Cmodels-2: SAT-based Answer Set Solver Enhanced to Non-tight Programs

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1 Introduction

Answer set programming is a new programming paradigm proposed in [1] and [2], and based on the answer set semantics of Prolog [3]. It is well known that an answer set for a logic program is also a model of the program's completion [4]. The converse is true when the logic program is "tight" [6, 5]. Lin and Zhao [7] showed that for non-tight programs the models of completion which do not correspond to answer sets can be eliminated by adding to the completion what they called "loop formulas". Nevertheless, their solver ASSAT[1] has some disadvantages: it can work only with basic rules, and it can compute only one answer set. Answer set solver CMODELS-1[2] [12] is a system that computes answer sets for logic programs that are tight or can be transformed into tight programs, and does not suffer from these limitations.

We are going to present a new system CMODELS-2[1], that is able to fix ASSAT's disadvantages. Another attractive feature of the new system is that it organizes the search process more efficiently than ASSAT, because it does not explore the same part of the search tree more than once. In the rest of the paper we omit number 2 in the name of the system.

2 General Information

The input language of CMODELS is generated by the preprocessor LPARSE. The input may contain negation as failure, cardinality expressions ("constraint literals" in the terminology of [9, Section 5.3]) and choice rules [9, Section 5.4]—two constructs widely used in answer set programming.[3] These constructs are eliminated in favor of nested expressions in the sense of [10] using the method described in [11]. CMODELS is an answer set solver that uses SAT solvers as search engines. It may invoke different SAT solvers for finding solutions, namely SIMO [4], MCHAFF and ZCHAFF [5], and RELSAT [6]. The system can be easily extended to new SAT solvers. This allows us to take advantage of the rapid progress in the area of satisfiability solvers.

[1] http://assat.cs.ust.hk/
[2] http://www.cs.utexas.edu/users/tag/cmodels/
[3] The input can also contain general weight expressions ("weight literals"). However, optimize statements [9, Section 5.6] are not allowed.
[4] http://www.mrg.dist.unige.it/~sim/simo/
[5] http://www.ee.princeton.edu/~chaff/
[6] http://www.satlib.org/Solvers/SAT/REL_SAT.2/

The algorithm of CMODELS for tight programs is identical to the one in CMODELS-1 and is described in details in [12]. The difference appears only when the program is non-tight. In such case CMODELS needs to verify that each model of completion is indeed the answer set. Whenever the model of completion does not correspond to any answer set the computation of loop formulas is performed. We will talk about the mechanism of dealing with non-tight programs in the following section.

3 CMODELS on Non-tight Programs

In case of non-tight programs the algorithm of CMODELS is similar to the one of system ASSAT described in [7], but there are several differences.

First, CMODELS works with more general programs, and uses extended definition of a loop formula [8]. The technique for computing loop formulas is nevertheless very similar to the one described in [7]. Second, CMODELS introduces a "generate and test" approach in accordance to the SAT-based methodology [13] with such SAT solvers as SIMO and ZCHAFF. According to the SAT-based methodology, we first:

- *generate* a total propositional model satisfying the propositional clauses, and then
- *test* if the generated valuation is an answer set.

Both ASSAT and CMODELS use a "generate and test" approach, but when CMODELS invokes SIMO or ZCHAFF for the computation:

- the SAT solver never explores the same part of the search tree (this is only partially true in case of ZCHAFF communication [7]).
- it is possible to compute more than one answer set.

The main difference between ASSAT and CMODELS is that ASSAT uses SAT solvers as black-boxes and CMODELS, in case of invoking SIMO and ZCHAFF , does not. Details will be presented in a future paper.

4 CMODELS Options

CMODELS command line is:

```
cmodels number [-mc] [-zc] [-si] [-sia] [-rs] [rs1] [-t] [-nt] [-s] [-le] [-bj]
```

`number` Specifies the number of answer sets to be found. 0 stands for "compute all answer sets"; 1 is the default.
`-mc` MCHAFF is used for finding answer sets (default).
`-zc` ZCHAFF is used for finding answer sets.
`-si` SIMO is used for finding answer sets.
`-sia` SIMO is used for finding answer sets with an ASSAT-like algorithm.
`-rs` RELSAT version 2 is used for finding answer sets.
`-rs1` RELSAT version 1.1.2 is used for finding answer sets.
`-t` Stands for omitting the tightness check [12]; CMODELS expects input program to be tight. By default, the tightness check is performed.
`-nt` Stands for omitting the tightness check [12]; CMODELS expects input program to be

[7] CMODELS uses an incremental learning option of ZCHAFF.

Instance name	CMODELS SIMO (-le)	SMODELS	CMODELS SIMO assat alg.
np40c	(42) 1.56	2.49	(27) 16.52
np60c	(106) 8.80	21.45	(35) 76.12
np70c	(217) 26.46	42.86	(41) 139.50
np80c	(223) 37.87	79.78	(44) 241.55
np100c	(286) 78.93	200.43	(51) 561.94
np120c	(698) 314.93	430.98	mem
np150c	(1074) 841.91	1171.38	mem
4xp20.1	(2) 73.26	timeout	(1) 2.03
4xp20.3	(13) 82.90	0.01	(5) 1.56

Fig. 1. Complete and hand-coded graphs CMODELS employing learning vs. SMODELS vs. CMODELS employing assat algorithm.

non-tight and invokes the procedures related to non-tight programs.
`-s` Stands for omitting the simplification step [12]. By default the simplification is performed.
`-le` and `-bj` are relevant to the invocation of SIMO. They refer to "learning" and "backjumping" using SAT terminology; by default [-le] is performed. For more details see [13].

5 Performance of CMODELS

In this section we report some experimental data. All experiments were run on two identical Pentium IV 1.8GHz processors with 512MB of RAM, DDR 266MHz, running Linux.

In Figures 1 and 2, CPU time is reported in seconds as the sum of *user* and *system* time using *time* UNIX command. *timeout* means that the process was stopped after one hour, *mem* means that the process reached the memory limit of the machine. The number in parentheses is the number of times CMODELS checked that a propositional model does not correspond to an answer set. We compare CMODELS only with SMODELS: this is due to the fact that DLV is optimized for disjunctive logic programs and ASSAT works with programs of more limited syntax. Nevertheless, we have implemented an ASSAT-like algorithm in our framework. We focus on finding one answer set.

First we evaluate the performances of CMODELS on Hamiltonian circuits (HC) benchmarks, in particular on some publicly available complete graphs and on hand-coded graphs. [8] We also built some bigger complete graphs. Complete graphs are in particular interesting because, as observed in [7], they have exponential number of loops. In Fig. 1 we present the comparison of CMODELS using SIMO with "learning", SMODELS and CMODELS using SIMO employing the algorithm of ASSAT. For complete graphs, we can see a clear edge between CMODELS running SIMO with "learning" and as black-box communication. This seem to point out the usefulness of a "non black-box" communication with a SAT solver. The advantage in comparison with SMODELS is smaller: around a factor of two. Instead, the results on hand-coded graphs are quite negative.

The second domain we demonstrate in Fig. 2 is bounded LTL model checking problem[9].

[8] `http://assat.cs.ust.hk/assat-1.0.html`
[9] `http://www.tcs.hut.fi/~kepa/experiments/boundsmodels/`

Instance Name	CMODELS ZCHAFF	CMODELS MCHAFF	CMODELS SIMO -le	SMODELS
dp_6.formula1-i-O2-b8	(8) 0.34	(28) 6.00	(17) 0.68	0.42
dp_6.formula1-s-O2-b7	(4) 0.13	(9) 0.77	(19) 0.27	0.19
dp_8.formula1-i-O2-b10	(28) 8.15	(24) 28.52	(42) 29.92	4.71
dp_8.formula1-s-O2-b8	(11) 1.02	(15) 4.85	(45) 1.11	1.65
dp_10.formula1-i-O2-b12	(24) 34.42	(21) 51.12	(313) 1094.38	415.57
dp_10.formula1-s-O2-b9	(41) 6.64	(24) 19.33	(140) 12.54	28.17
dp_12.formula1-i-O2-b14	timeout	(29) 461.29	timeout	timeout
dp_12.formula1-s-O2-b10	(139) 16.66	(69) 91.94	(140) 126.36	937.39

Fig. 2. Non-tight Bounded Model Checking CMODELS using MCHAFF employing ASSAT-like algorithm and ZCHAFF, SIMO employing learning vs. SMODELS

In this domain, we can see a clear edge between CMODELS using ZCHAFF with learning both versus CMODELS using MCHAFF as a black-box and SMODELS.

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[10] `http://arxiv.org/abs/cs.ai/0003042.`
[11] `http://www.cs.utexas.edu/users/appsmurf/papers/disjunctive.ps.`
[12] `http://www.tcs.hut.fi/software/smodels/lparse.ps.gz.`

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[13] http://www.cs.utexas.edu/users/yuliya/cmodels.ps.