Fast Image Processing using Halide

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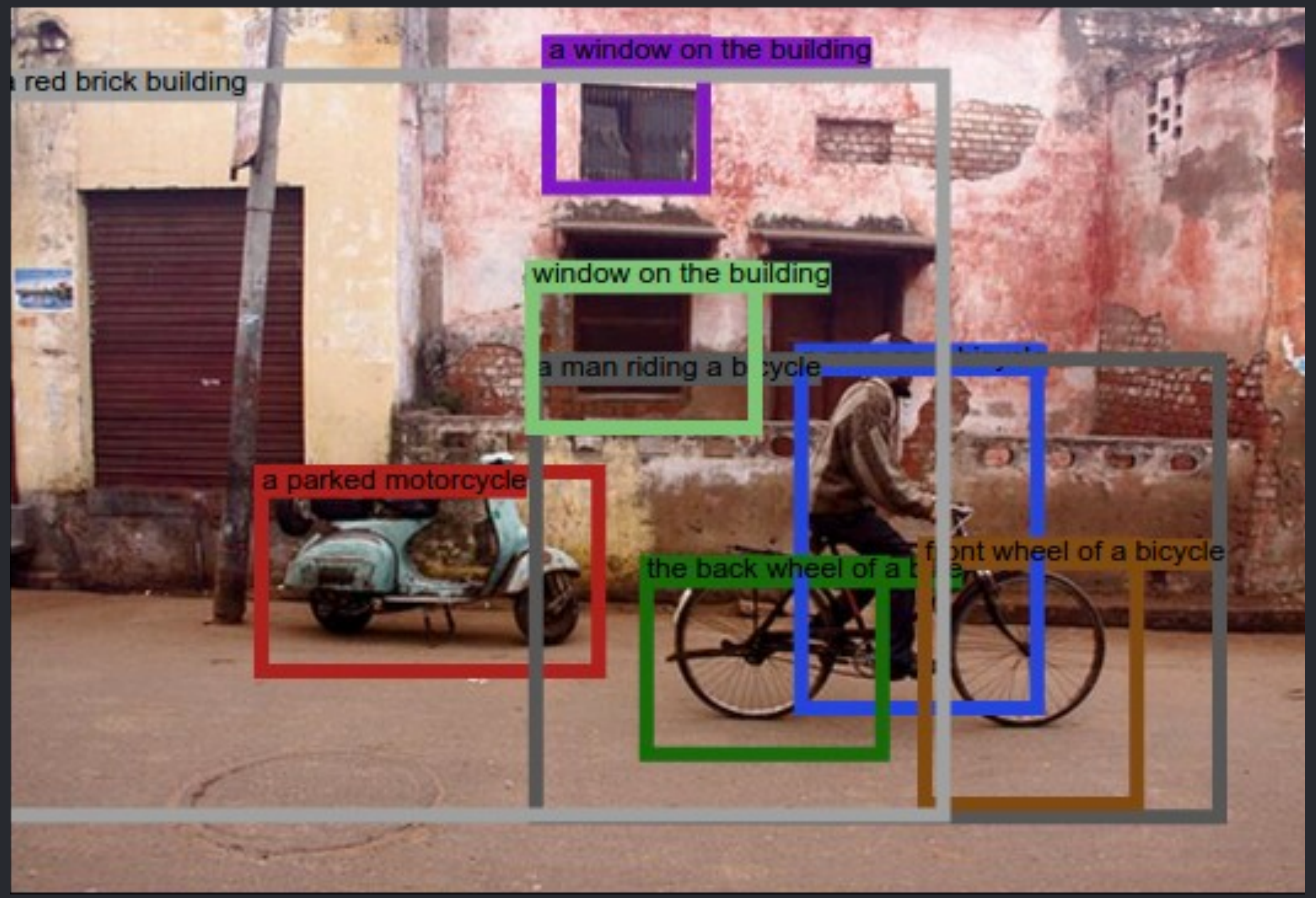
High demand for efficient image processing



Writing fast image processing pipelines is hard.

Halide is a language that makes it easier.

Big idea: separate algorithm from optimization

programmer defines both - no *“Sufficiently Smart Compiler”* needed

algorithm becomes simple, modular, portable

exploring optimizations is much easier

C/C++ is slow

```
void box_filter_3x3(const Image &in, Image &blury) {
  Image blurx(in.width(), in.height());  // allocate temporary array

  for (int y = 0; y < in.height(); y++)
    for (int x = 0; x < in.width(); x++)
      blurx(x, y) = (in(x-1, y) + in(x, y) + in(x+1, y))/3;

  for (int y = 0; y < in.height(); y++)
    for (int x = 0; x < in.width(); x++)
      blury(x, y) = (blurx(x, y-1) + blurx(x, y) + blurx(x, y+1))/3;
}
```

9.96 ms/megapixel
(quad core x86)

An optimized implementation is 11x faster

```
void box_filter_3x3(const Image &in, Image &blury) {
  __m128i one_third = _mm_set1_epi16(21846);
  #pragma omp parallel for
  for (int yTile = 0; yTile < in.height(); yTile += 32) {
    __m128i a, b, c, sum, avg;
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    for (int xTile = 0; xTile < in.width(); xTile += 256) {
      __m128i *blurxPtr = blurx;
      for (int y = -1; y < 32+1; y++) {
        const uint16_t *inPtr = &(in[yTile+y][xTile]);
        for (int x = 0; x < 256; x += 8) {
         a = _mm_loadu_si128((__m128i*)(inPtr-1));
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         sum = _mm_add_epi16(_mm_add_epi16(a, b), c);
         avg = _mm_mulhi_epi16(sum, one_third);
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      blurxPtr = blurx;
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          a = _mm_load_si128(blurxPtr+(2*256)/8);
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}}}}}
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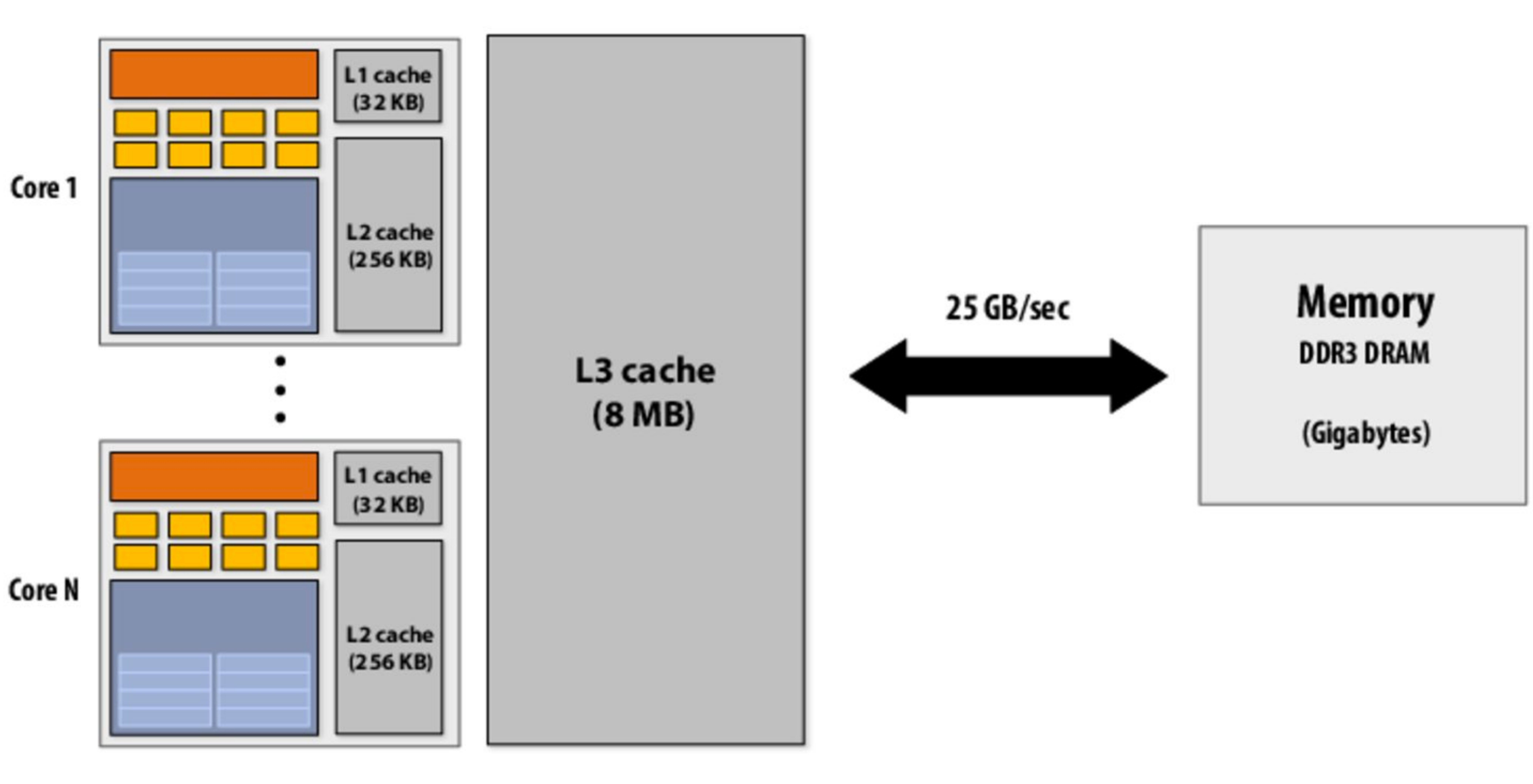
***11x faster** than a naïve implementation*

0.9 ms/megapixel (quad core x86)

A Modern Multi-Core Processor



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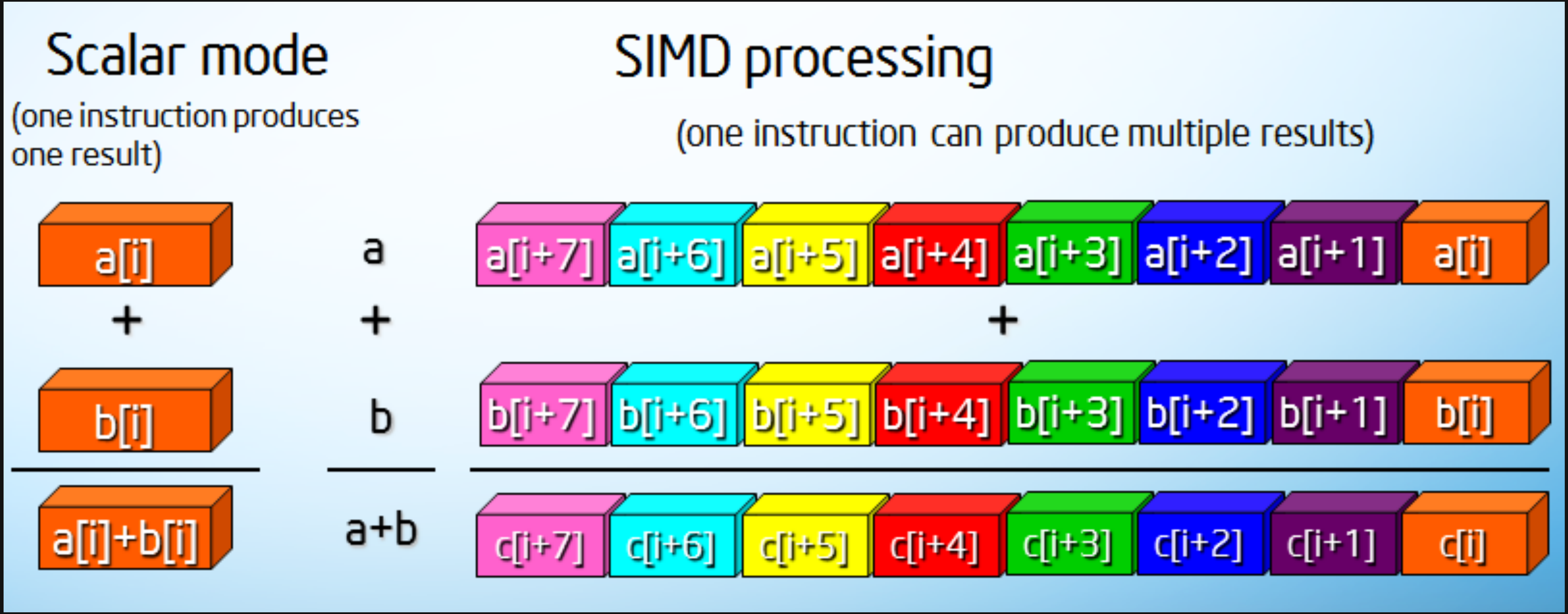

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parallelism

distribute across threads
SIMD parallel vectors

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interleave tiles of blurx, blury
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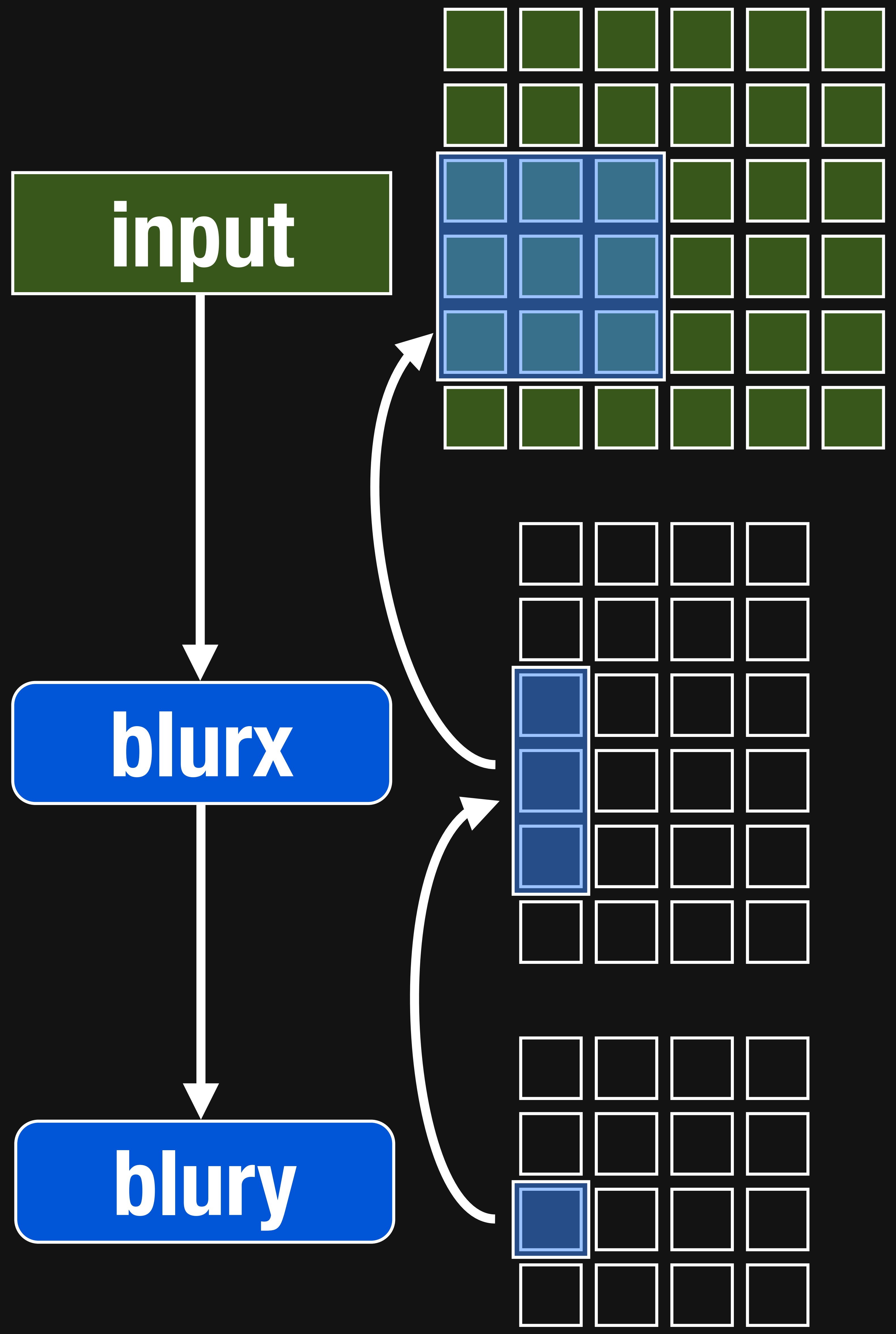

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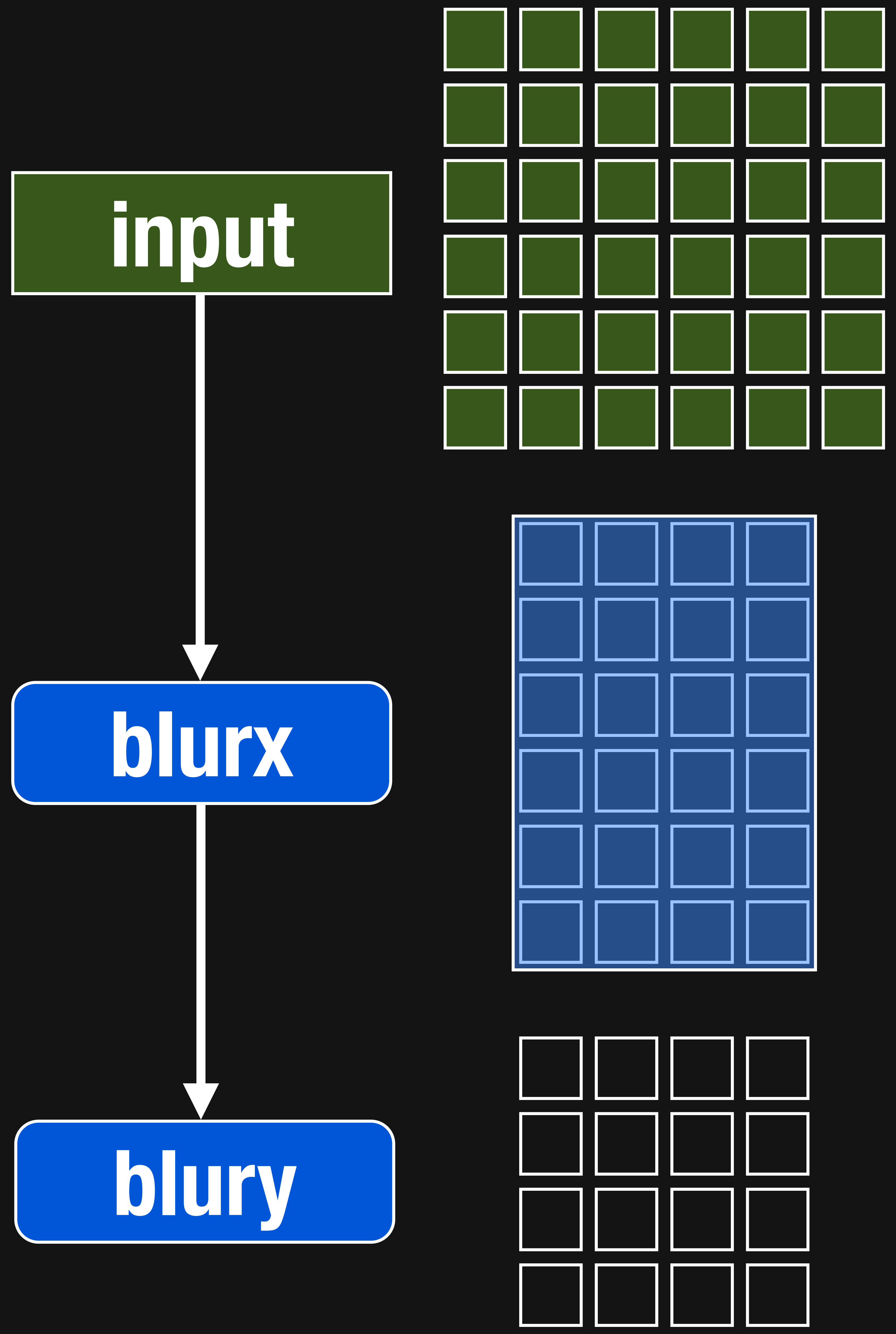

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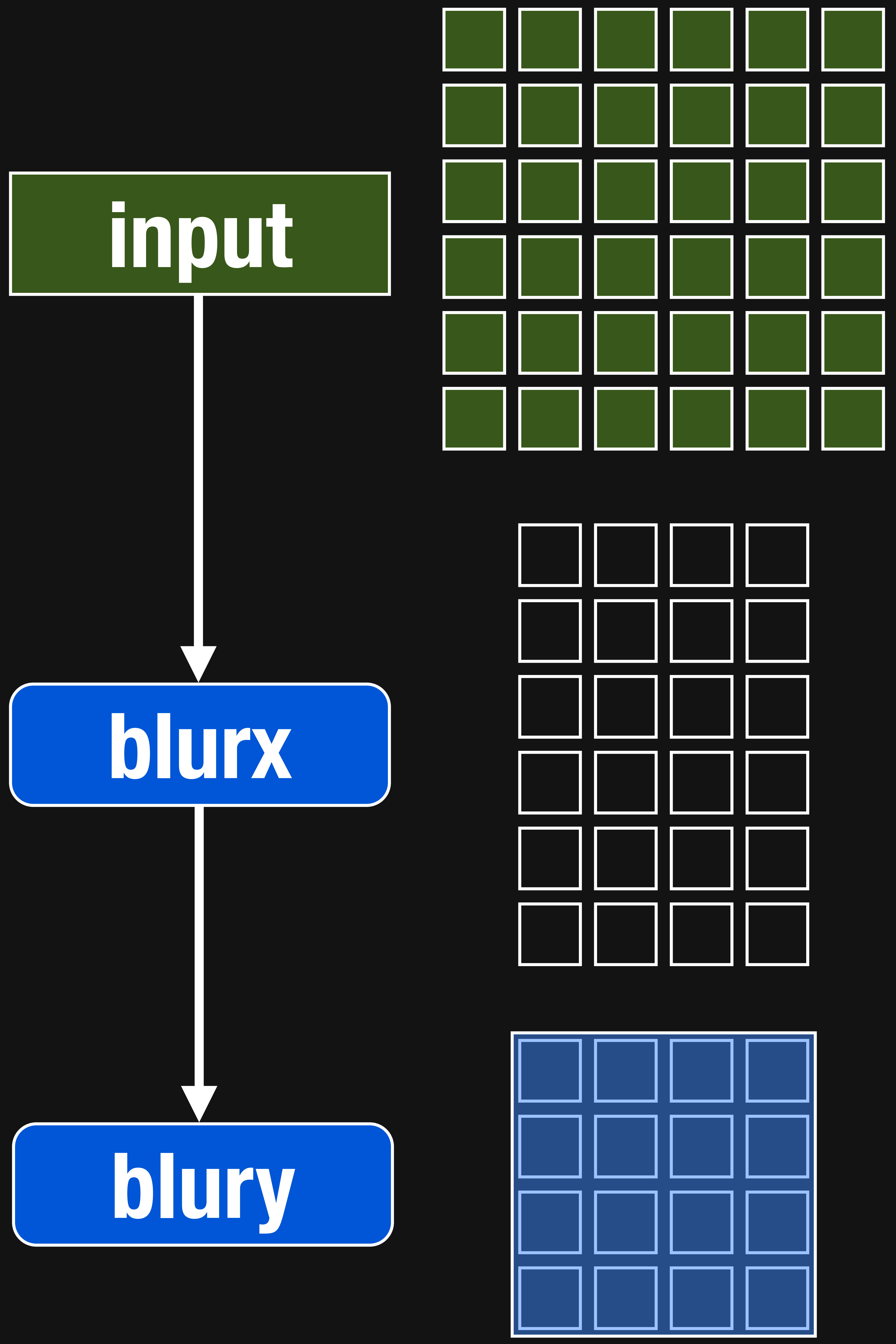

Fusing stages globally interleaves execution

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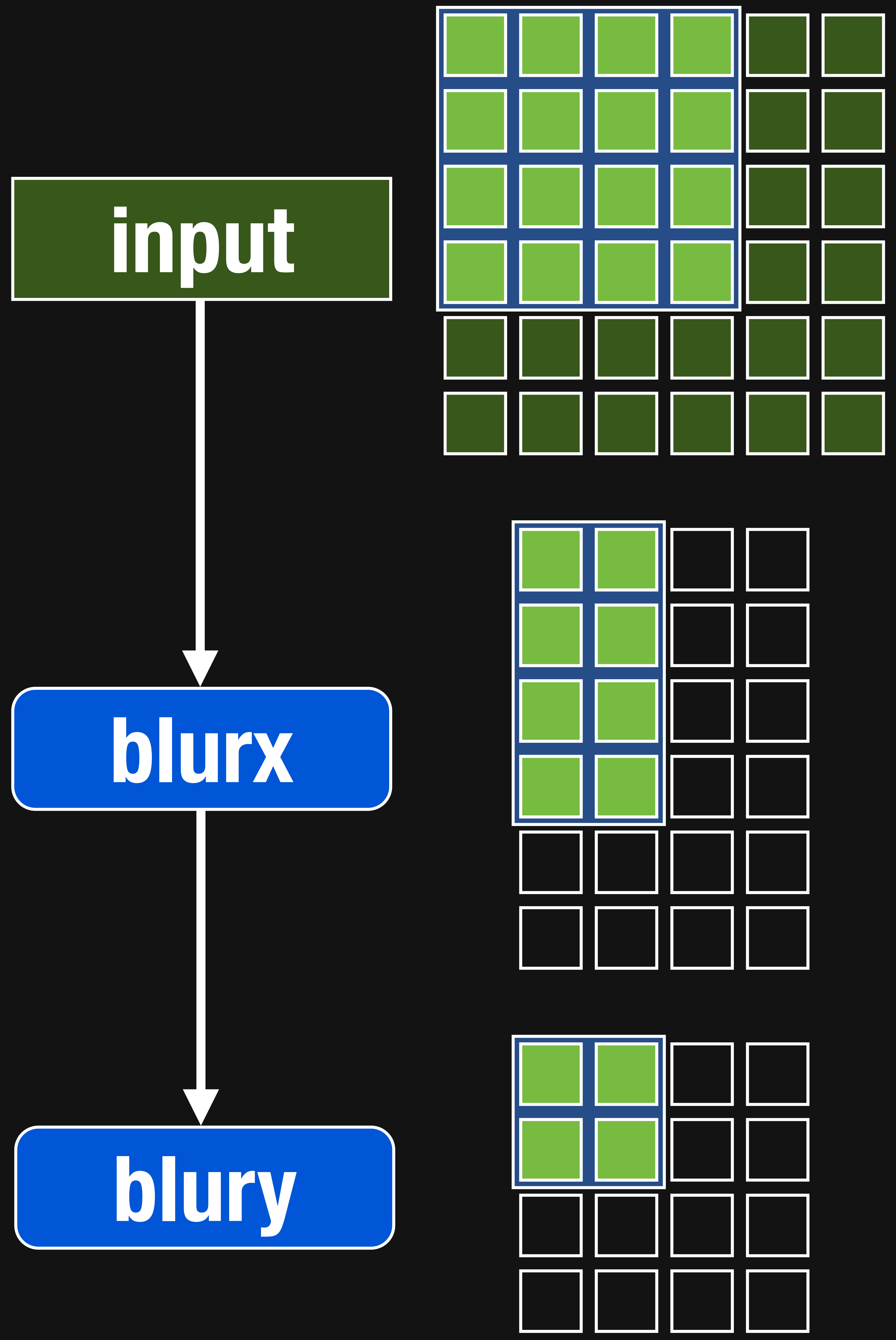

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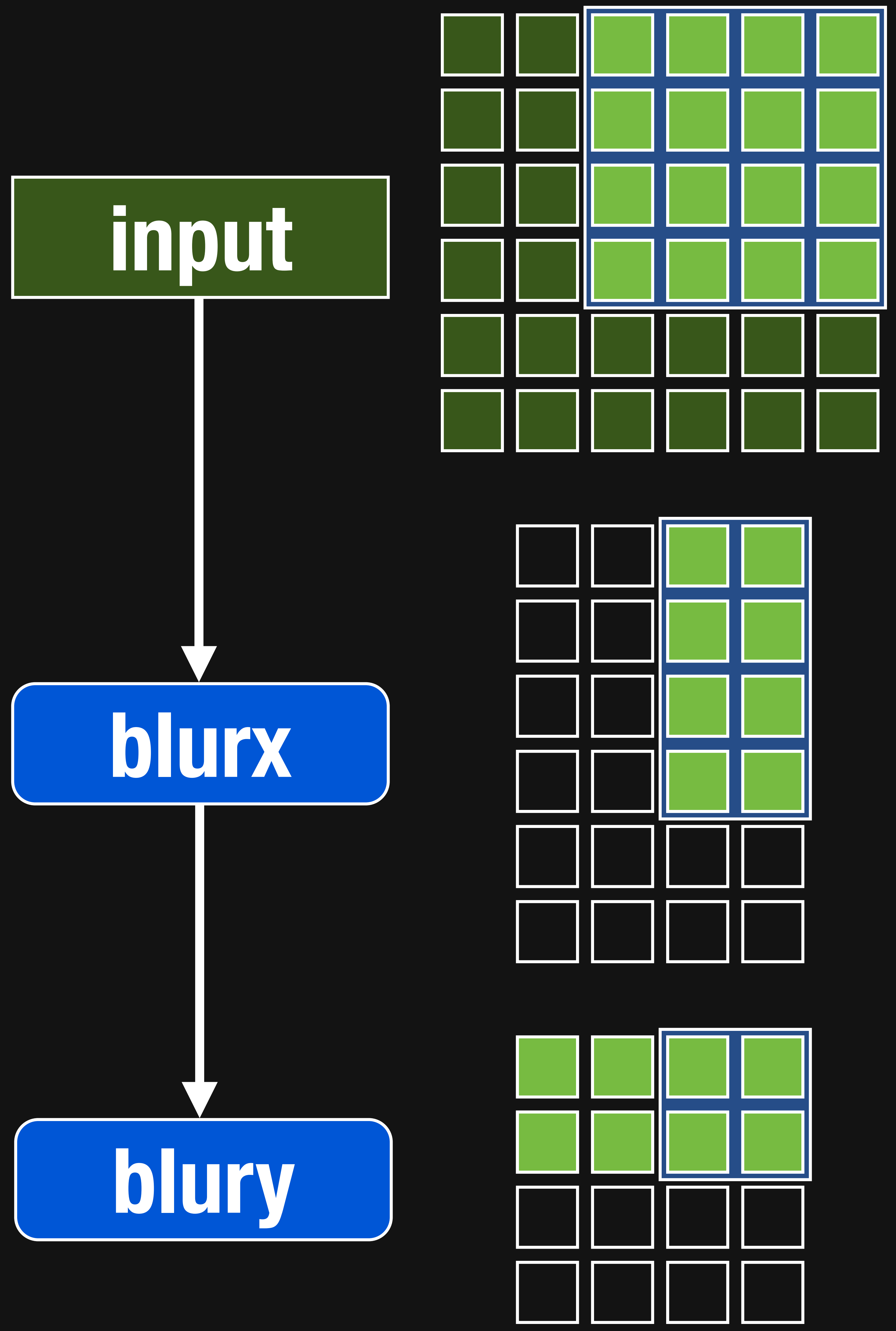

Fusion is a complex *tradeoff*

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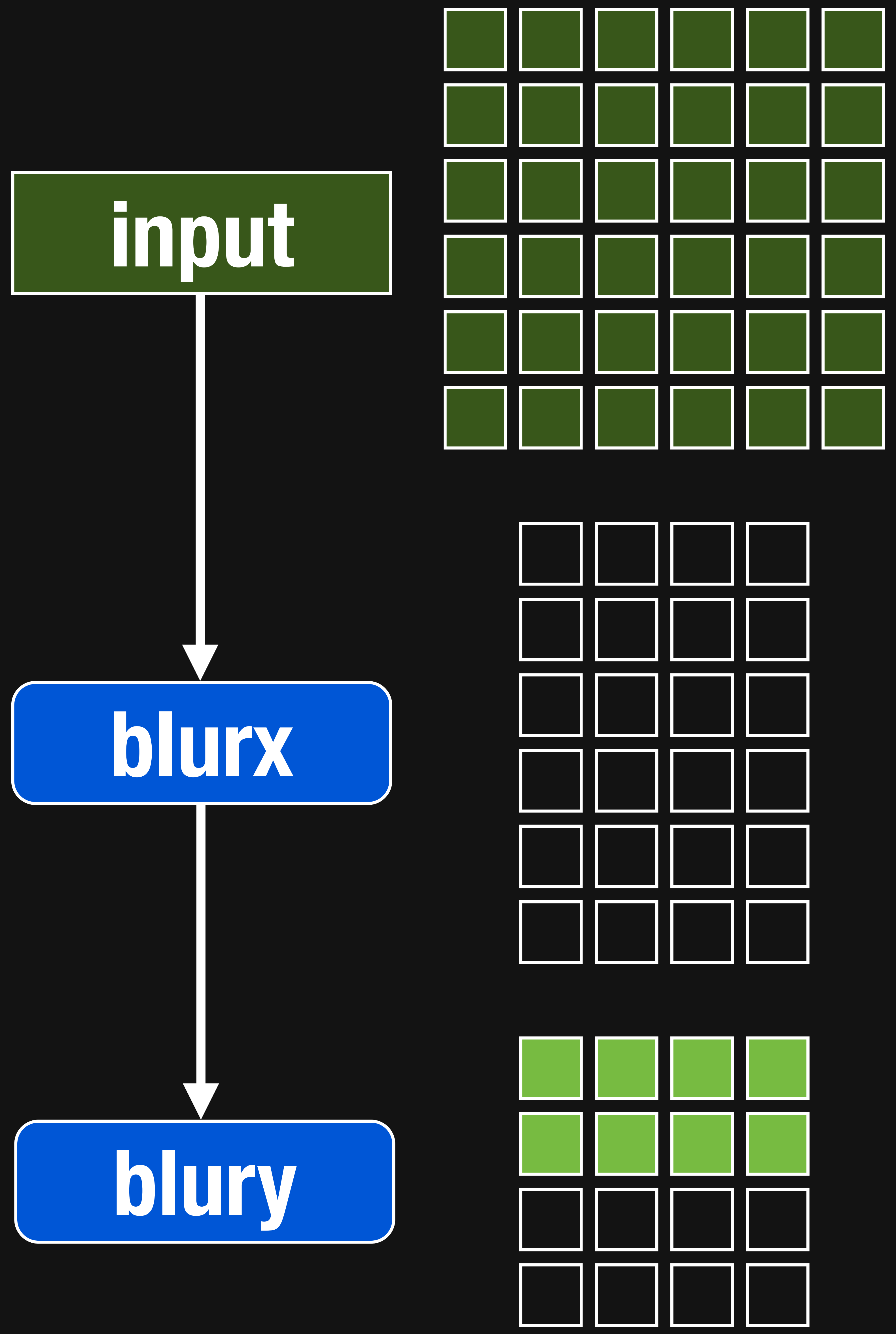

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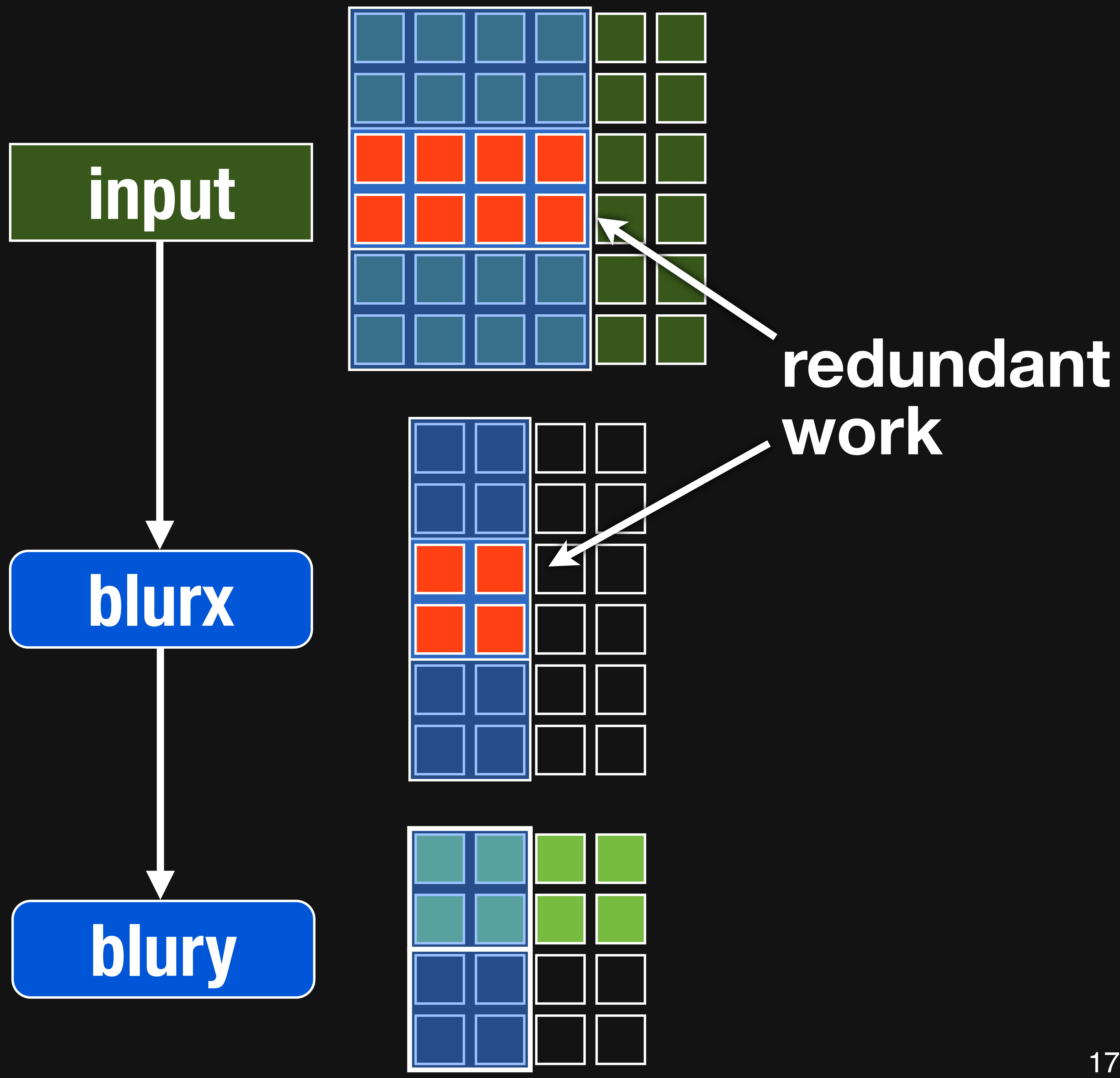


The choice space

For each stage:

Question 1) In what order should it compute its values?

In what order should I compute my values?

Serial y,
Serial x

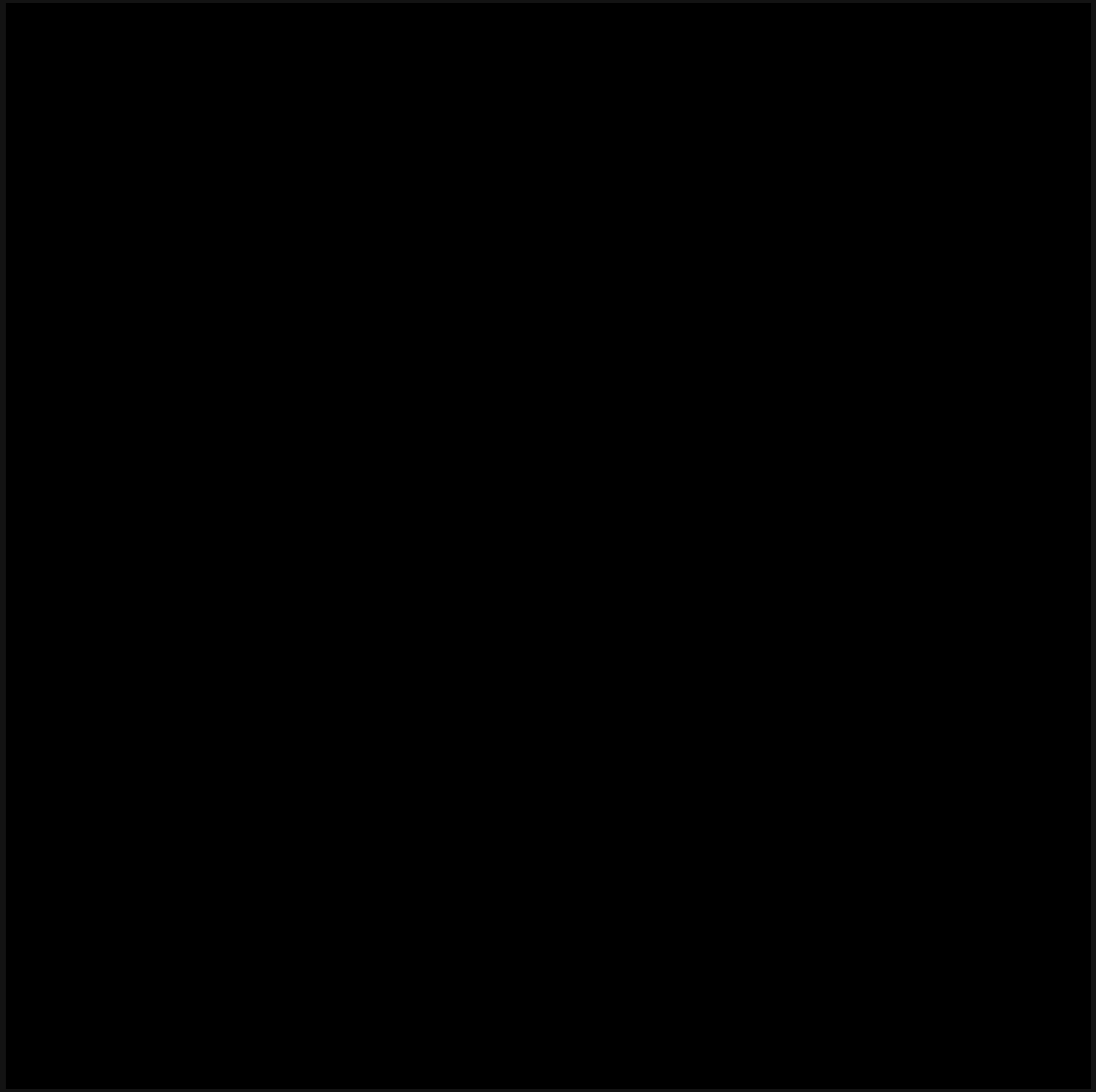
In what order should I compute my values?

Serial x,
Serial y

In what order should I compute my values?

Serial y,
Vectorize x by 4

In what order should I compute my values?



Parallel y,
Vectorize x by 4

In what order should I compute my values?

Split x by 4**,**
Split y by 4**.**
Serial y_{outer},
Serial x_{outer},
Serial y_{inner},
Serial x_{inner}

The choice space

For each stage:

Question 1) In what order should it compute its values?

Question 2) When should it compute its inputs?

When should I compute my inputs?

Poor locality

All at once, ahead of time

When should I compute my inputs?

Redundant recompute

As needed, discarding after use

When should I compute my inputs?

Poor parallelism

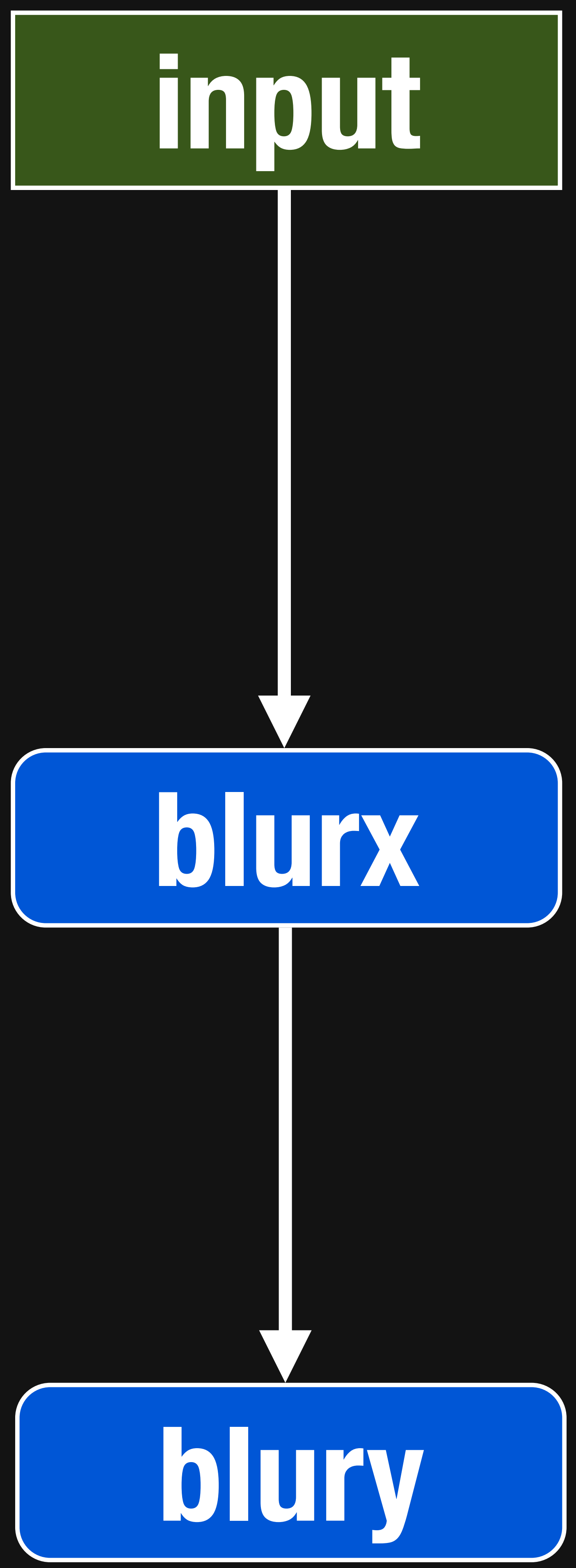
As needed, reusing old values

Some more points within the choice space

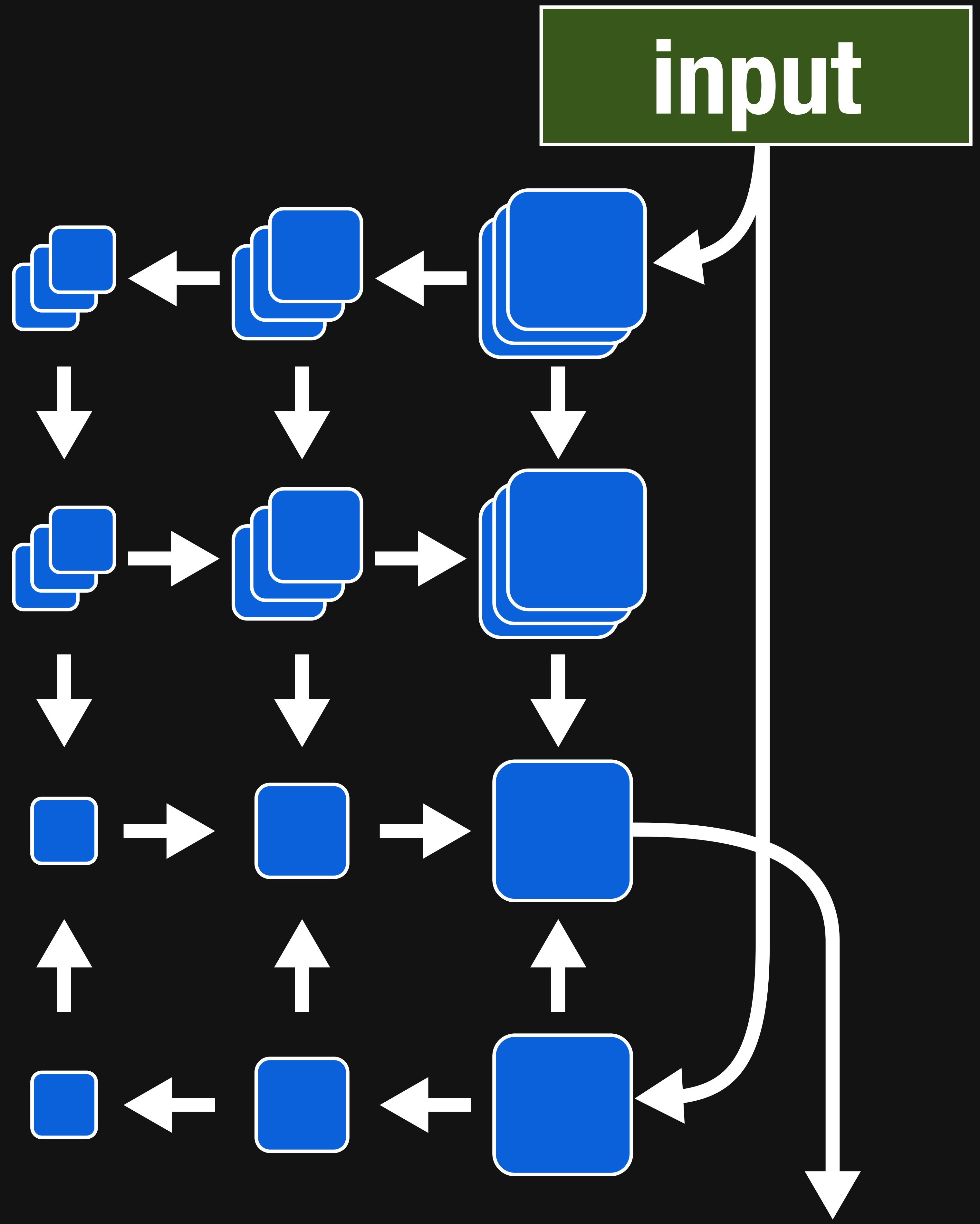
Some more points within the choice space

Some more points within the choice space

Scheduling is a complex *tradeoff*



3x3 box filter



local Laplacian filters

[Paris et al. 2010, Aubry et al. 2011]

Heterogeneity

A typical mobile SoC (System on Chip) has a CPU, DSP and a GPU.

Need ability to target different architectures and exploit them effectively.

Developing highly optimized low-level code for each architectures is not scalable.

Existing languages make optimizations hard

Parallelism

vectorization

multithreading

Locality

fusion

tiling

C - parallelism + tiling + fusion are hard to write *or* automate

CUDA, OpenCL, shaders - data parallelism is easy, fusion is hard

libraries don't help:

BLAS, IPP, MKL, OpenCV, MATLAB

Halide: *decouple* algorithm from schedule

Algorithm: ***what*** **is computed**
Schedule: ***where*** **and** ***when*** **it's computed**

Easy for programmers to build pipelines

simplifies algorithm code
improves modularity

Easy for programmers to specify & explore optimizations

fusion, tiling, parallelism, vectorization
can't break the algorithm

Easy for the compiler to generate fast code

The algorithm: pipelines as pure functions

Pipeline stages are functions from coordinates to values

no side effects

coordinates span an infinite domain

boundaries and required regions are inferred

Execution order and storage are unspecified

points can be evaluated (or reevaluated) in any order

results can be cached, duplicated, or recomputed anywhere

3x3 blur as a Halide *algorithm*:

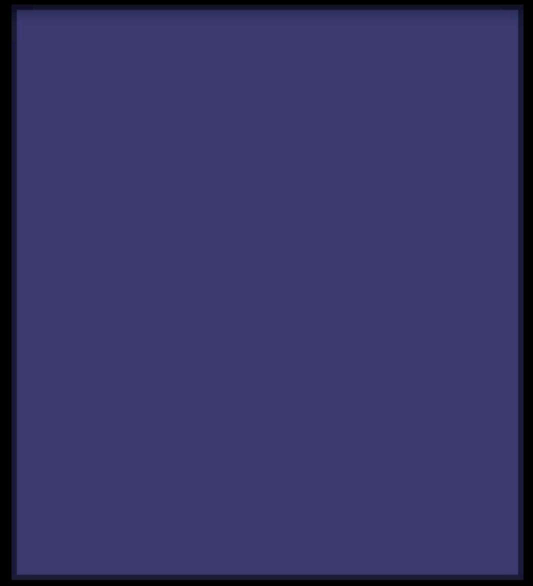
```
Func blurx, blury;
Var x, y;
blurx(x, y) = (in(x-1, y) + in(x, y) + in(x+1, y))/3;
blury(x, y) = (blurx(x, y-1) + blurx(x, y) + blurx(x, y+1))/3;
```

The schedule: producer-consumer interleaving

For each stage:

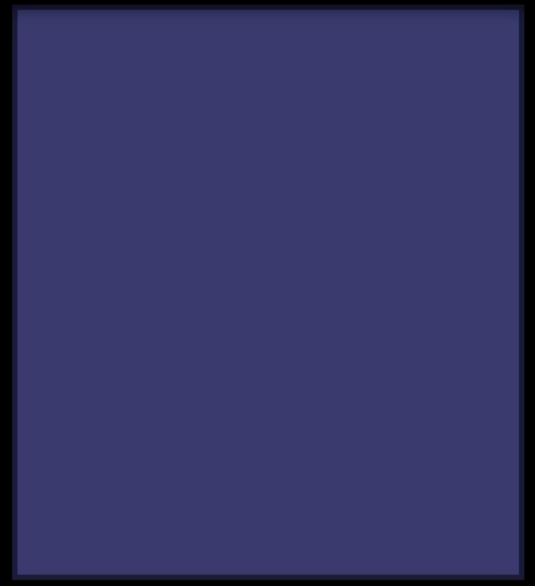
Question 1) In what order should it compute its output?

Question 2) When should it compute its inputs?

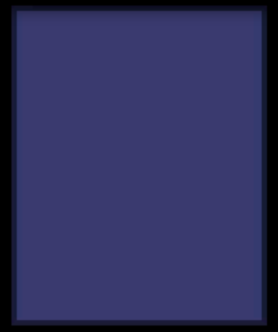


```
blur_x.compute_root();
```

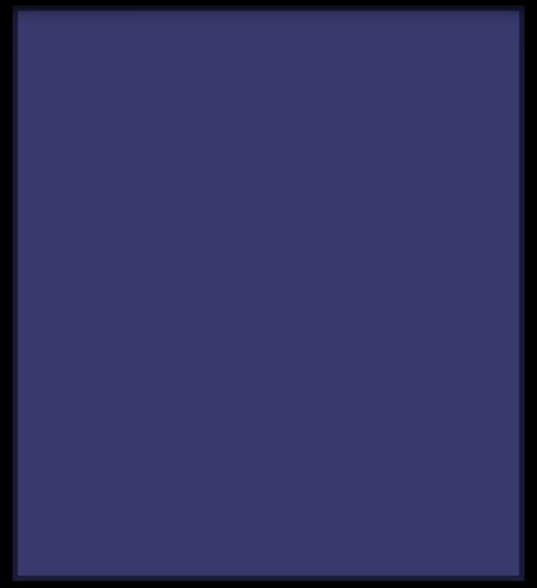
```
blur_x.compute_at(blur_y, x);
```



```
blur_x.store_root().compute_at(blur_y, x);
```



```
blur_x.compute_at(blur_y, x)
      .vectorize(x, 4);
blur_y.tile(x, y, xi, yi, 8, 8)
      .parallel(y)
      .vectorize(xi, 4);
```



```
blur_x.store_root()
      .compute_at(blur_y, y)
      .split(x, x, xi, 8)
      .vectorize(xi, 4).parallel(x);
blur_y.split(x, x, xi, 8)
      .vectorize(xi, 4).parallel(x);
```

```
blur_x.store_at(blur_y, y)
      .compute_at(blur_y, yi)
      .vectorize(x, 4);
blur_y.split(y, y, yi, 8)
      .vectorize(x, 4)
      .parallel(y);
```

Halide

0.9 ms/megapixel

```
Func box_filter_3x3(Func in) {
  Func blurx, blury;
  Var x, y, xi, yi;

  // The algorithm
  blurx(x, y) = (in(x-1, y) + in(x, y) + in(x+1, y))/3;
  blury(x, y) = (blurx(x, y-1) + blurx(x, y) + blurx(x, y+1))/3;

  // The schedule
  blury.tile(x, y, xi, yi, 256, 32)
       .vectorize(xi, 8).parallel(y);
  blurx.compute_at(blur_y, x).vectorize(x, 8);

  return blury;
}
```

Halide

0.9 ms/megapixel

```
Func box_filter_3x3(Func in) {
  Func blurx, blury;
  Var x, y, xi, yi;

  // The algorithm - no storage, order
  blurx(x, y) = (in(x-1, y) + in(x, y) + in(x+1, y))/3;
  blury(x, y) = (blurx(x, y-1) + blurx(x, y) + blurx(x, y+1))/3;

  // The schedule - defines order, locality; implies storage
  blury.tile(x, y, xi, yi, 256, 32)
       .vectorize(xi, 8).parallel(y);
  blurx.chunk(x).vectorize(x, 8);

  return blury;
}
```

C++

0.9 ms/megapixel

```
void box_filter_3x3(const Image &in, Image &blury) {
  __m128i one_third = _mm_set1_epi16(21846);
  #pragma omp parallel for
  for (int yTile = 0; yTile < in.height(); yTile += 32) {
    __m128i a, b, c, sum, avg;
    __m128i blurx[(256/8)*(32+2)]; // allocate tile blurx array
    for (int xTile = 0; xTile < in.width(); xTile += 256) {
      __m128i *blurxPtr = blurx;
      for (int y = -1; y < 32+1; y++) {
        const uint16_t *inPtr = &(in[yTile+y][xTile]);
        for (int x = 0; x < 256; x += 8) {
         a = _mm_loadu_si128((__m128i*)(inPtr-1));
         b = _mm_loadu_si128((__m128i*)(inPtr+1));
         c = _mm_load_si128((__m128i*)(inPtr));
         sum = _mm_add_epi16(_mm_add_epi16(a, b), c);
         avg = _mm_mulhi_epi16(sum, one_third);
         _mm_store_si128(blurxPtr++, avg);
         inPtr += 8;
      }}
      blurxPtr = blurx;
      for (int y = 0; y < 32; y++) {
        __m128i *outPtr = (__m128i *)(&(blury[yTile+y][xTile]));
        for (int x = 0; x < 256; x += 8) {
          a = _mm_load_si128(blurxPtr+(2*256)/8);
          b = _mm_load_si128(blurxPtr+256/8);
          c = _mm_load_si128(blurxPtr++);
          sum = _mm_add_epi16(_mm_add_epi16(a, b), c);
          avg = _mm_mulhi_epi16(sum, one_third);
          _mm_store_si128(outPtr++, avg);
}}}}}
```

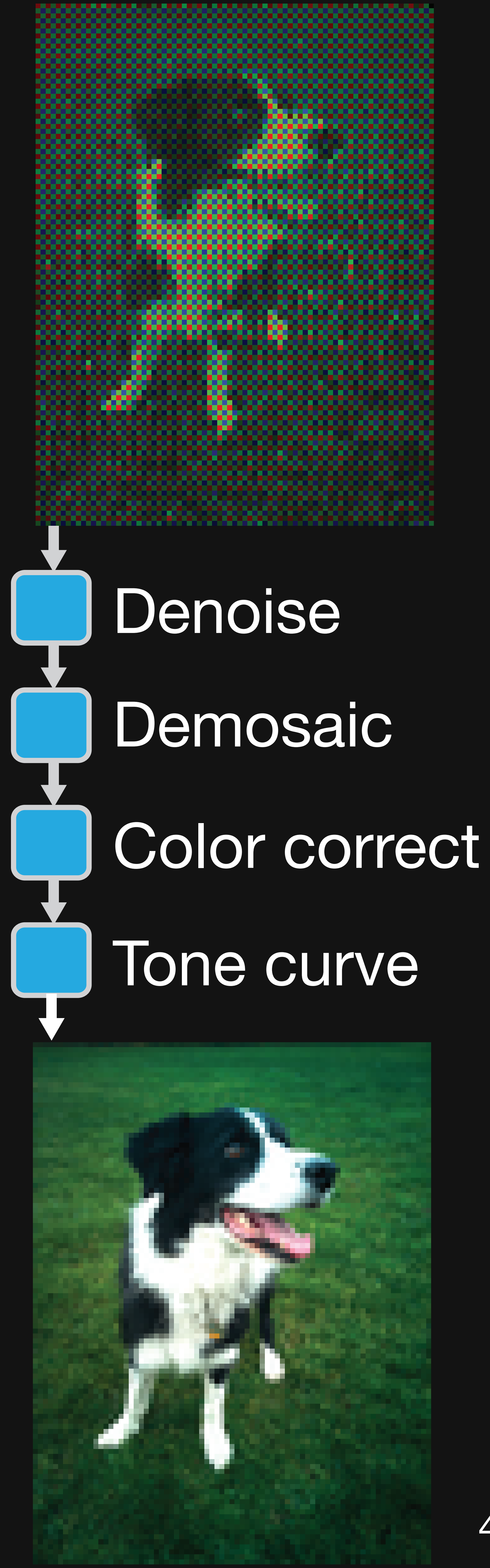
The FCam Raw Pipeline

[Adams et al. 2010]

Converts raw image sensor data into an image

The original code is 463 lines of ARM assembly and intrinsics in one big function

Rewritten in Halide, it is 2.75x less code, and runs 5% faster



Local Laplacian Filters

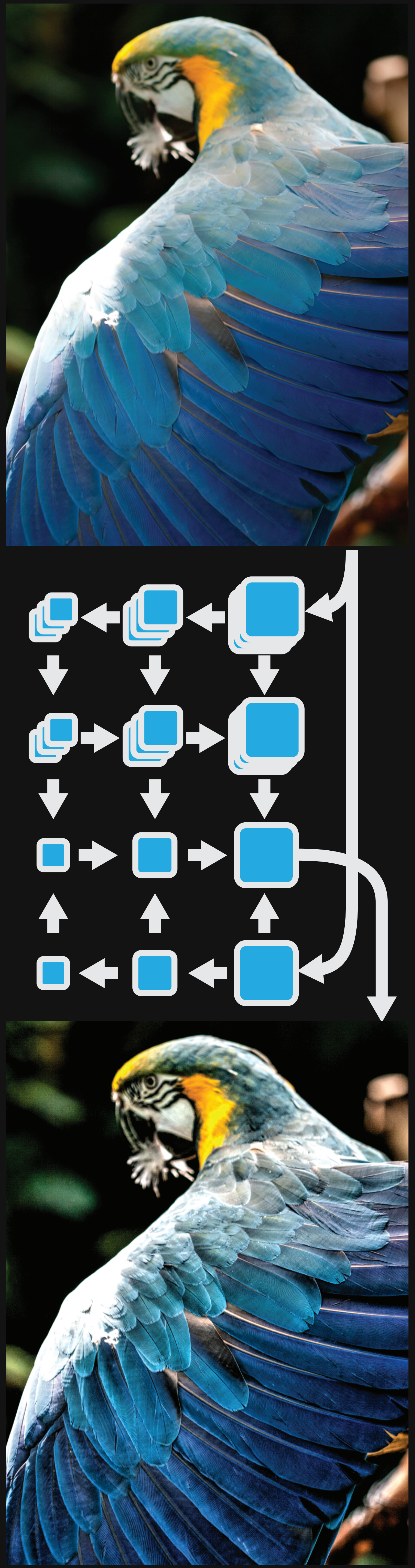
[Paris et al. 2010, Aubry et al. 2011]

Pyramid-based algorithm for increasing local contrast

Original is 262 lines of optimized C++ using OpenMP and Intel Performance Primitives (IPP)

Rewritten in Halide: 62 lines of code for the algorithm, 7 lines of code for the schedule

2.1x faster on CPU, 7x faster on GPU



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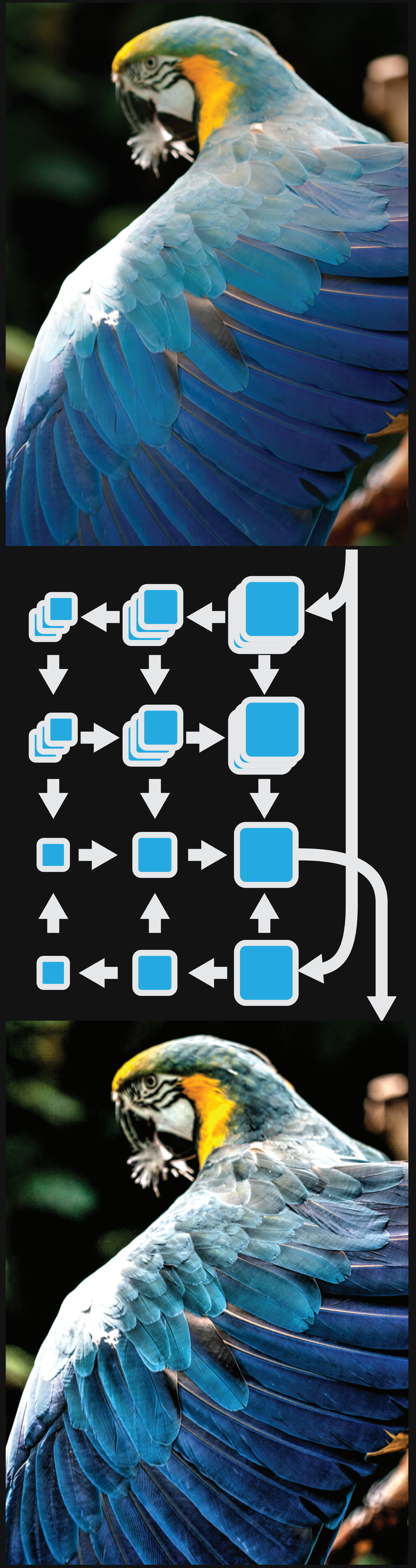


The Bilateral Grid

[Chen et al. 2007]

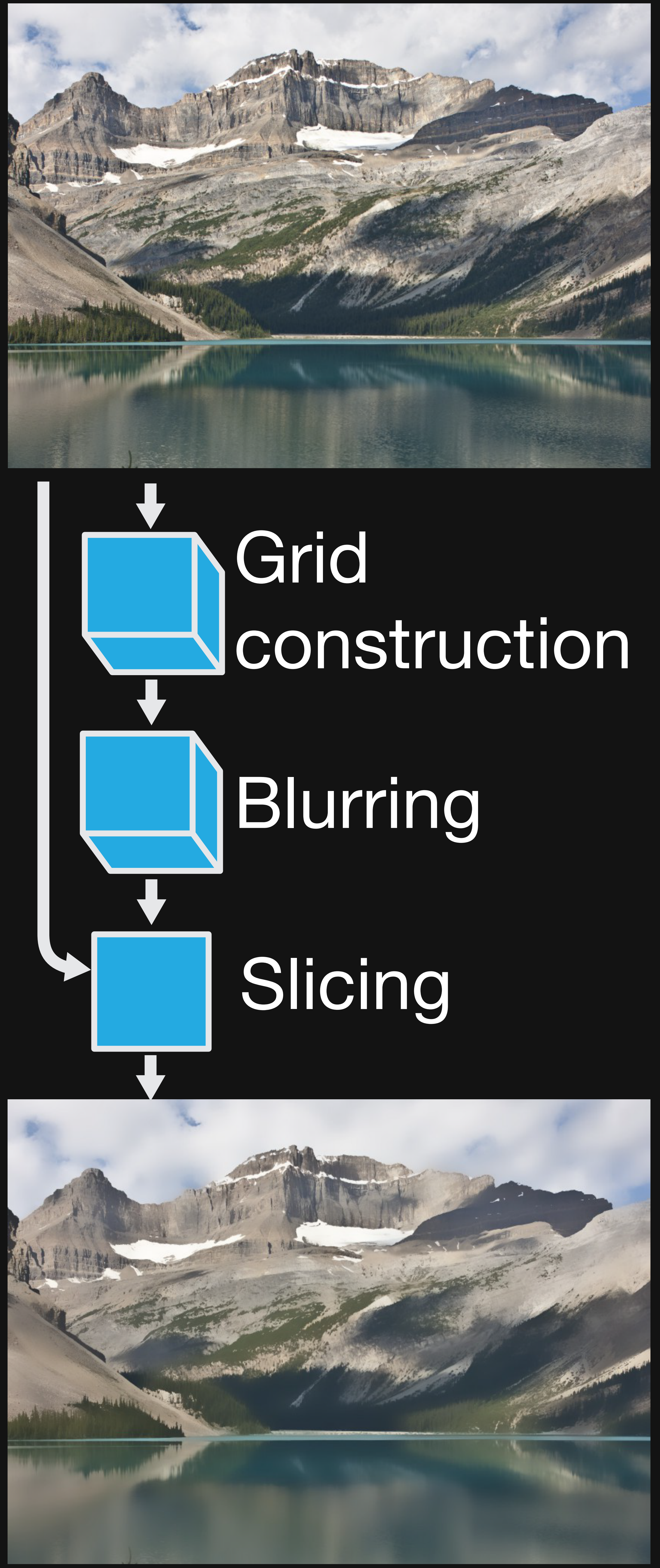
An accelerated bilateral filter

Original is 122 lines of clean C++

Halide version is 34 lines of algorithm, and 6 lines of schedule

On the CPU, 5.9x faster

On the GPU, 2x faster than Chen's hand-written CUDA version



Halide is embedded in C++

Build Halide functions and expressions using C++

Evaluate Halide functions immediately

Just-in-time compile to produce and run a Halide pipeline

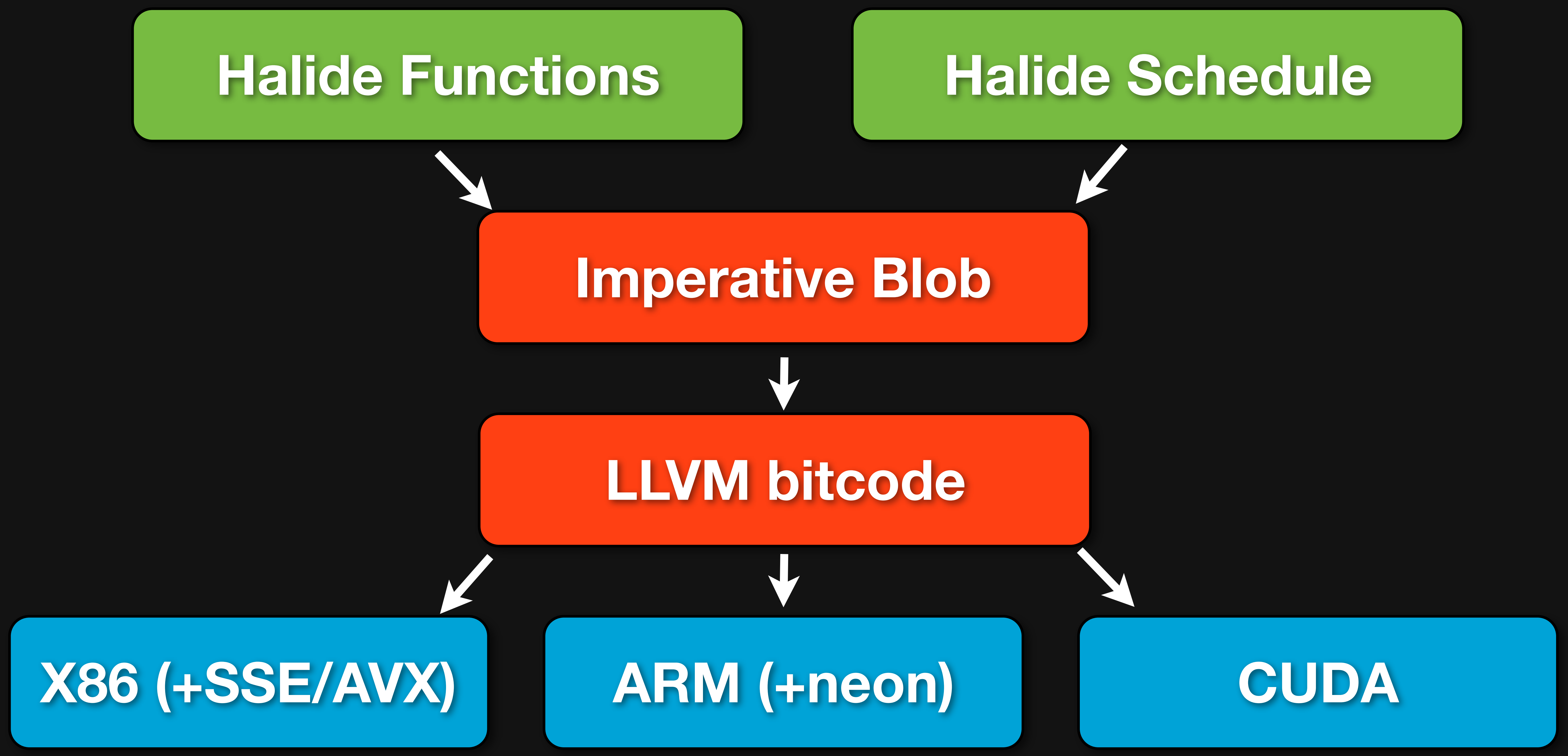
Or statically compile to an object file and header

One C++ program creates the Halide pipeline

When run, it produces an object file and header

You link this into your actual program

The Halide Compiler



Example Pipelines

Unsharp Mask

More apps in the public repo

A faster FFT than FFTW

A faster Gaussian blur than OpenCV

A faster matrix multiply than Eigen

http://halide-lang.org/

Getting Started

Public website at http://halide-lang.org

Tutorials at http://halide-lang.org/tutorials

Some limitations

Only handles feed-forward pipelines

Only images - no trees or lists or hash tables

~~Schedule must be specified manually~~

We welcome contributions

http://github.com/Halide/halide

Automatically Scheduling Halide Image Processing Pipelines

Ravi Teja Mullapudi (CMU)
Andrew Adams (Google)
Dillon Sharlet (Google)
Jonathan Ragan-Kelley (Stanford)
Kayvon Fatahalian (CMU)

Few developers have the skill set to author highly optimized schedules

Image processing algorithm developers

Algorithm description

```
Var x, y;
Func f, g;
g(x,y) = f(x,y) + …
h(x) = g(x,y) + …
```

Schedule (machine mapping)

```
parallelize y loop
tile output dims
vectorize y loop
```

> 10x Faster Implementation

Automatic scheduling of image processing pipelines

Image processing algorithm developers

Algorithm description

```
Var x, y;
Func f, g;
g(x,y) = f(x,y) + …
h(x) = g(x,y) + …
```

Generates expert-quality schedules in seconds

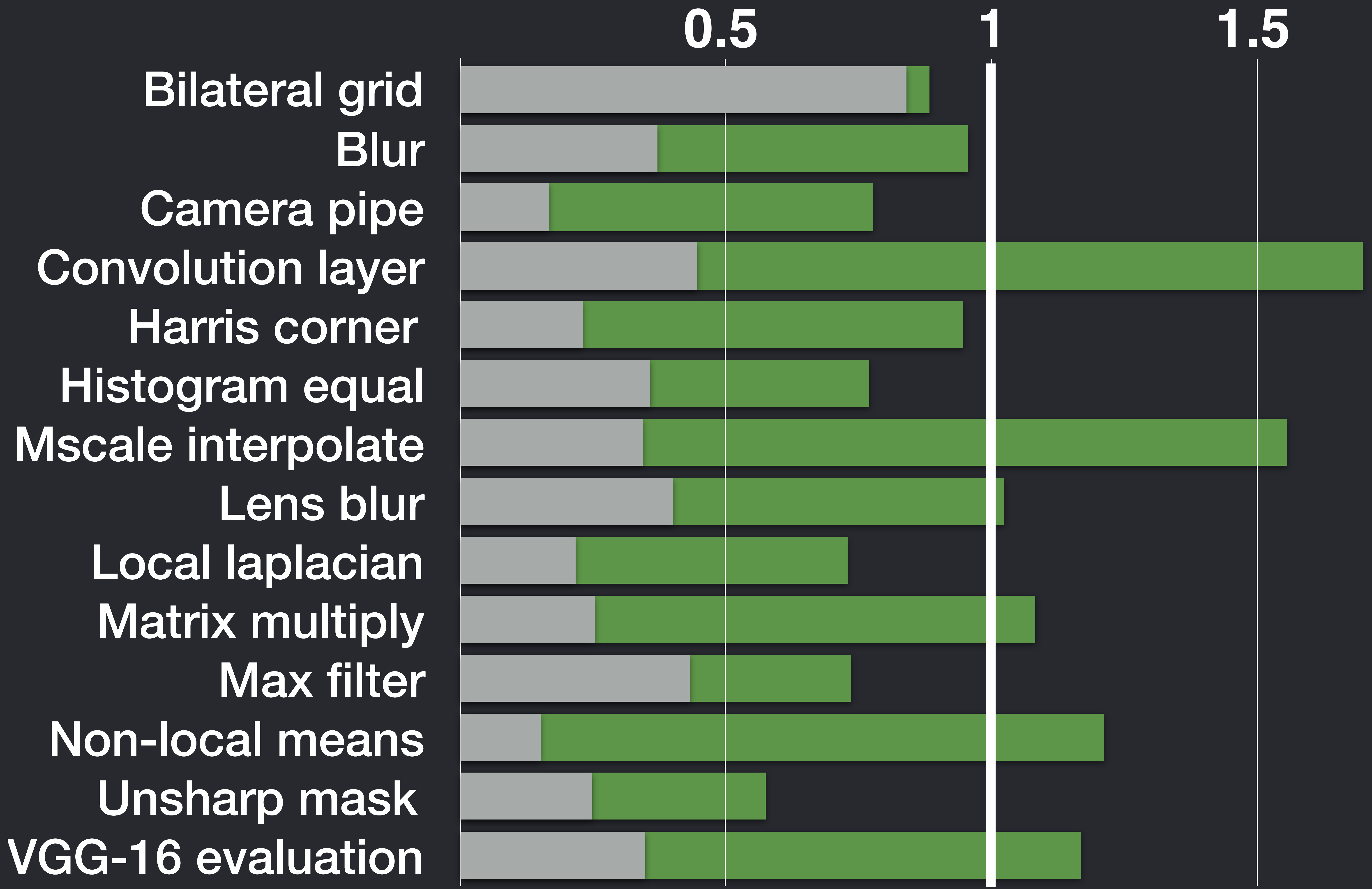
Scheduling Algorithm

> 10x Faster Implementation

Auto scheduler generates schedules in seconds

Benchmark	Stages	Compile time (s)
Blur	3	<1
Unsharp mask	9	<1
Harris corner detection	13	<1
Camera RAW processing	30	<1
Non-local means denoising	13	<1
Max-brightness filter	9	<1
Multi-scale interpolation	52	2.6
Local-laplacian filter	103	3.9
Synthetic depth-of-field	74	55
Bilateral filter	8	<1
Histogram equalization	7	<1
VGG-16 deep network eval	64	6.9

Auto scheduler performs comparably to experts

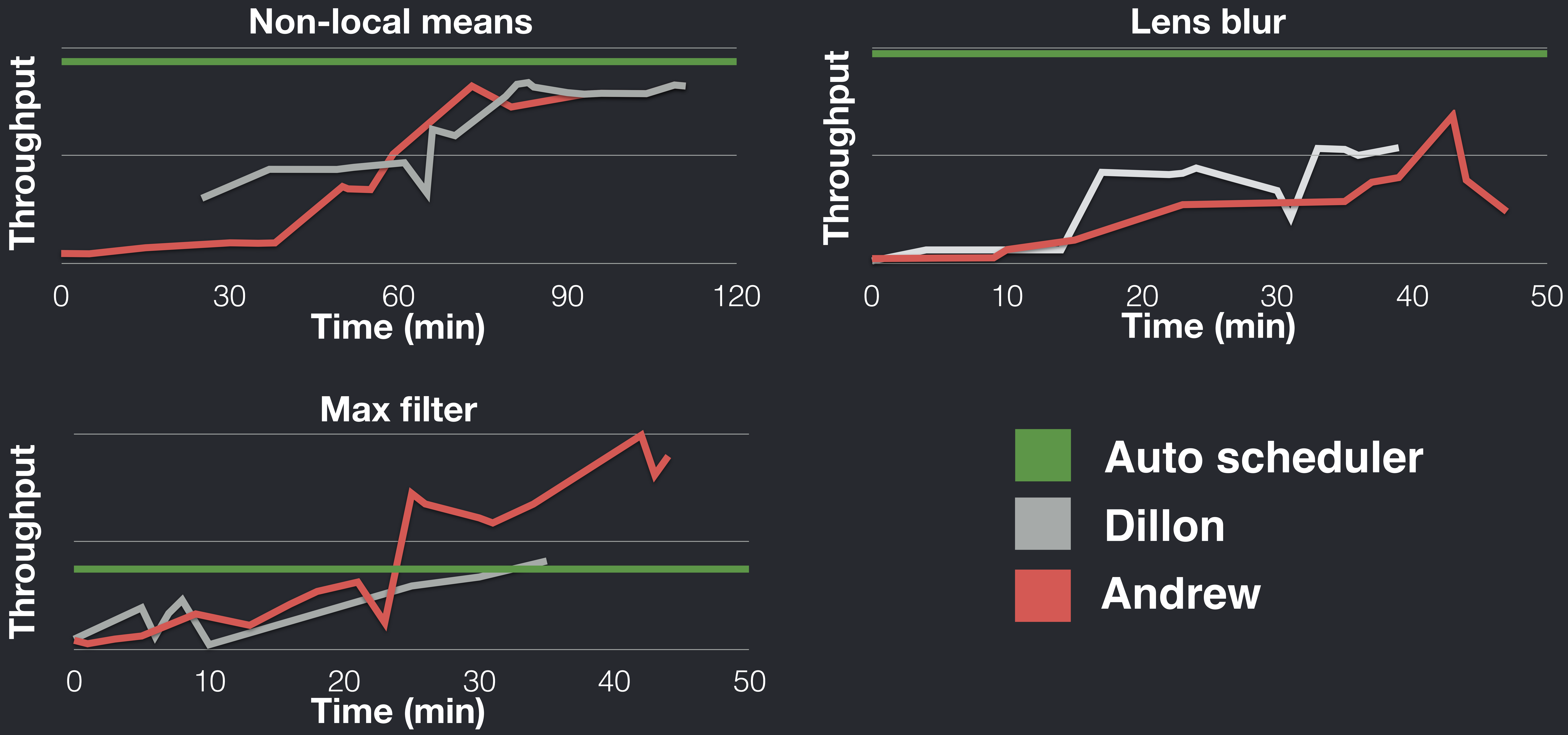


Performance relative to experts (6 core Xeon CPU)

On 8 of the 14 benchmarks performance within 10% of experts or better

Baseline schedules exploit multi-core and vector parallelism but no grouping

Auto scheduler can save time for experts



Halide at Google

Fast image processing is hard because you need to optimize for locality *and* parallelism

Halide helps, by separating the algorithm from the optimizations (the *schedule*)

code becomes more modular, readable, and portable

makes it easier to explore different optimizations

Get the compiler at http://halide-lang.org