A Fast Dynamic Language for Technical Computing

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What is a “technical/numerical” language?

An obvious answer:

- **specialized for numerical work**

Matlab:

- everything is a complex matrix

R (and **S** before it)**:**

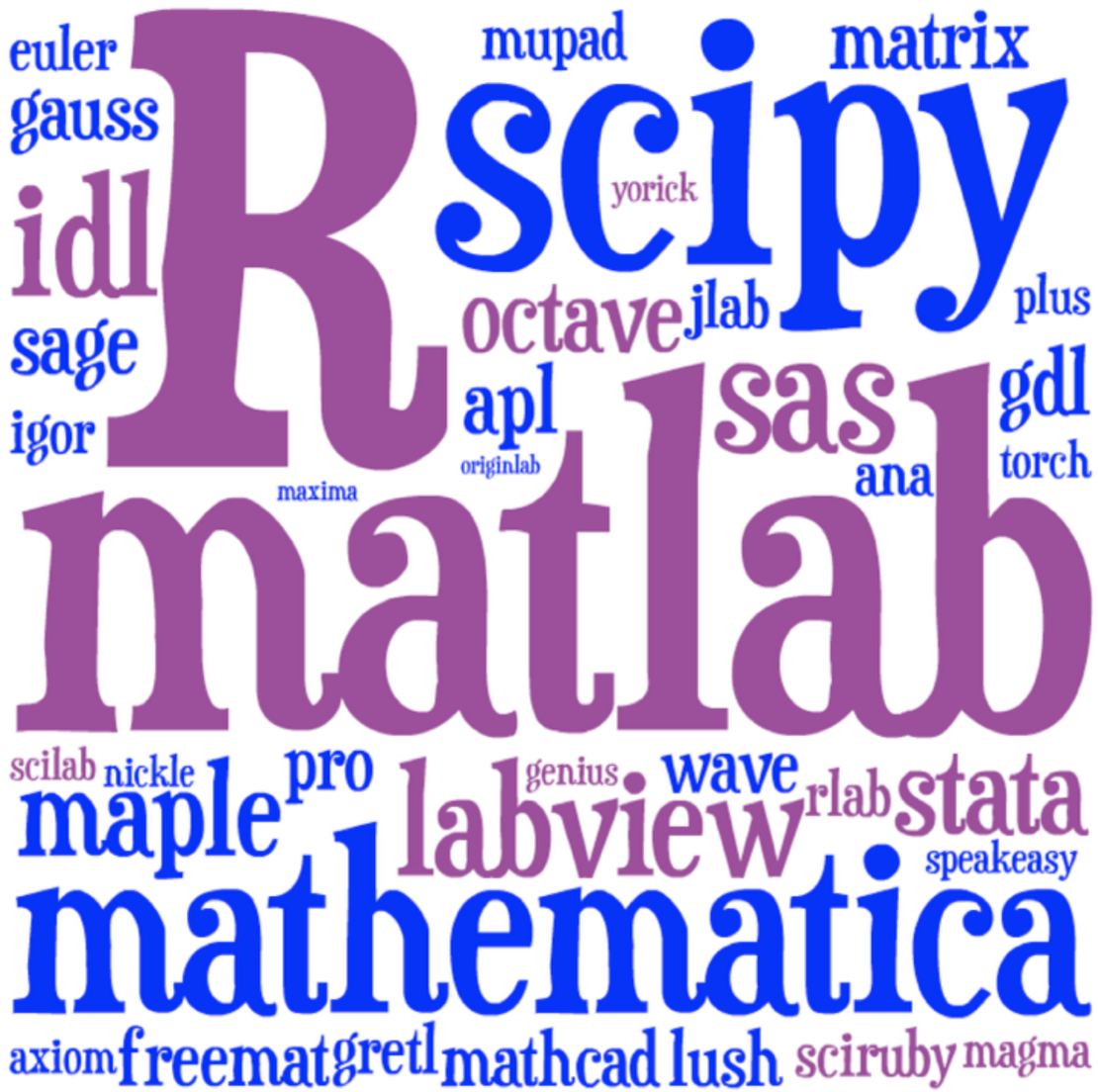
- allow “NA” values everywhere
- data frame as basic data type

Mathematica:

- symbolic rewriting everywhere

NumPy:

- typed arrays for Python



Are C and Scheme numerical?

Scheme R^{6}RS spec:

- **20% numerical**

C99 spec:

- **20% numerical**

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That's funny…

Numerical languages are strangely diverse

General languages are strangely numerical

What’s going on here?

The “niche hypothesis”

Numerical computing is still an **under-generalized** niche

- each language picks a **different way** of specializing numerically

  (also happens to be the oldest programming language niche – Fortran)

Hypothesis:

- many **diverse languages** in this niche can be replaced
- by a **single** sufficiently powerful, general-purpose language

History

Text processing was a niche with a similar variety of languages

- *SNOBOL, SPITBOL, COMIT, TRAC, TTM, Icon, Unicon, sed, awk, Perl4*

  lot's of **different views** of text processing and how to specialize for it

You don't see much of these anymore

- people use *one* of **Python, Ruby, or Perl5** instead

  (we still use sed and awk sometimes, but **could** use Perl/Python/Ruby)

A few general languages that **support** text processing

- replaced diverse languages that **specialized** in some aspect of it

History

Text processing was **diverse & hard.**

Now it’s **unified & easy.**

Can we do this for **numerical computing?**

History

We believe the answer is **“yes”**

Julia is our attempt to do this.

Before we go further

Let’s actually see some code.

Matlab-like

```
function randmatstat(t,n)
    v = zeros(t)
    w = zeros(t)
    for i = 1:t
        a = randn(n,n)
        b = randn(n,n)
        c = randn(n,n)
        d = randn(n,n)
        P = [a b c d]
        Q = [a b; c d]
        v[i] = trace((P'*P)^4)
        w[i] = trace((Q'*Q)^4)
    end
    std(v)/mean(v), std(w)/mean(w)
end
```

Low-level

```
function qsort!(a,lo,hi)
    i, j = lo, hi
    while i < hi
        pivot = a[(lo+hi)>>>1]
        while i <= j
            while a[i] < pivot; i = i+1; end
            while a[j] > pivot; j = j-1; end
            if i <= j
                a[i], a[j] = a[j], a[i]
                i, j = i+1, j-1
            end
        end
        if lo < j; qsort!(a,lo,j); end
        lo, j = i, hi
    end
    return a
end
```

Different

```
immutable ModInt{n} <: Integer
    k::Int
    ModInt(k) = new(mod(k,n))
end

-{n}(a::ModInt{n}) = ModInt{n}(-a.k)
+{n}(a::ModInt{n}, b::ModInt{n}) = ModInt{n}(a.k+b.k)
-{n}(a::ModInt{n}, b::ModInt{n}) = ModInt{n}(a.k-b.k)
*{n}(a::ModInt{n}, b::ModInt{n}) = ModInt{n}(a.k*b.k)

convert{n}(::Type{ModInt{n}}, i::Int) = ModInt{n}(i)
promote_rule{n}(::Type{ModInt{n}}, ::Type{Int}) = ModInt{n}

show{n}(io::IO, k::ModInt{n}) = print(io, "$(k.k) mod $n")
showcompact(io::IO, k::ModInt) = print(io, k.k)
```

Why are numbers hard?

Syntax

- numerical operators tend use **infix syntax**

Semantics

- numerical operators are usually **not “just functions”**
- things like “+” and indexing are **highly polymorphic**
- **special promotion** of arguments to a common type
- need **compact arrays** (of numbers at least)
- numbers are naturally **immutable**

Other things that scientists want...

- extreme **convenience** – things Just Work™
- code that looks like **pseudocode**
- massive **standard library**
- top **performance**

Julia design overview

high-level & **dynamic**

expressive **type-system**

- parametric, dependent, invariant
- concrete types are final

  but large abstract super-type hierarchy

  generic programming with abstract types
- **unobtrusive** – don't need to mention types

metaprogramming

- **homoiconic**: code represented as data

  can be constructed, manipulated, eval'd
- **macros:** `@time sleep(1)`

ubiquitous **multiple dispatch**

- everything is a **generic function**

  even basic performance-critical functions
- quantified methods (think templates)
- diagonal dispatch

concurrency & parallelism

- lightweight **coroutine**-based I/O
- distributed global address space

  first-class remote references

  easy to run code on a cluster of instances
- we're working on **multithreading**

Dynamic typing

Dynamic typing is hugely popular for numerical environments:

- exploratory, interactive, **tangible**
- **“customer is always right”**

Julia has a type system, but no **static type checking**

- Leah Hanson observed while learning Julia:

  “I like that Julia uses the type system in all the ways that don't end with the programmer arguing with the compiler.”

- not checking types can allow a more sophisticated type system

Two language compromise

People love **dynamic** environments

- for data analysis and **exploration**
- but dynamism and **performance** are at odds

A standard **compromise**:

- **slow** code in convenient dynamic language (Matlab, Python, R)
- **fast** code in static, low-level language (C, C++, Fortran)

Creates a huge impediment to **development**

- continually breaking the **abstraction barrier** = poor abstraction

Goldilocks

Graydon Hoare (creator of Rust) wrote [http://goo.gl/zQRGu6]:

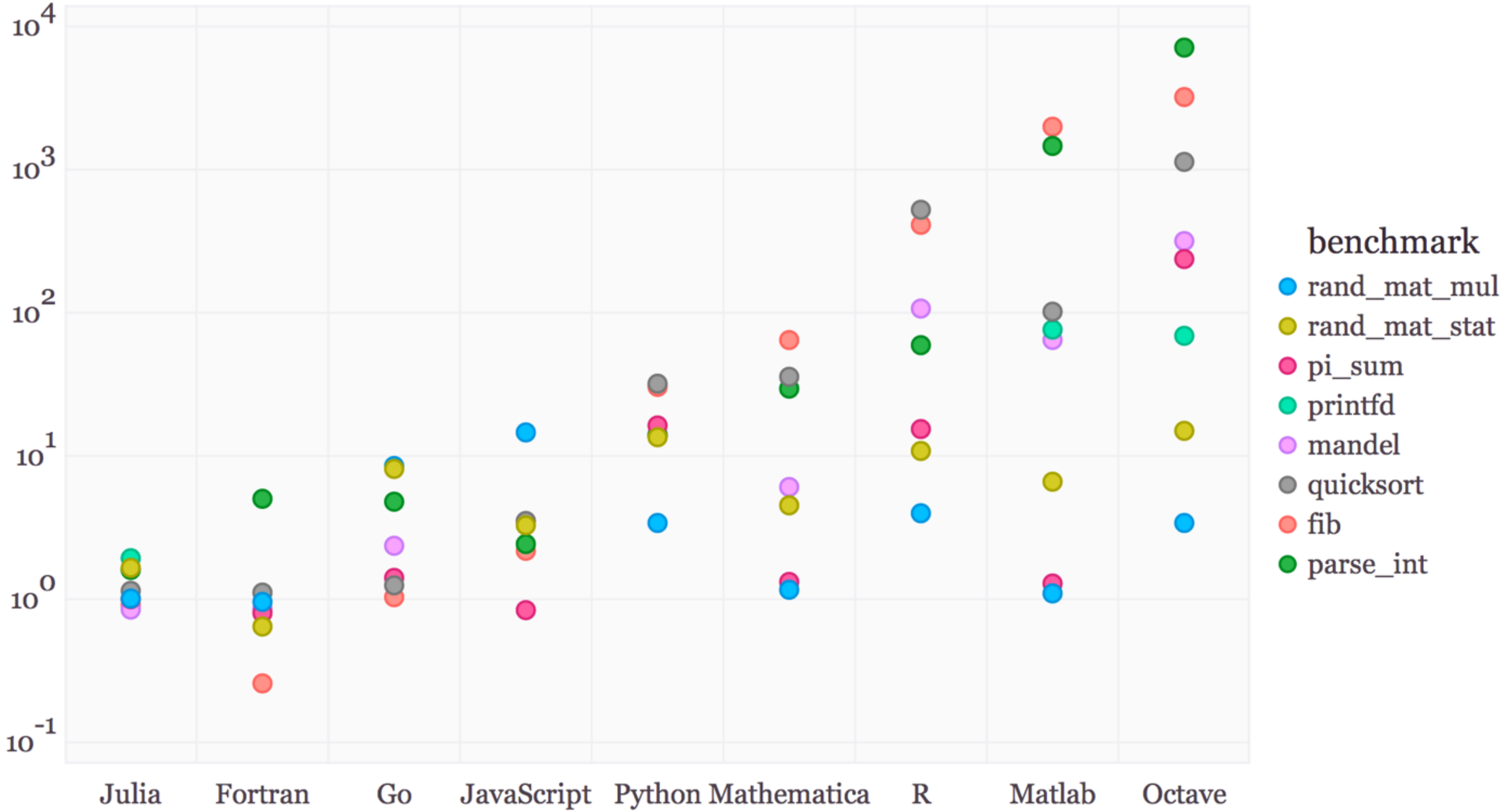
“Julia, like Dylan and Lisp before it, is a Goldilocks language.

It is trying to span the entire spectrum of its target users’ needs, from numerical inner loops to glue-language scripting to dynamic code generation and reflection.”

Goldilocks languages are the opposite of two-language systems:

- do everything in **one language** – both low level and high level work
- define the language **in itself** and give users just as much **power**

Microbenchmarks



Reports from the real world

"[R]eports ... indicate that Julia gives rather significant boosts over Matlab/R, sometimes by even more than the benchmarks might suggest. That was surprising to me, since I expected the gap to be largest for benchmarks.

...

[O]ne common factor was fairly sizable (but not ridiculous) memory requirements; perhaps Julia's ability to manage memory in a more fine-grained fashion pays major dividends for such problems."

– Tim Holy, WUSTL
http://goo.gl/r6qwz

Simplex Benchmarks

source: Miles Lubin & Iain Dunning

`https://github.com/mlubin/SimplexBenchmarks`

- Benchmark of some important operations:

	Julia	C++	C++bnd	Matlab	PyPy	Python
Sp. mat-sp. vec	1.29	0.90	1.00	5.79	19.20	417.16
Sp. vector scan	1.59	0.96	1.00	13.98	13.81	48.39
Sp. `axpy`	1.85	0.70	1.00	19.12	9.21	78.65

- C++bnd = C++ with bounds checking
- Execution times relative to C++bnd

Finite element programming

Comparison by Amuthan Ramabathiran [http://goo.gl/SRciE]:

- **FEniCS**

  “collection of software for high level finite element code development written in Python and C++”

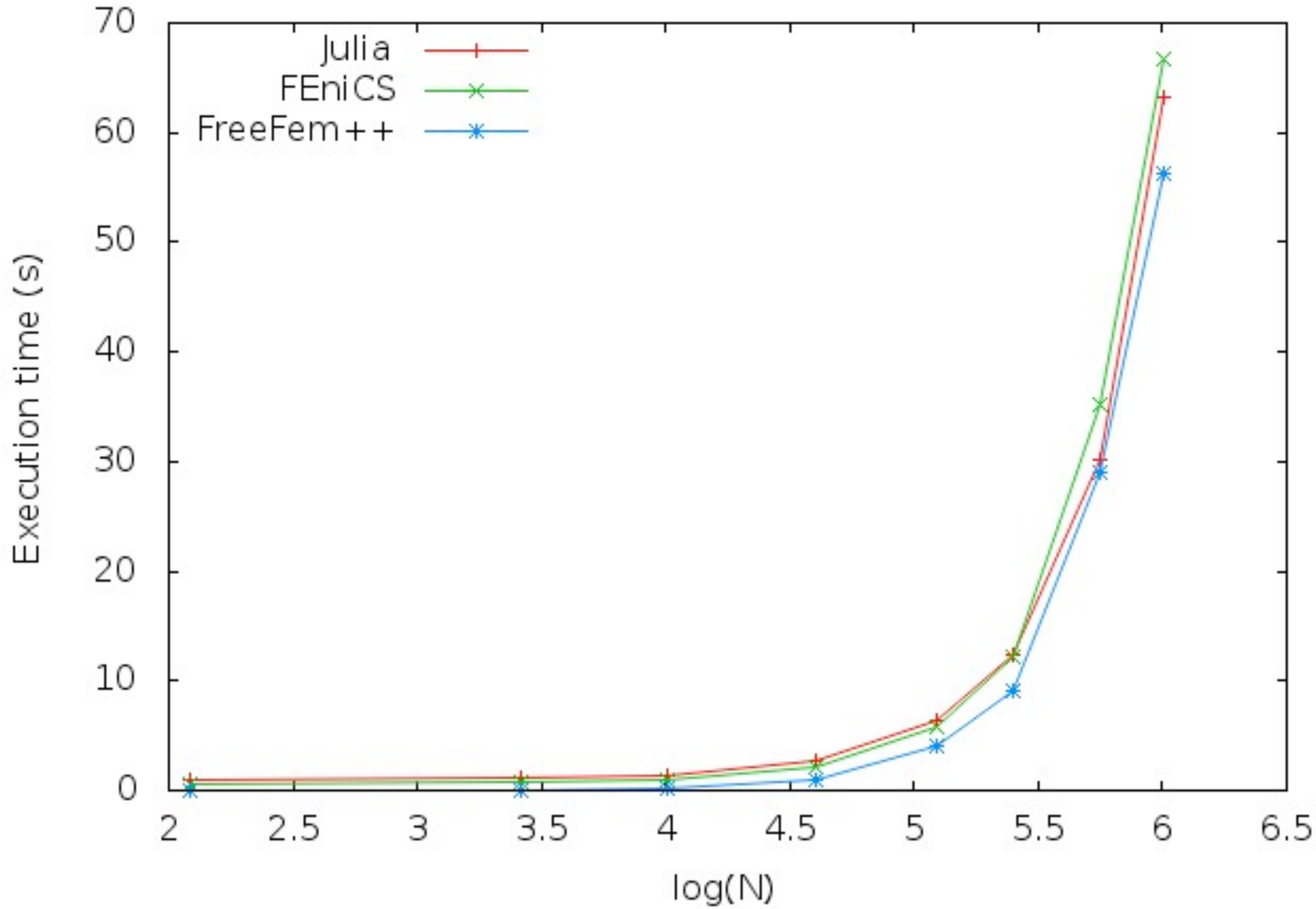
- **FreeFem++**

  “partial differential equations solver written in C++ with its own DSL (Domain Specific Language) with a C++ like syntax.”

- **Julia FEM**, simple solver

  “Thanks to Julia’s elegant syntax the code is largely self-explanatory.”

Finite element programming



Finite element programming

"[W]hat is really interesting about Julia is the relative ease with which various strategies can be implemented and tested without leading to code swell, while at the same time resulting in high performance code.

...

Julia appears to be a very good choice for developing research oriented finite element software that is both fast and easy to develop."

– Amuthan Ramabathiran
http://goo.gl/SRciE

How does Julia go fast?

There are many fast dynamic language implementations these days

- **JavaScript V8**, **LuaJIT**, **PyPy**, *etc.*

Julia doesn't work the way these do at all

- **"Julia does static compilation at run time"** – Carl Bolz, PyPy core developer

Basically, we've cheated

- made key design choices that make it much easier to make things fast

  native data types (machine ints, floats, etc.)

  type **annotations**; type **stability** in standard libraries

  immutable types; all concrete types are **final**

  multiple dispatch

Collatz

```
function collatz(n)
    k = 0
    while n > 1
        n = isodd(n) ? 3n+1 : n>>1
        k += 1
        end
        return k
    end
```

The Collatz conjecture:

- for all n ≥ 0 the function `collatz(n)` terminates

Cumulative Collatz

```
function collatz_up_to(m)
    c = fill(-1,m)
    c[1] = 0
    for n = 2:m
        n′, d = n, 0
        while n′ > length(c) || c[n′] < 0
            n′ = isodd(n′) ? 3n′+1 : n′>>1
            d += 1
        end
        d += c[n′]
        while n > length(c) || c[n] < 0
            n <= length(c) && (c[n] = d)
            n = isodd(n) ? 3n+1 : n>>1
            d -= 1
        end
    end
    return c
end
```

Other key performance tricks

Run-time (**just-in-time**) code generation using LLVM

- aggressive **specialization** on runtime types

Very clever data-flow **type inference** (not Hindley-Milner)

- http://localhost:8998/notebooks/dataflow_type_inference.ipynb

Jeff Bezanson is a true performance artist :-)

But Julia isn't really about performance

The benchmarks are what grab people, but…

- the real killer is writing **high-level generic code** that runs fast
- and **composing unrelated code** smoothly (and efficiently)

Sounds esoteric, but **multiple dispatch** is crucial

- choose implementation based on on **all arguments**, not just the first

  trivial to plug in code for efficient **special cases**

  easy to apply **existing code** to **new types**

  easy to apply **new code** to **existing types**

Multiple dispatch

What is multiple dispatch?

- **dispatch:** choose method based on runtime types, not static types
- **multiple:** based on all arguments, not just the receiver

Written as **function application:**

- `f(a,b,c)` ⟸ like this
- `a.f(b,c)` ⟸ not this

Multiple dispatch ≠ method overloading

Multiple dispatch in action

Let’s go to the IJulia Notebook:

- http://localhost:8998/notebooks/multiple_dispatch.ipynb

Multiple dispatch in Ruby

Arithmetic operators:

```
Number + Number     | String + String   | Array + Array
Number - Number     | Time - Time       | Time - Number      | Array - Array
Number * Number     | Array * Integer   | Array * String     | String * Integer
Integer << Integer  | String << String  | String << Integer
```

Arrays, Hashes & Strings:

```
(Array|Hash).fetch(index,default|block)
(Array|Hash).new(object|block)  | String.new(string)
(Array|Hash)[int|range]         | String[int|range|regex|string]
(Array|Hash)[int|range]=        | String[int|range|regex|string]=
Array.slice(int|range)          | String.slice(int|range|regex|string)
Array.slice!(int|range)         | String.slice!(int|range|regex|string)
```

Just Strings:

```
String.index(string|int|regex)
String.rindex(string|int|regex)
String.sub(pattern,replacement|block)
String.sub!(pattern,replacement|block)
String.gsub(pattern,replacement|block)
String.gsub!(pattern,replacement|block)
```

Multiple dispatch in English

Related meanings:

- “she goes (home|away)” go(subj::Noun, where::PlaceAdverb)
- “it went (wrong|well)” go(subj::Noun, how::MannerAdverb)

Default arguments:

- “go (home|away|well)” go(adv::Adverb) = go(Person("addressee"), adv)
- “he goes” go(subj::Noun) = go(subj, PlaceAdverb("somewhere"))
- “go” go() = go(PlaceAdverb("somewhere"))

Open source & friendly

Julia and most of its packages are

- MIT-licensed
- hosted on GitHub
  - built-in package manager
  - integrated with CI and coverage services (Travis & Coveralls.io)

Active, friendly and helpful community

- helpful for new and veteran programmers, alike
- huge expertise in an breadth of technical subjects

More than just a new language

Julia is a place for programmers, physical scientists, social scientists, computational scientists, mathematicians, and others to pool their collective knowledge in the form of code.