Logic Programming

The term *logic programming* refers to a programming paradigm that principally embodies the rules of *first-order logic* (also known as *predicate logic*). In first-order logic, you can express *facts* involving non-logical objects, and *relations*, where the relations involve facts, standard logical operations, variables, and (universal and existential) quantifiers. Logic programming uses *rules of inference* to "reason" about a collection of facts and relations.

In the imperative and functional example programming languages we have studied so far, we wanted the result of applying (or "running") a program with a given input. In logic programming, we want to determine whether a particular logic statement evaluates to *true* or *false*; or, more generally, to determine all of the values of the variables in a logic expression that make the expression true.

Prolog remains the dominant logic programming language implementation, though there exist variants that extend (or restrict) Prolog's functionality and purpose: **Datalog** is one such variant. **AbcDatalog**, developed at Harvard University, is a Java-based implementation of Datalog that we use in these notes. AbcDatalog is covered by the BSD License (see `http://abcdatalog.seas.harvard.edu/license.txt`).

Our implementation of AbcDatalog resides in the `ABC` language subdirectory of the `Code` directory. The `README.txt` file in this subdirectory provides some information about where to find the AbcDatalog source files and details about implementation specifics.

The tokens of the `ABC` language are given here:

```
skip WHITESPACE '\s+'
skip COMMENT '%.*'
PRINT 'Print'
CLEAR 'Clear'
DOT '\.'
NOT 'not'
EQ '='
NE '!='
IF ':-'
QUERY '\?'
DEL '~'
COMMA ','
RPAREN '\)'
LPAREN '\('
US '_'
VAR '[A-Z_][_\w]*'
LIT '[a-z][_\w]*'
```

Of these, the `PRINT` and `CLEAR` tokens are not part of the Harvard implementation of AbcDatalog.

Here is the grammar specification for the `ABC` language, in PLCC format:

```
<program>:DFRQ       ::= <head> <dfrq>
<program>:Print      ::= PRINT
<program>:Clear      ::= CLEAR
<dfrq>:Delete        ::= DEL
<dfrq>:Fact          ::= DOT
<dfrq>:Rule          ::= IF <conjuncts> DOT
<dfrq>:Query         ::= QUERY
<head>               ::= <LIT> LPAREN <args> RPAREN
<args>               **= <vlw> +COMMA
<vlw>:Var            ::= <VAR>
<vlw>:Lit            ::= <LIT>
<vlw>:WC             ::= US # wildcard
<conjuncts>          **= <conjunct> +COMMA
<conjunct>:HeadConj  ::= <head>
<conjunct>:RelConj   ::= <VAR>lh <rel> <vlw>rh
<conjunct>:NotConj   ::= NOT <head>
<rel>:EQRel          ::= EQ
<rel>:NERel          ::= NE
```

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The `<dfrq>` nonterminal suggests its four variants:

d stands for *delete*
f stands for *fact*
r stands for *rule*
q stands for *query*

Here are some examples of *facts*, written in the `ABC` language:

```
planet(earth).
planet(mercury).
planet(jupiter).
larger(jupiter,earth).
larger(earth,mercury).
```

If we want to find all of the planets that the current systems knows about, we would write the following *query*:

```
planet(X)?
```

The system responds with the following result (the planets may appear in any order):

```
3 matches:
planet(earth)
planet(mercury)
planet(jupiter)
```

Continuing the above example, the query '`larger(X,Y)?`' produces the following result:

```
2 matches:
larger(jupiter, earth)
larger(earth, mercury)
```

Can we logically deduce that jupiter is larger than mercury? The answer is 'no', since there is no fact that says this: if we were to try the query '`larger(jupiter,mercury)?`', we would get no matches.

To make the `larger` relation transitive, we build a *rule* that says that if `X` is larger than `Y`, and if `Y` is larger than `Z`, then `X` is larger than `Z`. We do so as follows:

```
larger(X,Z) :- larger(X,Y), larger(Y,Z).
```

The LHS of this rule (the part to the left of '`:-`') is called an *Atom*, and the RHS of this rule is a sequence of *Premises* separated by commas. You can read this rule as saying *the LHS is true if all of the Premises on the RHS are true*. The result is all of the possible substitutions of `X`, `Y`, and `Z` that make the rule true.

Once we have included this rule, our "larger" query reports this (in some order):

```
3 matches:
larger(jupiter, earth)
larger(earth, mercury)
larger(jupiter, mercury)
```

Entering facts, rules, and queries can be done interactively at the '`-->`' prompt.

What if we wanted to include the planet saturn in our list of planets? We would certainly add the fact

```
planet(saturn).
```

We know that saturn is larger than earth, so we might then add the fact

```
larger(saturn,earth).
```

But upon a query of the `larger` relation, we would see no `larger` relation between saturn and jupiter. Try it!

The important thing is that the query engine cannot deduce something that is not explicitly given in facts or explicitly deduced from rules.

A *binary relation* on a set A is defined to be a subset of the cartesian product $A \times A$. In the `ABC` language, we can represent a binary relation as a set of facts. For example, consider the set `A = {a,b,c,d}`. Define a binary relation called `rel` on `A` in the `ABC` language as follows, which you would enter as facts using the Java `Rep` program:

```
rel(a,b).
rel(a,d).
rel(d,a).
rel(c,c).
```

If you were to enter the query `rel(X,Y)?`, you would get a response back consisting of exactly the same four facts (in some order).

We use the term *reflexive* to describe a binary relation `rel` on `A` having the property that if `x` is any element in the set `A`, then `rel(x,x)` is true (*i.e.*, is a fact). You can see that the `rel` binary relation is definitely not reflexive, but we can add a rule to `rel` to make it reflexive, as follows:

```
rel(X,X) :- rel(X,_).
rel(X,X) :- rel(_,X).
```

We call the resulting modification to the relation `rel` its *reflexive closure*. Note that we are using the '_' variable as a place holder that can match anything already in the `rel` relation.

We similarly define a relation `rel` on `A` to be *symmetric* if `rel(x,y)` implies `rel(y,x)`. Just like we did for a reflexive closure, we can create the *symmetric closure* of the relation `rel` in the `ABC` language as follows:

```
rel(X,Y) :- rel(Y,X).
```

Finally, we define a relation `rel` on `A` to be *transitive* if `rel(x,y)` and `rel(y,z)` implies `rel(x,z)`. We can create the *transitive closure* of the relation `rel` in the `ABC` language as follows:

```
rel(X,Z) :- rel(X,Y), rel(Y,Z).
```

Notice that this is exactly what we did with the `larger` relation on the planets.

One can create any one of these closures individually, or all of them, if you wish. If your resulting relation is reflexive, symmetric, and transitive, it is called an *equivalence relation*, an important construct in first-order logic and set theory.

(Notice that the rule defining the reflexive closure assumes that everything in the set `A` is related to *something*.)

Logic Programming Puzzles

Consider the Fox/Goose/Corn river crossing puzzle (also known as the Wolf/Goat/Cabbage puzzle):

A farmer, a fox, a goose, and a bag of corn are on one side of a river. The farmer has a boat that can hold *at most one* other "passenger" – either the fox, the goose, the bag of corn, or nothing at all. The problem is to transport everything to the other side of the river using the boat. One constraint is that the farmer cannot leave the fox and the goose together on one side with the farmer on the other side – otherwise the fox, unsupervised, will eat the goose. Another constraint is that the farmer cannot leave the goose and the bag of corn together on one side with the farmer on the other side – otherwise the goose, unsupervised, will eat the corn. A final constraint is that the farmer and the boat will always be on the same side of the river together. *Can the farmer transport everything from one side of the river to the other using the boat, while maintaining the constraints?*

We will model this problem by considering all possible *states*, where a state is a string of the form `sbfgc`. Here, `s` is just the letter 's', which stands for *state*. The `bfgc` positions will be digits `0` or `1`, referring to which side of the river the boat (and the farmer), the fox, the goose, and the corn are on, respectively. We will use the digit `0` to mean the starting side and the digit `1` to mean the ending side. So the problem is to move from state `s0000` to state `s1111` by legal river crossings.

Notice that each river crossing will toggle the `b` position. (The word *toggle* means switching from a `0` to a `1` or *vice versa*.) At most one of the other `fgc` positions will also get toggled, depending on which passenger (or none) the farmer takes on the boat.

Some of the states do not satisfy the constraints. For example, `s011?` is not possible, since otherwise the boat (and the farmer) will be on the starting side and the fox and goose will be on the ending side. (the `?` just means it doesn't matter). Here are all of the impossible states:

```
s011? -- fox and goose unsupervised
s100? -- fox and goose unsupervised
s0?11 -- goose and corn unsupervised
s1?00 -- goose and corn unsupervised
```

Notice that the total number of states (possible and impossible) is 16 (2^4) and the number of impossible states is 6, so there are exactly 10 possible states to deal with. Five of these have the boat (and the farmer) on the start side.

A river *crossing* will consist of a transition from one state to another by toggling the `b` position (the farmer takes the boat from one side to the other, possibly with a passenger) and toggling at most one of the `fgc` positions (the passenger).

For example, in the first river crossing (starting from state `s0000`), the farmer takes the boat and the goose from the starting side to the ending side. We represent this in the `ABC` language by the following fact:

```
cross(s0000, g, s1010). % carry the goose in the boat
```

You can see that this is the *only* legal crossing starting from the initial state `s0000`. We use the letter `x` to mean a river crossing with no "passenger" in the boat.

Observe that for every legal crossing of the form

```
cross(s0..., ?, s1...).
```

(where the `?` can be any of `fgcx`) with the boat (and farmer) going from the starting side to the ending side of the river, there is a corresponding legal crossing of the form

```
cross(s1..., ?, s0...).
```

and *vice versa*. This means that we need only consider the legal crossings where the boat is on the starting side of the river, and use the following rule to generate the others:

```
cross(X, P, Y) :- cross(Y, P, X).
```

Logic Programming Puzzles

Here are all of the legal crossings where the boat is on the starting side of the river:

```
cross(s0000,g,s1010).
cross(s0001,g,s1011).
cross(s0001,f,s1101).
cross(s0010,x,s1010). % no passenger
cross(s0010,c,s1011).
cross(s0010,f,s1110).
cross(s0100,c,s1101).
cross(s0100,g,s1110).
cross(s0101,x,s1101). % no passenger
cross(s0101,g,s1111).
```

There are two ways to think of a solution to the fox/goose/corn puzzle:

- determine *if* there is a solution
- determine an explicit solution, giving the actual crossings

The first is easier, at least in the `ABC` language.

Logic Programming Puzzles

The idea is to define what it means for there to be a *path* from one state to another. First, we consider every crossing

```
cross(X,P,Y)
```

as a path from `X` to `Y`:

```
path(X,Y) :- cross(X,_,Y).
```

Then we develop the transitive closure of the relation `path`

```
path(X,Z) :- path(X,Y), cross(Y,_,Z).
```

to get all paths. Notice that the second clause in the RHS just needs the `cross` premise instead of the more general `path(Y,Z)` (why?).

The query

```
path(s0000, s1111)?
```

will produce a result if and only if there is a path from state `s0000` (everyone on the starting side) to state `s1111` (everyone on the ending side). You can check that this is the case!

Logic Programming Puzzles

Here is the complete `ABC` program, with the solution query:

```
cross(s0000,g,s1010).
cross(s0001,g,s1011).
cross(s0001,f,s1101).
cross(s0010,x,s1010). % no passenger
cross(s0010,c,s1011).
cross(s0010,f,s1110).
cross(s0100,c,s1101).
cross(s0100,g,s1110).
cross(s0101,x,s1101). % no passenger
cross(s0101,g,s1111).
cross(X,P,Y) :- cross(Y,P,X).
path(X,Y) :- cross(X,_,Y).
path(X,Z) :- path(X,Y), cross(Y,_,Z).
path(s0000,s1111)?
```

When you run this program, you will see the following result, showing that there is a solution!

```
1 match
path(s0000, s1111)
```

However, this doesn't show give an explicit soltuion to the puzzle. Unlike Prolog, the `ABC` language doesn't have a way to build the solution using some sort of list structure. So we do it by brute force!

First, observe that a minimal length solution path (with fewest crossings) cannot have two crossings that repeat a start side state, otherwise you would be back to a previous state. Since there are exactly 5 start side states of the form `s0???` that can be used for a crossing (see Slide 7.14), a minimum-length path can have at most nine crossings with different start side states. (Remember that a solution must have an odd number of crossings because a solution will always have the boat on the ending side.)

Define a premise `c1` for a single crossing:

```
c1(X,P1,Z) :- cross(X,P1,Z). % P1 is the passenger
```

Then define a premise `c2` for two consecutive crossings:

```
c2(X,P1,P2,Z) :- c1(X,P1,Y), cross(Y,P2,Z). % P1 then P2
```

Continue in this way to define three and more consecutive crossings:

```
c3(X,P1,P2,P3,Z) :- c2(X,P1,P2,Y), cross(Y,P3,Z).
c4(X,P1,P2,P3,P4,Z) :- c3(X,P1,P2,P3,Y), cross(Y,P4,Z).
c5(X,P1,P2,P3,P4,P5,Z) :- c4(X,P1,P2,P3,P4,Y), cross(Y,P5,Z).
c6(X,P1,P2,P3,P4,P5,P6,Z) :- c5(X,P1,P2,P3,P4,P5,Y), cross(Y,P6,Z).
c7(X,P1,P2,P3,P4,P5,P6,P7,Z) :- c6(X,P1,P2,P3,P4,P5,P6,Y),
                                cross(Y,P7,Z).
```

We can determine (by brute force) that less than seven crossings (always an odd number) will not get everything to the ending side. (For example, the query

```
c5(s0000,P1,P2,P3,P4,P5,s1111)?
```

gives no results.) However, `c7` has two matches:

```
c7(s0000, g, x, f, g, c, x, g, s1111)
c7(s0000, g, x, c, g, f, x, g, s1111)
```

Reading the letters from left to right gives the list of passengers (`g`=goose, `x`=no passenger, etc.) of a solution path from the start to the end state.

Observe that both solution paths have the goose as a passenger three times, but the fox only once.

Logic Programming Puzzles

Consider modifying the puzzle with the additional constraint that every crossing has at least one passenger. Is there a solution to this variant? To determine this, simply remove the `cross` premises with an `x` in the passenger slot (see Slide 7.14) and see if '`path(s0000, s1111)?`' returns a result.

Another variant would have a boat with two places for passengers, but the solution in this case would be trivial to see "by inspection", requiring no programming .

The Prolog language, upon which Datalog (and AbcDatalog) is based, has a much richer collection of data structures and operations that lends itself to expressing a larger set of problems, including those that require the use of lists and numeric operations.