

Highway

Open source C++ library for performance-portable SIMD

Jan Wassenberg, Rhett Stucki

Google Research



Agenda

- 01 What, why, how
- 02 Porting code
- 03 Runtime dispatch
- 04 Design rationale
- 05 Users

01

What, why, how

What is SIMD?

Single / same

Instruction / operation on

Multiple

Data (lanes)



Why SIMD?

- Widely available
 - X86, ARM, RISC-V, MIPS, ...
- Minimal incidental complexity
 - Same address space
- Vendor-independent
 - >1 implementation of x86/ARM/RISC-V
- Widely scalable in cloud
 - No special provisioning



How: autovec?

OpenMP 4.0, armclang, Intel compiler

Minimal code changes

Brittle (maintenance, compiler upgrade)

Risk of **poor codegen** ("SIMD" memcpy)

```
movzx    ecx, byte [rax+rdi*4+8]
movd     xmm1, ecx
pinsrb   xmm1, [rax+rdi*4+0 ], 1
pinsrb   xmm1, [rax+rdi*4+12], 2
pinsrb   xmm1, [rax+rdi*4+4 ], 3
```



How: assembly?

Used in FFMPEG

Potentially more efficient

Error-prone: major penalty for

MOVAPS xmm0, xmm1 vs.

VMOVAPS xmm0, xmm1

Laborious

- Porting: FMLA vs. vfmadd132ps, ...
- Manual register allocation



How: intrinsics?

Widely used, also on MSVC

Error-prone

Compiler bugs (see next slide)

Laborious

- Porting: `_mm512_mask_mov_ps`
vs. `_mm256_blendv_ps`
- Verbose: `_mm256_load_si256(
 reinterpret_cast<
 const __m256i*>(ptr))`



Compiler bugs

clang-6: incorrect codegen for partial vector writes. **Workaround:** memcpy instead of intrinsics
clang-6: incorrect ARMv7 codegen, read after write data hazard. **Workaround:** clobber memory
clang-6: suboptimal codegen for VBROADCASTI128. **Workaround:** inline assembly
clang-6: missing KORTTEST for AVX-512. **Workaround:** treat masks as integers
clang-6: incorrect msan codegen. **Abandoned:** require clang-7

clang-7: unaligned spills in asan. **User workaround:** shorter variable lifetime

clang-8: various "Do not know how to split". **Workaround:** find op, replace with other
clang-8: inconsistent inlining/attribute requirements. **Workaround:** use pragma
clang-8: pragma must be at global scope. **Workaround:** HWY_BEFORE_NAMESPACE

clang-9: crash due to vector class constructor. **Workaround:** aggregate init

gcc 9.2: incorrect intrinsics for signed compare. **Workaround:** vector extension

Wasm: bleeding edge. **Workaround:** emulate missing/broken instructions



How: Highway

Same code, multiple platforms

Reasonable to port (operator overloading)

Helps deal with compiler bugs

Reliable and predictable performance

Also designed for variable vectors (SVE)



Highway library

<https://github.com/google/highway>

Developed since 2017

Used in [JPEG XL image codec](#)

Collaborators: Jeffrey Lim, Rhett Stucki

Advice:

Connor Fitzgerald

Daniel Lemire

Jyrki Alakuijala

Povilas Kanapickas

Rich Winterton



02

Porting code

Annotate

AVX2: Clang/GCC require -mavx2 (unsafe) or function attribute

Could annotate each function with HWY_ATTR

Easy to forget, causes errors on other compilers

Or: single #pragma attribute/target (via HWY_*_NAMESPACE)

Convenient

Compiler-specific

Must be outside namespace (thanks Robert Obryk!)

```
HWY_BEFORE_NAMESPACE();  
namespace myproject {  
  namespace HWY_NAMESPACE {  
    HWY_ATTR void MyFunc(float* HWY_RESTRICT out) {}  
  } // namespace HWY_NAMESPACE  
} // namespace myproject  
HWY_AFTER_NAMESPACE();
```

Create vectors

```
// Defined by Highway:
template <typename Lane, size_t kLanes>
struct Simd { // Empty tag type
    using T = Lane;
};
Type128 Zero(Simd<float, 4> /*tag*/);
Type256 Zero(Simd<float, 8> /*tag*/);

// Your code
const HWY_FULL(float) d; // = Simd<float, ??>
const auto zero = Zero(d);
const auto one = Set(d, 1.0f);
```

Loops, memory

```
for (size_t x = 0; x < xsize;
-                                     ++x) {
+                                     x += Lanes(d)) {
-   const float xval = rowx[x];
-   const float yval = rowy[x];
+   const auto xval = Load(d, rowx + x);
+   const auto yval = Load(d, rowy + x);

-   const float scaler = s + (yw * (1.0f - s)) /
-                               (yw + yval * yval);
+   const auto scaler = s + (yw * (one - s)) /
+                               MulAdd(yval, yval, yw);

-   rownew[x] = scaler * xval;
+   Store(scaler * xval, d, rownew + x);
}
```

Alignment

```
std::vector<float> rowx(128);  
for (size_t x = 0; x < xsize; x += Lanes(d)) {  
    // CRASH - unaligned  
    const auto xval = Load(d, rowx.data() + x);  
    // ...  
}  
  
// less efficient  
const auto xval = LoadU(d, rowx.data() + x);  
  
// unsafe for member variables and large vectors  
HWY_ALIGN float rowx[128];  
  
// works for member variables and large vectors  
hwy::AlignedFreeUniquePtr<float[]> rowx =  
hwy::AllocateAligned<float>(128);
```


Data layout

```
struct Point {  
    float x;  
    float y;  
};  
hwy::AlignedFreeUniquePtr<Point[]> points =  
hwy::AllocateAligned<Point>(N);  
  
const HWY_FULL(float) d;  
  
// mixes x and y in vector  
auto mixed = Load(d, &points.data().x);  
  
hwy::AlignedFreeUniquePtr<float[]> all_x_then_y =  
hwy::AllocateAligned<float>(N * 2);  
auto only_x = Load(d, all_x_then_y.data());  
auto only_y = Load(d, all_x_then_y.data() + N);
```

Branches

```
float RemoveRangeAroundZero(float w, float x) {  
    return  
        x > w ? x - w :  
        x < -w ? x + w : 0.0f;  
}  
  
template<class V>  
V RemoveRangeAroundZero(V w, V x) {  
    return IfThenElse(x > w, x - w,  
        IfThenElseZero(x < Neg(w), x + w));  
}  
  
bool AllPositiveIntegers(int v) {  
    return v >= 0;  
}  
  
template<class V>  
bool AllPositiveIntegers(V v) {  
    // avoids/hides 'zero'/'sign bit' constant  
    return AllTrue(Abs(v) == v);  
}
```

[Headers]

```
// Special include guard
#if defined(MYPROJECT_FILE_INL_H_) == \
    defined(HWY_TARGET_TOGGLE)
#ifdef MYPROJECT_FILE_INL_H_
#undef MYPROJECT_FILE_INL_H_
#else
#define MYPROJECT_FILE_INL_H_
#endif

// header contents, like normal SIMD module

#endif // include guard
```

"Toggles" include guard macro - prevents multiple inclusion within a particular target

Thanks to Lode Vandevenne for this clever idea!

03

Runtime dispatch

Multi-target

```
// At top of file, before other hwy includes
#undef HWY_TARGET_INCLUDE
#define HWY_TARGET_INCLUDE "path/filename.cc"
#include <hwy/foreach_target.h>

HWY_BEFORE_NAMESPACE();
// implementation - compiled once per target
HWY_AFTER_NAMESPACE();

#if HWY_ONCE
namespace myproject {
HWY_EXPORT(MyFunc); // defines function table

void Caller() {
    // dispatches to best available implementation
    HWY_DYNAMIC_DISPATCH(MyFunc)(args);
}
#endif
```

Definitions

Target = instruction set (e.g. AVX2)

Baseline = what compiler targets (= CPU requirement)
Determined by -mavx2 or HWY_BASELINE_TARGETS

Enabled = non-denylisted targets
Determined by known issues / HWY_DISABLED_TARGETS

Static target = best enabled baseline

Attainable = extra targets Highway can generate
Determined by compiler: all enabled on x86, or baseline

Superseded: baseline \ static target
If SSE4 baseline, skip scalar to reduce code size

[Dynamic] targets = configurable: { scalar | static | attainable |
attainable \ superseded }

Dispatching

```
// Direct call into baseline from normal code:  
// (Can make sense if baseline is sufficient -  
// avoid generating for all targets)  
HWY_STATIC_DISPATCH(MyFunc)(args);
```

SupportedTargets() // bitfield, depends on CPU

```
// Indirect call into best available SIMD:  
HWY_DYNAMIC_DISPATCH(MyFunc)(args);
```

```
// Call for each target from anywhere:  
hwy::RunTest(func, args);
```

gTest adapters also provided.

04

Design rationale

Simd<T, N>:: ?

SVE backend: as of 2021-05, vectors are sizeless types

Cannot be a class member

→ API based on overloaded functions

Can we have Load(V(), ptr)?

No, V is builtin on SVE, cannot indicate limit on #lanes

What about Load(V(), IntConst<N>, ptr)?

Error-prone - can break if not all call sites updated

→ still have tag argument called Simd<T, N>

Why auto?

Rarely need to know vector type, can deduce

Even for output params: `auto out = Undefined(d);`

Large number of vector types (50-70)

Types: {u, i} x {8, 16, 32, 64}, f32, f64

Lanes: 1, 2, 4, 8, 16, 32, 64

For portability, encourage size-agnostic code

But: auto everywhere hard to read / understand

➡ compromise: user-defined typedef:

`using V = decltype(Zero(d));` or

`using V = Vec<decltype(d)>;`

Why not stack?

SVE: max size 256 bytes. Wasteful on stack

RISC-V V: large upper bound: 64K elements

One implementation actually has 16 KiB vectors.

➡ use `hwy/aligned_allocator.h` and actual size: `Lanes(d)`

Why >1 header?

Including everything actually expensive (huge immintrin.h)

base.h for users / headers who just want

HWY_RESTRICT (function parameter) or

HWY_REP4 (define input for LoadDup128) etc.

targets.h useful for callers who want to know/influence

which target is active

highway.h only for implementers of SIMD modules, not their users

05

Users

JPEG XL

Next-generation image compression. jpeg.org/jpegxl

Uses integer (random generation) and floating-point:

- DCT, filtering, color conversion, noise synthesis
- Quantization, function approximations, ...

Runtime dispatch, 1.4x speedup from AVX2 to AVX-512

9 engineers using Highway, positive feedback

Also used in [PIK](#) which morphed into JPEG XL.



Example: RNG

```
class Xorshift128Plus {  
public:  
    // 8 independent generators  
    // (= single iteration for AVX-512)  
    enum { N = 8 };  
  
    HWY_INLINE HWY_MAYBE_UNUSED void  
    Fill(uint64_t* HWY_RESTRICT random_bits) {  
        // see next slide  
    }  
  
    // unsafe, requires class to be aligned  
    HWY_ALIGN uint64_t s0_[N];  
    HWY_ALIGN uint64_t s1_[N];  
};
```

Porting RNG

```
for (size_t i = 0; i < N; ++i) {  
    auto s1 = s0_[i];  
    const auto s0 = s1_[i];  
    const auto bits = s1 + s0;  
    s0_[i] = s0;  
    s1 ^= s1 << 23;  
    random_bits[i] = bits;  
    s1 ^= s0 ^ (s1 >> 18) ^  
        (s0 >> 5);  
    s1_[i] = s1;  
}
```

```
const HWY_FULL(uint64_t) d; // assumes <= 512bit  
for (size_t i = 0; i < N; i += Lanes(d)) {  
    auto s1 = Load(d, s0_ + i);  
    const auto s0 = Load(d, s1_ + i);  
    const auto bits = s1 + s0;  
    Store(s0, d, s0_ + i);  
    s1 ^= ShiftLeft<23>(s1);  
    Store(bits, d, random_bits + i);  
    s1 ^= s0 ^ ShiftRight<18>(s1) ^  
        ShiftRight<5>(s0);  
    Store(s1, d, s1_ + i);  
}
```


Also related

HighwayHash: fast MAC/pseudorandom function

- Built around [SIMD multiply and permute](#)
- 64, 128, 256 bit result (1024 bit internal state)
- Difficult to create collisions ($> 2^{64}$ work)
- Similar SIMD via intrinsics + runtime dispatch

Randen: [Abseil's random generator](#)

- Cryptographic ([indistinguishable from random](#))
- Faster than some common insecure generators
- Enabled by SIMD AES (x86, ARM, POWER)
- Simpler SIMD wrapper over intrinsics



Questions/contact

janwas@google.com

Staff Software Engineer

highway-users@google.com