# Halide for Hexagon™ DSP with Hexagon Vector eXtensions (HVX) using LLVM

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4th Feb 2017

# Agenda

1. Halide
2. Hexagon with HVX
3. Implementation details of the Halide Compiler
4. Example 1: blur5
5. Example 2: camera_pipe

# Halide

## A new DSL for image processing and computational photography.

- Fast image-processing pipelines are difficult to write.
  - Definition of the stages of the pipeline.
  - Optimization of the pipeline - vectorization, multi-threading, tiling, etc.

- Traditional languages make expression of parallelism, tiling and other optimizations difficult to express.

- Solution: Halide enables rapid authoring and evaluation of optimized pipelines by separating the algorithm from the computational organization of the different stages of the pipeline (schedule).

- Programmer defines both, the algorithm and the schedule.

- Front end embedded in C++.

- Compiler targets include x86/SSE, ARM v7/NEON, CUDA, Hexagon™/HVX and OpenCL.

# Halide

## A new DSL for image processing and computational photography.

- Halide programs / pipelines consist of two major components
  - Algorithm
  - Schedule
- Algorithm specifies *what* will be computed at a pixel.
- Schedules specifies *how* the computation will be organized.

```
ImageParam input(Uint(8), 2) // Image with 8 bits per pixel.
Halide::Func f;

// horizontal blur - Algorithm.
f(x, y) =  (input(x-1, y) + input(x, y) + input(x+1, y))/3;
// Schedule
f.vectorize(x, 128).parallel(y, 16);
```

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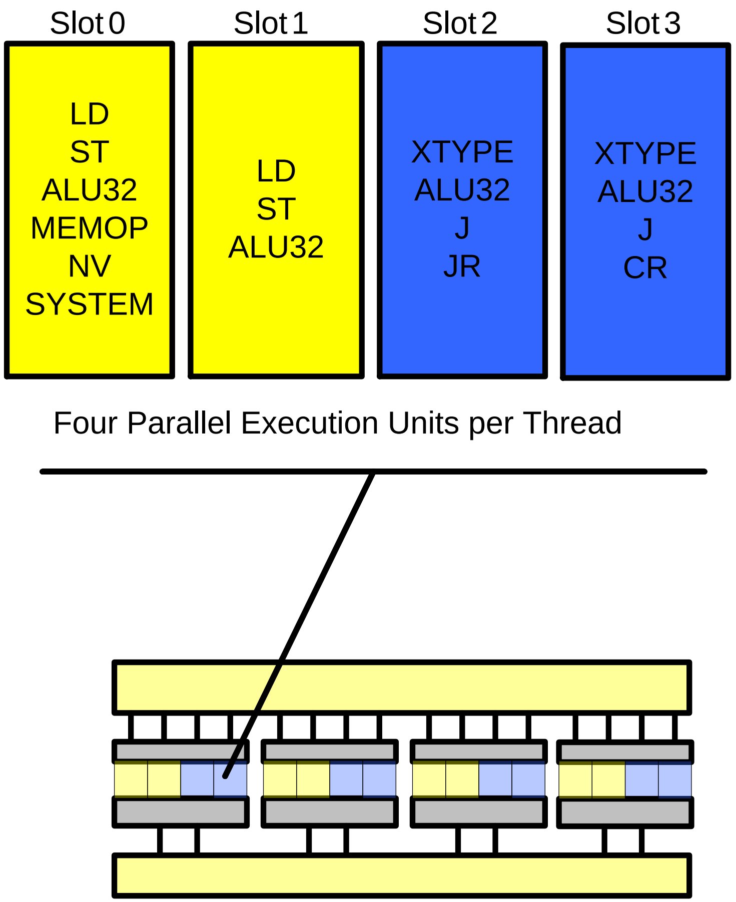
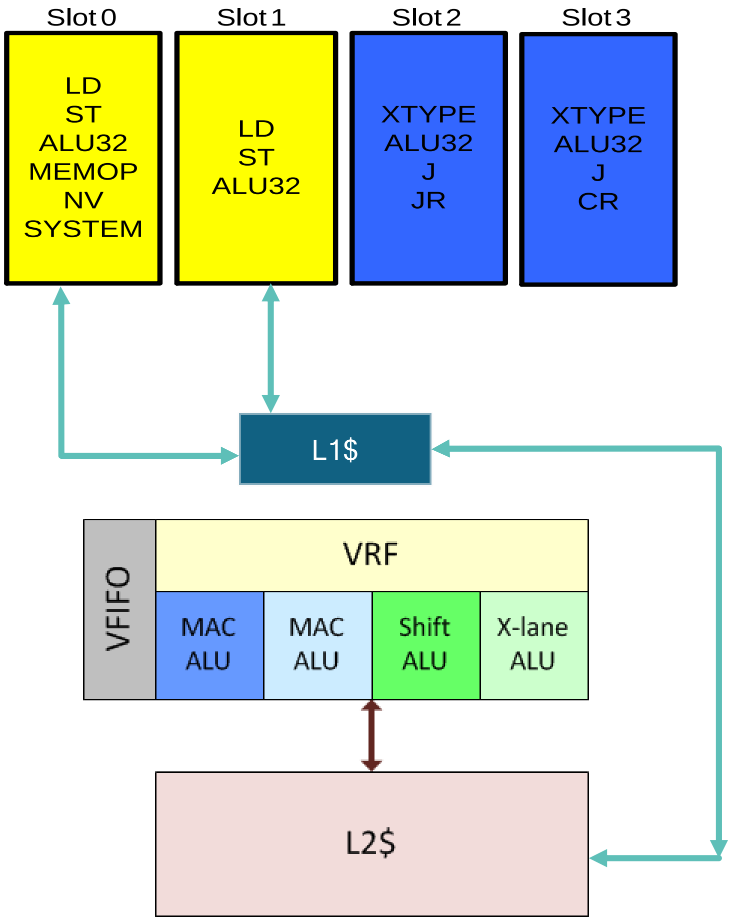
# Hexagon™ Processor

- 32 bit VLIW Processor.
- "Packets" group 1 to 4 instructions for parallel execution.
  - Compiler / assembly coder chooses instructions for parallel execution; No NOP padding necessary.
- 4 Hardware threads.
- FFT and circular addressing modes.
- Native numerical support for fractional real+imaginary data.
- Modern system architecture with precise exceptions, MMU with address translation and protection and capable of support Linux, Real-Time OS, etc.



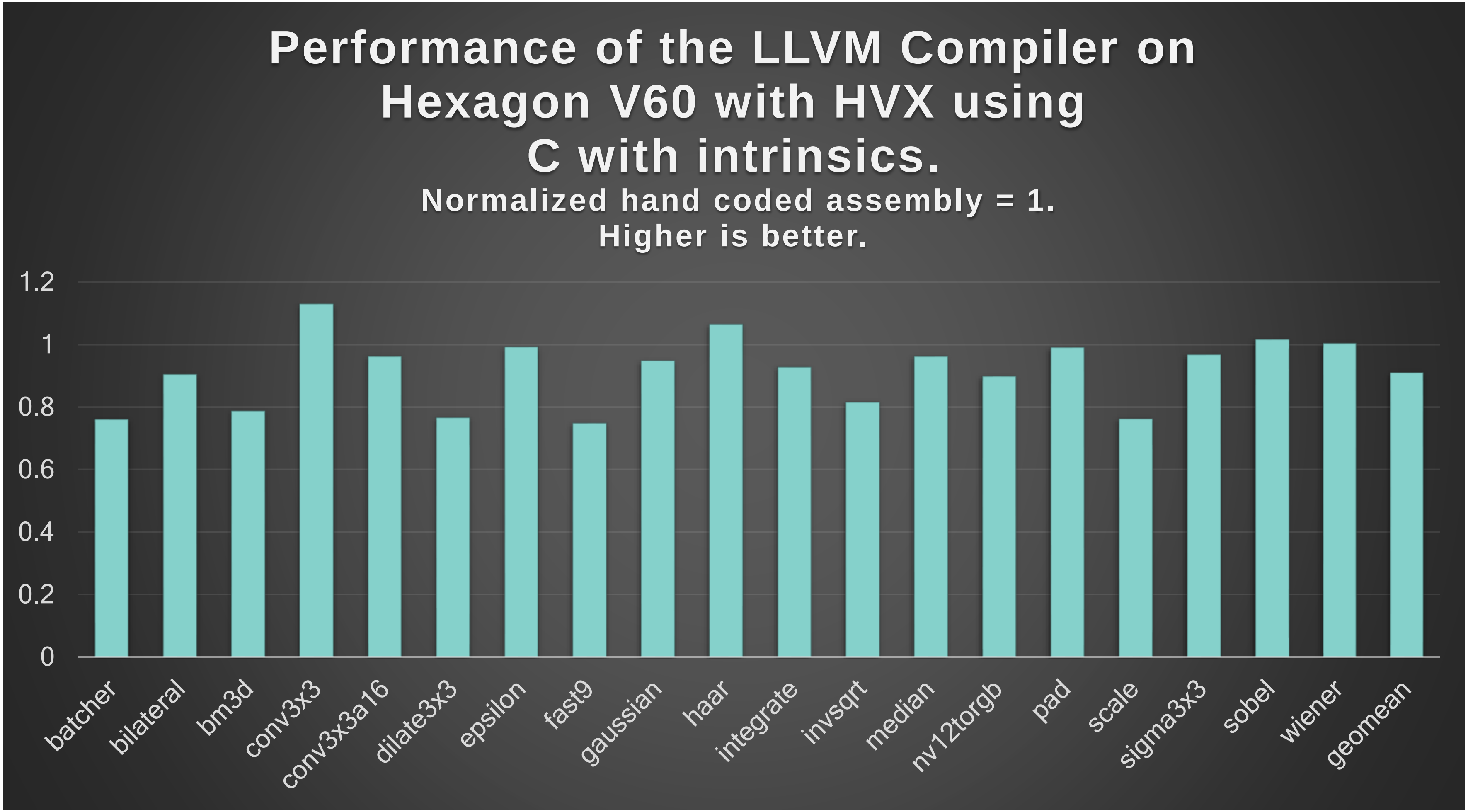
# Hexagon V60 with HVX

- Large vector (SIMD) extensions
  - 2 1024b vector contexts configurable as 4 512b vector contexts as well.
  - Vectors can hold 8-bit bytes, 16-bit halfwords, or 32-bit words.
- L2 is the first level memory for vector units.



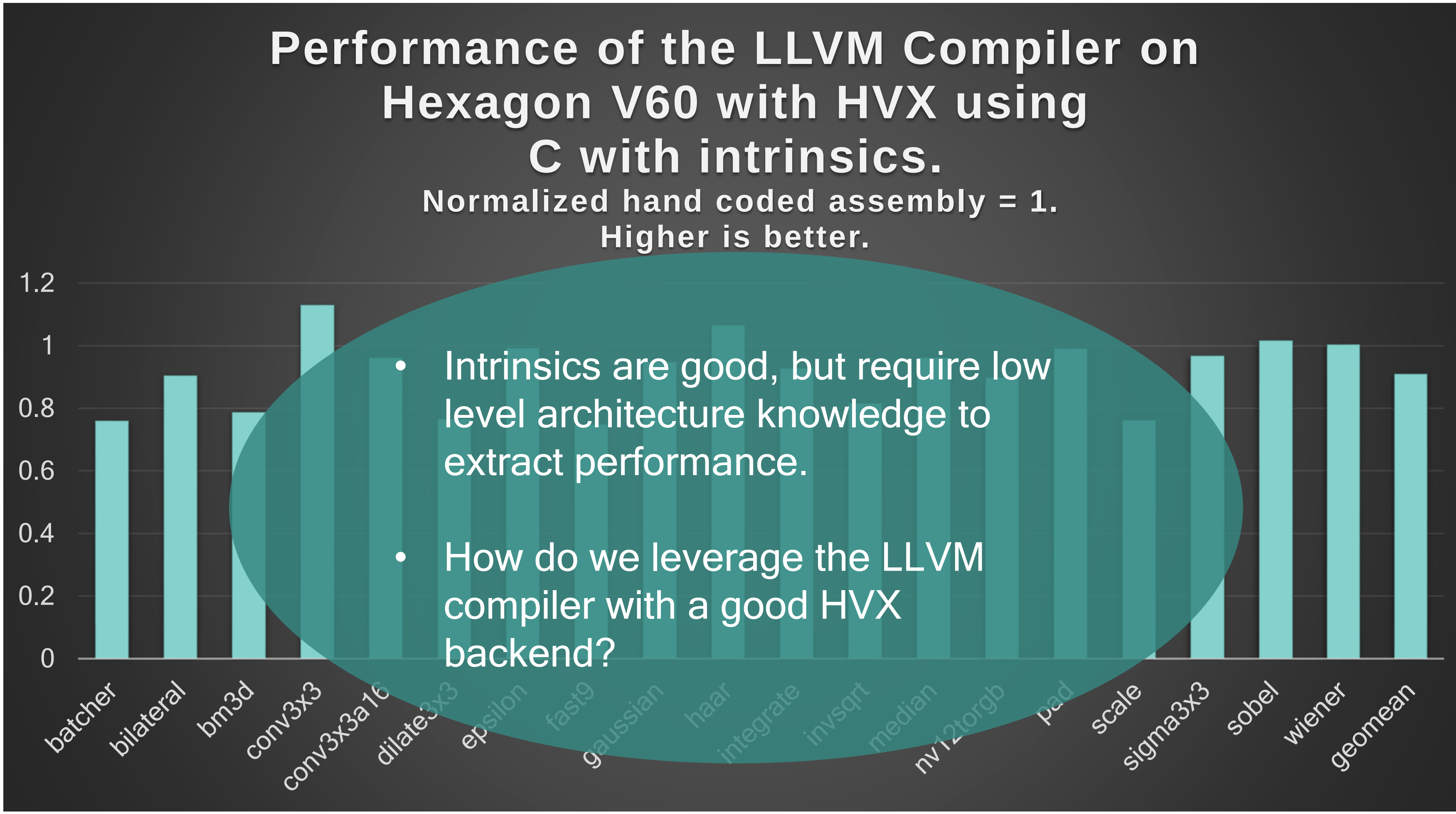
# Halide & HVX

## Motivation



# Halide & HVX

## Motivation




- Intrinsics are good, but require low level architecture knowledge to extract performance.
- How do we leverage the LLVM compiler with a good HVX backend?

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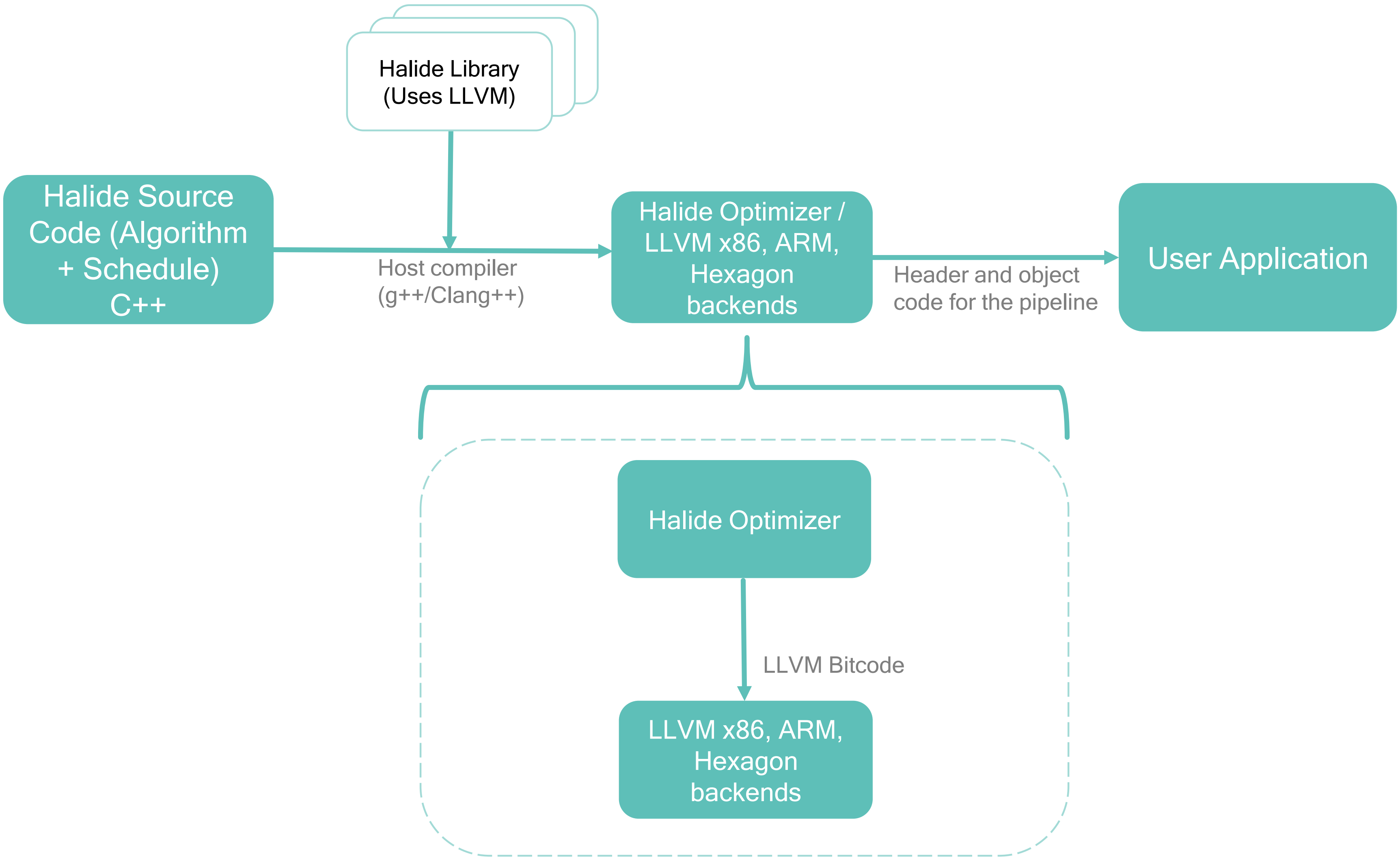
# Halide Compiler

## Ahead-of-time (AOT) compilation.



# Halide on Hexagon with HVX

- Halide provides two execution environments for HVX.
- Hardware model or the *offload* model.
  - Transparently dispatches Halide pipeline from the host CPU to the Hexagon™ processor.
  - Very easy to use as a developer.

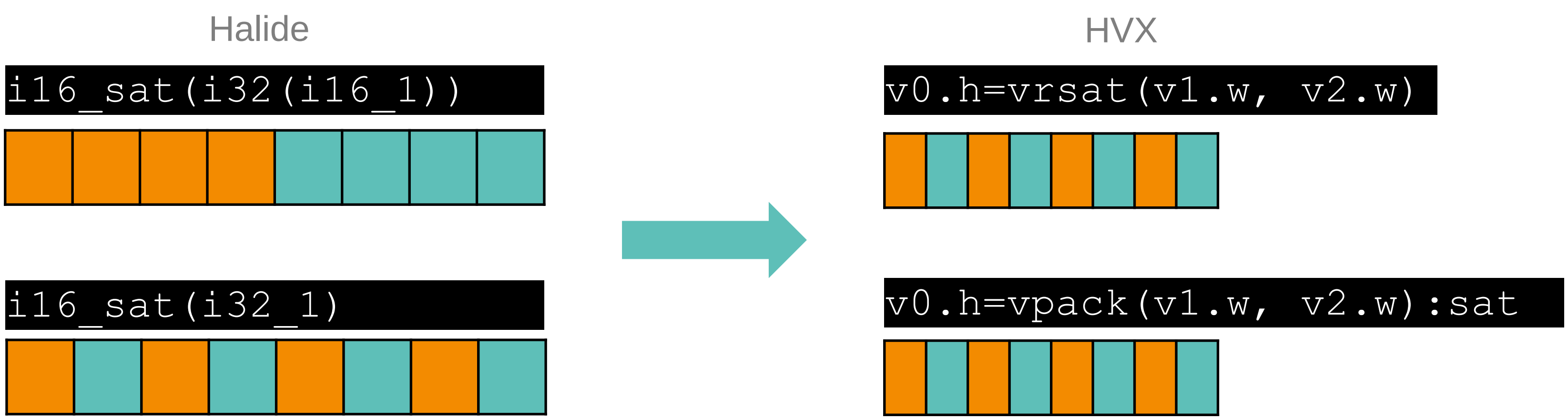
```
ImageParam input(Uint(8), 2) // Image with 8 bits per pixel.
Halide::Func f;

// horizontal blur - Algorithm.
f(x, y) =  (input(x-1, y) + input(x, y) + input(x+1, y))/3;
// Schedule
f.hexagon().vectorize(x, 128).parallel(y, 16);
```

- Standalone model, which can be used for both on-device execution and simulation.
  - Simpler startup.
  - Allows us to prototype future hardware features.

# Halide on Hexagon with HVX

## Vectorization, Alignment & Prefetching.

- HVX supports unaligned loads, but they are less efficient than aligned loads.
- Halide provides an abstraction to specify assumptions about the alignment of external memory buffers.
- Halide also provides a scheduling directive to prefetch data into the L2 cache. For example, "`my_func.prefetch(y, 2)`" will prefetch into the L2 cache, 2 iterations worth of data needed in the 'y' loop.
- HVX vectors are deinterleaved when widened and interleaved back together on truncation. Halide keeps track of "lanes"



# Halide on Hexagon with HVX

## Vectorization, Alignment & Prefetching.

- HVX supports unaligned loads, but they are less efficient than aligned loads.
- Halide provides an abstraction to specify assumptions about the alignment of external memory buffers.
- Halide also provides a scheduling directive to prefetch data into the L2 cache. For example, "`my_func.prefetch(y, 2)`" will prefetch into the L2 cache, 2 iterations worth of data needed in the 'y' loop.
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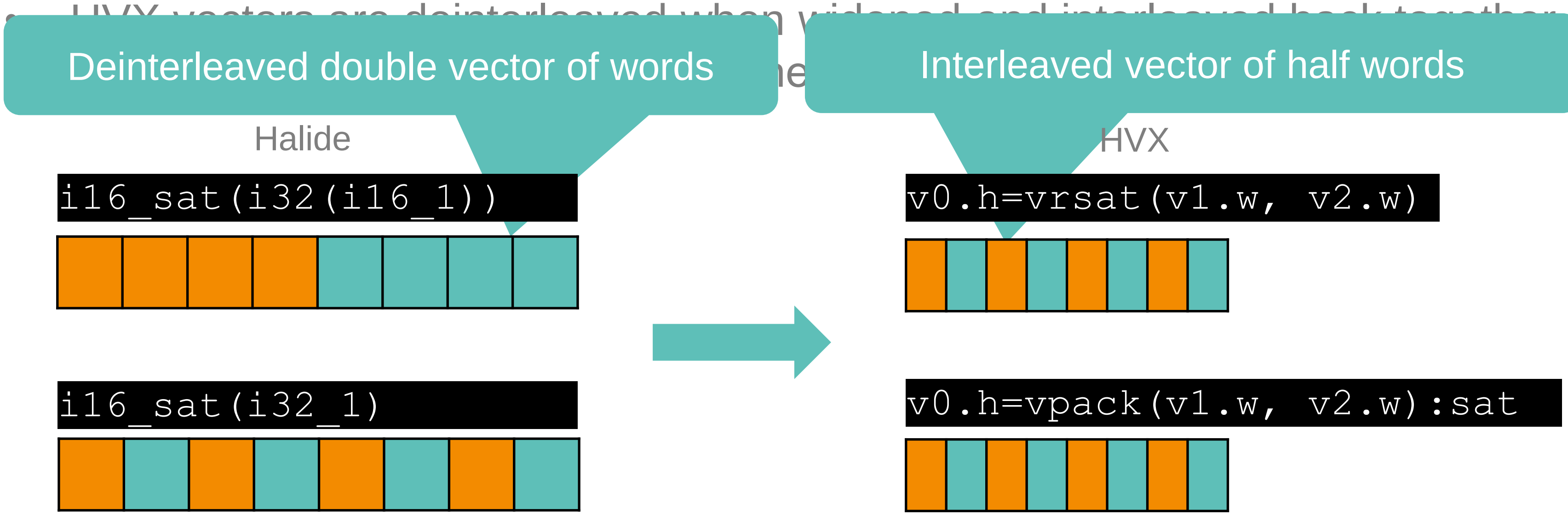

# Halide & LLVM (Median* Filter)

```
 .falign
.LBB135_11:
    {
        v5=valign(v10,v5,#1)
        v29.ub=vmax(v9.ub,v8.ub)
        v18=vmem(r1++#1)
        vmem(r0++#2)=v15
    }
    {
        v28.ub=vmin(v5.ub,v11.ub)
        v16.ub=vmin(v25.ub,v20.ub)
        v12.ub=vmax(v13.ub,v12.ub)
        v25.cur=vmem(r20++#1)
    }
    {
        v9.ub=vmax(v25.ub,v20.ub)
        v19.ub=vmax(v25.ub,v20.ub)
        v21.ub=vmin(v16.ub,v18.ub)
        v13=vmem(r10++#1)
    }
    {
        v11.ub=vmin(v9.ub,v18.ub)
        v5.ub=vmax(v9.ub,v18.ub)
        v20.ub=vmin(v25.ub,v20.ub)
        v10=vmem(r20++#1)
    }
```

* The assembly for the entire inner loop is not shown here.

```
    {
        v6=vlalign(v5,v6,#1)
        v2.ub=vmax(v3.ub,v2.ub)
        v26.ub=vmin(v7.ub,v4.ub)
        v17.ub=vmax(v30.ub,v13.ub)
    }
    {
        v22=vlalign(v1,v28,#1)
        v23.ub=vmin(v18.ub,v2.ub)
        v11.ub=vmin(v5.ub,v6.ub)
        v0=v30
    }
    {
        v27=valign(v14,v16,#1)
        v31.ub=vmax(v23.ub,v26.ub)
        v4=v17
        vmem(r11++#2)=v31.new
    }
    {
        v24=vlalign(v19,v24,#1)
        v6=v19
        v3.ub=vmax(v22.ub,v1.ub)
        v2.ub=vmin(v22.ub,v1.ub)
    }
    {
        v7.ub=vmin(v19.ub,v24.ub)
        v13.ub=vmin(v21.ub,v27.ub)
        v20=vmem(r10++#1)
    }:endloop0
```

# Halide & LLVM (Median* Filter)

```
 .falign
.LBB135_1
    {
                     .ub)
    }
    {
        v28.ub=vmin(v5.ub,v11.ub)
        v16.ub=vmin(v25.ub,v20.ub)
        v12.ub=vmax(v13.ub,v12.ub)
        v25.cur=vmem(r20++#1)
    }
    {
        v9.ub=vmax(v25.ub,v20.ub)
        v19.ub=vmax(v25.ub,v20.ub)
        v21.ub=vmin(v16.ub,v18.ub)
        v13=vmem(r10++#1)
    }
    {
        v11.ub=vmin(v9.ub,v18.ub)
        v5.ub=vmax(v9.ub,v18.ub)
        v20.ub=vmin(v25.ub,v20.ub)
        v10=vmem(r20++#1)
    }
```

Packetization

```
 * The assembly for the entire inner loop is
not shown here.
```

```
    {
        v6=
        v2                    )
        v2                    b)
        v1                    .ub)
    }
    {
        v2
        v23.                  .ub)
        v11.ub=vmin(v5.ub,v6.ub)
        v0=v30
    }
    {
        v27=valign(v14,v16,#1)
        v31.ub=vmax(v23.ub,v26.ub)
        v4=v17
        vmem(r11++#2)=v31.new

        v24=vlalign(v19,v24,#1)
        v6=v19
        v3.ub=vmax(v22.ub,v1.ub)
        v2.ub=vmin(v22.ub,v1.ub)

        v7.ub=vmin(v19.ub,v24.ub)
        v13.ub=vmin(v21.ub,v27.ub)
        v20=vmem(r10++#1)
    }:endloop0
```

Software Pipelined Loop.

Hardware Loops

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# Gaussian 5 point blur

## Halide Code

```
// Define a 1D Gaussian blur (a [1 4 6 4 1] filter) of 5 elements.
Expr blur5(Expr x0, Expr x1, Expr x2, Expr x3, Expr x4) {
    // Widen to 16 bits, so we don't overflow while computing the stencil.
    x0 = cast<uint16_t>(x0);    x1 = cast<uint16_t>(x1);
    x2 = cast<uint16_t>(x2);    x3 = cast<uint16_t>(x3);
    x4 = cast<uint16_t>(x4);
    return cast<uint8_t>((x0 + 4*x1 + 6*x2 + 4*x3 + x4 + 8)/16);
}
    // Algorithm
    ImageParam input(UInt(8), 3);
    // Apply a boundary condition to the input.
    Func input_bounded("input_bounded");
    input_bounded(x, y, c) = BoundaryConditions::repeat_edge(input)(x, y, c);
    // Implement this as a separable blur in y followed by x.
    Func blur_y("blur_y"), blur(“blur”);
    blur_y(x, y, c) = blur5(input_bounded(x, y - 2, c), input_bounded(x, y - 1, c),
                            input_bounded(x, y,     c), input_bounded(x, y + 1, c),
                            input_bounded(x, y + 2, c));
    blur(x, y, c) = blur5(blur_y(x - 2, y, c), blur_y(x - 1, y, c),
                          blur_y(x,     y, c), blur_y(x + 1, y, c),
                          blur_y(x + 2, y, c));
```

# Gaussian 5 point blur

## Halide : Schedule 1 - Vectorize

```
vector_size = 128;
blur.compute_root().hexagon().vectorize(x, vector_size);
```

### Loop Nest:

```
produce blur:
  for __outermost in [0, 0]<Hexagon>:
    for c:
      for y:
        for x.x:
          vectorized x.tmp in [0, 127]:
            blur(...) = ...
```

### Run on device:

```
Using HVX 128 schedule
Running pipeline...
Done, time: 0.0483019 s
Success!
```

# Gaussian 5 point blur

## Halide : Schedule 2 - compute_root

```
vector_size = 128;
input_bounded.compute_root();
blur.compute_root().hexagon().vectorize(x, vector_size);
```

## Loop Nest:

```
produce input_bounded:
  for c:
    for y:
      for x:
        input_bounded(...) = ...
consume input_bounded:
  produce blur:
    for __outermost in [0, 0]<Hexagon>:
      for c:
        for y:
          for x.x:
            vectorized x.tmp in [0, 127]:
              blur(...) = ...
  consume blur:
```

## Run on device:

```
Using HVX 128 schedule
Running pipeline...
Done, time: 0.0162422 s
Success!
```

# Gaussian 5 point blur

## Halide : Schedule 2 - compute_root

```
vector_size = 128;
input_bounded.compute_root();
blur.compute_root().hexagon().vectorize(x, vector_size);
```

## Loop Nest:

```
produce input_bounded:
  for c:
    for y:
      for x:
        input_bounded(...) = ...
consume input_bounded:
  produce blur:
    for __outermost in [0, 0]<Hexagon>:
      for c:
        for y:
          for x.x:
            vectorized x.tmp in [0, 127]:
              blur(...) = ...
  consume blur:
```

Executes on the Host

Executes on Hexagon

## Run on device:

```
Using HVX 128 schedule
Running pipeline...
Done, time: 0.0162422 s
Success!
```

# Gaussian 5 point blur

## Halide : Schedule 3 - blur_y.compute_at

```
input_bounded.compute_root();
blur_y.hexagon().compute_at(blur, y)
                .vectorize(x, vector_size, TailStrategy::RoundUp);
blur.compute_root().hexagon().vectorize(x, vector_size * 2);
```

## Loop Nest:

```
produce blur:
  for __outermost in [0, 0]<Hexagon>:
    for c:
      for y:
        produce blur_y:
          for __outermost in [0, 0]<Hexagon>:
            for c:
              for y:
                for x.x:
                  vectorized x.tmp in [0, 127]:
                    blur_y(...) = ...
          consume blur_y:
            for x.x:
              vectorized x.tmp in [0, 255]:
                blur(...) = ...
```

## Run on device:

```
Using HVX 128 schedule
Running pipeline...
Done, time: 0.0099081 s
Success!
```

# Gaussian 5 point blur

## Halide : Best Schedule (so far).

```
input_bounded.compute_at(blur, y)
             .vectorize(x, vector_size, TailStrategy::RoundUp)
             .align_storage(x, 64)
             .store_at(blur, yo).fold_storage(y, 8);
blur_y.compute_at(blur, y)
      .vectorize(x, vector_size, TailStrategy::RoundUp);
blur.compute_root()
    .hexagon().vectorize(x, vector_size*2, TailStrategy::RoundUp)
    .split(y, yo, y, 128).parallel(yo).prefetch(y, 2);
```

Run on device:

```
Using HVX 128 schedule
Running pipeline...
Done, time: 0.0035454 s
Success!
```

# Gaussian 5 Point Blur

## Halide code: Schedule 4 Loop Nest

```
produce blur:
  for __outermost in [0, 0]<Hexagon>:
    for c:
      parallel y.yo:
        store input_bounded:
          for y.y in [0, 127]:
            produce input_bounded:
              for c:
                for y:
                  for x.x:
                    vectorized x.tmp in [0, 127]:
                      input_bounded(...) = ...
            consume input_bounded:
              produce blur_y:
                for __outermost in [0, 0]<Hexagon>:
                  for c:
                    for y:
                      for x.x:
                        vectorized x.tmp in [0, 127]:
                          blur_y(...) = ...
              consume blur_y:
                for x.x:
                  vectorized x.tmp in [0, 255]:
                    blur(...) = ...
consume blur:
```

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Example 1: blur5

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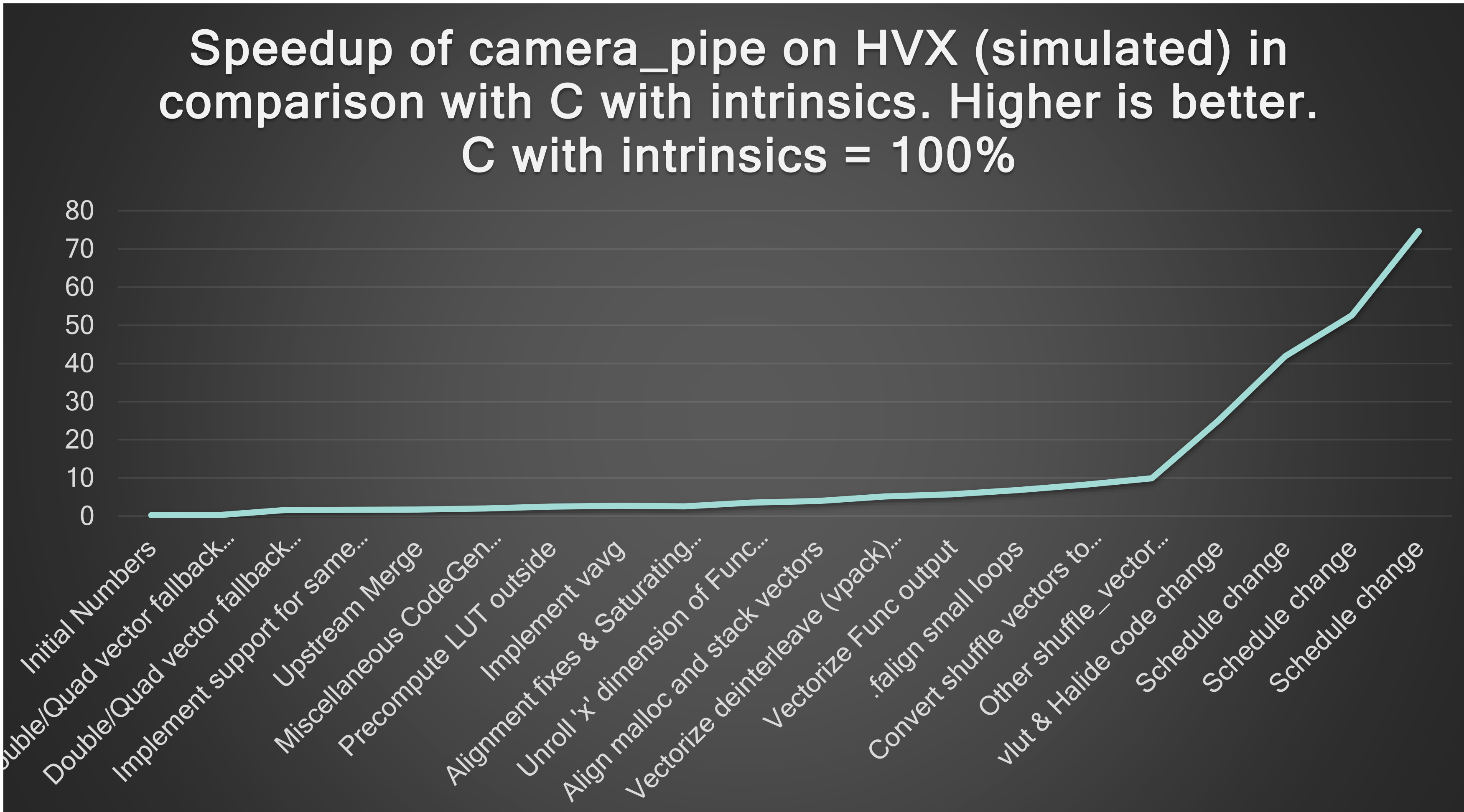
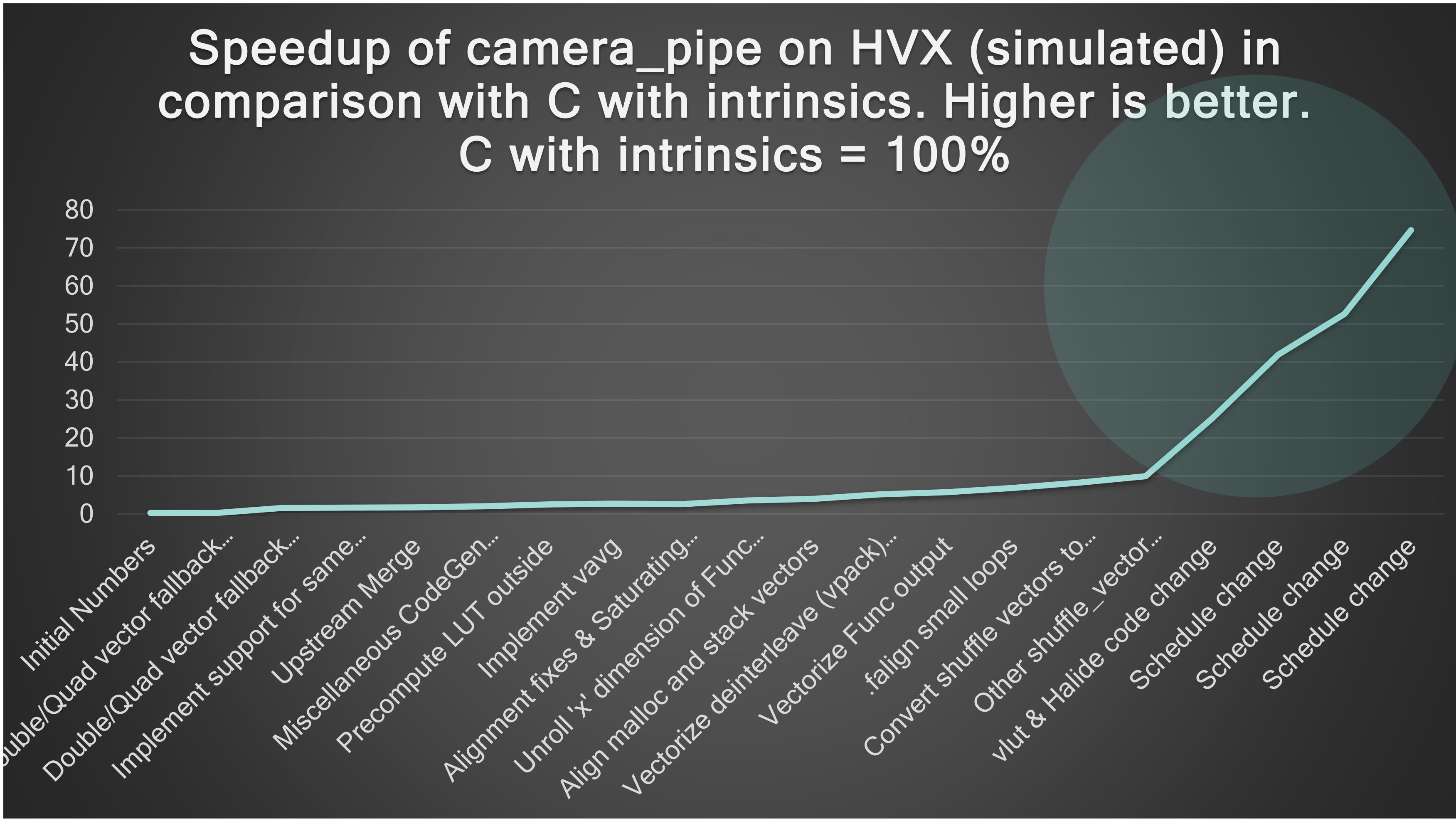
Example 2: camera_pipe

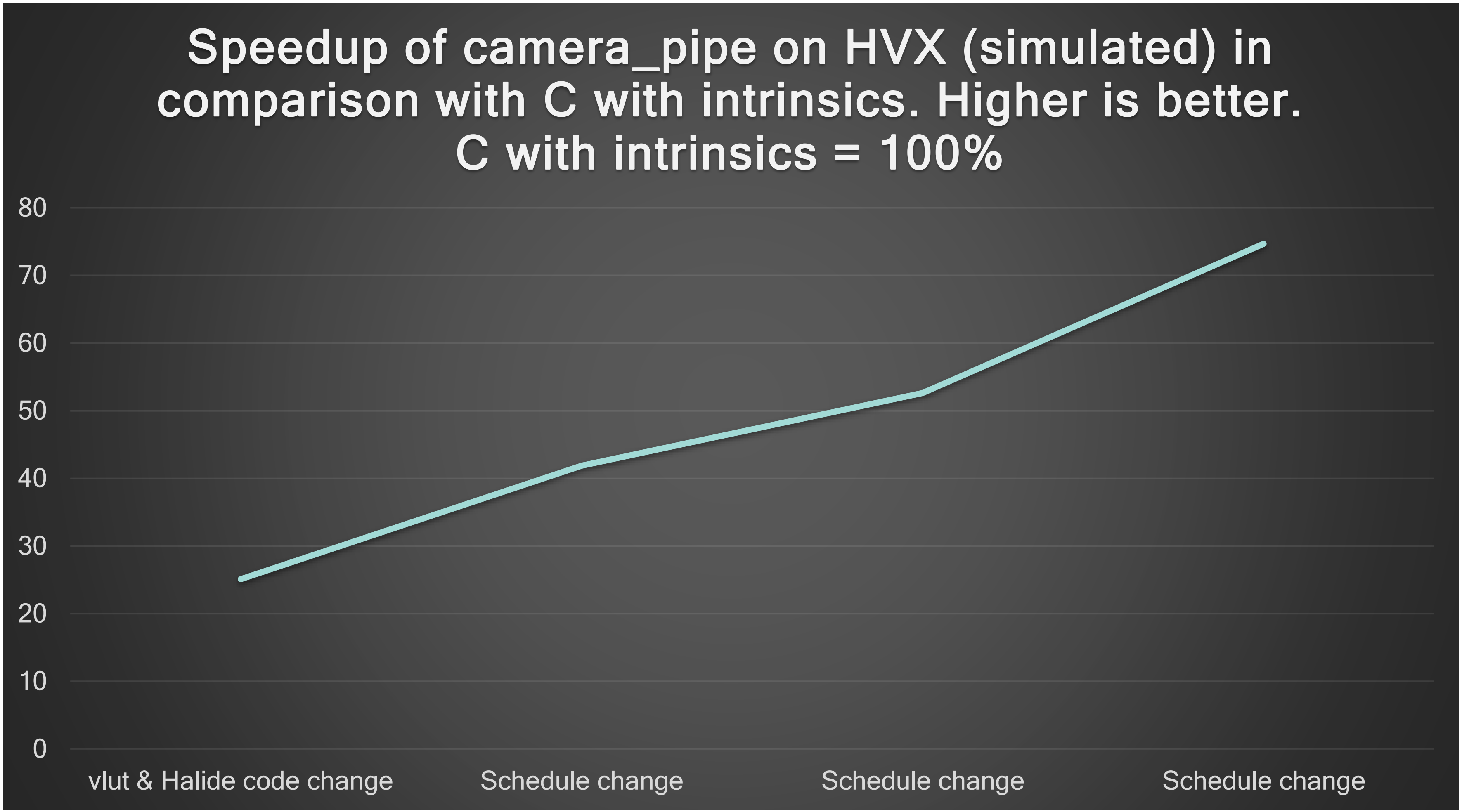
# Example 2: camera_pipe



# Example 2: camera_pipe



# Example 2: camera_pipe



# Thank you

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