it repeatedly (with its corresponding bit) until receiving an acknowledgment ($ack0$ or $ack1$) from a receiver R that contains the same protocol bit as the message being sent.
   $S = \overline{send0}.S + ack0.accept.S_1 + ack1.S$
   $S_1 = \overline{send1}.S_1 + ack1.accept.S + ack0.S_1$
   The transport channel transmits the message to the receiver, but it may lose the message (lossy channel) or transmit it several times (chatty channel).
   $T = send0.(T + T_1) + send1.(T + T_2)$
   $T_1 = \overline{receive0}.(T + T_1)$
   $T_2 = \overline{receive1}.(T + T_2)$
3. When R receives a message, it sends a reply to S that includes the protocol bit of the message received. When a message is received for the first time, the receiver delivers it for processing, while subsequent messages with the same bit are simply acknowledged. $R = receive0.\overline{deliver}.R_1 + \overline{reply1}.R + receive1.R$
   $R_1 = receive1.\overline{deliver}.R + \overline{reply0}.R_1 + receive0.R_1$
   Again the acknowledgement channel sends the ack to sender, and it also can acknowledge it several times or lose it on the way to the sender.
   $A = reply0.(A + A_1) + reply1.(A + A_2)$
   $A_1 = \overline{ack0}.(A + A_1)$
   $A_2 = \overline{ack1}.(A + A_2)$
4. When S receives an acknowledgment containing the same bit as the message it is currently transmitting, it stops transmitting that message, flips the protocol bit, and repeats the protocol for the next message.[Kul94][AG09]

In order to verify the alternating bit protocol, it needs to be proven that the implementation meets its specification, or more precisely it needs to be shown that $ABP \approx Imp$. Such a bisimulation R can be found as follows:

ABP implementation states	ABP specification states
$(S\|T\|R\|A)\setminus L$, $(S\|(T+T1)\|R\|A)\setminus L$, $(S\|(T+T1)\|R\|(A+A2))\setminus L$, $(S\|T\|R\|(A+A2))\setminus L$, $\big(S\|(T+T1)\|\overline{deliver}.R1\|A\big)\setminus L$, $\big(S\|(T+T1)\|\overline{deliver}.R1\|(A+A2)\big)\setminus L$, $(S1\|(T+T1)\|R1\|(A+A1))\setminus L$, $\big(S1\|(T+T2)\|\overline{deliver}.R\|(A+A1)\big)\setminus L$, $(S1\|(T+T2)\|R1\|(A+A1))\setminus L$, $(S\|(T+T2)\|R\|(A+A2))\setminus L$	ABP
$(accept.S1\|(T+T1)\|R1\|(A+A1))\setminus L$, $(S\|(T+T1)\|R1\|(A+A1))\setminus L$, $(S\|(T+T1)\|R1\|(A+A2))\setminus L$, $(S\|(T+T1)\|R1\|A)\setminus L$, $(S1\|(T+T2)\|R\|(A+A2))\setminus L$, $(accept.S\|(T+T2)\|R\|(A+A2))\setminus L$, $(S1\|(T+T2)\|R\|(A+A1))\setminus L$	ABP'

Table 1. Verification of Alternating Bit Protocol

4.1 Alternating Bit Protocol - Tool Usage Example

In this section we present how to use the tool to show that the specification and implementation of the ABP are weakly bisimiliar. As a first step we always need to generate the LTSs from both the specification and implementation of the system that we are trying to model. That can be done in the tab "CCS to LTS" in the tool. As shown in 6 in the upper text area we need to write down the ccs expressions that describe the system or load them from a file. One constraint here is that a general ccs expression that describes the whole system has to be put on the first line. The algorithm for generating the LTS graph starts evaulation and construction of the graph starting from the first line. When we have our ccs expressions put in place we have to click "Generate LTS". This action will make the application parse the expression and if no errors are found will start generating the LTS graph The results from the generated graph will be presented in the lower text area in Aldebaran format. The users can save the results in a file or can click "View LTS Graph" which causes the tool to display a computer generated image of the LTS graph.

LTS minimization can be done in the "LTS minimization" tab. The minimization is pretty straigthforward process. As shown in 7 and 8 LTS is loaded from file, a method of calculation has to be chosen and in order to perform calculation the user has to click the button "Calculate".

Checking for LTS bisimilarity is performed in the "LTS comparison" tab. This tab is similary to the one for the minimization. As shown in 9 and 10 two LTSs have to loaded from file. In order to check for LTS bisimilarity the user has to chose a method for calculatino and click on the button "Calculate". The results will be displayed on the right side of the button and they give information wheather the LTSs are bisimilar and how long the calculation lasted.

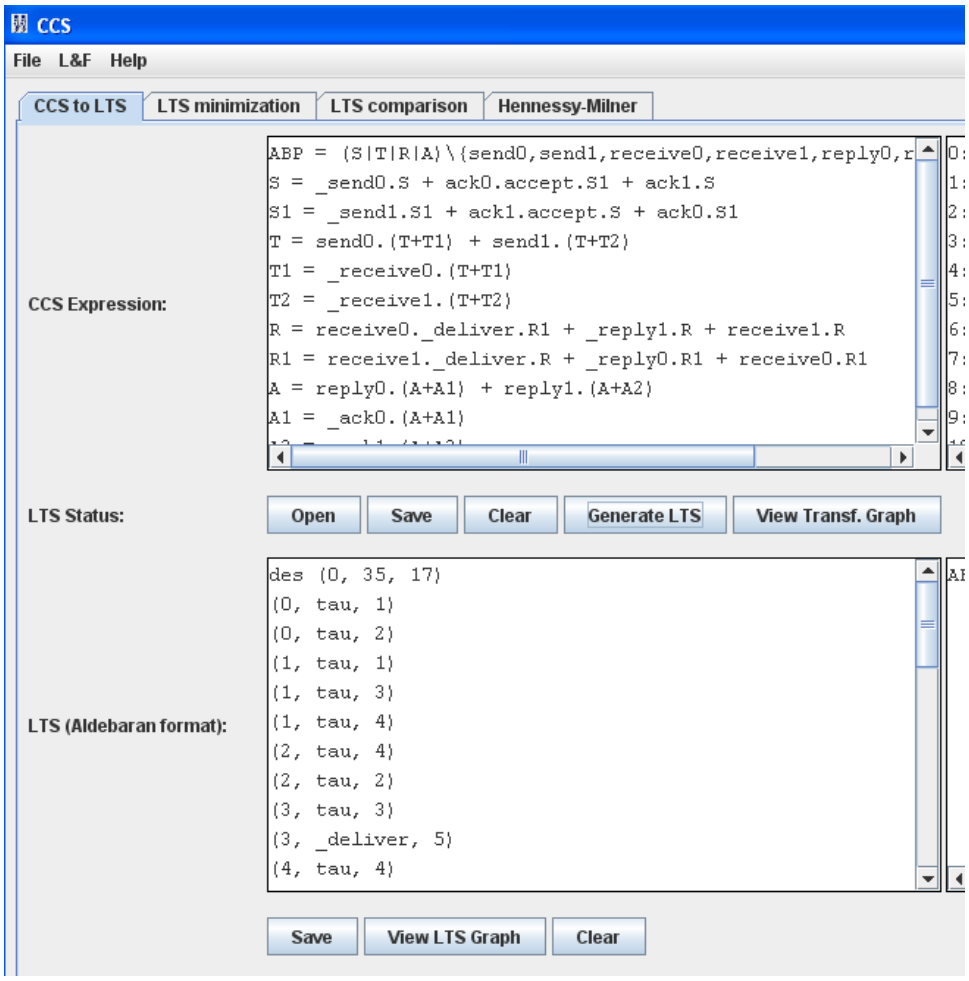

Fig. 6. Tool Usage: ABP Modeling and Generating LTS

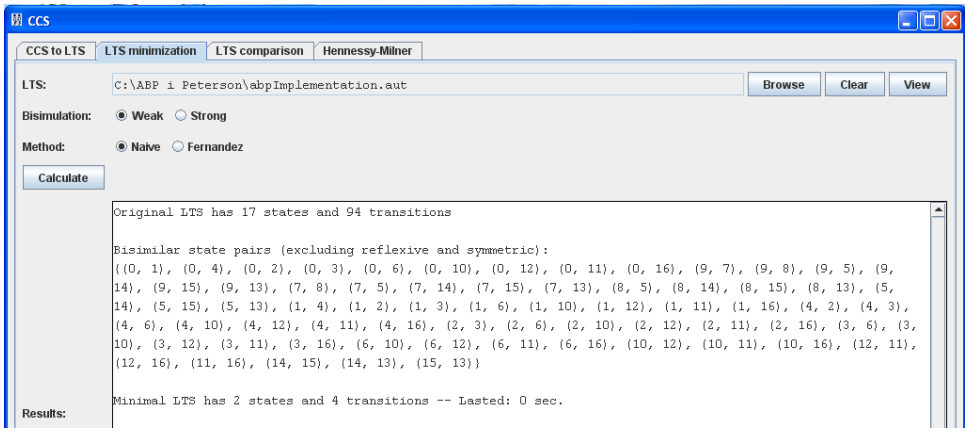

Fig. 7. Tool Usage: ABP Minimization, Weak, Naive

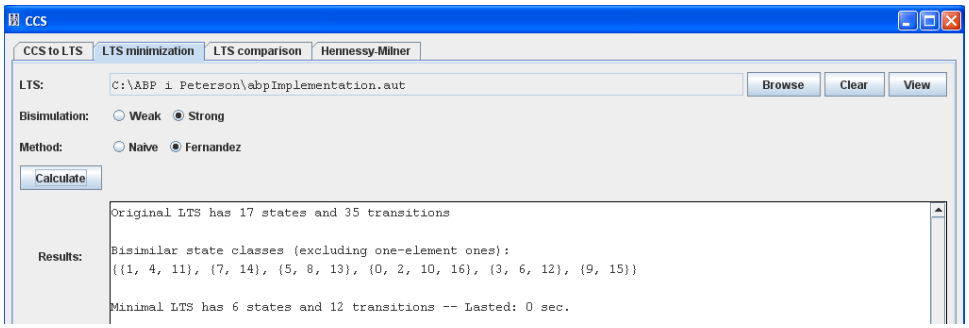

Fig. 8. Tool Usage: ABP Minimization, Strong, Fernandez

5 Peterson and Hamilton algorithm - Modeling, Specification and Testing

Peterson's algorithm (aka Peterson's solution) is a concurrent programming algorithm for mutual exclusion. Mutual exclusion (often abbreviated to mutex) algorithms are used in concurrent programming to avoid the simultaneous use of a common resource, such as a global variable, by pieces of computer code called critical sections. A critical section is a piece of code in which a process or thread accesses a common resource. The critical section by itself is not a mechanism or algorithm for mutual exclusion. A program, process, or thread can have the critical section in it without any mechanism or algorithm which implements

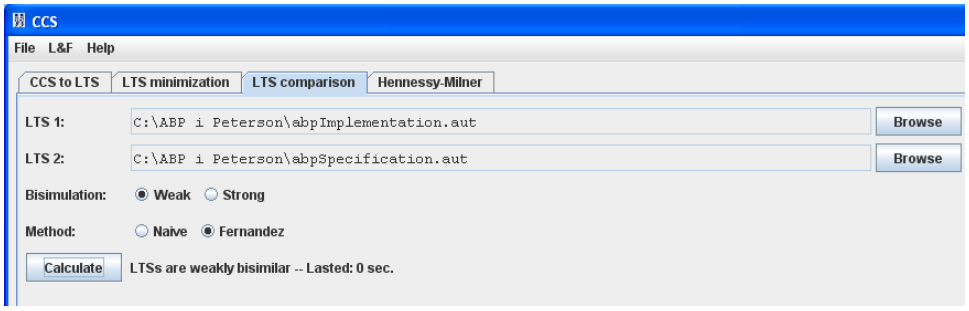

Fig. 9. Tool Usage: ABP Bisimilarity, Weak, Fernandez

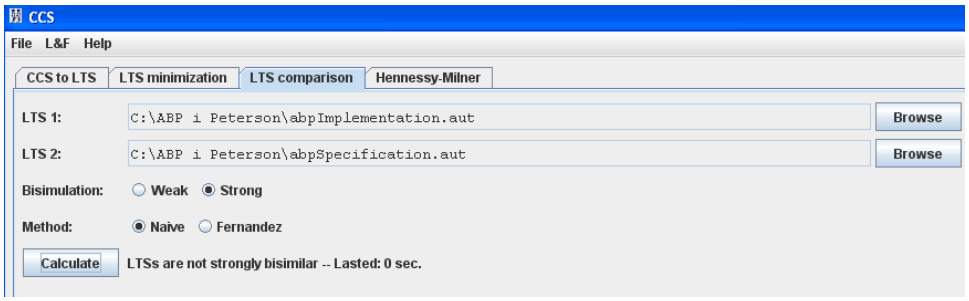

Fig. 10. Tool Usage: ABP Bisimilarity, String, Naive

mutual exclusion. Assume that a variable (memory location) can only have one value (never between values) and processes A and B write want to write to the same memory location at the "same time", either the value from A or the value from B will be written rather than some scrambling of bits. Peterson and Hamilton's algorithm is a simple algorithm that can be run by two processes to ensure mutual exclusion for one resource (say one variable or data structure). Shared variables are created and initialized before either process starts. The shared variables flag[0] and flag[1] are initialized to FALSE because neither process is yet interested in the critical section. The shared variable turn is set to either 0 or 1 randomly (or it can always be set to say 0). The next figure shows the algorithm.

There are two different processes which want to enter at critical section. This means that the processes are fighting for one resource (ex. Say one variable or data structure). flag[i]= true means that process I wants to enter the critical section and the turn=i means that process i is next to enter the critical section. At first the shared variables flag[0] and flag[1] are initialized to false because neither process is yet interested in the critical section. The shared variable turn is set to either 0 or 1 randomly (or it can always be set to say 0). If the process cant enter the critical section it waits in while loop.
Legend: turn 0, 1 flag0, flag1 true, false = t, f w write r read enter enter the critical section exit exit the critical section

```
var flag: array [0..1] of boolean;
turn: 0..1;
//flag[k] means that process[k] is interested in the critical section
flag[0] := FALSE;
flag[1] := FALSE;
turn := random(0..1)
//After initialization, each process, which is called process i in the code, runs this
code:
repeat
 flag[i] := TRUE;
 turn := j;
 while (flag[j] and turn=j) do no-op;
 //CRITICAL SECTION
 flag[i] := FALSE;
 //REMAINDER SECTION
until FALSE;
```

Fig. 11. Peterson-Hamilton's algorithm

Initialization:
turn=1
flag1 = flag2 = f

CCS Specification:
Peterson = (P1 — P2 — flag1f — flag2f — turn1) L
P1 = flag1wt.turnw2.P11
P11 = flag2rf.P12 + flag2rt.(turnr2. .P11 + turnr1.P12)
P12 = enter1.exit1.flag1wf.P1

P2 = flag2wt.turnw1.P21
P21 = flag1rf.P22 + flag1rt.(turnr1. .P21 + turnr2.P22)
P22 = enter2.exit2.flag2wf.P2

FLAG1f = flag1rf.flag1f + flag1wf.flag1f + flag1wt.flag1t
FLAG1t = flag1rt.flag1t + flag1wt.flag1t + flag1wf.flag1f

FLAG2f = flag2rf.flag2f + flag2wf.flag2f + flag2wt.flag2t
FLAG2t = flag2rt.flag2t + flag2wt.flag2t + flag2wf.flag2f
TURN1 = turnr1.turn1 + turnw1.turn1 + turnw2.turn2

TURN2 = turnr2.turn2 + turnw2.turn2 + turnw1.turn1

L = flag1wt, flag1rt, turnw2, union of the access sorts (r,w) of the variables

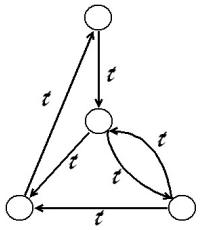

Fig. 12. Live cycle of one process

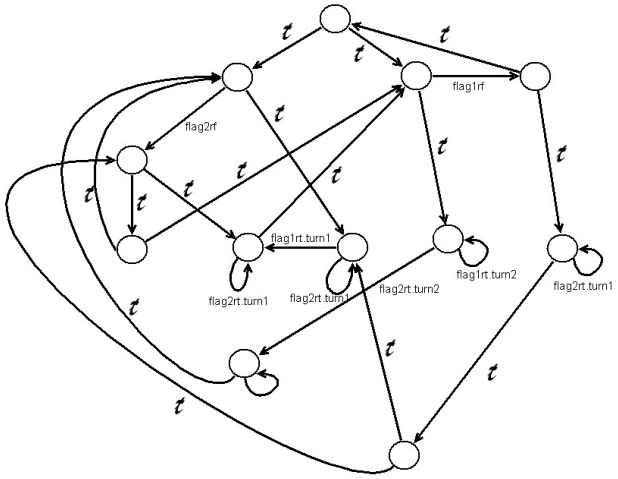

Fig. 13. Model of Peterson-Hamilton algorithm

The previous figures were shown pictures of life cycle of a one process and Model of Peterson - Hamilton algorithm.

The mutual exclusion requirement is assured. Suppose instead that both processes are in their critical section.

Only one can have the turn, so the other must have reached the while test before the process with the turn set its flag. But after setting its flag, the other process had to give away the turn. Contradicting our assumption, the process at the while test has already changed the turn and will not change it again. The progress requirement is assured.

Again, the turn variable is only considered when both processes are using, or trying to use, the resource. Deadlock is not possible. One of the processes must have the turn if both processes are testing the while condition. That process will proceed. Finally, bounded waiting is assured. When a process that has exited the CS reenters, it will give away the turn. If the other process is already waiting, it will be the next to proceed.

Test and set algorithm
repeat
while Test-and-Set(lock) do no-op;
critical section
lock := false;
remainder section
until false

Test-and-Set(target)
result := target;
target := true;
return result

Process 1	Process 2
Wants to set target to true	
Target is changed to true	
Result comes back false so no busy waiting	
	Wants to set target to true
	It receives the result true
	Busy waits as long as Process 1 is in critical section
Leaves critical section	
Set target to false	

6 HML and U^w and U^s operators

Henessy-Milner logic [HM85] is a multimodal logic used to characterize the properties of a system which describe some aspects of the system's behaviour. Its syntax is defined by the following BNF grammar [**?**]:

$$\phi ::= tt \mid ff \mid \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \langle a \rangle \phi \mid [a]\phi \tag{3}$$

A single HML formula can only describe a finite part of the overall behavious of a process. Therefore, the Henessy-Milner logic was extended to allow for recursive definitions by the introduction of two operators: the so called 'strong until' operator U^s and the so called 'weak until' operator U^w. These operators are expressed as follows [AILS07e]:

$$\begin{aligned} F\ U^s\ G &\overset{min}{=} G \vee (F \wedge \langle Act \rangle tt \wedge [Act]\,(F\ U^s\ G)) \\ F\ U^w\ G &\overset{max}{=} G \vee (F \wedge [Act]\,(F\ U^w\ G)) \end{aligned} \tag{4}$$

The BNF grammar describing the set of HML formulas with recursion is as follows [AI85]:

$$\phi ::= tt \mid ff \mid \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \langle a \rangle \phi \mid [a]\phi \mid X \mid min\,(X, \phi) \mid max\,(X, \phi) \tag{5}$$

where X is a formula variable and $min\,(X, \phi)$ (respectively $max\,(X, \phi)$) stands for the least (respectively largest) solution of the recursion equation $X = \phi$.

6.1 HML parsing

Our implementation of the Hennessy-Milner logic works as follows: For a given HML expression and a labeled transition system, we should get an output whether that expression is valid for the corresponding labeled graph. One HML expression can be made of these set of tokens {"AND", "OR", "UW", "US", "NOT", "[", "]", "⟨", "⟩", "TT", "FF", "(", ")", "{", "}", ","}

The first part of this process is called tokenization. Tokenization is the process of demarcating and possibly classifying sections of a string of input characters. The resulting tokens are then passed on to some other form of processing.

The process can be considered as a sub-task of parsing input. As the tokens are being read they are proceeded to the parser. The parser is a LR top-down parser. This parser is able to recognize a non-deterministic grammar which is essential for the evaluation of the Hennessy-Milner expression. As the parser is reading the tokens, thus in a way we move through the graph and determine if some of the following steps are possible. Every condition is in a way kept on stack and that enables later return to any of the previous conditions. The process is finished when the expression is processed or when it is in a condition from which none of the following actions can be taken over.

6.2 U^w and U^s implementation

The implementation of the U^w and U^s operators was done as follows. First we get the current state which is the state that contains all the nodes that satisfied the previous actions. For example if we have expression

$$\langle a\rangle\langle a\rangle TT\ U^s\ \langle b\rangle TT, \tag{6}$$

then we get all the nodes that we can reach, starting from the start node, with two actions a. When we get to the Until operation, in this case U^s, we take the start state and check if we can make an action b from some node. If we cannot do the action b, then we repeat the process, do action a again and check if can we do action b. This process is being repeated until we come to a state in which we can't do action a from all nodes in that state.

In the end we check the operator's type (strong or weak). If the operator is strong, then only one node in its state is enough. If it is weak, we check if there are no nodes in its new state or if we can get from the starting node to some of its neighbors through the action b.

7 Conclusions and Future Work

In this paper we presented a tool for recognizing CCS expressions, building LTS graphs and calculating if two LTS are strongly or weakly bisimilar by using naive

method or by using Fernandez's method. We have successfully tested the tool with large number of examples comparing the results obtained with mCRL2 and CWB, and we also presented few examples showing the tool usage.

Future work can include optimizing the tool response times for very large LTS graphs, also implementing prunung strategy for infinite LTS graphs. Also it would be usefull if the LTS graph is better visualized where every SOS rule is shown, with its source and sink nodes showing the CCS expression for each of the nodes. This visualization can be very helpfull for understanding the sematics of the CCS language for students that are starting to study it.

Appendix A: Comparison and Analysis of the bisimulation equivalence algorithms

There is no official set of benchmarks for testing algorithms for computing bisimulation equivalence [DPP04]. And it is also very difficult to randomly generate labeled transition systems suitable for proper testing of bisimulation equivalence. Therefore, we used the academical examples from mCRL2 as experimental test models.

The experiments were conducted on a portable computer with the following specifications:

1. CPU: Intel Pentium P6100 2.0 GHz
2. Memory: 3 GB
3. OS: Windows 2007 Premium

Each of the experiments carried out on our Java implementations of the two algorithms for computing bisimulation equivalence consisted of 10 repeated runs of each of the algorithms on each of the aldebaran test files and measuring the average running time in miliseconds. The results from these experiments are presented in Table 3. The table includes the running times in miliseconds and the absolute error in miliseconds for both of the algorithms, the number of pairs of bisimilar states obtained with the naive algorithm (excluding the reflexive and symmetric pairs) and the number of classes of bisimulation equivalence obtained with the algorithm due to Fernandez (excluding the one-element classes), as well as the ratio of the running time of the naive algorithm with respect to the running time of Fernandez's algorithm.

The results from the experiments carried out are presented graphically in Fig. 18 and Fig. 19 for the naive algorithm and the algorithm of Fernandez, respectively.

It can be seen that for all test models, with the exception of the first one, the running time of the naive algorithm is proportional to the number of states, the number of transitions and the number of resulting bisimilar pairs. However, we need to note that this is not a general conclusion and that in general the running time of the naive algorithm for computing bisimulation equivalence depends on the nature of the monotonic function used by this algorithm, which is strongly related with the form of the labeled transition system. As an example, dining3

			Naive		Fernandez				Ratio
aut	states	transitions	$t(ms)$	$\Delta t(ms)$	$t(ms)$	$\Delta t(ms)$	bisimilar pairs	bisimilar classes	t_n/t_f
scheduler	13	19	17.4	1.18	4.4	0.96	1	1	3.95
trains	32	52	64.5	7.3	7.6	1.76	6	6	8.48
mpsu	52	150	215.4	1.16	27.5	0.5	4	4	7.83
par	94	121	5909.4	22.68	28.5	0.7	170	27	207.34
abp	74	92	162.2	1.44	69.6	3.92	6	6	2.33
abpbw	97	122	287.9	0.94	173.3	5.22	32	27	1.661
leader	392	1128	/	/	841.5	41.5	/	20	/
tree	1025	1024	/	/	1858.1	55.16	/	8	/
dining3	93	431	16.8	0.8	250	2	1	2	0.067
cabp	672	2352	/	/	16184.3	198.94	/	90	/

Table 2. Results of the comperisons

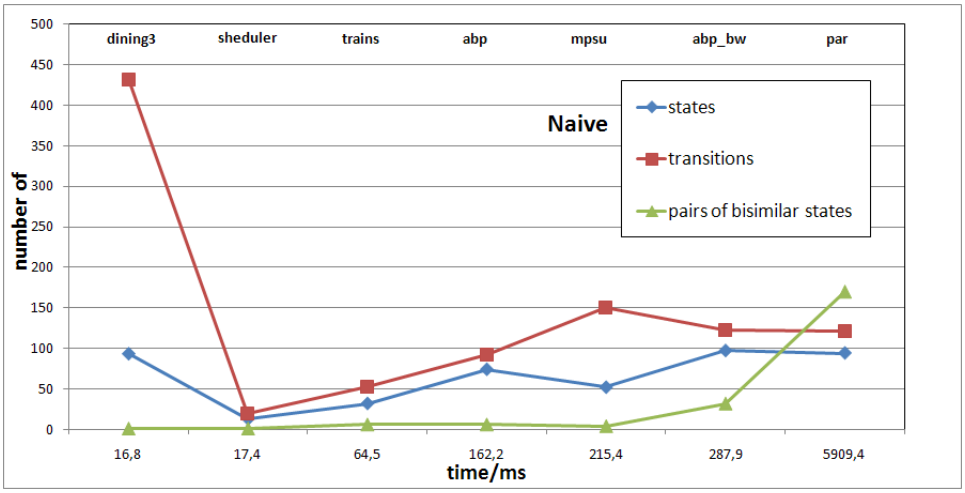

Fig. 14. Analysis of the running time of the naive bisimulation algorithm

is a labeled transition system that has big number of transitions, however in this test model the algorithm determines that the monotony condition is not fulfilled in the second development of the monotonic function and therefore the algorithm stops there.

Similar conclusions can be drawn for the algorithm due to Fernandez. Its running time is also proportional to the number of transitions, number of states and the number of bisimilar classes.

The comparison of running times of the two algorithms obtained with the experiment is shown in Fig. 20. As it can be clearly seen the algorithm of Fernandez is few times faster than the naive algorithm. The biggest difference can be noticed for the example par.aut where the ratio of the running times is 207.34.

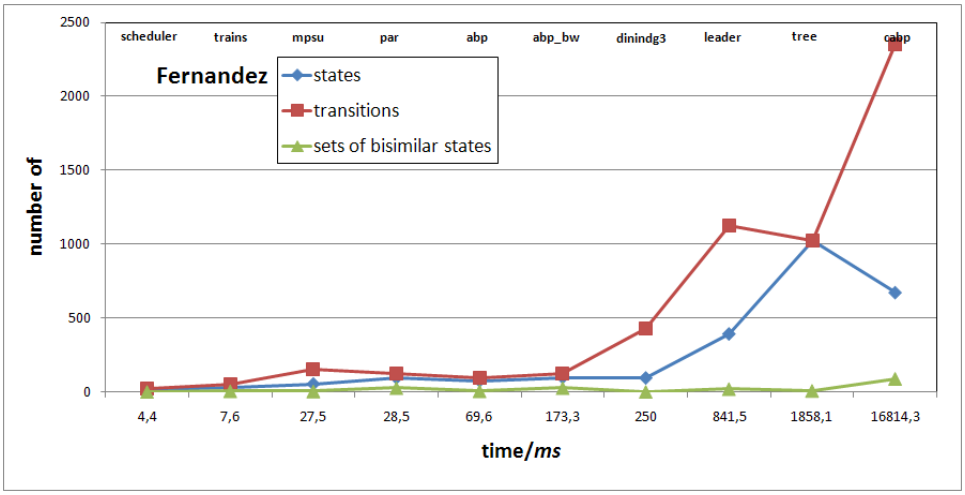

Fig. 15. Analysis of the running time of the bisimulation algorithm due to Fernandez

An exception is only the example dining3.aut for which the naive algorithm performs faster due to the reasons described earlier. The ration of the running times in this case is 0.0067. Fig. 21 shows the ratios of the running times of the two algorithms for each of the examples.

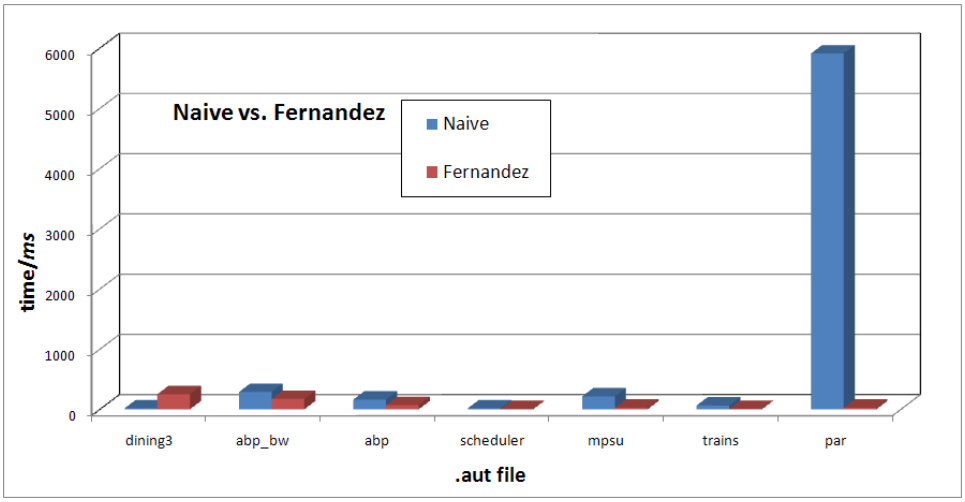

Fig. 16. Comparison of the running time of the two bisimulation algorithms

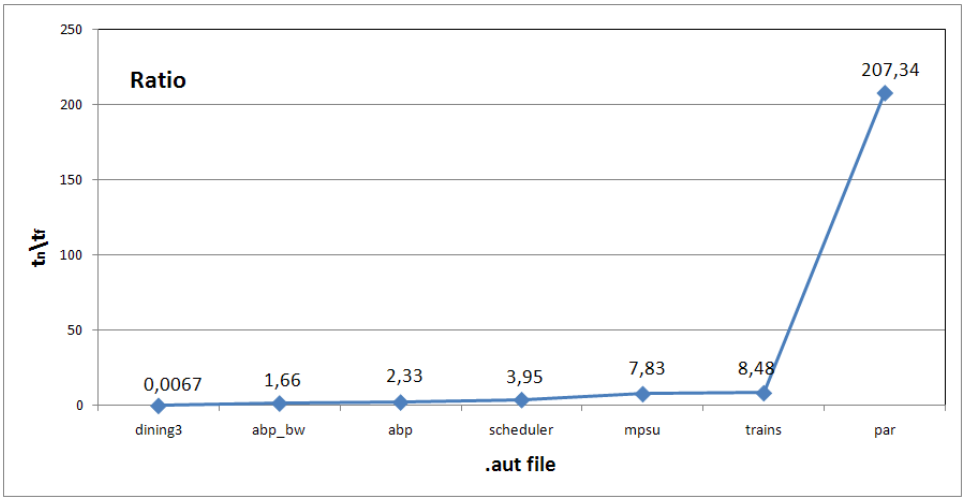

Fig. 17. Ratio of the running times of the two bisimulation algorithm

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mCRL2. Technical University of Eindhoven, LaQuSo, CWI and University of Twente, *micro Common Representation Language 2 (mCRL2)*, `http://www.mcrl2.org`

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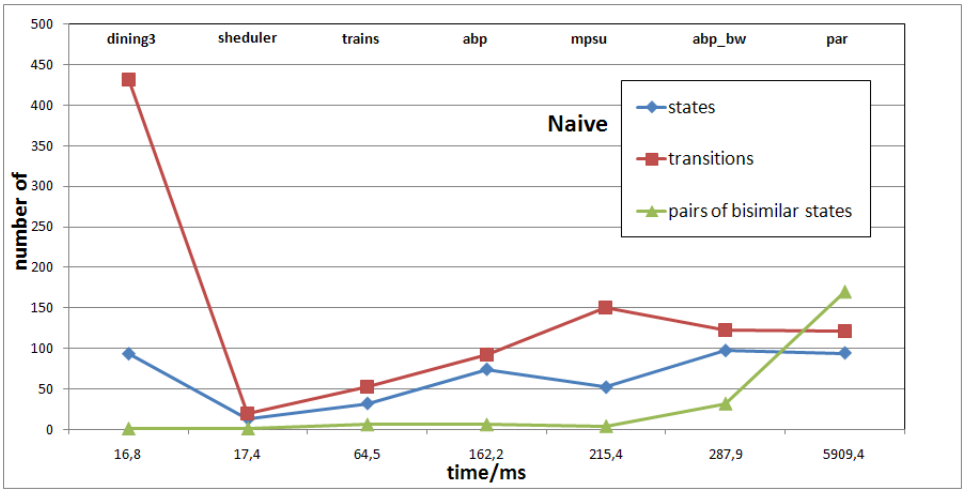
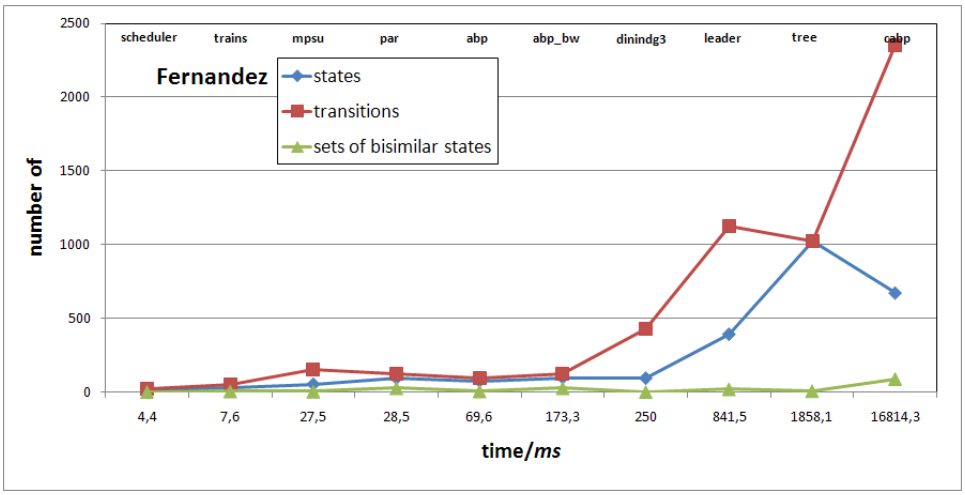


Fig. 18. Analysis of the running time of the naive bisimulation algorithm



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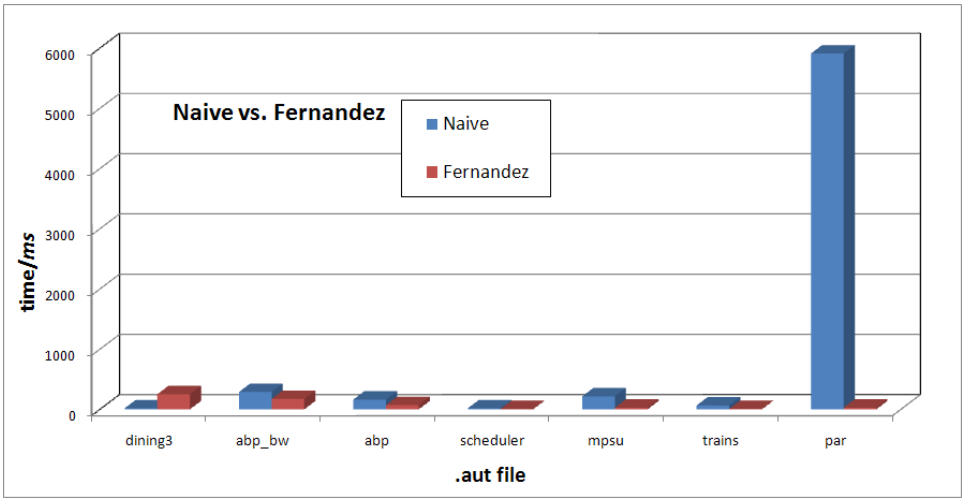

Fig. 20. Comparison of the running time of the two bisimulation algorithms

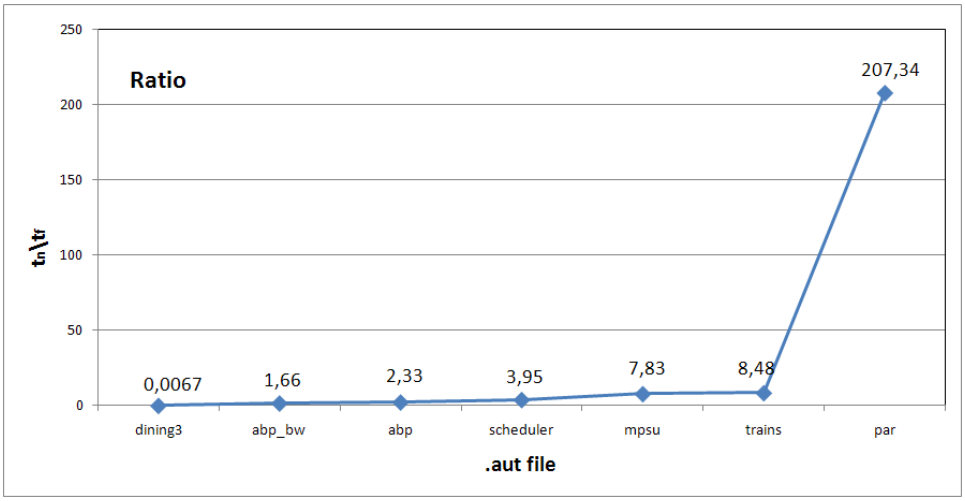

Fig. 21. Ratio of the running times of the two bisimulation algorithm

Appendix B: CCS grammar

One of the few standard ways of showing a grammar is a syntax diagram. On Fig. 22 we show the syntax diagram for the grammar that recognizes CCS expressions.

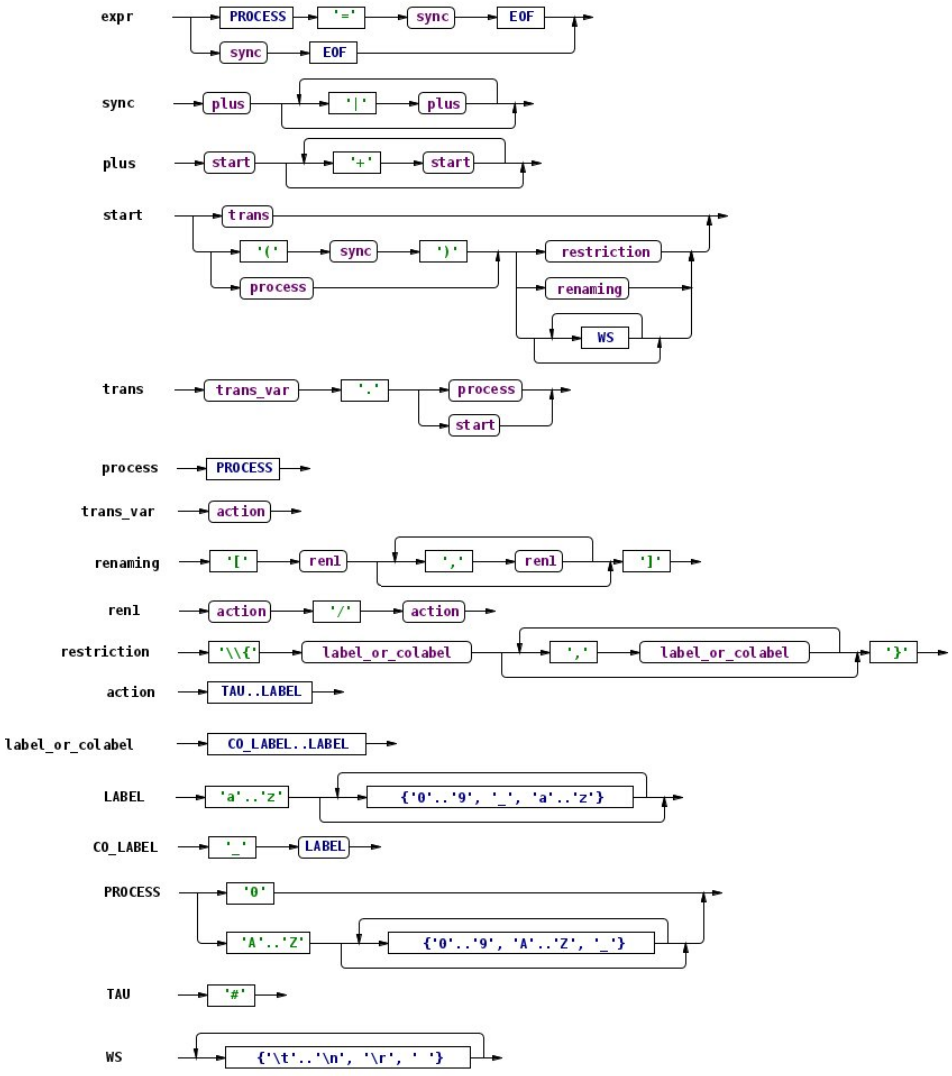

Fig. 22. Syntax diagram for the CCS grammar