Vectors and other Primitives

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JVM Language Summit, Santa Clara, July 2019

http://cr.openjdk.java.net/~jrose/pres/201907-Vectors.pdf

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What's cool about Panama vectors?

http://hg.openjdk.java.net/panama/dev/branches >> vectorIntrinsics

- nice demos (we hope)
- vectors = right-sized data processing (multi-word SIMD)
- good old Java is doing some new tricks on today's vector CPUs
  - (we just heard about some really creative JIT & JDK work)
  - assembly level performance, with all the comforts of `$JAVA_HOME`
- Valhalla mojo = object APIs without pointers/headers/heaps
- insight and experience navigating towards Java futures:
  - templated data and algorithms (like C++ but native to Java)
  - shaping new primitives: complex, unsigned-int, int128, etc.
  - higher-level vectors, with higher-level operations (`FORALL` in Java)

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DEMO

http://cr.openjdk.java.net/~jrose/vectors/DEMOJVMLS2019.jsh

```
// DEMOJVMLS2019.jsh : simple interactive demo of 2019 Vector API
// run jshell from a recent build of Panama vectorIntrinsics branch:
// $ cd panama; hg pull -u; hg co e45a5c05a746; make jdk
// $ build/macosx-x86_64-server-release/jdk/bin/jshell DEMOJVMLS2019.jsh
/env --add-modules jdk.incubator.vector
import jdk.incubator.vector.*;
import jdk.incubator.vector.Vector;
import static jdk.incubator.vector.VectorOperators.*;
// load successive squares into a, alternating signs into b, small k
float[] a = new float[24], b = new float[a.length], r = new float[a.length];
for (int i = 0; i < a.length; i++) { a[i] = i*i; b[i] = (i&1)==0?1:-1; }
var k = .002f;
var VSP = FloatVector.SPECIES_PREFERRED;
// compute forall<i>  r[i] = fma(sqrt(a[i]), b[i], k)
for (int i = 0; i < a.length; i += VSP.length()) {
 var av = FloatVector.fromArray(VSP, a, i);
 var bv = FloatVector.fromArray(VSP, b, i);
 var rv = av.lanewise(SQRT).lanewise(FMA, bv, k);
 rv.intoArray(r, i); }
var rv = VSP.fromArray(r, 0); rv; rv.species() // stuff to print
rv.lanewise(COS); rv.test(IS_NEGATIVE); rv.lanewise(COS).test(IS_NEGATIVE)
// once more with feeling!
/reload
```


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HOW ABOUT THOSE VECTORS…

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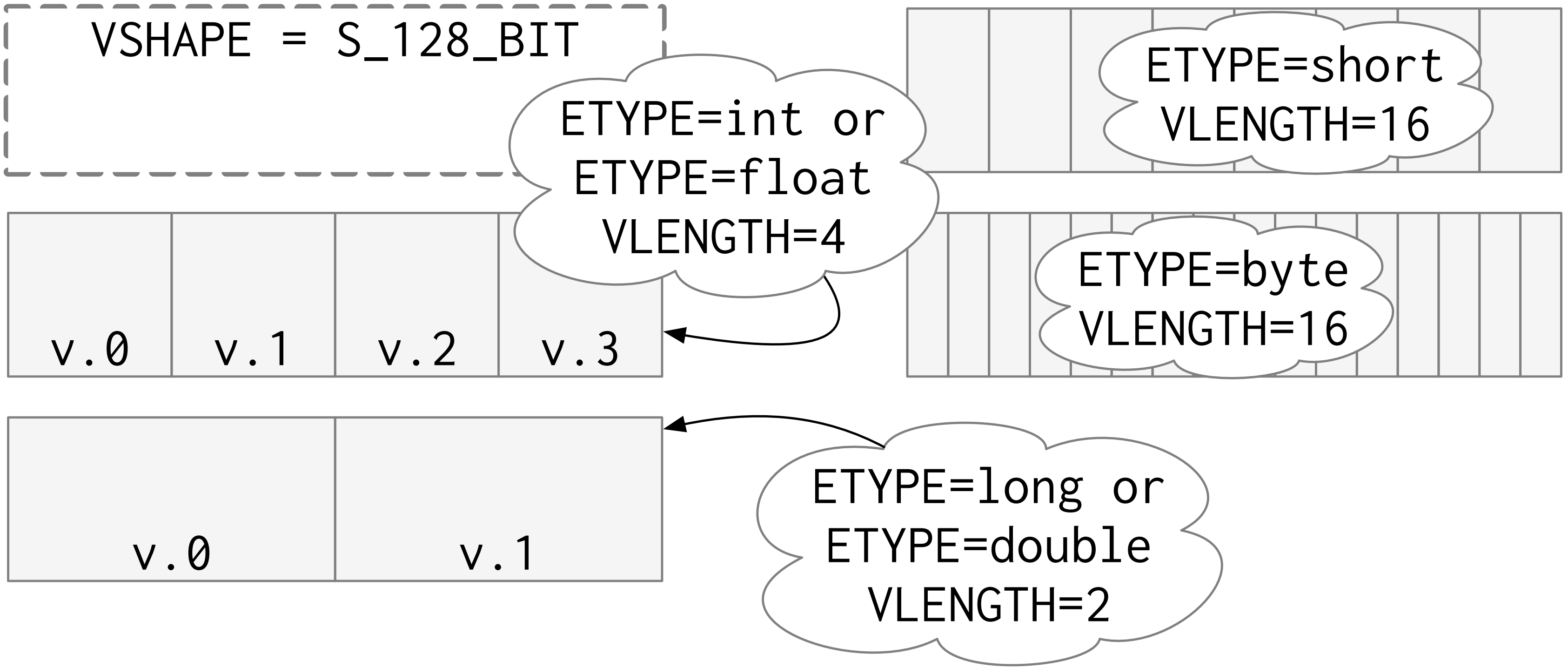
The basics: what’s in a vector?

doc/root/jdk.incubator.vector/jdk/incubator/vector/Vector.html

- A vector is a small, dense tuple of scalars of fixed length `VLENGTH`
- The scalars are all of the same primitive `ETYPE` (“element type”)
  - Each `ETYPE` has a size in bits (`ESIZE`). Also float, integral, …
- Each location in the vector is called a lane, numbered from zero
  - Thus, `v = [ v.0 | v.1 | … | v.7 ]` (`VLENGTH=8`)
- Vectors are close to the hardware, classified via total bit-size
  - `sizeof(v) = VLENGTH * ESIZE`
- Vector shape (`VSHAPE`) determines bit-size and register class.
  - `VSHAPE` and `ESIZE` together imply `VLENGTH`, maybe other things…
- Finally, `VSHAPE` plus `ETYPE` implies vector **species** (`VSPECIES`).

The basics: what's in a vector? *(dense payloads)*

doc/root/jdk.incubator.vector/jdk/incubator/vector/Vector.html



The basics: lane-wise operations are distributed

doc/root/…/Vector.html#lane-wise

- Unary distribution: `v ▷ op ≔ [ v.0 ▷ op | v.1 ▷ op | … ]`
- Scalar distribution: `v ▷ op(e) ≔ [ v.0 ▷ op(e) | v.1 ▷ op(e) | … ]`
  `broadcast(e) ≔ [ e | e | … ]` (for some particular `VSPECIES`)
- N-ary distribution: `v ▷ op(v*) ≔ [ v.0 ▷ op(v*.0) | v.1 ▷ op(v*.1) |…]`

```
//for (…i…) r[i] = fma(sqrt(a[i]), b[i], k);
for (int i…; i += VLENGTH) {
  for (int L = 0; L < VLENGTH; L++) {
    r[i+L] = fma(sqrt(a[i+L]), b[i+L], k);
    //rv = av ▷ SQRT ▷ FMA(bv, k);
    //rv = av.lanewise(SQRT).lanewise(FMA, bv, k);
} }
```

The basics: memory access is block-wise

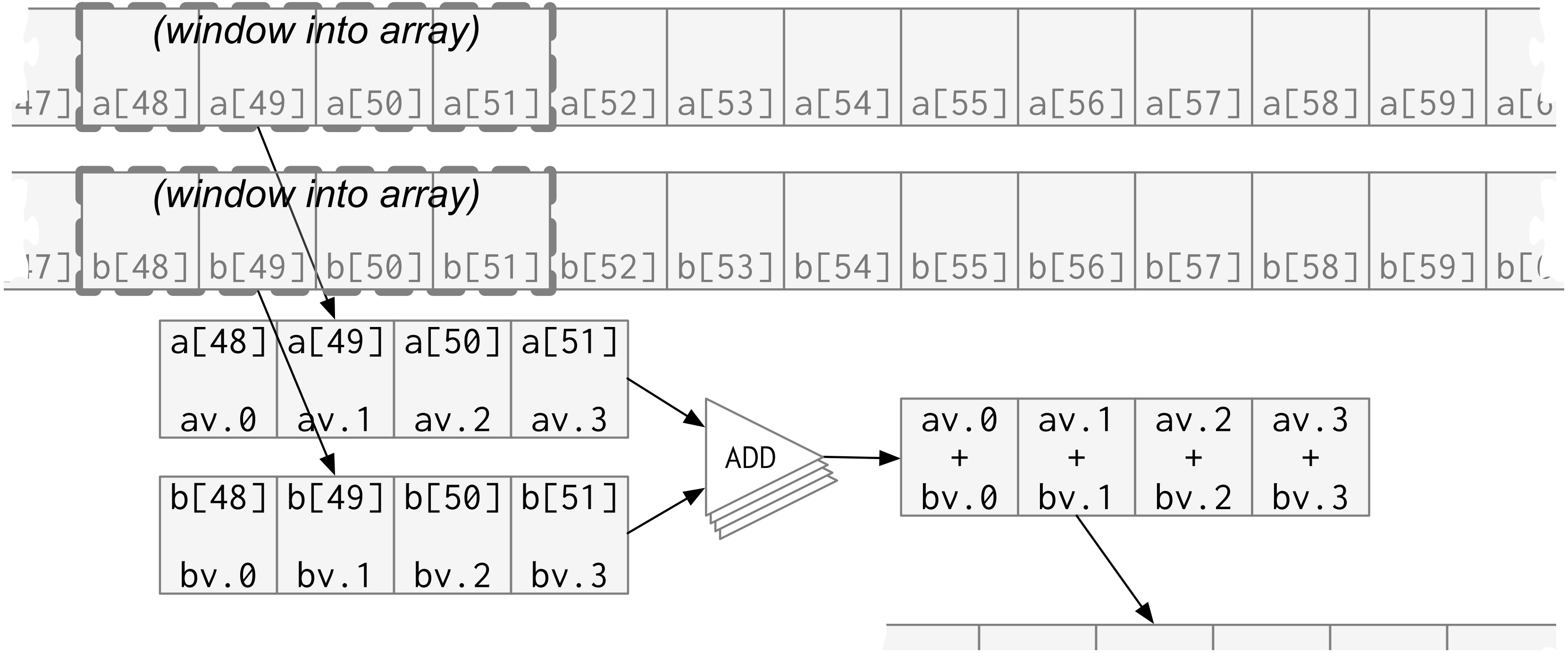
doc/root/.../Vector.html#lane-wise

- Load: `fromArray(a, i) ≔ [ a[i+0] | a[i+1] | … | a[i+VLENGTH-1] ]`
- Store to new: `v.toArray() ≔ new ETYPE[]{ v.0, v.1, … }`
- Store to old: `v.intoArray(a, i) ≔ { a[i+0] = v.0; a[i+1] = v.1; … }`

```
var VSP = FloatVector.SPECIES_PREFERRED;
for (int i…; i += VSP.length()) {
  var av = FloatVector.fromArray(VSP, a, i);
  var bv = FloatVector.fromArray(VSP, b, i);
  var rv = av.lanewise(SQRT).lanewise(FMA, bv, k);
  rv.intoArray(r, i);
}
```

Lane-wise is coherent with block-wise

SIMD programming: Single Instruction (operation) Multiple Data (lanes)



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The basics: why use a vector?

- Lane-wise operations run in parallel (speedup factor = `VLENGTH`).
  - arithmetic units replicated across lanes (this silicon is cheap)
- Loads/stores are the same scale (cache line) as memory fabric ops.
  - whole cache line used ⇒ memory traffic contains only useful data

- Lane operations "fly in formation" through CPU; low traffic control costs
  - Equivalent scalar loop must watch for cross-lane dependencies
- Resulting user model: Unroll all your loops by `VLENGTH` and repack.
  - Sometimes JITs can do this for you, but it's hard to control.
  - If your CPU is multiple-issue, the JIT may unroll more after that.

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Hand unrolling, really? Give us a break.

- There must be a better way.   What are workarounds for vectorization?
- Your original algorithm talks about big data (arrays) and scalars.
  - Vector code, in addition, deals with an intermediate scale (`VLENGTH`).
  - More complexity from the new entities and new edge conditions.
  - Greater performance ⇐ greater control ⇐ greater attention & skill.
- Scalar notations (C/Java for-loops) auto-vectorize ***if you are lucky***.
- Direct array processing notations work at the largest grain size.
  - Fortran `FORALL` statement, APL-like languages (Julia, MATLAB).
- Assembly code is fast, but very hard to write, with a short shelf life.
- Explicit vectors are sometimes the worst option—except all the others.

JAVA'S GOT A BRAND NEW BAG

the middle ground: High level explicit vector code

- What if you could get control close to assembly code, from C or Java?
  - After `VLENGTH` unrolling, the compiler or JIT finishes optimizing.
- C's `<immintrin.h>` : 1 intrinsic function call ≈ 1 instruction.
  - Downsides: Low-level notation. Not portable. C-level tooling.
- Enter Java's new trick: the Vector API
  - Explicit like C with intrinsics; 1 method call ≈ 1 instruction.
  - Packaged Java-style with interfaces, methods, generic types.
  - Works on the Java toolchain (IDEs, jshell, etc.)
- Extra benefit: JIT compilation can dynamically choose best `VLENGTH`
  - "Write once, unroll (differently) everywhere"

so, a Java API for explicit vector programming

- Types `FloatVector`, `IntVector` (… `Double/Long/Byte/ShortVector`)
  - Generic top-type `Vector<E>` (so `FloatVector <: Vector<Float>`)
  - `VectorSpecies<E>` to reflect over vector types; `VectorShape` enum.
- Methods to load/store to/from arrays & full NIO buffer integration.
- Lane-wise operator methods (arity 1/2/3) with many operations.
  - Also lane-wise test methods (arity 1/2) with more operations.
  - Also lane-wise conversion methods with yet more operations.
- `VectorMask<E>` to capture test results and steer subsequent ops.
  - Vector and mask operations to help control loop "edge cases".
- Local cross-lane movement represented with `VectorShuffle<E>`

Panama Vector API requirements

- Must look like Java: Objects, interfaces, generics, safety, tooling.
- Must be able to directly express a range of typical vector loop kernels
  - Dot product, hash code, string match, crypto, sort, …
- A vectorized for-loop must be maintainable (perhaps with tradeoffs)
  - Maintainable because appropriately abstract, legible, portable.
  - Vector shape must be abstractable from loop shape.
  - (Payoff: Legible, portable code has a longer shelf life!)
- Explicitly non-portable code should be possible, but not encouraged.
  - User makes final choices between performance and maintainability.
- Operator notations should be natural. ***THIS BIT ISN'T TRUE YET.***

Panama Vector API methods

```
L = .length(), ET = v.elementType(), VSP = v.species(), v.check(ET)
w = v.lanewise(OP [,v′/e [,v″/e]] [,m])  /*Unary|Binary|Ternary OP*/
w = v.add(v′/e [,m]), sub/mul/div/min/max/…  /*“full service” methods*/
w = v.addIndex(step)  /*add scaled lane index*/
m = v.compare(OP, v″/e [,m]),  m = v.test(OP [,m]), m = v.eq/lt(v′/e)
w = v.blend(v′, m)  /* lanewise(m ? v′ : v) */
w = v.convert(OP, part)  w = v.convertShape(OP, species, part)
w = v.reinterpretShape/AsBytes/AsInts/…
sh = v.toShuffle(),  w = v.viewAsIntegralLanes…
w = v.slice(origin [,v′] [,m]),  unslice…
w = v.rearrange(shuffle [,v′/m]),  w = v.selectFrom(v′)
v.intoArray(a, i), v.intoBB(bb,off,bo), a = v.toArray()
v = TVector.fromArray(a, i),  v = [v/TVector/VSP].broadcast(e)
```


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Vector operations

doc/root/jdk.incubator.vector/jdk/incubator/vector/VectorOperators.html

Binary OP: v.lanewise(OP,v′/e [,m]), v.reduce(OP [,m])				
ADD/SUB/MUL/…	MIN/MAX	AND/OR/XOR/…	LSHL/ASHR/…	ATAN2/POW/…

Unary OP: v.lanewise(OP [,m]), v.lanewise(OP,m)				
NOT	ABS	NEG	SIN/COS/TAN/…	EXP/LOG/SQRT/…

v.lw(OP,v′,v″)
FMA/…

v.compare(OP,v′/e)
LT/GT/EQ/…

v.test(OP)	
IS_DEFAULT	IS_NAN/…

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Vector comparison operations

doc/root/jdk.incubator.vector/jdk/incubator/vector/VectorOperators.html

Conversion OP: w=v.convert(OP,part)				
B2S/B2I/B2F/…	L2B/L2S/L2I/…	REINTERPRET_F2I	REINTERPRET_D2L	REINTERPRET_…
S2B/S2I/S2F/…	F2B/F2S/F2I/…	ZERO_EXTEND_B2I	ZERO_EXTEND_B2I	ZERO_EXTEND_I2L
I2B/I2S/I2F/…	D2B/D2S/D2I/…	INPLACE_B2I/S2I	INPLACE_D2F/D2I…	INPLACE_ZERO_ EXTEND_B2I/I2L/…

Fixed sized chunks vs. size-changing operations

doc/root/…/Vector.html#expansion

- Key idea: Reify potential size changes as a ***part-number*** parameter.
- Example: `(w, w′, w″, w‴) = v.convert(B2I, [part=0,1,2,3])`
- Example: `(w, w′, …) = v.reinterpretShape(VSP, [part=…])`
- Example: 16-bit square root, using temporary expansion:

```
var FSP = FloatVector.SPECIES_PREFERRED, VSP = FSP.withLanes(short.class);
for (int i…; i += VSP.length()) {
  var sv = ShortVector.fromArray(VSP, a, i);
  ShortVector rv = sv.broadcast(0);
  for (int part = 0; part < 2; part++) {
    var fv = sv.convert(S2F, part).lanewise(SQRT).plus(0.5f);
    rv = rv.lanewise(OR, fv.convert(F2S, -part));
  } rv.intoArray(a, i); }
```


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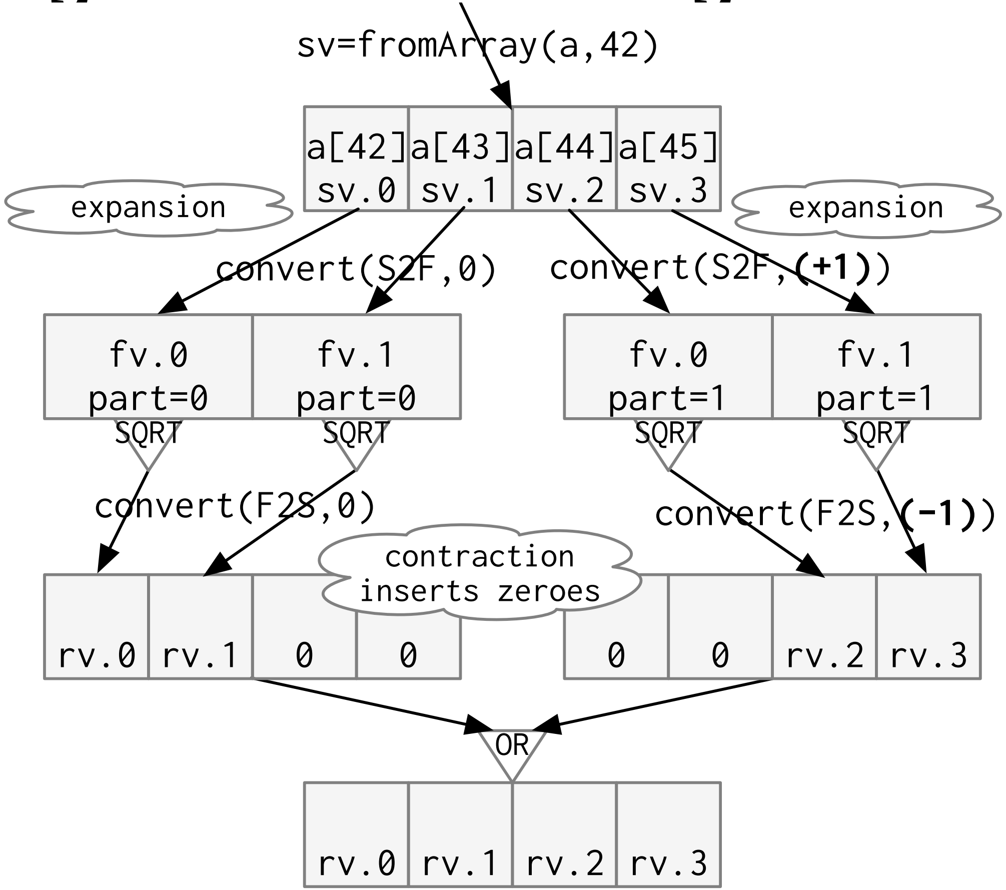
Expanding data flows through multi-part vectors



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influences from Intel AVX

https://software.intel.com/sites/landingpage/IntrinsicsGuide

- Vector shape control and abstraction from AVX, AVX2, AVX512
- Masks look forward to AVK512 ‘k’ registers.
  - But `VectorMask<E>` hides its implementation (it might be a vector)
- Large number of snowflake ops pushed us toward `lanewise(OP)`.
- Generally, the support for lane-wise C expressions is strong.
  - (Java and C have multiple scalar sizes, many ops & conversions.)
- Reductions (“horizontal add”) are common. (Scans are not.)
- Gather/scatter ops are incomplete until AVX512.
- Cross-lane permutations: General vperm, plus many “funny butterflies”.
  - `VectorShuffle<E>` is a thinly-veiled vector (or array?), like `VectorMask`.

ARM64 SVE

https://developer.arm.com/docs/ddi0584/latest

- Vectors might be long and oddly-sized, and will be detected at runtime.
  - This is a good match for Java's portability goals.
  - We had to remove power-of-two assumptions from the API.
- Like AVX, a good set of C-expression support (ops, conversions)
  - Similar treatment of `VSIZE = VLENGTH * ESIZE`
  - This helped us settle on shape-invariance as a normal user model.
- Nice suite of cross-lane movement (zip/unzip/pack/unpack/transpose)
  - We want to optimize "well known" shuffles into such instructions.
- Data-driven (mask-based) lane compression not covered yet.
  - (Intel doesn't have this operation. But it's `Stream::filter`!)

What works well…

- Vectors are objects, Java is good at modeling them. (No surprise.)
- Simple vector loops compile (often) to simple hot assembly loops.
- A large range of AVX, AVX2, & AVX512 instructions are reachable
  - It seems likely we can do the same with NEON, SVE and others
- We have reasonable-looking portable semantics
  - Byte order, bit order, exceptions and array range safety, masks
  - Conventions for “expansion” and “contraction” (zip/unzip, etc.).
- So, the same source code can run with different vector ISAs
- Source code can also be hand-tuned for particular vector ISAs
  - The data-driven operator scheme leaves room for “snowflake” ops.

And what doesn’t work so well…

- Vectors require very aggressive inlining and unboxing
  - Valhalla will make this systematic. For now it’s ad hoc and fragile.
- Code is tricky and hard to maintain, because of specialization hacks
  - A NIO-style textual preprocessor manages template types
  - A ton of `@ForceInline` gives us an effect like template methods
- We say `Vector<Integer>` when we really mean `Vector<int>`
  - Valhalla plans to address this problem, for the sake of inline types.
- Java stops at 8 primitive types, so no `Vector<complex>`, `Vector<int128>`
  - We expect Vahalla will let us define types like `complex` and `int128`.

Old-school algebra & FORTRAN are inescapable

- Vector expressions ***LOOK NOTHING LIKE*** scalar expressions.
- Algebra expressions like `r = a*x + b` are here to stay.
  - In Java that must be `r = a.mul(x).add(b)`. (As in Vector API.)
  - This is a readability problem. Users have a right to balk at this.
- *Operator overloading?* C++ and Python versions are too wild for Java.
  - Maybe we can cook up some algebras (operator suites w/ contracts).
  - But this needs research, and specialized generics are a prerequisite.
- A better near term solution is *lambda cracking* (a la .NET).
  - No language changes required, just a new form of reflection.
  - Lambdas could be checked at compile-time via javac intrinsics.
  - Smooth upgrade from limited operators (`ADD`, `FMA`) to lambdas.

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A gentle introduction to the cracking of lambdas

- Today: `vr = va.lanewise(SUB, vb.lanewise(MUL, 42)).lanewise(MAX, 0);`
  - **If you know how**, you can read it as: `r = max(a - b*42, 0);`
- Next we make a little AST language to extend type `Operator` types:

```
    static final Binary MYOP = MAX.of(SUB.of(A,MUL.of(B,42)), 0);
vr = va.lanewise(vb, MyOP);
```

- Mix in some static javac intrinsics, to perform some static checks: https://bugs.openjdk.java.net/browse/JDK-8205637
- Or, break out the parser: `MYOP = expression("max(a - b*42, 0)”);`
- And for dessert, sugary cracklin’ lambdas:

```
vr = va.lanewise(vb, (a,b)->max(a - b*42, 0);
```

  - It’s AST hacking under the hood. Maybe some can be at compile-time.
  - This is a long string to pull. Let’s eat this dessert for breakfast tomorrow.

Rash speculation about Primitives of the Future

- The challenge with Java primitives is they are “just data”, not methods.
  - Their behaviors are in odd places: JLS for operators, `Math.abs`.
- With Valhalla, methods on wrapper types find a natural home.
  - But operators don’t model well in single-receiver OOLs.
- An approach: Use generic interfaces to capture the rules of algebra.
  - “just the data” (`int`, `Complex`, `Unsigned`, `Vector`) is in type param(s).
  - The behavior parts are in “witness” object(s) that implement ops

```
interface BitwisePrimitive<T> { T and(T a, T b); … }
```

- Lambdas can be cracked and retargeted from (say) `long` to `Unsigned`, given the presence of a suitable witness `BitwisePrimitive<Unsigned>`
- Conversion rules are witnessed by `ConvertiblePrimitive<T,U>` (etc.)

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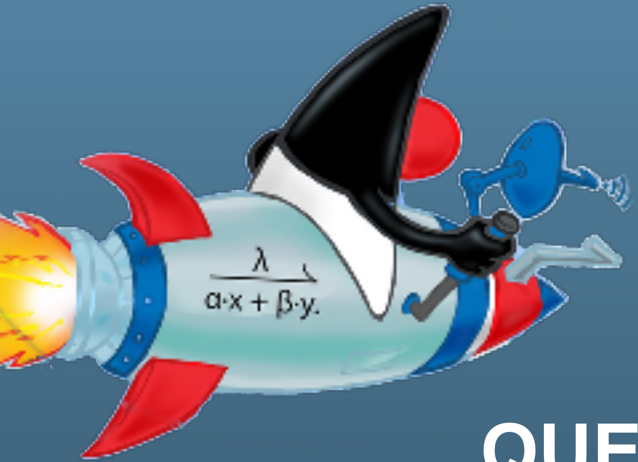
And we always want more…

- More operators: `REVERSE_BITS`, `ROUND`, `CEILING`, …
  - Macro-operators: AST first; then some sugary cracked lambdas)
  - Snowflakes: `AES_STEP`, `CLMUL`, `SATURATING_ADD`, funny butterflies, …
- More support for near-neighbor communication (shuffles, pack/unpack)
  - More flavors of zip/unzip/pack/unpack/transpose (SOA vs. AOS)
  - Data-driven lane packing (vectorized `Stream::filter`)
  - Segmented scan (reduce with partials and mask-driven reset)
- More loop shapes: Integrated pre/main/post notations.
  - Stream-based vector loops. Maybe array processing?
  - Experiment with BLAS heavy lifting (does it make sense?)
- Integration (via Panama) with vector types in system ABIs.
- More lane types (via Valhalla): complex, fixed-point, hyper-longs, single bits.



QUESTIONS?

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