Scientific Computing and (Big) Data Analysis with Julia

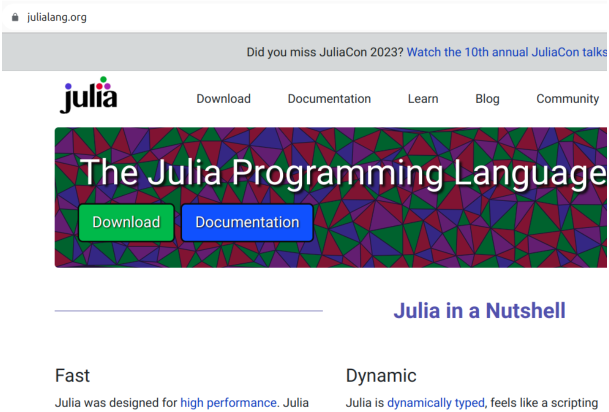
Prof.Dr.Mehmet Hakan Satman
mhsatman@istanbul.edu.tr

Istanbul University

2023.12.01

Julia Programming Language

julialang.org



Julia Programming Language

High Performance Computing & Dynamic

- Julia was designed for high performance. Julia programs automatically compile to efficient native code via LLVM, and support multiple platforms (Windows, MacOS, Linux, etc.).
- Julia is dynamically typed, feels like a scripting language, and has good support for interactive use, but can also optionally be separately compiled[1].

[1] `https://julialang.org/`

Julia Programming Language

Composable & Open Source

- Julia uses multiple dispatch as a paradigm, making it easy to express many object-oriented and functional programming patterns. The talk on the Unreasonable Effectiveness of Multiple Dispatch explains why it works so well.
- Julia is an open source project with over 1,000 contributors. It is made available under the MIT license. The source code is available on GitHub[2].

[2] `https://julialang.org/`

Julia Programming Language

Compilation to Binary

Julia code is compiled into binary executable via LLVM (Low-Level Virtual Machine).

```
julia> @code_native 2 - 5
        .text
        .file   "-"
        .globl  "julia_-_199"                   # -- Begin function julia_-_199
        .p2align        4, 0x90
        .type   "julia_-_199",@function
"julia_-_199":                          # @julia_-_199
; ┌ @ int.jl:86 within `-`
# %bb.0:                                # %top
        push    rbp
        mov     rax, rdi
        mov     rbp, rsp
        sub     rax, rsi
        pop     rbp
        ret
.Lfunc_end0:
        .size   "julia_-_199", .Lfunc_end0-"julia_-_199"
; └
                                        # -- End function
        .section        ".note.GNU-stack","",@progbits
```

Julia Programming Language

First things first!

helloworld.jl file

```
println("Hello, world!")
```

```
julia> include("helloworld.jl")
Hello, world!
```

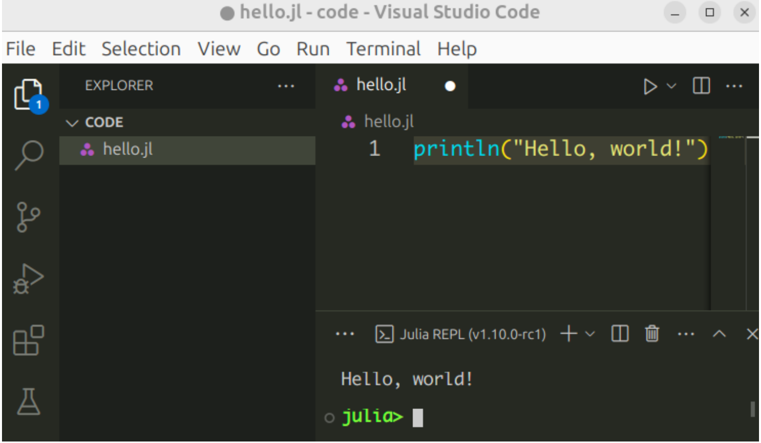
Julia Programming Language

Welcome!

```
               _
   _       _ _(_)_     |  Documentation: https://docs.julialang.org
  (_)     | (_) (_)    |
   _ _   _| |_  __ _   |  Type "?" for help, "]?" for Pkg help.
  | | | | | | |/ _` |  |
  | | |_| | | | (_| |  |  Version 1.10.0-rc1 (2023-11-03)
 _/ |\__'_|_|_|\__'_|  |  Official https://julialang.org/ release
|__/                   |

julia> println("Hello, world!")
Hello, world!

julia>
```

Julia Programming Language

The editor: Visual Studio Code



Julia Programming Language

Basics

Variables have types (Int, Float, Bool, String, etc.)

```
julia> a = 3
3
julia> b = 3.14159265
3.14159265
julia> typeof(a)
Int64
julia> typeof(b)
Float64
```

Julia Programming Language

Vectors

Vectors and Matrices are first-class citizens (no need for external libs)

```
julia> v = [1, 42, -8, 10]
4-element Vector{Int64}:
1
42
-8
10
```

Julia Programming Language

Matrices

```
julia> hcat(zeros(5), ones(5), 1:5, 5:(-1):1)
5x4 Matrix{Float64}:
 0.0  1.0  1.0  5.0
 0.0  1.0  2.0  4.0
 0.0  1.0  3.0  3.0
 0.0  1.0  4.0  2.0
 0.0  1.0  5.0  1.0
```

Julia Programming Language

Matrices

```
julia> m = zeros(5, 3)
5x3 Matrix{Float64}:
0.0  0.0  0.0
0.0  0.0  0.0
0.0  0.0  0.0
0.0  0.0  0.0
0.0  0.0  0.0

julia> size(m)
(5, 3)
```

Julia Programming Language

Installing packages

```
julia> using Pkg
julia> Pkg.add("JMcDM")
```

```
julia> ]
@v1.10) pkg> add JMcDM
```

Julia Programming Language

Importing Data

```
using CSV, DataFrames

mydata = CSV.read("data.csv",
                  delim = ";",
                  DataFrame)

show(mydata)
```

Julia Programming Language

Importing Data

```
julia> using Latexify
julia> latexify(mydata, env = :table) |> println
```

X	Y
1	2
2	4
3	5
4	-1
5	2

Julia Programming Language

if/elseif/else

```
function numberofrealroots(delta)
    if delta > 0
        return 2
    elseif delta == 0
        return 1
    else
        return 0
    end
end
```

Julia Programming Language

Pattern Matching

```julia
using Rematch

function numberofrealroots(delta)
    @match delta begin
        x where x > 0  => 2
        x where x == 0 => 1
        _              => 0
    end
end
```

Julia Programming Language

Loops

For loops are single threaded by design

```
results = zeros(10)

for i in 1:10
    results[i] = dosomethingwith(i)
end
```

Julia Programming Language

Threads

Using multiple threads[3]

```
using Base.Threads

results = zeros(10)

@threads for i in 1:10
    results[i] = dosomethingwith(i)
end
```

[3] # julia -t 10

Julia Programming Language

Distributed Programming

```
julia> using Distributed
julia> addprocs(5);
julia> pmap(abs, [1, 2, -5, 10, 100, -6])
6-element Vector{Int64}:
   1
   2
   5
  10
 100
   6
```

Julia Programming Language

Functions are first-class citizens

```
function apply(f, x)
    return f(x)
end

julia> apply(abs, -10)
10
```

- Functions can take functions as arguments.
- Functions can return functions as values.

Julia Programming Language

Multiple Dispatch

```
struct Point2D
    x::Float64
    y::Float64
end
```

- Structs are user-defined concrete data types.
- An object instance can be created like `Point2D(1, 2)`.
- Object fields can be accessed like `p.x` and `p.y`.

Julia Programming Language

Multiple Dispatch

```
function Base.:+(p::Point2D, other::Point2D)::Point2D
    Point2D(p.x + other.x, p.y + other.y)
end
```

```
julia> Point2D(1, 2) + Point2D(4, 5)
Point2D(5.0, 7.0)
```

- Operator + is overloaded for the type `Point2D`.
- Now, both `2 + 2` and `p1 + p2` are legal Julia codes where `p1` and `p2` are in type of `Point2D`.

Julia Programming Language

Multiple Dispatch

```
function Base.:*(p::Point2D, other::Point2D)::Float64
    return p.x * other.x + p.y * other.x
end
```

```
julia> Point2D(1, 2) * Point2D(4, 5)
12.0
```

- The operator `*` is overloaded for the type `Point2D`.
- `*` now operates like the *dot product* of vectors in linear algebra.

Linear Regression

The formulation

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{1}$$

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x \tag{2}$$

$$\hat{\boldsymbol{\beta}} = (X'X)^{-1}X'y \tag{3}$$

Linear Regression

Sample Data

$$X = \begin{bmatrix} 1 & 1 \\ 1 & 2 \\ 1 & 3 \\ 1 & 4 \\ 1 & 5 \end{bmatrix}, y = \begin{bmatrix} 2 \\ 5 \\ 5 \\ 8 \\ 12 \end{bmatrix} \tag{4}$$

Linear Regression

The Matrix Solution

```
using LinearAlgebra

x = [1, 2, 3, 4, 5]
y = [2, 5, 5, 8, 12]
X = hcat(ones(5), x)
betahats = inv(X'X)X'y
println(betahats)
```

```
julia> include("reg-matrix.jl")
[-0.5, 2.3]
```

Linear Regression

Pseudo Inverse - Numerical Fit

```
x = [1, 2, 3, 4, 5]
y = [2, 5, 5, 8, 12]

betahats = hcat(ones(5), x) \ y
println(betahats)
```

```
julia> include("reg-simple.jl")
[-0.5, 2.3]
```

Linear Regression

The GLM package

```
using GLM

x = [1, 2, 3, 4, 5]
y = [2, 5, 5, 8, 12]

result = lm(hcat(ones(5), x), y)

println(result)
```

Linear Regression

The GLM package - Results

```
julia> include("reg-glm.jl")

Coefficients:
───────────────────────────────
      Coef.   Std. Error      t    Pr(>|t|)  Lower 95%  Upper 95%
───────────────────────────────
x1    -0.5     1.25565    -0.40    0.7171    -4.49605    3.49605
x2     2.3     0.378594    6.08    0.0090     1.09515    3.50485
───────────────────────────────
```

```
julia> GLM.r2(result)
0.9248251748251748
```

MLJ

A Machine Learning Framework for Julia

```
julia> using MLJ
julia> models = MLJ.models()
julia> for m in models
           println(m[:name])
       end
ARDRegressor
AdaBoostClassifier
AdaBoostRegressor
AdaBoostStumpClassifier
...
KMedoids
KNNClassifier
...
NeuralNetworkRegressor
...
RandomForestClassifier
RandomForestImputer
RandomForestRegressor
...
SRRegressor
```

XOR

eXclusive OR

x_1	x_2	y
1	1	0
1	0	1
0	1	1
0	0	0

Table: $y = \text{xor}(x_1, x_2)$

Symbolic Regression

```
using SymbolicRegression, MLJ

x = (
    x1 = Float64[1, 1, 0, 0],
    x2 = Float64[1, 0, 1, 0]
)

y = Float64[0, 1, 1, 0]
```

Symbolic Regression

```
model = SRRegressor(
    niterations = 50,
    binary_operators = [+, -, *],
    unary_operators = [abs],
    should_simplify = true,
    save_to_file = false)
```

Symbolic Regression

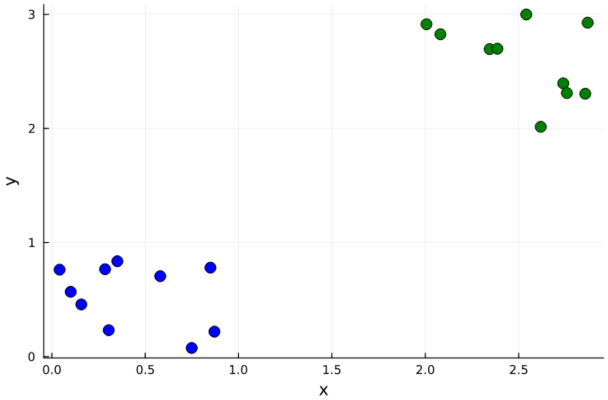
```
mach = machine(model, x, y)
fit!(mach)
report(mach)
@info predict(mach, x)
```

Symbolic Regression

```
Hall of Fame:
------------------
Complexity  Loss       Score      Equation
1           2.500e-01  3.604e+01   y = 0.5
4           0.000e+00  1.201e+01   y = abs(x1 - x2)
--------------------
[ Info: [0.0, 1.0, 1.0, 0.0]
```

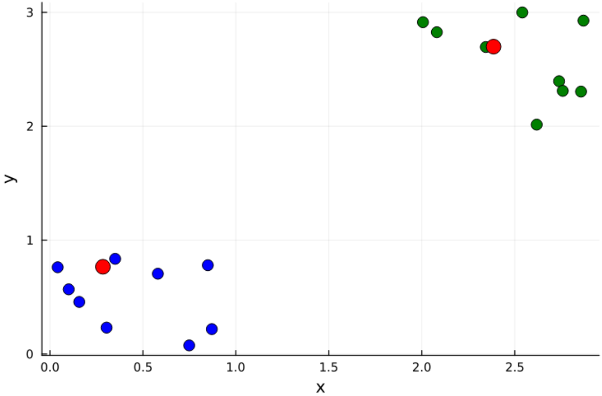
Clustering Multivariate Data

kmedoids



Clustering Multivariate Data

kmedoids



Clustering Multivariate Data

Problem of Distance Matrices

```
using Clustering, Plots, Distances

# data = Code for loading data...
plt = scatter(data[:, 1], data[:, 2])

dist = pairwise(euclidean, eachrow(data))

result = kmedoids(dist, 2)
centers = data[result.medoids, :];
scatter!(centers[:, 1], centers[:, 2])
```

A Distance Matrix

$$D = \begin{bmatrix} D_{11} & D_{12} & D_{13} & \dots & D_{1n} \\ D_{21} & D_{22} & D_{23} & \dots & D_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ D_{n1} & D_{n2} & D_{n3} & \dots & D_{nn} \end{bmatrix}_{n \times n}$$

Clustering Multivariate Data

Problem of Distance Matrices

```
dist = pairwise(euclidean, eachrow(data))
```

- A distance matrix holds the distance data of *ith* and *jth* points, e.g., $D_{ij} = D_{ji}$ due to the symmetry.
- If data has n rows then the distance matrix is in dimension of $n \times n$.
- Each distance is measured in 64-bits float numbers (`Float64`).
- If n is large, your machine will probably throw an *Out of Memory* error!

Big Distance Matrices

On-demand Distance Matrix

```
struct OnDemandDistanceMatrix <: AbstractMatrix{Float64}
    rawdata::Matrix
end

function Base.getindex(odm::OnDemandDistanceMatrix, i::Int, j::Int)::Float64
    return euclidean(odm.rawdata[i, :], odm.rawdata[j, :])
end

function Base.size(odm::OnDemandDistanceMatrix)
    n, _ = size(odm.rawdata)
    return (n, n)
end
```

Big Distance Matrices

On-demand Distance Matrix

```
# Example
data = Float64[
            1 2;
            0 5;
            1 2]

d = OnDemandDistanceMatrix(data)

println(d[1, 3])
```

Big Distance Matrices

On-demand Distance Matrix

```
data = Float64[
        1 2;
        0 5;
        1 2]

d = OnDemandDistanceMatrix(data)

# d is a usual distance matrix now!
kmedoids(d, 2)
```

Big Distance Matrices

On-demand Distance Matrix

- On-demand distance matrix costs zero memory
- Caution: But it's really slow just because the requested distance is calculated on demand!
- But it makes it possible! ☺

Big Matrices

Memory Mapped IO

- We need an efficient way to cope with big distance matrices
- Memory-mapped IO is an OS level solution to this problem
- The content of a matrix is stored in files (on disk!)
- Access to data is really fast 😎 (contrast to the previous one!)

Big Matrices

Memory-mapped IO

```
import Mmap

xio = open("/tmp/X.dat", "w+")
yio = open("/tmp/y.dat", "w+")

X = Mmap.mmap(xio, Matrix{Float64}, (n, 2))
y = Mmap.mmap(yio, Vector{Float64}, n)
```

- X and y are stored in files `X.dat` and `y.dat`
- But they are stored in files and mapped to memory (RAM).

Big Matrices

Memory-mapped IO

X and y are processed and accessed as normal matrices and vectors

```
X[1, :] = [1, 3]
y[5] = 9.7
betahats = inv(X'X)X'y
```

Distributions

The Normal Distribution

$$f(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2},\ -\infty < x < \infty \tag{5}$$

$$f(x;0,1) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2},\ -\infty < x < \infty \tag{6}$$

Distributions

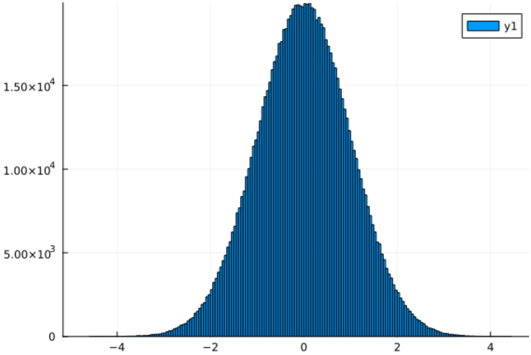
The Normal Distribution

```
julia> using Distributions

julia> quantile(Normal(), 0.05/2)
-1.9599639845400592

julia> quantile(Normal(), 0.10/2)
-1.6448536269514729

julia> quantile(Normal(), 0.01/2)
-2.5758293035489053
```

Distributions

Monte Carlo Simulations - Drawing Random Numbers

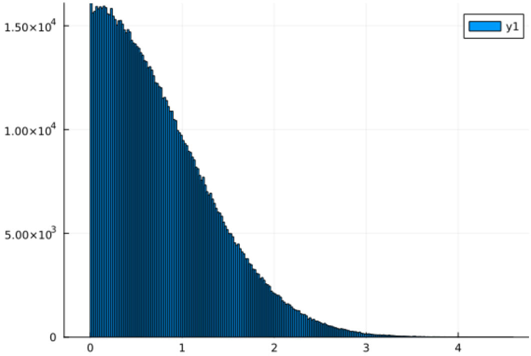
```
julia> using Plots, Distributions
julia> x = rand(Normal(), 1000000);
julia> histogram(x)
```



Distributions

Monte Carlo Simulations - Drawing Random Numbers

```
julia> histogram(abs.(x))
```



Numerical Integration

QuadGK

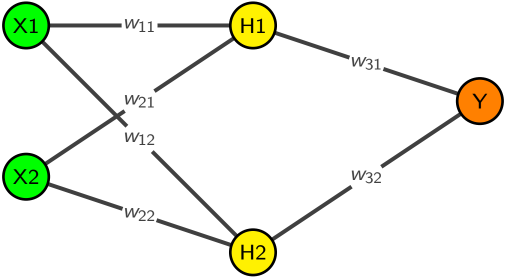
$$\int_{-1}^{1} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2} dx = ? \tag{7}$$

```
using QuadGK

function f(x)
    return 1/sqrt(2pi) * exp(-0.5x^2)
end

quadgk(f, -1.0, 1.0)
```

Optimizations

Simple Neural Network

$$H_1 = f(w_0 + x_1 w_{11} + x_2 w_{21})$$



Optimizations

Simple Neural Network

$$H_1 = f(w_{01} + x_1 w_{11} + x_2 w_{21})$$

$$H_2 = f(w_{02} + x_1 w_{12} + x_2 w_{22})$$

$$Y = f(w_{03} + w_{31} H_1 + w_{32} H_2)$$

What are the values of w_{ij}'s that minimize the total network error?

Optimizations

Simple Neural Network

```
function sigmoid(x)
    return 1.0/(1.0 + exp(-x))
end

function cost(w)
    error = 0.0
    for i in 1:4
        H1 = sigmoid(w[1] + w[2]*x1[i] + w[3]*x2[i])
        H2 = sigmoid(w[4] + w[5]*x1[i] + w[6]*x2[i])
        yhat = sigmoid(w[7] + w[8] * H1 + w[9] * H2)
        error += (yhat - y[i])^2
    end
    return error
end
```

Optimizations

Simple Neural Network

```julia
using Metaheuristics

x1 = [1, 1, 0, 0]
x2 = [1, 0, 1, 0]
y  = [0, 1, 1, 0]

bounds = vcat([-10000.0 for i in 1:9]',
              [10000.0 for i in 1:9]')

result = Metaheuristics.optimize(cost, bounds, MCCGA())

display(result)
```

Feeding the trained network

```
function forward(w)
    yhat = zeros(length(y))
    for i in 1:4
        H1 = sigmoid(w[1] + w[2]*x1[i] + w[3]*x2[i])
        H2 = sigmoid(w[4] + w[5]*x1[i] + w[6]*x2[i])
        H3 = sigmoid(w[7] + w[8] * H1 + w[9] * H2)
        yhat[i] = H3
    end
    return yhat
end
```

Optimizations

Mathematical Programming

$$\max z = 2x_1 + 3x_2$$

Subject to:

$$x_1 + 2x_2 \leq 100$$
$$2x_1 + x_2 \leq 150$$
$$x_1, x_2 \geq 0$$

Optimizations

JuMP

```
using JuMP, HiGHS

m = Model(HiGHS.Optimizer)

@variable(m, x1 >= 0)
@variable(m, x2 >= 0)

@objective(m, Max, 2x1 + 3x2)

@constraint(m, x1 + 2x2 <= 100)
@constraint(m, 2x1 + x2 <= 150)
```

Optimizations

JuMP

```
julia> optimize!(m)
Solving LP without presolve or with basis
Model   status        : Optimal
Objective value       :  1.8333333333e+02
HiGHS run time        :            0.00

julia> value.([x1, x2])
2-element Vector{Float64}:
66.66666666666667
16.666666666666657
```

SQL Integration
SQLite

```
using SQLite

db = SQLite.DB("database.db")

sqlst = """
    select item, price from Prices
    where date = '2023.12.01'
    order by price
"""

resultsql = DBInterface.execute(db, sqlst)

for row in resultsql
    println(row[:item], ": ", row[:price])
end

close(db)
```

- Julia can operate with R and Python.
- R and Python objects can be transferred in both ways.
- We don't need to give up on them, let's talk to the strangers!

Talking to Strangers

Calling into R

```
using RCall

x = [1, 2, 3, 4, 5]
y = [2, 5, 5, 8, 12]

@rput x y

R"result <- lm(y~x)"

jresult = @rget result
```

```
julia> jresult
  :coefficients  => [-0.5, 2.3]
  :residuals     => [0.2, 0.9, -1.4, -0.7, 1.0]
  :rank          => 2
  :fitted_values => [1.8, 4.1, 6.4, 8.7, 11.0]
  :assign        => [0, 1]
  :df_residual   => 3
  :xlevels       => OrderedDict{Symbol, Any}()
  :terms         => y ~ x
```

Talking to Strangers

Calling into Python

```
using PyCall

np = pyimport("numpy")
linalg = pyimport("numpy.linalg")

x = np.matrix([1.0 1; 1 2; 1 3; 1 4; 1 5])
y = np.array([2.0, 5, 5, 8, 12])

result = linalg.lstsq(x, y)
```

Talking to Strangers

Calling into Python

```
julia> include("pycaller.jl")
(
    [-0.5000000000000023, 2.3000000000000003],
    [4.299999999999995],
     2,
    [7.691213134104 82, 0.9193696350073228]
)
```

Thank you!

Any questions? ☕