Practical Vectorization in Julia

Make those SIMD units (that you bought) work for you.

Arch D. Robison – 6/27/2014

Scope

Julia v0.3.0-prerelease

- Download from http://julialang.org/downloads/

Julia master

- `git clone` [`https://github.com/JuliaLang/julia.git`](https://github.com/JuliaLang/julia.git)
- `Do not configure with USE_SYSTEM_LLVM=1`

Julia 0.2 has no vectorization.

Outline

SIMD hardware

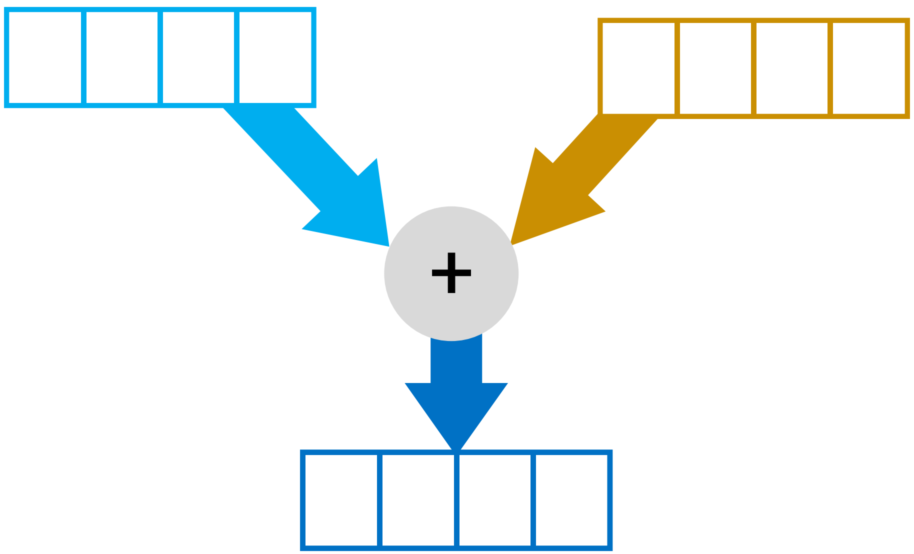
Vectorization basics

Recommendations on vectorization in Julia

Future directions

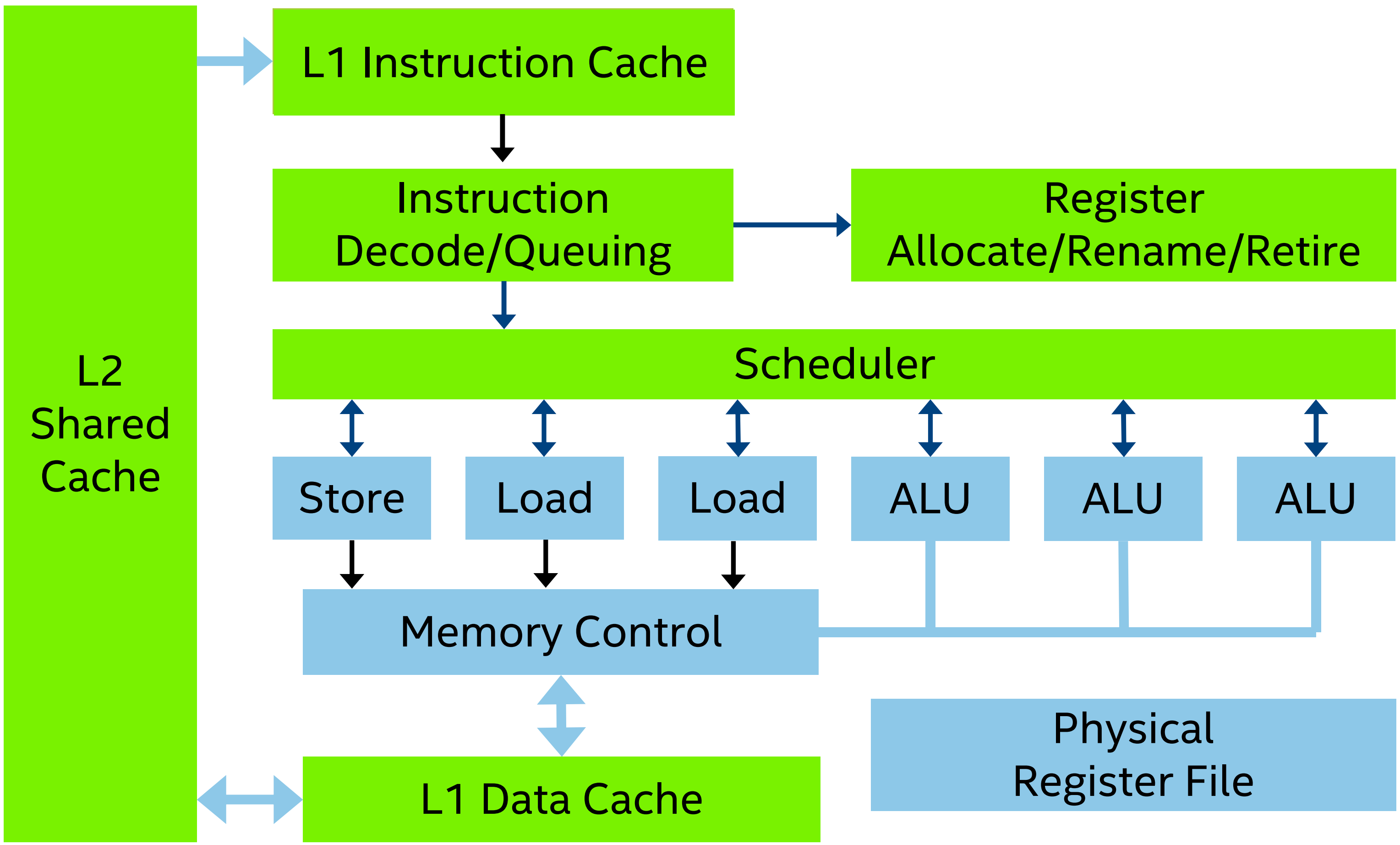
What is SIMD?

Single **I**nstruction **M**ultiple **D**ata



Single instruction operates across a tuple.

Why Hardware Designers Like SIMD



Optimization Notice

Vectorization

Program transformation for exploiting SIMD units

Vectorization of a Loop

```
function axpy( a, x, y )
    @simd for i=1:length(x)
        @inbounds y[i] = y[i]+a*x[i]
    end
end
```

Requires Julia 0.3-dev or later

```
function axpy( a::Float32, x::Array{Float32,1}, y::Array{Float32,1} )
    @inbounds for i=1:4:length(x)
        # Four logical iterations per physical iteration
        t1 = (x[i],x[i+1],x[i+2],x[i+3])   # Load tuple
        t2 = (y[i],y[i+1],y[i+2],y[i+3])   # Load tuple
        t3 = a*t1                          # Scalar times tuple
        t4 = t2+t3                         # Tuple add
        (y[i],y[i+1],y[i+2],y[i+3]) = t4   # Tuple store
    end
    ... Scalar loop for remaining iterations ...
end
```

Note: example assumes tuple math exists.

Serial Order of Evaluation

$t1_1=x[1]$	$t1_2=x[2]$	$t1_3=x[3]$	$t1_4=x[4]$
$t2_1=y[1]$	$t2_2=y[2]$	$t2_3=y[3]$	$t2_4=y[4]$
$t3_1=a*t1_1$	$t3_2=a*t1_2$	$t3_3=a*t1_3$	$t3_4=a*t1_4$
$t4_1=t2_1+t3_1$	$t4_2=t2_2+t3_2$	$t4_3=t2_3+t3_3$	$t4_4=t2_4+t3_4$
$y[1]=t4_1$	$y[2]=t4_2$	$y[3]=t4_3$	$y[4]=t4_4$

Vectorization Transposes the Order

$t1_1$=x[1] $t1_2$=x[2] $t1_3$=x[3] $t1_4$=x[4]

$t2_1$=y[1] $t2_2$=y[2] $t2_3$=y[3] $t2_4$=y[4]

$t3_1$=a*$t1_1$ $t3_2$=a*$t1_2$ $t3_3$=a*$t1_3$ $t3_4$=a*$t1_3$

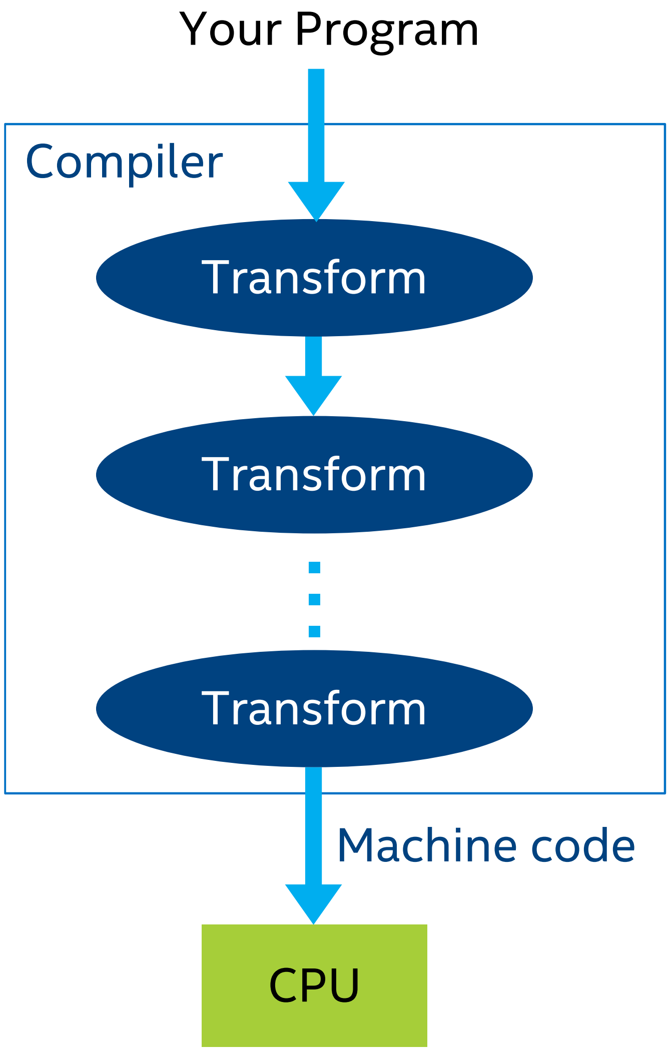
$t4_1$=$t2_1$+$t3_1$ $t4_2$=$t2_2$+$t3_2$ $t4_3$=$t2_3$+$t3_3$ $t4_4$=$t2_3$+$t3_3$

y[1] =$t4_1$ y[2] =$t4_2$ y[3] =$t4_3$ y[4] =$t4_4$

Vectorization transposes each chunk of iteration space.

Optimization Notice

Compilers 101



Three steps for a transform

1. Is it **legal**?
2. Is it **profitable**?
3. If so, **do** the transform.

Implicit vs. Explicit Vectorization

Implicit vectorization

Automatic

- Compiler proves that transposition/reassociation is legal

OR

- Inserts run-time checks

Explicit vectorization with @simd

Programmer intervention

- **Experimental feature**
- Programmer swears that transposition/reassociation is okay

Example of Run-Time Check

```
function axpy( a::Float32, x::Array{Float32,1}, y::Array{Float32,1} )
    n = length(x)
    if y[1:n] does not overlap x[1:n]
        @inbounds for i=1:4:length(x)
            y[…] += a*x[…]
        end
    end
    … Scalar loop for remaining iterations …
end
```

Limitations of run-time check

- Cost is often quadratic in number of arrays.
- Punts on tricky subscript patterns, such as in sparse matrix code.

    ... = w[k[i]]   # *"gather"*

    z[k[i]] = ...   # *"scatter"*

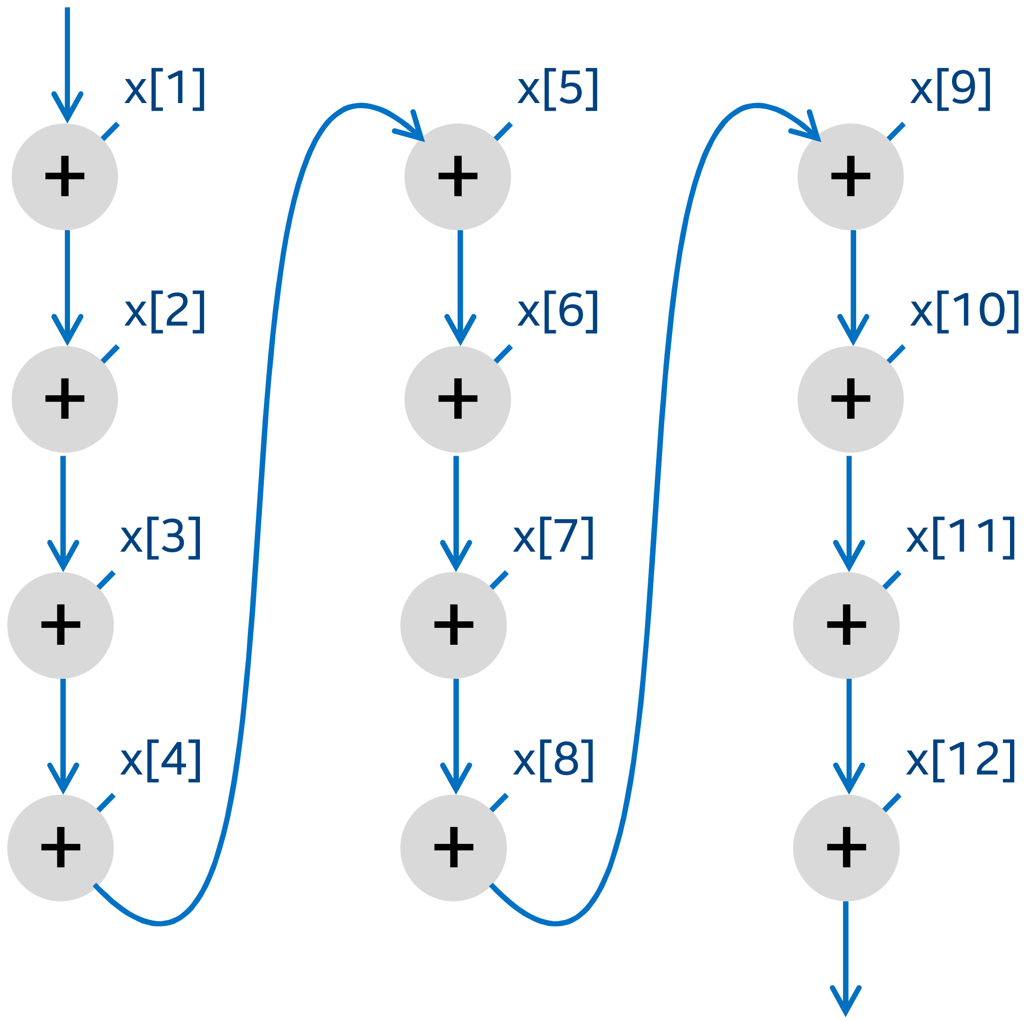
Vectorization of Reduction

```
function summation(x)
    s = zero(x[1])
    @simd for i=1:length(x)
        @inbounds s += x[i]
    end
    s
end
```

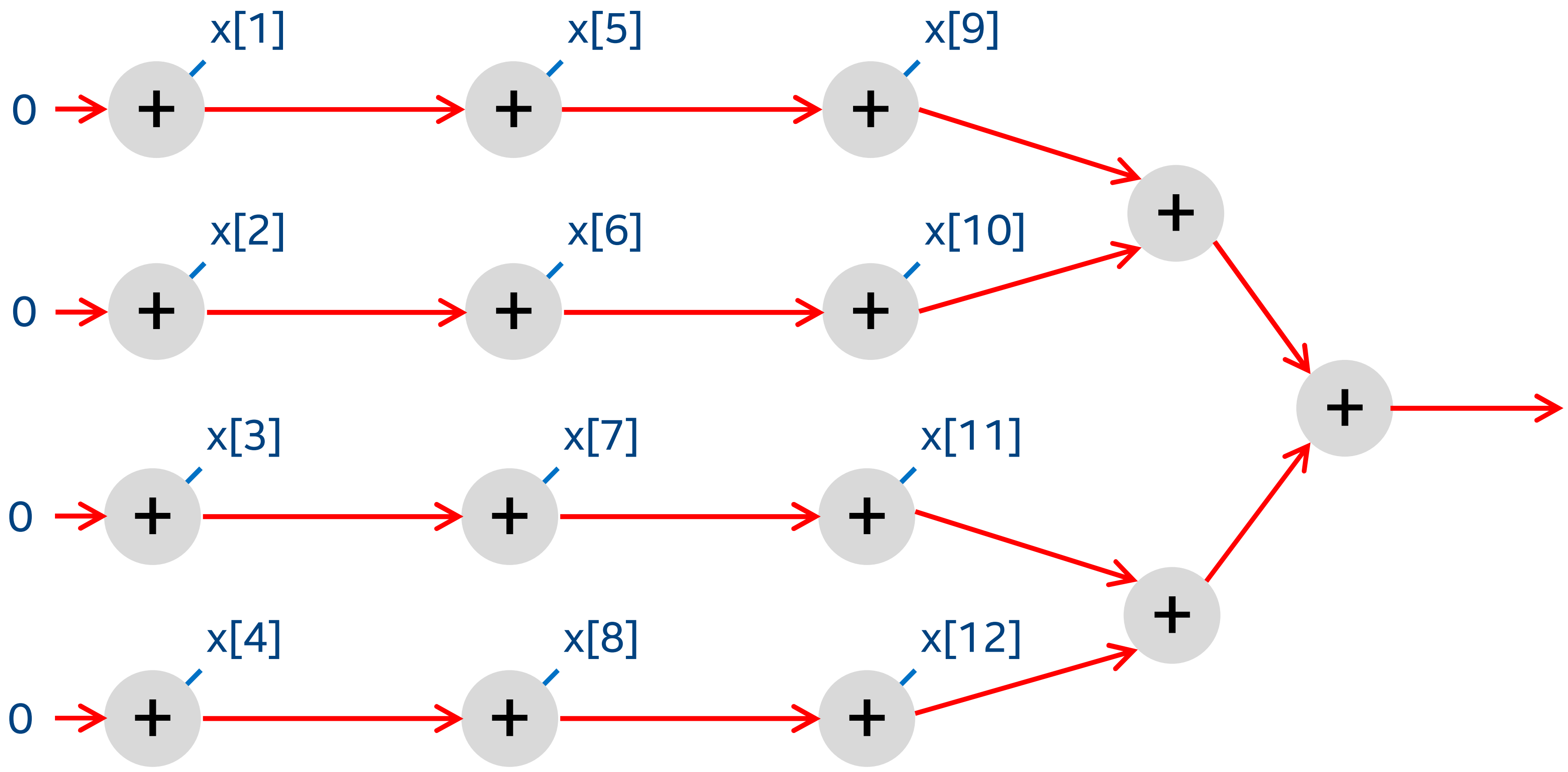
```
function summation(x::Array{Float32,1})
    t =(0f0,0f0,0f0,0f0)
    @inbounds for i=1:4:length(x)
        # Four logical iterations per physical iteration
        t += (x[i],x[i+1],x[i+2],x[i+3])
    end
    s = (t[1]+t[2]) + (t[3]+t[4])
    ... deal with remaining iterations ...
    s
end
```

Note: example assumes tuple math exists.

Serial Order of Summation



Vectorization Reorders Reduction



Impact of Reassociation Requirement

Implicit vectorization works for **integer** reductions

- +, *, &, |, $, min, max

Use `@simd` for **floating-point** reductions

- +, *

Not yet implemented

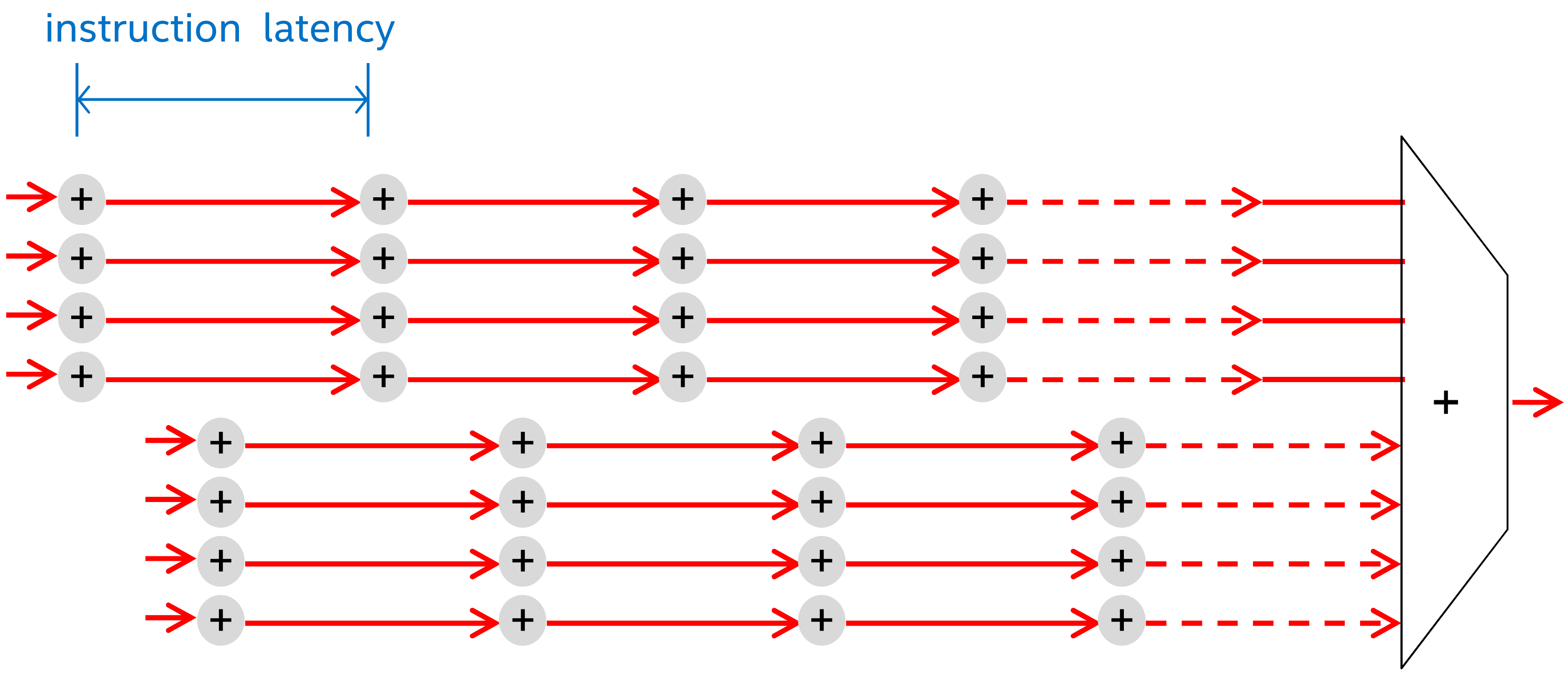
- floating-point min/max

Occasional Speedup Surprise

@simd observed to speed up `summation` example by 12x

- On hardware with vector size of 8!

Instruction Level Parallelism



Permission to reassociate/commute operations can improve instruction-level parallelism

Vectorization Recommendations (Julia with LLVM 3.3)

No cross-iteration dependencies

Trip count must be obvious

Loop body must be straight-line code

Subscripts should be unit-stride

Works best with Float32

No cross-iteration dependencies

Each iteration must not read or write a location written by another iteration

- Except for reduction variables, which must be local scalars

No iteration waits on another

- An academic issue for now in Julia.

`@simd` spec **not** same as classic vectorizable loop

- Classic definition allowed limited forms of dependencies
- `@simd` tells LLVM “there are no cross-iteration dependencies”

Trip Count Must Be Obvious

```
@simd for i=range
    …
end
```

`length(`*`range`*`)` should return integer

`m``:`*`n`* form of *range* works fine

Loop body should be straight-line code.

```
@simd for i=range
    … no control-flow altering constructs …
end
```

All method calls must be inlined

- Type inference must determine any call targets
- Learn how to write type-stable code

No exception constructs

- **Turn off bounds checking** (`@inbounds`)

Short a&&b, a||b, and a?b:c constructs *sometimes* work

- **If** LLVM converts it to "select" operation before vectorizer sees it

Example with ?: that works

```
function clip( x, a, b, )
    @simd for i=1:length(x)
        @inbounds x[i] = x[i]<a ? a : x[i]>b ? b : x[i]
    end
end

# Shows that code vectorizes for Float32
code_llvm( clip, (Array{Float32,1},Float32,Float32))
```

Skimming code_llvm output

Look for "vector.body" and <*size* x *type*>

```
vector.ph:                        ; preds = %L.preheader

   ...
vector.body:                      ; preds = %vector.body, %vector.ph
   ...
   %wide.load17 = load <8 x float>* %25, align 4
   %26 = fcmp uge <8 x float> %wide.load, %broadcast.splat19
   ...
   %36 = and <8 x i1> %27, %33
   ...
   store <8 x float> %predphi26, <8 x float>* %25, align 4
   ...
   %index.next = add i64 %index, 24
   %38 = icmp eq i64 %index.next, %n.vec
   br i1 %38, label %middle.block, label %vector.body
```

Subscripts should be unit-stride.

```
function stride2( a, b, x, y )
    @simd for i=1:length(y)
        @inbounds y[i] = a * x[2*i] + b
    end
end

code_llvm(stride2, (Float32,Float32,Array{Float32,1},Array{Float32,1}))
```

Code vectorizes for Float32, but badly

- Ran about 1.37x faster without `@simd` for me
- Stride-2 load synthesized from raft of separate loads

2D Arrays Can Work

```
function updateV( irange, jrange, U, Vx, Vy, A )
    for j in jrange
        @simd for i in irange
            @inbounds begin
                Vx[i,j] += (A[i,j+1]+A[i,j])*(U[i,j+1]-U[i,j])
                Vy[i,j] += (A[i+1,j]+A[i,j])*(U[i+1,j]-U[i,j])
            end
        end
    end
end

# Shows that code vectorizes for Float32
R = typeof(1:8)
A = Array{Float32,2}
code_llvm(sweep,(R,R,A,A,A,A,A))
```

In loop nest, put unit-stride loop innermost

Programmer Responsibilities

All vectorization (currently)

- No cross-iteration dependencies
- Straight-line loop body
  - @inbounds
  - All calls inlined (learn to write type-stable code)
- Unit-stride subscripts
- Float32 works best

Implicit vectorization

- Just a few arrays accessed
- No floating-point reductions

Explicit vectorization

- Use @simd
- Ensure there are no cross-iteration dependencies.
- Local scalars for reductions.

Future: LLVM 3.5

Vectorizer still limited to single basic block

- But often generates better code

Enables Intel® Advanced Vector Extensions 2 (Intel® AVX2)

- Fused multiply-add
  - Issue: requires “unsafe algebra” to enable.

Future Possibilities

SLPVectorizer (PR#6271)

- Vectorizes tuple math
- Slows down compilation

Vectorize loops with bounds checks

- Exploit reordering permissiveness to vectorize or hoist bounds checks

Vectorize loop bodies that are not straight-line code

- C/C++/Fortran compilers do this.
- SIMD extensions with masking (e.g. Intel® AVX-512) make this worthwhile
- Requires major LLVM hacking

Allow forward lexical dependencies

Diagnostics for why loop does not vectorize

Summary

Vectorization is optimization that speeds up *some* routines

- **Transposes** evaluation order

Implicit vectorization happens sometimes.

Explicit vectorization requires `@simd`

Current limitations that might be removed in future:

- Straight-line loop body
- Requires **`@inbounds`**
- Unit stride accesses to arrays
- Works best with Float32

There's much room for future improvement

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