

Intro and Julia basics

JGU Mainz, *Introduction to julia*

1. Introduction

We will use the geodynamics code LaMEM to solve geoscientific problems. LaMEM was developed in Mainz and solves the governing equations (conservation of mass, momentum and energy) using a staggered finite difference method and a marker-in-cell approach using non-linear visco-elasto-plastic rheologies. It is one of the most advanced codes available at the moment and is fully parallel and 3D even when we will not use much of that capabilities during the semester.

What you will mostly be busy with is to create a model setup. This is described on the LaMEM [github page](#). For simple geometries you can use the build-in geometry tools but for more complicated cases it is useful to use Julia to create the model setup. The Julia scientific programming language is fast, completely open source and comes with a nice package manager. It works on essentially all systems and has an extremely active user base. Moreover programming in julia is very similar to using MATLAB, so it will not be a big change for many of you. As a result, we are slowly transitioning the codes in our research group to julia.

We are assuming that you are not yet familiar with Julia. The purpose of these exercises is therefore to give you a crash course in how to install it on your system, create a few programs, make plots etc.

2. Installing Julia

2.1 Retrieve julia

The best way to start is to download a recent version of julia (1.9.1) from <https://julialang.org> (use a binary installer). Install that on your

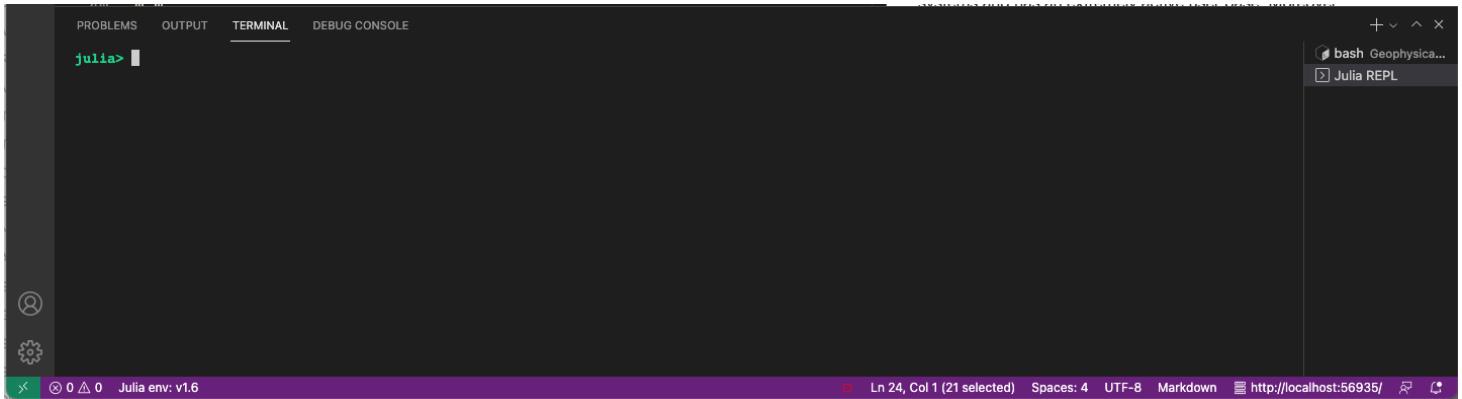
2.2 Install the julia plugin in VSCode

The recommended debugger for julia is [Microsoft Visual Studio Code](#), where you should install the julia [extension](#) which you find under "extensions" on the left side of the VSCode main window. See [this](#) page for more info.

Once this is done (in the order indicated above), you can start the Julia REPL (which stands for `read-eval-print-loop`, similar to the command window in MATLAB) by typing in the Command Palette (which you find in VS Code under the menu View->Command Palette) (or push F1 on most machines):

```
>Julia: Start REPL
```

This will take a bit of time initially, as it needs to compile. Once that is done, you should see the following:



Make sure that the julia environment at the bottom is 1.9 (unlike the picture above which is a bit out of date).

3. First steps

Let's start with some simple calculations within the REPL

```
julia> 2+3  
julia> 3*4  
julia> 5^2
```

Powers are performed before division and multiplication, which are done before subtraction and addition.

```
julia> 2+3*4^2
```

The arrow keys allow 'command-line editing' which cuts down on the amount of typing required, and allows easy error correction. Press the "up" arrow, and add `/2`. What will this produce?

```
julia> 2+3*4^2/2
```

Parentheses may be used to group terms, or to make them more readable.

```
julia> (2+3*4^2)/2
```

The equality sign is used to assign values to variables.

```
julia> a = 3
julia> b = a^2
julia> a/b
```

If no other name is given, an answer is saved in a variable named `ans`

```
julia> a/b
3.0

julia> ans
3.0

julia> c=2*ans
6.0

julia> ans
6.0
```

So far we worked with scalar values. We can always determine the type of a value with

```
julia> typeof(a)
Int64
```

which shows that `a` is an integer value.

If we define `a` as:

```
julia> a = 2.1
julia> typeof(a)
Float64
```

which shows that now `a` is a double precision number.

3.1 Vectors

Until now we dealt with scalar values. Working with vectors in Julia is simple:

```
julia> x=0:.1:2  
0.0:0.1:2.0
```

We can retrieve a particular value in the vector `x` by using square brackets:

```
julia> x[3]  
0.2
```

Arrays in julia start at 1:

```
julia> x[1]  
0.0
```

You can perform computations with `x`:

```
julia> y = x.^2 .+ 1  
21-element Vector{Float64}:  
0.0  
0.01000000000000002  
0.04000000000000001  
0.09  
0.1600000000000003  
0.25  
0.36  
0.4899999999999994  
:  
1.959999999999997  
2.25  
2.560000000000005  
2.889999999999997  
3.24  
3.61  
4.0
```

Note the dot `.` here, which tells julia that every entry of `x` should be squared and `1` is added.
If you want a vector with values, they should be separated by commas:

```
julia> a=[1.2, 3, 5, 6]  
4-element Vector{Float64}:  
1.2  
3.0  
5.0  
6.0
```

3.2 Matrixes

A matrix in julia can be defined as

```
julia> a = [1 2 3; 4 5 6]
2×3 Matrix{Int64}:
 1  2  3
 4  5  6
```

Note that the elements of a matrix being entered are enclosed by brackets; a matrix is entered in "row-major order" (i.e. all of the first row, then all of the second row, etc); rows are separated by a semicolon (or a newline), and the elements of the row should be separated by a space.

The element in the i'th row and j'th column of `a` is referred to in the usual way:

```
julia> a[1,2]
2
```

The transpose of a matrix is the result of interchanging rows and columns.

Julia denotes the transpose by following the matrix with the single-quote [apostrophe].

```
julia> a'
3×2 adjoint(::Matrix{Int64}) with eltype Int64:
 1  4
 2  5
 3  6
```

New matrices may be formed out of old ones, in many ways.

```
julia> c = [a; 7 8 9]
3×3 Matrix{Int64}:
 1  2  3
 4  5  6
 7  8  9
julia> [a; a; a]
6×3 Matrix{Int64}:
 1  2  3
 4  5  6
 1  2  3
 4  5  6
 1  2  3
 4  5  6
julia> [a a a]
2×9 Matrix{Int64}:
 1  2  3  1  2  3  1  2  3
 4  5  6  4  5  6  4  5  6
```

There are many built.-in matrix constructions. Here are a few:

```
julia> rand(1,3)
1×3 Matrix{Float64}:
 0.0398622  0.229126  0.148148

julia> rand(2)
2-element Vector{Float64}:
 0.668085153596309
 0.4275013437388613

julia> zeros(3)
3-element Vector{Float64}:
 0.0
 0.0
 0.0

julia> ones(3,2)
3×2 Matrix{Float64}:
 1.0  1.0
 1.0  1.0
 1.0  1.0
```

Use a semicolon to suppress output within the REPL:

```
julia> s = zeros(20,30);
```

This is useful, when working with large matrices.

An often used part of Julia is the 'colon operator,' which produces a list.

```
julia> -3:3  
-3:3
```

The default increment is by 1, but that can be changed.

```
julia> x=-3:.4:3
```

This can be read: `x` is the name of the list, which begins at -3, and whose entries increase by 0.4, until 3 is surpassed. You may think of `x` as a list, a vector, or a matrix, whichever you like.

You may wish use this construction to extract "subvectors," as follows.

```
julia> x[4:8]  
julia> x[9:-2:1]  
julia> x=10:100;  
julia> x[40:5:60]
```

The colon notation can also be combined with the earlier method of constructing matrices.

```
julia> a= [1:6 ; 2:7 ; 4:9]
```

A very common use of the colon notation is to extract rows, or columns, as a sort of "wild-card" operator which produces a default list. The following command demonstrates this

```
julia> s=rand(10,5); s[6:7,2:4]  
2x3 Matrix{Float64}:  
0.163274 0.923631 0.877122  
0.210374 0.321996 0.281341
```

Matrices may also be constructed by programming. Here is an example, creating a 'program loop.', which shows how

```
julia> A = [i/j for i=1:10,j=1:11]
```

4. Matrix arithmetic

If necessary, re-enter the matrices

```
julia> a=[1 2 3; 4 5 6; 7 8 10]
julia> b=[1 1 1]'
```

Scalars multiply matrices as expected, and matrices may be added in the usual way; both are done 'element by element.'

```
julia> 2*a, a/4
([2 4 6; 8 10 12; 14 16 20], [0.25 0.5 0.75; 1.0 1.25 1.5; 1.75 2.0 2.5])
```

Scalars added to matrices require you to add a dot, as

```
julia> a.+1
3x3 Matrix{Int64}:
 2  3   4
 5  6   7
 8  9  11
```

Matrix multiplication requires that the sizes match. If they don't, an error message is generated.

```
julia> a*b
3x1 Matrix{Int64}:
 6
15
25
julia> a*b'
ERROR: DimensionMismatch("matrix A has dimensions (3,3), matrix B has dimensions (1,3)")
Stacktrace:
[1] _generic_matmatmul!(C::Matrix{Int64}, tA::Char, tB::Char, A::Matrix{Int64}, B::Matrix{Int64}
 @ LinearAlgebra /Users/julia/buildbot/worker/package_macos64/build/usr/share/julia/stdlib/v1.
[2] generic_matmatmul!(C::Matrix{Int64}, tA::Char, tB::Char, A::Matrix{Int64}, B::Matrix{Int64})
 @ LinearAlgebra /Users/julia/buildbot/worker/package_macos64/build/usr/share/julia/stdlib/v1.
[3] mul!
 @ /Users/julia/buildbot/worker/package_macos64/build/usr/share/julia/stdlib/v1.6/LinearAlgebr
[4] mul!
 @ /Users/julia/buildbot/worker/package_macos64/build/usr/share/julia/stdlib/v1.6/LinearAlgebr
[5] *(A::Matrix{Int64}, B::Matrix{Int64})
 @ LinearAlgebra /Users/julia/buildbot/worker/package_macos64/build/usr/share/julia/stdlib/v1.
[6] top-level scope
 @ REPL[107]:1
```

A matrix-matrix multiplication is done with:

```
julia> a*a  
3x3 Matrix{Int64}:  
 30  36  45  
 66  81  102  
109 134 169
```

whereas adding a dot performs a pointwise multiplication:

```
julia> a.*a  
3x3 Matrix{Int64}:  
 1  4  9  
16 25 36  
49 64 100
```

5. Adding packages

Now it would be nice to create a plot of the results. In order to do so, you first need to install a plotting package. Many excellent are available, with the most widely used ones being [Plots.jl](#) and [Makie.jl](#).

Before being able to use a package, we first need to install it. Julia has a build-in package manager that automatically takes care of dependencies (that is: other packages that this package may use, including the correct version). You can start the package manager by typing `]` in the REPL:

```
julia> ]  
(@v1.6) pkg>
```

If you want to go back to the main REPL, use the backspace key.

As an example, lets install the `Plots` package:

```
(@v1.6) pkg> add Plots
```

This will download and precompile all dependencies and will look something like this:

```

PROBLEMS PORTS OUTPUT TERMINAL DEBUG CONSOLE

[9e88b42a] + Serialization
[1a1011a3] + SharedArrays
[6462fe0b] + Sockets
[2f01184e] + SparseArrays
[10745b16] + Statistics
[fa267f1f] + TOML
[a4e569a6] + Tar
[8dfed614] + Test
[cf7118a7] + UUIDs
[4ec0a83e] + Unicode
[e66e0078] + CompilerSupportLibraries_jll
[deac9b47] + LibCURL_jll
[29816b5a] + LibSSH2_jll
[c8ffd9c3] + MbedTLS_jll
[14a3606d] + MozillaCACerts_jll
[83775a58] + Zlib_jll
[8e850ede] + nghttp2_jll
[3f19e933] + p7zip_jll
Building GR → `~/.julia/scratchspaces/44cfe95a-1eb2-52ea-b672-e2afdf69b78f/c2178cfbc0a5a552e16
Precompiling project...
120 dependencies successfully precompiled in 148 seconds

(@v1.6) pkg> []

```

SSH: GEO21_gaia ⊗ 0 △ 0 ⚡ 0 Julia env: v1.6

The plotting package is fairly large so this will take some time, but this only has to be done once.

Once the installation is done, you can test whether the package works by running the build-in testing suite of that package (which is available for most julia packages):

```
(@v1.6) pkg> test Plots
```

This should look something like:

```

PROBLEMS OUTPUT TERMINAL DEBUG CONSOLE

[29816b5a] LibSSH2_jll `@stdlib/LibSSH2_jll`
[c8ffd9c3] MbedTLS_jll `@stdlib/MbedTLS_jll`
[14a3606d] MozillaCACerts_jll `@stdlib/MozillaCACerts_jll`
[4536629a] OpenBLAS_jll `@stdlib/OpenBLAS_jll`
[05823500] OpenLbm_jll `@stdlib/OpenLbm_jll`
[83775a58] Zlib_jll `@stdlib/Zlib_jll`
[8e850ede] nghttp2_jll `@stdlib/nghttp2_jll`
[3f19e933] p7zip_jll `@stdlib/p7zip_jll`
Precompiling project...
105 dependencies successfully precompiled in 158 seconds (160 already precompiled)
Testing Running tests...
Test Summary: | Pass  Total
Infrastructure   |    1     1
Test Summary: | Pass  Total
Plotly standalone |    6     6
Test Summary: | Pass  Total
Loading theme   |    2     2
Test Summary: | Pass  Total
plot            |    3     3
Test Summary: | Pass  Total
get axis limits |    2     2
Test Summary: | Pass  Total
Showaxis        |   50    50
Test Summary: | Pass  Total
Magic axis      |    2     2
Test Summary: | Pass  Total

⊗ 0 △ 0 Julia env: v1.6

```

Note that this takes a looong time, depending on your machine. If you get impatient, you can stop

this with `CTRL-C`.

Once you are done with the package manager, go back to the `REPL` with the backspace button.

5.1 Add more packages

Since we are installing packages, lets do some more. In this class we will be using the following packages:

- [GeophysicalModelGenerator](#). This is useful to visualize geophysical data in 3D and create model setups.
- [GLMakie](#). This is a plotting package that is fully written in julia.
- [LaMEM](#). This is the 3D geodynamics code, we will be using later
- [LinearFitXYerrors](#). This is a small package that can be used to fit a straight line between data points.

Please install them in the package manager. For `LaMEM` and `GeophysicalModelGenerator`, you can also run the testsuite, to make sure all is fine on your machine (the `GLMakie` tests take a really long time).

6. Create plots

Now that the plotting package is install, we are ready to create our first plot. First you load the `Plots` package

```
julia> using Plots
```

Next create a plot with

```
julia> plot(x,y)
```

Once the installation is done, you can test whether the package works by running the build-in testing suite of that package (which is available for most Julia packages):

```
87 Once the installation is done, you can test whether the package works by running the build-in testing suite of
88     ````julia
89     (@v1.6) pkg> test Plots
90     ````
91 This should look something like:
92 
93 Note that this take looong time, depending on your machine. If you get impatient, you can stop this with ``CTRL-C``.
94
95 Once you are done with installing the package, go back to the ``REPL`` with the backspace button.
96
97 ## 5. Create plots
98 Now that the plotting package is install, we are ready to create our first plot. First you load the ``Plots`` package
99 ````julia
100 julia> using Plots
101 ````
102 Next create a plot with
103 ````julia
104 julia> plot(x,y)
105 ````
106
```

PROBLEMS OUTPUT TERMINAL DEBUG CONSOLE

```
R7.3705e5|||||||||||||, 37092e5B
```

	Pass	Fail	Broken	Total
BackendTests	1	1	0	2
GR	52	3	55	110
UnicodePlots	12	0	12	24
PlotlyJS	1	1	0	2

Test Summary: | Pass Fail Broken Total
BackendTests | 1 1 0 2
GR | 52 3 55 110
UnicodePlots | 12 0 12 24
PlotlyJS | 1 1 0 2
ERROR: LoadError: Some tests did not pass: 67 passed, 3 failed, 0 errored, 1 broken.
in expression starting at /Users/kausb/.julia/packages/Plots/b10qb/test/runtests.jl:113
ERROR: Package Plots errored during testing

```
(@v1.6) pkg>
(@v1.6) pkg>
julia> using Plots
[ Info: Precompiling Plots [91a5bcdd-55d7-5cef-9e0b-520d859cae80]
julia>
julia> plot(x,y)
julia> plot(x,y)
julia> []
julia>
```

0 0 0 JuliaEnv v1.6 http://localhost:56935/

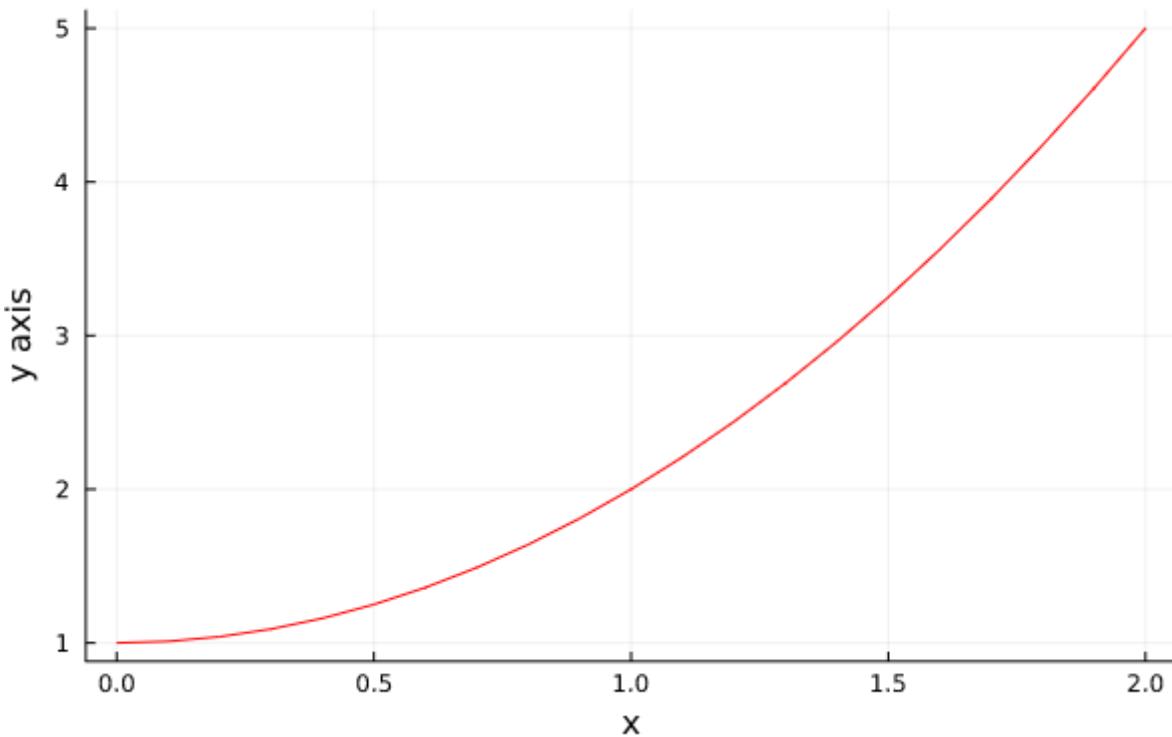
If you are using VSCode, it should show the plot in a separate tab as in the figure above.

We can add labels etc. with:

```
julia> x=0:.1:2
julia> y=x.^2 .+ 1
julia> plot(x,y, xlabel="x", ylabel="y axis", title="my first plot", label=:none, color=:red)
```

which gives:

my first plot



There are lots of options within the plotting package. Have a look at the tutorial [here](#).

If you are used to work with MATLAB/Octave, here a quick summary of how plotting options are called in the Plots.jl package of julia:

MATLAB/Octave	Julia
plot(x,y,'r--')	plot(x,y,linestyle=:dash, color=:red)
scatter(x,y)	scatter(x,y)
mesh(x,y,z)	wireframe(x,y,z)
surf(x,y,z)	plot(x,y,z,st=:surface)
pcolor(x,y,z)	heatmap(x,y,z)
contour(x,y,z,50)	contour(x,y,z,level=50)
contourf(x,y,z)	contour(x,y,z,level=50,fill=true)

7. Functions

A function in julia can be defined in an extremely simple manner:

```
julia> f(x) = x.^2 .+ 10
f (generic function with 1 method)
```

You can now use this function with scalars, vectors or arrays:

```
julia> f(10)
110
julia> x=1:3
julia> f(x)
3-element Vector{Int64}:
 11
 14
 19
julia> y=[1 2; 3 4]
julia> f(y)
2×2 Matrix{Int64}:
 11  14
 19  26
```

Functions ofcourse don't have to be one-liners, so you can also define it as:

```
julia> function f1(x)
    y = x.^2 .+ 11
    return y
end
f1 (generic function with 1 method)
```

This creates a new array `y` and returns that.

So how fast is this function? Lets start with defining a large vector:

```
julia> x=1:1e6;
```

It turns out that julia has a handy build-macro, called `@time`, with which you can record the time that a function took.

```
julia> @time f1(x)
 0.035543 seconds (205.05 k allocations: 21.952 MiB, 25.37% gc time, 69.65% compilation time)
1000000-element Vector{Float64}:
12.0
15.0
20.0
27.0
36.0
47.0
60.0
75.0
92.0
⋮
9.9998600006e11
9.99988000047e11
9.99990000036e11
9.99992000027e11
9.9999400002e11
9.99996000015e11
9.99998000012e11
1.000000000011e12
```

So this took 0.09 seconds on my machine. Yet, the first time any function in julia is executed, it is compiled and that's why 94% of the time was the compilation time. If we run the same function again, it is much faster and creates 2 allocations:

```
julia> @time f1(x)
 0.006275 seconds (2 allocations: 7.629 MiB)
```

In general, it is a very good idea to put things in functions within julia, as it allows julia to precompile the routines.

Also note that you need to restart the `REPL` or your Julia session every time you redefine a function or a structure.

If you want to do some more serious benchmarking, you need to install the package [BenchmarkTools](#), which runs the function 1000 times and does the timings:

```
julia> using BenchmarkTools
julia> @btime f(\$x);
 1.110 ms (2 allocations: 7.63 MiB)
```

note that you have to put a `$` sign in front of ever variable that is passed into the function. In this case the function took about a millisecond.

8. Scripts

In general, you want to put your code in a julia script so you don't have to type it always in the REPL.

Doing that is simple; you simply save it as a textfile that has `.*.jl` as an ending.

A simple example is the following `test1.jl` script:

```
using Plots

function rosenbrock(x,y; a=1,b=100)
    xt = x'      # transpose
    f  = (a .- xt).^2 .+ b.* (y .- xt.^2).^2
    return f
end

x = range(-2.0,2.0,length=50)
y = range(-1.0,1.5,length=50)
f = rosenbrock(x,y)

# Create a contourplot
contour(x,y,f, levels=0:10:200, fill=true,
        xlabel="X", ylabel="y", title="rosenbrock",
        color=:roma, clim=(1,200))
```

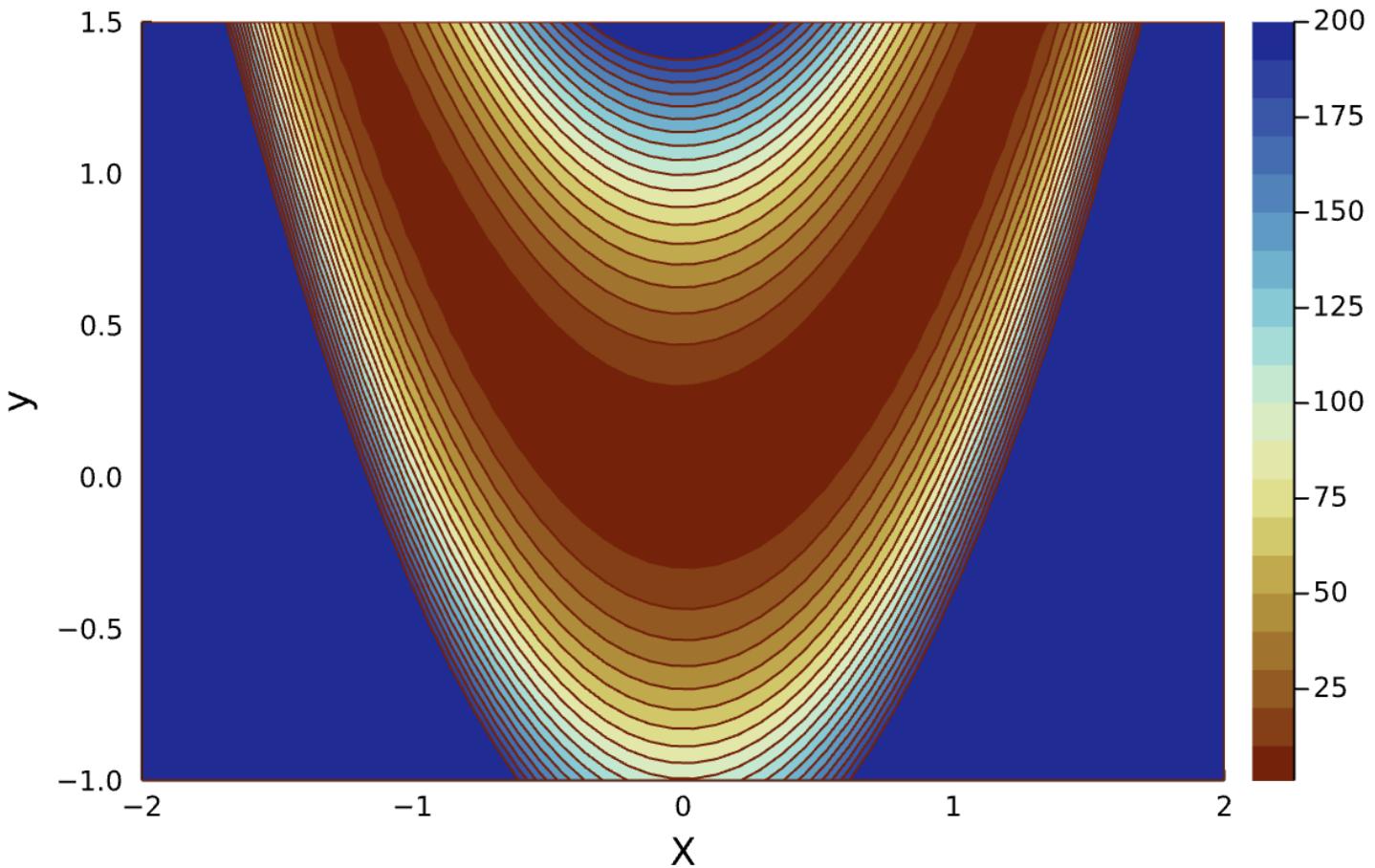
Note that the `rosenbrock` function has optional parameters (`a, b`). Calling it with only `X, Y` will invoke the default parameters, but you can specify the optional ones with `f=rosenbrock(x, y, b=200, a=3)`. You can run this script in the julia in the following way:

```
include("test1.jl")
```

Be aware that you need to be in the same directory as the script (see below on how you can change directories using the build-in shell in julia, by typing `;` in the REPL).

The result looks like (have a look at how we customized the colormap, and added info for the axes).

rosenbrock



9. Getting help

In general, you can get help for every function by typing `?` which brings you to the help terminal. Next type the name of the function.

For example, lets find out how to compute the average of an array

```
julia>?mean
```

You can add help info to your own functions by adding comments before the function, using `"""`

```

"""
y = f2_withhelp(x)

Computes the square of `x` and adds 10

Example
=====

julia> x=1:10
julia> y = f2_withhelp(x)
10-element Vector{Int64}:
 11
 14
 19
 26
 35
 46
 59
 74
 91
110
"""

function f2_withhelp(x)
    y = x.^2 .+ 10
    return y
end

```

9.1 Build-in terminal

Julia has a build in terminal, which you can reach by typing ; . This comes in handy if you want to check in which directory you are, change directories, or look at the files there.

```

julia>;
shell> pwd
/Users/kausb

```

Note that this invokes the default terminal on your operating system, so under windows the commands are a bit different than under linux.

Once you are done with the terminal, you get back to the REPL , by using the backspace.

9.2 Online help

The official julia [manual](#) is a good place to start. Many of the julia packages are hosted on github and have help pages as well. An example, which we will use in this class, is [GeophysicalModelGenerator.jl](#)

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JuliaGeodynamics / GeophysicalModelGenerator.jl Public

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About

Import, process and interpret geophysical data sets to be used in numerical models.

[Readme](#)

[MPL-2.0 License](#)

Releases 2

v0.3.0 [Latest](#)
on 22 Jul

+ 1 release

Packages

No packages published
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Environments 1

 github-pages [Active](#)

Languages

Julia 100.0%

README.md

Geophysical Model Generator

[docs stable](#) [docs dev](#) [CI](#) [passing](#)

Creating consistent 3D images of geophysical and geological datasets and turning that into an input model for geodynamic simulations is often challenging. The aim of this package is to help with this, by providing a number of routines to easily import data and create a consistent 3D visualisation from it in the VTK-toolkit format, which can for example be viewed with [Paraview](#). In addition, we provide a range of tools that helps to generate input models to perform geodynamic simulations and import the results of such simulations back into julia.



If you click on the blue buttons, you will be taken to the help pages. Note that it is quite easy to generate a new package in julia, add tests for that package, and create an online documentation. Doing that goes beyond the scope of this class, but if you are interested you can ask us or look at the julia manual.

10. Fitting a line through data-points

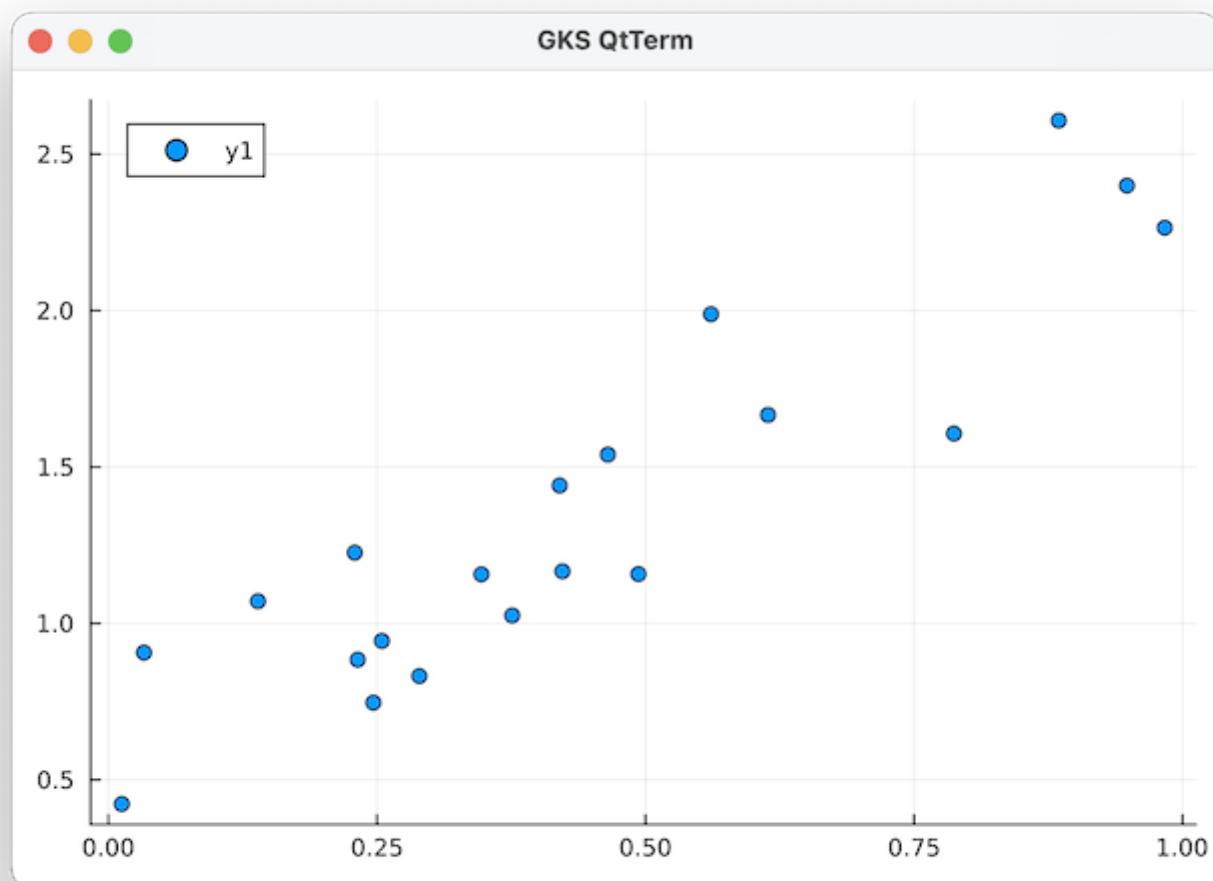
Imagine that we have some points and we want to fit a line through them

```
julia> x = rand(20)
julia> y = 2*x .+ rand(20)
4-element Vector{Float64}:
 3.0
 9.0
19.0
33.0
```

Note that you need to add . .

Lets plot this:

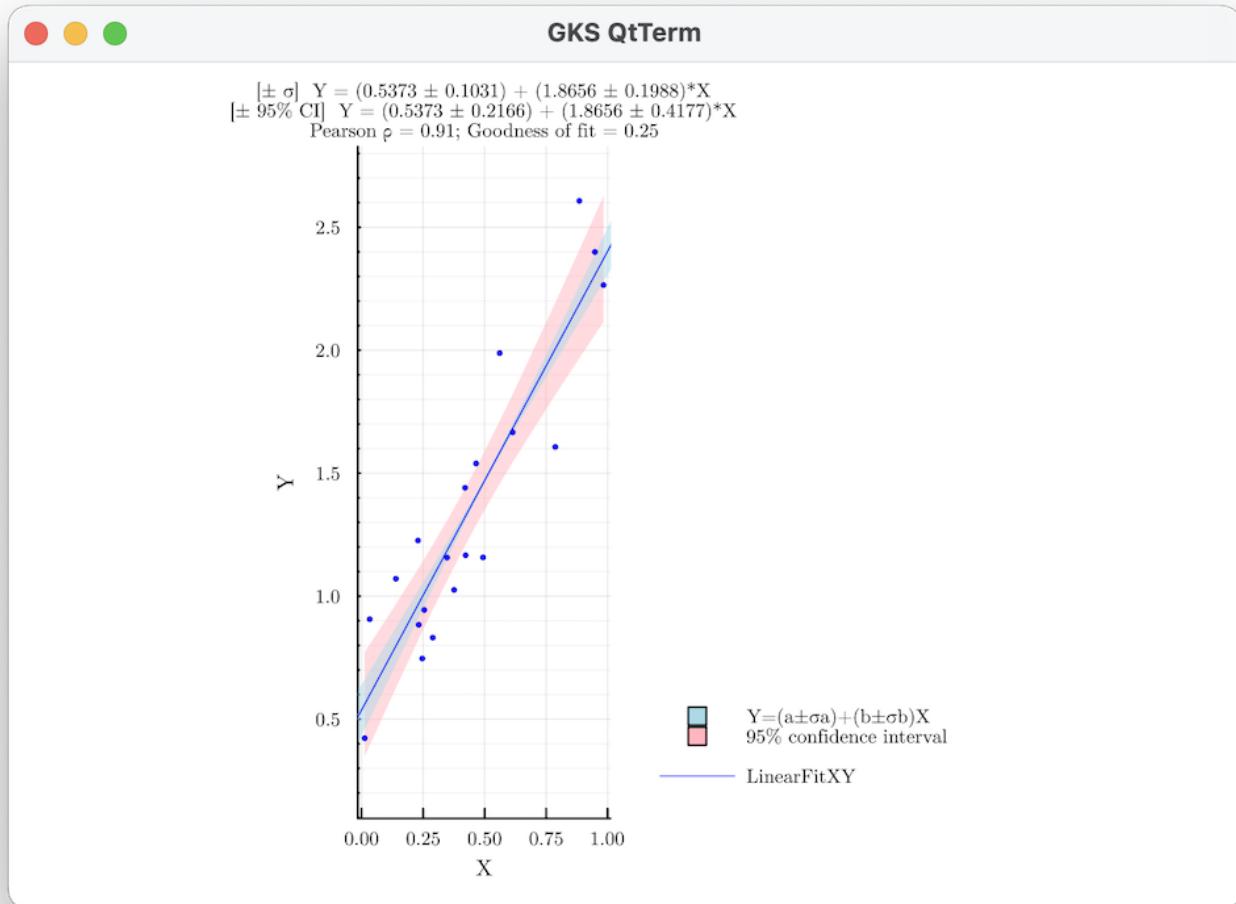
```
julia> using Plots
julia> scatter(x,y)
```



So obviously, there is some trend.

Now, lets fit a line through it. For that we can use the package we installed earlier:

```
julia> using LinearFitXYerrors
julia> st = linearfitxy(x,y, isplot=true);
>>> [± σ] Y = (0.5373 ± 0.1031) + (1.8656 ± 0.1988)*X
>>> [± 95% CI] Y = (0.5373 ± 0.2166) + (1.8656 ± 0.4177)*X
>>> Pearson ρ = 0.911; Goodness of fit = 0.248
```



So in this case the slope of the line is 1.86. Since we use random numbers, it might look slightly different for you.

Determining power law coefficients

Now lets consider the following equation:

There is an easy way to retrieve the powerlaw coefficient (3 in this case), by taking _____ of the equation:

Let's try:

```
julia> a = range(0.1,4.0)
julia>julia> b = 2.1*a.^3
4-element Vector{Float64}:
 0.002100000000000007
 2.7951000000000001
 19.448100000000004
 62.56110000000001
```

Note that if you want to take the of every entry in `a`, you need to add a `⋮`:

```
julia> log10.(a)
4-element Vector{Float64}:
 -1.0
 0.04139268515822508
 0.3222192947339193
 0.4913616938342727
```

That implies that the function `log10` is applied to every element in `a`.

Now we can compute the linear fit:

```
julia> st = linearfitxy(log10.(a),log10.(b), isplot=true);

>>> [± σ] Y = (0.3222 ± 0.0000) + (3.0000 ± 0.0000)*X
>>> [± 95% CI] Y = (0.3222 ± 0.0000) + (3.0000 ± 0.0000)*X
>>> Pearson ρ = 1.000; Goodness of fit = 0.000
```

And indeed the powerlaw is 3.0 (as we have no random noise in this case)

Keep the trick with the logarithms in mind as we will use it tomorrow.

11. Setting properties on markers

A common operation you will do during this class is setting material properties on markers.
Let's do some warming-up exercises for that.

We start with defining the `X,Z` coordinates of the markers:

```
julia> x=-5:.1:5
julia> z=-10:.2:0
julia> X = ones(size(z))*x'
julia> Z = z*ones(size(x))'
julia> Phase = zeros(Int64,size(X))
```

Phase is now a 2D array that defined the "rocktype" (or Phase) of ever marker, which is defined by the 2D coordinate arrays X,Z . Hint: you can copy-paste the whole block above tou your julia REPL . It will automatically remove the julia> at the beginning of every line.

11.1 Square

Now let's assume that all points between x=[-1 .. 1] and z=[-5 .. -4] have a different rock type. We can use that by finding all points that are between these coordinates, using the `findall` command.

```
julia> ind = findall( (X.>-1) .& (X.<1) .& (Z.>-5) .& (Z.<-4) );
julia> Phase[ind] .= 1
```

Note that you have to add brackets around every statement and that you have to use a dot (.) to indicate that it applies for every entry in the arrays.

Let's create a plot of the result:

```
julia> using Plots
julia> ind = findall(Phase == 0 )
julia> scatter(X[ind],Z[ind],color=:blue, legend=false, markersize=3)
julia> ind = findall(Phase == 1 )
julia> scatter!(X[ind],Z[ind],color=:red,markersize=3)
```

Note that we use the exclamation mark (!) to indicate that we want to keep the previous plot.

11.2 Circle

Similarly, we can add a circle with radius 2 and center (-2,-6) with

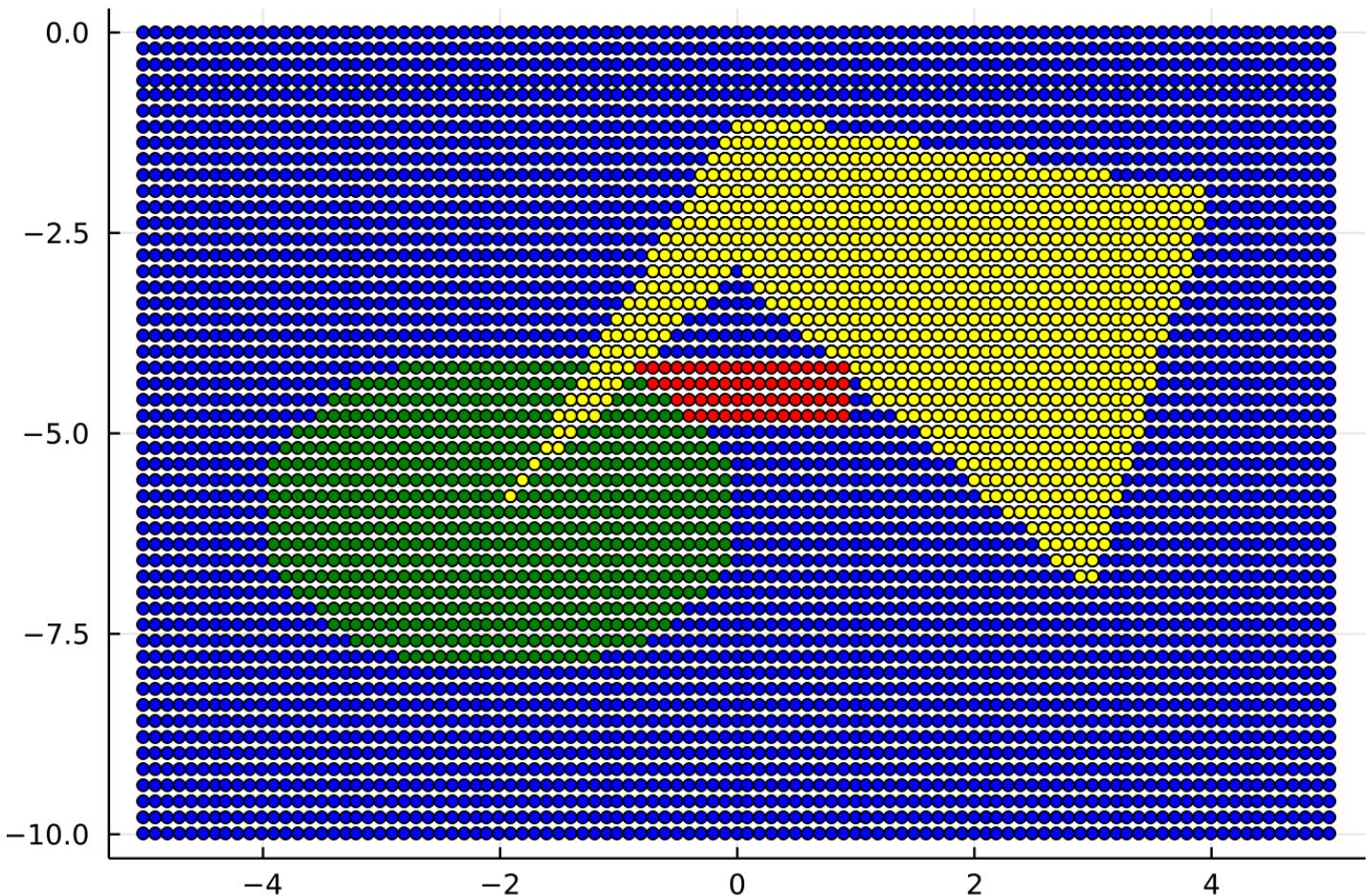
```
julia> xc,zc =-2,-6
julia> ind = findall( (X.-xc).^2 .+ (Z.-zc).^2 .< 2^2 )
julia> Phase[ind] .= 2
julia> id0, id1, id2 = findall(Phase==0), findall(Phase==1), findall(Phase==2)
julia> scatter(X[id0],Z[id0],color=:blue,markersize=3)
julia> scatter!(X[id1],Z[id1],color=:red,markersize=3)
julia> scatter!(X[id2],Z[id2],color=:green,markersize=3)
```

11.3 Polygons

We can also create more complicated polygons, by first creating the `x` and `z` coordinates of the polygon, and subsequently using the `inpolygon` function, which is part of the [PolygonOps.jl](#) package, which you'll have to install first:

```
julia> xp=[-2, 0, 3, 4, 0, -2]
julia> zp=[-6, -3, -7, -2, -1, -6]
julia> using PolygonOps
julia> polygon = [[x,z] for (x,z) in zip(xp,zp)]
julia> inside = [inpolygon([x,z], polygon) for (x,z) in zip(X,Z)]
julia> Phase[inside .== true] .= 3
julia> id3 = findall(Phase.==3)
julia> scatter!(X[id3],Z[id3],color=:yellow,markersize=3, legend=:none)
```

The result looks like this:



Note that we introduced a new julia concept here, namely inline iterators:

```
julia> polygon = [[x,z] for (x,z) in zip(xp,zp)]
6-element Vector{Vector{Int64}}:
 [-2, -6]
 [0, -3]
 [3, -7]
 [4, -2]
 [0, -1]
 [-2, -6]
```

This statement loops over all points in `xp`,`zp` and extracts `x,z` of that point, which it then puts in a vector `polygon` (which is what `PolygonOps` wants to have - see the help page of that package). Each entry of `polygon` thus contains the `x,z` coordinates of the respective point of the polygon:

```
julia> polygon[3]
2-element Vector{Int64}:
 3
 -7
```

11.4 Topography

As a final exercise in this part, lets assume we also have a topography, and we want to set all markers above the topography to be "air".

```
julia> x_topo =[-5, -2, -1,      1,   2,   5]
julia> z_topo =[-1, -1, -0.1,-0.1, -1, -1]
```

In this case, we want to know at which elevation the topography is for a given X-coordinate. For that, we can use the [Interpolations.jl](#) package which provides many (multi-dimensional) interpolation routines.

```
julia> using Interpolations
julia> interp_linear = LinearInterpolation(x_topo, z_topo)
julia> Z_topo = interp_linear.(X)
julia> ind = findall(Z.>Z_topo)
julia> Phase[ind] .= 4
julia> id4 = findall(Phase.==4)
julia> scatter!(X[id4],Z[id4],color=:lightblue,markersize=3, legend=:none)
```

12. Using GeophysicalModelGenerator

The package [GeophysicalModelGenerator](#) is quite handy to collect data of different parts of the world, and visualize that in 3D using [Paraview](#) which is an open-source 3D visualisation package.

Let's do some exercise with this, and plot the topography of Kigali. This requires you to install both the `GMT` and `GeophysicalModelGenerator` packages:

```
julia> using GeophysicalModelGenerator, GMT
```

The function `ImportTopo` can be used to import topography from any part of the world, by specifying the southwest and northeast corners.

If you want to know how it works, ask help:

```
julia>?ImportTopo
search: ImportTopo importWKT

Topo = ImportTopo(limits; file::String="@earth_relief_01m.grd")

Uses GMT to download the topography of a certain region, specified with limits=[lonmin, lonmax]
```

Note:

=====

- latitude values `in` the southern hemisphere should have a minus sign (e.g., `-2.8`)
- longitude values that are "`west`" should either come with a minus sign or are defined by \

Dataset	Resolution	Description
"@earth_relief_01s"	1 arc sec	SRTM tiles (14297 tiles, land only, 60S-60N) [NASA/USGS]
"@earth_relief_03s"	3 arc sec	SRTM tiles (14297 tiles, land only, 60S-60N) [NASA/USGS]
...		

The center of Kigali has latitude=-1.93 and longitude=30.08. We can automatically download the topography with:

```
julia> Topo = ImportTopo(lat=[-1.95, -1.92], lon=[30.0, 30.1], file="@earth_relief_01s.grd")
GMT [WARNING]: Remote dataset given to a data processing module but no registration was specified
grdbblend [ERROR]: Option -V given more than once
GeoData
  size      : (361, 121, 1)
  lon       ∈ [ 30.0 : 30.1]
  lat       ∈ [ -1.95 : -1.9166666666666667]
  depth     ∈ [ 1.357 : 1.419]
  fields    : (:Topography,)
  attributes: ["note"]
```

The structure `Topo` now contains the topography. We can write that into a file format that Paraview can read with:

```
julia> Write_Paraview(Topo, "Topo_Kigali")
Saved file: Topo_Kigali.vts
```

Next you can open this in paraview:

