10g. SIMD Packages

Martin Alfaro
PhD in Economics

INTRODUCTION

So far, we've relied on the built-in `@simd` macro to apply SIMD instructions. This approach, nonetheless, exhibits several limitations. First, `@simd` acts as a suggestion rather than a strict command: it hints to the compiler that SIMD optimizations might improve performance, but ultimately the implementation decision is up to the compiler's discretion. Second, `@simd` prioritizes code safety over speed, restricting access to advanced SIMD features to avoid unintended bugs. Third, its application is limited to for-loops.

To overcome these shortcomings, we introduce the `@turbo` macro from the `LoopVectorization` package. Unlike `@simd`, the `@turbo` macro enforces SIMD optimizations, guaranteeing that vectorized instructions are actually applied. It also performs more aggressive optimizations than `@simd`, shifting the responsibility for correctness and safety onto the user. Finally, `@turbo` extends beyond for-loops, also supporting broadcasting operations. Finally, `@turbo` integrates with the `SLEEFPirates` package. This provides SIMD-accelerated implementations of common mathematical functions such as logarithms, exponentials, powers, and trigonometric operations.

CAVEATS ABOUT IMPROPER USE OF @TURBO

In contrast to `@simd`, applying `@turbo` requires extra caution, as its misapplication can lead to incorrect results. The risk stems from the additional assumptions that `@turbo` makes to enable more aggressive optimization. In particular:

- **No bound checking**: `@turbo` omits index bound checks, potentially leading to out-of-bounds memory access.
- **Iteration order invariance**: `@turbo` assumes the outcome doesn't depend on the order of iteration, with the sole exception of reduction operations.

The second assumption is particularly relevant for floating-point arithmetic, where non-associativity can cause **results to vary with iteration order**. Integer operations, by contrast, are unaffected. The following example demonstrates this issue: because each iteration depends on the outcome of the previous one, applying `@turbo` produces incorrect results.

NO MACRO

```julia
x = [0.1, 0.2, 0.3]

function foo!(x)
    for i in 2:length(x)
        x[i] = x[i-1] + x[i]
    end
end
```

```
julia> foo!(x)

julia> x
3-element Vector{Float64}:
 0.1
 0.3
 0.6
```

@SIMD

```julia
x = [0.1, 0.2, 0.3]

function foo!(x)
    @inbounds @simd for i in 2:length(x)
        x[i] = x[i-1] + x[i]
    end
end
```

```
julia> foo!(x)

julia> x
3-element Vector{Float64}:
 0.1
 0.3
 0.6
```

@TURBO

```julia
x = [0.1, 0.2, 0.3]

function foo!(x)
    @turbo for i in 2:length(x)
        x[i] = x[i-1] + x[i]
    end
end
```

```
julia> foo!(x)

julia> x
3-element Vector{Float64}:
 0.1
 0.3
 0.5
```

Considering that `@turbo` isn't suitable for all operations, we next present cases where the macro can be safely applied.

SAFE APPLICATIONS OF @TURBO

There are two safe applications of `@turbo` that cover a wide range of cases. The first applies **when iterations are completely independent**, making execution order irrelevant for the final outcome.

The example below illustrates this case by performing an independent transformation on each element of a vector. Importantly, `@turbo` isn't restricted to for-loops, also allowing for broadcasted operations. We show both applications.

DEFAULT

```
x              = rand(1_000_000)
calculation(a) = a * 0.1 + a^2 * 0.2 - a^3 * 0.3 - a^4 * 0.4

function foo(x)
    output      = similar(x)

    for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  3.840 ms (3 allocations: 7.629 MiB)
```

@SIMD

```
x              = rand(1_000_000)
calculation(a) = a * 0.1 + a^2 * 0.2 - a^3 * 0.3 - a^4 * 0.4

function foo(x)
    output      = similar(x)

    @inbounds @simd for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  4.096 ms (3 allocations: 7.629 MiB)
```

@TURBO (FOR-LOOP)

```
x              = rand(1_000_000)
calculation(a) = a * 0.1 + a^2 * 0.2 - a^3 * 0.3 - a^4 * 0.4

function foo(x)
    output     = similar(x)

    @turbo for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  271.104 μs (3 allocations: 7.629 MiB)
```

@TURBO (BROADCASTING)

```
x              = rand(1_000_000)
calculation(a) = a * 0.1 + a^2 * 0.2 - a^3 * 0.3 - a^4 * 0.4

foo(x)         = @turbo calculation.(x)
```

```
julia> @btime foo($x)
  482.698 μs (3 allocations: 7.629 MiB)
```

The second safe application is **reductions**. While reductions consists of dependent iterations, they're a special case that `@turbo` handles properly.

DEFAULT

```
x              = rand(1_000_000)
calculation(a) = a * 0.1 + a^2 * 0.2 - a^3 * 0.3 - a^4 * 0.4

function foo(x)
    output     = 0.0

    for i in eachindex(x)
        output += calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  3.892 ms (0 allocations: 0 bytes)
```

@SIMD

```
x              = rand(1_000_000)
calculation(a) = a * 0.1 + a^2 * 0.2 - a^3 * 0.3 - a^4 * 0.4

function foo(x)
    output     = 0.0

    @inbounds @simd for i in eachindex(x)
        output += calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  3.937 ms (0 allocations: 0 bytes)
```

@TURBO

```
x              = rand(1_000_000)
calculation(a) = a * 0.1 + a^2 * 0.2 - a^3 * 0.3 - a^4 * 0.4

function foo(x)
    output     = 0.0

    @turbo for i in eachindex(x)
        output += calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  179.364 μs (0 allocations: 0 bytes)
```

SPECIAL FUNCTIONS

Another important application of `LoopVectorization` arises through its integration with the library *SLEEF* (an anocrym for "SIMD Library for Evaluating Elementary Functions"). SLEEF is exposed in `LoopVectorization` via the `SLEEFPirates` package, which accelerates the evaluation of several mathematical functions using SIMD instructions. In particular, it speeds up the computations of the exponential, logarithmic, power, and trigonometric functions.

Below, we illustrate the use of `@turbo` for each type of function. For a complete list of supported functions, see the **SLEEFPirates documentation**. All the examples rely on an element-wise transformation of `x` via the function `calculation`, which will take a different form depending on the function illustrated.

LOGARITHM

DEFAULT

```
x              = rand(1_000_000)
calculation(a) = log(a)

function foo(x)
    output     = similar(x)

    for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  3.542 ms (3 allocations: 7.629 MiB)
```

@SIMD

```
x              = rand(1_000_000)
calculation(a) = log(a)

function foo(x)
    output     = similar(x)

    @inbounds @simd for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  3.546 ms (3 allocations: 7.629 MiB)
```

@TURBO (FOR-LOOP)

```
x              = rand(1_000_000)
calculation(a) = log(a)

function foo(x)
    output     = similar(x)

    @turbo for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  1.617 ms (3 allocations: 7.629 MiB)
```

@TURBO (BROADCASTING)

```julia
x               = rand(1_000_000)
calculation(a) = log(a)

foo(x) = @turbo calculation.(x)
```

```
julia> @btime foo($x)
  1.618 ms (3 allocations: 7.629 MiB)
```

EXPONENTIAL FUNCTION

DEFAULT

```julia
x               = rand(1_000_000)
calculation(a) = exp(a)

function foo(x)
    output     = similar(x)

    for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  2.608 ms (3 allocations: 7.629 MiB)
```

@SIMD

```julia
x               = rand(1_000_000)
calculation(a) = exp(a)

function foo(x)
    output     = similar(x)

    @inbounds @simd for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  2.639 ms (3 allocations: 7.629 MiB)
```

@TURBO (FOR-LOOP)

```julia
x              = rand(1_000_000)
calculation(a) = exp(a)

function foo(x)
    output     = similar(x)

    @turbo for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  555.012 μs (3 allocations: 7.629 MiB)
```

@TURBO (BROADCASTING)

```julia
x              = rand(1_000_000)
calculation(a) = exp(a)

foo(x) = @turbo calculation.(x)
```

```
julia> @btime foo($x)
  544.043 μs (3 allocations: 7.629 MiB)
```

POWER FUNCTIONS

This includes any operation comprising terms x^y.

DEFAULT

```julia
x              = rand(1_000_000)
calculation(a) = a^4

function foo(x)
    output     = similar(x)

    for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  3.517 ms (3 allocations: 7.629 MiB)
```

@SIMD

```julia
x              = rand(1_000_000)
calculation(a) = a^4

function foo(x)
    output     = similar(x)

    @inbounds @simd for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  3.578 ms (3 allocations: 7.629 MiB)
```

@TURBO (FOR-LOOP)

```julia
x              = rand(1_000_000)
calculation(a) = a^4

function foo(x)
    output     = similar(x)

    @turbo for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  371.218 μs (3 allocations: 7.629 MiB)
```

@TURBO (BROADCASTING)

```julia
x              = rand(1_000_000)
calculation(a) = a^4

foo(x) = @turbo calculation.(x)
```

```
julia> @btime foo($x)
  302.605 μs (3 allocations: 7.629 MiB)
```

The implementation for power functions includes calls to other function, such as the one for square roots.

DEFAULT

```julia
x              = rand(1_000_000)
calculation(a) = sqrt(a)

function foo(x)
    output     = similar(x)

    for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  1.159 ms (3 allocations: 7.629 MiB)
```

@SIMD

```julia
x              = rand(1_000_000)
calculation(a) = sqrt(a)

function foo(x)
    output     = similar(x)

    @inbounds @simd for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  1.200 ms (3 allocations: 7.629 MiB)
```

@TURBO (FOR-LOOP)

```julia
x              = rand(1_000_000)
calculation(a) = sqrt(a)

function foo(x)
    output     = similar(x)

    @turbo for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  590.429 μs (3 allocations: 7.629 MiB)
```

@TURBO (BROADCASTING)

```julia
x              = rand(1_000_000)
calculation(a) = sqrt(a)

foo(x) = @turbo calculation.(x)
```

```
julia> @btime foo($x)
  578.698 μs (3 allocations: 7.629 MiB)
```

TRIGONOMETRIC FUNCTIONS

Among others, `@turbo` can handle the functions `sin`, `cos`, and `tan`. Below, we demonstrate its use with `sin`.

DEFAULT

```julia
x              = rand(1_000_000)
calculation(a) = sin(a)

function foo(x)
    output     = similar(x)

    for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  3.915 ms (3 allocations: 7.629 MiB)
```

@SIMD

```julia
x              = rand(1_000_000)
calculation(a) = sin(a)

function foo(x)
    output     = similar(x)

    @inbounds @simd for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  3.895 ms (3 allocations: 7.629 MiB)
```

@TURBO (FOR-LOOP)

```
x              = rand(1_000_000)
calculation(a) = sin(a)

function foo(x)
    output     = similar(x)

    @turbo for i in eachindex(x)
        output[i] = calculation(x[i])
    end

    return output
end
```

```
julia> @btime foo($x)
  1.341 ms (3 allocations: 7.629 MiB)
```

@TURBO (BROADCASTING)

```
x              = rand(1_000_000)
calculation(a) = sin(a)

foo(x) = @turbo calculation.(x)
```

```
julia> @btime foo($x)
  1.315 ms (3 allocations: 7.629 MiB)
```