Probabilistic Inference in SWI-Prolog

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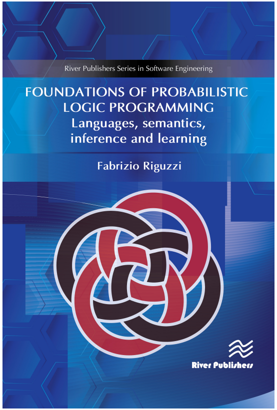
Outline

- Tabling in SWI-Prolog
- Answer Subsumption
- PITA
- PITA for SWI-Prolog



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Probabilistic Logic Programming

- Distribution Semantics [Sato ICLP95]
- A probabilistic logic program defines a probability distribution over normal logic programs (called instances or possible worlds or simply worlds)
- The distribution is extended to a joint distribution over worlds and interpretations (or queries)
- The probability of a query is obtained from this distribution

Probabilistic Logic Programming (PLP) Languages under the Distribution Semantics

- Probabilistic Logic Programs [Dantsin RCLP91]
- Probabilistic Horn Abduction [Poole NGC93], Independent Choice Logic (ICL) [Poole AI97]
- PRISM [Sato ICLP95]
- Logic Programs with Annotated Disjunctions (LPADs) [Vennekens et al ICLP04]
- ProbLog [De Raedt et al IJCAI07]
- They differ in the way they define the distribution over logic programs

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Logic Programs with Annotated Disjunctions

http://cplint.eu/e/sneezing.pl

$C_1 = strong\_sneezing(X) : 0.3 \; ; \; moderate\_sneezing(X) : 0.5 \leftarrow flu(X).$

$C_2 = strong\_sneezing(X) : 0.2 \; ; \; moderate\_sneezing(X) : 0.6 \leftarrow hay\_fever(X).$

$C_3 = flu(bob).$

$C_4 = hay\_fever(bob).$

- Distributions over the head of rules
- Worlds obtained by selecting one atom from the head of every grounding of each clause

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Tabling

- A logic programming technique for saving time and ensuring termination for programs without function symbols
- The Prolog interpreter keeps a store of the subgoals encountered in a derivation together with answers to these subgoals
- If one of the subgoals is encountered again, its answers are retrieved from the store rather than re-computing them
- Implemented in XSB, YAP, SWI-Prolog, B-Prolog, Ciao

Tabling in SWI-Prolog

- Implemented in SWI-Prolog using delimited control [Desouter et al TPLP15]
- Two operators, reset and shift
- `reset(Goal,Cont,Term1)` executes `Goal` and unifies the other two arguments on the basis of the results of calls to `shift/1`
- If `Goal` calls `shift(Term2)`
  - the execution of the goal is interrupted
  - the rest of its code up to the nearest call to `reset/3`, called delimited continuation, is represented as a Prolog term and unified with `Cont` in `reset/3`
  - `Term2` is unified with `Term1`
  - The execution restarts from the code just after the call to `reset/3`

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Example of Delimited Continuation

```
p :-  reset(q,Cont,Term1),
      writeln(Term1),
      writeln(Cont),
      writeln('end').

q :-  writeln('before shift'),
      shift('return value'),
      writeln('after shift').
```

- `shift/1` instantiates `Cont` with the `writeln('after shift')` goal and `Term1` with the term `'return value'` in `reset/3`

  ```
  ?- p.
  before shift
  return value
  [$cont$(785488,[])]
  end
  ```

- In q the execution is interrupted by the call to `shift/1`. The continuation in this case is not called, therefore what follows the call to `shift/1` is not executed

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Example of Delimited Continuation

- If we replace `writeln(Cont)` with `call(Cont)`

```
?- p.
before shift
after shift
end
```

- The continuation is called and the goal `writeln('after shift')` is executed

Tabling in SWI-Prolog

- Predicates are declared as tabled using the `table/1` directive
- Tabled predicates are transformed
- `table/2` retrieves the table data structure containing the answers to the tabled predicate

```
:- table p/2.

p(X,Y) :- p(X,Z), e(Z,Y).
p(X,Y) :- e(X,Y).
```

→

```
p(X,Y) :- table(p(X,Y),'p tabled'(X,Y)).

'p tabled'(X,Y) :- p(X,Z), e(Z,Y).
'p tabled'(X,Y) :- e(X,Y).
```

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Tabling in SWI-Prolog

- When a tabled predicate is called, the execution enters in a `reset` phase for delimited answer computation
- If this phase succeeds normally, the answer is added to the table of the tabled predicate
- If the tabled predicate calls a predicate that is tabled as well, then the computation enters in the `shift` phase without producing an answer and the first predicate is suspended, capturing the reminder in `Cont`
- At this point the so-called `completion` phase starts, collecting all the possible continuations, to find answers for the tabled predicate in the `reset` phase

Tabling in SWI-Prolog

- A leader is a call to a tabled predicate that has only non-tabled ancestors in the dynamic call graph
- Other calls to tabled predicates are followers
- Every follower has a leader as its ancestor
- The leader and its followers make up a scheduling component
- Multiple scheduling components can occur during program execution
- `completion` performed on one component at a time

Tabling in SWI-Prolog

- For each component:
- Global worklist: a queue of tables, each tables maps a subgoal for a tabled predicate (*call variant*) to a trie containing its answers and to a local worklist, a dequeue containing answers and dependencies
- *dependency*=(*source*, *continuation*, *target*)
- If collecting answers for a tabled call p requires the answers for a tabled call q (q may be p itself), then p is the target and q is the source
- Given an answer for the source call q, we can obtain an answer for the target call p by resuming the suspended continuation
- The continuation's answer is then unified with p

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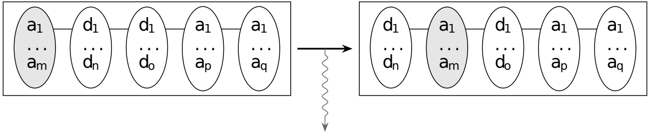
Tabling in SWI-Prolog

- `completion` phase: tables from the global worklist are extracted one at a time
- The local worklist of the table is used to find all the answers for the corresponding tabled call
- During the `reset` phase, each time an answer is found for a call p, it is added to the list of answers in the table for p and to the left of the dequeue of the local worklist of subgoals calling p
- During the `shift` phase, a new dependency for p is added to the right of its worklist
- Then, pairs (*answer*, *dependency*) are extracted from the dequeue of the local worklist to try to find new answers
- The *answer* in the pair is an answer for the *source* predicate

Tabling in SWI-Prolog



- (*answer*, *dependency*) created by associating an *answer* to the dependency that is immediately to its right in the dequeue
- After the combination, the *answer* and the *dependency* are swapped, moving the *answer* to the right of the *dependency*
- Then, *answer* and *dependency* from the pair are combined using values in *answer* to instantiate variables in *source*, *continuation* and *target*
- The predicate in *continuation* is called to find new answers for the target
- The new answer for *target* is then added to the answers list in its table and to the left of the dequeue of the local worklists where the predicate is the source of some dependencies
- The `completion` phase stops when all the answers in all the local worklists are on the left of all the dependencies

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Mode-Directed Tabling and Answer Subsumption

- *Answer subsumption*, also called *mode-directed tabling* [Swift, Warren TPLP 12, Vandenbroucke et al TPLP 16]
- A subset of the predicate arguments defines the call variant while answers for the remaining arguments are *aggregated*
- When a new answer is found, it is aggregated with an existing answer in the table
- Classical aggregation: minimum
- SWI-Prolog's original tabling implementation was extended with mode-directed tabling
- Specification inherited from XSB, B-Prolog, YAP,

Answer Subsumption Example

```
:- table connection(_,_,min).

connection(X, Y,1) :-
        connection(X, Y).
connection(X, Y,N) :-
        connection(X, Z,N1),
        connection(Z, Y),
        N is N1+1.

connection('Amsterdam', 'Schiphol').
connection('Amsterdam', 'Haarlem').
connection('Schiphol', 'Leiden').
connection('Haarlem', 'Leiden').
connection('Amsterdam', 'Leiden').

?- connection('Amsterdam','Leiden',N).
N=1
```

Mode-Directed Tabling and Answer Subsumption

- Most generic aggregation function: lattice, a user defined predicate determines the subsumer for the aggregated answer so far and a new answer

```
:- table pred(_,_,lattice(join)).
```

- The answer table assigns each answer in the trie an aggregated value

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Mode-Directed Tabling and Answer Subsumption

- Tabling does not guarantee a particular order in which suspended computations are resumed and thus requires the aggregation function to produce the correct result regardless of the order
- If one mode-directed tabled goal is the *follower* of another we may get incorrect results

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Mode-Directed Tabling and Answer Subsumption

```
:- table
    p(lattice(or/3)),
    s(lattice(or/3)).
or(A,B,A-B).
p(A) :- s(A).
s(1).
s(2).
```

- In the initial implementation `p(A)` succeeded with answer `A = 1-2-(1-2)` instead of the desired `A = (1-2)`

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Mode-Directed Tabling and Answer Subsumption

- [Vandenbroucke et al TPLP 16] showed that many implementations of mode-directed tabling produce unsound results
- Formal semantics for mode-directed tabling that allows the evaluation of the soundness of implementations
- Aggregation is a post-processing step
- Real systems aggregate intermediate results during resolution for efficiency and to avoid loops

Mode-Directed Tabling and Answer Subsumption

- In SWI-Prolog: create a new *component* for every fresh mode-directed tabled goal we encounter
- This component is completed before execution of the parent component is resumed with the complete aggregated result
- If in a subcomponent we encounter a variant of a tabled goal that was started before the subcomponent but has not yet been completed, failure

PITA

- PITA [Riguzzi, Swift ICLP10, ICLP11, TPLP13] applies a program transformation to an LPAD to create a normal program that contains calls for manipulating BDDs
- Library:
  - *init*, *end*: for allocation and deallocation of a BDD manager, a data structure used to keep track of the memory for storing BDD nodes;
  - *zero(-BDD)*, *one(-BDD)*, *not(+BDDI, -BDDO)*, *and(+BDD1, +BDD2, -BDDO)*, *or(+BDD1, +BDD2, -BDDO)*: Boolean operations between BDDs;
  - *add_var(+N_Val,+Probs,-Var)*: addition of a new multi-valued variable with *N_Val* values and parameters *Probs*;
  - *equality(+Var,+Value,-BDD)*: *BDD* represents *Var=Value*, i.e. that the random variable *Var* is assigned *Value* in the BDD;
  - *ret_prob(+BDD,-P)*: returns the probability of the formula encoded by *BDD*.

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PITA transformation

- Auxiliary predicate `get_var_n/4` used to wrap `add_var/3` and avoid adding a new variable when one already exists for an instantiation
- Atom a: $PITA(a, D)$, is a with the variable D added as the last argument
- Negative literal $b = \textbf{not}\ a$:

$$(PITA(a, DN) \rightarrow not(DN, D); one(D))$$

- Conjunction of literals $b_1, \ldots, b_m$:

$$\begin{aligned} PITA(b_1, \ldots, b_m, D) = {} & one(DD_0), \\ & PITA(b_1, D_1), and(DD_0, D_1, DD_1), \ldots, \\ & PITA(b_m, D_m), and(DD_{m-1}, D_m, D). \end{aligned}$$

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PITA transformation

- Disjunctive clause

$$C_r = h_1 : \Pi_1 \vee \ldots \vee h_n : \Pi_n \leftarrow b_1, \ldots, b_m.$$

$$\begin{array}{l} PITA(C_r, i) = PITA(h_i, D) \leftarrow PITA(b_1, \ldots, b_m, DD_m), \\ \quad get\_var\_n(r, S, [\Pi_1, \ldots, \Pi_n], Var), equality(Var, i, DD), \\ \quad and(DD_m, DD, D). \end{array}$$

for $i = 1, \ldots, n$, where S is a list containing all the variables appearing in r

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Medical example

- Clause C_1 from the example LPAD is translated to

$$
\begin{aligned}
&strong\_sneezing(X, BDD) \leftarrow one(BB_0), flu(X, B_1),\\
&\quad and(BB_0, B_1, BB_1),\\
&\quad get\_var\_n(1, [X], [0.3, 0.5, 0.2], Var),\\
&\quad equality(Var, 1, B), and(BB_1, B, BDD).\\
&moderate\_sneezing(X, BDD) \leftarrow one(BB_0), flu(X, B_1),\\
&\quad and(BB_0, B_1, BB_1),\\
&\quad get\_var\_n(1, [X], [0.3, 0.5, 0.2], Var),\\
&\quad equality(Var, 2, B), and(BB_1, B, BDD).
\end{aligned}
$$

- clause C_3:

$$flu(david, BDD) \quad \leftarrow one(BDD).$$

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PITA transformation

- Predicates tabled as

$$:-table\ p(\_,\ldots,lattice(or/3)),$$

- *prob(Goal,P)* to answer queries:

$$\begin{aligned}&prob(Goal,P) \leftarrow init, retractall(var(\_,\_,\_)),\\&\quad add\_bdd\_arg(Goal,BDD,GoalBDD),\\&\quad (call(GoalBDD) \rightarrow ret\_prob(BDD,P); P = 0.0),\\&\quad end.\end{aligned}$$

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Extension of PITA for SWI-Prolog

- Extra library predicate:
  - *and_check(+D1,+D2,-DO)* fails if one of the input arguments is the BDD representing the Boolean constant 0, otherwise it succeeds returning the conjunction of the input arguments
- The tabling implementation in SWI-Prolog doesn't handle cut
- Transformation for a negative literal $b = \textbf{not}\, a$, $PITA(b, DN)$:

$$PITA(a, D), not(D, DN)$$

- Conjunction of literals $b_1, \ldots, b_m$:

$$\begin{aligned} PITA(b_1, \ldots, b_m, D) = {} & one(DD_0), \\ & PITA(b_1, D_1), and\_check(DD_0, D_1, DD_1), \ldots, \\ & PITA(b_m, D_m), and\_check(DD_{m-1}, D_m, D). \end{aligned}$$

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Extension of PITA for SWI-Prolog

- For each predicate p/n, an extra clause (zero clauses) of the form

$$p(X_1, \ldots, X_n, D) \leftarrow nonvar(X_1), \ldots, nonvar(X_n), zero(D).$$

- If the goal fails, the only BDD returned is the one representing the 0 constant, negated we get the 1 constant
- In conjunctions, failure of *and_check/3*
- In disjunctions, the zero BDD is disjoint with other BDDs, keeping unchanged their truth value

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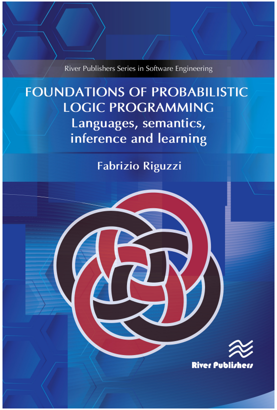
Conclusions & Future Work

- Conclusions
  - Tabling in SWI-Prolog
  - Answer Subsumption
  - PITA
  - PITA for SWI-Prolog
- Future work
  - Sharing tables between threads, incremental tabling, handling negation, improving space and time performance
  - Extending PITA for probabilistic abductive logic programs
  - Comparison with XSB in terms of performance



THANKS FOR LISTENING

AND

ANY QUESTIONS ?

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