Hasso Plattner Institut
Digital Engineering · Universität Potsdam

Advanced Probabilistic Machine Learning

Ralf Herbrich

Julia

Julia

- 2012 developed by Jeff Bezanson, Alan Edelman, Stefan Karpinski and Viral B. Shah at MIT
- Used for numerical and scientific computing with high performance
  - Execution speed is similar to C and FORTRAN
  - Hierarchical and parameterized type system as well as method overloading („multiple dispatching") as central concepts
  - Native calls from C-(compiled) code possible (without wrappers)
- Unicode is efficiently supported (e.g., UTF-8)
- Alongside C, C++ and FORTRAN, the only programming language that has entered the "PetaFlop Club"

Jeff Bezanson (1981–)

Alan Edelman (1963 –)

Stefan Karpsinski (1981–)

Viral Shah

Features of Julia

- **Just-in-time (JIT) compilation implemented using LLVM**
  - Approaching static compilation such as C!
- **Optional typing and type inference**
  - Every object has a type; type declaration *can* be made
  - Types are run-time objects
  - A rich language of types for constructing and describing objects
- **Multiple dispatch**
  - Functions are uniquely defined by their argument types
  - Alternative to classes in object-oriented programming
- **Very simple core language that imposes very little**
  - Julia Base and the standard library are written in Julia itself, including primitive operations like integer arithmetic
- **Language support for meta-programming**
  - Macros are a typed extensions to pre-processors that modify expression trees

Overview

1. Installation
2. Variables and Functions
3. Types
4. Methods & Interfaces
5. Modules

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1. **Installation**
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Command Line Installation

- All resources can be found on https://julialang.org/
- On command line, execute

```
curl -fsSL https://install.julialang.org | sh
```

- This will install the command line interface that can be launched with `julia`

```
               _
   _       _ _(_)_     |  Documentation: https://docs.julialang.org
  (_)     | (_) (_)    |
   _ _   _| |_  __ _   |  Type "?" for help, "]?" for Pkg help.
  | | | | | | |/ _` |  |
  | | |_| | | | (_| |  |  Version 1.10.2 (2024-03-01)
 _/ |\__'_|_|_|\__'_|  |  Official https://julialang.org/ release
|__/                   |
```

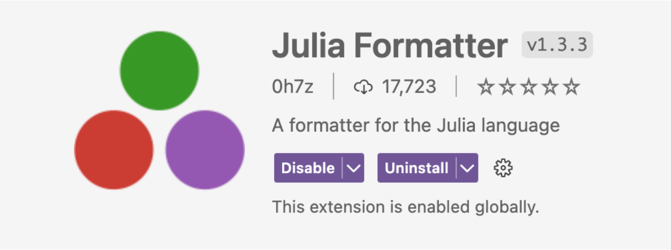
- The installation manager is called `juliaup` and you should regularly run

```
juliaup update
```

- `juliaup` can also be used to install several (older) versions of Julia in parallel!

Visual Studio Code Installation

- VS Code has excellent support for Julia but you should install two packages



- Syntax highlighting
- Integrated Julia REPL
- Code completion
- Linter
- Debugger
- Plot gallery
- Grid viewer for tabular data

- Automatic Julia code formatting

Overview

Julia Variables

- **Variables**: A name associated (or bound) to a value
  - Variables names can contain any Unicode character (best typed by \<LaTeX name>-*tab*

```
julia> δ = 0.00001
1.0e-5

julia> 안녕하세요 = "Hello"
"Hello"
```

- A variable assignment with = *binds* the value but does not change it

```
julia> a = [1,2,3] # an array of 3 integers
3-element Vector{Int64}:
 1
 2
 3

julia> b = a   # both b and a are names for the same array!
3-element Vector{Int64}:
 1
 2
 3

julia> a[1] = 42     # change the first element
42

julia> a = 3.14159   # a is now the name of a different object
3.14159

julia> b   # b refers to the original array object, which has been mutated
3-element Vector{Int64}:
 42
  2
  3
```

Julia Functions

- **Functions**: An object that maps a tuple of argument values to a return value
  - Julia functions are not pure mathematical functions: they can alter and be affected by the global state of the program

Long syntax

```
julia> function f(x,y)
           x + y
       end
f (generic function with 1 method)
```

Short syntax

```
julia> f(x,y) = x + y
f (generic function with 1 method)
```

```
julia> Σ(x,y) = x + y
Σ (generic function with 1 method)
```

- **Function call**: A function is called using parantheses syntax

```
julia> f(2,3)
5
```

```
julia> Σ(2, 3)
5
```

- **Functions are objects**: A function is an object that can be assigned

```
julia> g = f
f (generic function with 1 method)

julia> g(2,3)
5
```

Julia Functions: Arguments and Returns

- **Arguments**: Values are not copied when they are passed to functions
  - Function arguments themselves act as new variable bindings
  - Modifications to mutable values made within a function will be visible to the caller

Function definition

```
julia> function f(x, y)
           x[1] = 42    # mutates x
           y = 7 + y    # new binding for y, no mutation
           return y
       end
f (generic function with 1 method)
```

Function application

```
julia> a = [4,5,6]
3-element Vector{Int64}:
 4
 5
 6

julia> b = 3
3

julia> f(a, b) # returns 7 + b == 10
10

julia> a  # a[1] is changed to 42 by f
3-element Vector{Int64}:
 42
  5
  6

julia> b  # not changed
3
```

  - A common convention is to put an explanation mark in the function name if the function mutates an argument
- **Return**: The value returned by a function is the value of the last expression evaluated
  - The **`return`** keyword causes a function to return immediately

```
julia> function g(x,y)
           return x * y
           x + y
       end
g (generic function with 1 method)

julia> g(2,3)
6
```

Julia Functions: Operators & Anonymous Functions

- **Operators**: Operators are just functions with support for special syntax
  - Can also be applied using parenthesized argument lists
  - Can also be assigned to other variables

```
julia> +(1,2,3)
6
```

```
julia> f = +
+ (generic function with 189 methods)

julia> f(1,2,3)
6
```

- **Operators with Special Names**: A few special expressions correspond to calls to functions with special names
  - These operators can be made work for custom types by defining type-specific methods (see soon!)
- **Anonymous Functions**: A function object without a name
  - In other programming languages, they are called *lambda* functions

Expression	Calls
`[A B C ...]`	`hcat`
`[A; B; C; ...]`	`vcat`
`[A B; C D; ...]`	`hvcat`
`[A; B;; C; D;; ...]`	`hvncat`
`A'`	`adjoint`
`A[i]`	`getindex`
`A[i] = x`	`setindex!`
`A.n`	`getproperty`
`A.n = x`	`setproperty!`

Long syntax

```
julia> function (x)
           x^2 + 2x - 1
       end
#5 (generic function with 1 method)
```

Short syntax

```
julia> x -> x^2 + 2x - 1
#7 (generic function with 1 method)
```

Julia Functions: Control Flow (Conditionals)

- **Compound expressions**: Several sub-expressions that evaluate to the final expression

Long syntax

```
julia> z = begin
           x = 1
           y = 2
           x + y
       end
3
```

Short syntax

```
julia> z = (x = 1; y = 2; x + y)
3
```

- **Conditional evaluation**: Allows portions of code to be evaluated or not evaluated depending on the value of a *Boolean* expression

Function definition

```
julia> function test(x, y)
           if x < y
               println("x is less than y")
           elseif x > y
               println("x is greater than y")
           else
               println("x is equal to y")
           end
       end
test (generic function with 1 method)
```

Function application

```
julia> test(1, 2)
x is less than y

julia> test(2, 1)
x is greater than y

julia> test(1, 1)
x is equal to y
```

- **Ternary Operator**: Shorthand for an `if-then-else-end` expression

```
julia> test(x, y) = println(x < y ? "x is less than y" :
                            x > y ? "x is greater than y" : "x is equal to y")
test (generic function with 1 method)
```

```
julia> test(1, 2)
x is less than y

julia> test(2, 1)
x is greater than y

julia> test(1, 1)
x is equal to y
```

Julia Functions: Control Flow (Loops)

- **`while`-loop**: Evaluates the condition expression and as long it remains true, keeps also evaluating the body of the loop
- **`for`-loop**: Iterates through the container provided
  - A `for`-loop always introduces a new iteration variable in its body, regardless of whether a variable of the same name exists in the enclosing scope (a `while`-loop does not do that)

```
julia> i = 1
1

julia> while i <= 3
           println(i)
           i += 1
       end
1
2
3
```

```
julia> for i = 1:3
           println(i)
       end
1
2
3
```

```
julia> for i in [1,4,0]
           println(i)
       end
1
4
0
```

- **`break`**: Terminate the repetition of a `while`–loop before the test condition is false or stop iterating in a `for`-loop before the end of the iterable object is reached

```
julia> i = 1
1

julia> while true
           println(i)
           if i >= 3
               break
           end
           i += 1
       end
1
2
3
```

```
julia> for j = 1:1000
           println(j)
           if j >= 3
               break
           end
       end
1
2
3
```

Overview

Julia’s Type System

- Julia's type system is **dynamic** (i.e. types are not known until run time)
  - There is no meaningful concept of a "compile-time type”!
  - It is possible to indicate that certain values are of specific types
  - Explicit types are used for method dispatching (see soon!)
- Julia's type system is also **nominative** (i.e., hierarchical relationships between types are explicitly declared
  - Concrete types cannot subtype each other: all concrete types are final
  - Only abstract types can be supertypes
- Julia's type system is also **parametric**
  - Types can be parameterized by other types or by symbols (e.g. numbers)
  - Powerful for container types (e.g., lists)
- **Note**: Only values, not variables, have types!
  - Variables are simply names bound to values
  - "type of a variable" is shorthand for "type of the value to which a variable refers".

Julia Types: Type Declarations

- **`::` operator**: Can be used to attach type annotations to expressions and variables in programs

```
julia> (1+2)::AbstractFloat
ERROR: TypeError: in typeassert, expected AbstractFloat, got a value of type Int64
Stacktrace:
 [1] top-level scope
   @ REPL[27]:1

julia> (1+2)::Int
3
```

- **`typeof`** function: Returns the type of the value that is passed to it
- **Function return types**: Can be specified at function definition

`typeof` function

```
julia> function foo()
                x::Int8 = 100
                x
            end
foo (generic function with 1 method)

julia> x = foo()
100

julia> typeof(x)
Int8
```

Function return type

```
julia> function g(x, y)::Int8
           return x * y
       end;

julia> typeof(g(1, 2))
Int8
```

Julia Types: Abstract Types

- **Abstract Types**: Cannot be instantiated, and serve only as nodes in the type graph
  - Abstract types are declared using the **`abstract type`** keyword

```
abstract type «name» end
abstract type «name» <: «supertype» end
```

- **`:<`** function: Allows to specify a supertype relationship or test for it

Type declarations

```
julia> abstract type Number end
julia> abstract type Real          <: Number end
julia> abstract type AbstractFloat <: Real end
julia> abstract type Integer       <: Real end
julia> abstract type Signed        <: Integer end
julia> abstract type Unsigned      <: Integer end
```

Supertype check

```
julia> Integer <: Number
true

julia> Integer <: AbstractFloat
false
```

- No loss in performance when using function whose arguments are abstract types
  - They are recompiled for each tuple of concrete argument types with which it is invoked!

Julia Types: Primitive Types

- **Primitive Types**: Concrete type whose data consists of plain old bits
  - Primitive types are declared using the **`primitive type`** keyword

```
primitive type «name» «bits» end
primitive type «name» <: «supertype» «bits» end
```

- The number of bits indicates how much storage the type requires

Type declarations

```
julia> primitive type F16       <: AbstractFloat 16 end
julia> primitive type F32       <: AbstractFloat 32 end
julia> primitive type F64       <: AbstractFloat 64 end
julia> primitive type Integer8  <: Signed   8 end
julia> primitive type UInteger8 <: Unsigned 8 end
```

Supertype check

```
julia> Integer8 <: Integer
true
julia> Integer8 <: Real
true
julia> Integer8 <: AbstractFloat
false
```

- Unusual to redefine primitive types as Julia's primitive types are highly performant

Julia Types: Composite Types

- **Composite Types**: A collection of named fields
  - Composite types are declared using the **`struct`** keyword
  - New objects are created by applying the type name as a function *(default constructor)*
  - Fields can be accessed with the property notation <variable>.<fieldname>

```
julia> struct Foo
           bar
           baz::Int
           qux::Float64
       end
```

```
julia> foo = Foo("Hello, world.", 23, 1.5)
Foo("Hello, world.", 23, 1.5)

julia> typeof(foo)
Foo
```

```
julia> foo.bar
"Hello, world."

julia> foo.baz
23

julia> foo.qux
1.5
```

- Composite objects declared with **`struct`** are immutable!
  - Efficient and easier to reason about for the (just-in-time) compiler (can use registers!)
- Composite objects declared with **`mutable struct`** are mutable!
  - Such objects are generally allocated on the heap and have stable memory addresses

```
julia> mutable struct Bar
           baz
           qux::Float64
       end

julia> bar = Bar("Hello", 1.5)
Bar("Hello", 1.5)
```

```
julia> bar.qux = 2.0
2.0

julia> bar.baz = 1//2
1//2
```

Julia Types: Parametric Types

- **Parametric Types**: Types that have parameters that introduce a whole family of new types – one for each possible combination of parameter values
  - Type parameters are introduced after the type name, surrounded by curly braces
  - The type parameter can be any type at all (or a value of any primitive type!)

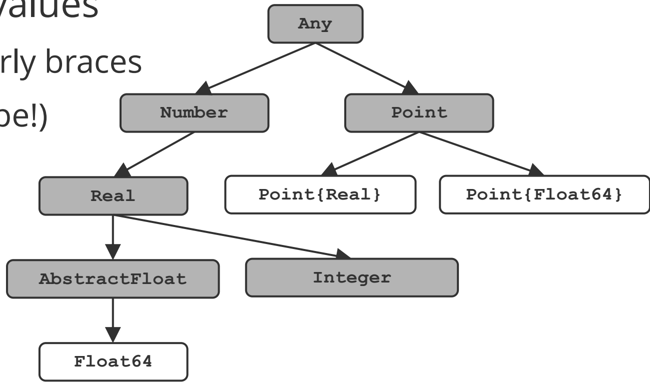
```
julia> struct Point{T}
           x::T
           y::T
       end
```

```
julia> p1 = Point{Float64}(1.0, 2.0)
Point{Float64}(1.0, 2.0)

julia> p2 = Point(1,2)
Point{Int64}(1, 2)

julia> typeof(p1)
Point{Float64}

julia> typeof(p2)
Point{Int64}
```



- The non-parametric type is a super-type of any specialized parametric type!

```
julia> Point{Float64} <: Point
true

julia> Point{Float64} <: Point{Real}
false

julia> Point{Float64} <: Point{<:Real}
true
```

Any type that is a subtype of `Real`

Julia Types: Tuple Types

- **Tuple Types**: Parameterized immutable type where each parameter is the type of one field
  - Tuple types may have any number of type parameters
  - Tuples do not have field names; fields are only accessed by index
  - Tuple types are *covariant* in their parameters

```
julia> struct Tuple2{A,B}
           a::A
           b::B
       end
```

```
julia> x = (1,"foo",2.5)
(1, "foo", 2.5)
```

```
julia> typeof(x)
Tuple{Int64, String, Float64}

julia> x[1]
1
```

```
julia> Tuple{Int,AbstractString} <: Tuple{Real,Any}
true

julia> Tuple{Int,AbstractString} <: Tuple{Real,Real}
false
```

- **Named Tuple Types**: Tuple types with field names
  - Field names can be used to access elements

```
julia> x = (a=1,b="hello")
(a = 1, b = "hello")

julia> y = NamedTuple{(:a, :b)}((1, ""))
(a = 1, b = "")
```

```
julia> typeof(x)
@NamedTuple{a::Int64, b::String}

julia> typeof(y)
@NamedTuple{a::Int64, b::String}
```

```
julia> x.b
"hello"

julia> y.a
1
```

- Tuple types are an abstraction of the arguments of a function

Julia Types: Numbers

- Julia provides a broad range of primitive numeric types
  - **Integers**: Hexadecimal, octal and binary literals are input via **`0x`**, **`0o`** and **`0b`**

```
julia> x = 0x1
0x01
```

```
julia> x = 0o010
0x08
```

```
julia> x = 0b10
0x02
```

  - **Floating Point Numbers**: 64-bit and 32-bit literals are input via <leading digits>**`e`**<exponent> or <leading digits>**`f`**<exponent>

```
julia> 2.5e-4
0.00025

julia> 2.5f-4
0.00025f0
```

```
julia> x = Float32(-1.5)
-1.5f0

julia> sizeof(Float16(4.))
2
```

Type	Signed?	Number of bits	Smallest value	Largest value
`Int8`	✓	8	-2^7	2^7 - 1
`UInt8`		8	0	2^8 - 1
`Int16`	✓	16	-2^15	2^15 - 1
`UInt16`		16	0	2^16 - 1
`Int32`	✓	32	-2^31	2^31 - 1
`UInt32`		32	0	2^32 - 1
`Int64`	✓	64	-2^63	2^63 - 1
`UInt64`		64	0	2^64 - 1
`Int128`	✓	128	-2^127	2^127 - 1
`UInt128`		128	0	2^128 - 1
`Bool`	N/A	8	`false` (0)	`true` (1)

- **Machine epsilon**: Distance between two adjacent floating-point numbers

```
julia> eps(1000.)
1.1368683772161603e-13

julia> eps(0.0)
5.0e-324
```

Type	Precision	Number of bits
`Float16`	half	16
`Float32`	single	32
`Float64`	double	64

- **Arbitrary Precision Arithmetic**: Julia wraps the GMP and GMPFR library

```
julia> string(big"2"^200, base=16)
"100000000000000000000000000000000000000000000000000"

julia> big"1.23456789012345678901"
1.234567890123456789010000000000000000000000000000000000000000000000000000000004
```

Julia Types: Strings

- Strings are finite sequences of characters
  - The built-in concrete type used for strings (and string literals) in Julia is **`String`**
  - It supports the full range of Unicode characters via the UTF-8 encoding
  - String literals are delimited by double quotes or triple double quotes
  - Strings are arrays of characters with the special indexers **`begin`** and **`end`**

```
julia> s2 = "\u2200 x \u2203 y"
"∀ x ∃ y"
```

```
julia> str = "Hello, world.\n"
"Hello, world.\n"

julia> s1 = """Contains "quote" characters"""
"Contains \"quote\" characters"
```

```
julia> str[begin]
'H': ASCII/Unicode U+0048 (category Lu: Letter, uppercase)

julia> str[1]
'H': ASCII/Unicode U+0048 (category Lu: Letter, uppercase)

julia> str[end]
'\n': ASCII/Unicode U+000A (category Cc: Other, control)

julia> str[end-1]
'.': ASCII/Unicode U+002E (category Po: Punctuation, other)
```

- Strings are concatenated with **`*`** and interpolated with **`$`**
  - The shortest complete expression after the **`$`** is taken as the expression whose value is to be interpolated into the string

```
julia> greet * ", " * whom * ".\n"
"Hello, world.\n"

julia> "$greet, $whom.\n"
"Hello, world.\n"
```

```
julia> greet = "Hello"
"Hello"

julia> whom = "world"
"world"
```

- Julia supports regular expression with the **`r`** string prefix for the regex:

```
julia> m = match(r"^\s*(?:#\s*(.*?)\s*$|$)", "# a comment ")
RegexMatch("# a comment ", 1="a comment")
```

Overview

Julia Methods

- A function is an object that maps a tuple of arguments to a return value
  - It is common for the same conceptual function or operation to be implemented quite differently for different types of arguments
- **Method**: A definition of one possible behavior for a function

```
julia> f(x::Float64, y::Float64) = 2x + y
f (generic function with 1 method)
```

```
julia> f(x::Number, y::Number) = 2x - y
f (generic function with 2 methods)
```

```
julia> methods(f)
# 2 methods for generic function "f" from Main:
 [1] f(x::Float64, y::Float64)
     @ REPL[100]:1
 [2] f(x::Number, y::Number)
     @ REPL[101]:1
```

- **Method dispatch**: Choice of method to execute when a function is applied
  - Multiple dispatch: Using all of a function's arguments to choose which method

```
julia> f(2.0, 3.0)
7.0

julia> f(2.0, 3)
1.0
```

```
julia> f("foo", 3)
ERROR: MethodError: no method matching f(::String, ::Int64)

Closest candidates are:
  f(::Number, ::Number)
   @ Main REPL[101]:1
```

```
julia> f(x,y) = println("Whoa there, Nelly.")
f (generic function with 3 methods)

julia> f("foo", 1)
Whoa there, Nelly.
```

Julia Parametric Methods

- Method definitions can have type parameters qualifying the signature

```
julia> same_type(x::T, y::T) where {T} = true
same_type (generic function with 1 method)

julia> same_type(x,y) = false
same_type (generic function with 2 methods)
```

```
julia> same_type(1, 2)
true

julia> same_type(1.0, 2.0)
true
```

```
julia> same_type(1, 2.0)
false

julia> same_type(Int32(1), Int64(2))
false
```

- Similar to subtype constraints on type parameters in type declarations one can also constrain type parameters of methods using **`where`**:

```
julia> same_type_numeric(x::T, y::T) where {T<:Number} = true
same_type_numeric (generic function with 1 method)

julia> same_type_numeric(x::Number, y::Number) = false
same_type_numeric (generic function with 2 methods)
```

```
julia> same_type_numeric(1, 2)
true

julia> same_type_numeric(1.0, 2.0)
true
```

```
julia> same_type_numeric(1, 2.0)
false

julia> same_type_numeric("foo", 2.0)
ERROR: MethodError: no method matching same_type_numeric(::String, ::Float64)
```

- **Constructor methods**: Constructor is just like any other function in Julia
  - Defining a method with the same name as composite type is called an *outer constructor*

```
julia> struct OrderedPair
           x::Real
           y::Real
           OrderedPair(x,y) = x > y ? error("out of order") : new(x,y)
       end
```

```
julia> OrderedPair(a) = OrderedPair(a,a)
OrderedPair

julia> OrderedPair(10)
OrderedPair(10, 10)
```

Julia Interfaces

- **Interface**: By extending a few specific methods to work for a custom type, objects of that type can be used in other methods that are written to generically build upon those behaviors.
- **Example**: Iterator interface

```
for item in iter   # or  "for item = iter"
    # body
end
```

```
next = iterate(iter)
while next !== nothing
    (item, state) = next
    # body
    next = iterate(iter, state)
end
```

Custom type

```
julia> struct Squares
           count::Int
       end
```

Interface definition

```
julia> Base.iterate(S::Squares, state=1) = state > S.count ? nothing : (state*state, state+1)
```

Interface usage

```
julia> for item in Squares(7)
           println(item)
       end
1
4
9
16
25
36
49
```

```
julia> 25 in Squares(10)
true

julia> sum(Squares(100))
338350
```

Julia Interfaces (ctd)

- **Indexing** interface allows any composite type to behave like an array
  - This is true even if the type never explicitly stores an array!
- **Example**: Array of square numbers

```
julia> function Base.getindex(S::Squares, i::Int)
           1 <= i <= S.count || throw(BoundsError(S, i))
           return i*i
       end

julia> Base.length(S::Squares) = S.count

julia> Base.firstindex(S::Squares) = 1

julia> Base.lastindex(S::Squares) = length(S)
```

```
julia> Squares(100)[23]
529

julia> Squares(23)[end]
529
```

Methods to implement	Brief description
`getindex(X, i)`	`X[i]`, indexed element access
`setindex!(X, v, i)`	`X[i] = v`, indexed assignment
`firstindex(X)`	The first index, used in `X[begin]`
`lastindex(X)`	The last index, used in `X[end]`

- The interface even allows to support new indexing modes!

```
julia> Base.getindex(S::Squares, i::Number) = S[convert(Int, i)]

julia> Base.getindex(S::Squares, I) = [S[i] for i in I]
```

```
julia> Squares(10)[[3,4.,5]]
3-element Vector{Int64}:
  9
 16
 25
```

Overview

1. Installation
2. Variables and Functions
3. Types
4. Methods & Interfaces
5. **Modules**

Julia Modules

- **Modules**: Help organize code into coherent units
  - Modules are separate namespaces, each introducing a new global scope
  - Same name can be used for different functions or global variables without conflict
  - Can be precompiled for faster loading, and may contain code for runtime initialization
- **Module Definition**: Using the keywords `module` … `end`
  - Explicit exports of symbols are done with `export`

```
julia> module NiceStuff
       export nice, DOG
       struct Dog end # singleton type, not exported
       const DOG = Dog() # named instance, exported
       nice(x) = "nice $x" # function, exported
       end
Main.NiceStuff
```

- **Module Usage**: Using the keywords `using`
  - Local defined modules start with a dot

```
julia> using .NiceStuff

julia> nice("house 🏠")
"nice house 🏠"
```

Summary

- **Julia Concepts**
  - Runs programs via JIT compilation implemented using LLVM (nearly as fast as C!)
  - Julia is 13 years old and has reached wide-spread adoption in scientific computing
  - Extensibility comes from using *method dispatch* and unbundling functions and data
  - Julia provides garbage collection and requires no explicit memory management
- **Julia Type System**
  - Julia's type system is dynamic, nominative and parametric
  - It only has abstract, primitive and composite types (and the latter ones are all final)
  - Every object has a type; type declaration can be made
- **Julia Methods**
  - A method is the concrete definition of a function's behavior
  - Every function can have many methods; Julia run-time picks the right method based on the types of the arguments *(method dispatch)*
- We only scratched the surface; keep using the language to get confident!

See you next week!