

# Solving Equations in With Julia-Defined Types

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One of the nice things about `DifferentialEquations.jl` is that it is designed with Julia's type system in mind. What this means is, if you have properly defined a `Number` type, you can use this number type in `DifferentialEquations.jl`'s algorithms! [Note that this is restricted to the native algorithms of `OrdinaryDiffEq.jl`. The other solvers such as `ODE.jl`, `Sundials.jl`, and `ODEInterface.jl` are not compatible with some number systems.]

`DifferentialEquations.jl` determines the numbers to use in its solvers via the types that are designated by `tspan` and the initial condition of the problem. It will keep the time values in the same type as `tspan`, and the solution values in the same type as the initial condition. [Note that adaptive timestepping requires that the time type is compatible with `sqrt` and `^` functions. Thus `dt` cannot be `Integer` or numbers like that if adaptive timestepping is chosen].

Let's solve the linear ODE first define an easy way to get `ODEProblems` for the linear ODE:

```
using DifferentialEquations
f = (u,p,t) -> (p*u)
prob_ode_linear = ODEProblem(f,1/2,(0.0,1.0),1.01);
```

First let's solve it using `Float64`s. To do so, we just need to set `u0` to a `Float64` (which is done by the default) and `dt` should be a float as well.

```
prob = prob_ode_linear
sol = solve(prob,Tsit5())
println(sol)
```

```
retcode: Success
Interpolation: specialized 4th order "free" interpolation
t: [0.0, 0.0996426, 0.345703, 0.677692, 1.0]
u: [0.5, 0.552939, 0.708938, 0.99136, 1.3728]
```

Notice that both the times and the solutions were saved as `Float64`. Let's change the time to use rational values. Rationals are not compatible with adaptive time stepping since they do not have an L2 norm (this can be worked around by defining `internallnorm`, but rationals already explode in size!). To account for this, let's turn off adaptivity as well:

```
prob = ODEProblem(f,1/2,(0//1,1//1),101//100);
```

```
sol = solve(prob,RK4(),dt=1/2^(6),adaptive=false)
println(sol)
```

retcode: Success

Interpolation: 3rd order Hermite

t: Rational{Int64}[0//1, 1//64, 1//32, 3//64, 1//16, 5//64, 3//32, 7//64, 1//8, 9//64, 5//32, 11//64, 3//16, 13//64, 7//32, 15//64, 1//4, 17//64, 9//32, 19//64, 5//16, 21//64, 11//32, 23//64, 3//8, 25//64, 13//32, 27//64, 7//16, 29//64, 15//32, 31//64, 1//2, 33//64, 17//32, 35//64, 9//16, 37//64, 19//32, 39//64, 5//8, 41//64, 21//32, 43//64, 11//16, 45//64, 23//32, 47//64, 3//4, 49//64, 25//32, 51//64, 13//16, 53//64, 27//32, 55//64, 7//8, 57//64, 29//32, 59//64, 15//16, 61//64, 31//32, 63//64, 1//1]

u: [0.5, 0.507953, 0.516033, 0.524241, 0.53258, 0.541051, 0.549658, 0.558401, 0.567283, 0.576306, 0.585473, 0.594786, 0.604247, 0.613858, 0.623623, 0.633542, 0.64362, 0.653857, 0.664258, 0.674824, 0.685558, 0.696463, 0.707541, 0.718795, 0.730229, 0.741844, 0.753644, 0.765632, 0.777811, 0.790183, 0.802752, 0.815521, 0.828493, 0.841671, 0.855059, 0.86866, 0.882477, 0.896514, 0.910775, 0.925262, 0.93998, 0.954931, 0.970121, 0.985552, 1.00123, 1.01715, 1.03333, 1.04977, 1.06647, 1.08343, 1.10067, 1.11817, 1.13596, 1.15403, 1.17239, 1.19103, 1.20998, 1.22923, 1.24878, 1.26864, 1.28882, 1.30932, 1.33015, 1.35131, 1.3728]

Now let's do something fun. Let's change the solution to use `Rational{BigInt}` and print out the value at the end of the simulation. To do so, simply change the definition of the initial condition.

```
prob = ODEProblem(f,BigInt(1)//BigInt(2),(0//1,1//1),101//100);
sol =solve(prob,RK4(),dt=1/2^(6),adaptive=false)
println(sol[end])
```

```
415403291938655888343294424838034348376204408921988582429386196369066828013
380062427154556444246064110042147806995712770513313913105317131993928991562
472219540324173687134074558951938783349315387199475055050716642476760417033
833225395963069751630544424879625010648869655282442577465289103178163815663
464066572670655356269579471636764679863656649012559514171272038086748586891
653145664881452891757769341753396504927956887980186316721217138912802907978
839488971277351483679854338427632656105429434285170828205087679096886906512
836058415177000071451519455149761416134211934766818795085616643778333812510
724294609438512646808081849075509246961483574876752196687093709017376892988
720208689912813268920171256693582145356856885176190731036088900945481923320
301926151164642204512204346142796306783141982263276125756548530824427611816
333393407861066935488564588880674178922907680658650707284447124975289884078
283531881659241492248450685643985785207092880524994430296917090030308304496
2139908567605824428891872081720287044135359380045755621121//302595526357001
916401850227786985339805854374596312639728370747077589271270423243703004392
074003302619884721642626495128918849830763359112247111187416392615737498981
461087857422550657171300852094084580555857942985570738231419687525783564788
285621871741725085612510228468354691202070954415518824737971685957295081128
193794470230767667945336581432859330595785427486755359414346047520148998708
472579747503225700773992946775819105236957926068135290787592745892648489231
54827578713239056475245050253159810279037690534441254912000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000
```

That's one huge fraction!

```
using DecFP
prob_ode_decfpllinear =
    ODEProblem(f,Dec128(1)/Dec128(2),(Dec128(0.0),Dec128(1.0)),Dec128(1.01))
sol =solve(prob_ode_decfpllinear,Tsit5())
```

Error: StackOverflowError:

```
println(sol[end]); println(typeof(sol[end]))
```

```
1.372800440903808727789283182314
ArbNumerics.ArbFloat{128}
```

**Decimals.jl** Install with `]add Decimals`.

```
using Decimals
prob_ode_decimallinear =
    ODEProblem(f,[decimal("1.0")]./[decimal("2.0")],(0//1,1//1),decimal(1.01))
sol =solve(prob_ode_decimallinear,RK4(),dt=1/2^(6)) #Fails
```

Error: MethodError: Decimals.Decimal(::Rational{Int64}) is ambiguous. Candidates:

```
(::Type{T})(x::Rational{S}) where {S, T<:AbstractFloat} in Base at rational.jl:92
```

```
Decimals.Decimal(num::Real) in Decimals at C:\Users\accou\.julia\packages\Decimals\Qfcas\src\decimal.jl:13
```

Possible fix, define

```
Decimals.Decimal(::Rational{S})
```

```
println(sol[end]); println(typeof(sol[end]))
```

```
1.372800440903808727789283182314
ArbNumerics.ArbFloat{128}
```

At the time of writing this, Decimals are not compatible. This is not on DifferentialEquations.jl's end, it's on partly on Decimal's end since it is not a subtype of Number. Thus it's not recommended you use Decimals with DifferentialEquations.jl

### 0.3 Conclusion

As you can see, DifferentialEquations.jl can use arbitrary Julia-defined number systems in its arithmetic. If you need 128-bit floats, i.e. a bit more precision but not arbitrary, DoubleFloats.jl is a very good choice! For arbitrary precision, ArbNumerics are the most feature-complete and give great performance compared to BigFloats, and thus I recommend their

use when high-precision (less than 512-800 bits) is required. DecFP is a great library for high-performance decimal numbers and works well as well. Other number systems could use some modernization.

## 0.4 Appendix

```
using DiffEqTutorials
DiffEqTutorials.tutorial_footer(WEAVE_ARGS[:folder],WEAVE_ARGS[:file])
```

These benchmarks are part of the DiffEqTutorials.jl repository, found at:

<https://github.com/JuliaDiffEq/DiffEqTutorials.jl>

To locally run this tutorial, do the following commands:

```
using DiffEqTutorials
DiffEqTutorials.weave_file(".", "type_handling/number_types.jmd")
```

Computer Information:

```
Julia Version 1.1.0
Commit 80516ca202 (2019-01-21 21:24 UTC)
Platform Info:
  OS: Windows (x86_64-w64-mingw32)
  CPU: Intel(R) Core(TM) i7-8700 CPU @ 3.20GHz
  WORD_SIZE: 64
  LIBM: libopenlibm
  LLVM: libLLVM-6.0.1 (ORCJIT, skylake)
Environment:
  JULIA_EDITOR = "C:\Users\accou\AppData\Local\atom\app-1.34.0\atom.exe" -a
  JULIA_NUM_THREADS = 6
```

Package Information:

```
Status `C:\Users\accou\.julia\environments\v1.1\Project.toml`
[7e558dbc] ArbNumerics v0.3.6
[c52e3926] Atom v0.7.14
[6e4b80f9] BenchmarkTools v0.4.2
[336ed68f] CSV v0.4.3
[3895d2a7] CUDAapi v0.5.4
[be33ccc6] CUDAnative v1.0.1
[3a865a2d] CuArrays v0.9.1
[a93c6f00] DataFrames v0.17.1
[55939f99] DecFP v0.4.8
[abce61dc] Decimals v0.4.0
[39dd38d3] Dierckx v0.4.1
[459566f4] DiffEqCallbacks v2.5.2
[f3b72e0c] DiffEqDevTools v2.6.1
[aae7a2af] DiffEqFlux v0.2.0
[c894b116] DiffEqJump v6.1.0+ [C:\Users\accou\.julia\dev\DiffEqJump]
[1130ab10] DiffEqParamEstim v1.6.0+ [C:\Users\accou\.julia\dev\DiffEqParamEstim]
[055956cb] DiffEqPhysics v3.1.0
[225cb15b] DiffEqTutorials v0.0.0 [C:\Users\accou\.julia\external\DiffEqTutorials.jl]
```

```

[0c46a032] DifferentialEquations v6.3.0
[497a8b3b] DoubleFloats v0.7.5
[587475ba] Flux v0.7.3
[f6369f11] ForwardDiff v0.10.3+ [C:\Users\accou\.julia\dev\ForwardDiff`]
[28b8d3ca] GR v0.38.1
[7073ff75] IJulia v1.17.0
[c601a237] Interact v0.9.1
[b6b21f68] Ipopt v0.5.4
[4076af6c] JuMP v0.19.0
[e5e0dc1b] Juno v0.5.4
[eff96d63] Measurements v2.0.0
[76087f3c] NLOpt v0.5.1
[429524aa] Optim v0.17.2
[1dea7af3] OrdinaryDiffEq v5.2.1+ [C:\Users\accou\.julia\dev\OrdinaryDif
fEq`]
[65888b18] ParameterizedFunctions v4.1.1
[91a5bcdd] Plots v0.23.0
[71ad9d73] PuMaS v0.0.0 [C:\Users\accou\.julia\dev\PuMaS`]
[d330b81b] PyPlot v2.7.0
[731186ca] RecursiveArrayTools v0.20.0
[90137ffa] StaticArrays v0.10.2
[789caeaf] StochasticDiffEq v6.1.1+ [C:\Users\accou\.julia\dev\Stochasti
cDiffEq`]
[c3572dad] Sundials v3.0.0
[1986cc42] Unitful v0.14.0
[44d3d7a6] Weave v0.7.1 [C:\Users\accou\.julia\dev>Weave`]

```