

Single Instruction Multiple Data (SIMD) processing



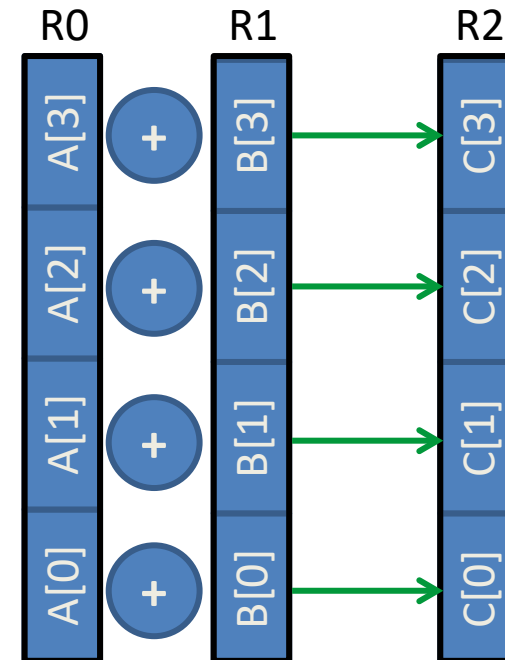
SIMD terminology

A word on terminology

- SIMD == “one instruction → several operations”
- “SIMD width” == number of operands that fit into a register
- No statement about parallelism among those operations
- Original vector computers: long registers, pipelined execution, but no parallelism (within the instruction)

Today

- x86: most SIMD instructions fully parallel
 - “Short Vector SIMD”
 - Some exceptions on some archs (e.g., vdivpd)
- NEC Tsubasa: 32-way parallelism but SIMD width = 256 (DP)



Scalar execution units

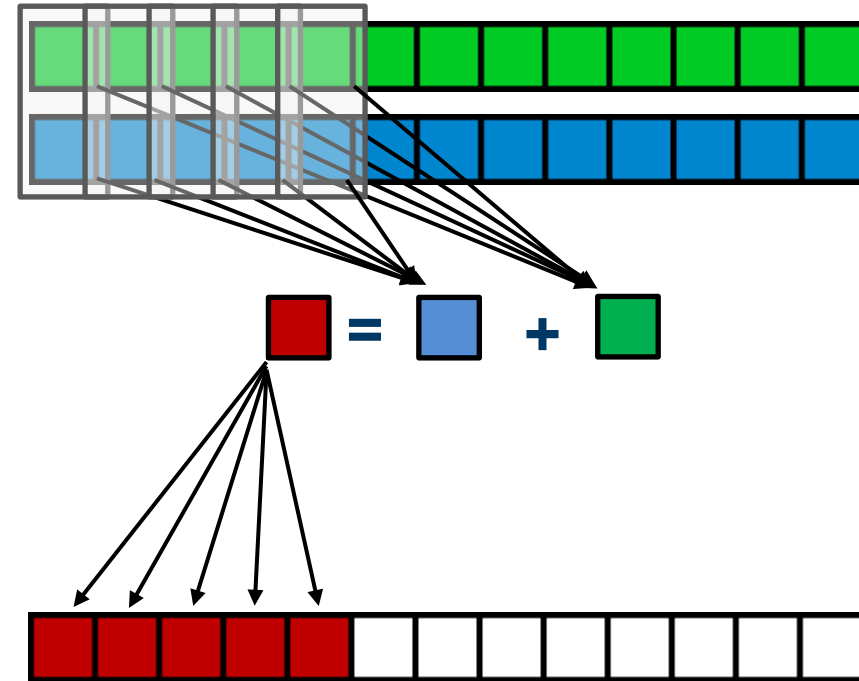
```
for (int j=0; j<size; j++){  
    A[j] = B[j] + C[j];  
}
```

Register widths

- 1 operand



Scalar execution



Data-parallel execution units (short vector SIMD)

```
for (int j=0; j<size; j++){  
    A[j] = B[j] + C[j];  
}
```

Register widths

- 1 operand



- 2 operands (SSE)



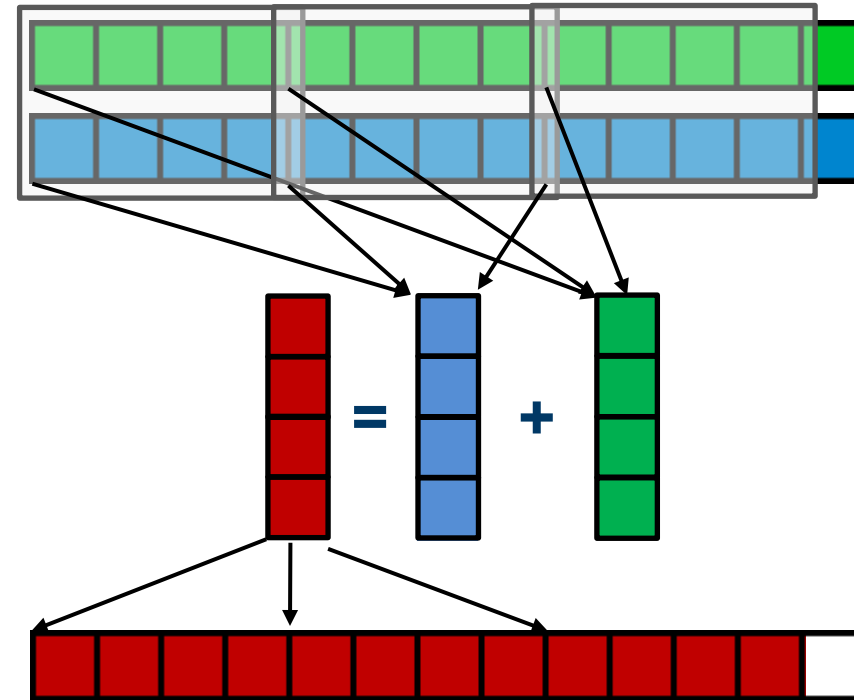
- 4 operands (AVX)



- 8 operands (AVX512)



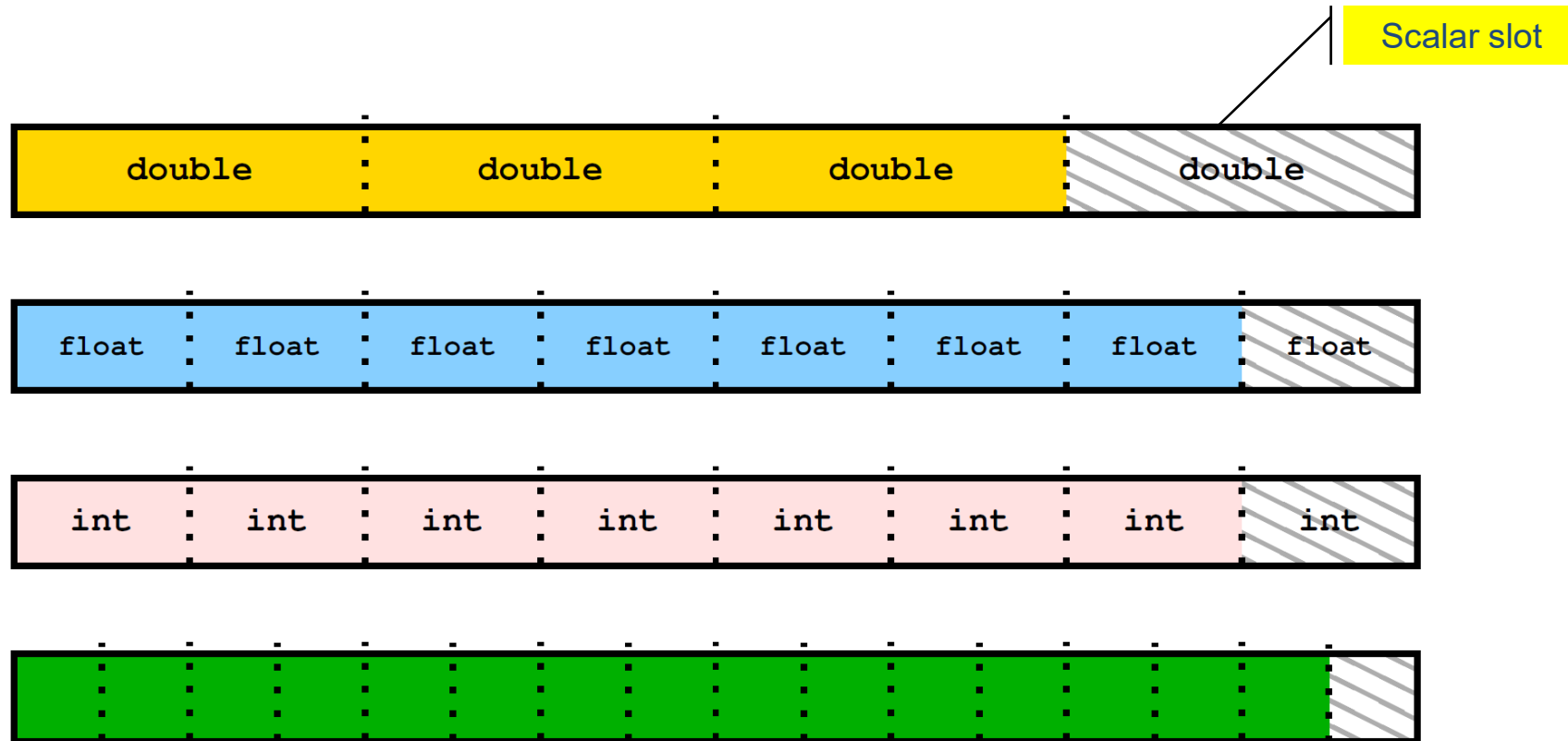
SIMD execution



Best code requires vectorized LOADs, STOREs, and arithmetic!

Data types in 32-byte SIMD registers

Supported data types depend on actual SIMD instruction set



SIMD

The Basics



SIMD processing – Basics

Steps (done by the compiler) for “SIMD processing”

```
for(int i=0; i<n;i++)  
  C[i]=A[i]+B[i];
```

“Loop unrolling”

```
for(int i=0; i<n;i+=4){  
  C[i]  =A[i]  +B[i];  
  C[i+1]=A[i+1]+B[i+1];  
  C[i+2]=A[i+2]+B[i+2];  
  C[i+3]=A[i+3]+B[i+3];}  
//remainder loop handling
```

This should not be done by hand!



Load 256 Bits starting from address of **A[i]** to register **R0**

Add the corresponding 64 Bit entries in **R0** and **R1** and store the 4 results to **R2**

Store **R2** (256 Bit) to address starting at **C[i]**

```
LABEL1:  
VLOAD R0 ← A[i]  
VLOAD R1 ← B[i]  
V64ADD[R0,R1] → R2  
VSTORE R2 → C[i]  
i ← i+4  
i < (n-4)? JMP LABEL1  
//remainder loop handling
```

SIMD processing: roadblocks

No SIMD vectorization for loops with data dependencies:

```
for(int i=1; i<n; i++)  
    A[i] = A[i-1] * s;
```

“**Pointer aliasing**” may prevent SIMDfication

```
void f(double *A, double *B, double *C, int n) {  
    for(int i=0; i<n; ++i)  
        C[i] = A[i] + B[i];  
}
```

C/C++ allows that $A \rightarrow \&C[-1]$ and $B \rightarrow \&C[-2]$

$\rightarrow C[i] = C[i-1] + C[i-2]$: dependency \rightarrow No SIMD

If “**pointer aliasing**” is not used, tell the compiler:

-fno-alias (Intel), **-Msafeptr** (PGI), **-fargument-noalias** (gcc)

restrict keyword (C only!):

```
void f(double *restrict A, double *restrict B, double *restrict C, int n) {...}
```


How to leverage SIMD: your options

Options:

- The **compiler** does it for you
(but: aliasing, alignment, language, abstractions)
- Compiler directives (**pragmas**)
- Alternative **programming models** for compute kernels (OpenCL, ispc)
- **Intrinsics** (restricted to C/C++)
- Implement directly in **assembly language**

Example: x86 SIMD (SSE) intrinsics

```
#include <x86intrin.h>
...
for (int j=0; j<size; j+=16){
    t0 = _mm_loadu_ps(data+j);
    t1 = _mm_loadu_ps(data+j+4);
    t2 = _mm_loadu_ps(data+j+8);
    t3 = _mm_loadu_ps(data+j+12);
    sum0 = _mm_add_ps(sum0, t0);
    sum1 = _mm_add_ps(sum1, t1);
    sum2 = _mm_add_ps(sum2, t2);
    sum3 = _mm_add_ps(sum3, t3);
}
```

Vectorization compiler options (Intel)

- The compiler will vectorize starting with `-O2`.
- To enable specific SIMD extensions use the `-x` option:

- `-xSSE2` vectorize for SSE2 capable machines

Available SIMD extensions:

`SSE2, SSE3, SSSE3, SSE4.1, SSE4.2, AVX, ...`

- `-xAVX` on Sandy/Ivy Bridge processors
- `-xCORE-AVX2` on Haswell/Broadwell
- `-xCORE-AVX512` on Skylake/CascadeLake

Recommended for AMD Zen:
`-O3 -mavx2`

Recommended option:

- `-xHost` will optimize for the Intel architecture you compile on

- To really enable 512-bit SIMD with current Intel compilers you need to set:

`-qopt-zmm-usage=high`

User-mandated vectorization (OpenMP 4)

- Since OpenMP 4.0, SIMD features are a part of the OpenMP standard
- `#pragma omp simd` enforces vectorization
- Essentially a standardized “go ahead, no dependencies here!”
 - **Do not lie** to the compiler here!
- Prerequisites:
 - Countable loop
 - Innermost loop
 - Must conform to for-loop style of OpenMP worksharing constructs
- There are additional clauses:
`reduction, simdlen, private, collapse, ...`

```
for (int j=0; j<n; j++) {  
    #pragma omp simd reduction(+:b[j])  
    for (int i=0; i<n; i++) {  
        b[j] += a[j][i];  
    }  
}
```

OpenMP SIMD support

Additional specifications enable better SIMD vectorization

```
double precision :: t,sum
integer :: i,j
! ...
j = 1
!$OMP SIMD REDUCTION(+:sum) LINEAR(j:2)
do i = 1,N
    sum = sum + a(i)*a(i)
    j = j+2
enddo
!$OMP END SIMD
```

j has linear relationship
with loop counter in SIMD
direction

SIMD clause can be combined with OpenMP work sharing

```
!$OMP DO SIMD SCHEDULE(SIMD:STATIC,c)
do i = 1,N
    a(i) = exp(b(i))
enddo
!$OMP END DO SIMD
```

Compiler will use
SIMD version of
function if present

Extend chunk
size to next
SIMD width
multiple

OpenMP SIMD support

Functions and subroutines can be declared as SIMD vectorizable and called from SIMD loops

```
double precision function hyp3d(a,b,c) result(h)
!$OMP DECLARE SIMD
  double precision :: a,b,c
  h = sqrt(a*a + b*b + c*c)
end function
```

[...]

Makes compiler
generate SIMD
version(s) of the
function

C version:

```
#pragma omp declare simd
double hyp3d(double a,
             double b,
             double c) {
  return sqrt(a*a + b*b + c*c);
}
```

```
double precision, dimension(N) :: a,b,c,hyp
!$OMP PARALLEL DO SIMD
  do i = 1,N
    hyp(i) = hyp3d(a(i),b(i),c(i))
  enddo
!$OMP END PARALLEL DO SIMD
```

SIMD loop calls
SIMD version of
function

SIMD

Reading Assembly Language
(Don't Panic)



Assembly: Why and how?

Why check the assembly code?

Sometimes the only way to make sure the compiler “did the right thing”

Example: “LOOP WAS VECTORIZED” message is printed, but an unnecessary dependency chain limits the performance!

Get the assembly code from the compiler (Intel/GCC/clang):

```
icc -S -O3 -xHost triad.c -o triad.s
```

Disassemble a binary:

```
objdump -d ./a.out | less
```

The x86 ISA is documented in:

Intel Software Development Manual (SDM) 2A and 2B
AMD64 Architecture Programmer's Manual Vol. 1-5

Basics of the x86-64 ISA

- Instructions have 0 to 3 operands (4 with AVX-512)
- Operands can be registers, memory references or immediates
- Opcodes (binary representation of instructions) vary from 1 to 15 (?) bytes
- There are two assembler syntax forms: Intel (left) and AT&T (right)
- Addressing Mode: $\text{BASE} + \text{INDEX} * \text{SCALE} + \text{DISPLACEMENT}$
- C: $\text{A}[\text{i}]$ equivalent to $*(\text{A} + \text{i})$ (a pointer has a type: $\text{A} + \text{i} * 8$)

Intel syntax

```
movaps [rdi + rax*8+48], xmm3
add rax, 8
js 1b
```

```
401b9f: 0f 29 5c c7 30
401ba4: 48 83 c0 08
401ba8: 78 a6
```

AT&T syntax

```
movaps %xmm3, 48(%rdi,%rax,8)
addq $8, %rax
js ..B1.4
```

```
movaps %xmm3,0x30(%rdi,%rax,8)
addq $0x8,%rax
js 401b50 <triad_asm+0x4b>
```


Basics of the x86-64 ISA with extensions

16 general purpose registers (64bit):

`rax, rbx, rcx, rdx, rsi, rdi, rsp, rbp, r8-r15`

alias with eight 32 bit register set:

`eax, ebx, ecx, edx, esi, edi, esp, ebp`

8 opmask registers (16 bit or 64 bit, AVX512 only):

`k0-k7`

Floating Point SIMD registers (aliased):

`xmm0-xmm15 (...xmm31)` SSE (128bit)

`ymm0-ymm15 (...xmm31)` AVX (256bit)

`zmm0-zmm31` AVX-512 (512bit)

SIMD instructions are distinguished by:

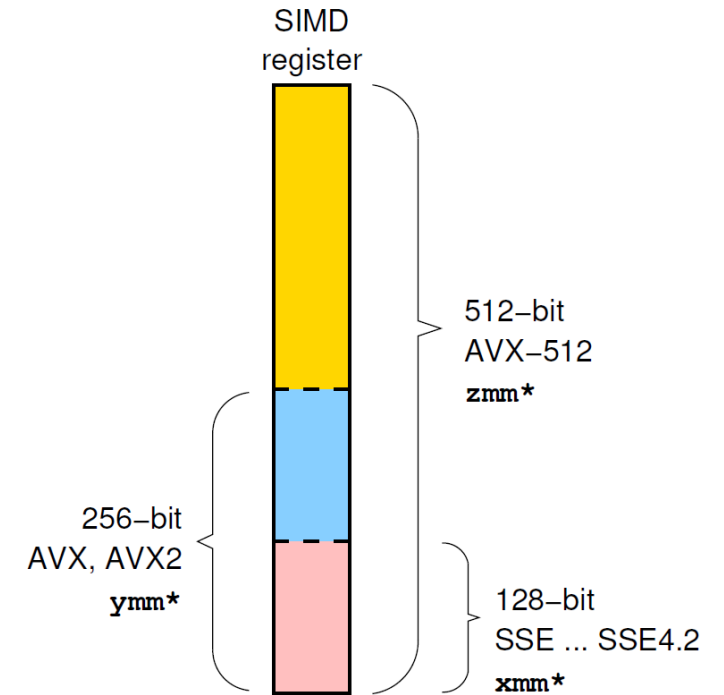
VEX/EVEX prefix: `v`

Operation: `mul, add, mov`

Modifier: nontemporal (`nt`), unaligned (`u`), aligned (`a`), high (`h`)

Width: scalar (`s`), packed (`p`)

Data type: single (`s`), double (`d`)



Case Study: Sum reduction (DP)

```
double sum = 0.0;

for (int i=0; i<size; i++) {
    sum += data[i];
}
```

To get object code use
`objdump -d` on object file or
executable or compile with `-S`

Assembly code w/ `-O1` (Intel syntax, Intel compiler):

```
.label:
    addsd    xmm0, [rdi + rax * 8]
    inc     rax
    cmp     rax, rsi
    jl     .label
```

AT&T syntax:
`addsd 0(%rdi,%rax,8),%xmm0`

Sum reduction (DP) – AVX512

Assembly code w/ `-O3 -xCORE-AVX512 -qopt-zmm-usage=high` :

```
.label:  
    vaddpd    zmm1, zmm1, [rdi+rcx*8]  
    vaddpd    zmm4, zmm4, [64+rdi+rcx*8]  
    vaddpd    zmm3, zmm3, [128+rdi+rcx*8]  
    vaddpd    zmm2, zmm2, [192+rdi+rcx*8]  
    add       rcx, 32  
    cmp       rcx, rdx  
    jb       .label
```

Bulk loop code
(8x4-way unrolled)

;

```
    vaddpd    zmm1, zmm1, zmm4  
    vaddpd    zmm2, zmm3, zmm2  
    vaddpd    zmm1, zmm1, zmm2
```

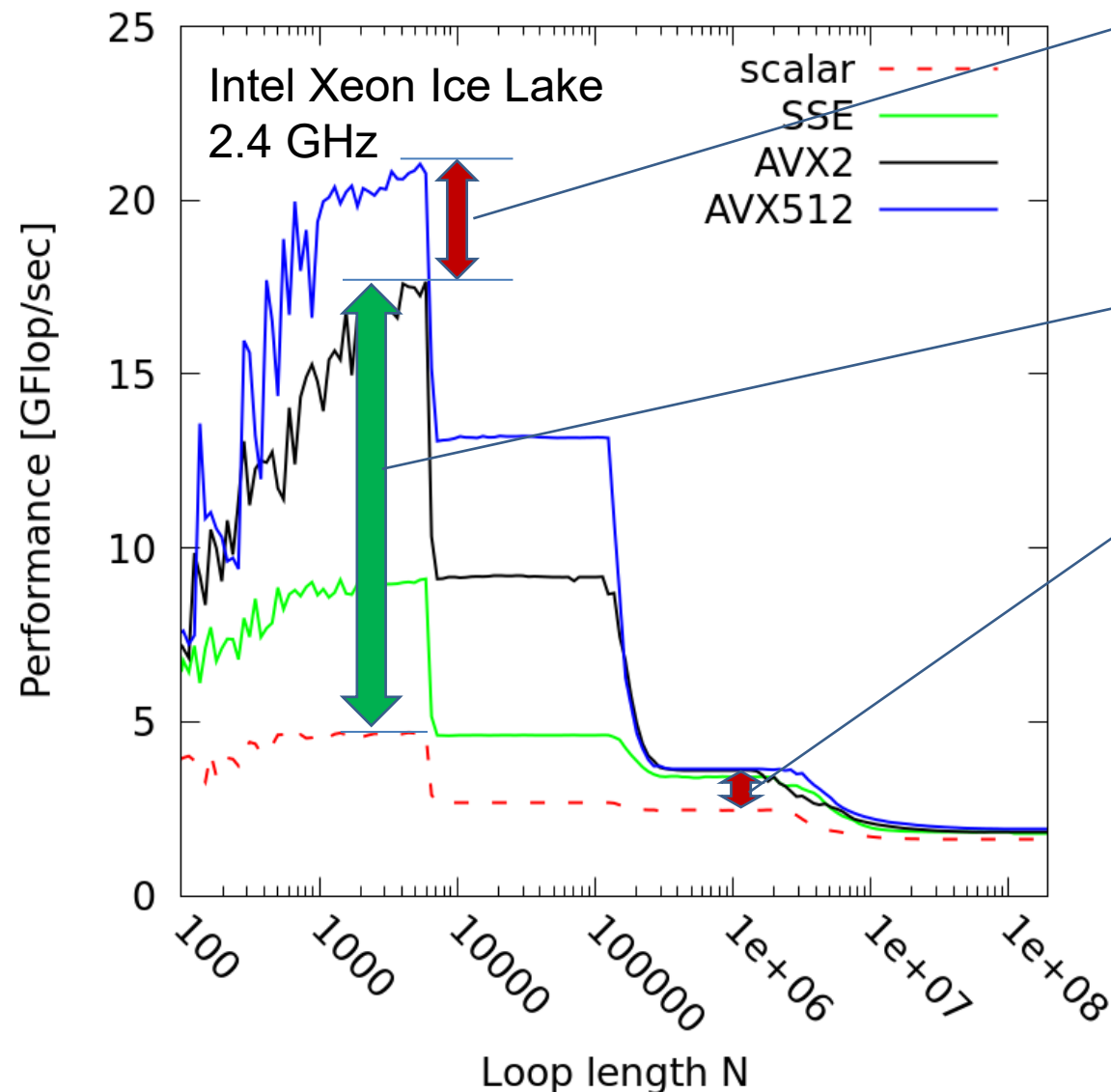
; [... SNIP ...]

← Remainder omitted

```
    vshuff32x4 zmm2, zmm1, zmm1, 238  
    vaddpd    zmm1, zmm2, zmm1  
    vpermpd   zmm3, zmm1, 78  
    vaddpd    zmm4, zmm1, zmm3  
    vpermpd   zmm5, zmm4, 177  
    vaddpd    zmm6, zmm4, zmm5  
    vaddsd    xmm0, xmm6, xmm0
```

Sum up 32
partial sums into
`xmm0.0`

Sum reduction (DP) – sequential performance



ICX can only do
1.1 AVX-512
Loads per cy

Expected speedup
in L1 with
scalar → AVX2

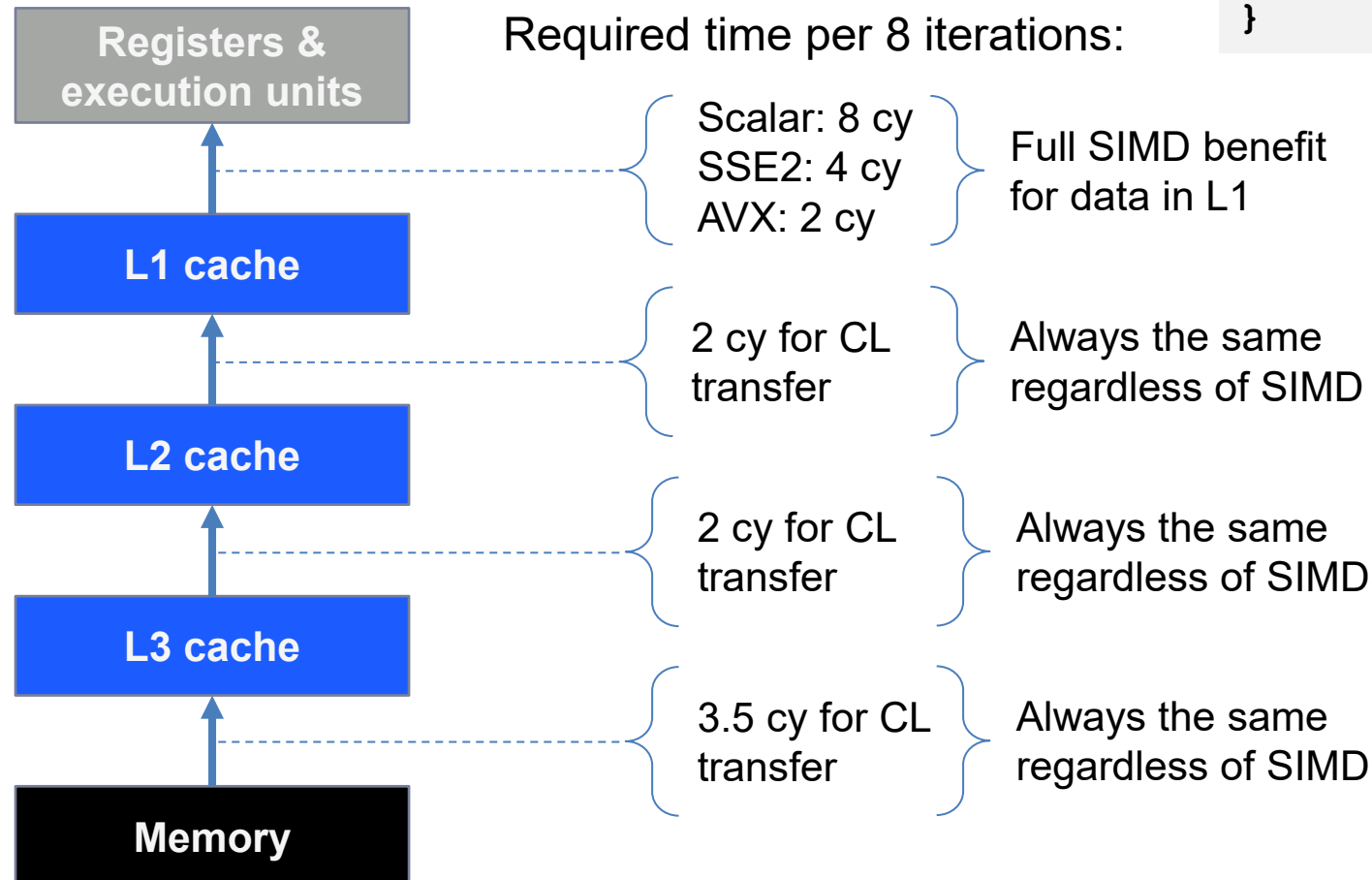
Limited speedup in
L3 and memory

- SIMD is an **in-core** performance feature!
- If the bottleneck is data transfer beyond L1, its benefit is limited
- Other in-core bottlenecks can reduce the expected speedup from SIMD

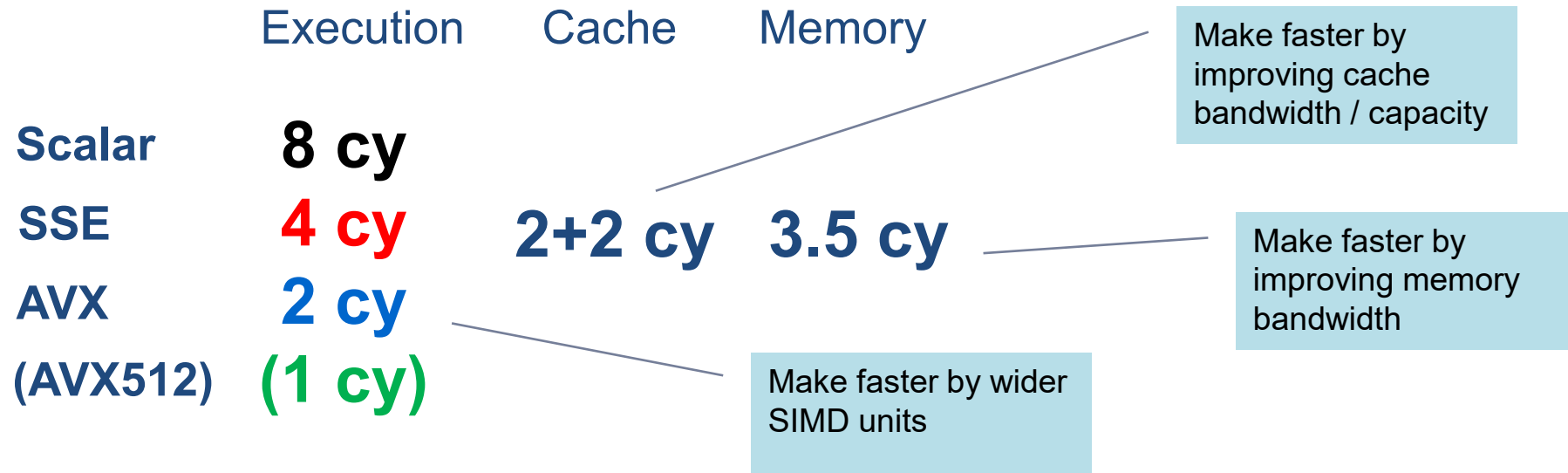
Limits of the SIMD benefit

- Why does SIMD usually not give the expected speedup? Analyze time contributions with data from memory (DP sum reduction on Ivy Bridge)

```
for (int i=0; i<size; i++){  
    sum += data[i];  
}
```



Limits of SIMD processing



On Intel x86 processors, these contributions have to be added to get the runtime:

	L1 [cy]	L2 [cy]	L3 [cy]	Memory [cy]	Sum [cy]
Scalar	8	2	2	3.5	15.5
SSE2	4	2	2	3.5	11.5
AVX	2	2	2	3.5	9.5

diminishing returns (Amdahl's Law!)

SIMD

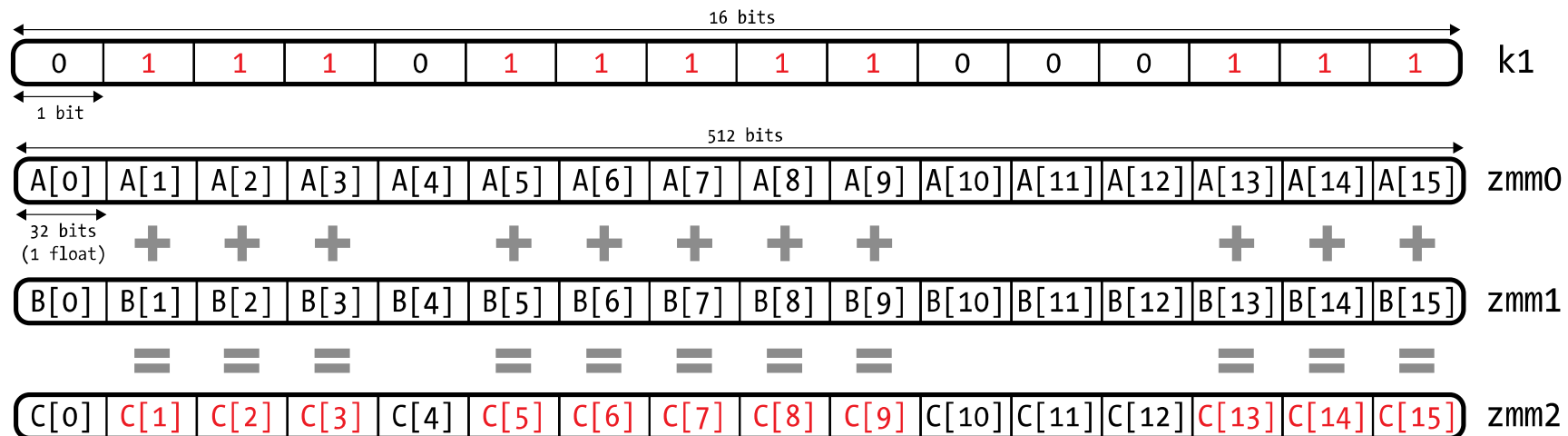
Masked SIMD execution and gather instructions



Example for masked execution

Masking is very helpful in cases such as, e.g., conditionals or remainder loop handling

Example: `vaddps zmm2{k1}, zmm1, zmm0`



Available on x86 since AVX-512

SIMD with masking: conditional sum reduction

```
double sum = 0.0;

for (int i=0; i<size; i++){
    if(data[i]>0.0)
        sum += data[i];
}
```

Bulk loop code
(8x4-way unrolled)

```
.label:
    vmovups    zmm5, [r12+rsi*8]
    vmovups    zmm6, [r12+rsi*8+64]
    vmovups    zmm7, [r12+rsi*8+128]
    vmovups    zmm8, [r12+rsi*8+192]
    vcmpgtpd   k1, zmm5, zmm4
    vcmpgtpd   k2, zmm6, zmm4
    vcmpgtpd   k3, zmm7, zmm4
    vcmpgtpd   k4, zmm8, zmm4
    vaddpd     zmm0{k1}, zmm0, zmm5
    vaddpd     zmm3{k2}, zmm3, zmm6
    vaddpd     zmm2{k3}, zmm2, zmm7
    vaddpd     zmm1{k4}, zmm1, zmm8
    add        rsi, 32
    cmp        rsi, rdx
    jb        .label
```

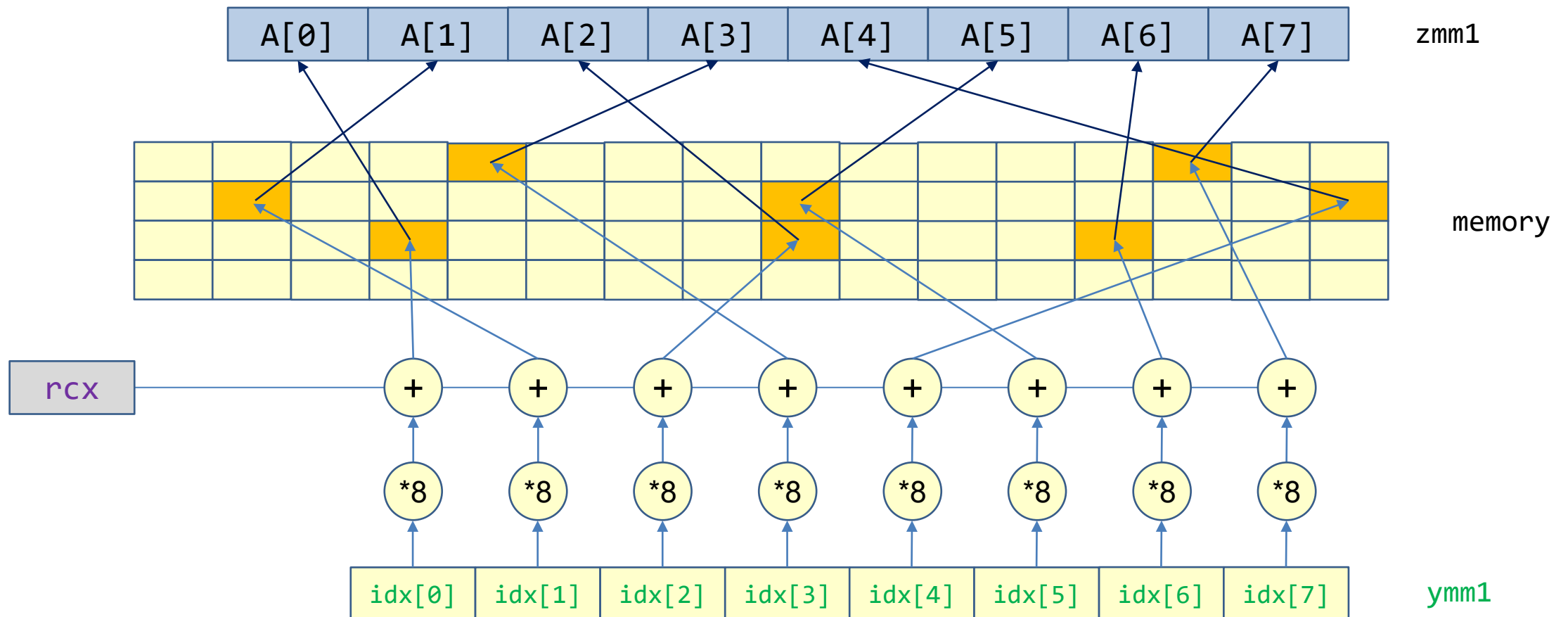
SIMD mask generation

masked SIMD ADDs (accumulates)

SIMD gather instructions

Gather instructions load scattered elements into a SIMD register using a short vector of indices

Example: `vgatherdpd zmm1, [rcx+ymm1*8]`



SIMD gather instructions: sparse matrix-vector multiplication

```
for (int row = 0; row < num_rows; ++row) {  
    double sum=0.0;  
    for (int j = row_ptr[row]; j < row_ptr[row + 1]; ++j)  
        sum += values[j] * x[col_idx[j]];  
    y[row] = sum;  
}
```

- Gather instructions can be subject to masking
- Data transfers are still managed through the cache hierarchy
 - Cache line concept applies

```
.label:  
    vpcmpgtq    k2, zmm3, zmm4  
    vpaddq     zmm4, zmm4, zmm1  
    vmovdqu32  ymm6{k2}{z}, [r12+r14*4]  
    vmovaps    zmm7, zmm2  
    kmovw     k1, k2  
    vgatherdpd zmm7{k1}, [rcx+ymm6*8]  
    vfmadd231pd zmm5{k2}, zmm7, [rdi+r14*8]  
    add       r14, 8  
    cmp      r14, rbx  
    jb      .label
```

Remainders
handled via
masking

Index load

(no MVE for brevity)

Rules and guidelines for vectorizable loops

1. **Inner** loop
2. **Countable** (loop length can be determined at loop entry)
3. Single entry and single exit
4. **Straight line** code (no conditionals) – unless masks can be used
5. No function calls (except intrinsic math functions and SIMD functions)

Better performance with:

1. Simple inner loops with unit stride (**contiguous** data access)
2. **Minimize indirect addressing**
3. Align data structures to SIMD width boundary (minor impact)

In C use the `restrict` keyword and/or `const` qualifiers and/or compiler options to rule out array/pointer aliasing

Keep it simple, stupid!