# rolog: Prolog queries from R

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# Abstract

Prolog is a classical logic programming language with many applications in expert systems, computer linguistics and traditional, that is, symbolic artificial intelligence. The main strength of Prolog is its concise representation of facts and rules for the representation of knowledge and grammar, as well as its very efficient built-in search engine for closed world domains. R is a statistical programming language for data analysis and statistical modeling which is widely used in academia and industry. Besides the core library, a lot of packages have been developed for all kinds of statistical problems, including new-style artificial intelligence tools such as neural networks for machine learning and deep learning. Whereas Prolog is weak in statistical computation, but strong in symbolic manipulation, the converse may be said for the R language. SWI-Prolog is a widely used Prolog system that offers a wide range of extensions for real world applications, and there already exist two Prolog “packs” to invoke R (rserve-client, real) from SWI-Prolog. However, given the large user community of R, there may also be a need for a connection in the reverse direction that allows invoking Prolog queries in R computations. The R package rolog embeds the SWI-Prolog system, thus enabling deterministic and non-deterministic queries to the Prolog interpreter. Usage of the rolog library is illustrated by a few examples.

## Keywords

Statistics; Logic Programming; Artificial Intelligence

# 1. rolog: Prolog queries from R

The R (R Core Team 2021) programming language and environment is a widely used open source software for statistical data analysis. The basic R is a functional language with lots of support for storage and manipulation of different data types, and a strong emphasis on operations involving vectors and arrays. Moreover, a huge number of R packages (e.g., CRAN, <https://cran.r-project.org/>) have been contributed that cover problems from diverse areas such as bioinformatics, machine learning, specialized statistical methods, web programming and connections to other programming languages. An interface to Prolog is lacking so far.

The logic programming language Prolog was invented in the 1970ies by Colmerauer (Colmerauer and Roussel 1996), mostly for the purpose of natural language processing. Since then, logic programming has become an important driving force in research on artificial intelligence, natural language processing, program analysis, knowledge representation and theorem proving (Shoham 1994; Lally and Fodor 2011; Carro 2004; Hsiang and Srivas 1987). SWI-Prolog (Jan Wielemaker et al. 2012) is an open-source implementation of Prolog that mainly targets developers of applications, with many users in academia, research and industry. SWI-Prolog includes a large number of libraries for “the real world”, for example, a web server, encryption, interfaces to C/C++ and other programming languages, as well as a development environment and debugger. In addition, pluggable extensions (so-called packs) are available for specific tasks to enhance its capabilities.

Unlike R, Prolog is a declarative programming language consisting of facts and rules that define relations, for example, in a problem space. Prolog’s major strength is its built-in query-driven search engine that efficiently deals with complex structured data, with the data not necessarily being numerical. In fact, Prolog only provides a basic collection of arithmetic calculations via a purely functional interface is/2. More complex calculations such as matrix algebra, statistical models or machine learning need help from other systems, for example, from R.

Angelopoulos et al. (Angelopoulos et al. 2013) summarize work at the intersection of symbolic knowledge representation and statistical inference, especially in the area of model fits (EM algorithms, MCMC, Sato and Kameya 2013; Angelopoulos and Cussens 2008) and stochastic logic programs (Cussens 2000; ProbLog 2011). One of the major strengths of logic programming is handling constraints; and a number of systems for constraint satisfaction tools have been developed (constraint logic programming on booleans, finite domains, reals, and intervals) for that purpose (e.g., Frühwirth 1998; Triska 2018). Some constraint handlers exist in R (see the CRAN task view for optimization problems), but more of them would be available via a bridge between R and Prolog.

Earlier approaches to connect Prolog and R have been published as SWI-Prolog packs (real, rserve\_client, Angelopoulos et al. 2013; Jan Wielemaker 2021) and as a YAP module (YapR, Azevedo 2011). Whereas real establishes a direct link to an embedded instance of R, rserve\_client communicates with a local or remote R service (Urbanek 2021). The former approach emphasizes speed, the latter might be preferred from a security perspective, especially in systems such as SWISH (Jan Wielemaker, Lager, and Riguzzi 2015) that accept only a set of sandboxed commands for Prolog, but do not impose restrictions on R. A common feature of the two packages is that they provide an interface for R calls from Prolog, but not the other way round, that is, querying Prolog from R is not possible so far.

rolog is an attempt to fill this gap, and to offer the possibilty to raise Prolog queries in R scripts, for example, to perform efficient symbolic computations, searches in complex graphs, parsing natural language and definite clause grammars. In addition, two Prolog predicates are provided that enable Prolog to ring back to the R system for bidirectional communication. Similar to rreal, tight communication between the two systems is established by linking to a shared library that embeds the current version of SWI-Prolog. The exchange of data is facilitated by the C++ interfaces of the two languages (Eddelbuettel and Balamuta 2018; J. Wielemaker 2021). A less tight connection might be established using the recently developed machine query interface (Zinda 2021) that allows socket-based communication between foreign languages and SWI-Prolog (and, in fact, the MQI documentation includes an example in which R is called).

A bidirectional bridge between R and Prolog might overcome the limitations of both languages, thereby combining the extensive numerical and statistical power of the R system with Prolog’s skills in the representation of knowledge and reasoning. In addition to the useful little tools shown in the examples below, rolog can therefore contribute to progress at the intersection of traditional artificial intelligence and contemporary statistical programming.

The next section presents the interface of rolog in detail. Section 3 presents possible extensions of the package at both ends, in R and Prolog. Section 4 is a list of illustrative examples that offer useful extensions to the R system. Conclusions and further perspectives are summarized in Section 5.

# 2. Basic syntax

rolog has a rather minimalistic syntax, providing only some basic ingredients to establish communication with an embedded SWI-Prolog. The ways to extend the interface are described in Section 3.

After installation (in R, with install.packages("rolog")), the package is loaded in the standard way using R’s library-command.

library(rolog)

#> Welcome to SWI-Prolog (threaded, 64 bits, version 8.5.10-52-gcd28f88fd-DIRTY)

#> SWI-Prolog comes with ABSOLUTELY NO WARRANTY. This is free software.

#> Please run ?- license. for legal details.

#>

#> For online help and background, visit https://www.swi-prolog.org

#> For built-in help, use ?- help(Topic). or ?- apropos(Word).

We can see SWI-Prolog’s typical welcome message.

## R interface

Most of the work can done using the three R functions query, submit, and clear. The functions consult, once, and findall are provided for convenience.

consult. In most applications, a number of Prolog facts and rules will be loaded into the system. To facilitate this recurrent task, the prolog directive consult/1 has been mirrored into R, consult(filename), with filename given as a string (or a list of strings if multiple files are to be consulted). Note that the full filename should be given, including the extension (e.g., “.pl”). The function returns TRUE on success; in case of problems, it returns FALSE and an error message is shown.

query. The function query(call, options) is used to create a Prolog query (without invoking it yet). The first argument call is a regular R call that is created using R’s function call(name, ...). This call represents the Prolog predicate which will be queried in the later course. The creation of such predicates and Prolog terms is described below and can become quite contrived (see the examples in Section 4). The second argument, options, may be used for ad hoc modifications of the translation between R and Prolog, see the section below. The function returns TRUE on success. Note that the function does not check if the corresponding Prolog predicate exists (but see submit() below).

Only a single query can be opened at a given time. If a new query is created while another query is still open, a warning is shown and the other query is closed.

submit. Once a query has been created, it can be submitted using submit(). If the query fails, the return value is FALSE. If the query succeeds, a list of constraints is returned, with bindings for the variables that satisfy the query. Repeated calls to submit are possible, returning the different solutions of a query (until it eventually fails). Programmatically distinguishing between the different types of return values for success and failure (list vs. FALSE) is facilitated by the R function isFALSE(x).

clear. Closes the query. The name of the function is chosen to avoid name clashes with R’s own built-in function close. The function returns an invisible TRUE, even if there is no open query.

The following short R program illustrates a query to Prolog’s member/2 using Rolog’s syntax rules.

# member(1, [1, 2.0, a, "b", X])

query(call("member", 1L, list(1L, 2.0, quote(a), "b", expression(X), TRUE)))

#> [1] TRUE

#> attr(,"query")

#> [1] "member(1, [1, 2.0, a, b, X, true])"

# returns an empty list, stating that member(1, [1 | \_]) is satisfied

submit()

#> list()

# returns a list, stating that the query is also satisfied if X = 1

submit()

#> $X

#> [1] 1

# close the query

clear()

**Listing 1.**

A query to Prolog’s member/2 predicate.

once and findall. The function once(call, options) is a convenience function that acts as a shortcut for query(call, options), submit(), and clear(). Similarly, findall(call, options) abbreviates the commands query(call, options), repetition of submit() until failure, and clear(), returning a list collecting the the return value of the individual calls to submit.

## Creating Prolog terms in R

Table 1 summarizes the rules for the translation from R to Prolog. Most rules work in both directions, but a few exceptions exist. For example, there is an empty atom in Prolog, but no empty symbol in R, so the empty atom is translated to a character string in R.

**Table 1**

Creating Prolog terms from R

| **R** | **Prolog** | **Note/Alternatives** |
| --- | --- | --- |
| expression(X) | Variable X | not necessarily uppercase |
| as.symbol(abc) | Atom abc | as.name, quote |
| TRUE, FALSE, NULL | Atoms true, false, null |  |
| "abc" | String "abc" |  |
| 3L | Integer 3 |  |
| 3 | Float 3.0 |  |
| call("term", 1L, 2L) | term(1, 2) |  |
| list(1L, 2L, 3L) | List [1, 2, 3] |  |
| list(a=1, b=2, c=3) | List [a-1, b-2, c-3] |  |
| c(1, 2, 3) | #(1.0, 2.0, 3.0) | vectors of length > 1 |
| c(1L, 2L, 3L) or 1:3 | '%'(1, 2, 3) |  |
| c("a", "b", "c") | $$("a", "b", "c") |  |
| c(TRUE, FALSE, NA) | !(true, false, na) |  |

Moreover, R is mostly vectorized, lacking support for scalar entities, that is, scalar entities are treated as vectors of length 1. Conversely, Prolog does not natively support vectors or matrices. The problem is solved in the following way:

* R vectors of length 0 are translated to Prolog’s empty list.
* R vectors of length 1 are translated to Prolog scalars.
* R vectors of length N > 1 are translated to Prolog terms #/N, %/N, $$/N, and !/N for floating points, integers, strings and logicals, respectively.

In the reverse direction, Prolog terms like #/N are translated back to R vectors of length N, including terms #/0 and #/1 that map to R vectors of length 0 and 1, respectively. To summarize, the rules for translation are not fully symmetrical. A quick check for symmetry of the representation is obtained by a query to r\_eval/2 (see also below, subsection Prolog interface):

once(call("r\_eval", c(1, 2, NA, NaN, Inf), expression(X)))

#> $X

#> [1] 1 2 NA NaN Inf

## Package options

A few package-specific options have been defined to allow some fine-tuning of the rules for translation between R and Prolog.

* realvec (string): Name of the prolog term for vectors of floats (default is #)
* intvec (string): same for vectors of integers (default is %)
* boolvec (string): same for vectors of logicals (default is !)
* charvec (string): same for vectors of character strings (default is $$). The single dollar cannot be used because it is the list operator in R.
* scalar (logical): if TRUE (default), R vectors of length 1 are translated to scalars in Prolog. If FALSE, R vectors are always translated to #/N etc., depending on the type.
* portray (logical): if TRUE (default), the result of query, once and findall includes an attribute with a representation of the query in Prolog.

The command rolog\_options() returns a list with all the options. The options can be globally modified like e.g. this:

options(rolog.intvec="%%")

In a given query, the options can be set in the optional argument, e.g.

query(call("member", expression(X), list(1:3, 4:6)), options=list(intvec="%%"))

## Prolog interface

rolog offers some basic support to call R from Prolog, that is, connecting the two systems in the reverse direction. Two predicates can be used for this purpose, r\_eval(Call) and r\_eval(Function, Result). The former just invokes R with the command Call (ignoring the result); the latter evaluates Function and unifies the result with Result. Note that proper quoting of R functions is needed at the Prolog end, especially with R functions that start with uppercase letters or contain a dot in their name.

Two use cases for r\_eval/2 are shown in Section 4 below.

# 3. Extending the package

The package is intentionally kept minimalistic, but can easily be extended by convenience functions on both ends, Prolog and R, to facilitate recurrent tasks and/or avoid cumbersome syntax. R is a functional language, whereas Prolog is declarative. Obviously, there cannot be a perfect one-to-one correspondence between the syntactic components of two programming languages that follow completely different paradigms. Whereas symbols, functions, numbers and character strings are easily mapped between R and Prolog, there are loose ends at both sides. In particular, Prolog variables are translated from and to R expressions (not to be confused with R symbols), and R vectors of length N > 1 are translated to the Prolog terms #/N, %/N, !/N, and $$/N, as mentioned above.

These rules are, in principle, arbitrary and can be intercepted at several stages of the process:

* R functions that may be used to pre-process specific R elements before translation into Prolog (see, e.g., the R function as.rolog())
* Prolog wrappers that manipulate the term before it is called and afterwards (see the dicts below)
* R functions that post-process the result of a query

The process is illustrated in Figure 1.

Query preproc(...) Result postproc(...) (rolog) preproc/2 Prolog (rolog) postproc/2

**Figure 1**

Workflow in rolog

## Pre-processing in R

We have seen above that raising even simple everyday Prolog queries such as member(X, [1, 2, 3, a, b]) require complicated R expressions such as

query(call("member", expression(X), list(1, 2, 3, as.symbol("a"), quote(b)))

The R function as.rolog(call) is meant to simplify this a bit by translating symbols starting with a dot to Prolog variables, and calls like ""[1, 2, 3, a, b] to lists. The argument call is typically a quoted R call or symbol:

q <- quote(member(.X, ""[1, 2, 3, a, b]))

query(as.rolog(q))

Note that the name of the variable will still be X in the later course, not “dot-X”. A bit flexibility is lost because quote() treats the arguments a, b as symbols; to evaluate them (i.e., “unquote”), they can be put in parentheses:

a <- 4

b <- 5

q <- quote(member(.X, ""[1, 2, 3, a, (b)]))

query(as.rolog(q))

resulting in the query member(X, [1, 2, 3, a, 5]). More sophisticated work with quasi-quotations (i.e., “unquoting” expressions) is described in the “Advanced R” book (Wickham 2019).

Section 4 includes an example for mathematical rendering of R expressions. In that example, a pre-processing function is used to bring function calls with named arguments to a canonical form which is then handled in Prolog.

## Post-processing in R

This may again be a function that reverts some of the manipulations during pre-processing. For once() and submit(), such a function would operate on the bindings. For example, many Prolog programmers are used to operate with atoms instead of character strings, the latter being the preferred representation of symbolic information in R. The following simple example illustrates conversion of the results for a query like member(X, [a, b, c]) to strings.

stringify <- function(x)

{

# replace Prolog variable by the value of an R variable with the same name

if(is.name(x))

return(as.character(x))

# Recurse into lists and calls

if(is.call(x))

x[-1] <- lapply(x[-1], FUN=stringify)

if(is.list(x))

x <- lapply(x, FUN=stringify)

# Leave the rest unchanged

return(x)

}

# Example illustration

q <- quote(member(.X, ""[a, b, c]))

r <- findall(as.rolog(q))

stringify(r)

#> [[1]]

#> [[1]]$X

#> [1] "a"

#>

#>

#> [[2]]

#> [[2]]$X

#> [1] "b"

#>

#>

#> [[3]]

#> [[3]]$X

#> [1] "c"

## Pre- and post-processing in Prolog

Recent versions of SWI-Prolog support so-called dictionaries of the form Tag{Key1:Value1, Key2:Value2, ...}. The tag is typically an atom (but can be a variable, as well), the keys are unique atom or integers; the values can be anything. Suppose we have a Prolog predicate that does something with dicts, and we would like to query it from R. The simplest solution is a wrapper in Prolog that translates key-value pairs [Key1-Value1, Key2-Value2, ...] back and forth to dicts:

do\_something\_with\_pairs(Pairs0, Pairs1) :-

dict\_pairs(Dict0, my\_dict, Pairs0),

do\_something\_with\_dicts(Dict0, Dict1),

dict\_pairs(Dict1, my\_dict, Pairs1).

do\_something\_with\_pairs/2 can then be queried from R using, e.g., lists with named elements.

once(call("do\_something\_with\_pairs", list(a=1, b=2), expression(X)))

In the code above, dict\_pairs/2 takes the role of both preproc/2 and postproc/2 in Figure 1. It illustrates that complicated syntax on the R side when can be much simpler to do the conversion at the Prolog end.

A way to extend Prolog by add-ons (“packs”) are shown in the next section.

# 4. Examples

In this section I present a few usage examples for the rolog package in increasing complexity. Although the code snippets are mostly self-explanatory, some familiarity with the Prolog language is helpful.

## Hello, world

Prolog’s typical hello world example is a search through a directed acyclic graph (DAG), for example, a family tree like the one given in Listing 1.

parent(pam, bob).

parent(tom, bob).

parent(bob, ann).

parent(bob, pat).

parent(pat, jim).

ancestor(X, Z) :-

parent(X, Z).

ancestor(X, Z) :-

parent(X, Y),

ancestor(Y, Z).

**Listing 1**

A family tree in Prolog (see also family.pl)

Listing 1 is included in the package and can be accessed from R using the function system.file(...). Within Prolog, the normal workflow is to consult the code with [family] and then to raise queries such as ancestor(X, jim), which returns, one by one, four solutions for the variable X. In R, we obtain the following results:

library(rolog)

# [family].

consult(system.file(file.path("pl", "family.pl"), package="rolog"))

# ancestor(X, jim).

query(call("ancestor", expression(X), quote(jim)))

#> [1] TRUE

#> attr(,"query")

#> [1] "ancestor(X, jim)"

# solutions for X, one by one

submit()

#> $X

#> pat

submit()

#> $X

#> pam

submit()

#> $X

#> bob

submit()

#> [1] FALSE

submit() # no more results (closing the query)

#> Warning in .submit(): submit: no open query.

#> [1] FALSE

submit() # warning that no query is open

#> Warning in .submit(): submit: no open query.

#> [1] FALSE

# clear() # normally used to close a query

As stated above, consult() loads the facts and rules of Listing 1 into the database. query(expr) initializes the query expr, and the subsequent calls to submit return the conditions under which the query succeeds. In this example, the query succeeds if X is either pat, pam, tom or bob. A query is closed with clear(), or automatically if the query fails. Note that it is generally not possible to open two queries simultaneously, so opening a second query while another one is still open will raise a warning. If we are interested in just the first solution, we can use once(expr) as a shortcut to query(expr)-submit()-clear(). If we want to collect all solutions of a query with a finite set of solutions, we can use findall(expr).

A rather cumbersome aspect of Rolog is the construction of Prolog terms and queries. expression(X) encapsulates the variable X, R symbols from quote(jim) or as.symbol("jim") are translated to Prolog atoms, and Prolog compounds such as ancestor/2 are generated using call("ancestor", ...). A simplified syntax is provided by as.rolog(...) that accepts quoted expressions with dots indicating Prolog variables:

q = quote(ancestor(.X, jim))

findall(as.rolog(q))

Note that as.rolog(...) removes the dot from the variable name (.X to X).

## Backdoor test

A more useful application of DAGs is confounder adjustment in causal analysis (Greenland, Pearl, and Robins 1999; Barrett 2021). The Prolog file backdoor.pl is an implementation of Greenland et al.’s criteria for the backdoor test for d-separation in DAGs, with a predicate minimal/3 that searches for minimally sufficient sets of variables for confounder adjustment on the causal path between exposure and outcome.

# [backdoor].

consult(system.file(file.path("pl", "backdoor.pl"), package="rolog"))

# Figure 12 in Greenland et al.

add\_node = function(N)

invisible(once(call("assert", call("node", N))))

add\_arrow = function(X, Y)

invisible(once(call("assert", call("arrow", X, Y))))

add\_node("a")

add\_node("b")

add\_node("c")

add\_node("d") # outcome

add\_node("e") # exposure

add\_node("f")

add\_node("u")

add\_arrow("a", "d")

add\_arrow("a", "f")

add\_arrow("b", "d")

add\_arrow("b", "f")

add\_arrow("c", "d")

add\_arrow("c", "f")

add\_arrow("e", "d")

add\_arrow("f", "e")

add\_arrow("u", "a")

add\_arrow("u", "b")

add\_arrow("u", "c")

findall(call("minimal", "e", "d", expression(S)))

#> [[1]]

#> [[1]]$S

#> [[1]]$S[[1]]

#> [1] "a"

#>

#> [[1]]$S[[2]]

#> [1] "b"

#>

#> [[1]]$S[[3]]

#> [1] "c"

#>

#>

#>

#> [[2]]

#> [[2]]$S

#> [[2]]$S[[1]]

#> [1] "f"

The query to minimal/3 returns two minimally sufficient sets of covariates for confounder adjustment (namely, {a, b, c} and {f}).

## Definite clause grammars

One of the main driving forces of Prolog development was natural language processing (Dahl 1981). Therefore, the next example is an illustration of sentence parsing using so-called definite clause grammars. As Listing 3 shows, rolog can access modules from SWI’s standard library (e.g., “dcg/basics.pl”).

:- use\_module(library(dcg/basics)).

% Translate R string to code points and invoke phrase/2

sentence(Tree, Sentence) :-

string\_codes(Sentence, Codes),

phrase(s(Tree), Codes).

% Simple grammar with sentences, noun, verb and participle phrases

s(s(NP, VP)) --> np(NP, C), blank, vp(VP, C).

np(NP, C) --> pn(NP, C).

np(np(Det, N), C) --> det(Det, C), blank, n(N, C).

np(np(Det, N, PP), C) --> det(Det, C), blank, n(N, C), blank, pp(PP).

vp(vp(V, NP), C) --> v(V, C), blank, np(NP, \_).

vp(vp(V, NP, PP), C) --> v(V, C), blank, np(NP, \_), blank, pp(PP).

pp(pp(P, NP)) --> p(P), blank, np(NP, \_).

% Determiners, personal nouns, nouns, verbs and participles

det(det(a), sg) --> `a`.

det(det(the), \_) --> `the`.

pn(pn(john), sg) --> `john`.

n(n(man), sg) --> `man`.

n(n(men), pl) --> `men`.

n(n(telescope), sg) --> `telescope`.

v(v(sees), sg) --> `sees`.

v(v(see), pl) --> `see`.

v(v(saw), \_) --> `saw`.

p(p(with)) --> `with`.

**Listing 2**

Simple grammar and lexicon. sentence/2 pre-processes the R call.

As in the first example, we first consult a little Prolog program with a minimalistic grammar and lexicon (Listing 2), and then raise a query asking for the syntactic structure of “john saw a man with a telescope”. Closer inspection of the two results reveals the two possible meanings, “john saw a man who carries a telescope” versus “john saw a man through a telescope”. More Prolog examples of natural language processing are found in Blackburn and Bos (Blackburn and Bos 2005), including the resolution of anaphoric references and the extraction of semantic meaning.

# [telescope].

consult(system.file(file.path("pl", "telescope.pl"), package="rolog"))

# findall(sentence(Tree, "john saw a man with a telescope")).

findall(call("sentence", expression(Tree), "john saw a man with a telescope"))

#> list()

## Installation of add-ons for Prolog

In description of the previous example, I noted in passing that rolog can use the built-in libraries of SWI-Prolog (e.g., by calls to use\_module/1). It is also possible to extend the installation by add-ons, including add-ons that require compilation, if the build tools (essentially, RTools) are properly configured. This is illustrated below by the demo add-on “environ” (J. Wielemaker 2012) that collects the current environment variables.

# pack\_install(environ, [interactive(false)]).

once(call("pack\_install", as.name("environ"), list(call("interactive", FALSE))))

# use\_module(library(environ))

once(call("use\_module", call("library", quote(environ))))

# environ(X)

once(call("environ", expression(X)))

The query then unifies X with a list with Key=Value terms. The purpose if this example is obviously not to mimic the built-in function Sys.getenv() from R, but to illustrate the installation and usage of Prolog extensions from within R.

## Term manipulation

Prolog is homoiconic, that is, code is data. In this example, we make use of Prolog’s ability to match expressions against given patterns and modify these expressions according to a few predefined “buggy rules” (Brown and Burton 1978), inspired by recurrent mistakes in the statistics exams of my students. Consider the \(t\)-statistic for comparing an observed group average to a population mean:

\[ T = \frac{\overline{X} - \mu}{s / \sqrt{N}} \]

Some mistakes may occur in this calculation, for example, omission of the implicit parentheses around the numerator and the denominator when typing the numbers into a calculator, resulting to \(\overline{X} - \frac{\mu}{s} \div \sqrt{N}\), or forgetting the square root around \(N\), or both. Prolog code for the two buggy rules is given in Listing 3.

% Correct step from task to solution

expert(tratio(X, Mu, S, N), frac(X - Mu, S / sqrt(N))).

% Mistakes

buggy(frac(X - Mu, S / SQRTN), X - frac(Mu, S) / SQRTN).

buggy(sqrt(N), N).

% Apply expert and buggy rules

step(X, Y) :-

expert(X, Y).

step(X, Y) :-

buggy(X, Y).

% Enter expressions

step(X, Y) :-

compound(X),

mapargs(search, X, Y),

dif(X, Y).

% Search through problem space

search(X, X).

search(X, Z) :-

step(X, Y),

search(Y, Z).

**Listing 3**

Manipulating terms in Prolog

The little e-learning system shown in Listing 2 (buggy.pl) is invoked using the R script below.

library(rolog)

consult(system.file(file.path("pl", "buggy.pl"), package="rolog"))

q <- quote(search(tratio(x, mu, s, n), .S))

findall(as.rolog(q))

#> [[1]]

#> [[1]]$S

#> tratio(x, mu, s, n)

#>

#>

#> [[2]]

#> [[2]]$S

#> frac(x - mu, s/sqrt(n))

#>

#>

#> [[3]]

#> [[3]]$S

#> x - frac(mu, s)/sqrt(n)

#>

#>

#> [[4]]

#> [[4]]$S

#> x - frac(mu, s)/n

#>

#>

#> [[5]]

#> [[5]]$S

#> frac(x - mu, s/n)

#>

#>

#> [[6]]

#> [[6]]$S

#> x - frac(mu, s)/n

The fourth and the sixth result are combinations of the two buggy rules (parenthesis, then square root, and the other way round). Some additional filters would be needed to eliminate trivial and redundant solutions (see, e.g., the chapter on generate-and-test in Sterling and Shapiro 1994).

It should be mentioned that R is homoiconic, too, and the Prolog code above can, in principle, be rewritten in R using non-standard evaluation techniques (Wickham 2019). Prolog’s inbuilt pattern matching algorithm simplifies things a lot, though. An important feature of such a term manipulation is that the evaluation of the term can be postponed; for example, there is no need to instantiate the variables X, Mu, s and N with given values before raising a query. This is especially helpful for variables that may represent larger sets of data in the later course.

## Rendering mathematical expressions

The R extension of the markdown language (Xie, Dervieux, and Riederer 2020) enables reproducible statistical reports with nice typesetting in HTML, Microsoft Word, and Latex. However, so far, R expressions such as pbinom(k, N, p) are typeset as-is; prettier mathematical expressions such as \(P\_\mathrm{Bi}(X \le k; N, p)\) require Latex commands like P\_\mathrm{Bi}\left(X \le k; N, p\right), which are cumbersome to type in and hard to read even if the expressions are simple. Since recently, manual pages include support for mathematical expressions (Sarkar and Hornik 2022), which already is a big improvement.

Below Prolog’s grammar rules are used for an automatic translation of R expressions to MathML. The result can then be used for calculations or it can be rendered on a web page. A limited set of rules for translation from R to MathML is found in pl/mathml.pl of the rolog package. The relevant code snippets are shown in the listings below, along with their output.

library(rolog)

consult(system.file(file.path("pl", "mathml.pl"), package="rolog"))

# R interface to Prolog predicate r2mathml/2

mathml = function(term)

{

t = once(call("r2mathml", term, expression(X)))

cat(paste(t$X, collapse=""))

}

**Listing 4**

Using rolog to generate MathML from R expressions

The first example is easy. At the Prolog end, there is a handler for pbinom/3 that translates the term into a pretty MathML syntax like P\_bi(X <= k; N, pi).

term = quote(pbinom(k, N, p))

# Pretty print

mathml(term)

PBi⁡(X≤k;N,p)

# Do some calculations with the same term

k = 10

N = 22

p = 0.4

eval(term)

[1] 0.77195

The next example is interesting because Prolog needs find out the name of the integration variable for sin. For that purpose, rolog provides a predicate r\_eval/2 that calls R from Prolog (i.e., the reverse direction, see also next example). Here, the predicate is used for the R function formalArgs(args(sin)), which returns the name of the function argument of sin, that is, x.

term = quote(integrate(sin, 0L, 2L\*pi))

mathml(term)

∫02⁢πsin⁡(x)dx

eval(term)

2.221482e-16 with absolute error < 4.4e-14

Note that the Prolog end, the handler for integrate/3 is rather rigid; it accepts only these three arguments in that particular order, and without names, that is, integrate(sin, lower=0L, upper=2L \* pi) would not print the desired result.

Therefore, pl/mathml.pl includes two handlers that accept terms with named arguments, integrate(f=Fn, lower=Lower, upper=Upper), as well as terms of the form $(integrate(Fn, Lower, Upper), value) that are needed for the evaluation below.

# Apply match.call to all components of a term

canonical <- function(term)

{

if(is.call(term))

{

f <- match.fun(term[[1]])

if(!is.primitive(f))

term <- match.call(f, term)

# Recurse into arguments

term[-1] <- lapply(term[-1], canonical)

}

return(term)

}

# A custom function

g <- function(u)

{

sin(u)

}

# Mixture of (partially) named and positional arguments in unusual order

term <- quote(2L \* integrate(low=-Inf, up=Inf, g)$value)

mathml(canonical(term))

2⋅∫-∞∞g⁡(u)du

# It is a bit of a mystery that R knows the result of this integral.

eval(term)

[1] 0

The extra R function canonical() applies match.call() to non-primitive R calls, basically cleaning up the arguments and bringing them into the correct order.

## Calling Prolog from R

The basic workflow of the bridge from R to Prolog is to (A) translate an R expression into a Prolog term (i.e., a predicate), (B) query the predicate, and then, (C) translate the result (i.e., the bindings of the variables) back to R. The reverse direction is straightforward, we start by translating a Prolog term to an R expression (i.e. Step C), evaluate the R expression, and then translate the result back to a Prolog term (Step A). Rolog provides two Prolog predicates for this purpose, r\_eval(Expr) and r\_eval(Expr, Res). The former is used to invoke an R expression Expr for its side effects (e.g., initializing a random number generator); it does not return a result. The latter is used to evaluate the R expression Expr and return the result Res. The code snippet in Listing 5 (r\_eval.pl) illustrates this behavior.

r\_seed(Seed) :-

r\_eval('set.seed'(Seed)).

r\_norm(N, L) :-

r\_eval(rnorm(N), L).

# [r\_eval].

consult(system.file(file.path("pl", "r\_eval.pl"), package="rolog"))

# rnorm(3)

once(call("r\_norm", 3L, expression(X)))

#> $X

#> [1] 0.2176166 -0.2860811 -0.3774166

**Listing 5**

Calling Prolog from R using r\_eval/1 and r\_eval/2. The R call set.seed is quoted because the dot is an operator in Prolog.

The example in Listing 5 is a bit trivial, basically illustrating the syntax and the workflow. More serious applications of r\_eval/1,2 are illustrated in the example on mathematical expressions where r\_eval/2 is used to obtain a names of a function argument, as well as in the next example on interval arithmetic, where r\_eval/2 is used with monotonically behaving R functions.

## Interval arithmetic

Let \(\langle\ell, u\rangle\) denote a number between \(\ell\) and \(u\), \(\ell\le u\). It is easily verified that the result of the difference \(\langle\ell\_1, u\_1\rangle - \langle\ell\_2, u\_2\rangle\) is somewhere in the interval \(\langle \ell\_1 - u\_2, u\_1 - \ell\_2\rangle\), and a number of rules exist for basic arithmetic operations and (piecewise) monotonically behaving functions (Hickey, Ju, and Emden 2001). For ratios, denominators with mixed sign yield two possible intervals, for example, \(\langle 1, 2\rangle / \langle -3, 3\rangle = \langle -\infty, 3\rangle \cup \langle 3, \infty\rangle\), as shown in Figure 4 in Hickey et al.’s article. The number of possible candidates increases if more complicated functions are involved, as unions of intervals themselves appear as arguments (e.g., if \(I\_1 \cup I\_2\) is added to \(I\_3 \cup I\_4\), the result is \(I\_1 + I\_3 \cup I\_1 + I\_4 \cup I\_2 + I\_3 \cup I\_2 + I\_4\)). As a consequence, calculations in interval arithmetic are non-deterministic in nature, and the number of possible results is not foreseeable and cannot, in general, be vectorized as is often done in R. Use cases for interval arithmetic are the limitations of floating-point representations in computer hardware, but intervals can also be used to represent the result of measurements with limited precision, or truncated intermediate results of students doing hand calculations. A few rules for basic interval arithmetic are found in pl/interval.pl; a few examples are shown below. Again, Prolog rings back to R via r\_eval/2 to determine the result of dbinom(X, Size, Prob, Log).

# [interval].

consult(system.file(file.path("pl", "interval.pl"), package="rolog"))

# findall(1 ... 2 / -3 ... 3, Res).

q <- quote(int(`...`(1, 2) / `...`(-3, 3), .Res))

findall(as.rolog(q))

#> [[1]]

#> [[1]]$Res

#> ...(-Inf, -0.333333333333333)

#>

#>

#> [[2]]

#> [[2]]$Res

#> ...(0.333333333333333, Inf)

# t-ratio

D = quote(`...`(5.7, 5.8))

mu = 4

s = quote(`...`(3.8, 3.9))

N = 24L

tratio = call("/", call("-", D, mu), call("/", s, call("sqrt", N)))

findall(call("int", tratio, expression(Res)))

#> [[1]]

#> [[1]]$Res

#> ...(2.13545259627251, 2.32056923000512)

# Binomial density

prob = quote(`...`(0.2, 0.3))

once(call("int", call("dbinom", 4L, 10L, prob, FALSE), expression(Res)))

#> $Res

#> ...(0.088080384, 0.200120949)

prob = quote(`...`(0.5, 0.6))

once(call("int", call("dbinom", 4L, 10L, prob, FALSE), expression(Res)))

#> $Res

#> ...(0.111476736, 0.205078125)

prob = quote(`...`(0.2, 0.6))

once(call("int", call("dbinom", 4L, 10L, prob, FALSE), expression(Res)))

#> $Res

#> ...(0.088080384, 0.250822656)

The slightly cumbersome syntax for entering an interval \(\langle \ell, u\rangle\) is due to the fact that the ellipsis is a reserved symbol in R and cannot be used as an infix operator. A way more powerful and comprehensive system for constraint logic programming over intervals is available as a Prolog pack (Workman 2021) and can easily be connected to R using, for example, the present package.

# 5. Conclusions

R has become the primary language for statistical programming and data science, but is currently lacking support for traditional, symbolic artificial intelligence. There are already two add-ons for SWI-Prolog that allow to run R calculations from Prolog (Angelopoulos et al. 2013; Jan Wielemaker 2021), but a connection in the other direction was missing, so far. rolog bridges this gap by providing an interface to a SWI-Prolog distribution embedded into an R package. The communication between the two systems is mainly in the form of queries from R to Prolog, but two Prolog predicates allow Prolog to ring back and evaluate terms in R. The design of the package is minimalistic, providing three main functions query(...), submit(), and clear(), and a very limited set of convenience tools (consult(...), once(...), and findall(...)) to facilitate everyday actions. As both systems are homoiconic in nature, it was easy to establish a one-to-one correspondence between the elements of the two languages. Most exceptions (e.g., lack of R support for empty symbols) can be avoided and/or circumvented by wrapper functions at both ends.

Simple ways to extend the package have been described in Section 3; such extensions could, for example, include R objects and structures like those returned by lm, or S4 classes. In many use cases, this may be realized by transforming the R object to a list with named elements, and “reconstruct” the object on the Prolog end if needed. After a query, the process is reversed. If speed is an issue, more of these steps can, in principle, be moved into the package and implemented in Rcpp.

rolog, thus, opens up a wide of applications in logic programming for statisticians and researchers at the intersection of symbolic and connectionist artificial intelligence, where concise knowledge representation is combined with statistical power. Moreover, rolog provides starting points for useful small-scale solutions for everyday issues in data science (term transformations, pretty mathematical output, interval arithmetic).

At its present stage, a major limitation of rolog is its rather slow speed. For example, translation of R lists or vectors to the respective elements of the Prolog language (lists, #/N) is done element-wise, in both directions. The translation is optimized using Rcpp (Eddelbuettel and Balamuta 2018), but there remains an upper bound in the efficiency, because Prolog does not support vectors or matrices. Of course, Prolog’s primary purpose is not vector or matrix calculation, so this limitation may not show up in real-world applications. Another issue, maybe a bit annoying, is the rather cumbersome syntax of the interface, with the need for quoted calls and R expressions being a bit misused for representing Prolog variables. rolog was deliberately chosen to be minimalistic and, so far, only depends on base R. A more concise form of representation might be obtained by tools from the “Tidyverse” ecosystem, as described in Chapter 19 of Advanced R (Wickham 2019). Finally, at this stage, rolog is unable to deal with cyclic Prolog terms (e.g., once(call("=", expression(A), call("f", expression(A)))) raises an error message).

rolog is available for R version 4.2 and later. The source code of the package is found at <https://github.com/mgondan/rolog/>, including installation instructions for Unix, Windows and macOS.

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