An introduction to Halide

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Today's agenda

Now: **the big ideas in Halide**

Later: **writing & optimizing real code**

Hello world (brightness)

Gaussian blur - *3x OpenCV*

Simple enhancement pipeline - *6x OpenCV*

break

MATLAB integration

IIR filter

CNN layers

break

GPU scheduling

Finally: **real-time HOG on a phone**

We are surrounded by computational cameras

Enormous opportunity,
demands extreme optimization

parallelism & locality limit
performance and energy

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(96MB/frame as *float*)

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Required arithmetic intensity > 40:1

Today's methodology

C++ w/multithreading, SIMD
CUDA/OpenCL
OpenGL/RenderScript

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libraries don’t solve this:
BLAS, IPP, MKL, OpenCV
optimized kernels compose into
inefficient pipelines (no fusion)

Local Laplacian Filters

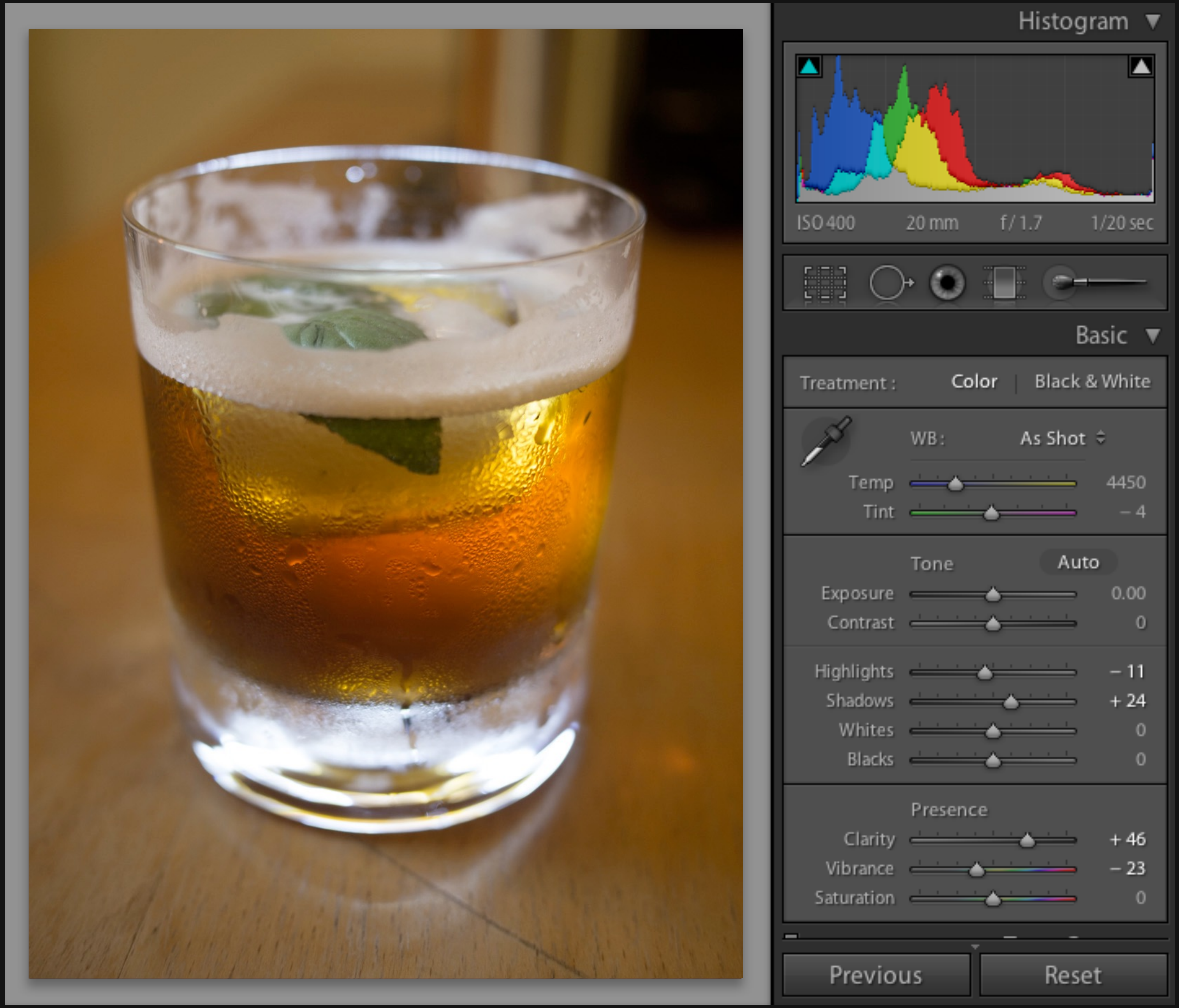
in Adobe Photoshop Camera Raw / Lightroom

1500 lines of expert-optimized C++

multi-threaded, SSE

3 months of work

10x faster *than reference C*



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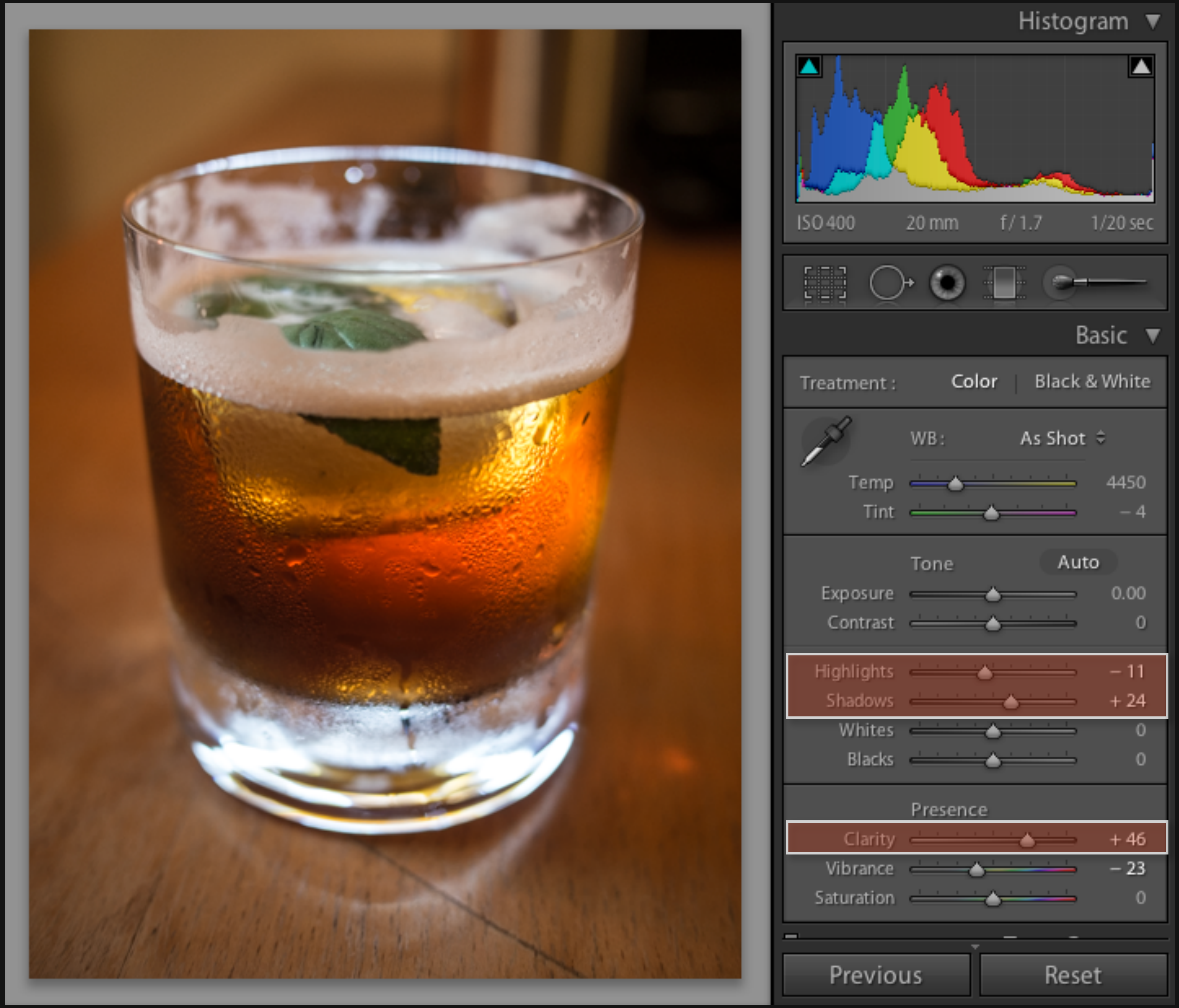

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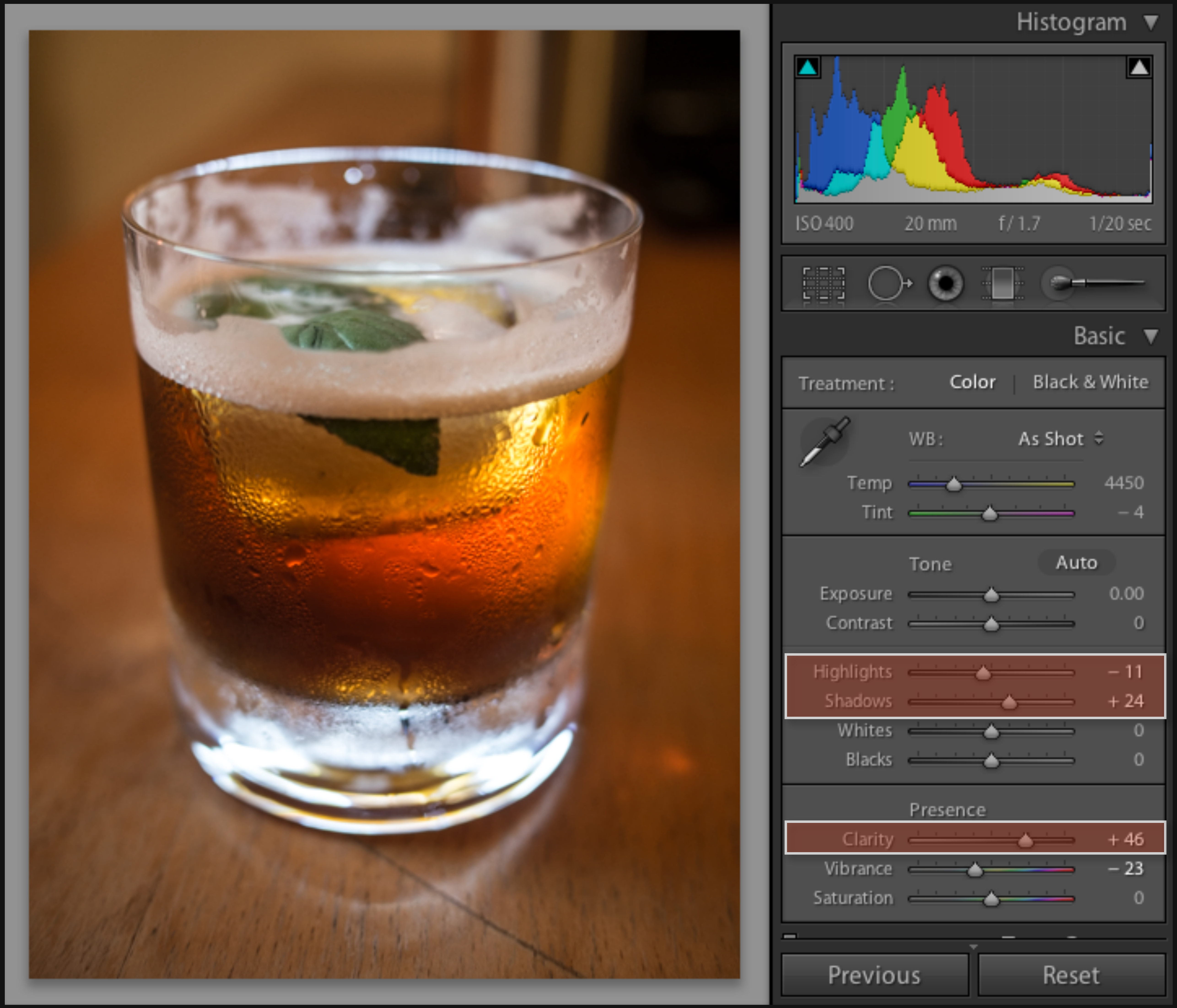

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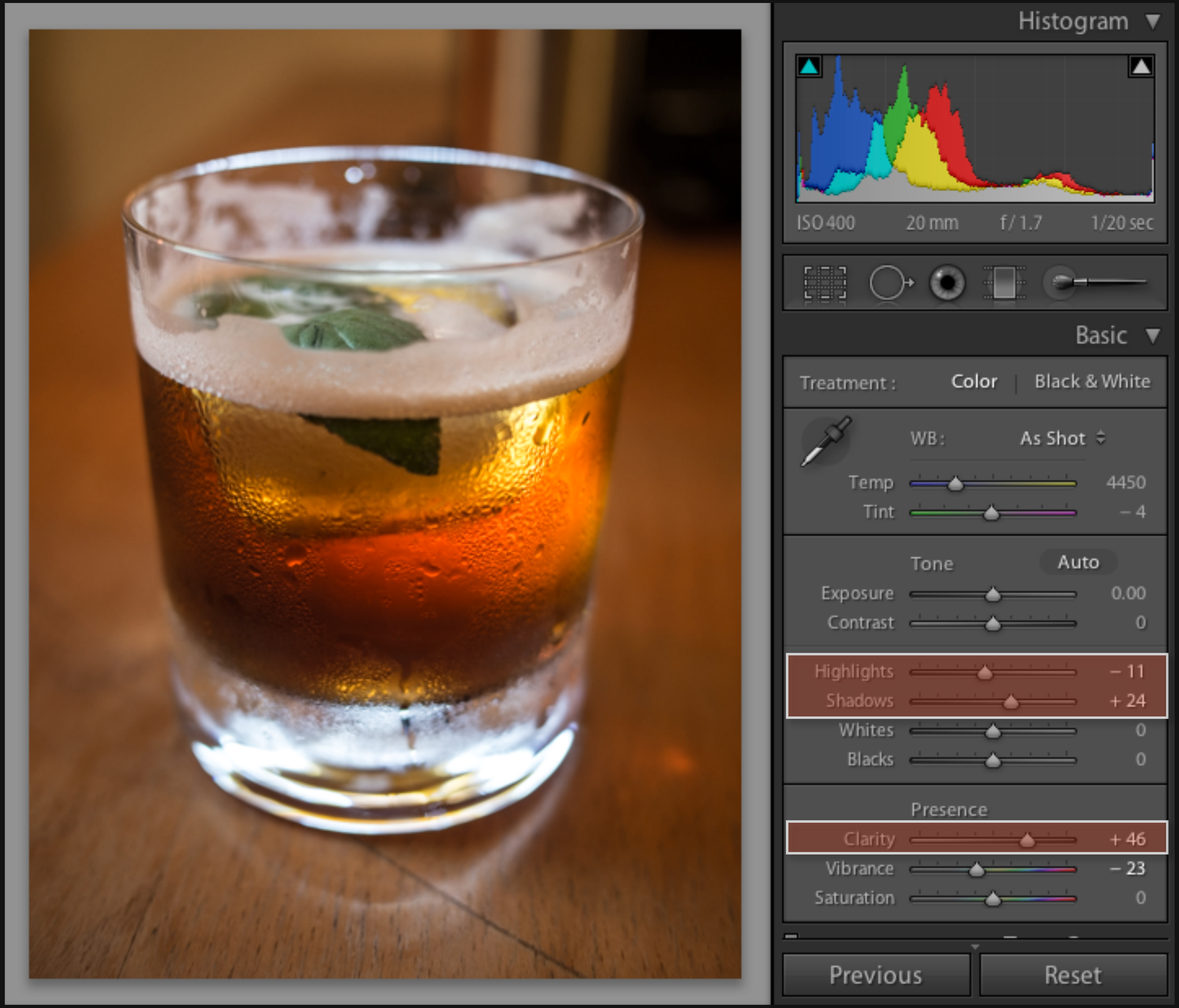
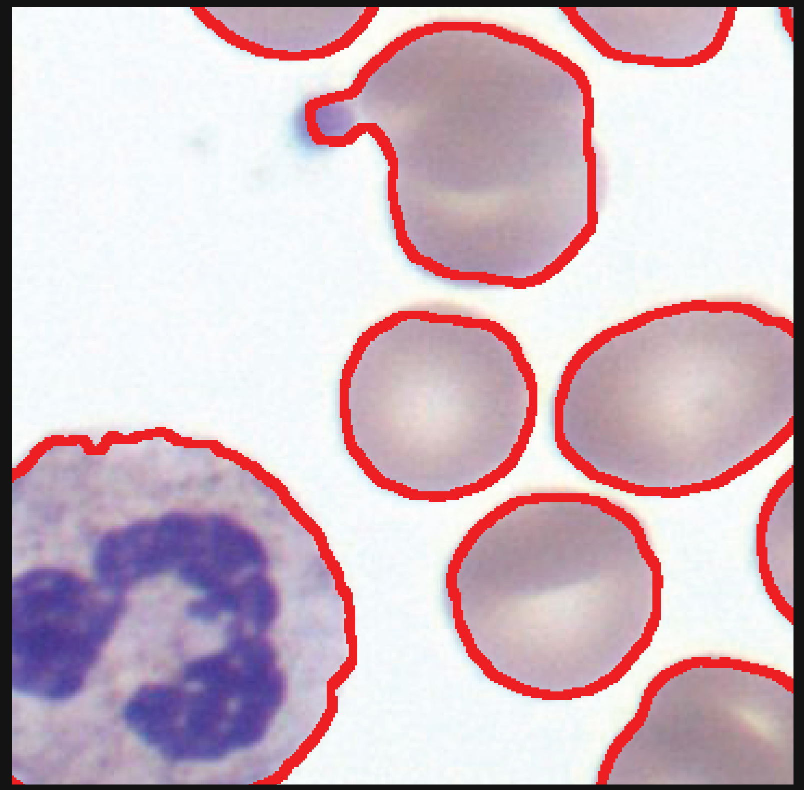
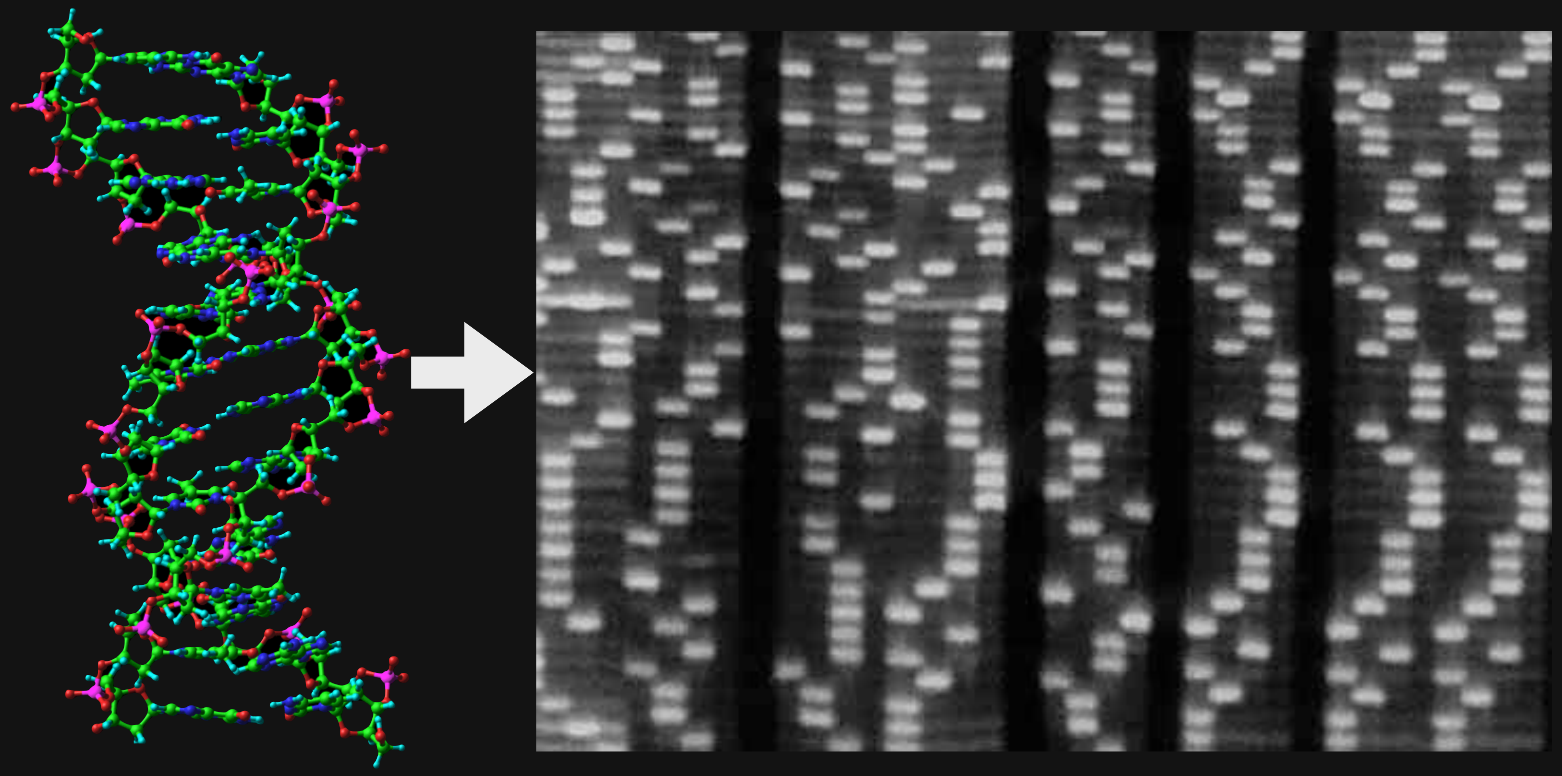
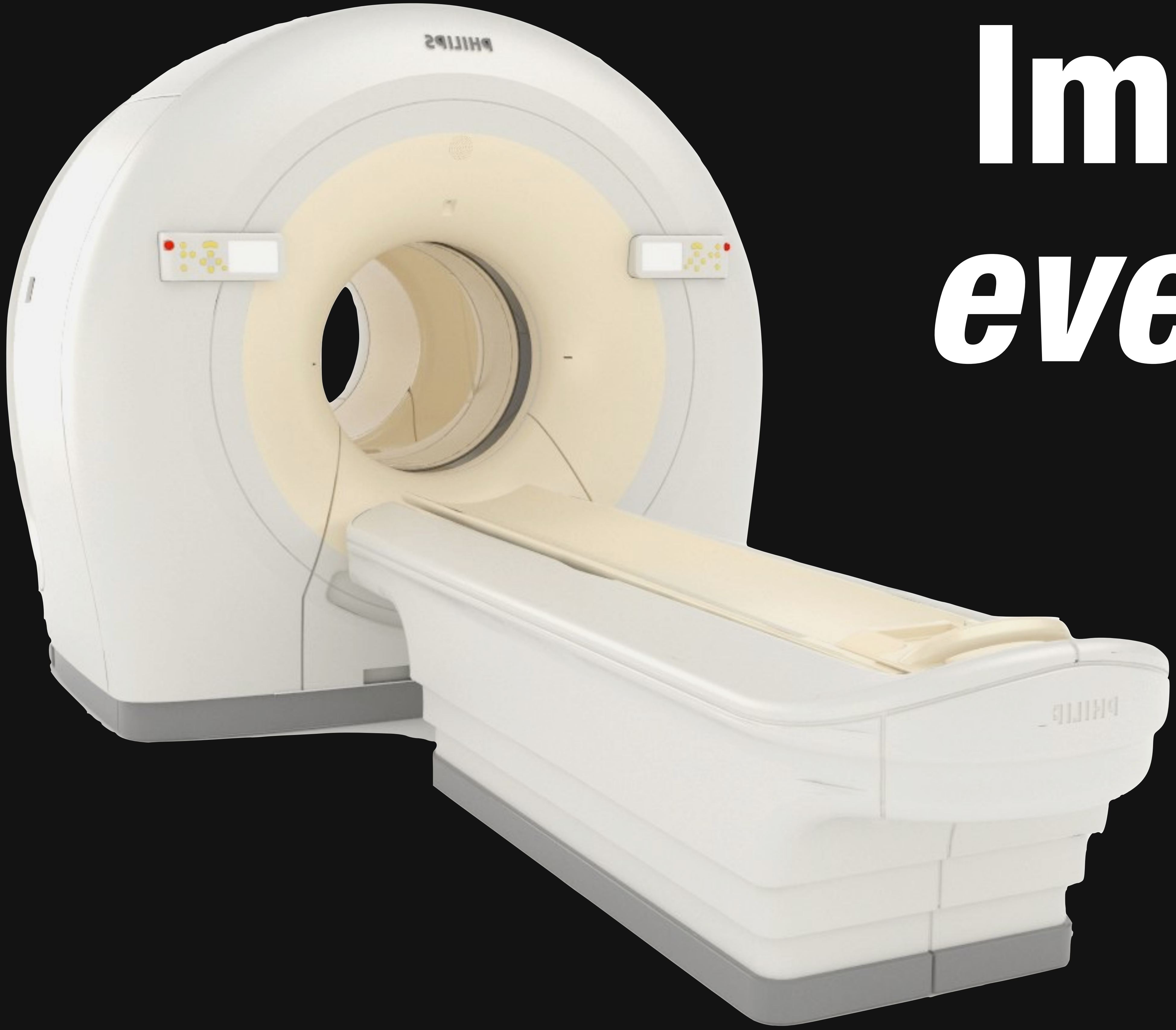
Just writing in C isn't nearly enough!

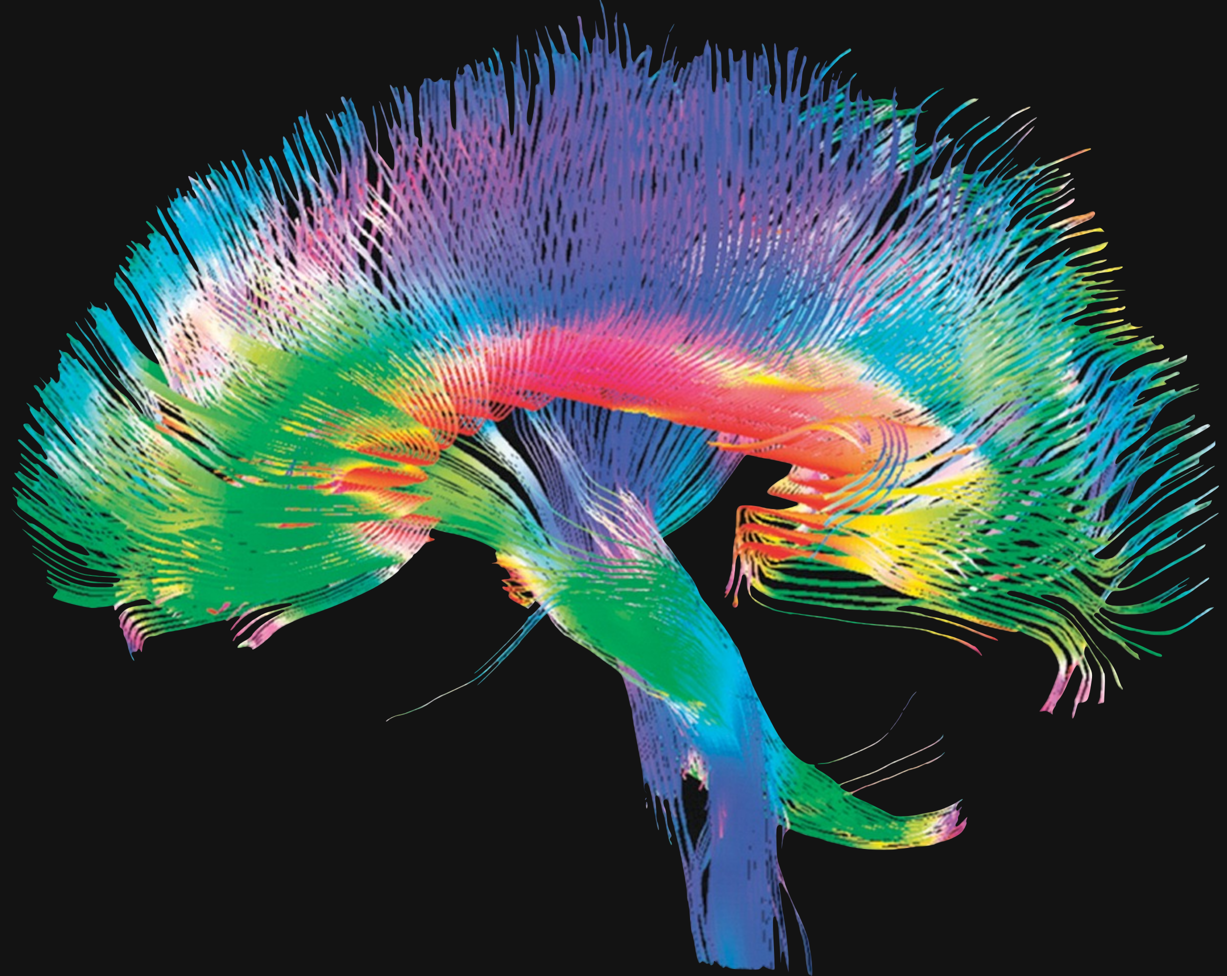


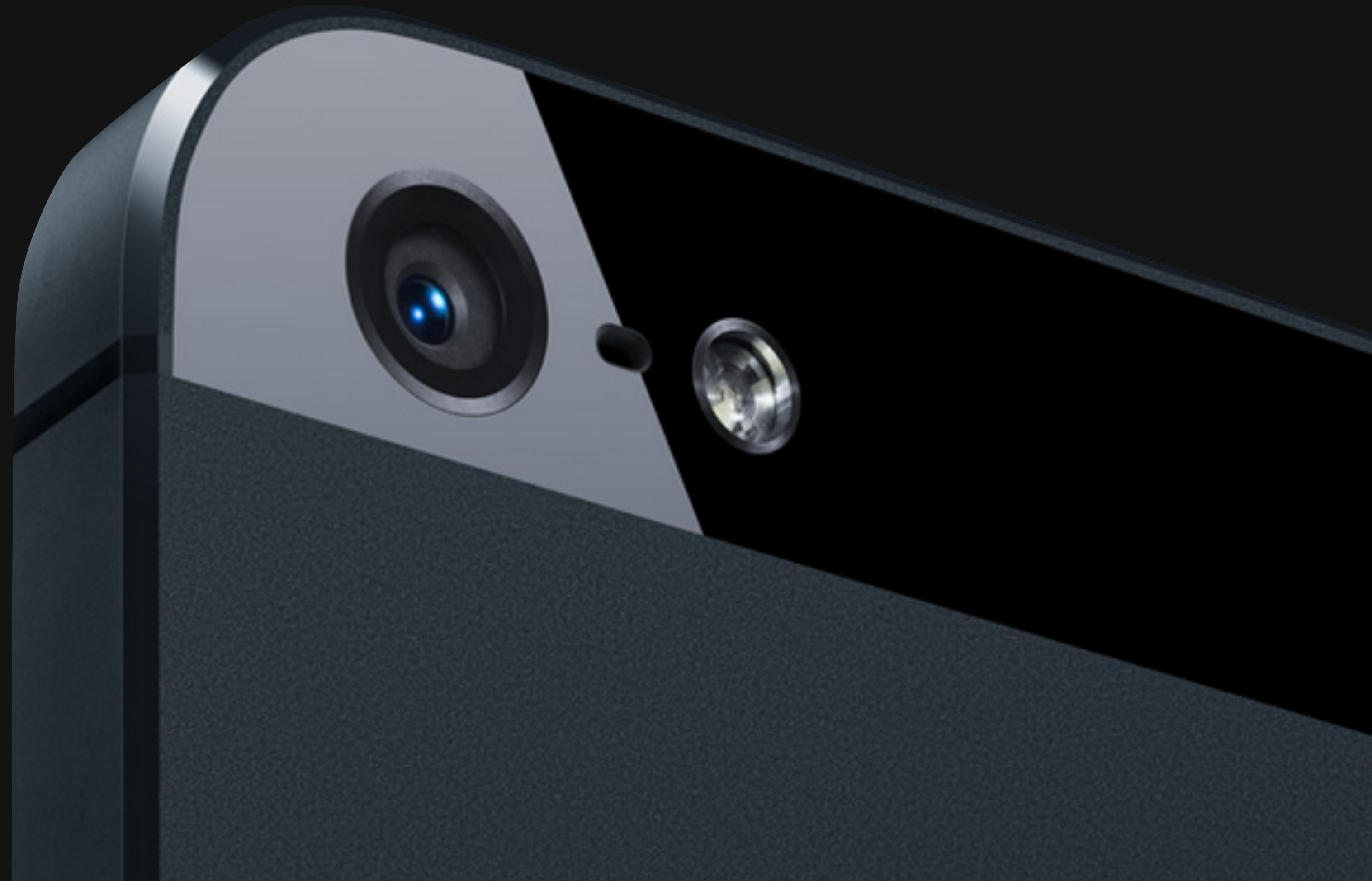




Imaging is *everywhere*







A simple example: 3x3 blur

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

Hand-optimized C++

9.9 → 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);
}}}}}
```

11x faster
(quad core x86)

Tiled, fused

Vectorized

Multithreaded

Redundant computation

Near roof-line optimum

Halide's answer: *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 defines pipelines as pure functions

Pipeline stages are *functions* from coordinates to values

Execution order and storage are unspecified

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Pipeline stages are *functions* from coordinates to values

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3x3 blur as a Halide *algorithm*:

```
Var x, y; Func blurx, blury;
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;
```

Domain scope
of the programming model

All computation is over **regular grids**.

Only **feed-forward pipelines**

Recursive/reduction computations are a (partial) escape hatch.

Recursion must have **bounded depth.**

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not Turing complete

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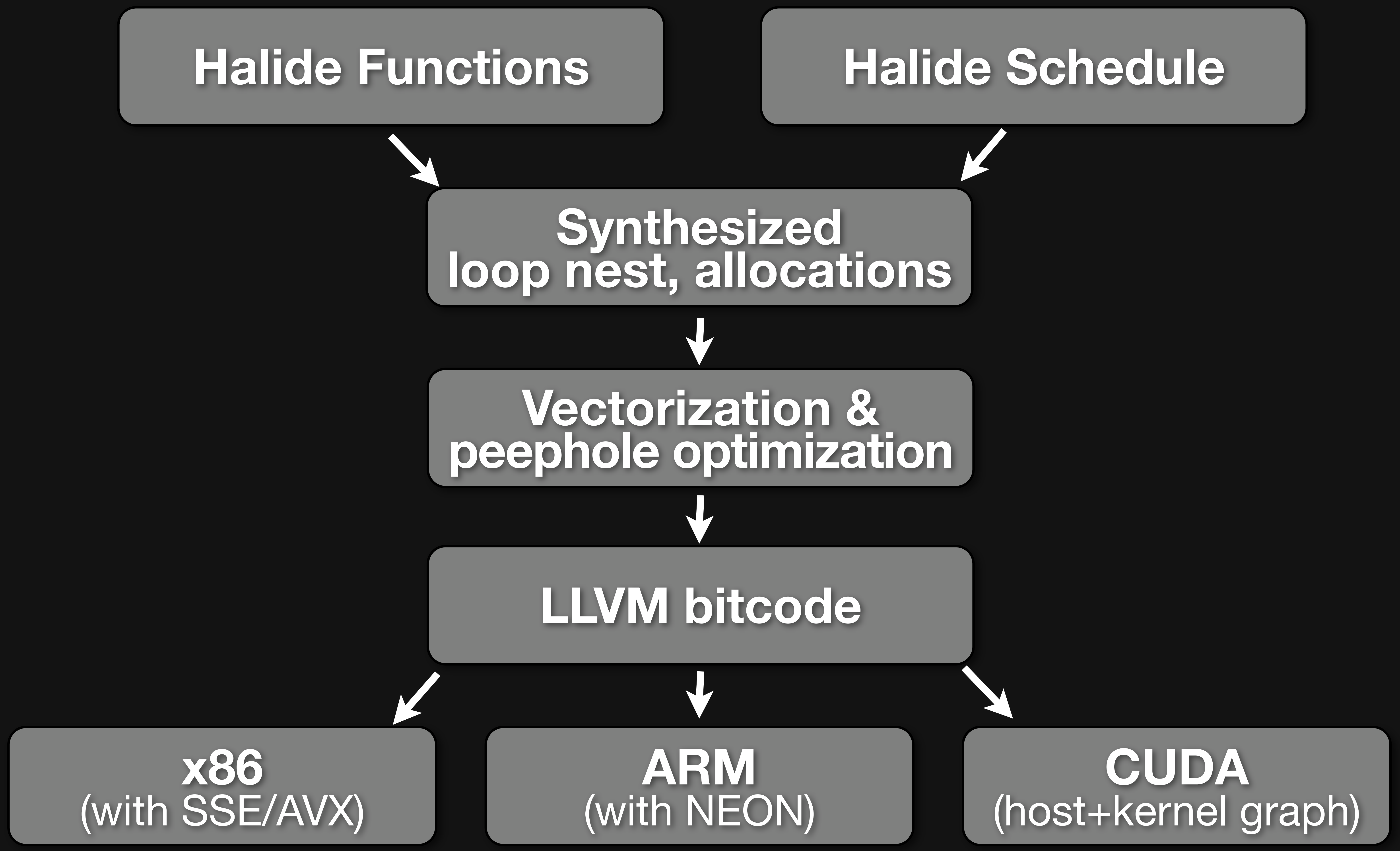
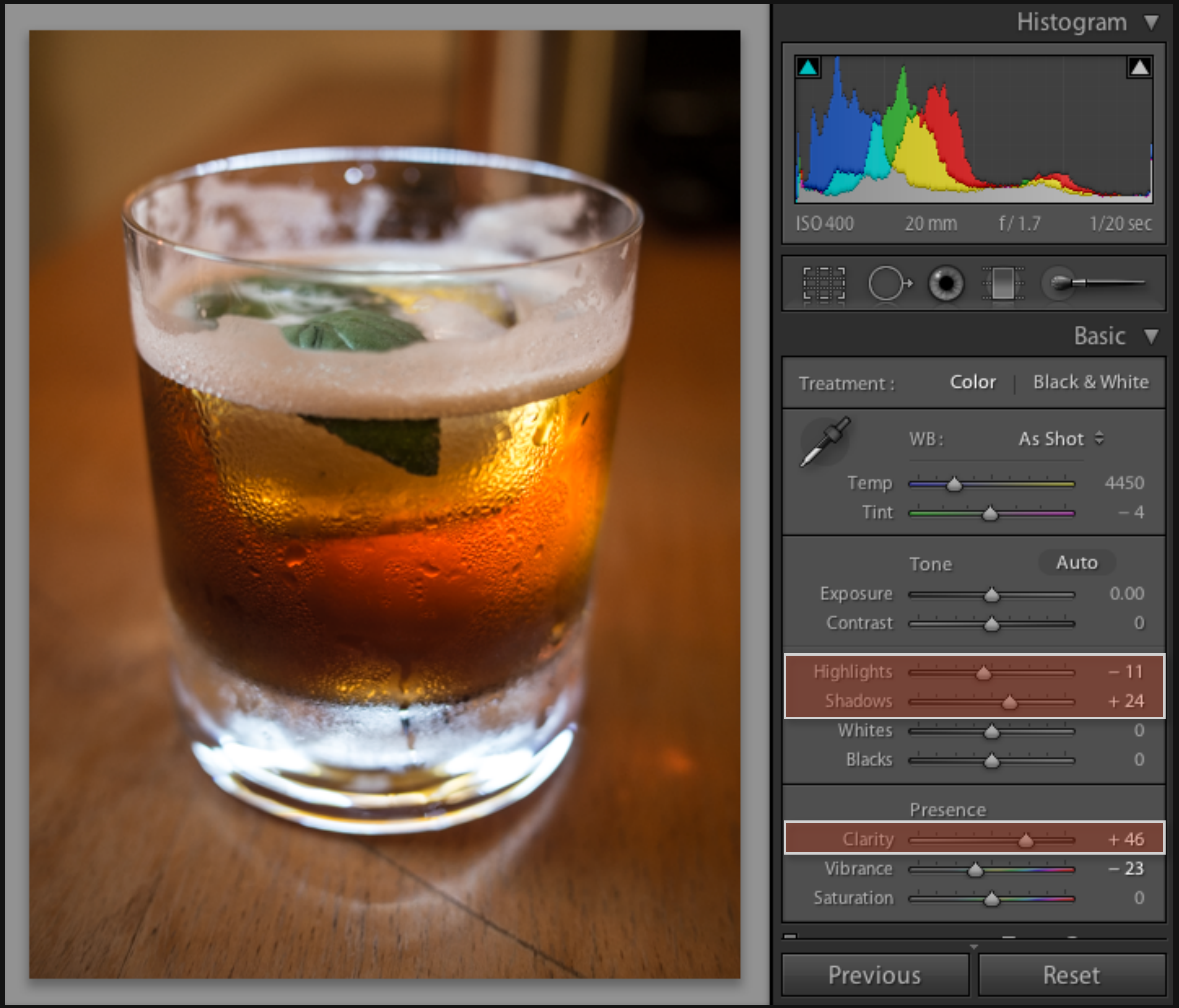


The Halide Compiler

Local Laplacian Filters

prototype for Adobe Photoshop Camera Raw / Lightroom



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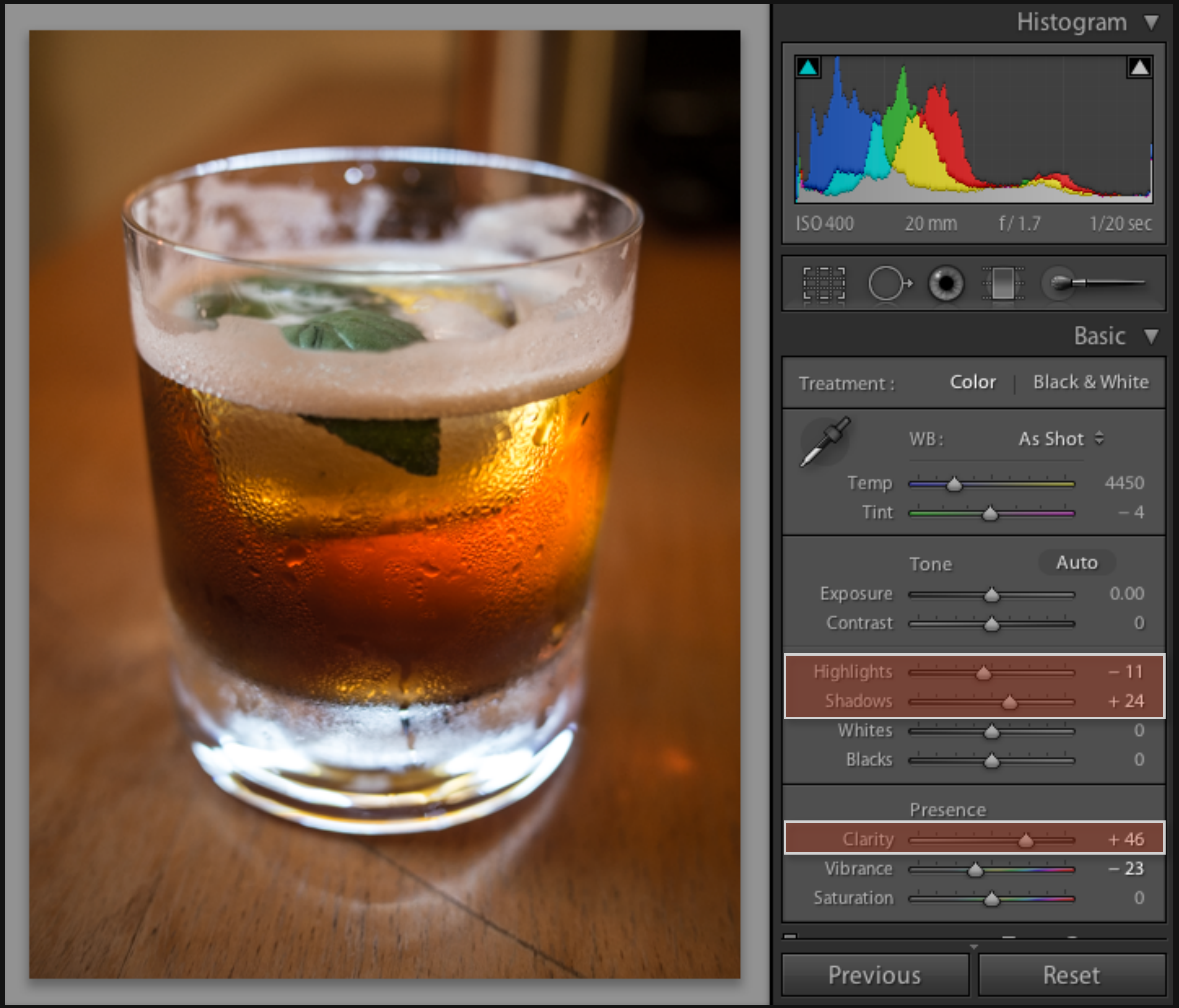
Reference: 300 lines C++

Adobe: 1500 lines

3 months of work

10x faster *(vs. reference)*



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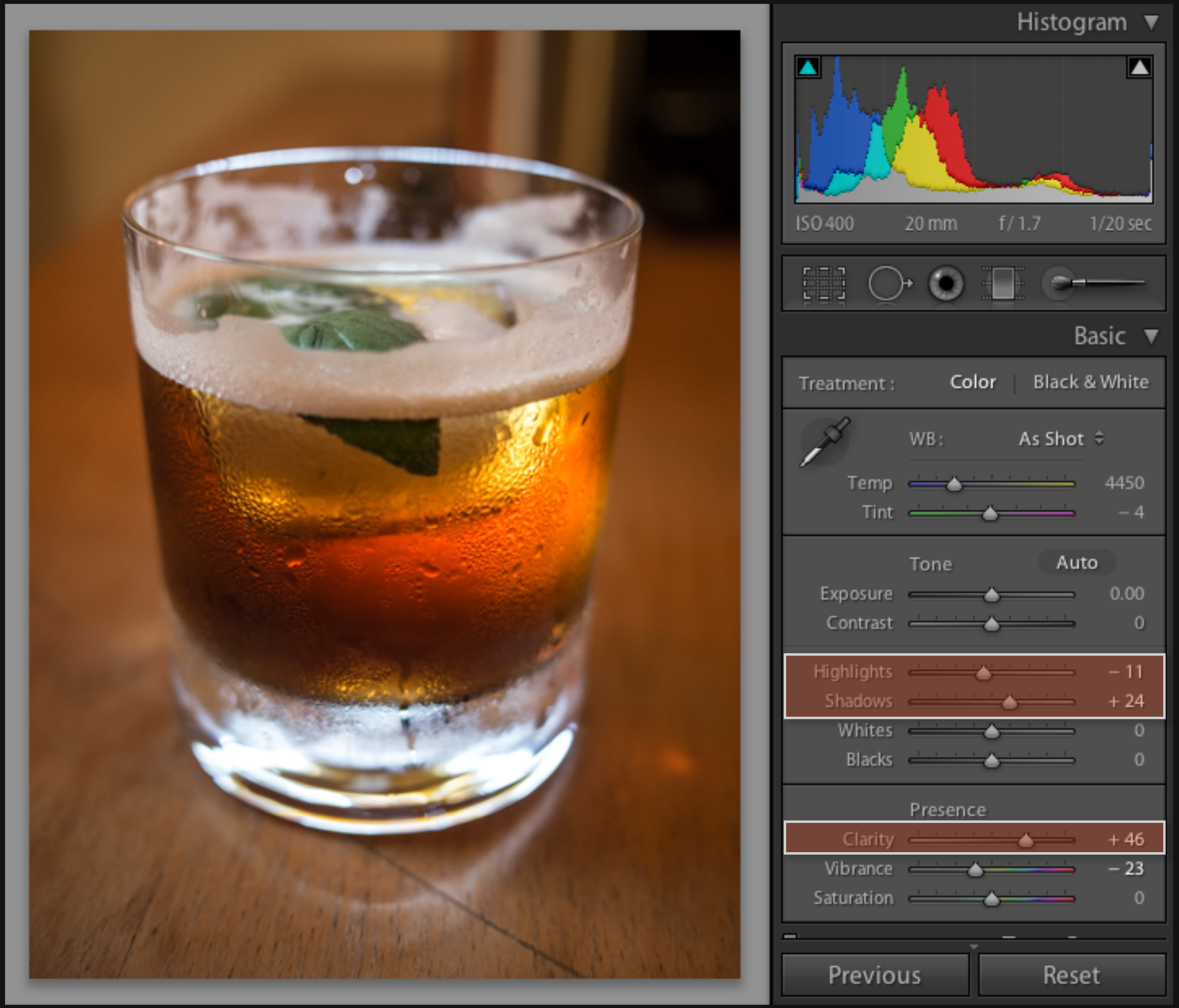
1 intern-day

20x faster (vs. reference)

2x faster (vs. Adobe)



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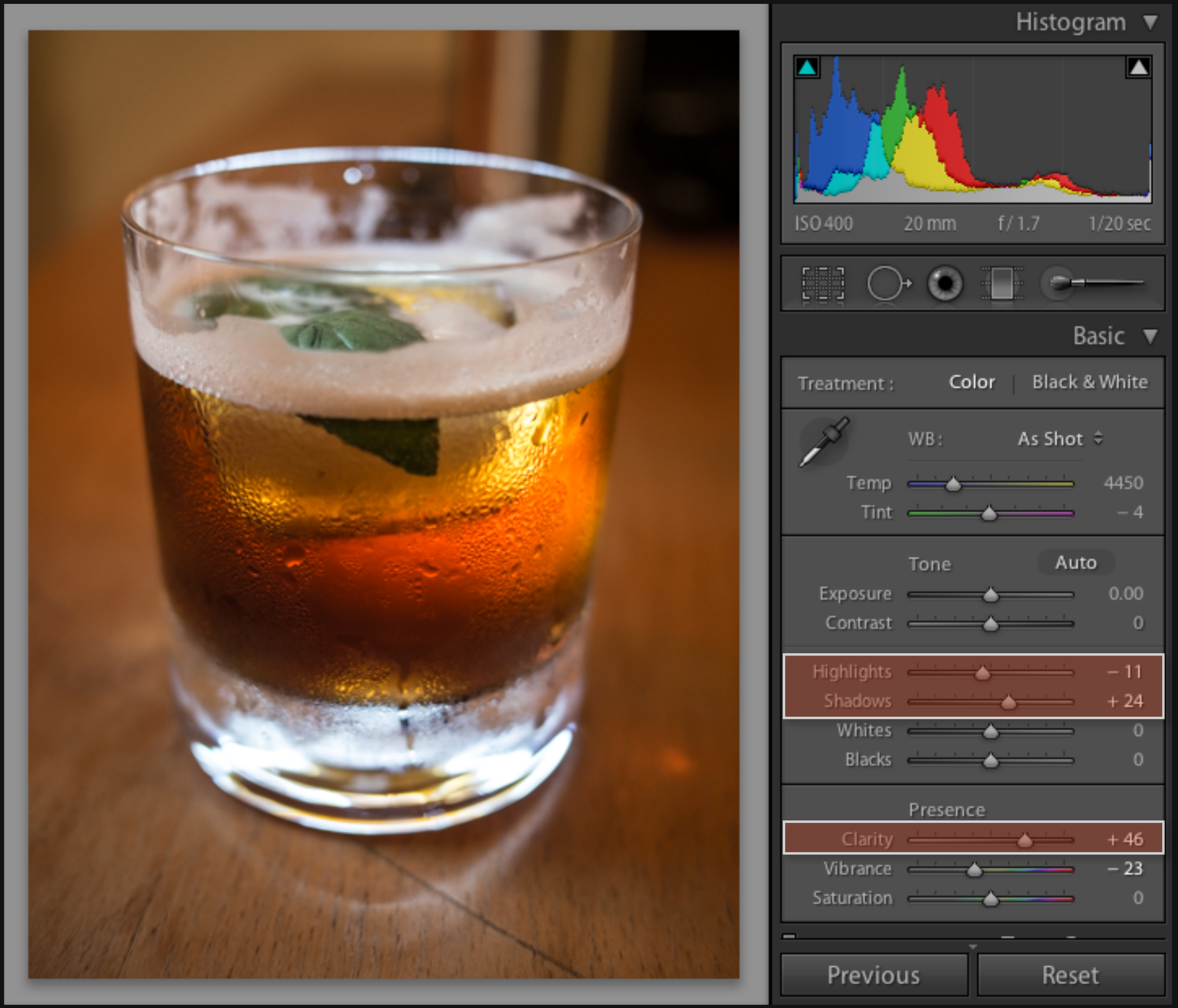
GPU: 90x faster (vs. reference)

9x faster (vs. Adobe)



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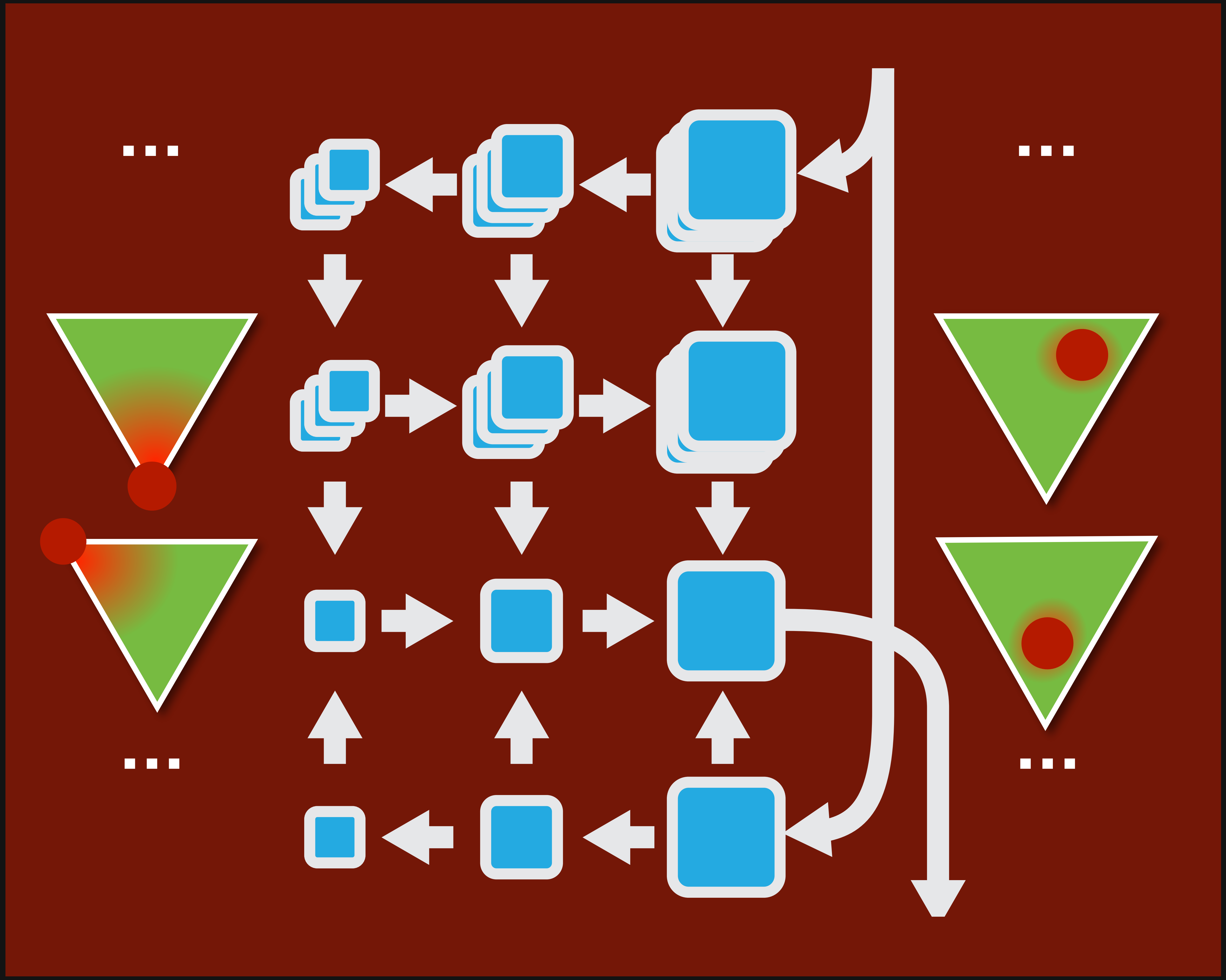

x86	Speedup	Factor shorter
Blur	1.2 ×	18 ×
Bilateral Grid	4.4 ×	4 ×
Camera pipeline	3.4 ×	2 ×
“Healing brush”	1.7 ×	7 ×
Local Laplacian	1.7 ×	5 ×

GPU	Speedup	Factor shorter
Bilateral Grid	2.3 ×	11 ×
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Gaussian Blur	1.5 ×	5 ×
FFT (vs. FFTW)	1.5 ×	*10s*
BLAS (vs. Eigen)	1 ×	*100s*

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Current status

open source at http://halide-lang.org

Google

65 active developers

> **200** pipelines

10s of kLOC in production

G Photos *auto-enhance*
Data center
Android
Chrome (PNaCl)

HDR+
Glass
Nexus devices

>20 companies
on Halide-Dev

***n* secret/unannounced projects**

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Gaussian blur - *3x OpenCV*

Simple enhancement pipeline - *6x OpenCV*

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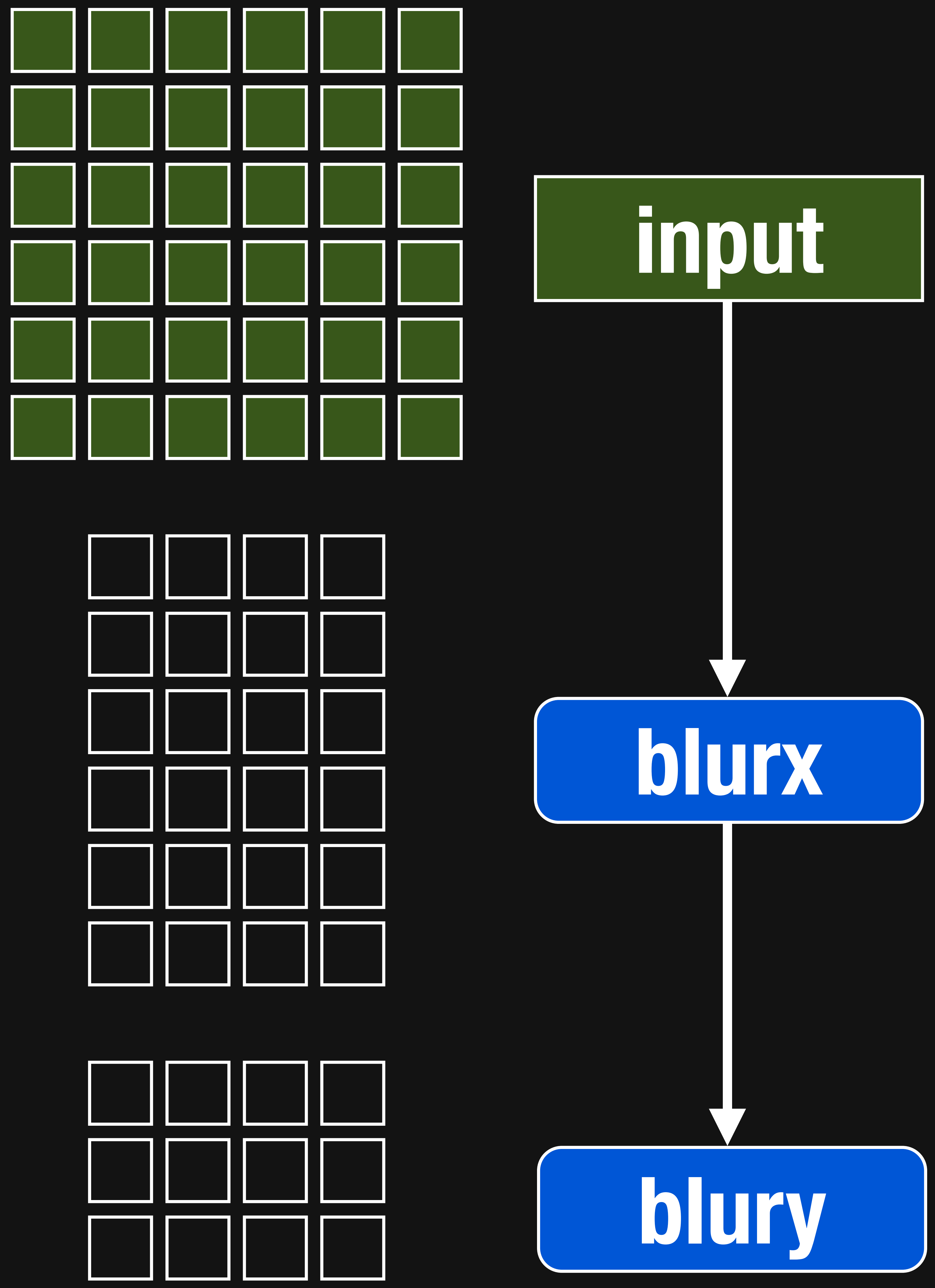
Finally: **real-time HOG on a phone**

The schedule defines intra-stage order, inter-stage interleaving



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For each stage:

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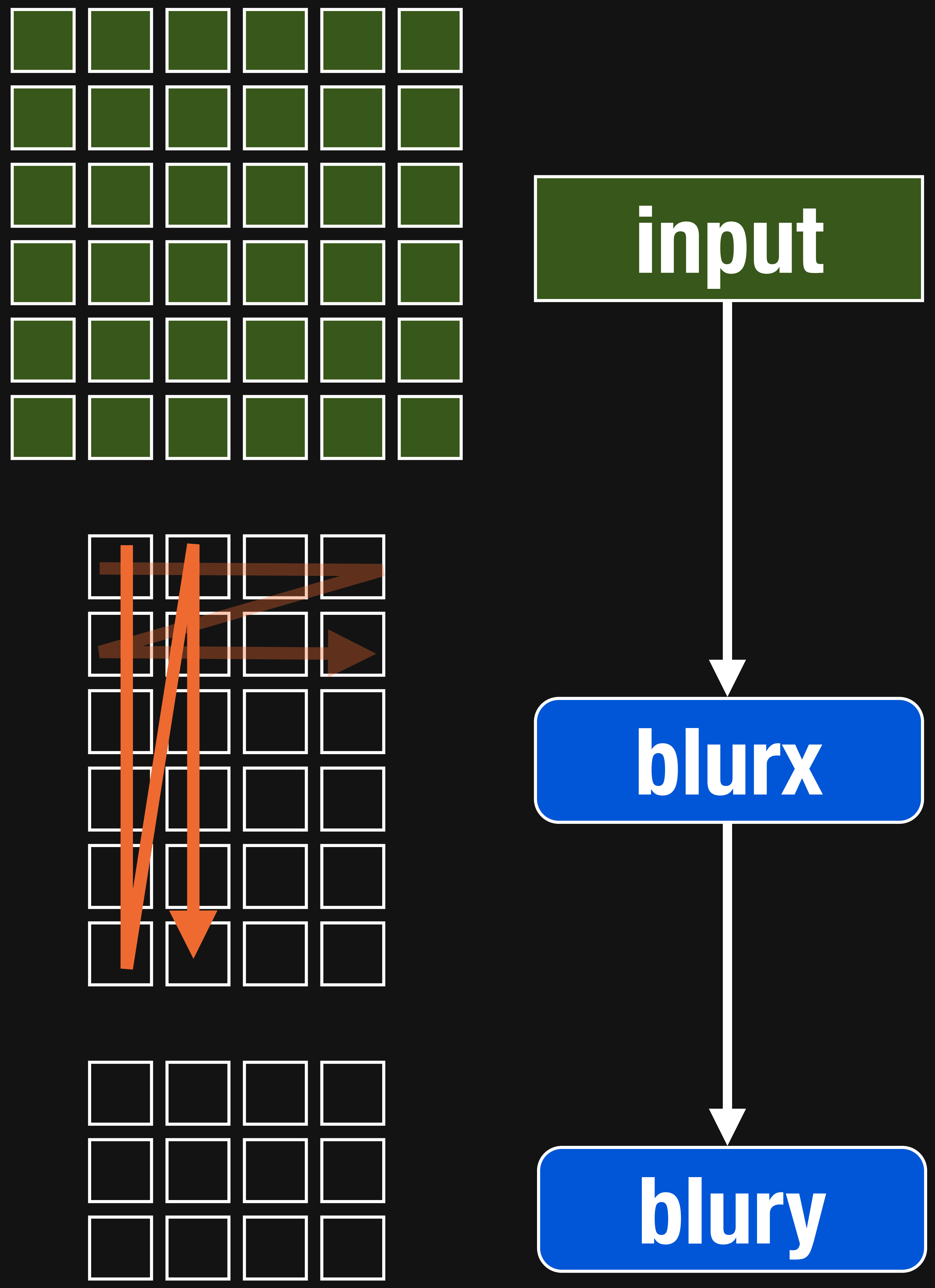

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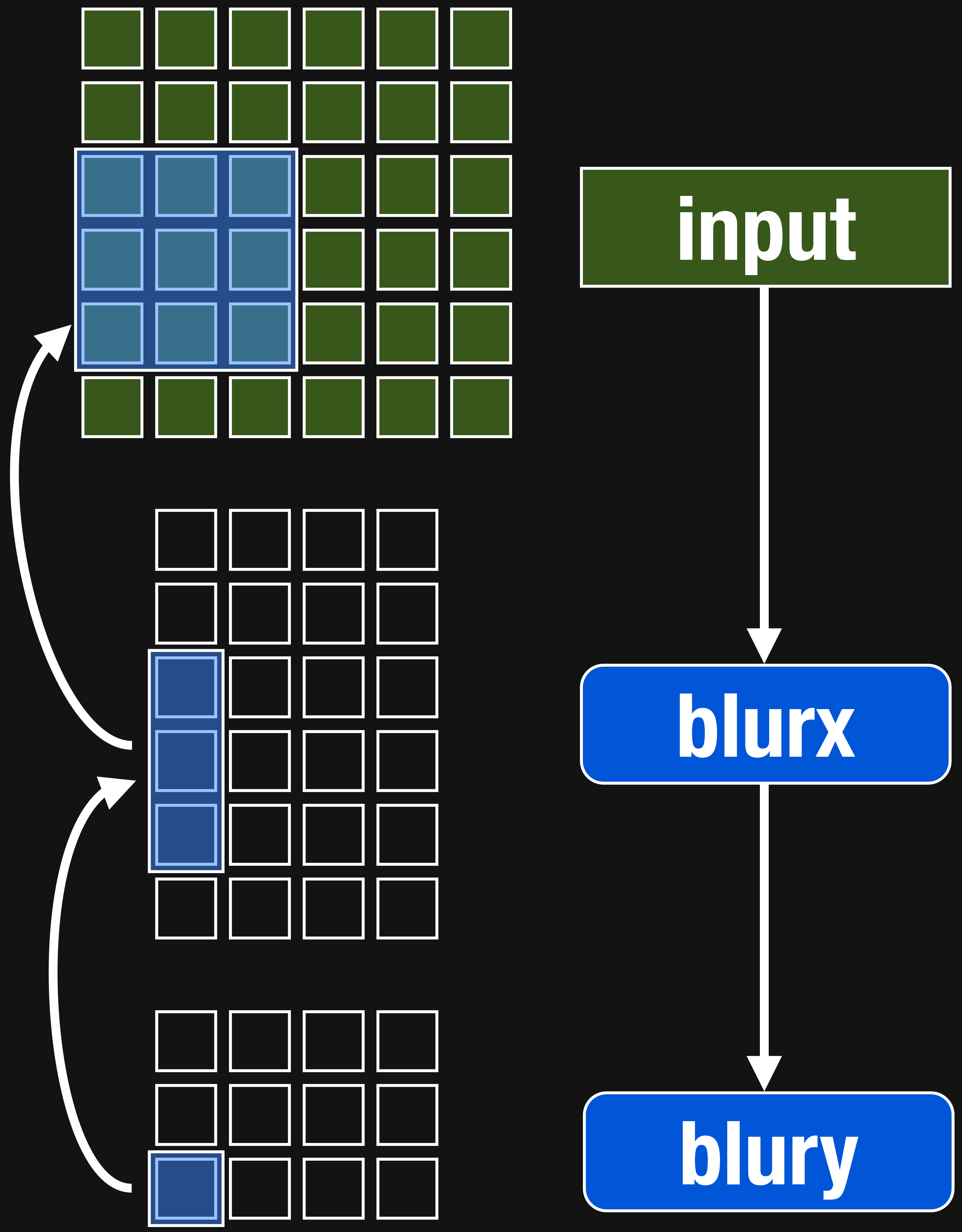

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Serial y,
Serial x

1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

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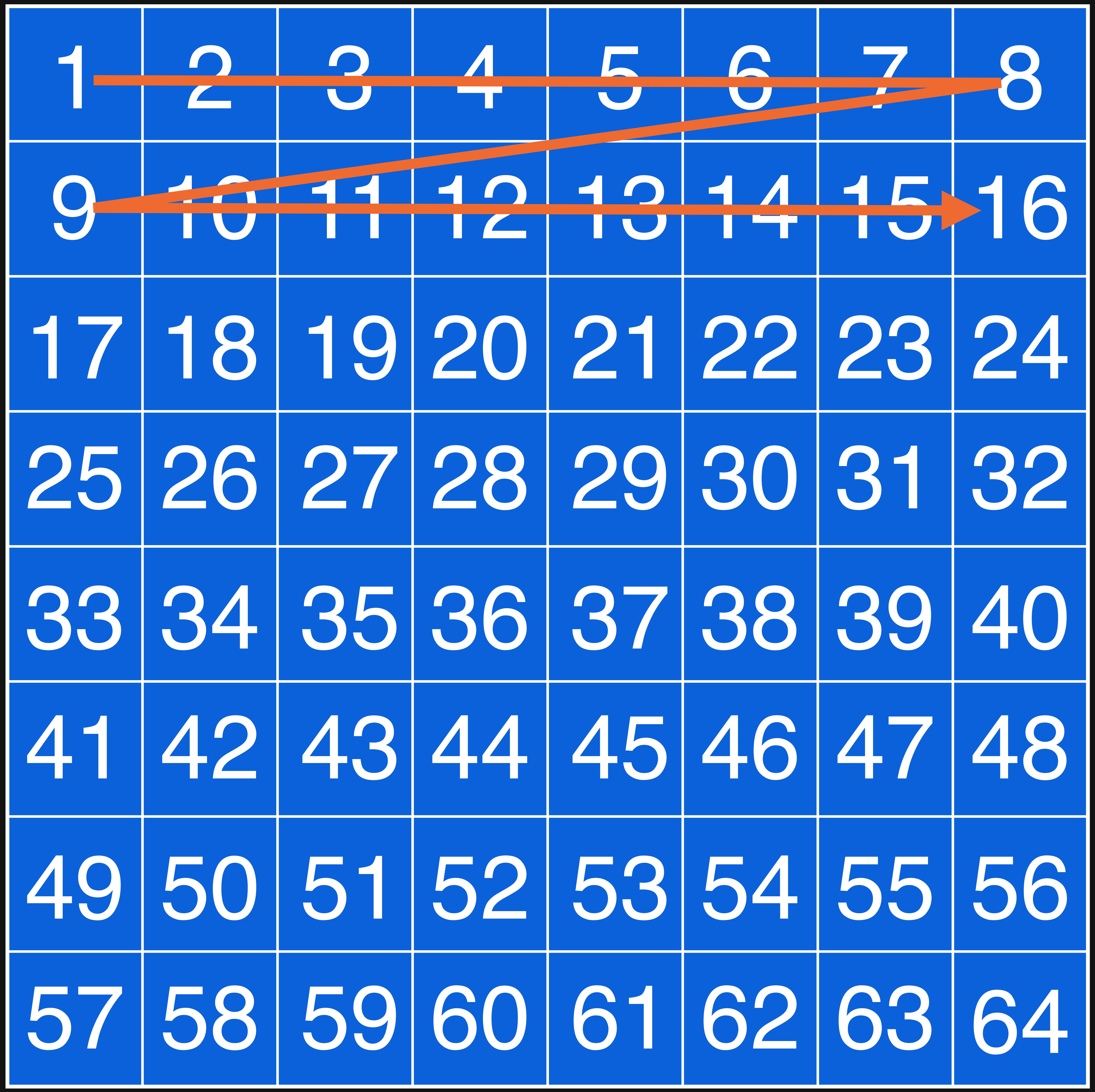

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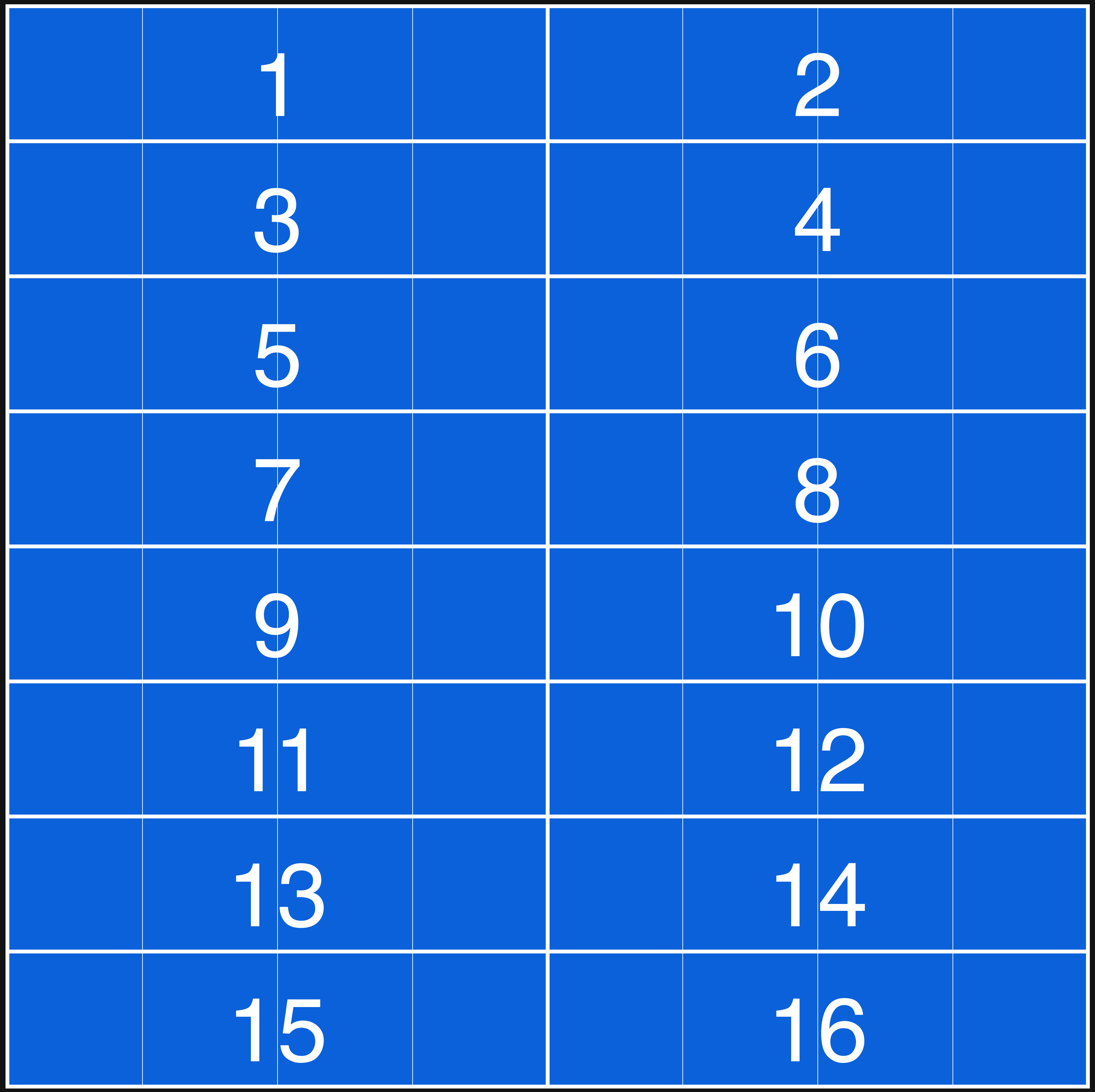
Serial y,
Vectorize x by 4



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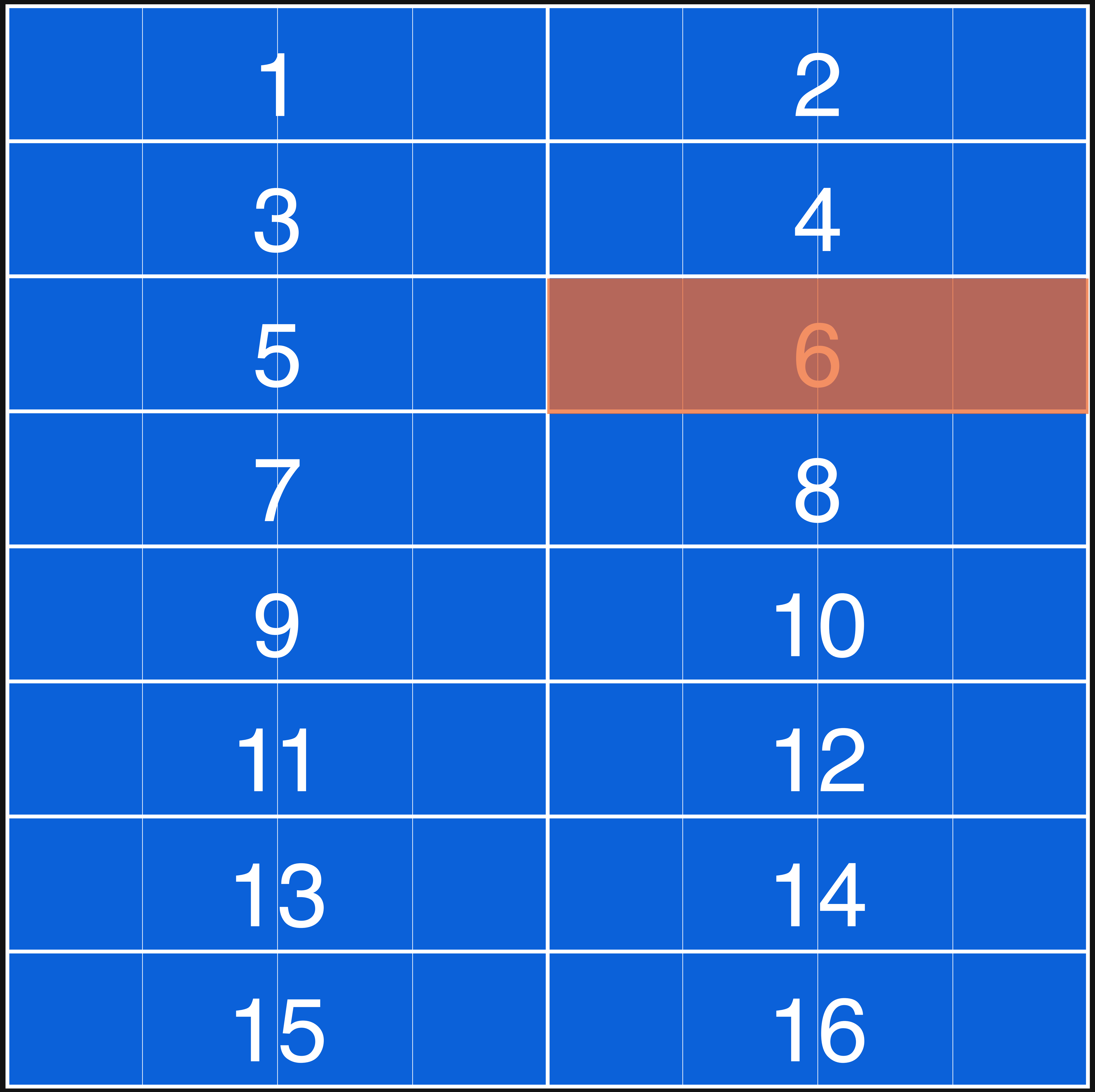

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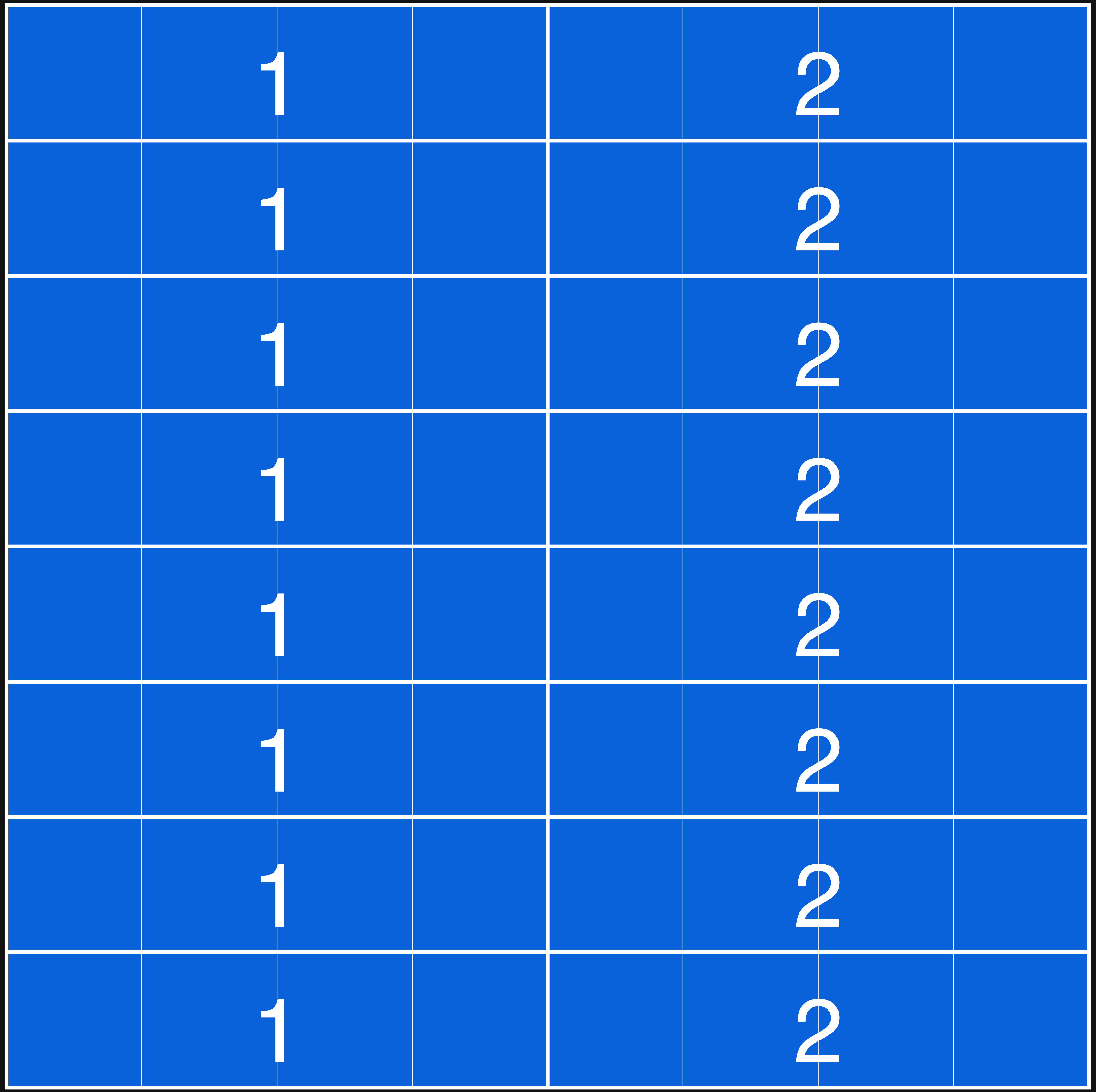
Parallel y,
Vectorize x by 4



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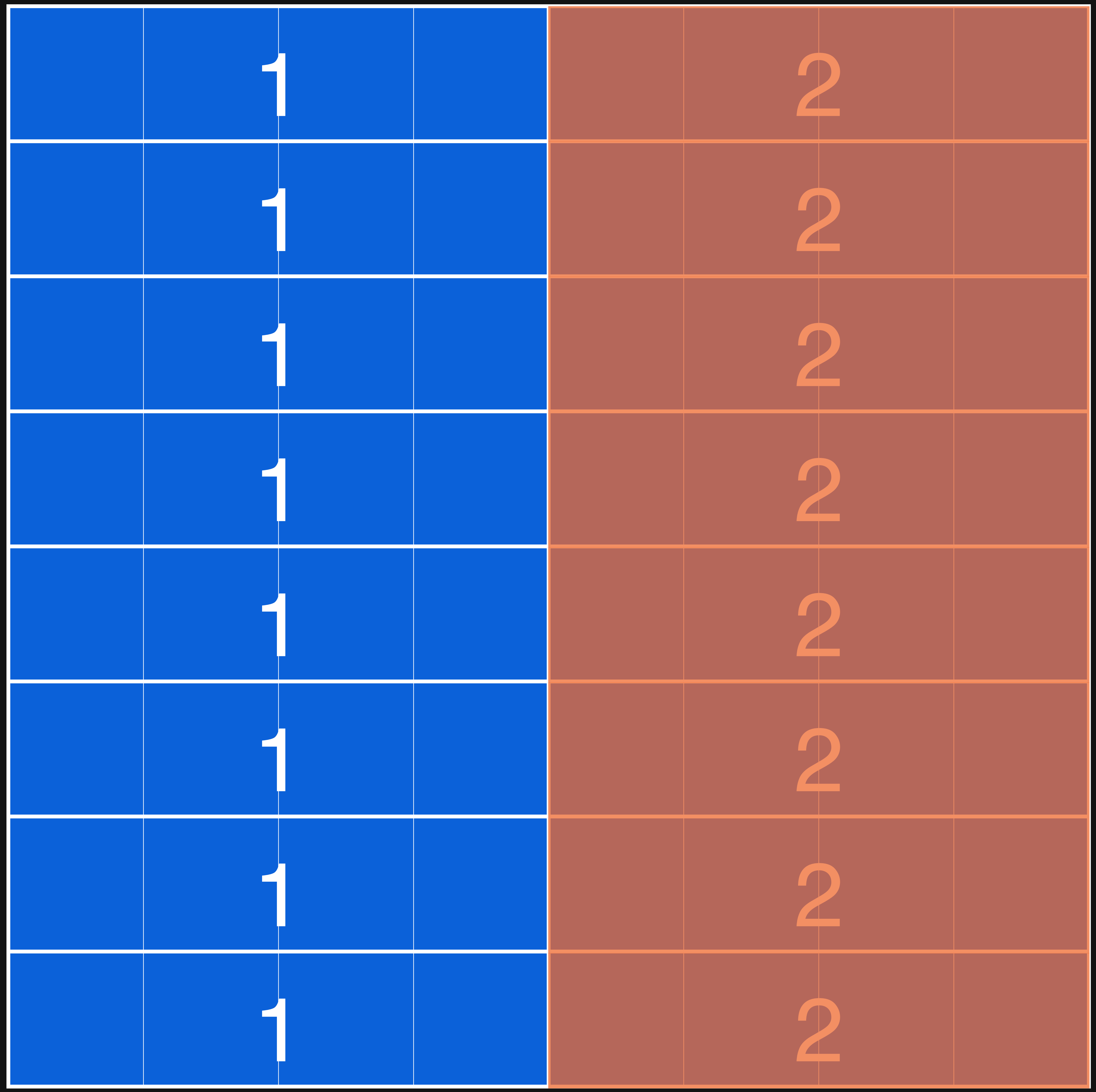


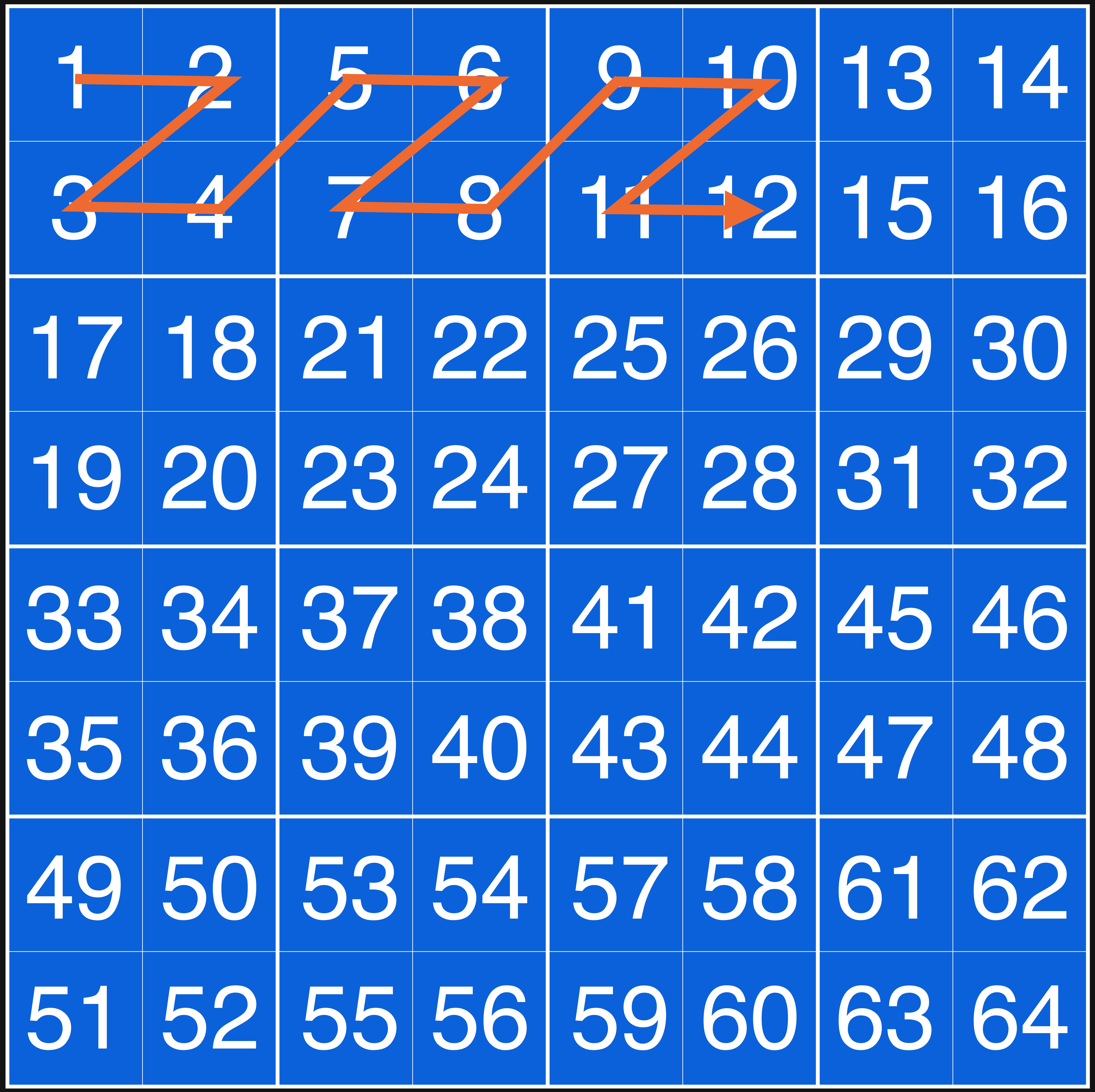
The schedule defines order & parallelism within stages

Split x by 2**,**
Split y by 2**.**

1	2	5	6	9	10	13	14
3	4	7	8	11	12	15	16
17	18	21	22	25	26	29	30
19	20	23	24	27	28	31	32
33	34	37	38	41	42	45	46
35	36	39	40	43	44	47	48
49	50	53	54	57	58	61	62
51	52	55	56	59	60	63	64

The schedule defines order & parallelism within stages

Split x by 2,
Split y by 2.
Serial y$_{\text{outer}}$,
Serial x$_{\text{outer}}$,
Serial y$_{\text{inner}}$,
Serial x$_{\text{inner}}$



Domain order defines a **loop nest** for each function

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```
brighten(x, y, c) = …
```

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```
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```

Default:

Serial c,
Serial y,
Serial x

```
for c:
  for y:
    for x:
      brighten(...) = ...
```

Parallel marks a loop to be multithreaded

```
brighten(x, y, c) = …

brighten.parallel(y)
```

```
for c:
  parallel y:
    for x:
      brighten(...) = ...
```

Parallel marks a loop to be multithreaded

```
brighten(x, y, c) = …

brighten.parallel(y)
        .vectorize(x, 8)
```

```
for c:
  parallel y:
    for x:
      vectorized x.v in [0,7]:
        brighten(...) = ...
```

Parallel marks a loop to be multithreaded

```
brighten(x, y, c) = …
```

```
brighten.parallel(y)
        .unroll(x, 4)
```

```
for c:
  parallel y:
    for x:
      unrolled x.v in [0,3]:
        brighten(...) = ...
```

Parallel marks a loop to be multithreaded

brighten(x, y, c) = …

for c:
  for y_o:
    for y_i in [0,63]:
      for x:
        brighten(...) = ...

brighten.split(y, y_o, y_i, 64)

Parallel marks a loop to be multithreaded

brighten(x, y, c) = …

brighten.split(y, y_o, y_i, 64)
        .reorder(c, y_o)

for y_o:
  for c:
    for y_i in [0,63]:
      for x:
        brighten(...) = ...

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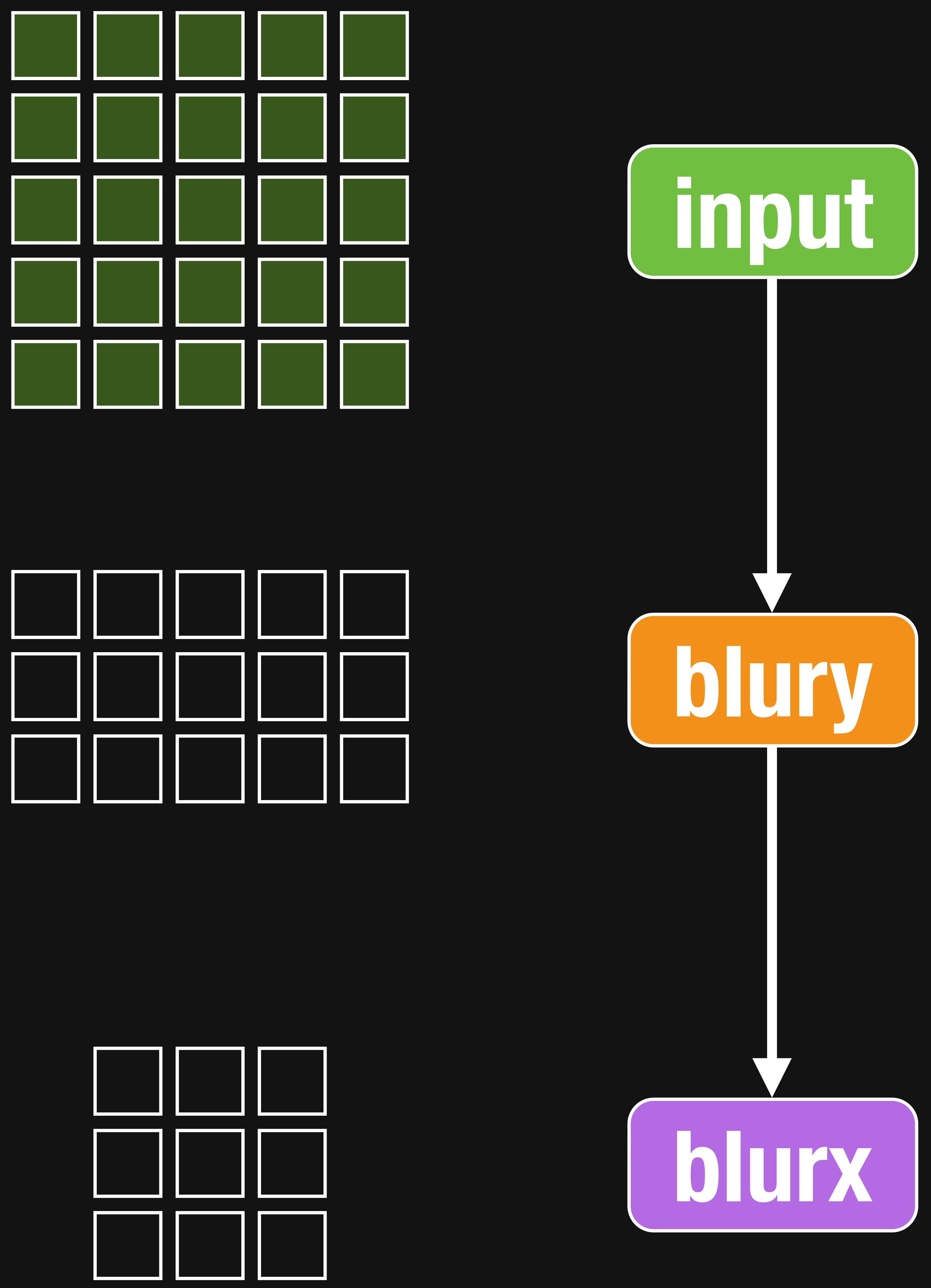

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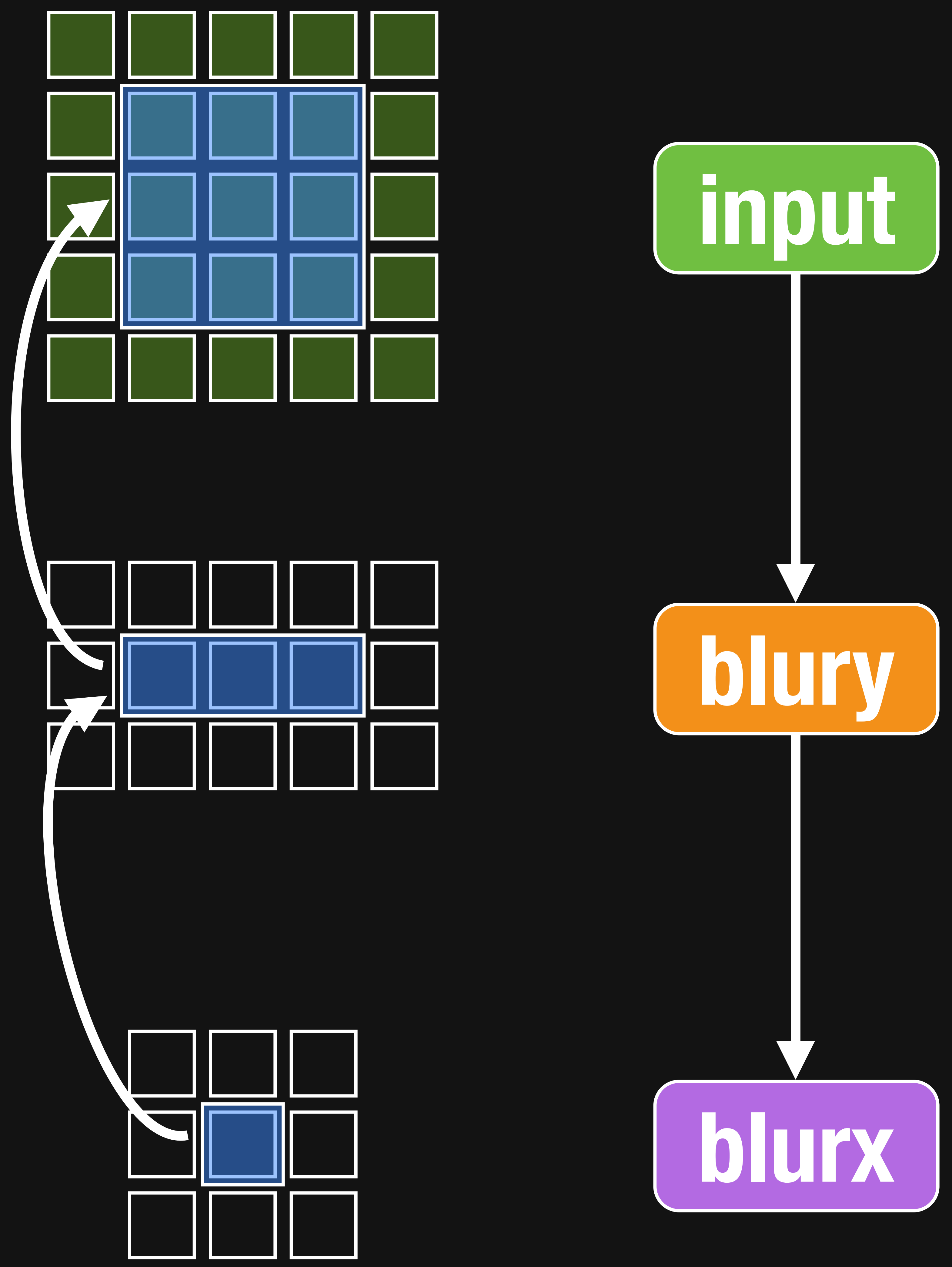

Organizing the algorithm
as a **data-parallel pipeline**
& **loops**

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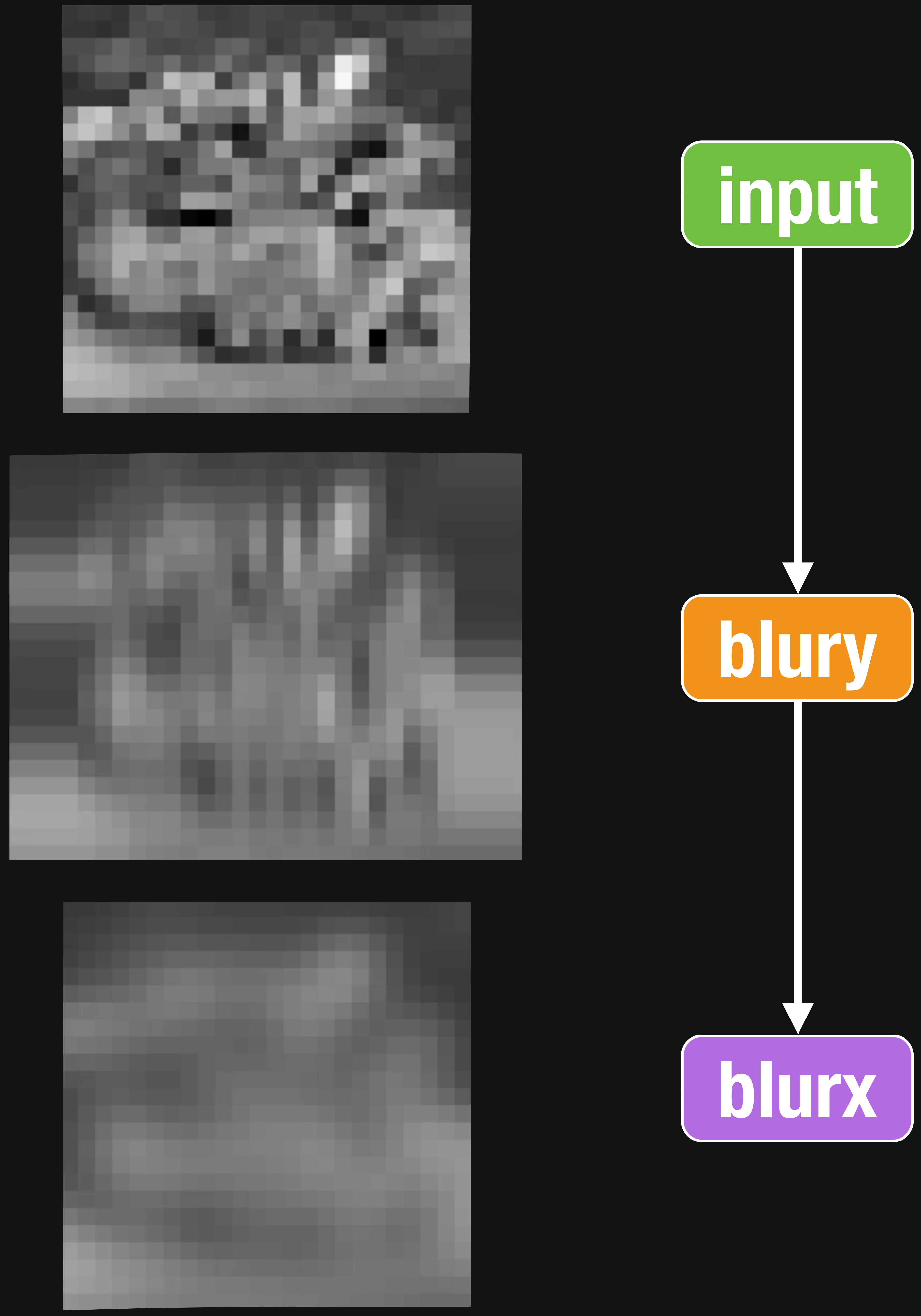
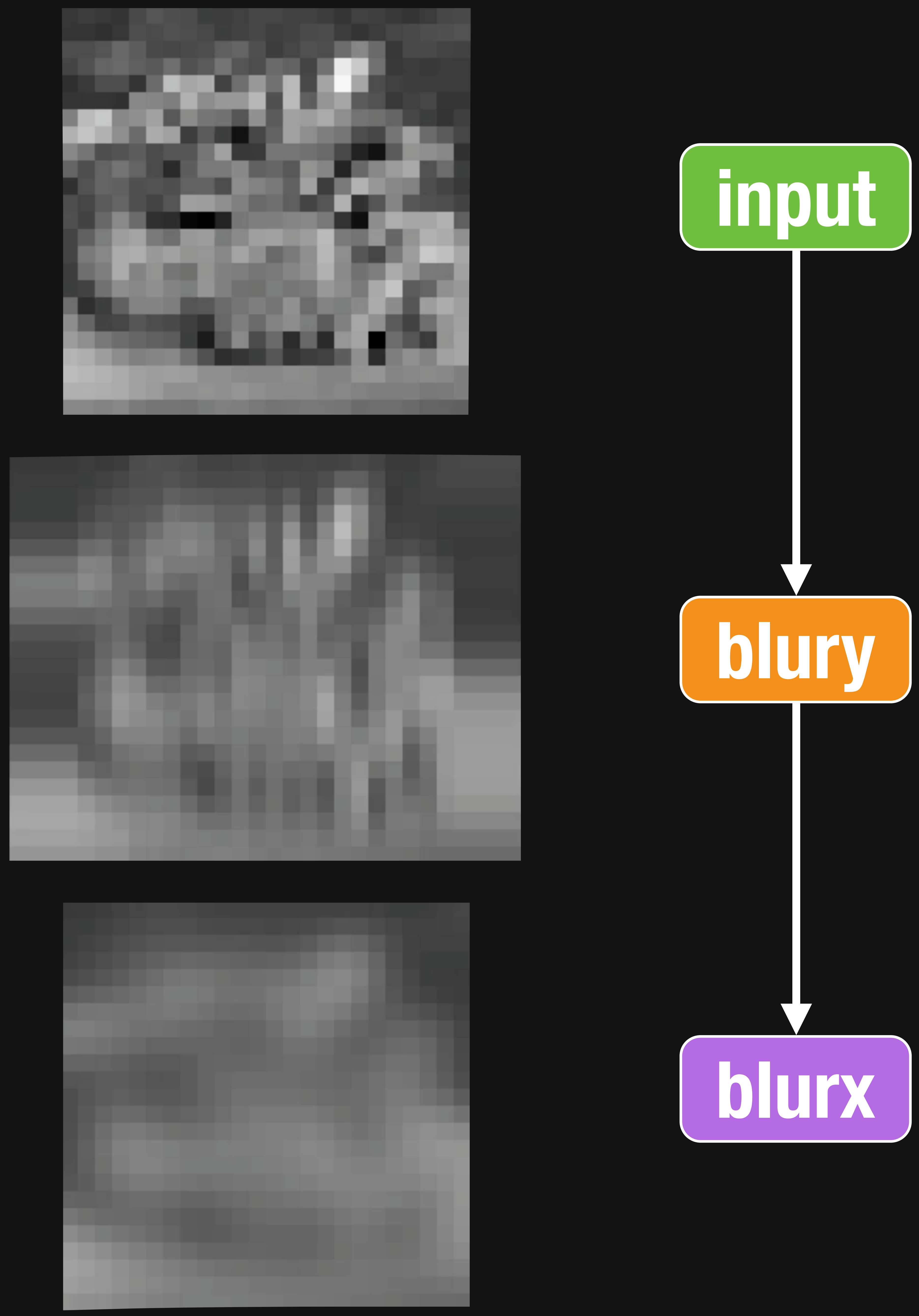


Organizing the algorithm as a **data-parallel pipeline** & **loops**




```
compute blury:
  for ...:
    blury(...) = ...
```

```
compute blurx:
  for ...:
    blurx(...) = ...
```

Inline maximizes **locality**, but also **recomputes values**


```
compute blurx:
  for c:
    for y:
      for x:
        blurx(...) =
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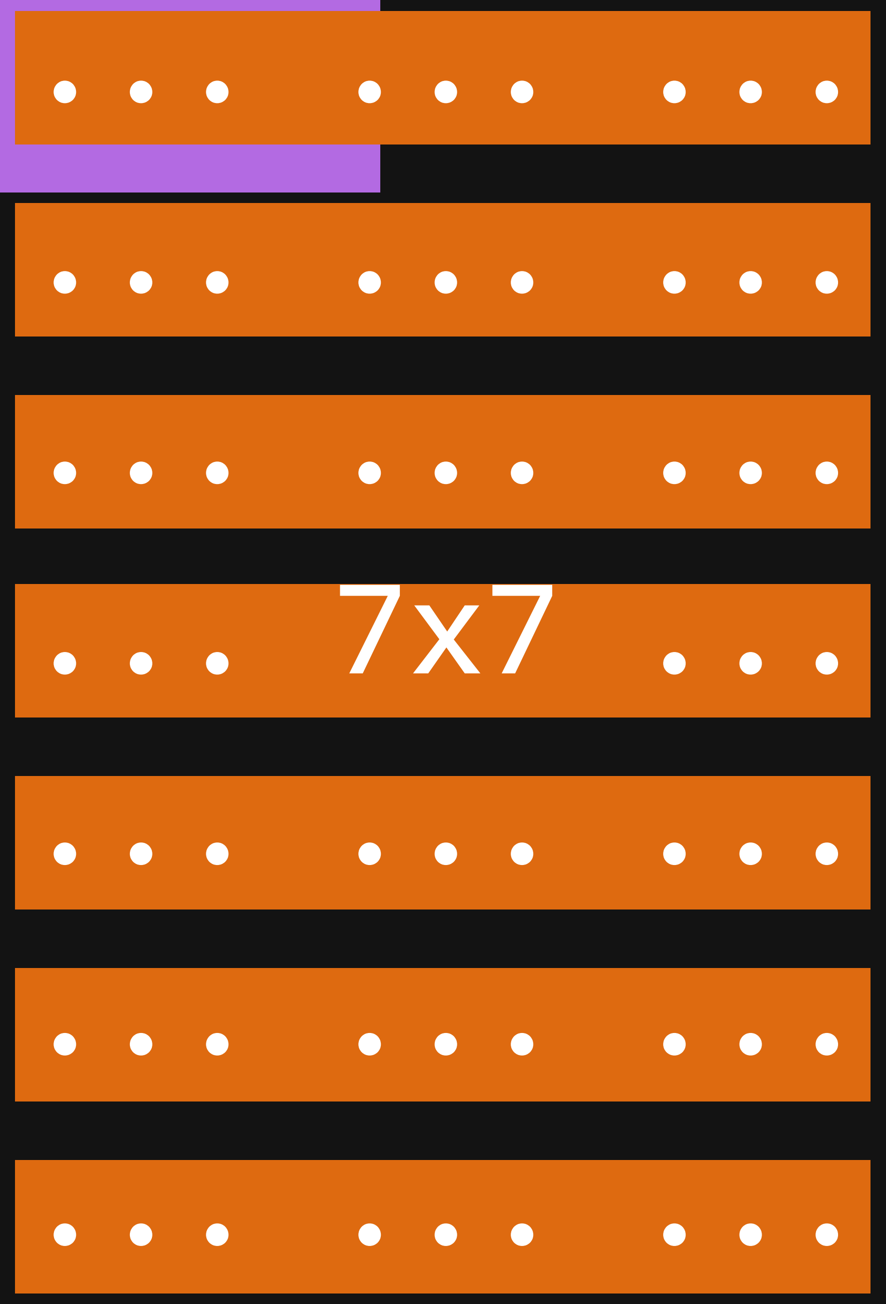

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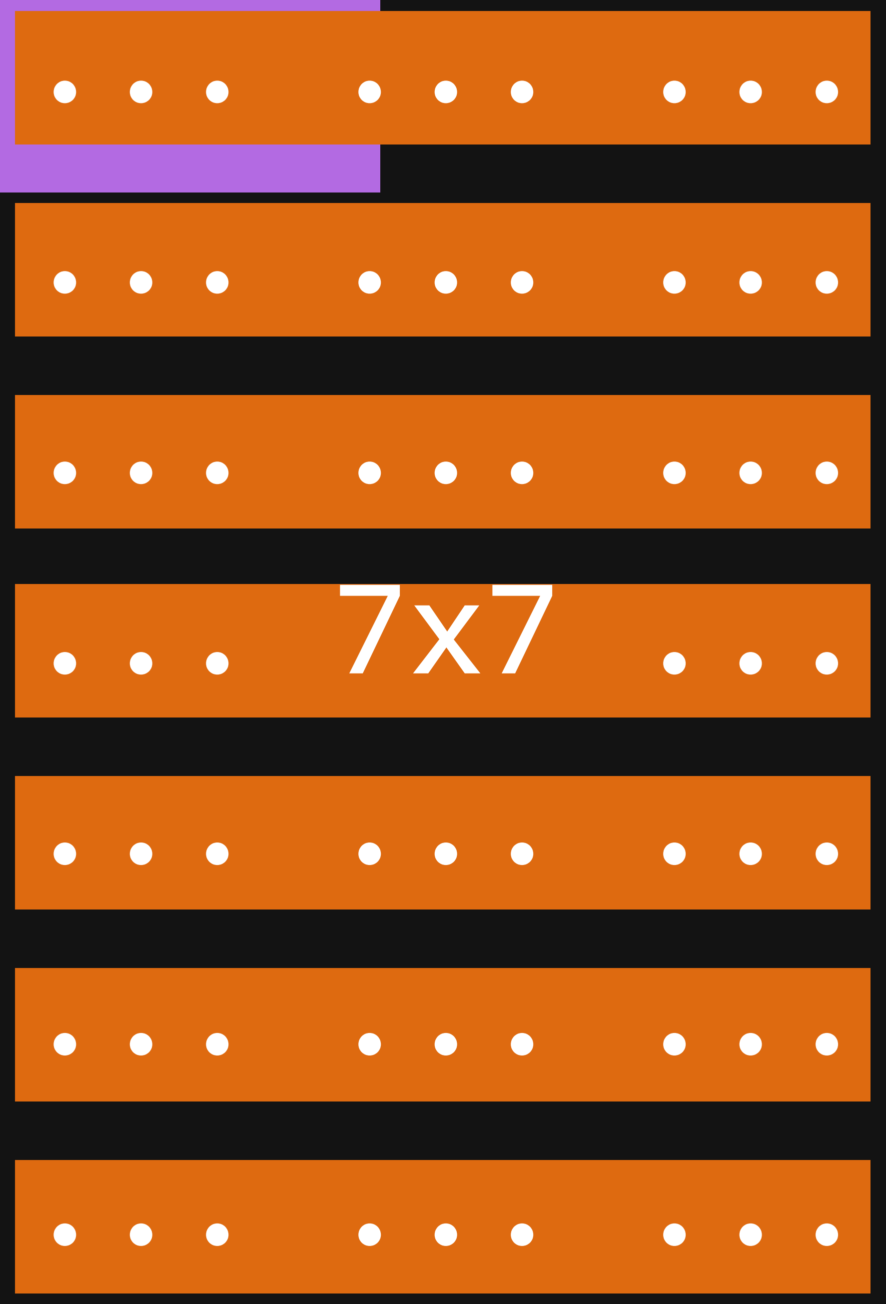

Compute root minimizes **recompute**, but also **locality**


```
compute blury:
  for c:
    for y:
      for x:
        blury(...) = ...
compute blurx:
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compute blurx:
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```

Compute at `blurx.y` interleaves scanlines for better **locality**


```
compute blurx:
  for c:
    for y:
      compute blury:
        for x:
          blury(...) = ...
      for x:
        blurx(...) = ...
```

Compute at `blurx.y` interleaves scanlines for better **locality**


```
compute blurx:
  for c:
    for y:
      compute blury:
        for x:
          blury(...) = ...
      for x:
        blurx(...) = ...
```

Today's agenda

the big ideas in Halide

writing & optimizing real code

Hello world (brightness)

Now: Gaussian blur - *3x OpenCV*

Simple enhancement pipeline - *6x OpenCV*

break

MATLAB integration

IIR filter

CNN layers

break

GPU scheduling

Finally: **real-time HOG on a phone**