The Julia Express

Bogumił Kamiński

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Contents

1 Introduction

The purpose of this document is to introduce programmers to the Julia programming by example. This is a simplified exposition of the language.[1]

It is simplest to execute these examples by copy-pasting to the Julia REPL (`https://docs.julialang.org/en/latest/stdlib/REPL/`) or copying them to a file and next running them using `include` function. The difference is that copy-paste approach will echo output of each instruction to the terminal.

If some package is missing on your system switch to the package manager mode by pressing `]` in the Julia REPL, and then write `add [package name]` to require installing it.

Over the years of using Julia I have learned that for each project you have it is best to have a separate project environment that keeps track of its dependencies. You can check out this blog post `https://bkamins.github.io/julialang/2020/05/18/project-workflow.html` to read more about it.

This is an introductory document. Important topics that a person learning the Julia should be aware of, that are not covered are:

1) parametric types;
2) parallel and distributed processing;
3) advanced I/O operations;
4) advanced package management;
5) interaction with system shell; see `run`;
6) exception handling; see `try`;
7) creation of coroutines;
8) integration with C, Fortran, Python and R.

You can read about them in the latest Julia documentation at `http://julia.readthedocs.org/en/latest/manual/`.

The Julia Express was tested using the following 64-bit Julia version (you can check your version by calling running `versioninfo()` in your Julia session):

```
Julia Version 1.8.4
Commit 00177ebc4f (2022-12-23 21:32 UTC)
Platform Info:
  OS: Windows (x86_64-w64-mingw32)
  CPU: 12 x Intel(R) Core(TM) i7-10850H CPU @ 2.70GHz
  WORD_SIZE: 64
  LIBM: libopenlibm
  LLVM: libLLVM-13.0.1 (ORCJIT, skylake)
  Threads: 1 on 12 virtual cores
```

If you prefer to read this document in a different format than PDF then the simplest approach to do it is to clone the project repository `https://github.com/bkamins/The-Julia-Express` to your local folder and use Pandoc to perform an appropriate conversion. For instance running the command

```
pandoc -i julia_express.tex -f latex -t html5 -s -o julia_express.html
```

will produce you a HTML output.

All suggestions how this guide can be improved are welcomed. Please contact me at bkamins@sgh.waw.pl.

2 Getting around

Running `julia` invokes an interactive (REPL) mode. In this mode some useful commands are:

1) `^D` (exits Julia);
2) `^C` (interrupts computations);
3) `?` (enters help mode);
4) `;` (enters system shell mode);
5) `]` (enters package manager mode);
6) `Ctrl-l` clears screen;
7) putting `;` after the expression will disable showing its value in REPL (not needed in scripts).

Examples of some essential functions in the Julia REPL (they can be also invoked in scripts):

```
  @edit max(1,2)      # show the definition of max function when invoked with arguments 1 and 2
  varinfo()           # list of global variables and their types
```

[1]The rocket ship clip is free for download at `http://www.clipartlord.com/free-cartoon-rocketship-clip-art-2/`.

```
cd("D:/")           # change working directory to D:/ (on Windows you can use /)
pwd()               # get current working directory
include("file.jl")  # execute source file
exit(1)             # exit Julia with code 1 (exit code 0 is used by default)
clipboard([1,2])    # copy data to system clipboard
clipboard()         # load data from system clipboard as a string
```

You can execute a Julia script from OS shell by running `julia script.jl`.

Try saving the following example script to a file and run it (more examples of all the constructs used are given in following sections):

```
"""Sieve of Eratosthenes function docstring"""
function es(n::Int) # accepts one integer argument
    isprime = trues(n) # n-element vector of true-s
    isprime[1] = false # 1 is not a prime
    for i in 2:isqrt(n) # loop integers less or equal than sqrt(n)
        if isprime[i] # conditional evaluation
            for j in i^2:i:n # sequence with step i
                isprime[j] = false
            end
        end
    end
    return filter(x -> isprime[x], 1:n) # filter using an anonymous function
end

println(es(100))        # print all primes less or equal than 100
@time length(es(10^6))   # check function execution time and memory usage
```

3 Basic literals and types

Basic scalar literals are the following:

```
1::Int       # 64 bit integer on 64 bit Julia, no overflow warnings
1.0::Float64 # 64 bit float, defines NaN, -Inf, Inf
true::Bool   # boolean, allows "true" and "false"
'c'::Char    # character, allows Unicode
"s"::String  # strings, allows Unicode, see also Strings below
```

The syntax `x::Type` is a literal `x` with type `Type` assertion. In practice the type assertion is not needed. Here we use it only to show the type of each kind of a literal. All basic types listed above are immutable.

Type assertions for variables are made in the same way and they can be useful to catch bugs in your code.

An important feature of integers in Julia is that by default they are 64 bit on 64 bit Julia and 32 bit on 32 bit Julia. This means that `1::Int32` assertion will fail on 64-bit Julia.

Notably `Int` is a constant whose value is either `Int64` or `Int32` depending on version (the same with unsigned integer `UInt`).

There is no automatic type conversion, unless some function explicitly performs it. This is especially important in function calls. The simplest, and preferred, way to perform the construction of a value `x` to type `T` by writing `T(x)`, for example:

```
Int64('a')      # character to integer
Int64(2.0)      # float to integer
Int64(1.3)      # inexact error
Int64("a")      # error no conversion possible
Float64(1)      # integer to float
Bool(1)         # constructs to boolean true
Bool(0)         # constructs to boolean false
Bool(2)         # construction error
Char(89)        # integer to char
string(true)    # cast Bool to string (works with other types, note small caps)
string(1, true) # string can take more than one argument and concatenate them
zero(10.0)      # zero of type of 10.0
```

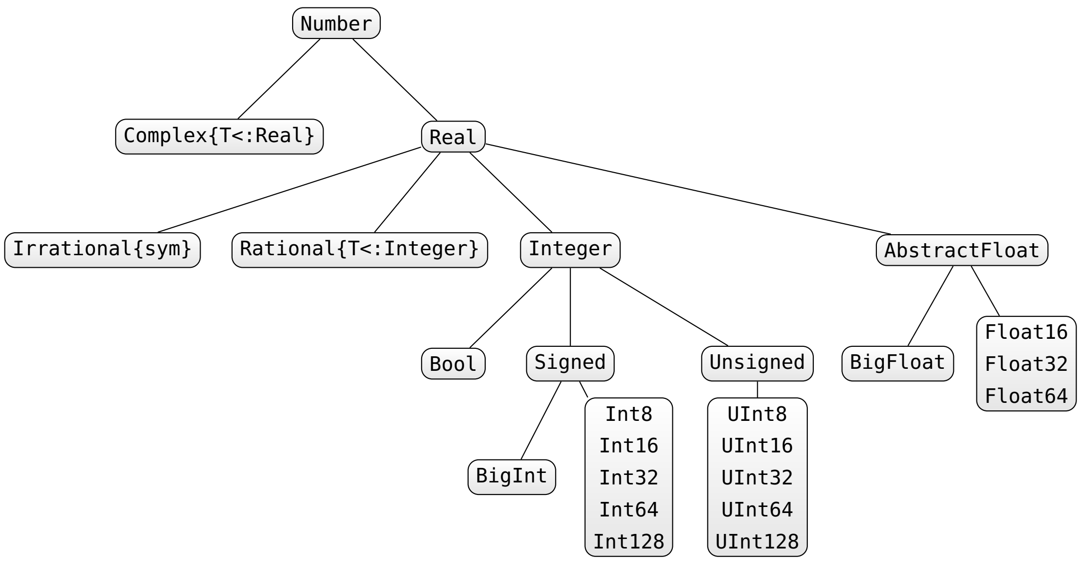


Figure 1: Hierarchy of numeric types

```
one(Int64)      # one of type Int64
```

Conversion can be done using `convert(Type, x)` (typically `convert` will not perform a copy if `x` already has type `Type`; for this reason it is typically preferable to perform construction, as it was explained above, rather than conversion):

```
convert(Int64, 1.0) # convert float to integer
```

Julia is throwing an inexact conversion error, if it cannot perform it exactly.

```
convert(Int64, 1.3) # convert float to integer -> throws inexact conversion error
```

Use `floor(Int64, 1.3)`, `ceil(Int64, 1.3)` or `round(Int64, 1.3)` to perform rounding.
Parsing strings can be done using `parse(Type, str)`:

```
parse(Int64, "1") # parse "1" string as Int64
```

Automatic promotion of many arguments to common type (if any exists) can be achieved using `promote` (typically you will not need to perform such promotion yourself):

```
promote(true, BigInt(1) // 3, 1.0) # tuple (see Tuples) of BigFloats, true promoted to 1.0
promote("a", 1)                    # error, promotion to a common type is not possible
```

Many operations (arithmetic, assignment) are defined in a way that performs automatic type promotion (so this is a way to work around no automatic type conversion rule in Julia).
One can verify type of a value in the following way:

```
typeof("abc")              # String returned which is a AbstractString subtype
isa("abc", AbstractString) # true
isa(1, Float64)            # false, integer is not a float
isa(1.0, Float64)          # true
1.0 isa Number             # an alternative syntax; true, Number is abstract type
supertype(Int64)           # supertype of Int64
subtypes(Real)             # subtypes of abstract type Real
Int <: Real                # true, <: checks if type is subtype of other type
```

It is possible to perform calculations using arbitrary precision arithmetic, complex and rational numbers:

```
BigInt(10) ^ 1000   # big integer
BigFloat(10) ^ 1000 # big float, see documentation how to change default precision
big(1.5)            # value of big type chosen appropriately, in this case BigFloat
1 + 1im             # a complex number
123 // 456          # rational numbers are created using // operator
```

Type hierarchy of all standard numeric types is given in Figure 1.
An important feature is that `Bool` is considered to be `Integer`. This is useful for performing arithmetic operations, but sometimes can be surprising.

4 Special literals and types

```
Any     # all objects are of this type
Union{} # subtype of all types, no object can have this type
Nothing # type indicating nothing (absence of a value), a subtype of Any
nothing # only instance of Nothing
Missing # type indicating missing value (a value exists but is unknown), a subtype of Any
missing # only instance of Missing
```

Additionally `#undef` indicates an incompletely initialized object element (see documentation for details).

4.1 Tuples and NamedTuples

Tuples are immutable sequences indexed from 1:

```
()            # an empty tuple
(1,)          # a one element tuple
("a", 1)      # a two element tuple
('a', false)::Tuple{Char, Bool} # tuple type assertion
x = (1, 2, 3)
x[1]          # 1 (element)
x[1:2]        # (1, 2) (tuple)
x[4]          # bounds error
x[1] = 1      # error - a tuple is not mutable
a, b = x      # tuple unpacking a == 1, b == 2
```

Additionally you can add names to tuple entries (via named tuples):

```
NamedTuple()  # an empty named tuple
(a=1,)        # a one element named tuple
(x="a", y=1)  # a two element named tuple
x = (p=1, q=2, r=3)
x.p           # access to element p of a tuple
typeof(x)     # NamedTuple{(:p, :q, :r),Tuple{Int64,Int64,Int64}}, field names are part of type
a, b, c = x   # NamedTuple also supports unpacking; here we define a, b, and c variables
(; a, b, c)   # a convenience syntax to create a named tuple with a, b, c fields from variables
```

`NamedTuple` can be thought of as an anonymous `struct` — see composite types below (so they behave in a different way than tuples when testing for subtyping). This is an advanced topic that we do not cover in this introduction, see the Julia manual for the details https://docs.julialang.org/en/latest/manual/types/).

4.2 Arrays

Arrays are mutable and passed by reference.
Useful array creation functions are the following:

```
Array{Char}(undef, 2, 3, 4) # uninitialized 2x3x4 array of Chars
Array{Int64}(undef, 0, 0)   # degenerate 0x0 array of Int64
zeros(5)             # vector of Float64 zeros
ones(5)              # vector of Float64 ones
ones(Int64, 2, 1)    # 2x1 array of Int64 ones
trues(3), falses(3)  # a tuple of a vector of trues and a vector of falses
Matrix(I, 3, 3)      # 3x3 Bool identity matrix, requires to run first: using LinearAlgebra
x = range(0, stop=1, length=11) # an iterator having 11 equally spaced elements
collect(x)           # converts an iterator to vector
1:10                 # iterable from 1 to 10
1:2:10               # iterable from 1 to 9 with 2 skip
reshape(1:12, 3, 4)  # a 3x4 matrix like object filled columnwise with values from 1 to 12
fill("a", 2, 2)      # a 2x2 array filled with "a"
repeat(rand(2,2), 3, 2) # a 2x2 random matrix repeated 3x2 times
x = [1, 2]           # a two element vector
resize!(x, 5)        # resize x in place to hold 5 values (filled with garbage)
```

```
[1]                  # a vector with one element (not a scalar)
[1;;]                # a matrix with one element (not a scalar)
[x * y for x in 1:2, y in 1:3] # a comprehension generating 2x3 array
Float64[x^2 for x in 1:4] # casting comprehension result element type to Float64
[1 2]                # 1x2 matrix (hcat function)
[1 2]'               # 2x1 Adjoint matrix (reuses memory)
permutedims([1 2])   # 2x1 matrix (permuted dimensions, new memory)
[1, 2]               # vector (concatenation)
[1; 2]               # vector (vcat function)
[1 2 3; 1 2 3]       # 2x3 matrix (hvcat function)
[1; 2] == [1 2]'     # false, different array dimensions
hcat(1:2)==[1 2]'    # true, dimensions match
[(1, 2)]             # 1-element vector
collect((1, 2))      # 2-element vector by tuple unpacking
[[1 2] 3]            # concatenate along rows (hcat)
[[1; 2]; 3]          # concatenate along columns (vcat)
tuple([1,2,3])       # a 1-element tuple containing a vector
Tuple([1,2,3])       # a 3-element tuple unpacking a vector
```

Vectors (1D arrays) are treated as column vectors.

Most of the functionality for working with matrices are in `LinearAlgebra` module. Additionally Julia offers sparse and distributed matrices (see the documentation for details).

Commonly needed array utility functions:

```
a = [x * y for x in 1:2, y in 1, z in 1:3] # 2x3 array of Int64; a singleton dimension is dropped
a = [x * y for x in 1:2, y in 1:1, z in 1:3] # 2x1x3 array of Int64; a singleton dimension is not dropped
ndims(a)             # number of dimensions in a
eltype(a)            # type of elements in a
length(a)            # number of elements in a
size(a)              # a tuple containing dimension sizes of a
axes(a)              # a tuple of ranges specifying array axes
eachindex(a)         # each index to an array a
CartesianIndices(a)  # a lazy iterator over Cartesian indices into a
LinearIndices(a)     # a lazy iterator over linear indices into a
vec(a)               # cast an array to vector (single dimension); reuses memory
dropdims(a, dims=2)  # remove the 2nd dimension as it has length 1
sum(a, dims=3)       # calculate sums for 3rd dimensions, similarly: mean, std,
                     # prod, minimum, maximum, any, all;
                     # using Statistics is required for statistical functions
count(>(0), a)       # count number of times a predicate is true, similar: all, any
                     # note that we create an anonymous function with >(0) here
```

Access functions:

```
a = 0:0.01:1         # range with step 0.01
a[1]                 # get scalar 0.0
a[begin]             # get scalar 0.0 (first position)
a[end]               # get scalar 1.0 (last position)
a[begin:2:end]       # every second element from range
view(a, 1:2:101)     # a view into a (a subarray of a)
a[[1, 3, 6]]         # 1st, 3rd and 6th element of a, Array{Float64,1}
lastindex(a)         # last index of the collection a; similarly firstindex
```

Observe the treatment of singleton dimensions:

```
a = reshape(1:12, 3, 4)
a[:, 1:2]          # 3x2 matrix
a[:, 1]            # 3 element vector
a[1, :]            # 4 element vector
a[1:1, :]          # 1x4 matrix
a[:, :, 1, 1]      # works 3x4 matrix
a[:, :, :, [true]] # works 3x4x1x1 matrix
a[1, 1, [false]]   # works 0-element Array{Int64,1}
```

Array assignment:

```
x = collect(reshape(1:8, 2, 4))
x[:,2:3] = [1 2]            # error; size mismatch
x[:,2:3] .= [1 2]           # OK, broadcasting with .
x[:,2:3] = repeat([1 2], 2) # OK
x[:,2:3] .= 3               # OK, need to use broadcast with .
```

Arrays are assigned and passed by reference. Therefore copying is provided:

```
x = Array{Any}(undef, 2)
x[1] = ones(2)
x[2] = trues(3)
a = x
b = copy(x)     # shallow copy
c = deepcopy(x) # deep copy
x[1] = "Bang"
x[2][1] = false
a               # identical as x
b               # only x[2][1] changed from the original x
c               # contents of the original x
```

Array types syntax examples:

```
[1 2]::Array{Int64, 2}      # 2 dimensional array of Int64
[true; false]::Vector{Bool} # vector of Bool
[1 2; 3 4]::Matrix{Int64}   # matrix of Int64
```

Numbers are treated as 0-dimensional containers:

```
x = 10    # an integer
x[]       # returns 10
x[1, 1]   # also returns 10, as trailing 1-s are ignored by Julia
size(x)   # an empty tuple
x = [10]  # a one element array can be also indexed with []
x[]       # gets you 10, this will only work for arrays with exactly 1 element
only(x)   # returns the one and only element of x, otherwise errors
```

`Ref` is a special 0-dimensional container that can store any value:

```
x = Ref("a") # an 0-dimensional containers storing "a" string
x[]          # returns "a"
```

4.3 Composite types

You can define and access composite types. Here is an example of a mutable composite type:

```
mutable struct Point
  x::Int64
  y::Float64
  meta
end
p = Point(0, 0.0, "Origin")
p.x               # access field
p.meta = 2        # change field value
p.x = 1.5         # error, wrong data type
p.z = 1           # error - no such field
fieldnames(Point) # get names of type fields
```

Similarly you can define some type to be immutable by removing `mutable` keyword (named tuples are anonymous immutable structs).

There are also union types (see documentation of *Type Unions* in the Julia manual for details).

Finally you can define that your type is a subtype of an abstract type to properly position it in the type hierarchy, or even define your own abstract types (see documentation of *Abstract Types* in the Julia manual for details).

4.4 Dictionaries

Associative collections (key-value dictionaries):

```
x = Dict{Float64, Int64}()        # an empty dictionary mapping floats to integers
y = Dict("a"=>1, "b"=>2)          # a filled dictionary
y["a"]                            # element retrieval
y["c"]                            # error
y["c"] = 3                        # added element
haskey(y, "b")                    # check if y contains key "b"
keys(y), values(y)                # tuple of collections returning keys and values in y
delete!(y, "b")                   # delete a key from a collection, see also: pop!
get(y, "c", "default")            # return y["c"] or "default" if not haskey(y,"c")
```

Julia also supports operations on sets, created similarly with `Set` constructor (please refer to the documentation for details).

5 Strings

String operations:

```
"Hi " * "there!"       # string concatenation
"Ho " ^ 3              # repeat string
string("a = ", 123.3)  # create using print function
repr(123.3)            # fetch value of show function to a string
occursin("CD", "ABCD") # check if the second string contains the first
"\"\n\t\$"             # C-like escaping in strings, new \$ escape
x = 123
"$x + 3 = $(x+3)"      # unescaped $ is used for interpolation
"\$199"                # to get a $ symbol you must escape it
raw"D:\path"           # a raw string literal; useful for paths under Windows
s = "abc"              # a string of type String
chop(s)                # remove last character from s, returns a SubString
```

Both `String` and `SubString` are subtypes of `AbstractString`. The `SubString` type is used to avoid copying of strings. Usually, when writing your own code, it is best to assume that the user will pass an arbitrary `AbstractString`.

PCRE regular expressions handling:

```
r = r"A|B"            # create new regexp
occursin(r, "CD")     # false, no match found
m = match(r, "ACBD") # find first regexp match, see the documentation for details
```

There is a vast number of string functions — please refer to the documentation.

Warning! Note that you can index-into a string, e.g. `"abc"[1]` will return you a character `'a'`. However, in general Julia encodes standard strings using UTF-8 and indexing is based on bytes not characters, so correct string indexing requires you to understand how UTF-8 encoding works. See the documentation for details.

6 Programming constructs

The simplest way to bind a value to a new variable is by an assignment:

```
x = 1.0          # x is bound to Float64 value
x = 1            # now x is bound to value Int32 on 32 bit machine and Int64 on 64 bit machine
```

Expressions can be compound using `;` or `begin end` block:

```
x = (a = 1; 2 * a) # after: x = 2; a = 1
y = begin
  b = 3
  3 * b
end              # after: y = 9; b = 3
```

There are standard programming constructs:

```
if false    # if clause requires Bool test
    z = 1
elseif 1 == 2
    z = 2
else
    a = 3
end         # after this a = 3 and z is undefined

1==2 ? "A" : "B" # standard ternary operator

i = 1
while true
    global i += 1
    if i > 10
      break
    end
end

for x in 1:10    # x in collection, can also use = here instead of in
    if 3 < x < 6
        continue # skip one iteration
    end
    println(x)
end              # x is defined in the inner scope of the loop
```

You can define your own functions:

```
f(x, y = 10) = x + y           # one line definition of a new function f with y defaulting to 10
                               # last expression result returned
function f(x, y=10)            # the same as above but allowing multiple expressions
    x + y                      # in the body of the function
end
f(3, 2)                        # a simple call, 5 returned
f(3)                           # 13 returned
(x -> x^2)(3)                  # an anonymous function with a call example
() -> 0                        # an anonymous function with no arguments
h(x...) = sum(x)/length(x) - mean(x) # a vararg function; x is a tuple; call first: using Statistics
h(1, 2, 3)                     # the result is 0
x = (2, 3)                     # a tuple
f(x)                           # error - we try to add 10 to (2,3)
f(x...)                        # OK - tuple unpacking
s(x; a = 1, b = 1) = x * a / b # function with keyword arguments a and b
s(3, b = 2)                    # call with a keyword argument
q(f::Function, x) = 2 * f(x)   # a function can be passed around; here we require that f is a Function
q(x -> 2x, 10)                 # 40 returned, no need to use * in 2x (means 2*x)
q(10) do x                     # creation of an anonymous function by do construct, useful eg. in IO
  2 * x
end
m = reshape(1:12, 3, 4)
map(x -> x ^ 2, m)             # 3x4 array returned with transformed data
filter(x -> bitstring(x)[end] == '0', 1:12)  # a fancy way to choose even integers from the range
==(1)                          # returns a function that tests for equality to 1
findall(==(1), 1:10)           # find indices of all elements equal to 1, similar: findfirst, findlast
```

As a convention functions with name ending with `!` change their arguments in-place. See for example `resize!` in this document.

Default function arguments are evaluated left to right:

```
y = 10
f1(x=y) = x; f1()      # 10
f2(x=y,y=1) = x; f2()  # 10
f3(y=1,x=y) = x; f3()  # 1
f4(;x=y) = x; f4()     # 10
```

```
f5(;x=y,y=1) = x; f5() # 10
f6(;y=1,x=y) = x; f6() # 1
```

There is an important part of Julia terminology is that a *function* can have multiple *methods*. Each method specifies a behavior of a function for a given set of argument types. This behavior is called multiple dispatch and works only for positional arguments. Here are some short examples. More details are given in *Methods* section of the Julia manual.

```
g(x, y) = println("all accepted") # method for g function accepting any type of x and y
function g(x::Int, y::Int)        # method called when both x and y are Int
  y, x
end
g(x::Int, y::Bool) = x * y        # this will be called when x is Int and y is Bool
g(1.0, 1)                         # the first definition is invoked
g(1, 1)                           # the second definition is invoked
g(1, true)                        # the third definition is invoked
methods(g)                        # list all methods defined for g
t(; x::Int64 = 2) = x             # a single keyword argument
t()                               # 2 returned
t(; x::Bool = true) = x           # no multiple dispatch for keyword arguments; function overwritten
t()                               # true; old function was overwritten
```

7 Variable scoping

The following constructs introduce a new variable scope: `function`, `while`, `for`, `try/catch`, `let`, `struct`, `mutable struct`. Additionally you can define variables as:

- `global`: use variable from a global scope of the current module;
- `local`: define a new variable in a current scope (useful to avoid variable name conflicts, or to make sure variable is present in outer scope; see examples below);
- `const`: signal to the compiler that variable type is constant (global only).

Special cases:

```
t                  # error, a variable t does not exist
f() = global t = 1
f()                # after the call t is defined globally

function f1(n)
  x = 0
  for i = 1:n
    x = i
  end
  x
end
f1(10)            # 10; inside the loop we use the outer local variable

function f2(n)
  x = 0
  for i = 1:n
    local x
    x = i
  end
  x
end
f2(10)            # 0; inside loop we use new local variable

function f3(n)
  for i = 1:n
    h = i
  end
  h
end
f3(10)            # error; h not defined in outer scope

function f4(n)
  local h
  for i = 1:n
    h = i
  end
  h
end
f4(10)            # 10; h is defined in outer scope

const x = 2
x = 3 # warning, value changed; but you should never do this as it might break compiled code
x = 3.0 # error, wrong type

function f()
    x::Int = 1 # this is a way to specify a required type of a variable
    x = 2.5 # error will be thrown when f() is called as x has to have type Int
end
```

Global constants speed up code execution as the compiler knows their type.

Loops and comprehensions rebind variables on each iteration, so they are safe to use then creating closures in iteration:

```
Fs = Array{Any}(undef, 2)
for i in 1:2
  Fs[i] = () -> i
end
Fs[1](), Fs[2]() # (1, 2)
```

Note that `for`, `while`, `try`, and `struct` use a so called *soft* local scope. Simplifying a bit this means that if they are used in a top level (global) scope they overwrite existing global variables if you are in an interactive mode (REPL, notebook):

```
julia> x = 5
5

julia> for i in 1:10
           x = i
       end

julia> x
10
```

However, the same code passed in an non-interactive session prints a warning and does not overwrite a global variable:

```
~$ julia -e "x=5; for i in 1:10 x = i end; println(x)"
| Warning: Assignment to `x` in soft scope is ambiguous because a global variable
by the same name exists: `x` will be treated as a new local. Disambiguate by using
`local x` to suppress this warning or `global x` to assign to the existing global variable.
| @ none:1
5
```

8 Modules

Modules encapsulate code and each module has its own global name space (module name of Julia REPL is `Main`).

```
module M # module name
export x # what module exposes for the world
x = 1
```

```
y = 2 # hidden variable
end

varinfo(M) # list exported variables
x       # not found in global scope
M.y     # direct variable access possible

# import all exported variables
# also load standard packages this way, but without . prefix
using .M

#import variable y to global scope (even if not exported)
import .M.y
```

Rebinding values of variables defined in other modules is not allowed. Here is a short typical example that often surprises people:

```
sin(1) # works
sin = 1 # fails in module Main you cannot rebind a value defined in module Base
cos = 1 # works, as cos was not called yet so it was not imported from Base into Main
cos # gives 1
cos(1) # fails - cos is bound to 1 in the module Main
Base.cos(1) # works
```

9 Operators

Julia follows standard operators with the following quirks:

```
true || false    # binary or operator (singletons only), || and && use short-circuit evaluation
[1 2] .& [2 1]   # bitwise and operator (vectorized by .)
[true, false] .&& [true false] # logical and operator (vectorized by .); the syntax creates truth table
1 < 2 < 3        # chaining conditions is OK (singletons only without .)
[1 2] .< [2 1]   # for vectorized operators need to add '.' in front
x = [1 2 3]
2x + 2(x .+ 1)   # multiplication can be omitted between a literal and a variable or a left parenthesis
y = [1, 2, 3]
x + y  # an error - dimensions do not match
x .+ y # a 3x3 matrix, dimension broadcasting
x + y' # a 1x3 matrix
x * y  # array multiplication, a 1-element vector (not scalar)
x .* y # element-wise multiplication, a 3x3 array

x == [1 2 3]  # true, object looks the same
x === [1 2 3] # false, objects not identical

z = reshape(1:9, 3, 3)
z + x  # error - dimensions do not match
z .+ x # x broadcasted vertically
z .+ y # y broadcasted horizontally

# an explicit broadcast of singleton dimensions
# function + is called for each array element
broadcast(+, [1 2], [1; 2])
# broadcasting using . operator
using Random
length([randstring(10) for i in 1:5]) # 5 - length of an array
length.([randstring(10) for i in 1:5]) # 5-element array of 10s - lengths of strings
```

Function broadcasting examples:

```
t(x::Float64, y::Float64 = 1.0) = x * y
t(1.0, 2.0)               # OK
```

```
t([1.0 2.0])              # error
t.([1.0 2.0])             # OK
t([1.0 2.0], 2.0)         # error
t.([1.0 2.0], 2.0)        # OK
t.(2.0, [1.0 2.0])        # OK
t.([1.0 2.0], [1.0 2.0])  # OK
t.([1.0, 2.0], [1.0 2.0]) # OK
```

10 Essential general usage functions

```
show(collect(1:100)) # show text representation of an object
eps()             # distance from 1.0 to next representable Float64
nextfloat(2.0)    # next float representable, similarly provided prevfloat
isequal(NaN, NaN) # true
NaN == NaN        # false
NaN === NaN       # true
isequal(1, 1.0)   # true
1 == 1.0          # true
1 === 1.0         # false
0.0 == -0.0       # true
0.0 === -0.0      # false
isfinite(Inf)     # false, similarly provided: isinf, isnan
fld(-5, 3), mod(-5, 3) # (-2, 1), division towards minus infinity
div(-5, 3), rem(-5, 3) # (-1, -2), division towards zero
findall(x -> mod(x, 2) == 0, 1:8) # find indices for which function returns true
x = [1 2]; identity(x) === x # true, identity function
@info "Info"      # print information, similarly @warn and @error (see Logging module)
ntuple(x->2x, 3)  # create tuple by calling x->2x with values 1, 2 and 3
@isdefined x      # if variable x is defined
y = Array{Any}(undef,2); isassigned(y, 3)  # is 3 in array is assigned (not out of bounds or #undef)
fieldtype(typeof(1:2),:start) # get type of the field in composite type (passed as symbol)
fieldnames(typeof(1:2)) # get field names of a type
zip(1:3, 1:3) |> collect # convert iterables to iterable tuple and pass it to collect
enumerate("abc")  # create iterator of tuples (index, collection element)
collect(enumerate("abc")) # and materialize it
isempty("abc")    # check if a collection is empty; strings are treated as collections of characters
'b' in "abc"      # check if element is in a collection
indexin(collect("abc"), collect("abrakadabra")) # [1, 2, nothing] ('c' not found), needs arrays
findall(in("abrakadabra"), "abc") # [1, 2] ('c' was not found)
unique("abrakadabra") # return unique elements
issubset("abc", "abcd") # check if every element in the first collection is in the second
argmax("abrakadabra") # an index of maximal element (3 - 'r' in this case)
findmax("abrakadabra") # tuple: a maximal element and its index
filter(x->mod(x,2)==0, 1:10) # retain elements of a collection that meet predicate
dump(1:2:5)       # show all user-visible structure of an object
sort(rand(10))    # sort 10 uniform random values, sort! for in-place operation
```

11 Reading and writing data

For I/O details refer documentation. There are numerous packages providing this functionality. Basic operations from `DelimitedFiles` module:

- `readdlm`: read from file
- `writedlm`: write to a file

Warning! Trailing spaces are not discarded if `delim=' '` in file reading.

12 Random numbers

Basic random numbers:

```
Random.seed!(1) # set random number generator seed to 1; needs calling first: using Random
rand()          # generate random number from U[0,1)
rand(3, 4)      # generate 3x4 matrix of random numbers from U[0,1]
rand(2:5, 10)   # generate vector of 10 random integer numbers in range form 2 to 5
randn(10)       # generate vector of 10 random numbers from standard normal distribution
```

Advanced randomness form Distributions.jl package (version 0.25.79):

```
using Distributions # load package
sample(1:10, 10)    # single bootstrap sample from set 1-10
b = Beta(0.4, 0.8)  # Beta distribution with parameters 0.4 and 0.8
                    # see documentation for supported distributions
mean(b)             # expected value of distribution b
                    # see documentation for other supported statistics
rand(b, 100)        # 100 independent random samples from distribution b
```

13 Statistics and machine learning

Visit `http://juliastats.github.io/` for the details (in particular R-like data frames).
There is a core language construct `Missing` that allows to represent missing value.

```
missing # Missing value
ismissing(missing) # true
coalesce(missing, 1, 2) # return first non-missing value, or missing if all are missing
```

Here are some most basic statistical functions shipped with Julia:

```
using Statistics # module defining the statistical functions
mean([1, 2, 3]) # mean
var([1, 2, 3]) # variance
std([1, 2, 3]) # standard deviation
quantile(1:100, 0.05) # quantiles
median(1:100) # median
cov(1:5, 5:-1:1) # covariance
cor(1:5, 5:-1:1) # Pearson's correlation
```

14 Macros

You can define macros (see documentation for details). Useful standard macros.
Assertions:

```
@assert 1 == 2 "ERROR"             # 2 macro arguments; error raised
using Test                         # load Test package
@test 1 == 2                       # similar to assert; error
@test_throws DomainError sqrt(-1) # passed, sqrt(-1) is not possible
```

Benchmarking:

```
@time [x for x in 1:10^6];    # print time and memory
@timed [x for x in 1:10^6];   # return value, time and memory
@elapsed [x for x in 1:10^6]   # return time
@allocated [x for x in 1:10^6] # return memory
```

Use BenchmarkTools.jl package (version 1.3.2) for a more powerful benchmarking functionality.

15 Plotting

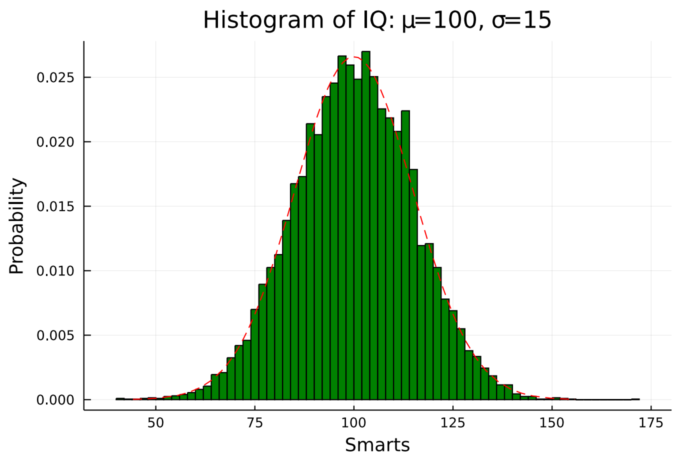
There are several plotting packages for Julia like Plots.jl (which is an umbrella packages for several plotting backends). Here we show how to use it (version 1.38.0):

```
using Plots
using Random
Random.seed!(1) # make the plot reproducible
x, y = 1:100, randn(100)
plot(x, y) # line plot
scatter(x, y) # scatter plot
histogram(y) # histogram
bar(y) # barplot
```

An example reproducing `https://matplotlib.org/1.2.1/examples/pylab_examples/histogram_demo.html` in which we also use StatsPlots.jl package (version 0.15.4):

```
using Distributions
using Plots
using Random
using StatsPlots

Random.seed!(1234)
mu, sigma = 100, 15
x = mu .+ sigma * randn(10000)

histogram(x,
          title="Histogram of IQ: \\mu=100, \\sigma=15",
          label=nothing,
          xlabel="Smarts",
          ylabel="Probability",
          color="green",
          normalize=true)
plot!(Normal(mu, sigma),
      color="red",
      label=nothing,
      linestyle=:dash)
savefig("hist.pdf")
```

producing:



16 Working with tabular data

There are multiple packages supporting tabular data for the Julia language.
Here we will show how DataFrames.jl (version 1.4.4) and CSV.jl (version 0.10.8) packages can be used.
Loading a CSV file:

```
using DataFrames
using CSV
path = joinpath(dirname(pathof(DataFrames)), "../docs/src/assets/iris.csv")
df = CSV.read(path, DataFrame);
first(df, 5) # print first 5 rows of a data frame; use the last function for last rows
```

produces the following output:

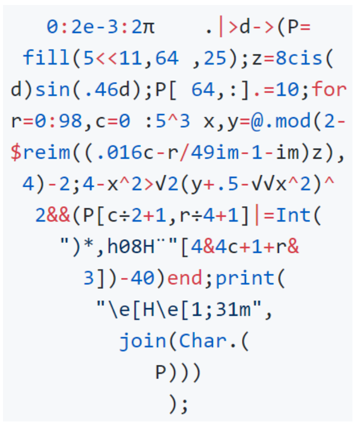
```
5x5 DataFrame
 Row | SepalLength  SepalWidth  PetalLength  PetalWidth  Species
     | Float64      Float64     Float64      Float64     String
---------------------------------------------------------------------
   1 |         5.1         3.5          1.4         0.2  Iris-setosa
   2 |         4.9         3.0          1.4         0.2  Iris-setosa
   3 |         4.7         3.2          1.3         0.2  Iris-setosa
   4 |         4.6         3.1          1.5         0.2  Iris-setosa
   5 |         5.0         3.6          1.4         0.2  Iris-setosa
```

Here is a limited list of most useful operations on a `DataFrame` we have just read in:

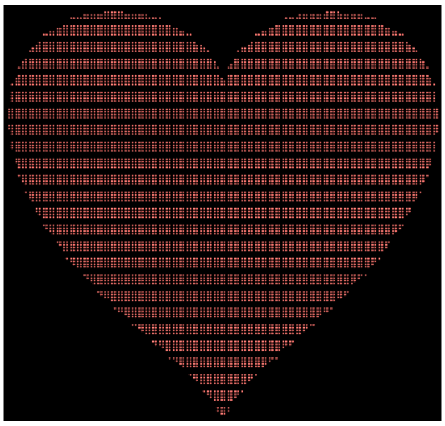
```
DataFrame(a=1:10, b=rand(10)) # manual creation of a DataFrame from a list of columns
describe(df) # get a summary information about a data frame
df.Species # get a column Species from a data frame without copying
df[!, :Species] # the same as above
df[:, :Species] # the same as above, but perform a copy
df[1, 5] # get a value from row 1 and column 5 (Species again) from a DataFrame
df[1:2, 1:2] # subset a data frame getting two first rows and two first columns
Matrix(df[:, 1:4]) # convert columns 1 to 4 to a matrix
names(df) # get column names in the data frame as strings
nrow(df), ncol(df) # number of rows and columns in a data frame
sort(df, :SepalWidth) # return a new data frame that is sorted by SepalWidth column
filter(:SepalWidth =>  >(3), df) # return a new data frame with only rows that meet the predicate
push!(df, (1, 2, 3, 4, "Some species")) # add a new row at the end of the data frame
df.key = axes(df, 1) # add a new variable named key to a data frame

# calculate sum of SepalLength column by Species column and store it in x column
combine(groupby(df, :Species), :SepalLength => sum)

# transform df to long format taking SepalLength as values and key and Species as id variable
df2 = stack(df, :SepalLength, [:key, :Species])
unstack(df2, [:key, :variable], :Species, :value) # a reverse operation - wide to long format
```

17 The Joy of Julia

The Julia language is so flexible that it allows you to transform

this 

```
   0:2e-3:2π    .|>d->(P=
  fill(5<<11,64 ,25);z=8cis(
 d)sin(.46d);P[ 64,:].=10;for
 r=0:98,c=0 :5^3 x,y=@.mod(2-
 $reim((.016c-r/49im-1-im)z),
  4)-2;4-x^2>√2(y+.5-√√x^2)^
   2&&(P[c÷2+1,r÷4+1]|=Int(
     ")*,h08H¨"[4&4c+1+r&
       3])-40)end;print(
        "\e[H\e[1;31m",
          join(Char.(
             P)))
              );
```

to this 

You can fully appreciate it (actually it is an animation of revolving hearts) when you run the code yourself. You can find it here https://github.com/maxbennedich/code-golf/tree/cea06287689868f2342959f9c12f0b629a1d0cf4/hearts.
Please make sure that you run the code on a fast terminal with font that supports Unicode.