

Stan Functions Reference

Stan Development Team

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About

This is the reference for the functions defined in the Stan math library and available in the Stan programming language.

The Stan project comprises a domain-specific language for probabilistic programming, a differentiable mathematics and probability library, algorithms for Bayesian posterior inference and posterior analysis, along with interfaces and analysis tools in all of the popular data analysis languages.

Interfaces and Platforms

Stan runs under Windows, Mac OS X, and Linux.

Stan uses a domain-specific programming language that is portable across data analysis languages. Stan has interfaces for R, Python, Julia, MATLAB, Mathematica, Stata, and the command line, as well as an alternative language interface in Scala. See the web site (link below) for links and getting started instructions.

Web Site

The official resource for all things related to Stan is the web site:

<http://mc-stan.org>

The web site links to all of the packages comprising Stan for both users and developers. This is the place to get started with Stan. Find the interface in the language you want to use and follow the download, installation, and getting started instructions.

GitHub Organization

Stan's source code and much of the developer process is hosted on GitHub. Stan's organization is:

<http://https://github.com/stan-dev>

Each package has its own repository within the `stan-dev` organization. The web site is also hosted and managed through GitHub. This is the place to peruse the source code, request features, and report bugs. Much of the ongoing design discussion is hosted on the GitHub Wiki.

Forums

Stan hosts message boards for discussing all things related to Stan.

<http://discourse.mc-stan.org>

This is the place to ask questions about Stan, including modeling, programming, and installation.

Licensing

The core C++ code underlying Stan, including the math library, language, and inference algorithms, is licensed under the BSD 3-clause licensed as detailed in each repository and on the web site along with the distribution links.

Acknowledgements

The Stan project could not exist without the generous grant funding of many grant agencies to the participants in the project. For more details of direct funding for the project, see the web site and project pages of the Stan developers.

The Stan project could also not exist without the generous contributions of its users in reporting and in many cases fixing bugs in the code and its documentation. We used to try to list all of those who contributed patches and bug reports for the manual here, but when that number passed into the hundreds, it became too difficult to manage reliably. Instead, we will defer to GitHub (link above), where all contributions to the project are made and tracked.

Finally, we should all thank the Stan developers, without whom this project could not exist. We used to try and list the developers here, but like the bug reporters, once the list grew into the dozens, it became difficult to track. Instead, we will defer to the Stan web page and GitHub itself for a list of core developers and all developer contributions respectively.

Part I

Built-In Functions

1. Void Functions

Stan does not technically support functions that do not return values. It does support two types of statements that look like functions, one for printing and one for rejecting outputs. Documentation on these functions is included here for completeness. The special keyword `void` is used for the return type of void functions, because they behave like variadic functions with void return type, even though they are special kinds of statements.

Although `print` and `reject` appear to have the syntax of functions, they are actually special kinds of statements with slightly different form and behavior than other functions. First, they are the constructs that allow a variable number of arguments. Second, they are the only constructs to accept string literals (e.g., "hello world") as arguments. Third, they have no effect on the log density function and operate solely through side effects.

1.1. Print “Function”

Printing has no effect on the model’s log probability function. Its sole purpose is the side effect (i.e., an effect not represented in a return value) of arguments being printed to whatever the standard output stream is connected to (e.g., the terminal in command-line Stan or the R console in RStan).

`void print(T1 x1, ..., TN xN)`

Print the values denoted by the arguments `x1` through `xN` on the output message stream. There are no spaces between items in the print, but a line feed (LF; Unicode U+000A; C++ literal `'\n'`) is inserted at the end of the printed line. The types `T1` through `TN` can be any of Stan’s built-in numerical types or double quoted strings of ASCII characters.

1.2. Reject “Function”

The reject statement has the same syntax as the print statement, accepting an arbitrary number of arguments of any type (including string literals). The effect of executing a reject statement is to throw an exception internally that terminates the current iteration with a rejection (the behavior of which will depend on the algorithmic context in which it occurs).

`void reject(T1 x1, ..., TN xN)`

Reject the current iteration and print the values denoted by the arguments `x1` through `xN` on the output message stream. There are no spaces between items

in the print, but a line feed (LF; Unicode U+000A; C++ literal `'\n'`) is inserted at the end of the printed line. The types T1 through TN can be any of Stan's built-in numerical types or double quoted strings of ASCII characters.

2. Integer-Valued Basic Functions

This chapter describes Stan's built-in function that take various types of arguments and return results of type integer.

2.1. Integer-Valued Arithmetic Operators

Stan's arithmetic is based on standard double-precision C++ integer and floating-point arithmetic. If the arguments to an arithmetic operator are both integers, as in $2 + 2$, integer arithmetic is used. If one argument is an integer and the other a floating-point value, as in $2.0 + 2$ and $2 + 2.0$, then the integer is promoted to a floating point value and floating-point arithmetic is used.

Integer arithmetic behaves slightly differently than floating point arithmetic. The first difference is how overflow is treated. If the sum or product of two integers overflows the maximum integer representable, the result is an undesirable wraparound behavior at the bit level. If the integers were first promoted to real numbers, they would not overflow a floating-point representation. There are no extra checks in Stan to flag overflows, so it is up to the user to make sure it does not occur.

Secondly, because the set of integers is not closed under division and there is no special infinite value for integers, integer division implicitly rounds the result. If both arguments are positive, the result is rounded down. For example, $1 / 2$ evaluates to 0 and $5 / 3$ evaluates to 1.

If one of the integer arguments to division is negative, the latest C++ specification (C++11), requires rounding toward zero. This would have $1 / 2$ and $-1 / 2$ evaluate to 0, $-7 / 2$ evaluate to -3, and $7 / 2$ evaluate to 3. Before the C++11 specification, the behavior was platform dependent, allowing rounding up or down. All compilers recent enough to be able to deal with Stan's templating should follow the C++11 specification, but it may be worth testing if you are not sure and plan to use integer division with negative values.

Unlike floating point division, where $1.0 / 0.0$ produces the special positive infinite value, integer division by zero, as in $1 / 0$, has undefined behavior in the C++ standard. For example, the `clang++` compiler on Mac OS X returns 3764, whereas the `g++` compiler throws an exception and aborts the program with a warning. As with overflow, it is up to the user to make sure integer divide-by-zero does not occur.

Binary Infix Operators

Operators are described using the C++ syntax. For instance, the binary operator of addition, written $X + Y$, would have the Stan signature `int operator+(int,int)` indicating it takes two real arguments and returns a real value. As noted previously,

the value of integer division is platform-dependent when rounding is platform dependent before C++11; the descriptions below provide the C++11 definition.

int **operator+**(int x, int y)

The sum of the addends x and y

$$\text{operator+}(x, y) = (x + y)$$

int **operator-**(int x, int y)

The difference between the minuend x and subtrahend y

$$\text{operator-}(x, y) = (x - y)$$

int **operator***(int x, int y)

The product of the factors x and y

$$\text{operator*}(x, y) = (x \times y)$$

int **operator/**(int x, int y)

The integer quotient of the dividend x and divisor y

$$\text{operator/}(x, y) = \begin{cases} \lfloor x/y \rfloor & \text{if } x/y \geq 0 \\ -\lfloor \text{floor}(-x/y) \rfloor & \text{if } x/y < 0. \end{cases}$$

int **operator%**(int x, int y)

x modulo y , which is the positive remainder after dividing x by y . If both x and y are non-negative, so is the result; otherwise, the sign of the result is platform dependent.

$$\text{operator\%}(x, y) = x \bmod y = x - y * \lfloor x/y \rfloor$$

Unary Prefix Operators

int **operator-**(int x)

The negation of the subtrahend x

$$\text{operator-}(x) = -x$$

`int operator+(int x)`

This is a no-op.

$$\text{operator}+(x) = x$$

2.2. Absolute Functions

R **abs**(T x)

Returns the (elementwise) absolute value of x ,

$$\text{abs}(x) = |x|$$

for any argument type T; see Section 3.1 for details including return type R.

`int int_step(int x)`

`int int_step(real x)`

Returns the step function of x as an integer,

$$\text{int_step}(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x \leq 0 \text{ or } x \text{ is } \text{NaN} \end{cases}$$

Warning: `int_step(0)` and `int_step(NaN)` return 0 whereas `step(0)` and `step(NaN)` return 1.

See the warning in Section 3.7 about the dangers of step functions applied to anything other than data.

2.3. Bound Functions

`int min(int x, int y)`

Returns the minimum of x and y .

$$\min(x, y) = \begin{cases} x & \text{if } x < y \\ y & \text{otherwise} \end{cases}$$

`int max(int x, int y)`

Returns the maximum of x and y .

$$\max(x, y) = \begin{cases} x & \text{if } x > y \\ y & \text{otherwise} \end{cases}$$

3. Real-Valued Basic Functions

This chapter describes built-in functions that take zero or more real or integer arguments and return real values.

3.1. Vectorization of Real-Valued Functions

Although listed in this chapter, many of Stan's built-in functions are vectorized so that they may be applied to any argument type. The vectorized form of these functions is not any faster than writing an explicit loop that iterates over the elements applying the function—it's just easier to read and write and less error prone.

Unary Function Vectorization

Many of Stan's unary functions can be applied to any argument type. For example, the exponential function, `exp`, can be applied to `real` arguments or arrays of `real` arguments. Other than for integer arguments, the result type is the same as the argument type, including dimensionality and size. Integer arguments are first promoted to real values, but the result will still have the same dimensionality and size as the argument.

Real and real array arguments

When applied to a simple real value, the result is a real value. When applied to arrays, vectorized functions like `exp()` are defined elementwise. For example,

```
// declare some variables for arguments
real x0;
real x1[5];
real x2[4, 7];
...
// declare some variables for results
real y0;
real y1[5];
real y2[4, 7];
...
// calculate and assign results
y0 = exp(x0);
y1 = exp(x1);
y2 = exp(x2);
```

When `exp` is applied to an array, it applies elementwise. For example, the statement above,

```
y2 = exp(x2);
```

produces the same result for y2 as the explicit loop

```
for (i in 1:4)
  for (j in 1:7)
    y2[i, j] = exp(x2[i, j]);
```

Vector and matrix arguments

Vectorized functions also apply elementwise to vectors and matrices. For example,

```
vector[5] xv;
row_vector[7] xrv;
matrix[10, 20] xm;
...
vector[5] yv;
row_vector[7] yrv;
matrix[10, 20] ym;
```

```
yv = exp(xv);
yrv = exp(xrv);
ym = exp(xm);
```

Arrays of vectors and matrices work the same way. For example,

```
matrix[17, 93] u[12];
...
matrix[17, 93] z[12];
...
z = exp(u);
```

After this has been executed, $z[i, j, k]$ will be equal to $\exp(u[i, j, k])$.

Integer and integer array arguments

Integer arguments are promoted to real values in vectorized unary functions. Thus if n is of type `int`, $\exp(n)$ is of type `real`. Arrays work the same way, so that if $n2$ is a one dimensional array of integers, then $\exp(n2)$ will be a one-dimensional array of reals with the same number of elements as $n2$. For example,

```
int n1[23];
...
real z1[23];
...
z1 = exp(n1);
```

It would be illegal to try to assign `exp(n1)` to an array of integers; the return type is a real array.

3.2. Mathematical Constants

Constants are represented as functions with no arguments and must be called as such. For instance, the mathematical constant π must be written in a Stan program as `pi()`.

`real pi()`

π , the ratio of a circle's circumference to its diameter

`real e()`

e , the base of the natural logarithm

`real sqrt2()`

The square root of 2

`real log2()`

The natural logarithm of 2

`real log10()`

The natural logarithm of 10

3.3. Special Values

`real not_a_number()`

Not-a-number, a special non-finite real value returned to signal an error

`real positive_infinity()`

Positive infinity, a special non-finite real value larger than all finite numbers

`real negative_infinity()`

Negative infinity, a special non-finite real value smaller than all finite numbers

`real machine_precision()`

The smallest number x such that $(x + 1) \neq 1$ in floating-point arithmetic on the current hardware platform

3.4. Log Probability Function

The basic purpose of a Stan program is to compute a log probability function and its derivatives. The log probability function in a Stan model outputs the log density on the unconstrained scale. A log probability accumulator starts at zero and is then incremented in various ways by a Stan program. The variables are first transformed from unconstrained to constrained, and the log Jacobian determinant added to the log probability accumulator. Then the model block is executed on the constrained parameters, with each sampling statement (\sim) and log probability increment statement (`increment_log_prob`) adding to the accumulator. At the end of the model block execution, the value of the log probability accumulator is the log probability value returned by the Stan program.

Stan provides a special built-in function `target()` that takes no arguments and returns the current value of the log probability accumulator.¹

This function is primarily useful for debugging purposes, where for instance, it may be used with a `print` statement to display the log probability accumulator at various stages of execution to see where it becomes ill defined.

real `target()`

Returns the current value of the log probability accumulator.

real `get_lp()`

Returns the current value of the log probability accumulator; **deprecated**: — use `target()` instead).

Both `target` and the deprecated `get_lp` act like other functions ending in `_lp`, meaning that they may only be used in the model block.

3.5. Logical Functions

Like C++, BUGS, and R, Stan uses 0 to encode false, and 1 to encode true. Stan supports the usual boolean comparison operations and boolean operators. These all have the same syntax and precedence as in C++; for the full list of operators and precedences, see the reference manual.

Comparison Operators

All comparison operators return boolean values, either 0 or 1. Each operator has two signatures, one for integer comparisons and one for floating-point comparisons.

¹This function used to be called `get_lp()`, but that name has been deprecated; using it will print a warning. The function `get_lp()` will be removed in a future release.

Comparing an integer and real value is carried out by first promoting the integer value.

int **operator<**(int x, int y)

int **operator<**(real x, real y)

Returns 1 if x is less than y and 0 otherwise.

$$\text{operator}<(x, y) = \begin{cases} 1 & \text{if } x < y \\ 0 & \text{otherwise} \end{cases}$$

int **operator<=**(int x, int y)

int **operator<=**(real x, real y)

Returns 1 if x is less than or equal y and 0 otherwise.

$$\text{operator}<=(x, y) = \begin{cases} 1 & \text{if } x \leq y \\ 0 & \text{otherwise} \end{cases}$$

int **operator>**(int x, int y)

int **operator>**(real x, real y)

Returns 1 if x is greater than y and 0 otherwise.

$$\text{operator}> = \begin{cases} 1 & \text{if } x > y \\ 0 & \text{otherwise} \end{cases}$$

int **operator>=**(int x, int y)

int **operator>=**(real x, real y)

Returns 1 if x is greater than or equal to y and 0 otherwise.

$$\text{operator}>= = \begin{cases} 1 & \text{if } x \geq y \\ 0 & \text{otherwise} \end{cases}$$

int **operator==**(int x, int y)

int **operator==**(real x, real y)

Returns 1 if x is equal to y and 0 otherwise.

$$\text{operator}==(x, y) = \begin{cases} 1 & \text{if } x = y \\ 0 & \text{otherwise} \end{cases}$$

```
int operator!=(int x, int y)
int operator!=(real x, real y)
```

Returns 1 if x is not equal to y and 0 otherwise.

$$\text{operator}!=(x, y) = \begin{cases} 1 & \text{if } x \neq y \\ 0 & \text{otherwise} \end{cases}$$

Boolean Operators

Boolean operators return either 0 for false or 1 for true. Inputs may be any real or integer values, with non-zero values being treated as true and zero values treated as false. These operators have the usual precedences, with negation (not) binding the most tightly, conjunction the next and disjunction the weakest; all of the operators bind more tightly than the comparisons. Thus an expression such as `!a && b` is interpreted as `(!a) && b`, and `a < b || c >= d && e != f` as `(a < b) || (((c >= d) && (e != f)))`.

```
int operator!(int x)
int operator!(real x)
```

Returns 1 if x is zero and 0 otherwise.

$$\text{operator}!(x) = \begin{cases} 0 & \text{if } x \neq 0 \\ 1 & \text{if } x = 0 \end{cases}$$

```
int operator&&(int x, int y)
int operator&&(real x, real y)
```

Returns 1 if x is unequal to 0 and y is unequal to 0.

$$\text{operator}\&\&(x, y) = \begin{cases} 1 & \text{if } x \neq 0 \text{ and } y \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

```
int operator||(int x, int y)
int operator||(real x, real y)
```

Returns 1 if x is unequal to 0 or y is unequal to 0.

$$\text{operator}|| (x, y) = \begin{cases} 1 & \text{if } x \neq 0 \text{ or } y \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

Boolean Operator Short Circuiting

Like in C++, the boolean operators `&&` and `||` and are implemented to short circuit directly to a return value after evaluating the first argument if it is sufficient to resolve the result. In evaluating `a || b`, if `a` evaluates to a value other than zero, the expression returns the value 1 without evaluating the expression `b`. Similarly, evaluating `a && b` first evaluates `a`, and if the result is zero, returns 0 without evaluating `b`.

Logical Functions

The logical functions introduce conditional behavior functionally and are primarily provided for compatibility with BUGS and JAGS.

real `step`(real `x`)

Returns 1 if `x` is positive and 0 otherwise.

$$\text{step}(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1 & \text{otherwise} \end{cases}$$

Warning: `int_step(0)` and `int_step(NaN)` return 0 whereas `step(0)` and `step(NaN)` return 1.

The step function is often used in BUGS to perform conditional operations. For instance, `step(a - b)` evaluates to 1 if `a` is greater than `b` and evaluates to 0 otherwise. `step` is a step-like functions; see the warning in Section 3.7 applied to expressions dependent on parameters.

int `is_inf`(real `x`)

Returns 1 if `x` is infinite (positive or negative) and 0 otherwise.

int `is_nan`(real `x`)

Returns 1 if `x` is NaN and 0 otherwise.

Care must be taken because both of these indicator functions are step-like and thus can cause discontinuities in gradients when applied to parameters; see Section 3.7 for details.

3.6. Real-Valued Arithmetic Operators

The arithmetic operators are presented using C++ notation. For instance `operator+(x,y)` refers to the binary addition operator and `operator-(x)` to the unary negation operator. In Stan programs, these are written using the usual infix and prefix notations as `x + y` and `-x`, respectively.

Binary Infix Operators

real **operator+**(real x , real y)

Returns the sum of x and y .

$$(x + y) = \text{operator+}(x, y) = x + y$$

real **operator-**(real x , real y)

Returns the difference between x and y .

$$(x - y) = \text{operator-}(x, y) = x - y$$

real **operator***(real x , real y)

Returns the product of x and y .

$$(x * y) = \text{operator*}(x, y) = xy$$

real **operator/**(real x , real y)

Returns the quotient of x and y .

$$(x/y) = \text{operator/}(x, y) = \frac{x}{y}$$

real **operator^**(real x , real y)

Return x raised to the power of y .

$$(x^y) = \text{operator^}(x, y) = x^y$$

Unary Prefix Operators

real **operator-**(real x)

Returns the negation of the subtrahend x .

$$\text{operator-}(x) = (-x)$$

`real operator+(real x)`
Returns the value of x .

$$\text{operator}+(x) = x$$

3.7. Step-like Functions

Warning: *These functions can seriously hinder sampling and optimization efficiency for gradient-based methods (e.g., NUTS, HMC, BFGS) if applied to parameters (including transformed parameters and local variables in the transformed parameters or model block). The problem is that they break gradients due to discontinuities coupled with zero gradients elsewhere. They do not hinder sampling when used in the data, transformed data, or generated quantities blocks.*

Absolute Value Functions

R **fabs**(T x)

Returns the (elementwise) absolute value of x ,

$$\text{abs}(x) = |x|$$

See the warning at start of Section 3.7 for application to parameters. for any argument type T; see Section 3.1 for details including return type R.

`real abs(real x)`

Returns the absolute value of x , defined by

$$\text{abs}(x) = |x|$$

See the warning at start of Section 3.7 for application to parameters.

`int abs(int x)`

Returns the absolute value of x , defined by

$$\text{abs}(x) = |x|$$

`real fdim(real x, real y)`

Returns the positive difference between x and y , which is $x - y$ if x is greater than y and 0 otherwise; see warning at start of Section 3.7.

$$\text{fdim}(x, y) = \begin{cases} x - y & \text{if } x \geq y \\ 0 & \text{otherwise} \end{cases}$$

Bounds Functions

`real fmin(real x, real y)`

Returns the minimum of x and y ; see warning at start of Section 3.7.

$$\text{fmin}(x, y) = \begin{cases} x & \text{if } x \leq y \\ y & \text{otherwise} \end{cases}$$

`real fmax(real x, real y)`

Returns the maximum of x and y ; see warning at start of Section 3.7.

$$\text{fmax}(x, y) = \begin{cases} x & \text{if } x \geq y \\ y & \text{otherwise} \end{cases}$$

Arithmetic Functions

`real fmod(real x, real y)`

Returns the real value remainder after dividing x by y ; see warning at start of Section 3.7.

$$\text{fmod}(x, y) = x - \left\lfloor \frac{x}{y} \right\rfloor y$$

The operator $\lfloor u \rfloor$ is the floor operation; see below.

Rounding Functions

Warning: Rounding functions convert real values to integers. Because the output is an integer, any gradient information resulting from functions applied to the integer is not passed to the real value it was derived from. With MCMC sampling using HMC or NUTS, the MCMC acceptance procedure will correct for any error due to poor gradient calculations, but the result is likely to be reduced acceptance probabilities and less efficient sampling.

The rounding functions cannot be used as indices to arrays because they return real values. Stan may introduce integer-valued versions of these in the future, but as of now, there is no good workaround.

`R floor(T x)`

Returns the (elementwise) floor of x , which is the largest integer less than or equal to x , converted to a real value; see warning at start of Section 3.7,

$$\text{floor}(x) = \lfloor x \rfloor$$

for any argument type T; see Section 3.1 for details including return type R.

R **ceil**(T x)

Returns the (elementwise) ceiling of x , which is the smallest integer greater than or equal to x , converted to a real value; see warning at start of Section 3.7,

$$\text{ceil}(x) = \lceil x \rceil$$

for any argument type T; see Section 3.1 for details including return type R.

R **round**(T x)

Returns the (elementwise) nearest integer to x , converted to a real value; see warning at start of Section 3.7,

$$\text{round}(x) = \begin{cases} \lceil x \rceil & \text{if } x - \lfloor x \rfloor \geq 0.5 \\ \lfloor x \rfloor & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **trunc**(T x)

Returns the (elementwise) integer nearest to but no larger in magnitude than x , converted to a double value; see warning at start of Section 3.7,

$$\text{trunc}(x) = \lfloor x \rfloor$$

Note that this function is redundant with `floor`. for any argument type T; see Section 3.1 for details including return type R.

3.8. Power and Logarithm Functions

R **sqrt**(T x)

Returns the (elementwise) square root of x ,

$$\text{sqrt}(x) = \begin{cases} \sqrt{x} & \text{if } x \geq 0 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **cbrt**(T x)

Returns the (elementwise) cube root of x ,

$$\text{cbrt}(x) = \sqrt[3]{x}$$

for any argument type T; see Section 3.1 for details including return type R.

R **square**(T x)

Returns the (elementwise) square of x ,

$$\text{square}(x) = x^2$$

for any argument type T; see Section 3.1 for details including return type R.

R **exp**(T x)

Returns the (elementwise) natural exponential of x ,

$$\text{exp}(x) = \exp(x) = e^x$$

for any argument type T; see Section 3.1 for details including return type R.

R **exp2**(T x)

Returns the (elementwise) base-2 exponential of x ,

$$\text{exp2}(x) = 2^x$$

for any argument type T; see Section 3.1 for details including return type R.

R **log**(T x)

Returns the (elementwise) natural logarithm of x ,

$$\text{log}(x) = \log x = \begin{cases} \log_e(x) & \text{if } x \geq 0 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **log2**(T x)

Returns the (elementwise) base-2 logarithm of x ,

$$\text{log2}(x) = \begin{cases} \log_2(x) & \text{if } x \geq 0 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **log10**(T x)

Returns the (elementwise) base-10 logarithm of x ,

$$\text{log10}(x) = \begin{cases} \log_{10}(x) & \text{if } x \geq 0 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

real pow(real x , real y)

Returns x raised to the power of y .

$$\text{pow}(x, y) = x^y$$

R inv(T x)

Returns the (elementwise) inverse of x ,

$$\text{inv}(x) = \frac{1}{x}$$

for any argument type T; see Section 3.1 for details including return type R.

R inv_sqrt(T x)

Returns the (elementwise) inverse of the square root of x ,

$$\text{inv_sqrt}(x) = \begin{cases} \frac{1}{\sqrt{x}} & \text{if } x \geq 0 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R inv_square(T x)

Returns the (elementwise) inverse of the square of x ,

$$\text{inv_square}(x) = \frac{1}{x^2}$$

for any argument type T; see Section 3.1 for details including return type R.

3.9. Trigonometric Functions

real hypot(real x , real y)

Returns the length of the hypotenuse of a right triangle with sides of length x and y .

$$\text{hypot}(x, y) = \begin{cases} \sqrt{x^2 + y^2} & \text{if } x, y \geq 0 \\ \text{NaN} & \text{otherwise} \end{cases}$$

R cos(T x)

Returns the (elementwise) cosine of the angle x (in radians),

$$\text{cos}(x) = \cos(x)$$

for any argument type T; see Section 3.1 for details including return type R.

R **sin**(T x)

Returns the (elementwise) sine of the angle x (in radians),

$$\sin(x) = \sin(x)$$

for any argument type T; see Section 3.1 for details including return type R.

R **tan**(T x)

Returns the (elementwise) tangent of the angle x (in radians),

$$\tan(x) = \tan(x)$$

for any argument type T; see Section 3.1 for details including return type R.

R **acos**(T x)

Returns the (elementwise) principal arc (inverse) cosine (in radians) of x ,

$$\operatorname{acos}(x) = \begin{cases} \arccos(x) & \text{if } -1 \leq x \leq 1 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **asin**(T x)

Returns the (elementwise) principal arc (inverse) sine (in radians) of x ,

$$\operatorname{asin}(x) = \begin{cases} \arcsin(x) & \text{if } -1 \leq x \leq 1 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **atan**(T x)

Returns the (elementwise) principal arc (inverse) tangent (in radians) of x , with values from $-\pi$ to π ,

$$\operatorname{atan}(x) = \arctan(x)$$

for any argument type T; see Section 3.1 for details including return type R.

real **atan2**(real y, real x)

Returns the principal arc (inverse) tangent (in radians) of y divided by x ,

$$\operatorname{atan2}(y, x) = \arctan\left(\frac{y}{x}\right)$$

3.10. Hyperbolic Trigonometric Functions

R **cosh**(T x)

Returns the (elementwise) hyperbolic cosine of x (in radians),

$$\cosh(x) = \cosh(x)$$

for any argument type T; see Section 3.1 for details including return type R.

R **sinh**(T x)

Returns the (elementwise) hyperbolic sine of x (in radians),

$$\sinh(x) = \sinh(x)$$

for any argument type T; see Section 3.1 for details including return type R.

R **tanh**(T x)

Returns the (elementwise) hyperbolic tangent of x (in radians),

$$\tanh(x) = \tanh(x)$$

for any argument type T; see Section 3.1 for details including return type R.

R **acosh**(T x)

Returns the (elementwise) inverse hyperbolic cosine (in radians),

$$\operatorname{acosh}(x) = \begin{cases} \cosh^{-1}(x) & \text{if } x \geq 1 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **asinh**(T x)

Returns the (elementwise) inverse hyperbolic cosine (in radians),

$$\operatorname{asinh}(x) = \sinh^{-1}(x)$$

for any argument type T; see Section 3.1 for details including return type R.

R **atanh**(T x)

Returns the (elementwise) inverse hyperbolic tangent (in radians) of x ,

$$\operatorname{atanh}(x) = \begin{cases} \tanh^{-1}(x) & \text{if } -1 \leq x \leq 1 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

3.11. Link Functions

The following functions are commonly used as link functions in generalized linear models. The function Φ is also commonly used as a link function (see Section 3.12).

R **logit**(T x)

Returns the (elementwise) log odds, or logit, function applied to x ,

$$\text{logit}(x) = \begin{cases} \log \frac{x}{1-x} & \text{if } 0 \leq x \leq 1 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **inv_logit**(T x)

Returns the (elementwise) logistic sigmoid function applied to x ,

$$\text{inv_logit}(x) = \frac{1}{1 + \exp(-x)}$$

for any argument type T; see Section 3.1 for details including return type R.

R **inv_cloglog**(T x)

Returns the (elementwise) inverse of the complementary log-log function applied to x ,

$$\text{inv_cloglog}(x) = 1 - \exp(-\exp(x))$$

for any argument type T; see Section 3.1 for details including return type R.

3.12. Probability-Related Functions

Normal Cumulative Distribution Functions

The error function erf is related to the standard normal cumulative distribution function Φ by scaling. See Section 15.1 for the general normal cumulative distribution function (and its complement).

R **erf**(T x)

Returns the (elementwise) error function, also known as the Gauss error function, of x ,

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$

for any argument type T; see Section 3.1 for details including return type R.

R **erfc**(T x)

Returns the (elementwise) complementary error function of x ,

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt$$

for any argument type T; see Section 3.1 for details including return type R.

R **Phi**(T x)

Returns the (elementwise) standard normal cumulative distribution function of x ,

$$\text{Phi}(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-t^2/2} dt$$

for any argument type T; see Section 3.1 for details including return type R.

R **inv_Phi**(T x)

Returns the (elementwise) standard normal inverse cumulative distribution function of p , otherwise known as the quantile function,

$$\text{Phi}(\text{inv_Phi}(p)) = p$$

for any argument type T; see Section 3.1 for details including return type R.

R **Phi_approx**(T x)

Returns the (elementwise) fast approximation of the unit (may replace Phi for probit regression with maximum absolute error of 0.00014, see (Bowling et al., 2009) for details),

$$\text{Phi_approx}(x) = \text{logit}^{-1}(0.07056 x^3 + 1.5976 x)$$

for any argument type T; see Section 3.1 for details including return type R.

Other Probability-Related Functions

real **binary_log_loss**(int y , real y_hat)

Returns the log loss function for predicting $\hat{y} \in [0, 1]$ for boolean outcome $y \in \{0, 1\}$.

$$\text{binary_log_loss}(y, \hat{y}) = \begin{cases} -\log \hat{y} & \text{if } y = 0 \\ -\log(1 - \hat{y}) & \text{otherwise} \end{cases}$$

real owens_t(real h, real a)

Returns the Owen's T function for the probability of the event $X > h$ and $0 < Y < aX$ where X and Y are independent standard normal random variables.

$$\text{owens_t}(h, a) = \frac{1}{2\pi} \int_0^a \frac{\exp(-\frac{1}{2}h^2(1+x^2))}{1+x^2} dx$$

3.13. Combinatorial Functions

real inc_beta(real alpha, real beta, real x)

Returns the incomplete beta function up to x applied to $alpha$ and $beta$. See Section A.2 for a definition.

real lbeta(real alpha, real beta)

Returns the natural logarithm of the beta function applied to $alpha$ and $beta$. The beta function, $B(\alpha, \beta)$, computes the normalizing constant for the beta distribution, and is defined for $\alpha > 0$ and $\beta > 0$.

$$\text{lbeta}(\alpha, \beta) = \log \Gamma(a) + \log \Gamma(b) - \log \Gamma(a + b)$$

See Section A.1 for definition of $B(\alpha, \beta)$.

R tgamma(T x)

Returns the (elementwise) gamma function applied to x . The gamma function is the generalization of the factorial function to continuous variables, defined so that $\Gamma(n + 1) = n!$. See Section A.3 for a full definition of $\Gamma(x)$. The function is defined for positive numbers and non-integral negative numbers,,

$$\text{tgamma}(x) = \begin{cases} \Gamma(x) & \text{if } x \notin \{\dots, -3, -2, -1, 0\} \\ \text{error} & \text{otherwise} \end{cases}$$

See Section A.3 for a definition of $\Gamma(x)$. for any argument type T; see Section 3.1 for details including return type R.

R lgamma(T x)

Returns the (elementwise) natural logarithm of the gamma function applied to x ,

$$\text{lgamma}(x) = \begin{cases} \log \Gamma(x) & \text{if } x \notin \{\dots, -3, -2, -1, 0\} \\ \text{error} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **digamma**(T x)

Returns the (elementwise) digamma function applied to x . The digamma function is the derivative of the natural logarithm of the Gamma function. The function is defined for positive numbers and non-integral negative numbers,

$$\text{digamma}(x) = \begin{cases} \frac{\Gamma'(x)}{\Gamma(x)} & \text{if } x \notin \{\dots, -3, -2, -1, 0\} \\ \text{error} & \text{otherwise} \end{cases}$$

See Section [A.3](#) for definition of $\Gamma(x)$. for any argument type T; see Section [3.1](#) for details including return type R.

R **trigamma**(T x)

Returns the (elementwise) trigamma function applied to x . The trigamma function is the second derivative of the natural logarithm of the Gamma function,

$$\text{trigamma}(x) = \begin{cases} \sum_{n=0}^{\infty} \frac{1}{(x+n)^2} & \text{if } x \notin \{\dots, -3, -2, -1, 0\} \\ \text{error} & \text{otherwise} \end{cases}$$

for any argument type T; see Section [3.1](#) for details including return type R.

real **lmgamma**(int n , real x)

Returns the natural logarithm of the multivariate gamma function Γ_n with n dimensions applied to x .

$$\text{lmgamma}(n, x) = \begin{cases} \frac{n(n-1)}{4} \log \pi + \sum_{j=1}^n \log \Gamma\left(x + \frac{1-j}{2}\right) & \text{if } x \notin \{\dots, -3, -2, -1, 0\} \\ \text{error} & \text{otherwise} \end{cases}$$

real **gamma_p**(real a , real z)

Returns the normalized lower incomplete gamma function of a and z defined for positive a and nonnegative z .

$$\text{gamma_p}(a, z) = \begin{cases} \frac{1}{\Gamma(a)} \int_0^z t^{a-1} e^{-t} dt & \text{if } a > 0, z \geq 0 \\ \text{error} & \text{otherwise} \end{cases}$$

real **gamma_q**(real a , real z)

Returns the normalized upper incomplete gamma function of a and z defined for positive a and nonnegative z .

$$\text{gamma_q}(a, z) = \begin{cases} \frac{1}{\Gamma(a)} \int_z^\infty t^{a-1} e^{-t} dt & \text{if } a > 0, z \geq 0 \\ \text{error} & \text{otherwise} \end{cases}$$

real binomial_coefficient_log(real x, real y)

Warning: This function is deprecated and should be replaced with `lchoose`.

Returns the natural logarithm of the binomial coefficient of x and y . For non-negative integer inputs, the binomial coefficient function is written as $\binom{x}{y}$ and pronounced “ x choose y .” This function generalizes to real numbers using the gamma function.

For $0 \leq y \leq x$,

$$\text{binomial_coefficient_log}(x, y) = \log \Gamma(x+1) - \log \Gamma(y+1) - \log \Gamma(x-y+1).$$

int choose(int x, int y)

Returns the binomial coefficient of x and y . For non-negative integer inputs, the binomial coefficient function is written as $\binom{x}{y}$ and pronounced “ x choose y .” In its the antilog of the `lchoose` function but returns an integer rather than a real number with no non-zero decimal places.

For $0 \leq y \leq x$, the binomial coefficient function can be defined via the factorial function

$$\text{choose}(x, y) = \frac{x!}{(y!) (x-y)!}.$$

real bessel_first_kind(int v, real x)

Returns the Bessel function of the first kind with order v applied to x .

$$\text{bessel_first_kind}(v, x) = J_v(x),$$

where

$$J_v(x) = \left(\frac{1}{2}x\right)^v \sum_{k=0}^{\infty} \frac{\left(-\frac{1}{4}x^2\right)^k}{k! \Gamma(v+k+1)}$$

real **bessel_second_kind**(int ν , real x)

Returns the Bessel function of the second kind with order ν applied to x defined for positive x and ν .

For $x, \nu > 0$,

$$\text{bessel_second_kind}(\nu, x) = \begin{cases} Y_\nu(x) & \text{if } x > 0 \\ \text{error} & \text{otherwise} \end{cases}$$

where

$$Y_\nu(x) = \frac{J_\nu(x) \cos(\nu\pi) - J_{-\nu}(x)}{\sin(\nu\pi)}$$

real **modified_bessel_first_kind**(int ν , real z)

Returns the modified Bessel function of the first kind with order ν applied to z defined for all z and ν .

$$\text{modified_bessel_first_kind}(\nu, z) = I_\nu(z)$$

where

$$I_\nu(z) = \left(\frac{1}{2}z\right)^\nu \sum_{k=0}^{\infty} \frac{\left(\frac{1}{4}z^2\right)^k}{k!\Gamma(\nu + k + 1)}$$

real **modified_bessel_second_kind**(int ν , real z)

Returns the modified Bessel function of the second kind with order ν applied to z defined for positive z and ν .

$$\text{modified_bessel_second_kind}(\nu, z) = \begin{cases} K_\nu(z) & \text{if } z > 0 \\ \text{error} & \text{if } z \leq 0 \end{cases}$$

where

$$K_\nu(z) = \frac{\pi}{2} \cdot \frac{I_{-\nu}(z) - I_\nu(z)}{\sin(\nu\pi)}$$

real **falling_factorial**(real x , real n)

Returns the falling factorial of x with power n defined for positive x and real n .

$$\text{falling_factorial}(x, n) = \begin{cases} (x)_n & \text{if } x > 0 \\ \text{error} & \text{if } x \leq 0 \end{cases}$$

where

$$(x)_n = \frac{\Gamma(x+1)}{\Gamma(x-n+1)}$$

real lchoose(real x, real y)

Returns the natural logarithm of the generalized binomial coefficient of x and y . For non-negative integer inputs, the binomial coefficient function is written as $\binom{x}{y}$ and pronounced “ x choose y .” This function generalizes to real numbers using the gamma function.

For $0 \leq y \leq x$,

$$\text{binomial_coefficient_log}(x, y) = \log \Gamma(x+1) - \log \Gamma(y+1) - \log \Gamma(x-y+1).$$

real log_falling_factorial(real x, real n)

Returns the log of the falling factorial of x with power n defined for positive x and real n .

$$\text{log_falling_factorial}(x, n) = \begin{cases} \log(x)_n & \text{if } x > 0 \\ \text{error} & \text{if } x \leq 0 \end{cases}$$

real rising_factorial(real x, real n)

Returns the rising factorial of x with power n defined for positive x and real n .

$$\text{rising_factorial}(x, n) = \begin{cases} x^{(n)} & \text{if } x > 0 \\ \text{error} & \text{if } x \leq 0 \end{cases}$$

where

$$x^{(n)} = \frac{\Gamma(x+n)}{\Gamma(x)}$$

real log_rising_factorial(real x, real n)

Returns the log of the rising factorial of x with power n defined for positive x and real n .

$$\text{log_rising_factorial}(x, n) = \begin{cases} \log x^{(n)} & \text{if } x > 0 \\ \text{error} & \text{if } x \leq 0 \end{cases}$$

3.14. Composed Functions

The functions in this section are equivalent in theory to combinations of other functions. In practice, they are implemented to be more efficient and more numerically stable than defining them directly using more basic Stan functions.

R **expm1**(T x)

Returns the (elementwise) natural exponential of x minus 1,

$$\text{expm1}(x) = e^x - 1$$

for any argument type T; see Section 3.1 for details including return type R.

real **fma**(real x, real y, real z)

Returns z plus the result of x multiplied by y .

$$\text{fma}(x, y, z) = (x \times y) + z$$

real **multiply_log**(real x, real y)

Warning: This function is deprecated and should be replaced with `lmultiply`.

Returns the product of x and the natural logarithm of y .

$$\text{multiply_log}(x, y) = \begin{cases} 0 & \text{if } x = y = 0 \\ x \log y & \text{if } x, y \neq 0 \\ \text{NaN} & \text{otherwise} \end{cases}$$

real **lmultiply**(real x, real y)

Returns the product of x and the natural logarithm of y .

$$\text{lmultiply}(x, y) = \begin{cases} 0 & \text{if } x = y = 0 \\ x \log y & \text{if } x, y \neq 0 \\ \text{NaN} & \text{otherwise} \end{cases}$$

R **log1p**(T x)

Returns the (elementwise) natural logarithm of 1 plus x ,

$$\text{log1p}(x) = \begin{cases} \log(1 + x) & \text{if } x \geq -1 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **log1m**(T x)

Returns the (elementwise) natural logarithm of 1 minus x ,

$$\text{log1m}(x) = \begin{cases} \log(1 - x) & \text{if } x \leq 1 \\ \text{NaN} & \text{otherwise} \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

R **log1p_exp**(T x)

Returns the (elementwise) natural logarithm of one plus the natural exponentiation of x ,

$$\text{log1p_exp}(x) = \log(1 + \exp(x))$$

for any argument type T; see Section 3.1 for details including return type R.

R **log1m_exp**(T x)

Returns the (elementwise) logarithm of one minus the natural exponentiation of x ,

$$\text{log1m_exp}(x) = \begin{cases} \log(1 - \exp(x)) & \text{if } x < 0 \\ \text{NaN} & \text{if } x \geq 0 \end{cases}$$

for any argument type T; see Section 3.1 for details including return type R.

real **log_diff_exp**(real x, real y)

Returns the natural logarithm of the difference of the natural exponentiation of x and the natural exponentiation of y .

$$\text{log_diff_exp}(x, y) = \begin{cases} \log(\exp(x) - \exp(y)) & \text{if } x > y \\ \text{NaN} & \text{otherwise} \end{cases}$$

real **log_mix**(real theta, real lp1, real lp2)

Returns the log mixture of the log densities $lp1$ and $lp2$ with mixing proportion $theta$, defined by

$$\begin{aligned} \text{log_mix}(\theta, \lambda_1, \lambda_2) &= \log(\theta \exp(\lambda_1) + (1 - \theta) \exp(\lambda_2)) \\ &= \text{log_sum_exp}(\log(\theta) + \lambda_1, \log(1 - \theta) + \lambda_2). \end{aligned}$$

real **log_sum_exp**(real x, real y)

Returns the natural logarithm of the sum of the natural exponentiation of x and the natural exponentiation of y .

$$\text{log_sum_exp}(x, y) = \log(\exp(x) + \exp(y))$$

R `log_inv_logit`(T x)

Returns the (elementwise) natural logarithm of the inverse logit function of x ,

$$\text{log_inv_logit}(x) = \log \text{logit}^{-1}(x)$$

See Section 3.11 for a definition of inverse logit. for any argument type T; see Section 3.1 for details including return type R.

R `log1m_inv_logit`(T x)

Returns the (elementwise) natural logarithm of 1 minus the inverse logit function of x ,

$$\text{log1m_inv_logit}(x) = \log(1 - \text{logit}^{-1}(x))$$

See Section 3.11 for a definition of inverse logit. for any argument type T; see Section 3.1 for details including return type R.

4. Array Operations

4.1. Reductions

The following operations take arrays as input and produce single output values. The boundary values for size 0 arrays are the unit with respect to the combination operation (min, max, sum, or product).

Minimum and Maximum

`real min(real[] x)`

The minimum value in x , or $+\infty$ if x is size 0.

`int min(int[] x)`

The minimum value in x , or error if x is size 0.

`real max(real[] x)`

The maximum value in x , or $-\infty$ if x is size 0.

`int max(int[] x)`

The maximum value in x , or error if x is size 0.

Sum, Product, and Log Sum of Exp

`int sum(int[] x)`

The sum of the elements in x , defined for x of size N by

$$\text{sum}(x) = \begin{cases} \sum_{n=1}^N x_n & \text{if } N > 0 \\ 0 & \text{if } N = 0 \end{cases}$$

`real sum(real[] x)`

The sum of the elements in x ; see definition above.

`real prod(real[] x)`

The product of the elements in x , or 1 if x is size 0.

`real prod(int[] x)`

The product of the elements in x ,

$$\text{product}(x) = \begin{cases} \prod_{n=1}^N x_n & \text{if } N > 0 \\ 1 & \text{if } N = 0 \end{cases}$$

`real log_sum_exp(real[] x)`

The natural logarithm of the sum of the exponentials of the elements in x , or $-\infty$ if the array is empty.

Sample Mean, Variance, and Standard Deviation

The sample mean, variance, and standard deviation are calculated in the usual way. For i.i.d. draws from a distribution of finite mean, the sample mean is an unbiased estimate of the mean of the distribution. Similarly, for i.i.d. draws from a distribution of finite variance, the sample variance is an unbiased estimate of the variance.¹ The sample deviation is defined as the square root of the sample deviation, but is not unbiased.

`real mean(real[] x)`

The sample mean of the elements in x . For an array x of size $N > 0$,

$$\text{mean}(x) = \bar{x} = \frac{1}{N} \sum_{n=1}^N x_n.$$

It is an error to call the mean function with an array of size 0.

`real variance(real[] x)`

The sample variance of the elements in x . For $N > 0$,

$$\text{variance}(x) = \begin{cases} \frac{1}{N-1} \sum_{n=1}^N (x_n - \bar{x})^2 & \text{if } N > 1 \\ 0 & \text{if } N = 1 \end{cases}$$

It is an error to call the variance function with an array of size 0.

`real sd(real[] x)`

The sample standard deviation of elements in x .

$$\text{sd}(x) = \begin{cases} \sqrt{\text{variance}(x)} & \text{if } N > 1 \\ 0 & \text{if } N = 0 \end{cases}$$

It is an error to call the sd function with an array of size 0.

¹Dividing by N rather than $(N - 1)$ produces a maximum likelihood estimate of variance, which is biased to underestimate variance.

Euclidean Distance and Squared Distance

real **distance**(vector *x*, vector *y*)

The Euclidean distance between *x* and *y*, defined by

$$\text{distance}(x, y) = \sqrt{\sum_{n=1}^N (x_n - y_n)^2}$$

where *N* is the size of *x* and *y*. It is an error to call **distance** with arguments of unequal size.

real **distance**(vector *x*, row_vector *y*)

The Euclidean distance between *x* and *y*

real **distance**(row_vector *x*, vector *y*)

The Euclidean distance between *x* and *y*

real **distance**(row_vector *x*, row_vector *y*)

The Euclidean distance between *x* and *y*

real **squared_distance**(vector *x*, vector *y*)

The squared Euclidean distance between *x* and *y*, defined by

$$\text{squared_distance}(x, y) = \text{distance}(x, y)^2 = \sum_{n=1}^N (x_n - y_n)^2,$$

where *N* is the size of *x* and *y*. It is an error to call **squared_distance** with arguments of unequal size.

real **squared_distance**(vector *x*, row_vector [] *y*)

The squared Euclidean distance between *x* and *y*

real **squared_distance**(row_vector *x*, vector [] *y*)

The squared Euclidean distance between *x* and *y*

real **squared_distance**(row_vector *x*, row_vector [] *y*)

The Euclidean distance between *x* and *y*

4.2. Array Size and Dimension Function

The size of an array or matrix can be obtained using the **dims()** function. The **dims()** function is defined to take an argument consisting of any variable with up to 8 array dimensions (and up to 2 additional matrix dimensions) and returns an array of integers with the dimensions. For example, if two variables are declared as follows,


```
real x[7,8,9];
matrix[8,9] y[7];
```

then calling `dims(x)` or `dims(y)` returns an integer array of size 3 containing the elements 7, 8, and 9 in that order.

The `size()` function extracts the number of elements in an array. This is just the top-level elements, so if the array is declared as

```
real a[M,N];
```

the size of `a` is `M`.

The function `num_elements`, on the other hand, measures all of the elements, so that the array `a` above has $M \times N$ elements.

The specialized functions `rows()` and `cols()` should be used to extract the dimensions of vectors and matrices.

```
int[] dims(T x)
```

Returns an integer array containing the dimensions of `x`; the type of the argument `T` can be any Stan type with up to 8 array dimensions.

```
int num_elements(T[] x)
```

Returns the total number of elements in the array `x` including all elements in contained arrays, vectors, and matrices. `T` can be any array type. For example, if `x` is of type `real[4,3]` then `num_elements(x)` is 12, and if `y` is declared as `matrix[3,4] y[5]`, then `size(y)` evaluates to 60.

```
int size(T[] x)
```

Returns the number of elements in the array `x`; the type of the array `T` can be any type, but the size is just the size of the top level array, not the total number of elements contained. For example, if `x` is of type `real[4,3]` then `size(x)` is 4.

4.3. Array Broadcasting

The following operations create arrays by repeating elements to fill an array of a specified size. These operations work for all input types `T`, including reals, integers, vectors, row vectors, matrices, or arrays.

```
T[] rep_array(T x, int n)
```

Return the `n` array with every entry assigned to `x`.

```
T[, ] rep_array(T x, int m, int n)
```

Return the `m` by `n` array with every entry assigned to `x`.

$T[, ,]$ **rep_array**(T x , int k , int m , int n)

Return the k by m by n array with every entry assigned to x .

For example, `rep_array(1.0,5)` produces a real array (type `real[]`) of size 5 with all values set to 1.0. On the other hand, `rep_array(1,5)` produces an integer array (type `int[]`) of size 5 with all values set to 1. This distinction is important because it is not possible to assign an integer array to a real array. For example, the following example contrasts legal with illegal array creation and assignment

```
real y[5];
int x[5];

x = rep_array(1,5);    // ok
y = rep_array(1.0,5);  // ok

x = rep_array(1.0,5);  // illegal
y = rep_array(1,5);    // illegal

x = y;                 // illegal
y = x;                 // illegal
```

If the value being repeated v is a vector (i.e., T is vector), then `rep_array(v,27)` is a size 27 array consisting of 27 copies of the vector v .

```
vector[5] v;
vector[5] a[3];
// ...
a = rep_array(v,3); // fill a with copies of v
a[2,4] = 9.0;       // v[4], a[1,4], a[2,4] unchanged
```

If the type T of x is itself an array type, then the result will be an array with one, two, or three added dimensions, depending on which of the `rep_array` functions is called. For instance, consider the following legal code snippet.

```
real a[5,6];
real b[3,4,5,6];
// ...
b = rep_array(a,3,4); // make (3 x 4) copies of a
b[1,1,1,1] = 27.9;    // a[1,1] unchanged
```

After the assignment to b , the value for $b[j,k,m,n]$ is equal to $a[m,n]$ where it is defined, for j in 1:3, k in 1:4, m in 1:5, and n in 1:6.

4.4. Array Concatenation

T `append_array(T x, T y)`

Return the concatenation of two arrays in the order of the arguments. T must be an N-dimensional array of any Stan type (with a maximum N of 7). All dimensions but the first must match.

For example, the following code appends two three dimensional arrays of matrices together. Note that all dimensions except the first match. Any mismatches will cause an error to be thrown.

```
matrix[4, 6] x1[2, 1, 7];
matrix[4, 6] x2[3, 1, 7];
matrix[4, 6] x3[5, 1, 7];
// ...
x3 = append_array(x1, x2);
```

4.5. Sorting functions

Sorting can be used to sort values or the indices of those values in either ascending or descending order. For example, if `v` is declared as a real array of size 3, with values

$$v = (1, -10.3, 20.987),$$

then the various sort routines produce

$$\begin{aligned}\text{sort_asc}(v) &= (-10.3, 1, 20.987) \\ \text{sort_desc}(v) &= (20.987, 1, -10.3) \\ \text{sort_indices_asc}(v) &= (2, 1, 3) \\ \text{sort_indices_desc}(v) &= (3, 1, 2)\end{aligned}$$

`real[] sort_asc(real[] v)`

Sort the elements of `v` in ascending order

`int[] sort_asc(int[] v)`

Sort the elements of `v` in ascending order

`real[] sort_desc(real[] v)`

Sort the elements of `v` in descending order

`int[] sort_desc(int[] v)`

Sort the elements of `v` in descending order

int[] sort_indices_asc(real[] v)

Return an array of indices between 1 and the size of v , sorted to index v in ascending order.

int[] sort_indices_asc(int[] v)

Return an array of indices between 1 and the size of v , sorted to index v in ascending order.

int[] sort_indices_desc(real[] v)

Return an array of indices between 1 and the size of v , sorted to index v in descending order.

int[] sort_indices_desc(int[] v)

Return an array of indices between 1 and the size of v , sorted to index v in descending order.

int rank(real[] v, int s)

Number of components of v less than $v[s]$

int rank(int[] v, int s)

Number of components of v less than $v[s]$

5. Matrix Operations

5.1. Integer-Valued Matrix Size Functions

int num_elements(vector x)

The total number of elements in the vector x (same as function `rows`)

int num_elements(row_vector x)

The total number of elements in the vector x (same as function `cols`)

int num_elements(matrix x)

The total number of elements in the matrix x . For example, if x is a 5×3 matrix, then `num_elements(x)` is 15

int rows(vector x)

The number of rows in the vector x

int rows(row_vector x)

The number of rows in the row vector x , namely 1

int rows(matrix x)

The number of rows in the matrix x

int cols(vector x)

The number of columns in the vector x , namely 1

int cols(row_vector x)

The number of columns in the row vector x

int cols(matrix x)

The number of columns in the matrix x

5.2. Matrix Arithmetic Operators

Stan supports the basic matrix operations using infix, prefix and postfix operations. This section lists the operations supported by Stan along with their argument and result types.

Negation Prefix Operators

`vector operator-(vector x)`

The negation of the vector x .

`row_vector operator-(row_vector x)`

The negation of the row vector x .

`matrix operator-(matrix x)`

The negation of the matrix x .

Infix Matrix Operators

`vector operator+(vector x, vector y)`

The sum of the vectors x and y .

`row_vector operator+(row_vector x, row_vector y)`

The sum of the row vectors x and y .

`matrix operator+(matrix x, matrix y)`

The sum of the matrices x and y

`vector operator-(vector x, vector y)`

The difference between the vectors x and y .

`row_vector operator-(row_vector x, row_vector y)`

The difference between the row vectors x and y

`matrix operator-(matrix x, matrix y)`

The difference between the matrices x and y

`vector operator*(real x, vector y)`

The product of the scalar x and vector y

`row_vector operator*(real x, row_vector y)`

The product of the scalar x and the row vector y

`matrix operator*(real x, matrix y)`

The product of the scalar x and the matrix y

`vector operator*(vector x, real y)`

The product of the scalar y and vector x

`matrix operator*(vector x, row_vector y)`

The product of the vector x and row vector y

`row_vector operator*(row_vector x, real y)`

The product of the scalar y and row vector x

`real operator*(row_vector x, vector y)`

The product of the row vector x and vector y

`row_vector operator*(row_vector x, matrix y)`

The product of the row vector x and matrix y

`matrix operator*(matrix x, real y)`

The product of the scalar y and matrix x

`vector operator*(matrix x, vector y)`

The product of the matrix x and vector y

`matrix operator*(matrix x, matrix y)`

The product of the matrices x and y

Broadcast Infix Operators

`vector operator+(vector x, real y)`

The result of adding y to every entry in the vector x

`vector operator+(real x, vector y)`

The result of adding x to every entry in the vector y

`row_vector operator+(row_vector x, real y)`

The result of adding y to every entry in the row vector x

`row_vector operator+(real x, row_vector y)`

The result of adding x to every entry in the row vector y

`matrix operator+(matrix x, real y)`

The result of adding y to every entry in the matrix x

`matrix operator+(real x, matrix y)`

The result of adding x to every entry in the matrix y

`vector operator-(vector x, real y)`

The result of subtracting y from every entry in the vector x

vector operator-(real x , vector y)

The result of adding x to every entry in the negation of the vector y

row_vector operator-(row_vector x , real y)

The result of subtracting y from every entry in the row vector x

row_vector operator-(real x , row_vector y)

The result of adding x to every entry in the negation of the row vector y

matrix operator-(matrix x , real y)

The result of subtracting y from every entry in the matrix x

matrix operator-(real x , matrix y)

The result of adding x to every entry in negation of the matrix y

vector operator/(vector x , real y)

The result of dividing each entry in the vector x by y

row_vector operator/(row_vector x , real y)

The result of dividing each entry in the row vector x by y

matrix operator/(matrix x , real y)

The result of dividing each entry in the matrix x by y

Elementwise Arithmetic Operations

vector operator.*(vector x , vector y)

The elementwise product of y and x

row_vector operator.*(row_vector x , row_vector y)

The elementwise product of y and x

matrix operator.*(matrix x , matrix y)

The elementwise product of y and x

vector operator./(vector x , vector y)

The elementwise quotient of y and x

vector operator./(vector x , real y)

The elementwise quotient of y and x

`vector operator./(real x, vector y)`

The elementwise quotient of y and x

`row_vector operator./(row_vector x, row_vector y)`

The elementwise quotient of y and x

`row_vector operator./(row_vector x, real y)`

The elementwise quotient of y and x

`row_vector operator./(real x, row_vector y)`

The elementwise quotient of y and x

`matrix operator./(matrix x, matrix y)`

The elementwise quotient of y and x

`matrix operator./(matrix x, real y)`

The elementwise quotient of y and x

`matrix operator./(real x, matrix y)`

The elementwise quotient of y and x

5.3. Transposition Operator

Matrix transposition is represented using a postfix operator.

`matrix operator'(matrix x)`

The transpose of the matrix x , written as x'

`row_vector operator'(vector x)`

The transpose of the vector x , written as x'

`vector operator'(row_vector x)`

The transpose of the row vector x , written as x'

5.4. Elementwise Functions

Elementwise functions apply a function to each element of a vector or matrix, returning a result of the same shape as the argument. There are many functions that are vectorized in addition to the ad hoc cases listed in this section; see Section 3.1 for the general cases.

5.5. Dot Products and Specialized Products

real **dot_product**(vector *x*, vector *y*)

The dot product of *x* and *y*

real **dot_product**(vector *x*, row_vector *y*)

The dot product of *x* and *y*

real **dot_product**(row_vector *x*, vector *y*)

The dot product of *x* and *y*

real **dot_product**(row_vector *x*, row_vector *y*)

The dot product of *x* and *y*

row_vector **columns_dot_product**(vector *x*, vector *y*)

The dot product of the columns of *x* and *y*

row_vector **columns_dot_product**(row_vector *x*, row_vector *y*)

The dot product of the columns of *x* and *y*

row_vector **columns_dot_product**(matrix *x*, matrix *y*)

The dot product of the columns of *x* and *y*

vector **rows_dot_product**(vector *x*, vector *y*)

The dot product of the rows of *x* and *y*

vector **rows_dot_product**(row_vector *x*, row_vector *y*)

The dot product of the rows of *x* and *y*

vector **rows_dot_product**(matrix *x*, matrix *y*)

The dot product of the rows of *x* and *y*

real **dot_self**(vector *x*)

The dot product of the vector *x* with itself

real **dot_self**(row_vector *x*)

The dot product of the row vector *x* with itself

row_vector **columns_dot_self**(vector *x*)

The dot product of the columns of *x* with themselves

row_vector **columns_dot_self**(row_vector *x*)

The dot product of the columns of *x* with themselves

`row_vector columns_dot_self(matrix x)`

The dot product of the columns of x with themselves

`vector rows_dot_self(vector x)`

The dot product of the rows of x with themselves

`vector rows_dot_self(row_vector x)`

The dot product of the rows of x with themselves

`vector rows_dot_self(matrix x)`

The dot product of the rows of x with themselves

Specialized Products

`matrix tcrossprod(matrix x)`

The product of x postmultiplied by its own transpose, similar to the `tcrossprod(x)` function in R. The result is a symmetric matrix $x x^T$.

`matrix crossprod(matrix x)`

The product of x premultiplied by its own transpose, similar to the `crossprod(x)` function in R. The result is a symmetric matrix $x^T x$.

The following functions all provide shorthand forms for common expressions, which are also much more efficient.

`matrix quad_form(matrix A, matrix B)`

The quadratic form, i.e., $B' * A * B$.

`real quad_form(matrix A, vector B)`

The quadratic form, i.e., $B' * A * B$.

`matrix quad_form_diag(matrix m, vector v)`

The quadratic form using the column vector v as a diagonal matrix, i.e., `diag_matrix(v) * m * diag_matrix(v)`.

`matrix quad_form_diag(matrix m, row_vector rv)`

The quadratic form using the row vector rv as a diagonal matrix, i.e., `diag_matrix(rv) * m * diag_matrix(rv)`.

`matrix quad_form_sym(matrix A, matrix B)`

Similarly to `quad_form`, gives $B' * A * B$, but additionally checks if A is symmetric and ensures that the result is also symmetric.

real quad_form_sym(matrix *A*, vector *B*)

Similarly to **quad_form**, gives $B' * A * B$, but additionally checks if *A* is symmetric and ensures that the result is also symmetric.

real trace_quad_form(matrix *A*, matrix *B*)

The trace of the quadratic form, i.e., $\text{trace}(B' * A * B)$.

real trace_gen_quad_form(matrix *D*, matrix *A*, matrix *B*)

The trace of a generalized quadratic form, i.e., $\text{trace}(D * B' * A * B)$.

matrix multiply_lower_tri_self_transpose(matrix *x*)

The product of the lower triangular portion of *x* (including the diagonal) times its own transpose; that is, if *L* is a matrix of the same dimensions as *x* with $L(m,n)$ equal to $x(m,n)$ for $n \leq m$ and $L(m,n)$ equal to 0 if $n > m$, the result is the symmetric matrix LL^T . This is a specialization of **tcrossprod**(*x*) for lower-triangular matrices. The input matrix does not need to be square.

matrix diag_pre_multiply(vector *v*, matrix *m*)

Return the product of the diagonal matrix formed from the vector *v* and the matrix *m*, i.e., $\text{diag_matrix}(v) * m$.

matrix diag_pre_multiply(row_vector *rv*, matrix *m*)

Return the product of the diagonal matrix formed from the vector *rv* and the matrix *m*, i.e., $\text{diag_matrix}(rv) * m$.

matrix diag_post_multiply(matrix *m*, vector *v*)

Return the product of the matrix *m* and the diagonal matrix formed from the vector *v*, i.e., $m * \text{diag_matrix}(v)$.

matrix diag_post_multiply(matrix *m*, row_vector *rv*)

Return the product of the matrix *m* and the diagonal matrix formed from the row vector *rv*, i.e., $m * \text{diag_matrix}(rv)$.

5.6. Reductions

Log Sum of Exponents

real log_sum_exp(vector *x*)

The natural logarithm of the sum of the exponentials of the elements in *x*

real log_sum_exp(row_vector *x*)

The natural logarithm of the sum of the exponentials of the elements in *x*

real log_sum_exp(matrix x)

The natural logarithm of the sum of the exponentials of the elements in x

Minimum and Maximum

real min(vector x)

The minimum value in x , or $+\infty$ if x is empty

real min(row_vector x)

The minimum value in x , or $+\infty$ if x is empty

real min(matrix x)

The minimum value in x , or $+\infty$ if x is empty

real max(vector x)

The maximum value in x , or $-\infty$ if x is empty

real max(row_vector x)

The maximum value in x , or $-\infty$ if x is empty

real max(matrix x)

The maximum value in x , or $-\infty$ if x is empty

Sums and Products

real sum(vector x)

The sum of the values in x , or 0 if x is empty

real sum(row_vector x)

The sum of the values in x , or 0 if x is empty

real sum(matrix x)

The sum of the values in x , or 0 if x is empty

real prod(vector x)

The product of the values in x , or 1 if x is empty

real prod(row_vector x)

The product of the values in x , or 1 if x is empty

real prod(matrix x)

The product of the values in x , or 1 if x is empty

Sample Moments

Full definitions are provided for sample moments in Section 4.1.

`real mean(vector x)`

The sample mean of the values in x ; see Section 4.1 for details.

`real mean(row_vector x)`

The sample mean of the values in x ; see Section 4.1 for details.

`real mean(matrix x)`

The sample mean of the values in x ; see Section 4.1 for details.

`real variance(vector x)`

The sample variance of the values in x ; see Section 4.1 for details.

`real variance(row_vector x)`

The sample variance of the values in x ; see Section 4.1 for details.

`real variance(matrix x)`

The sample variance of the values in x ; see Section 4.1 for details.

`real sd(vector x)`

The sample standard deviation of the values in x ; see Section 4.1 for details.

`real sd(row_vector x)`

The sample standard deviation of the values in x ; see Section 4.1 for details.

`real sd(matrix x)`

The sample standard deviation of the values in x ; see Section 4.1 for details.

5.7. Broadcast Functions

The following broadcast functions allow vectors, row vectors and matrices to be created by copying a single element into all of their cells. Matrices may also be created by stacking copies of row vectors vertically or stacking copies of column vectors horizontally.

`vector rep_vector(real x, int m)`

Return the size m (column) vector consisting of copies of x .

`row_vector rep_row_vector(real x, int n)`

Return the size n row vector consisting of copies of x .

`matrix rep_matrix(real x, int m, int n)`

Return the m by n matrix consisting of copies of x .

`matrix rep_matrix(vector v, int n)`

Return the m by n matrix consisting of n copies of the (column) vector v of size m .

`matrix rep_matrix(row_vector rv, int m)`

Return the m by n matrix consisting of m copies of the row vector rv of size n .

Unlike the situation with array broadcasting (see Section 4.3), where there is a distinction between integer and real arguments, the following two statements produce the same result for vector broadcasting; row vector and matrix broadcasting behave similarly.

```
vector[3] x;  
x = rep_vector(1, 3);  
x = rep_vector(1.0, 3);
```

There are no integer vector or matrix types, so integer values are automatically promoted.

5.8. Diagonal Matrix Functions

`vector diagonal(matrix x)`

The diagonal of the matrix x

`matrix diag_matrix(vector x)`

The diagonal matrix with diagonal x

Although the `diag_matrix` function is available, it is unlikely to ever show up in an efficient Stan program. For example, rather than converting a diagonal to a full matrix for use as a covariance matrix,

```
y ~ multi_normal(mu, diag_matrix(square(sigma)));
```

it is much more efficient to just use a univariate normal, which produces the same density,

```
y ~ normal(mu, sigma);
```

Rather than writing `m * diag_matrix(v)` where `m` is a matrix and `v` is a vector, it is much more efficient to write `diag_post_multiply(m, v)` (and similarly for pre-multiplication). By the same token, it is better to use `quad_form_diag(m, v)` rather than `quad_form(m, diag_matrix(v))`.

5.9. Slicing and Blocking Functions

Stan provides several functions for generating slices or blocks or diagonal entries for matrices.

Columns and Rows

vector **col**(matrix `x`, int `n`)

The n -th column of matrix `x`

row_vector **row**(matrix `x`, int `m`)

The m -th row of matrix `x`

The `row` function is special in that it may be used as an lvalue in an assignment statement (i.e., something to which a value may be assigned). The `row` function is also special in that the indexing notation `x[m]` is just an alternative way of writing `row(x,m)`. The `col` function may *not* be used as an lvalue, nor is there an indexing based shorthand for it.

Block Operations

Matrix Slicing Operations

Block operations may be used to extract a sub-block of a matrix.

matrix **block**(matrix `x`, int `i`, int `j`, int `n_rows`, int `n_cols`)

Return the submatrix of `x` that starts at row `i` and column `j` and extends `n_rows` rows and `n_cols` columns.

The sub-row and sub-column operations may be used to extract a slice of row or column from a matrix

vector **sub_col**(matrix `x`, int `i`, int `j`, int `n_rows`)

Return the sub-column of `x` that starts at row `i` and column `j` and extends `n_rows` rows and 1 column.

row_vector **sub_row**(matrix `x`, int `i`, int `j`, int `n_cols`)

Return the sub-row of `x` that starts at row `i` and column `j` and extends 1 row and `n_cols` columns.

Vector and Array Slicing Operations

The head operation extracts the first n elements of a vector and the tail operation the last. The segment operation extracts an arbitrary subvector.

vector head(vector v , int n)

Return the vector consisting of the first n elements of v .

row_vector head(row_vector rv , int n)

Return the row vector consisting of the first n elements of rv .

T[] head(T[] sv , int n)

Return the array consisting of the first n elements of sv ; applies to up to three-dimensional arrays containing any type of elements T.

vector tail(vector v , int n)

Return the vector consisting of the last n elements of v .

row_vector tail(row_vector rv , int n)

Return the row vector consisting of the last n elements of rv .

T[] tail(T[] sv , int n)

Return the array consisting of the last n elements of sv ; applies to up to three-dimensional arrays containing any type of elements T.

vector segment(vector v , int i , int n)

Return the vector consisting of the n elements of v starting at i ; i.e., elements i through through $i + n - 1$.

row_vector segment(row_vector rv , int i , int n)

Return the row vector consisting of the n elements of rv starting at i ; i.e., elements i through through $i + n - 1$.

T[] segment(T[] sv , int i , int n)

Return the array consisting of the n elements of sv starting at i ; i.e., elements i through through $i + n - 1$. Applies to up to three-dimensional arrays containing any type of elements T.

5.10. Matrix Concatenation

Stan's matrix concatenation operations `append_col` and `append_row` are like the operations `cbind` and `rbind` in R.

Horizontal concatenation

matrix **append_col**(**matrix** *x*, **matrix** *y*)

Combine matrices *x* and *y* by columns. The matrices must have the same number of rows.

matrix **append_col**(**matrix** *x*, **vector** *y*)

Combine matrix *x* and vector *y* by columns. The matrix and the vector must have the same number of rows.

matrix **append_col**(**vector** *x*, **matrix** *y*)

Combine vector *x* and matrix *y* by columns. The vector and the matrix must have the same number of rows.

matrix **append_col**(**vector** *x*, **vector** *y*)

Combine vectors *x* and *y* by columns. The vectors must have the same number of rows.

row_vector **append_col**(**row_vector** *x*, **row_vector** *y*)

Combine row vectors *x* and *y* of any size into another row vector.

row_vector **append_col**(**real** *x*, **row_vector** *y*)

Append *x* to the front of *y*, returning another row vector.

row_vector **append_col**(**row_vector** *x*, **real** *y*)

Append *y* to the end of *x*, returning another row vector.

Vertical concatenation

matrix **append_row**(**matrix** *x*, **matrix** *y*)

Combine matrices *x* and *y* by rows. The matrices must have the same number of columns.

matrix **append_row**(**matrix** *x*, **row_vector** *y*)

Combine matrix *x* and row vector *y* by rows. The matrix and the row vector must have the same number of columns.

matrix **append_row**(**row_vector** *x*, **matrix** *y*)

Combine row vector *x* and matrix *y* by rows. The row vector and the matrix must have the same number of columns.

matrix `append_row`(row_vector *x*, row_vector *y*)

Combine row vectors *x* and *y* by row. The row vectors must have the same number of columns.

vector `append_row`(vector *x*, vector *y*)

Concatenate vectors *x* and *y* of any size into another vector.

vector `append_row`(real *x*, vector *y*)

Append *x* to the top of *y*, returning another vector.

vector `append_row`(vector *x*, real *y*)

Append *y* to the bottom of *x*, returning another vector.

5.11. Special Matrix Functions

Softmax

The softmax function¹ maps $y \in \mathbb{R}^K$ to the K -simplex by

$$\text{softmax}(y) = \frac{\exp(y)}{\sum_{k=1}^K \exp(y_k)},$$

where $\exp(y)$ is the componentwise exponentiation of y . Softmax is usually calculated on the log scale,

$$\begin{aligned} \log \text{softmax}(y) &= y - \log \sum_{k=1}^K \exp(y_k) \\ &= y - \log_sum_exp(y). \end{aligned}$$

where the vector y minus the scalar $\log_sum_exp(y)$ subtracts the scalar from each component of y .

Stan provides the following functions for softmax and its log.

vector `softmax`(vector *x*)

The softmax of *x*

vector `log_softmax`(vector *x*)

The natural logarithm of the softmax of *x*

¹The softmax function is so called because in the limit as $y_n \rightarrow \infty$ with y_m for $m \neq n$ held constant, the result tends toward the “one-hot” vector θ with $\theta_n = 1$ and $\theta_m = 0$ for $m \neq n$, thus providing a “soft” version of the maximum function.

Cumulative Sums

The cumulative sum of a sequence x_1, \dots, x_N is the sequence y_1, \dots, y_N , where

$$y_n = \sum_{m=1}^n x_m.$$

`real[] cumulative_sum(real[] x)`

The cumulative sum of x

`vector cumulative_sum(vector v)`

The cumulative sum of v

`row_vector cumulative_sum(row_vector rv)`

The cumulative sum of rv

5.12. Covariance Functions

Exponentiated quadratic covariance function

The exponentiated quadratic kernel defines the covariance between $f(x_i)$ and $f(x_j)$ where $f: \mathbb{R}^D \mapsto \mathbb{R}$ as a function of the squared Euclidian distance between $x_i \in \mathbb{R}^D$ and $x_j \in \mathbb{R}^D$:

$$\text{cov}(f(x_i), f(x_j)) = k(x_i, x_j) = \alpha^2 \exp \left(-\frac{1}{2\rho^2} \sum_{d=1}^D (x_{i,d} - x_{j,d})^2 \right)$$

with α and ρ constrained to be positive.

There are two variants of the exponentiated quadratic covariance function in Stan. One builds a covariance matrix, $K \in \mathbb{R}^{N \times N}$ for x_1, \dots, x_N , where $K_{i,j} = k(x_i, x_j)$, which is necessarily symmetric and positive semidefinite by construction. There is a second variant of the exponentiated quadratic covariance function that builds a $K \in \mathbb{R}^{N \times M}$ covariance matrix for x_1, \dots, x_N and x'_1, \dots, x'_M , where $x_i \in \mathbb{R}^D$ and $x'_i \in \mathbb{R}^D$ and $K_{i,j} = k(x_i, x'_j)$.

`matrix cov_exp_quad(row_vectors x, real alpha, real rho)`

The covariance matrix with an exponentiated quadratic kernel of x .

`matrix cov_exp_quad(vectors x, real alpha, real rho)`

The covariance matrix with an exponentiated quadratic kernel of x .

`matrix cov_exp_quad(real[] x, real alpha, real rho)`

The covariance matrix with an exponentiated quadratic kernel of x .

```
matrix cov_exp_quad(row_vectors x1, row_vectors x2,
                    real alpha, real rho)
```

The covariance matrix with an exponentiated quadratic kernel of $x1$ and $x2$.

```
matrix cov_exp_quad(vectors x1, vectors x2,
                    real alpha, real rho)
```

The covariance matrix with an exponentiated quadratic kernel of $x1$ and $x2$.

```
matrix cov_exp_quad(real[] x1, real[] x2,
                    real alpha, real rho)
```

The covariance matrix with an exponentiated quadratic kernel of $x1$ and $x2$.

5.13. Linear Algebra Functions and Solvers

Matrix Division Operators and Functions

In general, it is much more efficient and also more arithmetically stable to use matrix division than to multiply by an inverse. There are specialized forms for lower triangular matrices and for symmetric, positive-definite matrices.

Matrix division operators

```
row_vector operator/(row_vector b, matrix A)
```

The right division of b by A ; equivalently $b * \text{inverse}(A)$

```
matrix operator/(matrix B, matrix A)
```

The right division of B by A ; equivalently $B * \text{inverse}(A)$

```
vector operator\(matrix A, vector b)
```

The left division of b by A ; equivalently $\text{inverse}(A) * b$

```
matrix operator\(matrix A, matrix B)
```

The left division of B by A ; equivalently $\text{inverse}(A) * B$

Lower-triangular matrix division functions

There are four division functions which use lower triangular views of a matrix. The lower triangular view of a matrix $\text{tri}(A)$ is used in the definitions and defined by

$$\text{tri}(A)[m, n] = \begin{cases} A[m, n] & \text{if } m \geq n, \text{ and} \\ 0 & \text{otherwise.} \end{cases}$$

When a lower triangular view of a matrix is used, the elements above the diagonal are ignored.

vector `mdivide_left_tri_low`(matrix *A*, vector *b*)

The left division of *b* by a lower-triangular view of *A*; algebraically equivalent to the less efficient and stable form `inverse(tri(A)) * b`, where `tri(A)` is the lower-triangular portion of *A* with the above-diagonal entries set to zero.

matrix `mdivide_left_tri_low`(matrix *A*, matrix *B*)

The left division of *B* by a triangular view of *A*; algebraically equivalent to the less efficient and stable form `inverse(tri(A)) * B`, where `tri(A)` is the lower-triangular portion of *A* with the above-diagonal entries set to zero.

row_vector `mdivide_right_tri_low`(row_vector *b*, matrix *A*)

The right division of *b* by a triangular view of *A*; algebraically equivalent to the less efficient and stable form `b * inverse(tri(A))`, where `tri(A)` is the lower-triangular portion of *A* with the above-diagonal entries set to zero.

matrix `mdivide_right_tri_low`(matrix *B*, matrix *A*)

The right division of *B* by a triangular view of *A*; algebraically equivalent to the less efficient and stable form `B * inverse(tri(A))`, where `tri(A)` is the lower-triangular portion of *A* with the above-diagonal entries set to zero.

Symmetric positive-definite matrix division functions

There are four division functions which are specialized for efficiency and stability for symmetric positive-definite matrix dividends. If the matrix dividend argument is not symmetric and positive definite, these will reject and print warnings.

matrix `mdivide_left_spd`(matrix *A*, vector *b*)

The left division of *b* by the symmetric, positive-definite matrix *A*; algebraically equivalent to the less efficient and stable form `inverse(A) * b`.

vector `mdivide_left_spd`(matrix *A*, matrix *B*)

The left division of *B* by the symmetric, positive-definite matrix *A*; algebraically equivalent to the less efficient and stable form `inverse(A) * B`.

row_vector `mdivide_right_spd`(row_vector *b*, matrix *A*)

The right division of *b* by the symmetric, positive-definite matrix *A*; algebraically equivalent to the less efficient and stable form `b * inverse(A)`.

matrix `mdivide_right_spd`(matrix *B*, matrix *A*)

The right division of *B* by the symmetric, positive-definite matrix *A*; algebraically equivalent to the less efficient and stable form `B * inverse(A)`.

Matrix Exponential

The exponential of the matrix A is formally defined by the convergent power series:

$$e^A = \sum_{n=0}^{\infty} \frac{A^n}{n!}$$

matrix **matrix_exp**(matrix A)

The matrix exponential of A

matrix **matrix_exp_multiply**(matrix A , matrix B)

The multiplication of matrix exponential of A and matrix B ; algebraically equivalent to the less efficient form `matrix_exp(A) * B` .

matrix **scale_matrix_exp_multiply**(real t , matrix A , matrix B)

The multiplication of matrix exponential of tA and matrix B ; algebraically equivalent to the less efficient form `matrix_exp(tA) * B` .

Linear Algebra Functions

Trace

real **trace**(matrix A)

The trace of A , or 0 if A is empty; A is not required to be diagonal

Determinants

real **determinant**(matrix A)

The determinant of A

real **log_determinant**(matrix A)

The log of the absolute value of the determinant of A

Inverses

It is almost never a good idea to use matrix inverses directly because they are both inefficient and arithmetically unstable compared to the alternatives. Rather than inverting a matrix m and post-multiplying by a vector or matrix a , as in `inverse(m) * a` , it is better to code this using matrix division, as in `$m \setminus a$` . The pre-multiplication case is similar, with `$b * \text{inverse}(m)$` being more efficiently coded as `b / m` . There are also useful special cases for triangular and symmetric, positive-definite matrices that use more efficient solvers.

Warning: The function `inv(m)` is the elementwise inverse function, which returns $1 / m[i, j]$ for each element.

matrix inverse(matrix A)

The inverse of A

matrix inverse_spd(matrix A)

The inverse of A where A is symmetric, positive definite. This version is faster and more arithmetically stable when the input is symmetric and positive definite.

Eigendecomposition

vector eigenvalues_sym(matrix A)

The vector of eigenvalues of a symmetric matrix A in ascending order

matrix eigenvectors_sym(matrix A)

The matrix with the (column) eigenvectors of symmetric matrix A in the same order as returned by the function `eigenvalues_sym`

Because multiplying an eigenvector by -1 results in an eigenvector, eigenvectors returned by a decomposition are only identified up to a sign change. In order to compare the eigenvectors produced by Stan's eigendecomposition to others, signs may need to be normalized in some way, such as by fixing the sign of a component, or doing comparisons allowing a multiplication by -1 .

The condition number of a symmetric matrix is defined to be the ratio of the largest eigenvalue to the smallest eigenvalue. Large condition numbers lead to difficulty in numerical algorithms such as computing inverses, and thus known as “ill conditioned.” The ratio can even be infinite in the case of singular matrices (i.e., those with eigenvalues of 0).

QR Decomposition

matrix qr_thin_Q(matrix A)

The orthogonal matrix in the thin QR decomposition of A , which implies that the resulting matrix has the same dimensions as A

matrix qr_thin_R(matrix A)

The upper triangular matrix in the thin QR decomposition of A , which implies that the resulting matrix is square with the same number of columns as A

matrix qr_Q(matrix A)

The orthogonal matrix in the fat QR decomposition of A , which implies that the resulting matrix is square with the same number of rows as A

matrix qr_R(matrix A)

The upper trapezoidal matrix in the fat QR decomposition of A , which implies that the resulting matrix will be square with the same number of rows as A

The thin QR decomposition is always preferable because it will consume much less memory when the input matrix is large than will the fat QR decomposition. Both versions of the decomposition represent the input matrix as

$$A = QR.$$

Multiplying a column of an orthogonal matrix by -1 still results in an orthogonal matrix, and you can multiply the corresponding row of the upper trapezoidal matrix by -1 without changing the product. Thus, Stan adopts the normalization that the diagonal elements of the upper trapezoidal matrix are strictly positive and the columns of the orthogonal matrix are reflected if necessary. Also, these QR decomposition algorithms do not utilize pivoting and thus may be numerically unstable on input matrices that have less than full rank.

Cholesky Decomposition

Every symmetric, positive-definite matrix (such as a correlation or covariance matrix) has a Cholesky decomposition. If Σ is a symmetric, positive-definite matrix, its Cholesky decomposition is the lower-triangular vector L such that

$$\Sigma = LL^T.$$

matrix cholesky_decompose(matrix A)

The lower-triangular Cholesky factor of the symmetric positive-definite matrix A

Singular Value Decomposition

Stan only provides functions for the singular values, not for the singular vectors involved in a singular value decomposition (SVD).

vector singular_values(matrix A)

The singular values of A in descending order

5.14. Sort Functions

See Section 4.5 for examples of how the functions work.

vector **sort_asc**(vector v)

Sort the elements of v in ascending order

row_vector **sort_asc**(row_vector v)

Sort the elements of v in ascending order

vector **sort_desc**(vector v)

Sort the elements of v in descending order

row_vector **sort_desc**(row_vector v)

Sort the elements of v in descending order

int[] **sort_indices_asc**(vector v)

Return an array of indices between 1 and the size of v , sorted to index v in ascending order.

int[] **sort_indices_asc**(row_vector v)

Return an array of indices between 1 and the size of v , sorted to index v in ascending order.

int[] **sort_indices_desc**(vector v)

Return an array of indices between 1 and the size of v , sorted to index v in descending order.

int[] **sort_indices_desc**(row_vector v)

Return an array of indices between 1 and the size of v , sorted to index v in descending order.

int **rank**(vector v , int s)

Number of components of v less than $v[s]$

int **rank**(row_vector v , int s)

Number of components of v less than $v[s]$

6. Sparse Matrix Operations

For sparse matrices, for which many elements are zero, it is more efficient to use specialized representations to save memory and speed up matrix arithmetic (including derivative calculations). Given Stan's implementation, there is substantial space (memory) savings by using sparse matrices. Because of the ease of optimizing dense matrix operations, speed improvements only arise at 90% or even greater sparsity; below that level, dense matrices are faster but use more memory.

Because of this speedup and space savings, it may even be useful to read in a dense matrix and convert it to a sparse matrix before multiplying it by a vector. This chapter covers a very specific form of sparsity consisting of a sparse matrix multiplied by a dense vector.

6.1. Compressed Row Storage

Sparse matrices are represented in Stan using compressed row storage (CSR). For example, the matrix

$$A = \begin{bmatrix} 19 & 27 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 52 \\ 81 & 0 & 95 & 33 \end{bmatrix}$$

is translated into a vector of the non-zero real values, read by row from the matrix A ,

$$w(A) = [19 \quad 27 \quad 52 \quad 81 \quad 95 \quad 33]^\top,$$

an array of integer column indices for the values,

$$v(A) = [1 \quad 2 \quad 4 \quad 1 \quad 3 \quad 4],$$

and an array of integer indices indicating where in $w(A)$ a given row's values start,

$$u(A) = [1 \quad 3 \quad 3 \quad 4 \quad 7],$$

with a padded value at the end to guarantee that

$$u(A)[n+1] - u(A)[n]$$

is the number of non-zero elements in row n of the matrix (here 2, 0, 1, and 3). Note that because the second row has no non-zero elements both the second and third elements of $u(A)$ correspond to the third element of $w(A)$, which is 52. The values $(w(A), v(A), u(A))$ are sufficient to reconstruct A .

The values are structured so that there is a real value and integer column index for each non-zero entry in the array, plus one integer for each row of the matrix, plus one for padding. There is also underlying storage for internal container pointers and sizes. The total memory usage is roughly $12K + M$ bytes plus a small constant overhead, which is often considerably fewer bytes than the $M \times N$ required to store a dense matrix. Even more importantly, zero values do not introduce derivatives under multiplication or addition, so many storage and evaluation steps are saved when sparse matrices are multiplied.

6.2. Conversion Functions

Conversion functions between dense and sparse matrices are provided.

Dense to Sparse Conversion

Converting a dense matrix m to a sparse representation produces a vector w and two integer arrays, u and v .

vector **csr_extract_w**(matrix a)

Return non-zero values in matrix a ; see Section 6.1.

int[] **csr_extract_v**(matrix a)

Return column indices for values in **csr_extract_w**(a); see Section 6.1.

int[] **csr_extract_u**(matrix a)

Return array of row starting indices for entries in **csr_extract_w**(a) followed by the size of **csr_extract_w**(a) plus one; see Section 6.1.

Sparse to Dense Conversion

To convert a sparse matrix representation to a dense matrix, there is a single function.

matrix **csr_to_dense_matrix**(int m , int n , vector w , int[] v , int[] u)

Return dense $m \times n$ matrix with non-zero matrix entries w , column indices v , and row starting indices u ; the vector w and arrays v and u must all be the same size, and the arrays v and u must have index values bounded by m and n . See Section 6.1 for more details.

6.3. Sparse Matrix Arithmetic

Sparse Matrix Multiplication

The only supported operation is the multiplication of a sparse matrix A and a dense vector b to produce a dense vector Ab . Multiplying a dense row vector b and a sparse matrix A can be coded using transposition as

$$bA = (A^\top b^\top)^\top,$$

but care must be taken to represent A^\top rather than A as a sparse matrix.

```
vector csr_matrix_times_vector(int  $m$ , int  $n$ , vector  $w$ ,  
                               int[]  $v$ , int[]  $u$ , vector  $b$ )
```

Multiply the $m \times n$ matrix represented by values w , column indices v , and row start indices u by the vector b ; see Section [6.1](#).

7. Mixed Operations

These functions perform conversions between Stan containers `matrix`, `vector`, `row_vector` and arrays.

`matrix to_matrix(matrix m)`

Return the matrix *m* itself.

`matrix to_matrix(vector v)`

Convert the column vector *v* to a `size(v)` by 1 matrix.

`matrix to_matrix(row_vector v)`

Convert the row vector *v* to a 1 by `size(v)` matrix.

`matrix to_matrix(matrix m, int m, int n)`

Convert a matrix *m* to a matrix with *m* rows and *n* columns filled in column-major order.

`matrix to_matrix(vector v, int m, int n)`

Convert a vector *v* to a matrix with *m* rows and *n* columns filled in column-major order.

`matrix to_matrix(row_vector v, int m, int n)`

Convert a `row_vector a` to a matrix with *m* rows and *n* columns filled in column-major order.

`matrix to_matrix(matrix m, int m, int n, int col_major)`

Convert a matrix *m* to a matrix with *m* rows and *n* columns filled in row-major order if `col_major` equals 0 (otherwise, they get filled in column-major order).

`matrix to_matrix(vector v, int m, int n, int col_major)`

Convert a vector *v* to a matrix with *m* rows and *n* columns filled in row-major order if `col_major` equals 0 (otherwise, they get filled in column-major order).

`matrix to_matrix(row_vector v, int m, int n, int col_major)`

Convert a `row_vector a` to a matrix with *m* rows and *n* columns filled in row-major order if `col_major` equals 0 (otherwise, they get filled in column-major order).

`matrix to_matrix(real[] a, int m, int n)`

Convert a one-dimensional array *a* to a matrix with *m* rows and *n* columns filled in column-major order.

matrix to_matrix(int[] *a*, int *m*, int *n*)

Convert a one-dimensional array *a* to a matrix with *m* rows and *n* columns filled in column-major order.

matrix to_matrix(real[] *a*, int *m*, int *n*, int col_major)

Convert a one-dimensional array *a* to a matrix with *m* rows and *n* columns filled in row-major order if col_major equals 0 (otherwise, they get filled in column-major order).

matrix to_matrix(int[] *a*, int *m*, int *n*, int col_major)

Convert a one-dimensional array *a* to a matrix with *m* rows and *n* columns filled in row-major order if col_major equals 0 (otherwise, they get filled in column-major order).

matrix to_matrix(real[,] *a*)

Convert the two dimensional array *a* to a matrix with the same dimensions and indexing order.

matrix to_matrix(int[,] *a*)

Convert the two dimensional array *a* to a matrix with the same dimensions and indexing order. If any of the dimensions of *a* are zero, the result will be a 0×0 matrix.

vector to_vector(matrix *m*)

Convert the matrix *m* to a column vector in column-major order.

vector to_vector(vector *v*)

Return the column vector *v* itself.

vector to_vector(row_vector *v*)

Convert the row vector *v* to a column vector.

vector to_vector(real[] *a*)

Convert the one-dimensional array *a* to a column vector.

vector to_vector(int[] *a*)

Convert the one-dimensional integer array *a* to a column vector.

row_vector to_row_vector(matrix *m*)

Convert the matrix *m* to a row vector in column-major order.

row_vector to_row_vector(vector *v*)

Convert the column vector *v* to a row vector.

`row_vector to_row_vector(row_vector v)`

Return the row vector *v* itself.

`row_vector to_row_vector(real[] a)`

Convert the one-dimensional array *a* to a row vector.

`row_vector to_row_vector(int[] a)`

Convert the one-dimensional array *a* to a row vector.

`real[,] to_array_2d(matrix m)`

Convert the matrix *m* to a two dimensional array with the same dimensions and indexing order.

`real[] to_array_1d(vector v)`

Convert the column vector *v* to a one-dimensional array.

`real[] to_array_1d(row_vector v)`

Convert the row vector *v* to a one-dimensional array.

`real[] to_array_1d(matrix m)`

Convert the matrix *m* to a one-dimensional array in column-major order.

`real[] to_array_1d(real[...] a)`

Convert the array *a* (of any dimension up to 10) to a one-dimensional array in row-major order.

`int[] to_array_1d(int[...] a)`

Convert the array *a* (of any dimension up to 10) to a one-dimensional array in row-major order.

8. Compound Arithmetic and Assignment

Compound arithmetic and assignment statements combine an arithmetic operation and assignment,

```
x = x op y;
```

replacing them with the compound form

```
x op= y;
```

For example, $x = x + 1$ may be replaced with $x += 1$.

The signatures of the supported compound arithmetic and assignment operations are as follows.

8.1. Compound Addition and Assignment

```
void operator+=(int x, int y)
```

$x += y$ is equivalent to $x = x + y$.

```
void operator+=(real x, real y)
```

$x += y$ is equivalent to $x = x + y$.

```
void operator+=(vector x, real y)
```

$x += y$ is equivalent to $x = x + y$.

```
void operator+=(row_vector x, real y)
```

$x += y$ is equivalent to $x = x + y$.

```
void operator+=(matrix x, real y)
```

$x += y$ is equivalent to $x = x + y$.

```
void operator+=(vector x, vector y)
```

$x += y$ is equivalent to $x = x + y$.

```
void operator+=(row_vector x, row_vector y)
```

$x += y$ is equivalent to $x = x + y$.

```
void operator+=(matrix x, matrix y)
```

$x += y$ is equivalent to $x = x + y$.

8.2. Compound Subtraction and Assignment

`void operator--(int x, int y)`

`x -= y` is equivalent to `x = x - y`.

`void operator--(real x, real y)`

`x -= y` is equivalent to `x = x - y`.

`void operator--(vector x, real y)`

`x -= y` is equivalent to `x = x - y`.

`void operator--(row_vector x, real y)`

`x -= y` is equivalent to `x = x - y`.

`void operator--(matrix x, real y)`

`x -= y` is equivalent to `x = x - y`.

`void operator--(vector x, vector y)`

`x -= y` is equivalent to `x = x - y`.

`void operator--(row_vector x, row_vector y)`

`x -= y` is equivalent to `x = x - y`.

`void operator--(matrix x, matrix y)`

`x -= y` is equivalent to `x = x - y`.

8.3. Compound Multiplication and Assignment

`void operator*=(int x, int y)`

`x *= y` is equivalent to `x = x * y`.

`void operator*=(real x, real y)`

`x *= y` is equivalent to `x = x * y`.

`void operator*=(vector x, real y)`

`x *= y` is equivalent to `x = x * y`.

`void operator*=(row_vector x, real y)`

`x *= y` is equivalent to `x = x * y`.

`void operator*=(matrix x, real y)`

`x *= y` is equivalent to `x = x * y`.

void **operator**+=(row_vector x, matrix y)

$x += y$ is equivalent to $x = x + y$.

void **operator**+=(matrix x, matrix y)

$x += y$ is equivalent to $x = x + y$.

8.4. Compound Division and Assignment

void **operator**/=(int x, int y)

$x /= y$ is equivalent to $x = x / y$.

void **operator**/=(real x, real y)

$x /= y$ is equivalent to $x = x / y$.

void **operator**/=(vector x, real y)

$x /= y$ is equivalent to $x = x / y$.

void **operator**/=(row_vector x, real y)

$x /= y$ is equivalent to $x = x / y$.

void **operator**/=(matrix x, real y)

$x /= y$ is equivalent to $x = x / y$.

8.5. Compound Elementwise Multiplication and Assignment

void **operator**.*(vector x, vector y)

$x .*= y$ is equivalent to $x = x .* y$.

void **operator**.*(row_vector x, row_vector y)

$x .*= y$ is equivalent to $x = x .* y$.

void **operator**.*(matrix x, matrix y)

$x .*= y$ is equivalent to $x = x .* y$.

8.6. Compound Elementwise Division and Assignment

void **operator**./=(vector x, vector y)

$x ./= y$ is equivalent to $x = x ./ y$.

void **operator**./=(row_vector x, row_vector y)

$x ./= y$ is equivalent to $x = x ./ y$.

void **operator./**=(matrix x, matrix y)

$x ./= y$ is equivalent to $x = x ./ y$.

void **operator./**=(vector x, real y)

$x ./= y$ is equivalent to $x = x ./ y$.

void **operator./**=(row_vector x, real y)

$x ./= y$ is equivalent to $x = x ./ y$.

void **operator./**=(matrix x, real y)

$x ./= y$ is equivalent to $x = x ./ y$.

9. Higher-Order Functions

Stan provides a few higher-order functions that act on other functions. In all cases, the function arguments to the higher-order functions are defined as functions within the Stan language and passed by name to the higher-order functions.

9.1. Algebraic Equation Solver

Stan provides a built-in algebraic equation solver. Although it looks like other function applications, the algebraic solver is special in two ways.

First, the algebraic solver is a higher-order function, i.e. it takes another function as one of its arguments. The only other functions in Stan which share this feature are the ordinary differential equation solvers (see Section 9.2). Ordinary Stan functions do not allow functions as arguments.

Second, some of the arguments of the algebraic solvers are restricted to data only expressions. These expressions must not contain variables other than those declared in the data or transformed data blocks. Ordinary Stan functions place no restriction on the origin of variables in their argument expressions.

Specifying an Algebraic Equation as a Function

An algebraic system is specified as an ordinary function in Stan within the function block. The algebraic system function must have this signature:

```
vector algebra_system(vector y, vector theta,  
                      real[] x_r, int[] x_i)
```

The algebraic system function should return the value of the algebraic function which goes to 0, when we plug in the solution to the algebraic system.

The argument of this function are:

- *y*, the unknowns we wish to solve for
- *theta*, parameter values used to evaluate the algebraic system
- *x_r*, data values used to evaluate the algebraic system
- *x_i*, integer data used to evaluate the algebraic system

The algebraic system function separates parameter values, *theta*, from data values, *x_r*, for efficiency in computing the gradients of the algebraic system.

Call to the Algebraic Solver

```
vector algebra_solver(function algebra_system,  
                      vector y_guess,  
                      vector theta, real[] x_r, int[] x_i)
```

Solves the algebraic system, given an initial guess, using the Powell hybrid algorithm.

```
vector algebra_solver(function algebra_system,  
                      vector y_guess,  
                      vector theta, real[] x_r, int[] x_i,  
                      real rel_tol, real f_tol, int max_steps)
```

Solves the algebraic system, given an initial guess, using the Powell hybrid algorithm with additional control parameters for the solver.

Arguments to the Algebraic Solver

The arguments to the algebraic solver are as follows:

1. *algebra_system*: function literal referring to a function specifying the system of algebraic equations with signature

(vector, vector, real[], int[]):vector

The arguments represent (1) unknowns, (2) parameters, (3) real data, and (4) integer data, and the return value contains the value of the algebraic function, which goes to 0 when we plug in the solution to the algebraic system,

2. *y_guess*: initial guess for the solution, type vector,
3. *theta*: parameters only, type vector,
4. *x_r*: real data only, type real[], and
5. *x_i*: integer data only, type int[].

For more fine-grained control of the algebraic solver, these parameters can also be provided:

6. *rel_tol*: relative tolerance for the algebraic solver, type real, data only,
7. *function_tol*: function tolerance for the algebraic solver, type real, data only,
8. *max_num_steps*: maximum number of steps to take in the algebraic solver, type int, data only.

Return value

The return value for the algebraic solver is an object of type `vector`, with values which, when plugged in as `y` make the algebraic function go to 0.

Sizes and parallel arrays

Certain sizes have to be consistent. The initial guess, return value of the solver, and return value of the algebraic function must all be the same size.

The parameters, real data, and integer data will be passed from the solver directly to the system function.

Algorithmic details

The algebraic solver uses the Powell hybrid method (Powell, 1970), which in turn uses first-order derivatives. The Stan code builds on the implementation of the hybrid solver in the unsupported module for nonlinear optimization problems of the Eigen library (Guennebaud et al., 2010). This solver is in turn based on the algorithm developed for the package MINPACK-1 (Jorge J. More, 1980).

The Jacobian of the solution with respect to auxiliary parameters is computed using the implicit function theorem. Intermediate Jacobians (of the the algebraic function's output with respect to the unknowns `y` and with respect to the auxiliary parameters `theta`) are computed using Stan's automatic differentiation.

9.2. Ordinary Differential Equation Solvers

Stan provides built-in ordinary differential equation (ODE) solvers. Although they look like function applications, the ODE solvers are special in two ways.

First, the first argument to each of the solvers is a function specifying the ODE system as an argument, like PKBugs (Lunn et al., 1999). Ordinary Stan functions do not allow functions as arguments.

Second, some of the arguments to the ODE solvers are restricted to data only expressions. These expressions must not contain variables other than those declared in the data or transformed data blocks. Ordinary Stan functions place no restriction on the origin of variables in their argument expressions.

Specifying an Ordinary Differential Equation as a Function

A system of ODEs is specified as an ordinary function in Stan within the functions block. The ODE system function must have this function signature:

```
real[] ode(real time, real[] state, real[] theta,
           real[] x_r, int[] x_i)
```

The ODE system function should return the derivative of the state with respect to time at the time provided. The length of the returned real array must match the length of the state input into the function.

The arguments to this function are:

- *time*, the time to evaluate the ODE system
- *state*, the state of the ODE system at the time specified
- *theta*, parameter values used to evaluate the ODE system
- *x_r*, data values used to evaluate the ODE system
- *x_i*, integer data values used to evaluate the ODE system.

The ODE system function separates parameter values, *theta*, from data values, *x_r*, for efficiency in computing the gradients of the ODE.

Non-Stiff Solver

```
real[ , ] integrate_ode_rk45(function ode, real[] initial_state,
                             real initial_time, real[] times,
                             real[] theta, real[] x_r, int[] x_i)
```

Solves the ODE system for the times provided using the Runge Kutta Dopri algorithm with the implementation from Boost.

```
real[ , ] integrate_ode_rk45(function ode, real[] initial_state,
                             real initial_time, real[] times,
                             real[] theta, real[] x_r, int[] x_i,
                             real rel_tol, real abs_tol, int max_num_steps)
```

Solves the ODE system for the times provided using the Runge Kutta Dopri algorithm with the implementation from Boost with additional control parameters for the solver.

```
real[ , ] integrate_ode(function ode, real[] initial_state,
                        real initial_time, real[] times,
                        real[] theta, real[] x_r, int[] x_i)
```

Deprecated. Solves the ODE system for the times provided with a non-stiff solver. This calls the Runge Kutta Dopri algorithm.

Stiff Solver

```
real[] integrate_ode_bdf(function ode, real[] initial_state,  
    real initial_time, real[] times,  
    real[] theta, data real[] x_r, data int[] x_i)
```

Solves the ODE system for the times provided using the backward differentiation formula (BDF) method with the implementation from CVODES.

```
real[] integrate_ode_bdf(function ode, real[] initial_state,  
    real initial_time, real[] times,  
    real[] theta, data real[] x_r, data int[] x_i,  
    data real rel_tol, data real abs_tol, data int  
max_num_steps)
```

Solves the ODE system for the times provided using the backward differentiation formula (BDF) method with the implementation from CVODES with additional control parameters for the CVODES solver.

Arguments to the ODE solvers

The arguments to the ODE solvers in both the stiff and non-stiff cases are as follows.

1. *ode*: function literal referring to a function specifying the system of differential equations with signature described in Section 9.2.1:

```
(real, real[], real[], data real[], data int[]):real[]
```

The arguments represent (1) time, (2) system state, (3) parameters, (4) real data, and (5) integer data, and the return value contains the derivatives with respect to time of the state,

2. *initial_state*: initial state, type `real[]`,
3. *initial_time*: initial time, type `int` or `real`,
4. *times*: solution times, type `real[]`,
5. *theta*: parameters, type `real[]`,
6. data *x_r*: real data, type `real[]`, data only, and
7. data *x_i*: integer data, type `int[]`, data only.

For more fine-grained control of the ODE solvers, these parameters can also be provided:

8. data *rel_tol*: relative tolerance for the ODE solver, type `real`, data only,

9. data *abs_tol*: absolute tolerance for the ODE solver, type `real`, data only, and
10. data *max_num_steps*: maximum number of steps to take in the ODE solver, type `int`, data only.

Return values

The return value for the ODE solvers is an array of type `real[,]`, with values consisting of solutions at the specified times.

Sizes and parallel arrays

The sizes must match, and in particular, the following groups are of the same size:

- state variables passed into the system function, derivatives returned by the system function, initial state passed into the solver, and rows of the return value of the solver,
- solution times and number of rows of the return value of the solver,
- parameters, real data and integer data passed to the solver will be passed to the system function

9.3. Higher-Order Map

Stan provides a higher-order map function. This allows map-reduce functionality to be coded in Stan as described in the user's guide.

Specifying the Mapped Function

The function being mapped must have a signature identical to that of the function `f` in the following declaration.

```
vector f(vector phi, vector theta,  
         data real[] x_r, data int[] x_i);
```

The map function returns the sequence of results for the particular shard being evaluated. The arguments to the mapped function are:

- *phi*, the sequence of parameters shared across shards
- *theta*, the sequence of parameters specific to this shard
- *x_r*, sequence of real-valued data

- x_i , sequence of integer data

All input for the mapped function must be packed into these sequences and all output from the mapped function must be packed into a single vector. The vector of output from each mapped function is concatenated into the final result.

Rectangular Map

The rectangular map function operates on rectangular (not ragged) data structures, with parallel data structures for job-specific parameters, job-specific real data, and job-specific integer data.

```
vector map_rect(F f, vector phi, vector[] theta, data real[,] x_r,
                data int[,] x_i)
```

Return the concatenation of the results of applying the function *f*, of type (vector, vector, real[], int[]):vector elementwise, i.e., $f(\phi, \theta[n], x_r[n], x_i[n])$ for each n in $1:N$, where N is the size of the parallel arrays of job-specific/local parameters *theta*, real data *x_r*, and integer data *x_i*. The shared/global parameters *phi* are passed to each invocation of *f*.

Part II

Discrete Distributions

10. Conventions for Probability Functions

Functions associated with distributions are set up to follow the same naming conventions for both built-in distributions and for user-defined distributions.

10.1. Suffix Marks Type of Function

The suffix is determined by the type of function according to the following table.

<i>function</i>	<i>outcome</i>	<i>suffix</i>
log probability mass function	discrete	<code>_lpmf</code>
log probability density function	continuous	<code>_lpdf</code>
log cumulative distribution function	any	<code>_lcdf</code>
log complementary cumulative distribution function	any	<code>_lccdf</code>
random number generator	any	<code>_rng</code>

For example, `normal_lpdf` is the log of the normal probability density function (pdf) and `bernoulli_lpmf` is the log of the bernoulli probability mass function (pmf). The log of the corresponding cumulative distribution functions (cdf) use the same suffix, `normal_lcdf` and `bernoulli_lcdf`.

10.2. Argument Order and the Vertical Bar

Each probability function has a specific outcome value and a number of parameters. Following conditional probability notation, probability density and mass functions use a vertical bar to separate the outcome from the parameters of the distribution. For example, `normal_lpdf(y | mu, sigma)` returns the value of mathematical formula $\log \text{Normal}(y | \mu, \sigma)$. Cumulative distribution functions separate the outcome from the parameters in the same way (e.g., `normal_lcdf(y_low | mu, sigma)`).

10.3. Sampling Notation

The notation

```
y ~ normal(mu, sigma);
```

provides the same (proportional) contribution to the model log density as the explicit target density increment,

```
target += normal_lpdf(y | mu, sigma);
```

In both cases, the effect is to add terms to the target log density. The only difference is that the example with the sampling (\sim) notation drops all additive constants in the log density; the constants are not necessary for any of Stan's sampling, approximation, or optimization algorithms.

10.4. Finite Inputs

All of the distribution functions are configured to throw exceptions (effectively rejecting samples or optimization steps) when they are supplied with non-finite arguments. The two cases of non-finite arguments are the infinite values and not-a-number value—these are standard in floating-point arithmetic.

10.5. Boundary Conditions

Many distributions are defined with support or constraints on parameters forming an open interval. For example, the normal density function accepts a scale parameter $\sigma > 0$. If $\sigma = 0$, the probability function will throw an exception.

This is true even for (complementary) cumulative distribution functions, which will throw exceptions when given input that is out of the support.

10.6. Pseudorandom Number Generators

For most of the probability functions, there is a matching pseudorandom number generator (PRNG) with the suffix `_rng`. For example, the function `normal_rng(real, real)` accepts two real arguments, an unconstrained location μ and positive scale $\sigma > 0$, and returns an unconstrained pseudorandom value drawn from $\text{Normal}(\mu, \sigma)$. There are also vectorized forms of random number generators which return more than one random variate at a time.

Restricted to Generated Quantities

Unlike regular functions, the PRNG functions may only be used in the generated quantities block.

Limited Vectorization

Unlike the probability functions, only some of the PRNG functions are vectorized.

10.7. Cumulative Distribution Functions

For most of the univariate probability functions, there is a corresponding cumulative distribution function, log cumulative distribution function, and log complementary cumulative distribution function.

For a univariate random variable Y with probability function $p_Y(y | \theta)$, the cumulative distribution function (CDF) F_Y is defined by

$$F_Y(y) = \Pr[Y < y] = \int_{-\infty}^y p(y | \theta) dy.$$

The complementary cumulative distribution function (CCDF) is defined as

$$\Pr[Y \geq y] = 1 - F_Y(y).$$

The reason to use CCDFs instead of CDFs in floating-point arithmetic is that it is possible to represent numbers very close to 0 (the closest you can get is roughly 10^{-300}), but not numbers very close to 1 (the closest you can get is roughly $1 - 10^{-15}$).

In Stan, there is a cumulative distribution function for each probability function. For instance, `normal_cdf(y, mu, sigma)` is defined by

$$\int_{-\infty}^y \text{Normal}(y | \mu, \sigma) dy.$$

There are also log forms of the CDF and CCDF for most univariate distributions. For example, `normal_lcdf(y | mu, sigma)` is defined by

$$\log \left(\int_{-\infty}^y \text{Normal}(y | \mu, \sigma) dy \right)$$

and `normal_lccdf(y | mu, sigma)` is defined by

$$\log \left(1 - \int_{-\infty}^y \text{Normal}(y | \mu, \sigma) dy \right).$$

10.8. Vectorization

Stan's univariate log probability functions, including the log density functions, log mass functions, log CDFs, and log CCDFs, all support vectorized function application, with results defined to be the sum of the elementwise application of the function. Some of the PRNG functions support vectorization, see Section 10.8.3 for more details.

In all cases, matrix operations are at least as fast and usually faster than loops and vectorized log probability functions are faster than their equivalent form defined with

loops. This isn't because loops are slow in Stan, but because more efficient automatic differentiation can be used. The efficiency comes from the fact that a vectorized log probability function only introduces one new node into the expression graph, thus reducing the number of virtual function calls required to compute gradients in C++, as well as from allowing caching of repeated computations.

Stan also overloads the multivariate normal distribution, including the Cholesky-factor form, allowing arrays of row vectors or vectors for the variate and location parameter. This is a huge savings in speed because the work required to solve the linear system for the covariance matrix is only done once.

Stan also overloads some scalar functions, such as `log` and `exp`, to apply to vectors (arrays) and return vectors (arrays). These vectorizations are defined elementwise and unlike the probability functions, provide only minimal efficiency speedups over repeated application and assignment in a loop.

Vectorized Function Signatures

Vectorized Scalar Arguments

The normal probability function is specified with the signature

```
normal_lpdf(reals | reals, reals);
```

The pseudotype `reals` is used to indicate that an argument position may be vectorized. Argument positions declared as `reals` may be filled with a real, a one-dimensional array, a vector, or a row-vector. If there is more than one array or vector argument, their types can be anything but their size must match. For instance, it is legal to use `normal_lpdf(row_vector | vector, real)` as long as the vector and row vector have the same size.

Vectorized Vector and Row Vector Arguments

The multivariate normal distribution accepting vector or array of vector arguments is written as

```
multi_normal_lpdf(vectors | vectors, matrix);
```

These arguments may be row vectors, column vectors, or arrays of row vectors or column vectors.

Vectorized Integer Arguments

The pseudotype `ints` is used for vectorized integer arguments. Where it appears either an integer or array of integers may be used.

Evaluating Vectorized Log Probability Functions

The result of a vectorized log probability function is equivalent to the sum of the evaluations on each element. Any non-vector argument, namely `real` or `int`, is repeated. For instance, if `y` is a vector of size `N`, `mu` is a vector of size `N`, and `sigma` is a scalar, then

```
ll = normal_lpdf(y | mu, sigma);
```

is just a more efficient way to write

```
ll = 0;
for (n in 1:N)
  ll = ll + normal_lpdf(y[n] | mu[n], sigma);
```

With the same arguments, the vectorized sampling statement

```
y ~ normal(mu, sigma);
```

has the same effect on the total log probability as

```
for (n in 1:N)
  y[n] ~ normal(mu[n], sigma);
```

Evaluating Vectorized PRNG Functions

Some PRNG functions accept sequences as well as scalars as arguments. Such functions are indicated by argument pseudotypes `reals` or `ints`. In cases of sequence arguments, the output will also be a sequence. For example, the following is allowed in the generated quantities block.

```
vector[3] mu = ...;
real x[3] = normal_rng(mu, 3);
```

Argument types

In the case of PRNG functions, arguments marked `ints` may be integers or integer arrays, whereas arguments marked `reals` may be integers or reals, integer or real arrays, vectors, or row vectors.

<i>pseudotype</i>	<i>allowable PRNG arguments</i>
<code>ints</code>	<code>int</code> , <code>int[]</code>
<code>reals</code>	<code>int</code> , <code>int[]</code> , <code>real</code> , <code>real[]</code> , <code>vector</code> , <code>row_vector</code>

Dimension matching

In general, if there are multiple non-scalar arguments, they must all have the same dimensions, but need not have the same type. For example, the `normal_rng` function may be called with one vector argument and one real array argument as long as they have the same number of elements.

```
vector[3] mu = ...;  
real sigma[3] = ...;  
real x[3] = normal_rng(mu, sigma);
```

Return type

The result of a vectorized PRNG function depends on the size of the arguments and the distribution's support. If all arguments are scalars, then the return type is a scalar. For a continuous distribution, if there are any non-scalar arguments, the return type is a real array (`real[]`) matching the size of any of the non-scalar arguments, as all non-scalar arguments must have matching size. Discrete distributions return `ints` and continuous distributions return `reals`, each of appropriate size. The symbol `R` denotes such a return type.

11. Binary Distributions

Binary probability distributions have support on $\{0, 1\}$, where 1 represents the value true and 0 the value false.

11.1. Bernoulli Distribution

Probability Mass Function

If $\theta \in [0, 1]$, then for $y \in \{0, 1\}$,

$$\text{Bernoulli}(y|\theta) = \begin{cases} \theta & \text{if } y = 1, \text{ and} \\ 1 - \theta & \text{if } y = 0. \end{cases}$$

Sampling Statement

$y \sim \text{bernoulli}(\theta)$;

Increment target log probability density with `bernoulli_lpmf(y | θ)`, dropping constant additive terms.

Stan Functions

```
real bernoulli_lpmf(ints y | reals  $\theta$ )
```

The log Bernoulli probability mass of y given chance of success θ

```
real bernoulli_cdf(ints y, reals  $\theta$ )
```

The Bernoulli cumulative distribution function of y given chance of success θ

```
real bernoulli_lcdf(ints y | reals  $\theta$ )
```

The log of the Bernoulli cumulative distribution function of y given chance of success θ

```
real bernoulli_lccdf(ints y | reals  $\theta$ )
```

The log of the Bernoulli complementary cumulative distribution function of y given chance of success θ

```
R bernoulli_rng(reals  $\theta$ )
```

Generate a Bernoulli variate with chance of success θ ; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

11.2. Bernoulli Distribution, Logit Parameterization

Stan also supplies a direct parameterization in terms of a logit-transformed chance-of-success parameter. This parameterization is more numerically stable if the chance-of-success parameter is on the logit scale, as with the linear predictor in a logistic regression.

Probability Mass Function

If $\alpha \in \mathbb{R}$, then for $c \in \{0, 1\}$,

$$\text{BernoulliLogit}(c|\alpha) = \text{Bernoulli}(c|\text{logit}^{-1}(\alpha)) = \begin{cases} \text{logit}^{-1}(\alpha) & \text{if } y = 1, \text{ and} \\ 1 - \text{logit}^{-1}(\alpha) & \text{if } y = 0. \end{cases}$$

Sampling Statement

```
y ~ bernoulli_logit(alpha);
```

Increment target log probability density with `bernoulli_logit_lpmf(y | alpha)`, dropping constant additive terms.

Stan Functions

```
real bernoulli_logit_lpmf(ints y | reals alpha)
```

The log Bernoulli probability mass of y given chance of success `inv_logit(alpha)`

```
int bernoulli_logit_rng(real alpha)
```

Generate a Bernoulli variate with chance of success $\text{logit}^{-1}(\alpha)$; may only be used in generated quantities block

12. Bounded Discrete Distributions

Bounded discrete probability functions have support on $\{0, \dots, N\}$ for some upper bound N .

12.1. Binomial Distribution

Probability Mass Function

Suppose $N \in \mathbb{N}$ and $\theta \in [0, 1]$, and $n \in \{0, \dots, N\}$.

$$\text{Binomial}(n|N, \theta) = \binom{N}{n} \theta^n (1 - \theta)^{N-n}.$$

Log Probability Mass Function

$$\begin{aligned} \log \text{Binomial}(n|N, \theta) &= \log \Gamma(N + 1) - \log \Gamma(n + 1) - \log \Gamma(N - n + 1) \\ &\quad + n \log \theta + (N - n) \log(1 - \theta), \end{aligned}$$

Gradient of Log Probability Mass Function

$$\frac{\partial}{\partial \theta} \log \text{Binomial}(n|N, \theta) = \frac{n}{\theta} - \frac{N - n}{1 - \theta}$$

Sampling Statement

$n \sim \text{binomial}(N, \text{theta});$

Increment target log probability density with `binomial_lpmf(n | N , theta)`, dropping constant additive terms.

Stan Functions

`real binomial_lpmf(ints n | ints N , reals theta)`

The log binomial probability mass of n successes in N trials given chance of success theta

`real binomial_cdf(ints n , ints N , reals theta)`

The binomial cumulative distribution function of n successes in N trials given chance of success theta

real binomial_lcdf(ints n | ints N , reals θ)

The log of the binomial cumulative distribution function of n successes in N trials given chance of success θ

real binomial_lccdf(ints n | ints N , reals θ)

The log of the binomial complementary cumulative distribution function of n successes in N trials given chance of success θ

R binomial_rng(ints N , reals θ)

Generate a binomial variate with N trials and chance of success θ ; may only be used in generated quantities block. For a description of argument and return types, see Section 10.8.3.

12.2. Binomial Distribution, Logit Parameterization

Stan also provides a version of the binomial probability mass function distribution with the chance of success parameterized on the unconstrained logistic scale.

Probability Mass Function

Suppose $N \in \mathbb{N}$, $\alpha \in \mathbb{R}$, and $n \in \{0, \dots, N\}$.

$$\begin{aligned}\text{BinomialLogit}(n|N, \alpha) &= \text{Binomial}(n|N, \text{logit}^{-1}(\alpha)) \\ &= \binom{N}{n} \left(\text{logit}^{-1}(\alpha) \right)^n \left(1 - \text{logit}^{-1}(\alpha) \right)^{N-n}.\end{aligned}$$

Log Probability Mass Function

$$\begin{aligned}\log \text{BinomialLogit}(n|N, \alpha) &= \log \Gamma(N+1) - \log \Gamma(n+1) - \log \Gamma(N-n+1) \\ &\quad + n \log \text{logit}^{-1}(\alpha) + (N-n) \log \left(1 - \text{logit}^{-1}(\alpha) \right),\end{aligned}$$

Gradient of Log Probability Mass Function

$$\frac{\partial}{\partial \alpha} \log \text{BinomialLogit}(n|N, \alpha) = \frac{n}{\text{logit}^{-1}(\alpha)} - \frac{N-n}{1 - \text{logit}^{-1}(\alpha)}$$

Sampling Statement

$n \sim \text{binomial_logit}(N, \text{alpha});$

Increment target log probability density with `binomial_logit_lpmf($n \mid N, \text{alpha}$)`, dropping constant additive terms.

Stan Functions

`real binomial_logit_lpmf(ints $n \mid$ ints N , reals alpha)`

The log binomial probability mass of n successes in N trials given logit-scaled chance of success alpha

12.3. Beta-Binomial Distribution

Probability Mass Function

If $N \in \mathbb{N}$, $\alpha \in \mathbb{R}^+$, and $\beta \in \mathbb{R}^+$, then for $n \in \{0, \dots, N\}$,

$$\text{BetaBinomial}(n|N, \alpha, \beta) = \binom{N}{n} \frac{B(n + \alpha, N - n + \beta)}{B(\alpha, \beta)},$$

where the beta function $B(u, v)$ is defined for $u \in \mathbb{R}^+$ and $v \in \mathbb{R}^+$ by

$$B(u, v) = \frac{\Gamma(u) \Gamma(v)}{\Gamma(u + v)}.$$

Sampling Statement

$n \sim \text{beta_binomial}(N, \text{alpha}, \text{beta});$

Increment target log probability density with `beta_binomial_lpmf($n \mid N, \text{alpha}, \text{beta}$)`, dropping constant additive terms.

Stan Functions

`real beta_binomial_lpmf(ints $n \mid$ ints N , reals alpha , reals beta)`

The log beta-binomial probability mass of n successes in N trials given prior success count (plus one) of alpha and prior failure count (plus one) of beta

`real beta_binomial_cdf(ints n , ints N , reals alpha , reals beta)`

The beta-binomial cumulative distribution function of n successes in N trials given prior success count (plus one) of alpha and prior failure count (plus one) of beta

real beta_binomial_lcdf(ints n | ints N , reals α , reals β)

The log of the beta-binomial cumulative distribution function of n successes in N trials given prior success count (plus one) of α and prior failure count (plus one) of β

real beta_binomial_lccdf(ints n | ints N , reals α , reals β)

The log of the beta-binomial complementary cumulative distribution function of n successes in N trials given prior success count (plus one) of α and prior failure count (plus one) of β

R beta_binomial_rng(ints N , reals α , reals β)

Generate a beta-binomial variate with N trials, prior success count (plus one) of α , and prior failure count (plus one) of β ; may only be used in generated quantities block. For a description of argument and return types, see [Section 10.8.3](#).

12.4. Hypergeometric Distribution

Probability Mass Function

If $a \in \mathbb{N}$, $b \in \mathbb{N}$, and $N \in \{0, \dots, a + b\}$, then for $n \in \{\max(0, N - b), \dots, \min(a, N)\}$,

$$\text{Hypergeometric}(n|N, a, b) = \frac{\binom{a}{n} \binom{b}{N-n}}{\binom{a+b}{N}}.$$

Sampling Statement

$n \sim \text{hypergeometric}(N, a, b);$

Increment target log probability density with `hypergeometric_lpmf(n | N , a , b)`, dropping constant additive terms.

Stan Functions

real hypergeometric_lpmf(int n | int N , int a , int b)

The log hypergeometric probability mass of n successes in N trials given total success count of a and total failure count of b

int hypergeometric_rng(int N , int a , int2 b)

Generate a hypergeometric variate with N trials, total success count of a , and total failure count of b ; may only be used in generated quantities block

12.5. Categorical Distribution

Probability Mass Functions

If $N \in \mathbb{N}$, $N > 0$, and if $\theta \in \mathbb{R}^N$ forms an N -simplex (i.e., has nonnegative entries summing to one), then for $y \in \{1, \dots, N\}$,

$$\text{Categorical}(y|\theta) = \theta_y.$$

In addition, Stan provides a log-odds scaled categorical distribution,

$$\text{CategoricalLogit}(y|\beta) = \text{Categorical}(y|\text{softmax}(\beta)).$$

See Section 5.11 for the definition of the softmax function.

Sampling Statement

```
y ~ categorical(theta);  
Increment target log probability density with categorical_lpmf(y | theta),  
dropping constant additive terms.
```

Sampling Statement

```
y ~ categorical_logit(beta);  
Increment target log probability density with categorical_logit_lpmf(y |  
beta), dropping constant additive terms.
```

Stan Functions

All of the categorical distributions are vectorized so that the outcome y can be a single integer (type `int`) or an array of integers (type `int[]`).

```
real categorical_lpmf(ints y | vector theta)
```

The log categorical probability mass function with outcome(s) y in $1 : N$ given N -vector of outcome probabilities θ . The parameter θ must have non-negative entries that sum to one, but it need not be a variable declared as a simplex.

```
real categorical_logit_lpmf(ints y | vector beta)
```

The log categorical probability mass function with outcome(s) y in $1 : N$ given log-odds of outcomes β .

int **categorical_rng**(vector *theta*)

Generate a categorical variate with N -simplex distribution parameter *theta*; may only be used in generated quantities block

int **categorical_logit_rng**(vector *beta*)

Generate a categorical variate with outcome in range $1 : N$ from log-odds vector *beta*; may only be used in generated quantities block

12.6. Ordered Logistic Distribution

Probability Mass Function

If $K \in \mathbb{N}$ with $K > 2$, $c \in \mathbb{R}^{K-1}$ such that $c_k < c_{k+1}$ for $k \in \{1, \dots, K-2\}$, and $\eta \in \mathbb{R}$, then for $k \in \{1, \dots, K\}$,

$$\text{OrderedLogistic}(k|\eta, c) = \begin{cases} 1 - \text{logit}^{-1}(\eta - c_1) & \text{if } k = 1, \\ \text{logit}^{-1}(\eta - c_{k-1}) - \text{logit}^{-1}(\eta - c_k) & \text{if } 1 < k < K, \text{ and} \\ \text{logit}^{-1}(\eta - c_{K-1}) - 0 & \text{if } k = K. \end{cases}$$

The $k = K$ case is written with the redundant subtraction of zero to illustrate the parallelism of the cases; the $k = 1$ and $k = K$ edge cases can be subsumed into the general definition by setting $c_0 = -\infty$ and $c_K = +\infty$ with $\text{logit}^{-1}(-\infty) = 0$ and $\text{logit}^{-1}(\infty) = 1$.

Sampling Statement

$k \sim \text{ordered_logistic}(\eta, c);$

Increment target log probability density with `ordered_logistic_lpmf(k | eta, c)`, dropping constant additive terms.

Stan Functions

real **ordered_logistic_lpmf**(ints *k* | vector *eta*, vectors *c*)

The log ordered logistic probability mass of *k* given linear predictors *eta*, and cutpoints *c*.

int **ordered_logistic_rng**(real *eta*, vector *c*)

Generate an ordered logistic variate with linear predictor *eta* and cutpoints *c*; may only be used in generated quantities block

12.7. Ordered Probit Distribution

Probability Mass Function

If $K \in \mathbb{N}$ with $K > 2$, $c \in \mathbb{R}^{K-1}$ such that $c_k < c_{k+1}$ for $k \in \{1, \dots, K-2\}$, and $\eta \in \mathbb{R}$, then for $k \in \{1, \dots, K\}$,

$$\text{OrderedProbit}(k|\eta, c) = \begin{cases} 1 - \Phi(\eta - c_1) & \text{if } k = 1, \\ \Phi(\eta - c_{k-1}) - \Phi(\eta - c_k) & \text{if } 1 < k < K, \text{ and} \\ \Phi(\eta - c_{K-1}) - 0 & \text{if } k = K. \end{cases}$$

The $k = K$ case is written with the redundant subtraction of zero to illustrate the parallelism of the cases; the $k = 1$ and $k = K$ edge cases can be subsumed into the general definition by setting $c_0 = -\infty$ and $c_K = +\infty$ with $\Phi(-\infty) = 0$ and $\Phi(\infty) = 1$.

Sampling Statement

$k \sim \text{ordered_probit}(\eta, c);$

Increment target log probability density with `ordered_probit_lpmf(k | η , c)`, dropping constant additive terms.

Stan Functions

`real ordered_probit_lpmf(ints k | vector η , vectors c)`

The log ordered probit probability mass of k given linear predictors η , and cutpoints c .

`int ordered_probit_rng(real η , vector c)`

Generate an ordered probit variate with linear predictor η and cutpoints c ; may only be used in generated quantities block

13. Unbounded Discrete Distributions

The unbounded discrete distributions have support over the natural numbers (i.e., the non-negative integers).

13.1. Negative Binomial Distribution

For the negative binomial distribution Stan uses the parameterization described in [Gelman et al. \(2013\)](#). For alternative parameterizations, see Section 13.2.

Probability Mass Function

If $\alpha \in \mathbb{R}^+$ and $\beta \in \mathbb{R}^+$, then for $y \in \mathbb{N}$,

$$\text{NegBinomial}(y|\alpha, \beta) = \binom{y + \alpha - 1}{\alpha - 1} \left(\frac{\beta}{\beta + 1} \right)^\alpha \left(\frac{1}{\beta + 1} \right)^y.$$

The mean and variance of a random variable $y \sim \text{NegBinomial}(\alpha, \beta)$ are given by

$$\mathbb{E}[y] = \frac{\alpha}{\beta} \quad \text{and} \quad \text{Var}[Y] = \frac{\alpha}{\beta^2}(\beta + 1).$$

Sampling Statement

```
 $n \sim \text{neg\_binomial}(\text{alpha}, \text{beta});$ 
```

Increment target log probability density with `neg_binomial_lpmf(n | alpha , beta)`, dropping constant additive terms.

Stan Functions

```
real neg_binomial_lpmf(ints  $n$  | reals  $\text{alpha}$ , reals  $\text{beta}$ )
```

The log negative binomial probability mass of n given shape alpha and inverse scale beta

```
real neg_binomial_cdf(ints  $n$ , reals  $\text{alpha}$ , reals  $\text{beta}$ )
```

The negative binomial cumulative distribution function of n given shape alpha and inverse scale beta

```
real neg_binomial_lcdf(ints  $n$  | reals  $\text{alpha}$ , reals  $\text{beta}$ )
```

The log of the negative binomial cumulative distribution function of n given shape alpha and inverse scale beta

```
real neg_binomial_1ccdf(ints n | reals alpha, reals beta)
```

The log of the negative binomial complementary cumulative distribution function of n given shape α and inverse scale β

```
R neg_binomial_rng(reals alpha, reals beta)
```

Generate a negative binomial variate with shape α and inverse scale β ; may only be used in generated quantities block. α / β must be less than 2^{29} . For a description of argument and return types, see Section 10.8.3.

13.2. Negative Binomial Distribution (alternative parameterization)

Stan also provides an alternative parameterization of the negative binomial distribution directly using a mean (i.e., location) parameter and a parameter that controls overdispersion relative to the square of the mean. Section 13.3, below, provides a second alternative parameterization directly in terms of the log mean.

Probability Mass Function

The first parameterization is for $\mu \in \mathbb{R}^+$ and $\phi \in \mathbb{R}^+$, which for $y \in \mathbb{N}$ is defined as

$$\text{NegBinomial2}(y | \mu, \phi) = \binom{y + \phi - 1}{y} \left(\frac{\mu}{\mu + \phi} \right)^y \left(\frac{\phi}{\mu + \phi} \right)^\phi.$$

The mean and variance of a random variable $y \sim \text{NegBinomial2}(y | \mu, \phi)$ are

$$\mathbb{E}[Y] = \mu \quad \text{and} \quad \text{Var}[Y] = \mu + \frac{\mu^2}{\phi}.$$

Recall that $\text{Poisson}(\mu)$ has variance μ , so $\mu^2/\phi > 0$ is the additional variance of the negative binomial above that of the Poisson with mean μ . So the inverse of parameter ϕ controls the overdispersion, scaled by the square of the mean, μ^2 .

Sampling Statement

```
y ~ neg_binomial_2(mu, phi);
```

Increment target log probability density with `neg_binomial_2_lpmf(y | mu, phi)`, dropping constant additive terms.

Stan Functions

```
real neg_binomial_2_lpmf(ints y | reals mu, reals phi)
```

The negative binomial probability mass of n given location μ and precision ϕ .

`real neg_binomial_2_cdf(ints n, reals mu, reals phi)`

The negative binomial cumulative distribution function of n given location μ and precision ϕ .

`real neg_binomial_2_lcdf(ints n | reals mu, reals phi)`

The log of the negative binomial cumulative distribution function of n given location μ and precision ϕ .

`real neg_binomial_2_lccdf(ints n | reals mu, reals phi)`

The log of the negative binomial complementary cumulative distribution function of n given location μ and precision ϕ .

`R neg_binomial_2_rng(reals mu, reals phi)`

Generate a negative binomial variate with location μ and precision ϕ ; may only be used in generated quantities block. μ must be less than 2^{29} . For a description of argument and return types, see Section 10.8.3.

13.3. Negative Binomial Distribution (log alternative parameterization)

Related to the parameterization in Section 13.2, the following parameterization uses a log mean parameter $\eta = \log(\mu)$, defined for $\eta \in \mathbb{R}$, $\phi \in \mathbb{R}^+$, so that for $y \in \mathbb{N}$,

$$\text{NegBinomial2Log}(y | \eta, \phi) = \text{NegBinomial2}(y | \exp(\eta), \phi).$$

This alternative may be used for sampling, as a function, and for random number generation, but as of yet, there are no CDFs implemented for it.

Sampling Statement

$y \sim \text{neg_binomial_2_log}(\eta, \phi);$

Increment target log probability density with `neg_binomial_2_log_lpmf(y | η , ϕ)`, dropping constant additive terms.

13.4. Stan Functions

`real neg_binomial_2_log_lpmf(ints y | reals eta, reals phi)`

The log negative binomial probability mass of n given log-location η and inverse overdispersion control ϕ . This is especially useful for log-linear negative binomial regressions.

R **neg_binomial_2_log_rng**(reals *eta*, reals *phi*)

Generate a negative binomial variate with log-location *eta* and inverse overdispersion control *phi*; may only be used in generated quantities block. *eta* must be less than $29\log 2$. For a description of argument and return types, see Section 10.8.3.

13.5. Poisson Distribution

Probability Mass Function

If $\lambda \in \mathbb{R}^+$, then for $n \in \mathbb{N}$,

$$\text{Poisson}(n|\lambda) = \frac{1}{n!} \lambda^n \exp(-\lambda).$$

Sampling Statement

$n \sim \text{poisson}(\textit{lambda})$;

Increment target log probability density with `poisson_lpmf(n | lambda)`, dropping constant additive terms.

Stan Functions

real **poisson_lpmf**(ints *n* | reals *lambda*)

The log Poisson probability mass of *n* given rate *lambda*

real **poisson_cdf**(ints *n*, reals *lambda*)

The Poisson cumulative distribution function of *n* given rate *lambda*

real **poisson_lcdf**(ints *n* | reals *lambda*)

The log of the Poisson cumulative distribution function of *n* given rate *lambda*

real **poisson_lccdf**(ints *n* | reals *lambda*)

The log of the Poisson complementary cumulative distribution function of *n* given rate *lambda*

R **poisson_rng**(reals *lambda*)

Generate a Poisson variate with rate *lambda*; may only be used in generated quantities block. *lambda* must be less than 2^{30} . For a description of argument and return types, see Section 10.8.3.

13.6. Poisson Distribution, Log Parameterization

Stan also provides a parameterization of the Poisson using the log rate $\alpha = \log \lambda$ as a parameter. This is useful for log-linear Poisson regressions so that the predictor does not need to be exponentiated and passed into the standard Poisson probability function.

Probability Mass Function

If $\alpha \in \mathbb{R}$, then for $n \in \mathbb{N}$,

$$\text{PoissonLog}(n|\alpha) = \frac{1}{n!} \exp(n\alpha - \exp(\alpha)).$$

Sampling Statement

```
n ~ poisson_log(alpha);
```

Increment target log probability density with `poisson_log_lpmf(n | alpha)`, dropping constant additive terms.

Stan Functions

```
real poisson_log_lpmf(ints n | reals alpha)
```

The log Poisson probability mass of n given log rate α

```
R poisson_log_rng(reals alpha)
```

Generate a Poisson variate with log rate α ; may only be used in generated quantities block. α must be less than $30 \log 2$. For a description of argument and return types, see Section [10.8.3](#).

14. Multivariate Discrete Distributions

The multivariate discrete distributions are over multiple integer values, which are expressed in Stan as arrays.

14.1. Multinomial Distribution

Probability Mass Function

If $K \in \mathbb{N}$, $N \in \mathbb{N}$, and $\theta \in K$ -simplex, then for $y \in \mathbb{N}^K$ such that $\sum_{k=1}^K y_k = N$,

$$\text{Multinomial}(y|\theta) = \binom{N}{y_1, \dots, y_K} \prod_{k=1}^K \theta_k^{y_k},$$

where the multinomial coefficient is defined by

$$\binom{N}{y_1, \dots, y_K} = \frac{N!}{\prod_{k=1}^K y_k!}.$$

Sampling Statement

$y \sim \text{multinomial}(\theta);$

Increment target log probability density with `multinomial_lpmf(y | theta)`, dropping constant additive terms.

Stan Functions

`real multinomial_lpmf(int[] y | vector theta)`

The log multinomial probability mass function with outcome array `y` of size K given the K -simplex distribution parameter `theta` and (implicit) total count $N = \text{sum}(y)$

`int[] multinomial_rng(vector theta, int N)`

Generate a multinomial variate with simplex distribution parameter `theta` and total count N ; may only be used in generated quantities block

Part III

Continuous Distributions

15. Unbounded Continuous Distributions

The unbounded univariate continuous probability distributions have support on all real numbers.

15.1. Normal Distribution

Probability Density Function

If $\mu \in \mathbb{R}$ and $\sigma \in \mathbb{R}^+$, then for $y \in \mathbb{R}$,

$$\text{Normal}(y|\mu, \sigma) = \frac{1}{\sqrt{2\pi} \sigma} \exp\left(-\frac{1}{2} \left(\frac{y - \mu}{\sigma}\right)^2\right).$$

Sampling Statement

$y \sim \text{normal}(\mu, \sigma);$

Increment target log probability density with `normal_lpdf(y | mu, sigma)`, dropping constant additive terms.

Stan Functions

`real normal_lpdf(reals y | reals mu, reals sigma)`

The log of the normal density of y given location μ and scale σ

`real normal_cdf(reals y, reals mu, reals sigma)`

The cumulative normal distribution of y given location μ and scale σ ; `normal_cdf` will underflow to 0 for $\frac{y-\mu}{\sigma}$ below -37.5 and overflow to 1 for $\frac{y-\mu}{\sigma}$ above 8.25; the function `Phi_approx` is more robust in the tails, but must be scaled and translated for anything other than a standard normal.

`real normal_lcdf(reals y | reals mu, reals sigma)`

The log of the cumulative normal distribution of y given location μ and scale σ ; `normal_lcdf` will underflow to $-\infty$ for $\frac{y-\mu}{\sigma}$ below -37.5 and overflow to 0 for $\frac{y-\mu}{\sigma}$ above 8.25; see above for discussion of `Phi_approx` as an alternative.

`real normal_lccdf(reals y | reals mu, reals sigma)`

The log of the complementary cumulative normal distribution of y given location μ and scale σ ; `normal_lccdf` will overflow to 0 for $\frac{y-\mu}{\sigma}$ below -37.5 and underflow to $-\infty$ for $\frac{y-\mu}{\sigma}$ above 8.25; see above for discussion of `Phi_approx` as an alternative.

R **normal_rng**(reals *mu*, reals *sigma*)

Generate a normal variate with location *mu* and scale *sigma*; may only be used in generated quantities block. For a description of argument and return types, see Section 10.8.3.

Standard Normal Distribution

The standard normal distribution is so-called because its parameters are the units for their respective operations—the location (mean) is zero and the scale (standard deviation) one. The standard normal is parameter free and the unit parameters allow considerable simplification of the expression for the density.

$$\text{StdNormal}(y) = \text{Normal}(y \mid 0, 1) = \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-y^2}{2}\right).$$

Up to a proportion on the log scale, where Stan computes,

$$\log \text{Normal}(y \mid 0, 1) = \frac{-y^2}{2} + \text{const.}$$

With no logarithm, no subtraction, and no division by a parameter, the standard normal log density is much more efficient to compute than the normal log density with constant location 0 and scale 1.

Stan Functions

Only the log probability density function is available for the standard normal distribution; for other functions, use the `normal_` versions with parameters $\mu = 0$ and $\sigma = 1$.

real **std_normal_lpdf**(reals *y*)

The standard normal (location zero, scale one) log probability density of *y*.

Sampling Statement

y ~ **std_normal**();

Increment target log probability density with `std_normal_lpmf(y)`, dropping constant additive terms.

15.2. Exponentially Modified Normal Distribution

Probability Density Function

If $\mu \in \mathbb{R}$, $\sigma \in \mathbb{R}^+$, and $\lambda \in \mathbb{R}^+$, then for $y \in \mathbb{R}$,

$$\text{ExpModNormal}(y|\mu, \sigma, \lambda) = \frac{\lambda}{2} \exp\left(\frac{\lambda}{2}(2\mu + \lambda\sigma^2 - 2y)\right) \text{erfc}\left(\frac{\mu + \lambda\sigma^2 - y}{\sqrt{2}\sigma}\right).$$

Sampling Statement

$y \sim \text{exp_mod_normal}(\text{mu}, \text{sigma}, \text{lambda});$
Increment target log probability density with `exp_mod_normal_lpdf(y | mu, sigma, lambda)`, dropping constant additive terms.

Stan Functions

```
real exp_mod_normal_lpdf(reals y | reals mu, reals sigma,  
    reals lambda)
```

The log of the exponentially modified normal density of y given location mu , scale sigma , and shape lambda

```
real exp_mod_normal_cdf(reals y, reals mu, reals sigma,  
    reals lambda)
```

The exponentially modified normal cumulative distribution function of y given location mu , scale sigma , and shape lambda

```
real exp_mod_normal_lcdf(reals y | reals mu, reals sigma,  
    reals lambda)
```

The log of the exponentially modified normal cumulative distribution function of y given location mu , scale sigma , and shape lambda

```
real exp_mod_normal_lccdf(reals y | reals mu, reals sigma,  
    reals lambda)
```

The log of the exponentially modified normal complementary cumulative distribution function of y given location mu , scale sigma , and shape lambda

```
R exp_mod_normal_rng(reals mu, reals sigma, reals lambda)
```

Generate a exponentially modified normal variate with location mu , scale sigma , and shape lambda ; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

15.3. Skew Normal Distribution

Probability Density Function

If $\xi \in \mathbb{R}$, $\omega \in \mathbb{R}^+$, and $\alpha \in \mathbb{R}$, then for $y \in \mathbb{R}$,

$$\text{SkewNormal}(y \mid \xi, \omega, \alpha) = \frac{1}{\omega\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{y-\xi}{\omega}\right)^2\right) \left(1 + \text{erf}\left(\alpha\left(\frac{y-\xi}{\omega\sqrt{2}}\right)\right)\right).$$

Sampling Statement

$y \sim \text{skew_normal}(xi, \omega, \alpha);$

Increment target log probability density with `skew_normal_lpdf(y | xi, omega, alpha)`, dropping constant additive terms.

Stan Functions

`real skew_normal_lpdf(reals y | reals xi, reals omega, reals alpha)`

The log of the skew normal density of y given location xi , scale $omega$, and shape $alpha$

`real skew_normal_cdf(reals y, reals xi, reals omega, reals alpha)`

The skew normal distribution function of y given location xi , scale $omega$, and shape $alpha$

`real skew_normal_lcdf(reals y | reals xi, reals omega,
 reals alpha)`

The log of the skew normal cumulative distribution function of y given location xi , scale $omega$, and shape $alpha$

`real skew_normal_lccdf(reals y | reals xi, reals omega,
 reals alpha)`

The log of the skew normal complementary cumulative distribution function of y given location xi , scale $omega$, and shape $alpha$

`R skew_normal_rng(reals xi, reals omega, real alpha)`

Generate a skew normal variate with location xi , scale $omega$, and shape $alpha$; may only be used in generated quantities block. For a description of argument and return types, see Section 10.8.3.

15.4. Student- t Distribution

Probability Density Function

If $\nu \in \mathbb{R}^+$, $\mu \in \mathbb{R}$, and $\sigma \in \mathbb{R}^+$, then for $y \in \mathbb{R}$,

$$\text{StudentT}(y|\nu, \mu, \sigma) = \frac{\Gamma((\nu+1)/2)}{\Gamma(\nu/2)} \frac{1}{\sqrt{\nu\pi} \sigma} \left(1 + \frac{1}{\nu} \left(\frac{y-\mu}{\sigma}\right)^2\right)^{-(\nu+1)/2}.$$

Sampling Statement

$y \sim \text{student_t}(nu, mu, sigma);$

Increment target log probability density with `student_t_lpdf(y | nu, mu, sigma)`, dropping constant additive terms.

Stan Functions

`real student_t_lpdf(reals y | reals nu, reals mu, reals sigma)`

The log of the Student- t density of y given degrees of freedom nu , location mu , and scale $sigma$

`real student_t_cdf(reals y, reals nu, reals mu, reals sigma)`

The Student- t cumulative distribution function of y given degrees of freedom nu , location mu , and scale $sigma$

`real student_t_lcdf(reals y | reals nu, reals mu, reals sigma)`

The log of the Student- t cumulative distribution function of y given degrees of freedom nu , location mu , and scale $sigma$

`real student_t_lccdf(reals y | reals nu, reals mu, reals sigma)`

The log of the Student- t complementary cumulative distribution function of y given degrees of freedom nu , location mu , and scale $sigma$

`R student_t_rng(reals nu, reals mu, reals sigma)`

Generate a Student- t variate with degrees of freedom nu , location mu , and scale $sigma$; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

15.5. Cauchy Distribution

Probability Density Function

If $\mu \in \mathbb{R}$ and $\sigma \in \mathbb{R}^+$, then for $y \in \mathbb{R}$,

$$\text{Cauchy}(y|\mu, \sigma) = \frac{1}{\pi\sigma} \frac{1}{1 + ((y - \mu)/\sigma)^2}.$$

Sampling Statement

$y \sim \text{cauchy}(\mu, \sigma);$

Increment target log probability density with `cauchy_lpdf(y | mu, sigma)`, dropping constant additive terms.

Stan Functions

`real cauchy_lpdf(reals y | reals mu, reals sigma)`

The log of the Cauchy density of y given location μ and scale σ

`real cauchy_cdf(reals y, reals mu, reals sigma)`

The Cauchy cumulative distribution function of y given location μ and scale σ

`real cauchy_lcdf(reals y | reals mu, reals sigma)`

The log of the Cauchy cumulative distribution function of y given location μ and scale σ

`real cauchy_lccdf(reals y | reals mu, reals sigma)`

The log of the Cauchy complementary cumulative distribution function of y given location μ and scale σ

`R cauchy_rng(reals mu, reals sigma)`

Generate a Cauchy variate with location μ and scale σ ; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

15.6. Double Exponential (Laplace) Distribution

Probability Density Function

If $\mu \in \mathbb{R}$ and $\sigma \in \mathbb{R}^+$, then for $y \in \mathbb{R}$,

$$\text{DoubleExponential}(y|\mu, \sigma) = \frac{1}{2\sigma} \exp\left(-\frac{|y - \mu|}{\sigma}\right).$$

Note that the double exponential distribution is parameterized in terms of the scale, in contrast to the exponential distribution (see Section 16.5), which is parameterized in terms of inverse scale.

The double-exponential distribution can be defined as a compound exponential-normal distribution. Specifically, if

$$\alpha \sim \text{Exponential}\left(\frac{1}{\lambda}\right)$$

and

$$\beta \sim \text{Normal}(\mu, \alpha),$$

then

$$\beta \sim \text{DoubleExponential}(\mu, \lambda).$$

This may be used to code a non-centered parameterization by taking

$$\beta^{\text{raw}} \sim \text{Normal}(0, 1)$$

and defining

$$\beta = \mu + \alpha \beta^{\text{raw}}.$$

Sampling Statement

```
y ~ double_exponential(mu, sigma);
```

Increment target log probability density with `double_exponential_lpdf(y | mu, sigma)`, dropping constant additive terms.

Stan Functions

```
real double_exponential_lpdf(reals y | reals mu, reals sigma)
```

The log of the double exponential density of y given location mu and scale $sigma$

```
real double_exponential_cdf(reals y, reals mu, reals sigma)
```

The double exponential cumulative distribution function of y given location mu and scale $sigma$

real double_exponential_lcdf(reals *y* | reals *mu*, reals *sigma*)

The log of the double exponential cumulative distribution function of *y* given location *mu* and scale *sigma*

real double_exponential_lccdf(reals *y* | reals *mu*, reals *sigma*)

The log of the double exponential complementary cumulative distribution function of *y* given location *mu* and scale *sigma*

R double_exponential_rng(reals *mu*, reals *sigma*)

Generate a double exponential variate with location *mu* and scale *sigma*; may only be used in generated quantities block. For a description of argument and return types, see Section 10.8.3.

15.7. Logistic Distribution

Probability Density Function

If $\mu \in \mathbb{R}$ and $\sigma \in \mathbb{R}^+$, then for $y \in \mathbb{R}$,

$$\text{Logistic}(y|\mu, \sigma) = \frac{1}{\sigma} \exp\left(-\frac{y-\mu}{\sigma}\right) \left(1 + \exp\left(-\frac{y-\mu}{\sigma}\right)\right)^{-2}.$$

Sampling Statement

$y \sim \text{logistic}(\mu, \sigma);$

Increment target log probability density with `logistic_lpdf(y | mu, sigma)`, dropping constant additive terms.

Stan Functions

real logistic_lpdf(reals *y* | reals *mu*, reals *sigma*)

The log of the logistic density of *y* given location *mu* and scale *sigma*

real logistic_cdf(reals *y*, reals *mu*, reals *sigma*)

The logistic cumulative distribution function of *y* given location *mu* and scale *sigma*

real logistic_lcdf(reals *y* | reals *mu*, reals *sigma*)

The log of the logistic cumulative distribution function of *y* given location *mu* and scale *sigma*

`real logistic_lccdf(reals y | reals mu, reals sigma)`

The log of the logistic complementary cumulative distribution function of *y* given location *mu* and scale *sigma*

`R logistic_rng(reals mu, reals sigma)`

Generate a logistic variate with location *mu* and scale *sigma*; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

15.8. Gumbel Distribution

Probability Density Function

If $\mu \in \mathbb{R}$ and $\beta \in \mathbb{R}^+$, then for $y \in \mathbb{R}$,

$$\text{Gumbel}(y|\mu, \beta) = \frac{1}{\beta} \exp\left(-\frac{y-\mu}{\beta} - \exp\left(-\frac{y-\mu}{\beta}\right)\right).$$

Sampling Statement

$y \sim \text{gumbel}(mu, beta);$

Increment target log probability density with `gumbel_lpdf(y | mu, beta)`, dropping constant additive terms.

Stan Functions

`real gumbel_lpdf(reals y | reals mu, reals beta)`

The log of the gumbel density of *y* given location *mu* and scale *beta*

`real gumbel_cdf(reals y, reals mu, reals beta)`

The gumbel cumulative distribution function of *y* given location *mu* and scale *beta*

`real gumbel_lcdf(reals y | reals mu, reals beta)`

The log of the gumbel cumulative distribution function of *y* given location *mu* and scale *beta*

`real gumbel_lccdf(reals y | reals mu, reals beta)`

The log of the gumbel complementary cumulative distribution function of *y* given location *mu* and scale *beta*

R **gumbel_rng**(reals *mu*, reals *beta*)

Generate a gumbel variate with location *mu* and scale *beta*; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

16. Positive Continuous Distributions

The positive continuous probability functions have support on the positive real numbers.

16.1. Lognormal Distribution

Probability Density Function

If $\mu \in \mathbb{R}$ and $\sigma \in \mathbb{R}^+$, then for $y \in \mathbb{R}^+$,

$$\text{LogNormal}(y|\mu, \sigma) = \frac{1}{\sqrt{2\pi} \sigma} \frac{1}{y} \exp\left(-\frac{1}{2} \left(\frac{\log y - \mu}{\sigma}\right)^2\right).$$

Sampling Statement

$y \sim \text{lognormal}(\mu, \sigma);$

Increment target log probability density with `lognormal_lpdf(y | mu, sigma)`, dropping constant additive terms.

Stan Functions

`real lognormal_lpdf(reals y | reals mu, reals sigma)`

The log of the lognormal density of y given location μ and scale σ

`real lognormal_cdf(reals y, reals mu, reals sigma)`

The cumulative lognormal distribution function of y given location μ and scale σ

`real lognormal_lcdf(reals y | reals mu, reals sigma)`

The log of the lognormal cumulative distribution function of y given location μ and scale σ

`real lognormal_lccdf(reals y | reals mu, reals sigma)`

The log of the lognormal complementary cumulative distribution function of y given location μ and scale σ

`R lognormal_rng(reals mu, reals sigma)`

Generate a lognormal variate with location μ and scale σ ; may only be used in generated quantities block. For a description of argument and return types, see Section 10.8.3.

16.2. Chi-Square Distribution

Probability Density Function

If $\nu \in \mathbb{R}^+$, then for $y \in \mathbb{R}^+$,

$$\text{ChiSquare}(y|\nu) = \frac{2^{-\nu/2}}{\Gamma(\nu/2)} y^{\nu/2-1} \exp\left(-\frac{1}{2}y\right).$$

Sampling Statement

$y \sim \text{chi_square}(\nu);$

Increment target log probability density with `chi_square_lpdf(y | ν)`, dropping constant additive terms.

Stan Functions

`real chi_square_lpdf(reals y | reals ν)`

The log of the Chi-square density of y given degrees of freedom ν

`real chi_square_cdf(reals y, reals ν)`

The Chi-square cumulative distribution function of y given degrees of freedom ν

`real chi_square_lcdf(reals y | reals ν)`

The log of the Chi-square cumulative distribution function of y given degrees of freedom ν

`real chi_square_lccdf(reals y | reals ν)`

The log of the complementary Chi-square cumulative distribution function of y given degrees of freedom ν

`R chi_square_rng(reals ν)`

Generate a Chi-square variate with degrees of freedom ν ; may only be used in generated quantities block. For a description of argument and return types, see [Section 10.8.3](#).

16.3. Inverse Chi-Square Distribution

Probability Density Function

If $\nu \in \mathbb{R}^+$, then for $y \in \mathbb{R}^+$,

$$\text{InvChiSquare}(y \mid \nu) = \frac{2^{-\nu/2}}{\Gamma(\nu/2)} y^{-\nu/2-1} \exp\left(-\frac{1}{2} \frac{1}{y}\right).$$

Sampling Statement

$y \sim \text{inv_chi_square}(nu);$

Increment target log probability density with `inv_chi_square_lpdf(y | nu)`, dropping constant additive terms.

Stan Functions

`real inv_chi_square_lpdf(reals y | reals nu)`

The log of the inverse Chi-square density of y given degrees of freedom nu

`real inv_chi_square_cdf(reals y, reals nu)`

The inverse Chi-squared cumulative distribution function of y given degrees of freedom nu

`real inv_chi_square_lcdf(reals y | reals nu)`

The log of the inverse Chi-squared cumulative distribution function of y given degrees of freedom nu

`real inv_chi_square_lccdf(reals y | reals nu)`

The log of the inverse Chi-squared complementary cumulative distribution function of y given degrees of freedom nu

`R inv_chi_square_rng(reals nu)`

Generate an inverse Chi-squared variate with degrees of freedom nu ; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

16.4. Scaled Inverse Chi-Square Distribution

Probability Density Function

If $\nu \in \mathbb{R}^+$ and $\sigma \in \mathbb{R}^+$, then for $y \in \mathbb{R}^+$,

$$\text{ScaledInvChiSquare}(y|\nu, \sigma) = \frac{(\nu/2)^{\nu/2}}{\Gamma(\nu/2)} \sigma^\nu y^{-(\nu/2+1)} \exp\left(-\frac{1}{2} \nu \sigma^2 \frac{1}{y}\right).$$

Sampling Statement

$y \sim \text{scaled_inv_chi_square}(\text{nu}, \text{sigma});$
Increment target log probability density with
`scaled_inv_chi_square_lpdf(y | nu, sigma)`, dropping constant additive terms.

Stan Functions

`real scaled_inv_chi_square_lpdf(reals y | reals nu, reals sigma)`
The log of the scaled inverse Chi-square density of y given degrees of freedom nu and scale $sigma$

`real scaled_inv_chi_square_cdf(reals y, reals nu, reals sigma)`
The scaled inverse Chi-square cumulative distribution function of y given degrees of freedom nu and scale $sigma$

`real scaled_inv_chi_square_lcdf(reals y | reals nu, reals sigma)`
The log of the scaled inverse Chi-square cumulative distribution function of y given degrees of freedom nu and scale $sigma$

`real scaled_inv_chi_square_lccdf(reals y | reals nu, reals sigma)`
The log of the scaled inverse Chi-square complementary cumulative distribution function of y given degrees of freedom nu and scale $sigma$

`R scaled_inv_chi_square_rng(reals nu, reals sigma)`
Generate a scaled inverse Chi-squared variate with degrees of freedom nu and scale $sigma$; may only be used in generated quantities block. For a description of argument and return types, see Section 10.8.3.

16.5. Exponential Distribution

Probability Density Function

If $\beta \in \mathbb{R}^+$, then for $y \in \mathbb{R}^+$,

$$\text{Exponential}(y|\beta) = \beta \exp(-\beta y).$$

Sampling Statement

$y \sim \text{exponential}(\text{beta});$

Increment target log probability density with `exponential_lpdf(y | beta)`, dropping constant additive terms.

Stan Functions

`real exponential_lpdf(reals y | reals beta)`

The log of the exponential density of y given inverse scale *beta*

`real exponential_cdf(reals y, reals beta)`

The exponential cumulative distribution function of y given inverse scale *beta*

`real exponential_lcdf(reals y | reals beta)`

The log of the exponential cumulative distribution function of y given inverse scale *beta*

`real exponential_lccdf(reals y | reals beta)`

The log of the exponential complementary cumulative distribution function of y given inverse scale *beta*

`R exponential_rng(reals beta)`

Generate an exponential variate with inverse scale *beta*; may only be used in generated quantities block. For a description of argument and return types, see [Section 10.8.3](#).

16.6. Gamma Distribution

Probability Density Function

If $\alpha \in \mathbb{R}^+$ and $\beta \in \mathbb{R}^+$, then for $y \in \mathbb{R}^+$,

$$\text{Gamma}(y|\alpha, \beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} y^{\alpha-1} \exp(-\beta y).$$

Sampling Statement

$y \sim \text{gamma}(\alpha, \beta);$
Increment target log probability density with `gamma_lpdf(y | α , β)`, dropping constant additive terms.

Stan Functions

`real gamma_lpdf(reals y | reals α , reals β)`
The log of the gamma density of y given shape α and inverse scale β

`real gamma_cdf(reals y, reals α , reals β)`
The cumulative gamma distribution function of y given shape α and inverse scale β

`real gamma_lcdf(reals y | reals α , reals β)`
The log of the cumulative gamma distribution function of y given shape α and inverse scale β

`real gamma_lccdf(reals y | reals α , reals β)`
The log of the complementary cumulative gamma distribution function of y given shape α and inverse scale β

`R gamma_rng(reals α , reals β)`
Generate a gamma variate with shape α and inverse scale β ; may only be used in generated quantities block. For a description of argument and return types, see Section 10.8.3.

16.7. Inverse Gamma Distribution

Probability Density Function

If $\alpha \in \mathbb{R}^+$ and $\beta \in \mathbb{R}^+$, then for $y \in \mathbb{R}^+$,

$$\text{InvGamma}(y|\alpha, \beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} y^{-(\alpha+1)} \exp\left(-\beta \frac{1}{y}\right).$$

Sampling Statement

$y \sim \text{inv_gamma}(\alpha, \beta);$
Increment target log probability density with `inv_gamma_lpdf(y | α , β)`, dropping constant additive terms.

Stan Functions

real **inv_gamma_lpdf**(reals y | reals $alpha$, reals $beta$)

The log of the inverse gamma density of y given shape $alpha$ and scale $beta$

real **inv_gamma_cdf**(reals y , reals $alpha$, reals $beta$)

The inverse gamma cumulative distribution function of y given shape $alpha$ and scale $beta$

real **inv_gamma_lcdf**(reals y | reals $alpha$, reals $beta$)

The log of the inverse gamma cumulative distribution function of y given shape $alpha$ and scale $beta$

real **inv_gamma_lccdf**(reals y | reals $alpha$, reals $beta$)

The log of the inverse gamma complementary cumulative distribution function of y given shape $alpha$ and scale $beta$

R **inv_gamma_rng**(reals $alpha$, reals $beta$)

Generate an inverse gamma variate with shape $alpha$ and scale $beta$; may only be used in generated quantities block. For a description of argument and return types, see Section 10.8.3.

16.8. Weibull Distribution

Probability Density Function

If $\alpha \in \mathbb{R}^+$ and $\sigma \in \mathbb{R}^+$, then for $y \in [0, \infty)$,

$$\text{Weibull}(y|\alpha, \sigma) = \frac{\alpha}{\sigma} \left(\frac{y}{\sigma}\right)^{\alpha-1} \exp\left(-\left(\frac{y}{\sigma}\right)^\alpha\right).$$

Note that if $Y \propto \text{Weibull}(\alpha, \sigma)$, then $Y^{-1} \propto \text{Frechet}(\alpha, \sigma^{-1})$.

Sampling Statement

$y \sim \text{weibull}(alpha, sigma);$

Increment target log probability density with `weibull_lpdf(y | alpha, sigma)`, dropping constant additive terms.

Stan Functions

real **weibull_lpdf**(reals y | reals α , reals σ)

The log of the Weibull density of y given shape α and scale σ

real **weibull_cdf**(reals y , reals α , reals σ)

The Weibull cumulative distribution function of y given shape α and scale σ

real **weibull_lcdf**(reals y | reals α , reals σ)

The log of the Weibull cumulative distribution function of y given shape α and scale σ

real **weibull_lccdf**(reals y | reals α , reals σ)

The log of the Weibull complementary cumulative distribution function of y given shape α and scale σ

R **weibull_rng**(reals α , reals σ)

Generate a weibull variate with shape α and scale σ ; may only be used in generated quantities block. For a description of argument and return types, see Section 10.8.3.

16.9. Fréchet Distribution

Probability Density Function

If $\alpha \in \mathbb{R}^+$ and $\sigma \in \mathbb{R}^+$, then for $y \in \mathbb{R}^+$,

$$\text{Frechet}(y|\alpha, \sigma) = \frac{\alpha}{\sigma} \left(\frac{y}{\sigma}\right)^{-\alpha-1} \exp\left(-\left(\frac{y}{\sigma}\right)^{-\alpha}\right).$$

Note that if $Y \propto \text{Frechet}(\alpha, \sigma)$, then $Y^{-1} \propto \text{Weibull}(\alpha, \sigma^{-1})$.

Sampling Statement

$y \sim \text{frechet}(\alpha, \sigma);$

Increment target log probability density with `frechet_lpdf(y | α , σ)`, dropping constant additive terms.

Stan Functions

real **frechet_lpdf**(reals y | reals α , reals σ)

The log of the Fréchet density of y given shape α and scale σ

real **frechet_cdf**(reals y , reals α , reals σ)

The Fréchet cumulative distribution function of y given shape α and scale σ

real **frechet_lcdf**(reals y | reals α , reals σ)

The log of the Fréchet cumulative distribution function of y given shape α and scale σ

real **frechet_lccdf**(reals y | reals α , reals σ)

The log of the Fréchet complementary cumulative distribution function of y given shape α and scale σ

R **frechet_rng**(reals α , reals σ)

Generate an Fréchet variate with shape α and scale σ ; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

17. Non-negative Continuous Distributions

The non-negative continuous probability functions have support on the non-negative real numbers.

17.1. Rayleigh Distribution

Probability Density Function

If $\sigma \in \mathbb{R}^+$, then for $y \in [0, \infty)$,

$$\text{Rayleigh}(y|\sigma) = \frac{y}{\sigma^2} \exp(-y^2/2\sigma^2).$$

Sampling Statement

$y \sim \text{rayleigh}(\text{sigma});$

Increment target log probability density with `rayleigh_lpdf(y | sigma)`, dropping constant additive terms.

Stan Functions

`real rayleigh_lpdf(reals y | reals sigma)`

The log of the Rayleigh density of y given scale sigma

`real rayleigh_cdf(real y, real sigma)`

The Rayleigh cumulative distribution of y given scale sigma

`real rayleigh_lcdf(real y | real sigma)`

The log of the Rayleigh cumulative distribution of y given scale sigma

`real rayleigh_lccdf(real y | real sigma)`

The log of the Rayleigh complementary cumulative distribution of y given scale sigma

`R rayleigh_rng(reals sigma)`

Generate a Rayleigh variate with scale sigma ; may only be used in generated quantities block. For a description of argument and return types, see [Section 10.8.3](#).

17.2. Wiener First Passage Time Distribution

Probability Density Function

If $\alpha \in \mathbb{R}^+$, $\tau \in \mathbb{R}^+$, $\beta \in [0, 1]$ and $\delta \in \mathbb{R}$, then for $y > \tau$,

$$\text{Wiener}(y|\alpha, \tau, \beta, \delta) = \frac{\alpha^3}{(y - \tau)^{3/2}} \exp\left(-\delta\alpha\beta - \frac{\delta^2(y - \tau)}{2}\right) \sum_{k=-\infty}^{\infty} (2k + \beta) \phi\left(\frac{2k\alpha + \beta}{\sqrt{y - \tau}}\right)$$

where $\phi(x)$ denotes the standard normal density function; see (Feller, 1968; Navarro and Fuss, 2009).

Sampling Statement

$y \sim \text{wiener}(\text{alpha}, \text{tau}, \text{beta}, \text{delta});$
Increment target log probability density with `wiener_lpdf(y | alpha, tau, beta, delta)`, dropping constant additive terms.

Stan Functions

```
real wiener_lpdf(reals y | reals alpha, reals tau, reals beta,  
                 reals delta)
```

The log of the Wiener first passage time density of y given boundary separation *alpha*, non-decision time *tau*, a-priori bias *beta* and drift rate *delta*

Boundaries

Stan returns the first passage time of the accumulation process over the upper boundary only. To get the result for the lower boundary, use

$$\text{wiener}(y|\alpha, \tau, 1 - \beta, -\delta)$$

For more details, see the appendix of Vandekerckhove and Wabersich (2014).

18. Positive Lower-Bounded Probabilities

The positive lower-bounded probabilities have support on real values above some positive minimum value.

18.1. Pareto Distribution

Probability Density Function

If $y_{\min} \in \mathbb{R}^+$ and $\alpha \in \mathbb{R}^+$, then for $y \in \mathbb{R}^+$ with $y \geq y_{\min}$,

$$\text{Pareto}(y|y_{\min}, \alpha) = \frac{\alpha y_{\min}^{\alpha}}{y^{\alpha+1}}.$$

Sampling Statement

$y \sim \text{pareto}(y_{\min}, \alpha);$
Increment target log probability density with `pareto_lpdf(y | y_min, alpha)`, dropping constant additive terms.

Stan Functions

```
real pareto_lpdf(reals y | reals y_min, reals alpha)
  The log of the Pareto density of  $y$  given positive minimum value  $y_{\min}$  and shape  $\alpha$ 
```

```
real pareto_cdf(reals y, reals y_min, reals alpha)
  The Pareto cumulative distribution function of  $y$  given positive minimum value  $y_{\min}$  and shape  $\alpha$ 
```

```
real pareto_lcdf(reals y | reals y_min, reals alpha)
  The log of the Pareto cumulative distribution function of  $y$  given positive minimum value  $y_{\min}$  and shape  $\alpha$ 
```

```
real pareto_lccdf(reals y | reals y_min, reals alpha)
  The log of the Pareto complementary cumulative distribution function of  $y$  given positive minimum value  $y_{\min}$  and shape  $\alpha$ 
```

```
R pareto_rng(reals y_min, reals alpha)
```

Generate a Pareto variate with positive minimum value y_{\min} and shape α ; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

18.2. Pareto Type 2 Distribution

Probability Density Function

If $\mu \in \mathbb{R}$, $\lambda \in \mathbb{R}^+$, and $\alpha \in \mathbb{R}^+$, then for $y \geq \mu$,

$$\text{Pareto_Type_2}(y|\mu, \lambda, \alpha) = \frac{\alpha}{\lambda} \left(1 + \frac{y - \mu}{\lambda}\right)^{-(\alpha+1)}.$$

Note that the Lomax distribution is a Pareto Type 2 distribution with $\mu = 0$.

Sampling Statement

$y \sim \text{pareto_type_2}(\mu, \lambda, \alpha);$

Increment target log probability density with `pareto_type_2_lpdf(y | mu, lambda, alpha)`, dropping constant additive terms.

Stan Functions

```
real pareto_type_2_lpdf(reals y | reals mu, reals lambda,  
                      reals alpha)
```

The log of the Pareto Type 2 density of y given location μ , scale λ , and shape α

```
real pareto_type_2_cdf(reals y, reals mu, reals lambda,  
                      reals alpha)
```

The Pareto Type 2 cumulative distribution function of y given location μ , scale λ , and shape α

```
real pareto_type_2_lcdf(reals y | reals mu, reals lambda,  
                      reals alpha)
```

The log of the Pareto Type 2 cumulative distribution function of y given location μ , scale λ , and shape α

```
real pareto_type_2_lccdf(reals y | reals mu, reals lambda,  
                      reals alpha)
```

The log of the Pareto Type 2 complementary cumulative distribution function of y given location μ , scale λ , and shape α

```
R pareto_type_2_rng(reals mu, reals lambda, reals alpha)
```

Generate a Pareto Type 2 variate with location μ , scale λ , and shape α ; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

19. Continuous Distributions on [0, 1]

The continuous distributions with outcomes in the interval [0, 1] are used to characterize bounded quantities, including probabilities.

19.1. Beta Distribution

Probability Density Function

If $\alpha \in \mathbb{R}^+$ and $\beta \in \mathbb{R}^+$, then for $\theta \in (0, 1)$,

$$\text{Beta}(\theta|\alpha, \beta) = \frac{1}{B(\alpha, \beta)} \theta^{\alpha-1} (1 - \theta)^{\beta-1},$$

where the beta function $B()$ is as defined in Section 3.13.

Warning: If $\theta = 0$ or $\theta = 1$, then the probability is 0 and the log probability is $-\infty$. Similarly, the distribution requires strictly positive parameters, $\alpha, \beta > 0$.

Sampling Statement

`theta ~ beta(alpha, beta);`

Increment target log probability density with `beta_lpdf(theta | alpha, beta)`, dropping constant additive terms.

Stan Functions

`real beta_lpdf(reals theta | reals alpha, reals beta)`

The log of the beta density of `theta` in [0, 1] given positive prior successes (plus one) `alpha` and prior failures (plus one) `beta`

`real beta_cdf(reals theta, reals alpha, reals beta)`

The beta cumulative distribution function of `theta` in [0, 1] given positive prior successes (plus one) `alpha` and prior failures (plus one) `beta`

`real beta_lcdf(reals theta | reals alpha, reals beta)`

The log of the beta cumulative distribution function of `theta` in [0, 1] given positive prior successes (plus one) `alpha` and prior failures (plus one) `beta`

`real beta_lccdf(reals theta | reals alpha, reals beta)`

The log of the beta complementary cumulative distribution function of `theta` in [0, 1] given positive prior successes (plus one) `alpha` and prior failures (plus one) `beta`

R **beta_rng**(reals *alpha*, reals *beta*)

Generate a beta variate with positive prior successes (plus one) *alpha* and prior failures (plus one) *beta*; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

20. Circular Distributions

Circular distributions are defined for finite values y in any interval of length 2π .

20.1. Von Mises Distribution

Probability Density Function

If $\mu \in \mathbb{R}$ and $\kappa \in \mathbb{R}^+$, then for $y \in \mathbb{R}$,

$$\text{VonMises}(y|\mu, \kappa) = \frac{\exp(\kappa \cos(y - \mu))}{2\pi I_0(\kappa)}.$$

In order for this density to properly normalize, y must be restricted to some interval $(c, c + 2\pi)$ of length 2π , because

$$\int_c^{c+2\pi} \text{VonMises}(y|\mu, \kappa) dy = 1.$$

Similarly, if μ is a parameter, it will typically be restricted to the same range as y .

A von Mises distribution with its 2π interval of support centered around its location μ will have a single mode at μ ; for example, restricting y to $(-\pi, \pi)$ and taking $\mu = 0$ leads to a single local optimum at the model μ . If the location μ is not in the center of the support, the density is circularly translated and there will be a second local maximum at the boundary furthest from the mode. Ideally, the parameterization and support will be set up so that the bulk of the probability mass is in a continuous interval around the mean μ .

Sampling Statement

```
y ~ von_mises(mu, kappa);
```

Increment target log probability density with `von_mises_lpdf(y | mu, kappa)`, dropping constant additive terms.

Stan Functions

```
R von_mises_lpdf(reals y | reals mu, reals kappa)
```

The log of the von mises density of y given location mu and scale $kappa$. For a description of argument and return types, see Section [10.8.3](#).

```
R von_mises_rng(reals mu, reals kappa)
```

Generate a Von Mises variate with location mu and scale $kappa$ (i.e. returns

values in the interval $[(\mu \bmod 2\pi) - \pi, (\mu \bmod 2\pi) + \pi]$; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

Numerical Stability

Evaluating the Von Mises distribution for $\kappa > 100$ is numerically unstable in the current implementation. Nathanael I. Lichti suggested the following workaround on the Stan users group, based on the fact that as $\kappa \rightarrow \infty$,

$$\text{VonMises}(y|\mu, \kappa) \rightarrow \text{Normal}(\mu, \sqrt{1/\kappa}).$$

The workaround is to replace `y ~ von_mises(mu, kappa)` with

```
if (kappa < 100)
  y ~ von_mises(mu, kappa);
else
  y ~ normal(mu, sqrt(1 / kappa));
```

21. Bounded Continuous Probabilities

The bounded continuous probabilities have support on a finite interval of real numbers.

21.1. Uniform Distribution

Probability Density Function

If $\alpha \in \mathbb{R}$ and $\beta \in (\alpha, \infty)$, then for $y \in [\alpha, \beta]$,

$$\text{Uniform}(y|\alpha, \beta) = \frac{1}{\beta - \alpha}.$$

Sampling Statement

$y \sim \text{uniform}(\alpha, \beta);$

Increment target log probability density with `uniform_lpdf(y | α , β)`, dropping constant additive terms.

Stan Functions

`real uniform_lpdf(reals y | reals α , reals β)`

The log of the uniform density of y given lower bound α and upper bound β

`real uniform_cdf(reals y, reals α , reals β)`

The uniform cumulative distribution function of y given lower bound α and upper bound β

`real uniform_lcdf(reals y | reals α , reals β)`

The log of the uniform cumulative distribution function of y given lower bound α and upper bound β

`real uniform_lccdf(reals y | reals α , reals β)`

The log of the uniform complementary cumulative distribution function of y given lower bound α and upper bound β

`R uniform_rng(reals α , reals β)`

Generate a uniform variate with lower bound α and upper bound β ; may only be used in generated quantities block. For a description of argument and return types, see Section [10.8.3](#).

22. Distributions over Unbounded Vectors

The unbounded vector probability distributions have support on all of \mathbb{R}^K for some fixed K .

22.1. Multivariate Normal Distribution

Probability Density Function

If $K \in \mathbb{N}$, $\mu \in \mathbb{R}^K$, and $\Sigma \in \mathbb{R}^{K \times K}$ is symmetric and positive definite, then for $y \in \mathbb{R}^K$,

$$\text{MultiNormal}(y|\mu, \Sigma) = \frac{1}{(2\pi)^{K/2}} \frac{1}{\sqrt{|\Sigma|}} \exp\left(-\frac{1}{2}(y - \mu)^\top \Sigma^{-1} (y - \mu)\right),$$

where $|\Sigma|$ is the absolute determinant of Σ .

Sampling Statement

$y \sim \text{multi_normal}(\mu, \Sigma);$
Increment target log probability density with `multi_normal_lpdf(y | μ , Σ)`, dropping constant additive terms.

Stan Functions

The multivariate normal probability function is overloaded to allow the variate vector y and location vector μ to be vectors or row vectors (or to mix the two types). The density function is also vectorized, so it allows arrays of row vectors or vectors as arguments; see Section 10.8.1 for a description of vectorization.

```
real multi_normal_lpdf(vectors y | vectors mu, matrix Sigma)
```

The log of the multivariate normal density of vector(s) y given location vector(s) μ and covariance matrix Σ

```
real multi_normal_lpdf(vectors y | row_vectors mu, matrix Sigma)
```

The log of the multivariate normal density of vector(s) y given location row vector(s) μ and covariance matrix Σ

```
real multi_normal_lpdf(row_vectors y | vectors mu, matrix Sigma)
```

The log of the multivariate normal density of row vector(s) y given location vector(s) μ and covariance matrix Σ

real **multi_normal_lpdf**(row_vectors y | row_vectors μ , matrix Σ)

The log of the multivariate normal density of row vector(s) y given location row vector(s) μ and covariance matrix Σ

Although there is a direct multi-normal RNG function, if more than one result is required, it's much more efficient to Cholesky factor the covariance matrix and call **multi_normal_cholesky_rng**; see Section 22.3.

vector **multi_normal_rng**(vector μ , matrix Σ)

Generate a multivariate normal variate with location μ and covariance matrix Σ ; may only be used in generated quantities block

vector **multi_normal_rng**(row_vector μ , matrix Σ)

Generate a multivariate normal variate with location μ and covariance matrix Σ ; may only be used in generated quantities block

vectors **multi_normal_rng**(vectors μ , matrix Σ)

Generate an array of multivariate normal variates with locations μ and covariance matrix Σ ; may only be used in generated quantities block

vectors **multi_normal_rng**(row_vectors μ , matrix Σ)

Generate an array of multivariate normal variates with locations μ and covariance matrix Σ ; may only be used in generated quantities block

22.2. Multivariate Normal Distribution, Precision Parameterization

Probability Density Function

If $K \in \mathbb{N}$, $\mu \in \mathbb{R}^K$, and $\Omega \in \mathbb{R}^{K \times K}$ is symmetric and positive definite, then for $y \in \mathbb{R}^K$,

$$\text{MultiNormalPrecision}(y|\mu, \Omega) = \text{MultiNormal}(y|\mu, \Sigma^{-1})$$

Sampling Statement

$y \sim \text{multi_normal_prec}(\mu, \Omega);$

Increment target log probability density with **multi_normal_prec_lpdf**(y | μ , Ω), dropping constant additive terms.

Stan Functions

```
real multi_normal_prec_lpdf(vectors y | vectors mu,  
                             matrix Omega)
```

The log of the multivariate normal density of vector(s) y given location vector(s) μ and positive definite precision matrix Ω

```
real multi_normal_prec_lpdf(vectors y | row_vectors mu,  
                             matrix Omega)
```

The log of the multivariate normal density of vector(s) y given location row vector(s) μ and positive definite precision matrix Ω

```
real multi_normal_prec_lpdf(row_vectors y | vectors mu,  
                             matrix Omega)
```

The log of the multivariate normal density of row vector(s) y given location vector(s) μ and positive definite precision matrix Ω

```
real multi_normal_prec_lpdf(row_vectors y | row_vectors mu,  
                             matrix Omega)
```

The log of the multivariate normal density of row vector(s) y given location row vector(s) μ and positive definite precision matrix Ω

22.3. Multivariate Normal Distribution, Cholesky Parameterization

Probability Density Function

If $K \in \mathbb{N}$, $\mu \in \mathbb{R}^K$, and $L \in \mathbb{R}^{K \times K}$ is lower triangular and such that LL^\top is positive definite, then for $y \in \mathbb{R}^K$,

$$\text{MultiNormalCholesky}(y|\mu, L) = \text{MultiNormal}(y|\mu, LL^\top).$$

If L is lower triangular and LL^{top} is a $K \times K$ positive definite matrix, then $L_{k,k}$ must be strictly positive for $k \in 1:K$. If an L is provided that is not the Cholesky factor of a positive-definite matrix, the probability functions will raise errors.

Sampling Statement

```
y ~ multi_normal_cholesky(mu, L);  
Increment      target      log      probability      density      with  
multi_normal_cholesky_lpdf(y | mu, L), dropping constant additive  
terms.
```

Stan Functions

real multi_normal_cholesky_lpdf(vectors y | vectors μ ,
matrix L)

The log of the multivariate normal density of vector(s) y given location vector(s) μ and lower-triangular Cholesky factor of the covariance matrix L

real multi_normal_cholesky_lpdf(vectors y | row_vectors μ ,
matrix L)

The log of the multivariate normal density of vector(s) y given location row vector(s) μ and lower-triangular Cholesky factor of the covariance matrix L

real multi_normal_cholesky_lpdf(row_vectors y | vectors μ ,
matrix L)

The log of the multivariate normal density of row vector(s) y given location vector(s) μ and lower-triangular Cholesky factor of the covariance matrix L

real multi_normal_cholesky_lpdf(row_vectors y | row_vectors μ ,
matrix L)

The log of the multivariate normal density of row vector(s) y given location row vector(s) μ and lower-triangular Cholesky factor of the covariance matrix L

vector multi_normal_cholesky_rng(vector μ , matrix L)

Generate a multivariate normal variate with location μ and lower-triangular Cholesky factor of the covariance matrix L ; may only be used in generated quantities block

vector multi_normal_cholesky_rng(row_vector μ , matrix L)

Generate a multivariate normal variate with location μ and lower-triangular Cholesky factor of the covariance matrix L ; may only be used in generated quantities block

vectors multi_normal_cholesky_rng(vectors μ , matrix L)

Generate an array of multivariate normal variates with locations μ and lower-triangular Cholesky factor of the covariance matrix L ; may only be used in generated quantities block

vectors multi_normal_cholesky_rng(row_vectors μ , matrix L)

Generate an array of multivariate normal variates with locations μ and lower-triangular Cholesky factor of the covariance matrix L ; may only be used in generated quantities block

22.4. Multivariate Gaussian Process Distribution

Probability Density Function

If $K, N \in \mathbb{N}$, $\Sigma \in \mathbb{R}^{N \times N}$ is symmetric, positive definite kernel matrix and $w \in \mathbb{R}^K$ is a vector of positive inverse scales, then for $y \in \mathbb{R}^{K \times N}$,

$$\text{MultiGP}(y|\Sigma, w) = \prod_{i=1}^K \text{MultiNormal}(y_i|0, w_i^{-1}\Sigma),$$

where y_i is the i th row of y . This is used to efficiently handle Gaussian Processes with multi-variate outputs where only the output dimensions share a kernel function but vary based on their scale. Note that this function does not take into account the mean prediction.

Sampling Statement

```
y ~ multi_gp(Sigma, w);  
Increment target log probability density with multi_gp_lpdf(y | Sigma, w),  
dropping constant additive terms.
```

Stan Functions

```
real multi_gp_lpdf(matrix y | matrix Sigma, vector w)  
The log of the multivariate GP density of matrix  $y$  given kernel matrix  $\Sigma$   
and inverses scales  $w$ 
```

22.5. Multivariate Gaussian Process Distribution, Cholesky parameterization

Probability Density Function

If $K, N \in \mathbb{N}$, $L \in \mathbb{R}^{N \times N}$ is lower triangular and such that LL^\top is positive definite kernel matrix (implying $L_{n,n} > 0$ for $n \in 1:N$), and $w \in \mathbb{R}^K$ is a vector of positive inverse scales, then for $y \in \mathbb{R}^{K \times N}$,

$$\text{MultiGPCholesky}(y | L, w) = \prod_{i=1}^K \text{MultiNormal}(y_i|0, w_i^{-1}LL^\top),$$

where y_i is the i th row of y . This is used to efficiently handle Gaussian Processes with multi-variate outputs where only the output dimensions share a kernel function but vary based on their scale. If the model allows parameterization in terms of Cholesky

factor of the kernel matrix, this distribution is also more efficient than `MultiGP()`. Note that this function does not take into account the mean prediction.

Sampling Statement

$y \sim \text{multi_gp_cholesky}(L, w);$

Increment target log probability density with `multi_gp_cholesky_lpdf(y | L, w)`, dropping constant additive terms.

Stan Functions

`real multi_gp_cholesky_lpdf(matrix y | matrix L, vector w)`

The log of the multivariate GP density of matrix y given lower-triangular Cholesky factor of the kernel matrix L and inverses scales w

22.6. Multivariate Student- t Distribution

Probability Density Function

If $K \in \mathbb{N}$, $\nu \in \mathbb{R}^+$, $\mu \in \mathbb{R}^K$, and $\Sigma \in \mathbb{R}^{K \times K}$ is symmetric and positive definite, then for $y \in \mathbb{R}^K$,

`MultiStudentT(y| ν, μ, Σ)`

$$= \frac{1}{\pi^{K/2}} \frac{1}{\nu^{K/2}} \frac{\Gamma((\nu + K)/2)}{\Gamma(\nu/2)} \frac{1}{\sqrt{|\Sigma|}} \left(1 + \frac{1}{\nu} (y - \mu)^\top \Sigma^{-1} (y - \mu) \right)^{-(\nu+K)/2}.$$

Sampling Statement

$y \sim \text{multi_student_t}(nu, mu, Sigma);$

Increment target log probability density with `multi_student_t_lpdf(y | nu, mu, Sigma)`, dropping constant additive terms.

Stan Functions

`real multi_student_t_lpdf(vectors y | real nu, vectors mu, matrix Sigma)`

The log of the multivariate Student- t density of vector(s) y given degrees of freedom nu , location vector(s) mu , and scale matrix $Sigma$

real multi_student_t_lpdf(vectors y | real nu , row_vectors mu ,
matrix $Sigma$)

The log of the multivariate Student- t density of vector(s) y given degrees of freedom nu , location row vector(s) mu , and scale matrix $Sigma$

real multi_student_t_lpdf(row_vectors y | real nu , vectors mu ,
matrix $Sigma$)

The log of the multivariate Student- t density of row vector(s) y given degrees of freedom nu , location vector(s) mu , and scale matrix $Sigma$

real multi_student_t_lpdf(row_vectors y | real nu , row_vectors mu ,
matrix $Sigma$)

The log of the multivariate Student- t density of row vector(s) y given degrees of freedom nu , location row vector(s) mu , and scale matrix $Sigma$

vector multi_student_t_rng(real nu , vector mu , matrix $Sigma$)

Generate a multivariate Student- t variate with degrees of freedom nu , location mu , and scale matrix $Sigma$; may only be used in generated quantities block

vector multi_student_t_rng(real nu , row_vector mu , matrix $Sigma$)

Generate a multivariate Student- t variate with degrees of freedom nu , location mu , and scale matrix $Sigma$; may only be used in generated quantities block

vectors multi_student_t_rng(real nu , vectors mu , matrix $Sigma$)

Generate an array of multivariate Student- t variates with degrees of freedom nu , locations mu , and scale matrix $Sigma$; may only be used in generated quantities block

vectors multi_student_t_rng(real nu , row_vectors mu , matrix $Sigma$)

Generate an array of multivariate Student- t variates with degrees of freedom nu , locations mu , and scale matrix $Sigma$; may only be used in generated quantities block

22.7. Gaussian Dynamic Linear Models

A Gaussian Dynamic Linear model is defined as follows, For $t \in 1, \dots, T$,

$$y_t \sim N(F' \theta_t, V)$$

$$\theta_t \sim N(G \theta_{t-1}, W)$$

$$\theta_0 \sim N(m_0, C_0)$$

where y is $n \times T$ matrix where rows are variables and columns are observations. These functions calculate the log-likelihood of the observations marginalizing over the latent states ($p(y|F, G, V, W, m_0, C_0)$). This log-likelihood is a system that is calculated using the Kalman Filter. If V is diagonal, then a more efficient algorithm which sequentially processes observations and avoids a matrix inversions can be used ([Durbin and Koopman, 2001](#), Sec 6.4).

Sampling Statement

```
 $y \sim \text{gaussian\_d1m\_obs}(F, G, V, W, m0, C0);$ 
```

Increment target log probability density with `gaussian_d1m_obs_lpdf(y | F, G, V, W, m0, C0)`, dropping constant additive terms.

Stan Functions

The following two functions differ in the type of their V , the first taking a full observation covariance matrix V and the second a vector V representing the diagonal of the observation covariance matrix. The sampling statement defined in the previous section works with either type of observation V .

```
real gaussian_d1m_obs_lpdf(matrix y | matrix F, matrix G, matrix V,  
                           matrix W, vector m0, matrix C0)
```

The log of the density of the Gaussian Dynamic Linear model with observation matrix y in which rows are variables and columns are observations, design matrix F , transition matrix G , observation covariance matrix V , system covariance matrix W , and the initial state is distributed normal with mean $m0$ and covariance $C0$.

```
real gaussian_d1m_obs_lpdf(matrix y | matrix F, matrix G, vector V,  
                           matrix W, vector m0, matrix C0)
```

The log of the density of the Gaussian Dynamic Linear model with observation matrix y in which rows are variables and columns are observations, design matrix F , transition matrix G , observation covariance matrix with diagonal V , system covariance matrix W , and the initial state is distributed normal with mean $m0$ and covariance $C0$.

23. Simplex Distributions

The simplex probabilities have support on the unit K -simplex for a specified K . A K -dimensional vector θ is a unit K -simplex if $\theta_k \geq 0$ for $k \in \{1, \dots, K\}$ and $\sum_{k=1}^K \theta_k = 1$.

23.1. Dirichlet Distribution

Probability Density Function

If $K \in \mathbb{N}$ and $\alpha \in (\mathbb{R}^+)^K$, then for $\theta \in K$ -simplex,

$$\text{Dirichlet}(\theta|\alpha) = \frac{\Gamma\left(\sum_{k=1}^K \alpha_k\right)}{\prod_{k=1}^K \Gamma(\alpha_k)} \prod_{k=1}^K \theta_k^{\alpha_k-1}.$$

Warning: If any of the components of θ satisfies $\theta_i = 0$ or $\theta_i = 1$, then the probability is 0 and the log probability is $-\infty$. Similarly, the distribution requires strictly positive parameters, with $\alpha_i > 0$ for each i .

Meaning of Dirichlet Parameters

A symmetric Dirichlet prior is $[\alpha, \dots, \alpha]^\top$. To code this in Stan,

```
data {  
  int<lower = 1> K;  
  real<lower = 0> alpha;  
}  
generated quantities {  
  vector[K] theta = dirichlet_rng(rep_vector(alpha, K));  
}
```

Taking $K = 10$, here are the first five draws for $\alpha = 0.001$. For $\alpha = 1$, the distribution is uniform over simplexes.

```
1) 0.17 0.05 0.07 0.17 0.03 0.13 0.03 0.03 0.27 0.05  
2) 0.08 0.02 0.12 0.07 0.52 0.01 0.07 0.04 0.01 0.06  
3) 0.02 0.03 0.22 0.29 0.17 0.10 0.09 0.00 0.05 0.03  
4) 0.04 0.03 0.21 0.13 0.04 0.01 0.10 0.04 0.22 0.18  
5) 0.11 0.22 0.02 0.01 0.06 0.18 0.33 0.04 0.01 0.01
```

That does not mean it's uniform over the marginal probabilities of each element. As the size of the simplex grows, the marginal draws become more and more concentrated below (not around) $1/K$. When one component of the simplex is large, the

others must all be relatively small to compensate. For example, in a uniform distribution on 10-simplexes, the probability that a component is greater than the mean of $1/10$ is only 39%. Most of the posterior marginal probability mass for each component is in the interval $(0, 0.1)$.

When the α value is small, the draws gravitate to the corners of the simplex. Here are the first five draws for $\alpha = 0.001$.

```
1) 3e-203 0e+00 2e-298 9e-106 1e+000 0e+00 0e+000 1e-047 0e+00 4e-279
2) 1e+000 0e+00 5e-279 2e-014 1e-275 0e+00 3e-285 9e-147 0e+00 0e+000
3) 1e-308 0e+00 1e-213 0e+000 0e+000 8e-75 0e+000 1e+000 4e-58 7e-112
4) 6e-166 5e-65 3e-068 3e-147 0e+000 1e+00 3e-249 0e+000 0e+00 0e+000
5) 2e-091 0e+00 0e+000 0e+000 1e-060 0e+00 4e-312 1e+000 0e+00 0e+000
```

Each row denotes a draw. Each draw has a single value that rounds to one and other values that are very close to zero or rounded down to zero.

As α increases, the draws become increasingly uniform. For $\alpha = 1000$,

```
1) 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10
2) 0.10 0.10 0.09 0.10 0.10 0.10 0.11 0.10 0.10 0.10
3) 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10
4) 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10
5) 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10 0.10
```

Sampling Statement

```
theta ~ dirichlet(alpha);
```

Increment target log probability density with `dirichlet_lpdf(theta | alpha)`, dropping constant additive terms.

Stan Functions

```
real dirichlet_lpdf(vector theta | vector alpha)
```

The log of the Dirichlet density for simplex *theta* given prior counts (plus one) *alpha*

```
vector dirichlet_rng(vector alpha)
```

Generate a Dirichlet variate with prior counts (plus one) *alpha*; may only be used in generated quantities block

24. Correlation Matrix Distributions

The correlation matrix distributions have support on the (Cholesky factors of) correlation matrices. A Cholesky factor L for a $K \times K$ correlation matrix Σ of dimension K has rows of unit length so that the diagonal of LL^\top is the unit K -vector. Even though models are usually conceptualized in terms of correlation matrices, it is better to operationalize them in terms of their Cholesky factors. If you are interested in the posterior distribution of the correlations, you can recover them in the generated quantities block via

```
generated quantities {  
  corr_matrix[K] Sigma;  
  Sigma = multiply_lower_tri_self_transpose(L);  
}
```

24.1. LKJ Correlation Distribution

Probability Density Function

For $\eta > 0$, if Σ a positive-definite, symmetric matrix with unit diagonal (i.e., a correlation matrix), then

$$\text{LkjCorr}(\Sigma|\eta) \propto \det(\Sigma)^{(\eta-1)}.$$

The expectation is the identity matrix for any positive value of the shape parameter η , which can be interpreted like the shape parameter of a symmetric beta distribution:

- if $\eta = 1$, then the density is uniform over correlation matrices of order K ;
- if $\eta > 1$, the identity matrix is the modal correlation matrix, with a sharper peak in the density at the identity matrix for larger η ; and
- for $0 < \eta < 1$, the density has a trough at the identity matrix.
- if η were an unknown parameter, the Jeffreys prior is proportional to $\sqrt{2 \sum_{k=1}^{K-1} \left(\psi_1 \left(\eta + \frac{K-k-1}{2} \right) - 2\psi_1(2\eta + K - k - 1) \right)}$, where $\psi_1(\cdot)$ is the trigamma function

See (Lewandowski et al., 2009) for definitions. However, it is much better computationally to work directly with the Cholesky factor of Σ , so this distribution should never be explicitly used in practice.

Sampling Statement

```
y ~ lkj_corr(eta);
```

Increment target log probability density with `lkj_corr_lpdf(y | eta)`, dropping constant additive terms.

Stan Functions

```
real lkj_corr_lpdf(matrix y | real eta)
```

The log of the LKJ density for the correlation matrix `y` given nonnegative shape `eta`. The only reason to use this density function is if you want the code to run slower and consume more memory with more risk of numerical errors. Use its Cholesky factor as described in the next section.

```
matrix lkj_corr_rng(int K, real eta)
```

Generate a LKJ random correlation matrix of order `K` with shape `eta`; may only be used in generated quantities block

24.2. Cholesky LKJ Correlation Distribution

Stan provides an implicit parameterization of the LKJ correlation matrix density in terms of its Cholesky factor, which you should use rather than the explicit parameterization in the previous section. For example, if `L` is a Cholesky factor of a correlation matrix, then

```
L ~ lkj_corr_cholesky(2.0);  
# implies L * L' ~ lkj_corr(2.0);
```

Because Stan requires models to have support on all valid constrained parameters, `L` will almost always ¹ be a parameter declared with the type of a Cholesky factor for a correlation matrix; for example,

```
parameters {  
  cholesky_factor_corr[K] L;  
  # rather than corr_matrix[K] Sigma;  
  // ...
```

¹It is possible to build up a valid `L` within Stan, but that would then require Jacobian adjustments to imply the intended posterior.

Probability Density Function

For $\eta > 0$, if L is a $K \times K$ lower-triangular Cholesky factor of a symmetric positive-definite matrix with unit diagonal (i.e., a correlation matrix), then

$$\text{LkjCholesky}(L|\eta) \propto |J| \det(LL^\top)^{(\eta-1)} = \prod_{k=2}^K L_{kk}^{K-k+2\eta-2}.$$

See the previous section for details on interpreting the shape parameter η . Note that even if $\eta = 1$, it is still essential to evaluate the density function because the density of L is not constant, regardless of the value of η , even though the density of LL^\top is constant iff $\eta = 1$.

A lower triangular L is a Cholesky factor for a correlation matrix if and only if $L_{k,k} > 0$ for $k \in 1:K$ and each row L_k has unit Euclidean length.

Sampling Statement

$L \sim \text{lkj_corr_cholesky}(\eta);$

Increment target log probability density with `lkj_corr_cholesky_lpdf(L | η)`, dropping constant additive terms.

Stan Functions

`real lkj_corr_cholesky_lpdf(matrix L | real η)`

The log of the LKJ density for the lower-triangular Cholesky factor L of a correlation matrix given shape η .

`matrix lkj_corr_cholesky_rng(int K, real η)`

Generate a random Cholesky factor of a correlation matrix of order K that is distributed LKJ with shape η ; may only be used in generated quantities block

25. Covariance Matrix Distributions

The covariance matrix distributions have support on symmetric, positive-definite $K \times K$ matrices.

25.1. Wishart Distribution

Probability Density Function

If $K \in \mathbb{N}$, $\nu \in (K - 1, \infty)$, and $S \in \mathbb{R}^{K \times K}$ is symmetric and positive definite, then for symmetric and positive-definite $W \in \mathbb{R}^{K \times K}$,

$$\text{Wishart}(W|\nu, S) = \frac{1}{2^{\nu K/2}} \frac{1}{\Gamma_K\left(\frac{\nu}{2}\right)} |S|^{-\nu/2} |W|^{(\nu-K-1)/2} \exp\left(-\frac{1}{2} \text{tr}(S^{-1}W)\right),$$

where $\text{tr}()$ is the matrix trace function, and $\Gamma_K()$ is the multivariate Gamma function,

$$\Gamma_K(x) = \frac{1}{\pi^{K(K-1)/4}} \prod_{k=1}^K \Gamma\left(x + \frac{1-k}{2}\right).$$

Sampling Statement

$W \sim \text{wishart}(nu, Sigma);$

Increment target log probability density with `wishart_lpdf(W | nu , $Sigma$)`, dropping constant additive terms.

Stan Functions

`real wishart_lpdf(matrix W | real nu , matrix $Sigma$)`

The log of the Wishart density for symmetric and positive-definite matrix W given degrees of freedom nu and symmetric and positive-definite scale matrix $Sigma$

`matrix wishart_rng(real nu , matrix $Sigma$)`

Generate a Wishart variate with degrees of freedom nu and symmetric and positive-definite scale matrix $Sigma$; may only be used in generated quantities block

25.2. Inverse Wishart Distribution

Probability Density Function

If $K \in \mathbb{N}$, $\nu \in (K - 1, \infty)$, and $S \in \mathbb{R}^{K \times K}$ is symmetric and positive definite, then for symmetric and positive-definite $W \in \mathbb{R}^{K \times K}$,

$$\text{InvWishart}(W|\nu, S) = \frac{1}{2^{\nu K/2}} \frac{1}{\Gamma_K\left(\frac{\nu}{2}\right)} |S|^{\nu/2} |W|^{-(\nu+K+1)/2} \exp\left(-\frac{1}{2} \text{tr}(SW^{-1})\right).$$

Sampling Statement

$W \sim \text{inv_wishart}(\nu, S);$

Increment target log probability density with `inv_wishart_lpdf(W | nu, Sigma)`, dropping constant additive terms.

Stan Functions

`real inv_wishart_lpdf(matrix W | real nu, matrix Sigma)`

The log of the inverse Wishart density for symmetric and positive-definite matrix W given degrees of freedom ν and symmetric and positive-definite scale matrix $Sigma$

`matrix inv_wishart_rng(real nu, matrix Sigma)`

Generate an inverse Wishart variate with degrees of freedom ν and symmetric and positive-definite scale matrix $Sigma$; may only be used in generated quantities block

A. Mathematical Functions

This appendix provides the definition of several mathematical functions used throughout the manual.

A.1. Beta

The beta function, $B(\alpha, \beta)$, computes the normalizing constant for the beta distribution, and is defined for $a > 0$ and $b > 0$ by

$$B(a, b) = \int_0^1 u^{a-1} (1-u)^{b-1} du = \frac{\Gamma(a) \Gamma(b)}{\Gamma(a+b)}.$$

A.2. Incomplete Beta

The incomplete beta function, $B(x; a, b)$, is defined for $x \in [0, 1]$ and $a, b \geq 0$ such that $a + b \neq 0$ by

$$B(x; a, b) = \int_0^x u^{a-1} (1-u)^{b-1} du,$$

where $B(a, b)$ is the beta function defined in Section A.1. If $x = 1$, the incomplete beta function reduces to the beta function, $B(1; a, b) = B(a, b)$.

The regularized incomplete beta function divides the incomplete beta function by the beta function,

$$I_x(a, b) = \frac{B(x; a, b)}{B(a, b)}.$$

A.3. Gamma

The gamma function, $\Gamma(x)$, is the generalization of the factorial function to continuous variables, defined so that for positive integers n ,

$$\Gamma(n+1) = n!$$

Generalizing to all positive numbers and non-integer negative numbers,

$$\Gamma(x) = \int_0^\infty u^{x-1} \exp(-u) du.$$

A.4. Digamma

The digamma function Ψ is the derivative of the $\log \Gamma$ function,

$$\Psi(u) = \frac{d}{du} \log \Gamma(u) = \frac{1}{\Gamma(u)} \frac{d}{du} \Gamma(u).$$

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