Halide: A Language and Compiler for Optimizing Parallelism, Locality, and Recomputation in Image Processing Pipelines

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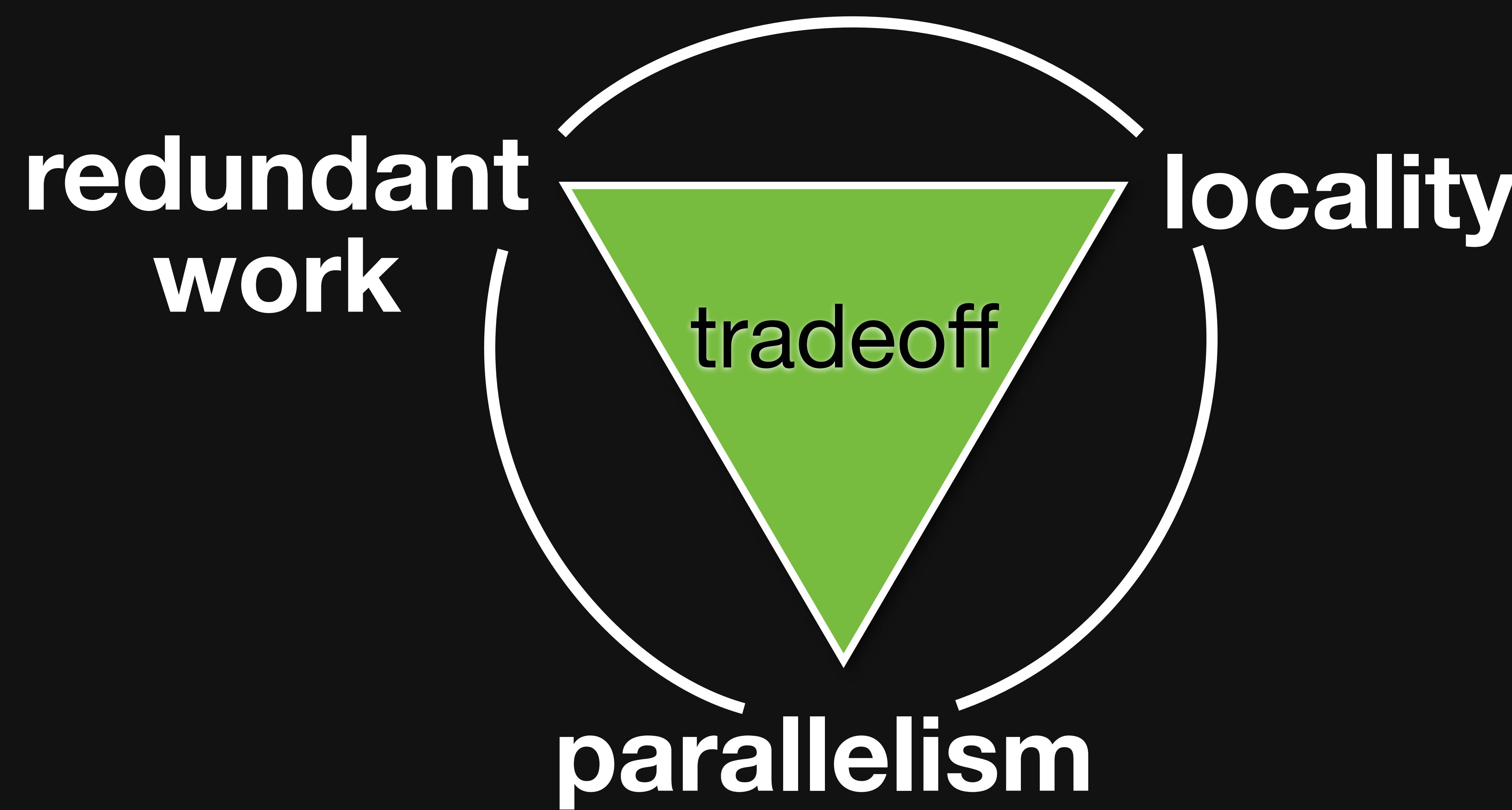
High Performance Image Processing

Parallelism
"Moore's law" growth will require exponentially more parallelism.

Locality
Data should move as little as possible.

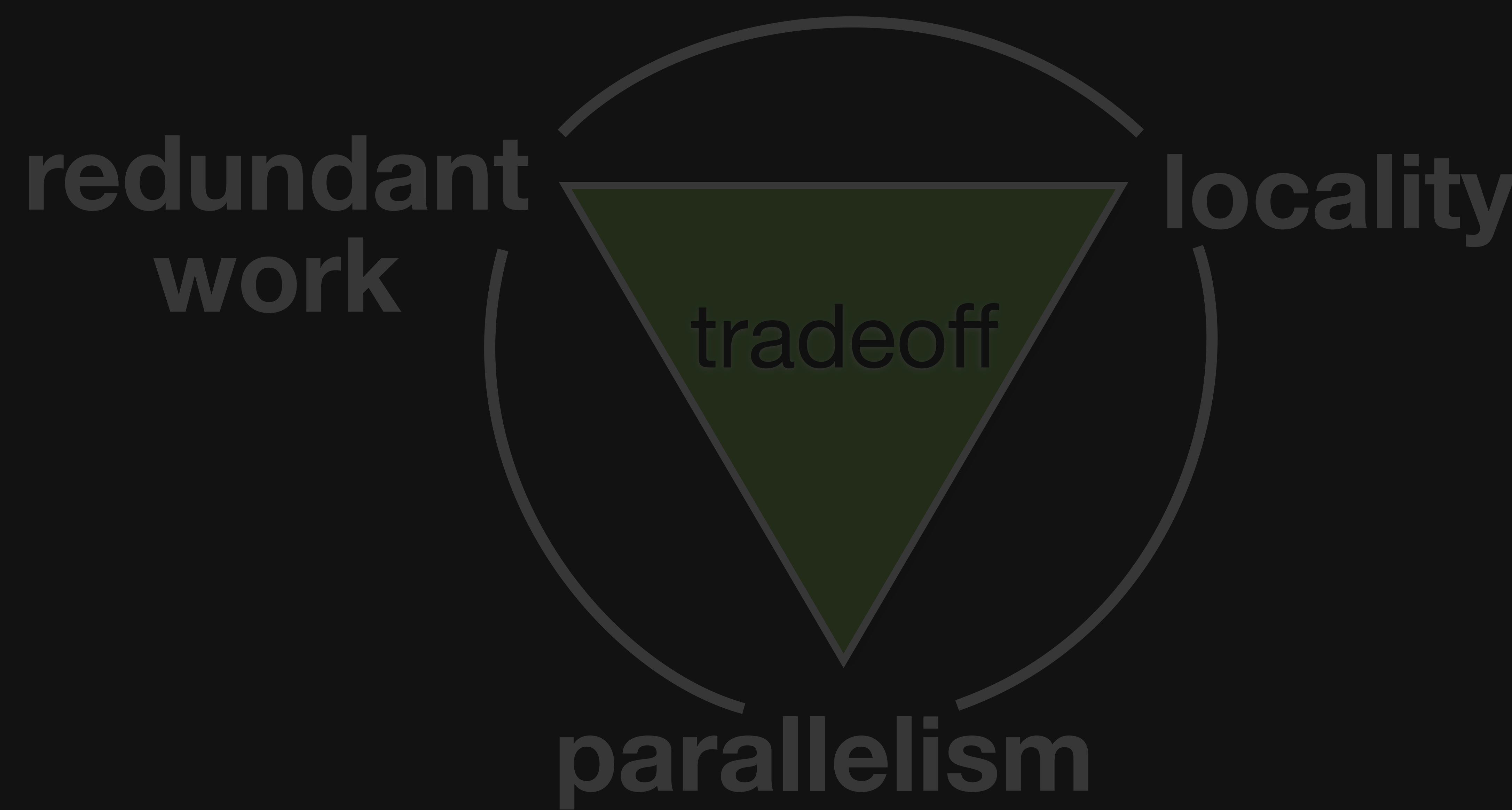
Message #1: Performance requires complex tradeoffs



Where does performance come from?

Program

Hardware



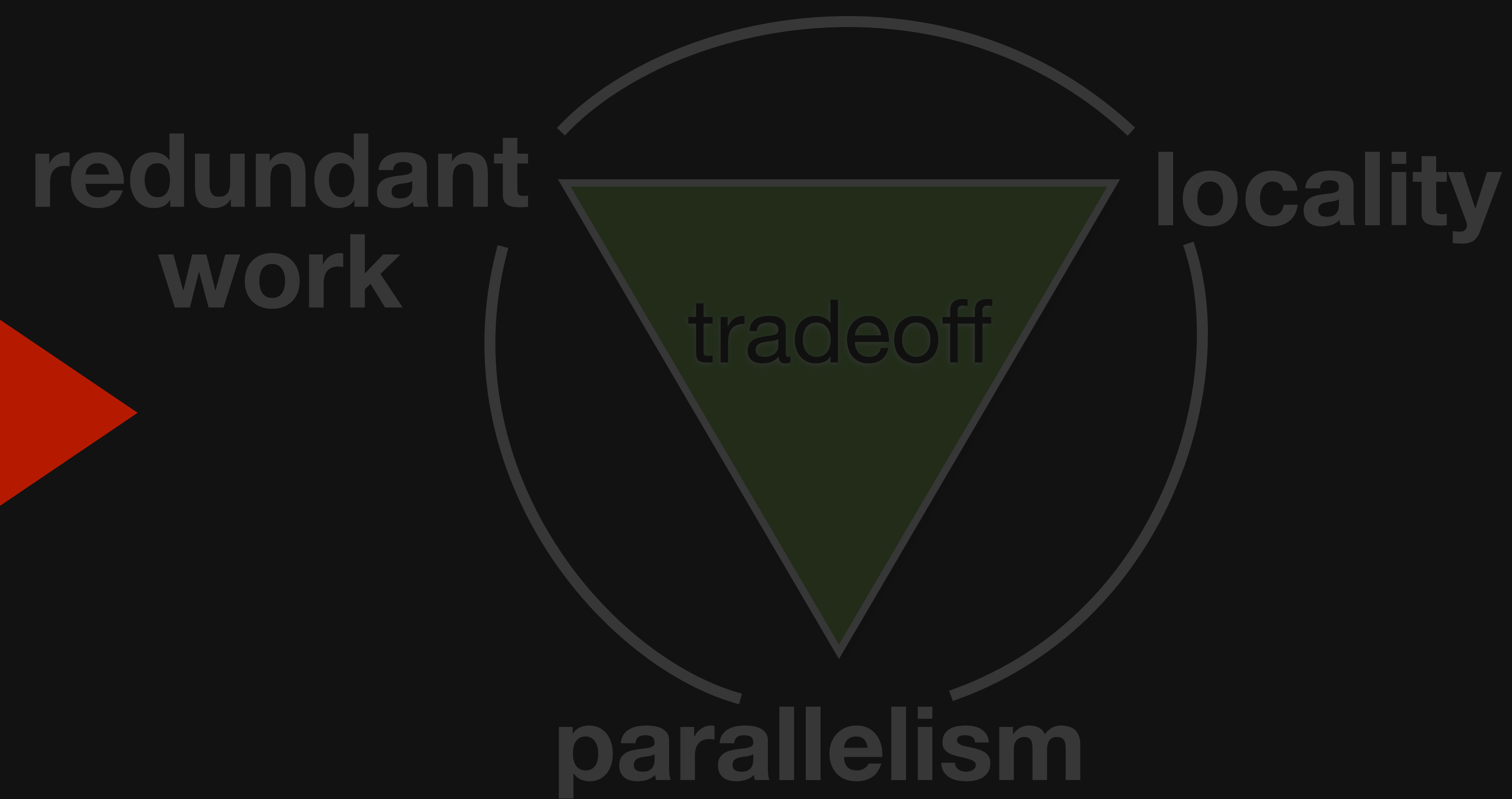
Message #2: organization of computation
is a first-class issue

Program:

Algorithm

Organization of computation

Hardware



Algorithm vs. Organization: 3x3 blur

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

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

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

Same algorithm, different organization

One of them is 15x faster

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));
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         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);
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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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}}}}}
```

11x faster
(quad core x86)

Tiled, fused

Vectorized

Multithreaded

Redundant computation

Near roof-line optimum

Same algorithm, different organization

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

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      blury(x, y) = (blurx(x, y-1) + blurx(x, y) + blurx(x, y+1))/3;
}
```
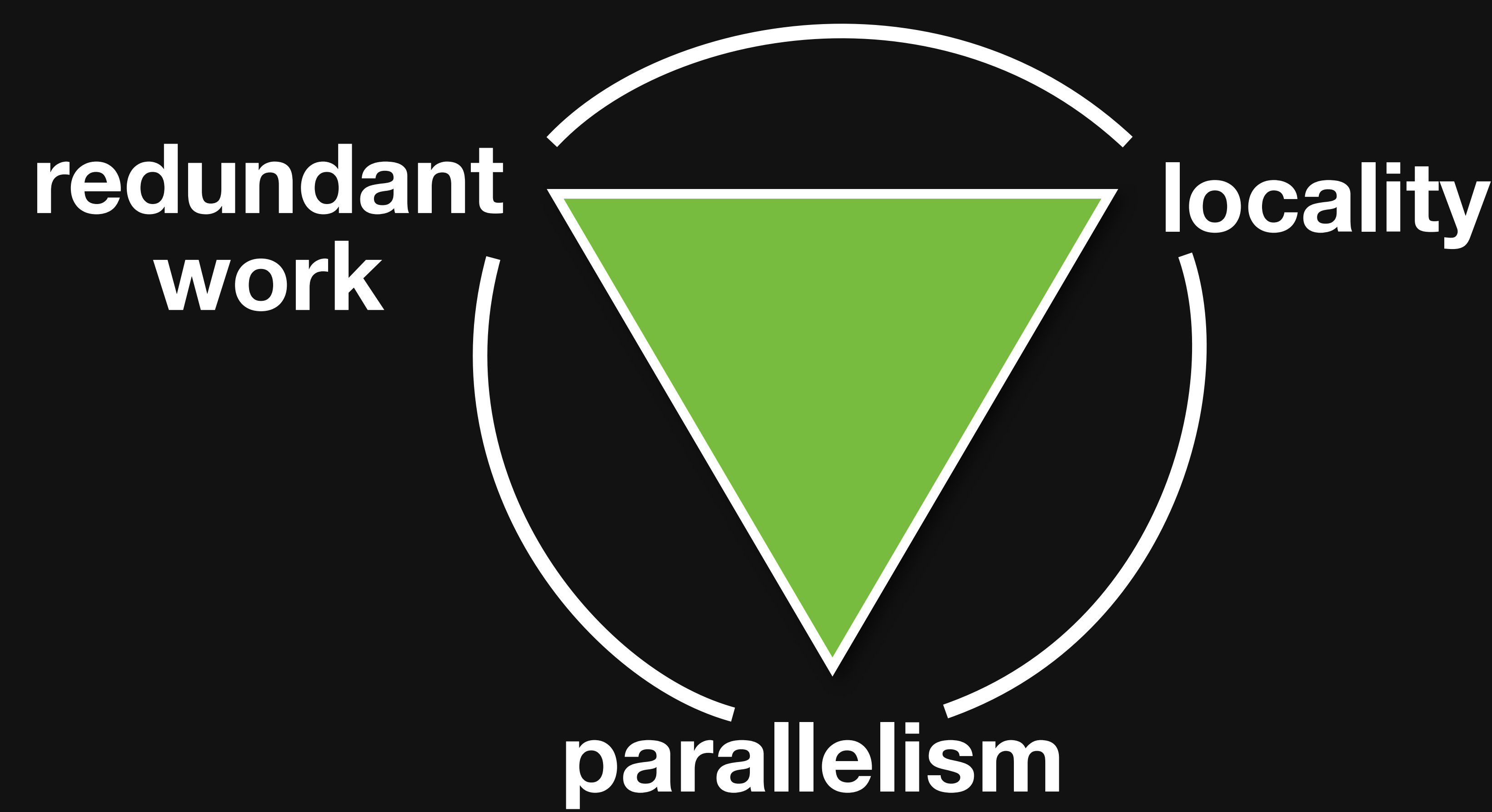

For a given algorithm, organize to optimize:



(Re)organizing computation is hard

Optimizing parallelism, locality requires
transforming program & data structure.

What transformations are *legal*?

What transformations are *beneficial*?

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

Halide's answer: *decouple* algorithm from schedule

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

Easy for programmers to build pipelines

Easy to specify & explore optimizations
manual or automatic search

Easy for the compiler to generate fast code

Halide *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;
```

Halide *schedule*:

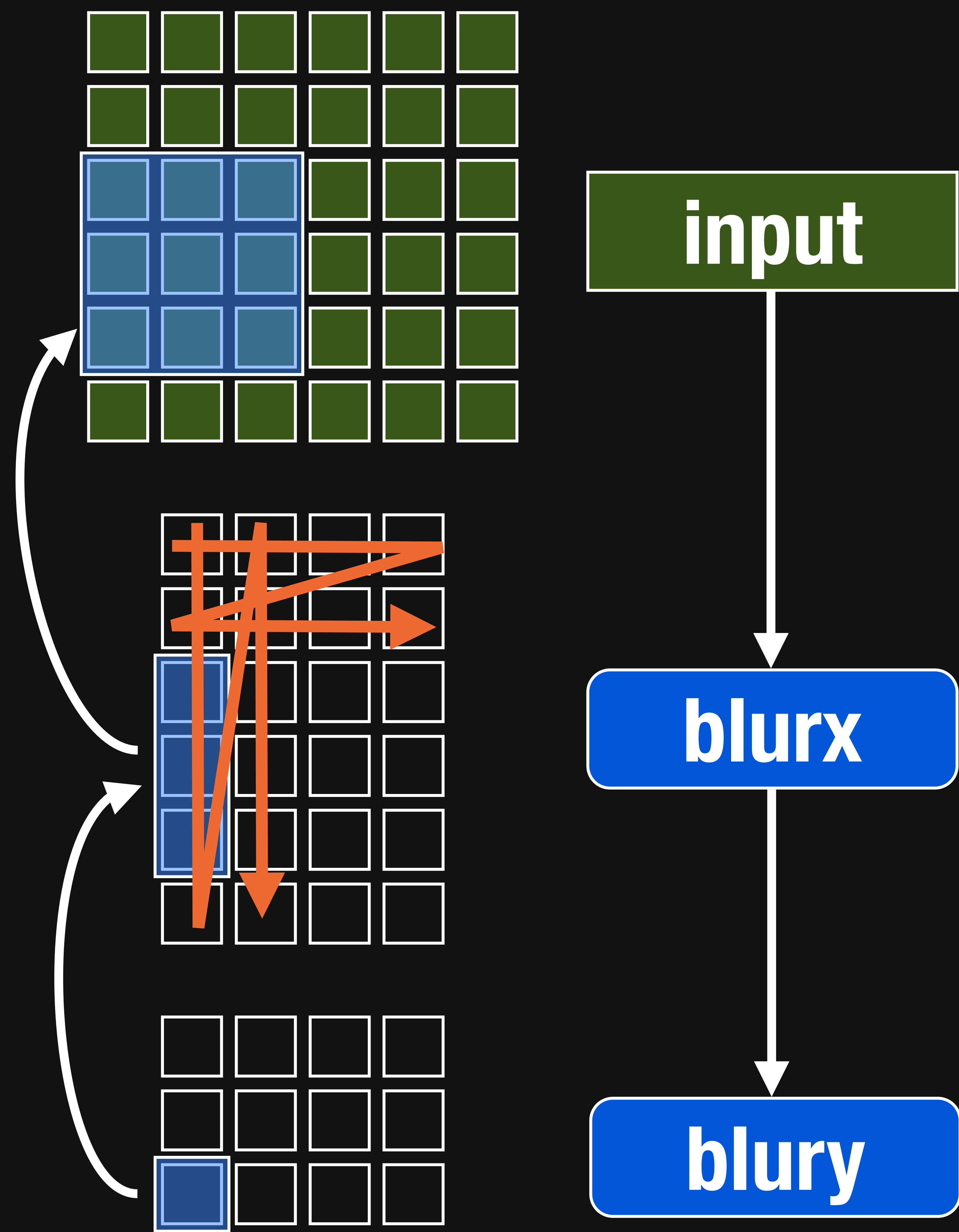
```
blury.tile(x, y, xi, yi, 256, 32).vectorize(xi, 8).parallel(y);
blurx.compute_at(blury, x).store_at(blury, x).vectorize(x, 8);
```

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

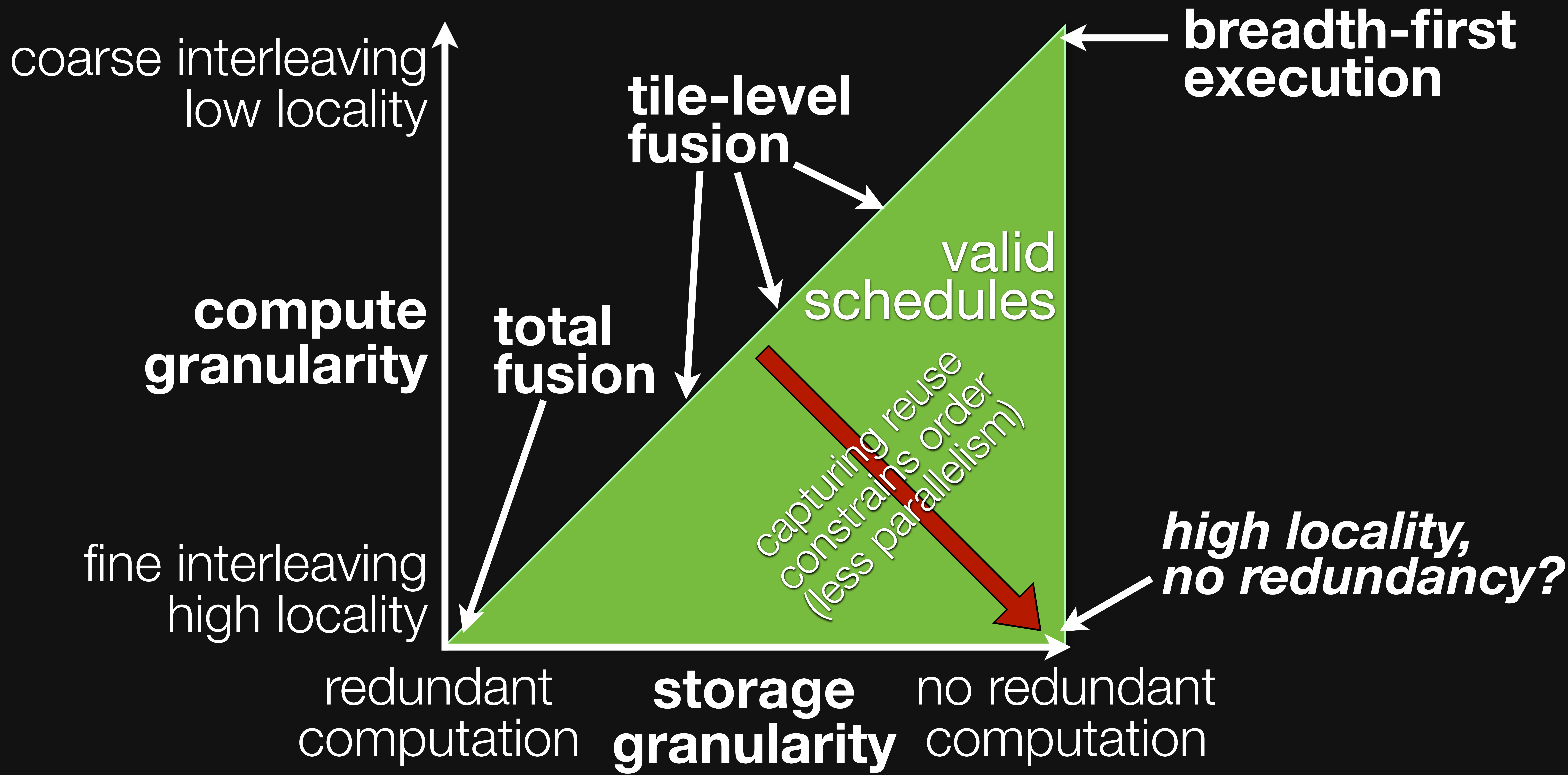
For each stage:

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

2) **When** should it **compute** its **inputs**?



Tradeoff space modeled by **granularity of interleaving**



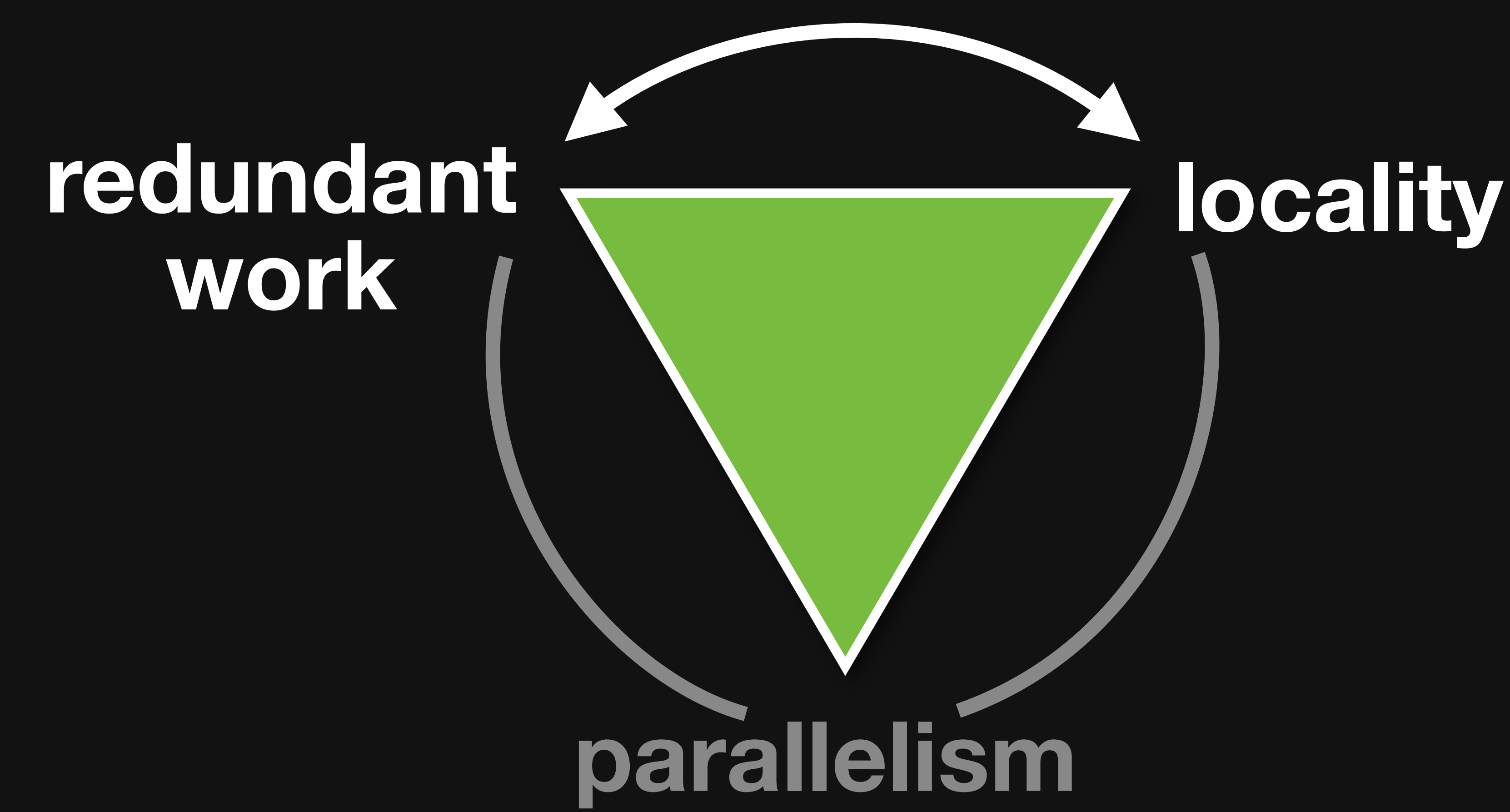
The schedule defines producer-consumer interleaving

Fine-grained fusion optimizes locality for point-wise operations

Breadth-first execution minimizes recomputation for large kernels

Tile-level fusion **trades off locality vs. recomputation for stencils**

Halide's *schedule* is designed to span these tradeoffs



Schedule primitives **compose** to create many organizations

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.compute_at(blury, x).store_at(blury, 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);
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         avg = _mm_mulhi_epi16(sum, one_third);
         _mm_store_si128(blurxPtr++, avg);
         inPtr += 8;
      }}
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}}}}}
```

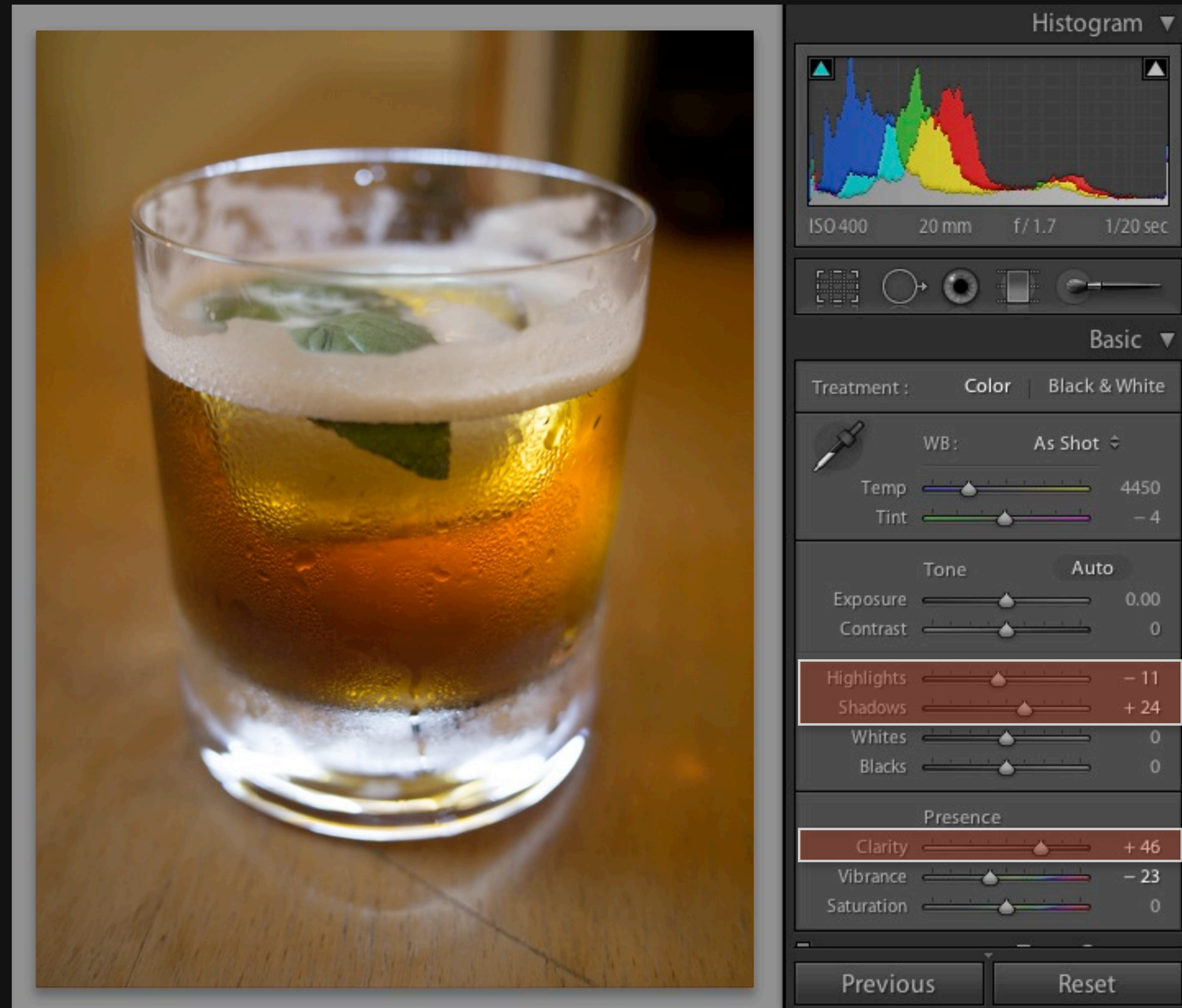
Local Laplacian Filters

prototype for Adobe Photoshop Camera Raw / Lightroom

Adobe: 1500 lines of expert-optimized C++
multi-threaded, SSE
3 months of work
10x faster *than original C++*

Halide: 60 lines
1 intern-day

2x faster on CPU,
7x faster on GPU



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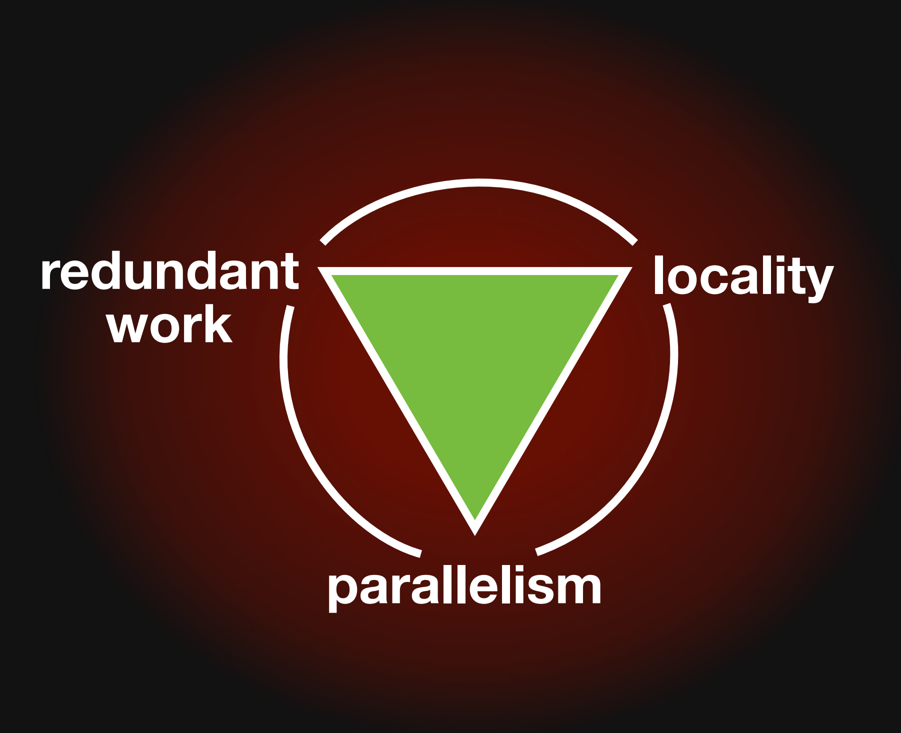
The Halide language & compiler

Decouples **algorithm** from **organization** through a **scheduling co-language** to navigate fundamental **tradeoffs**.



Simpler programs

Faster than hand-tuned code

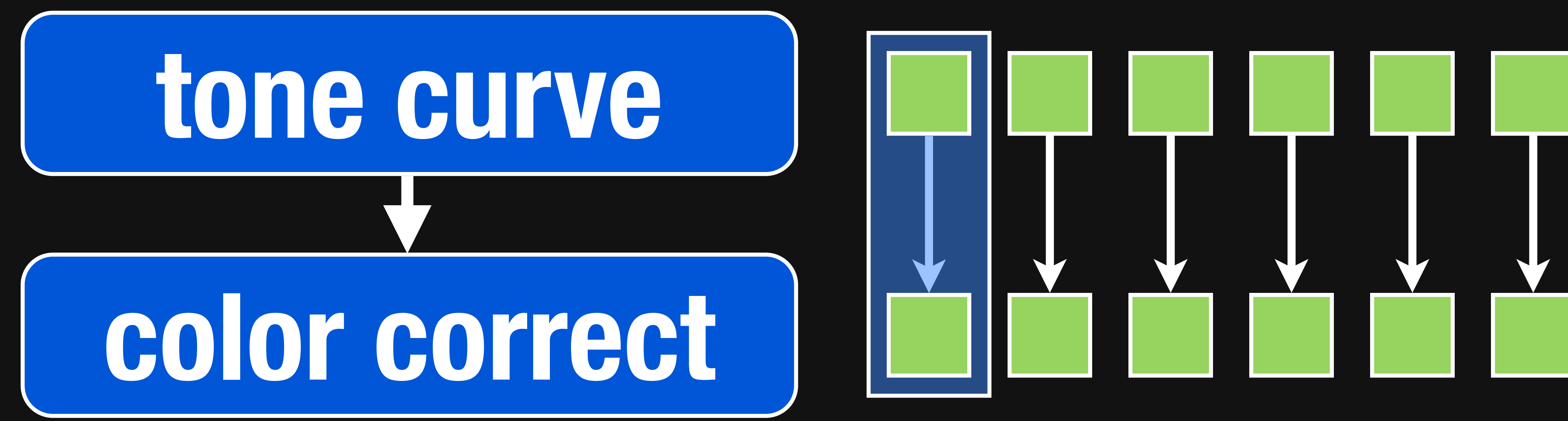
Scalable across architectures

Fredo XXX: remind two (three) big messages

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

The schedule defines producer-consumer interleaving

Fine-grained fusion optimizes locality for point-wise operations



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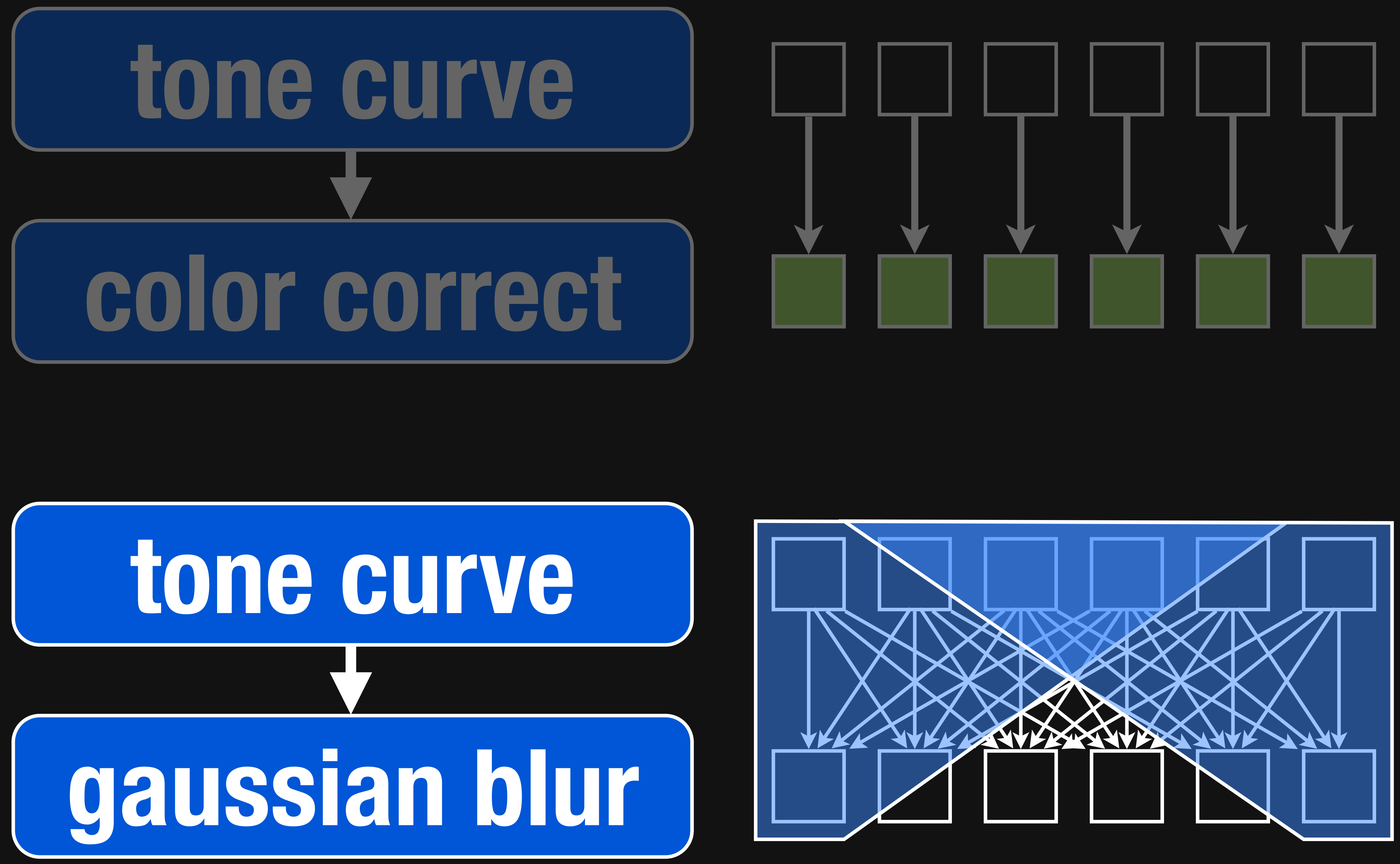

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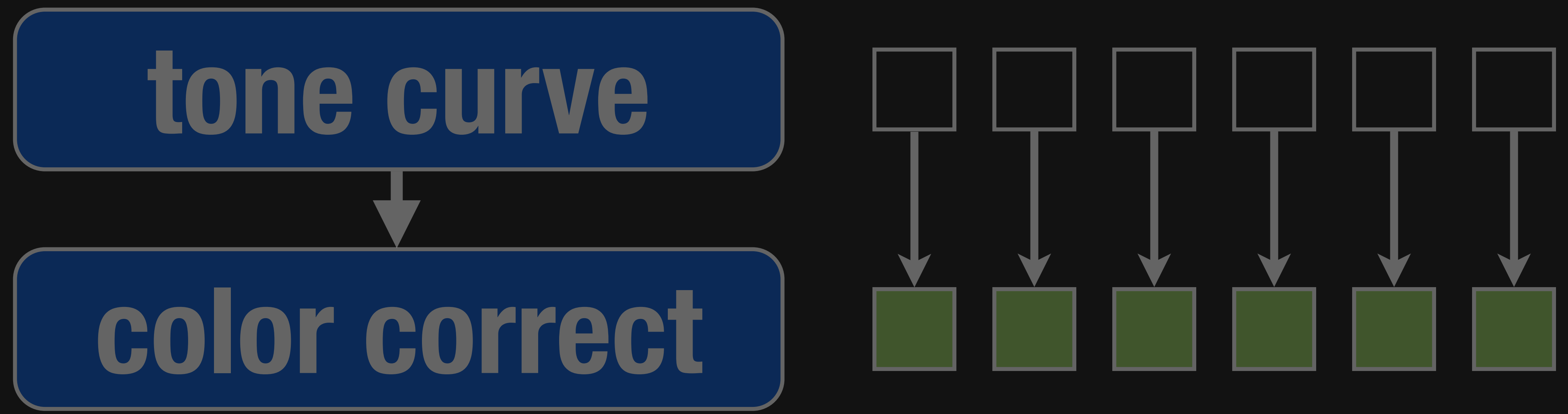
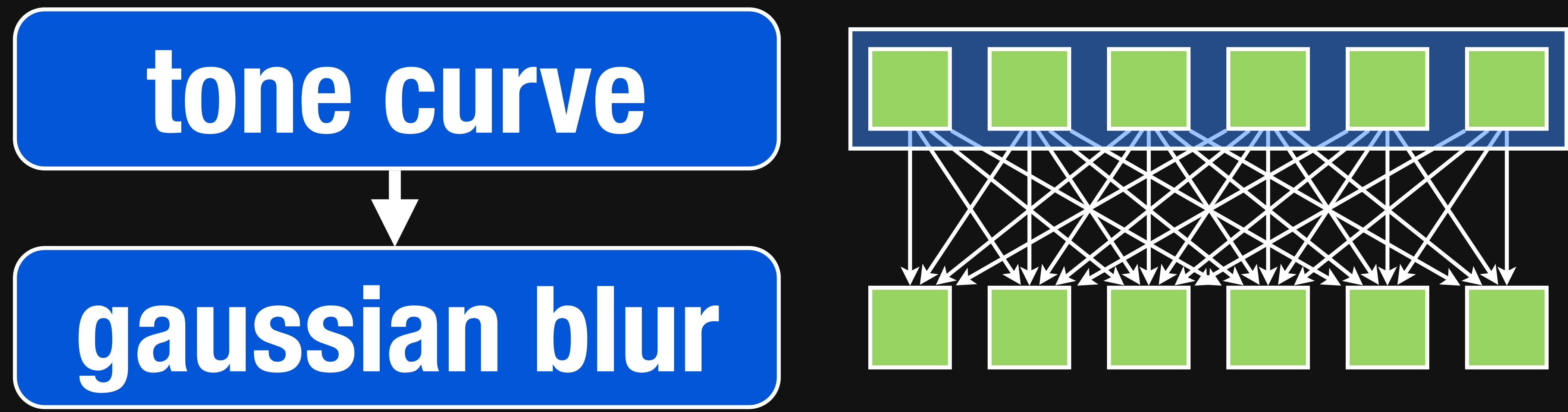


Breadth-first execution minimizes recomputation for large kernels



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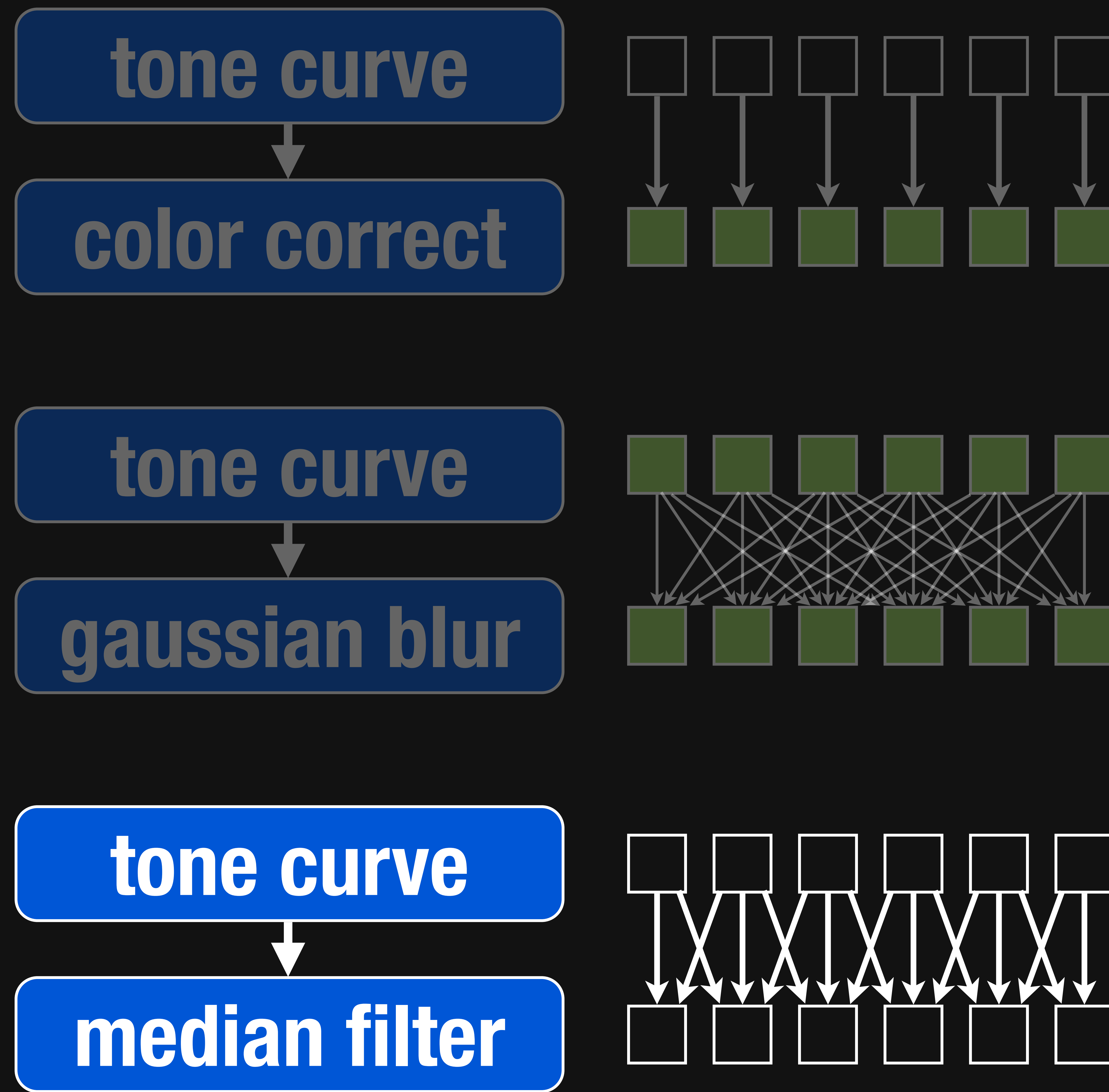

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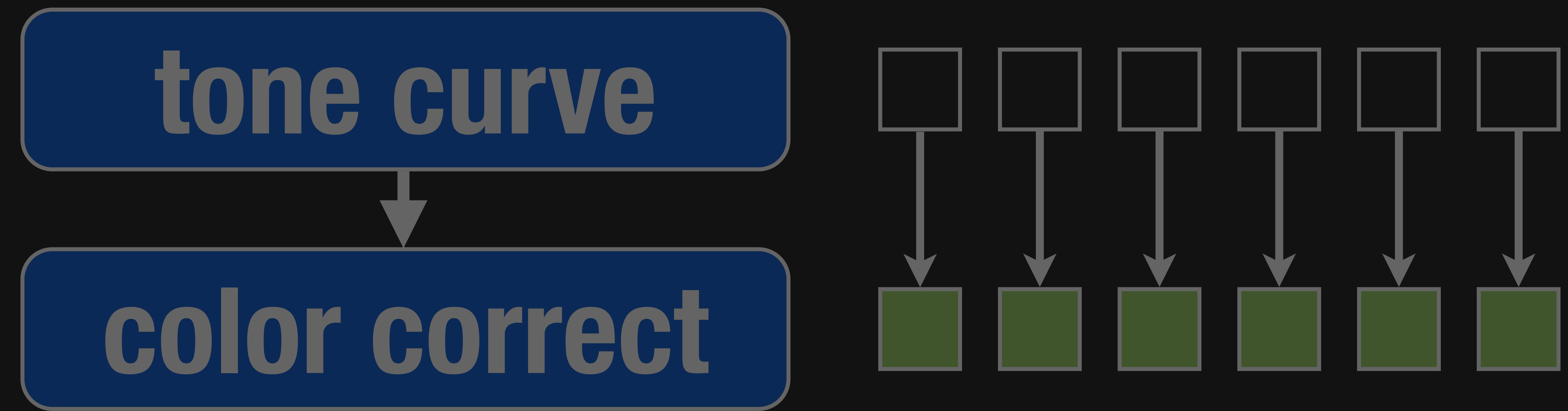

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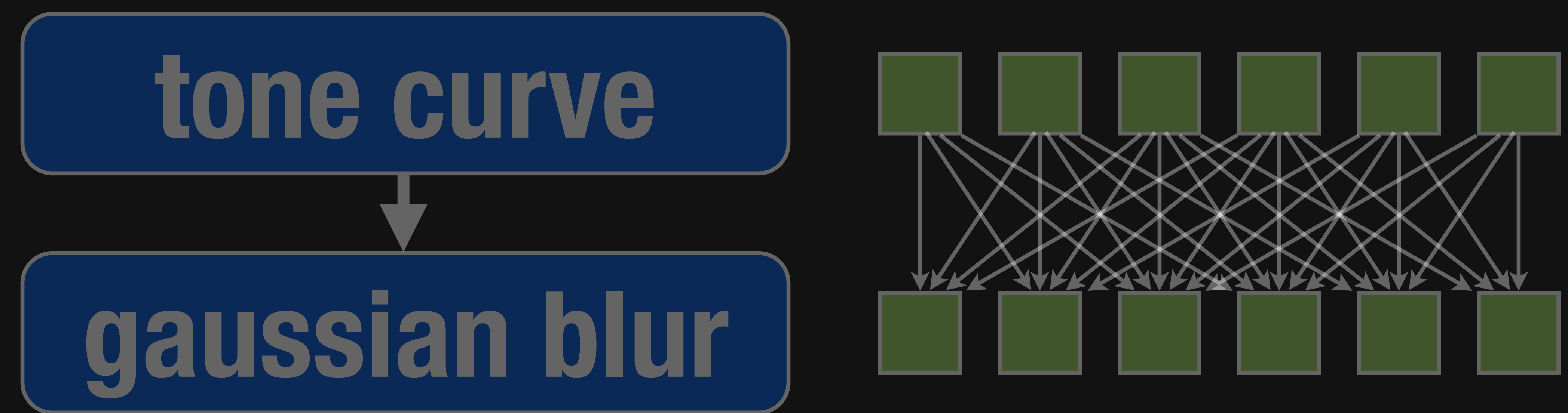
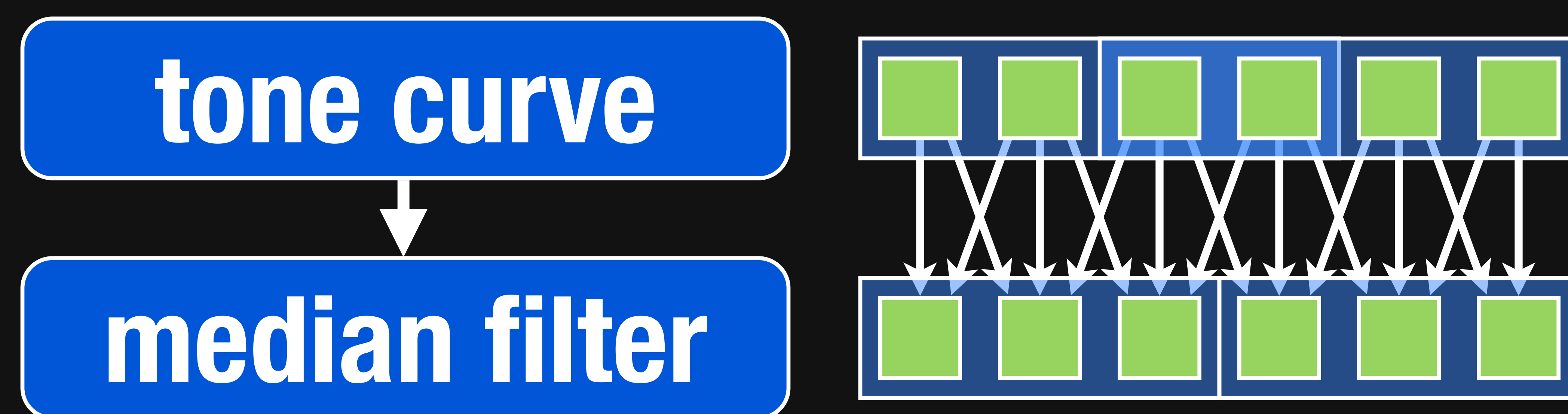


Tile-level fusion **trades off locality vs. recomputation for stencils**



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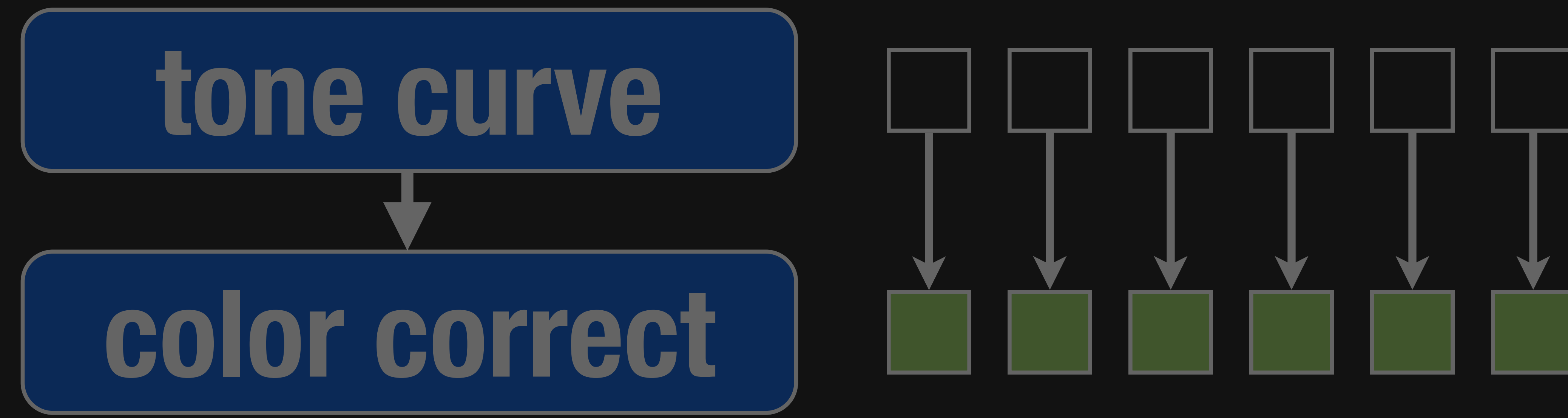

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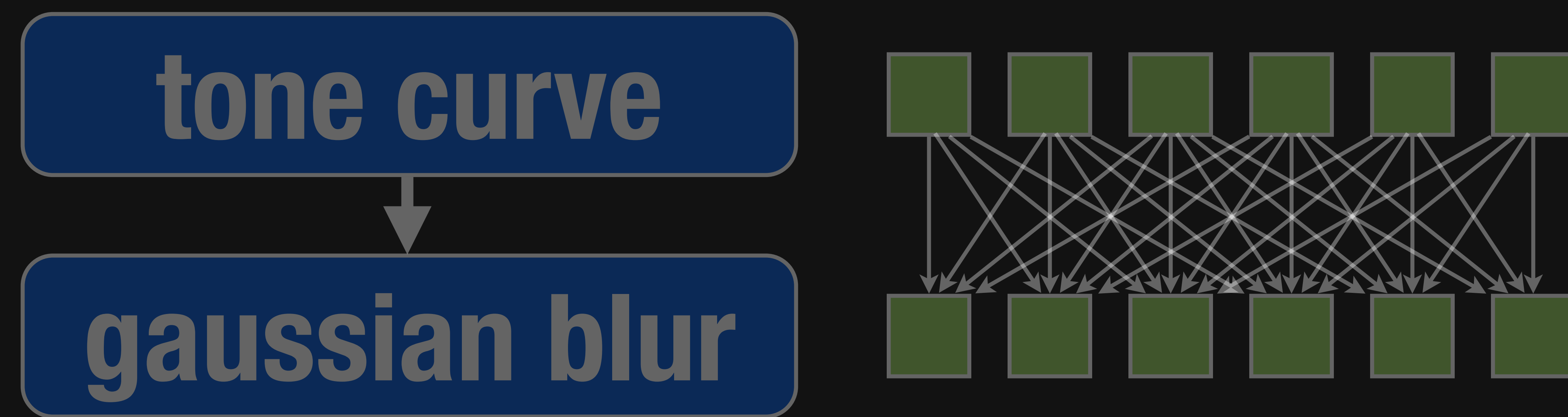

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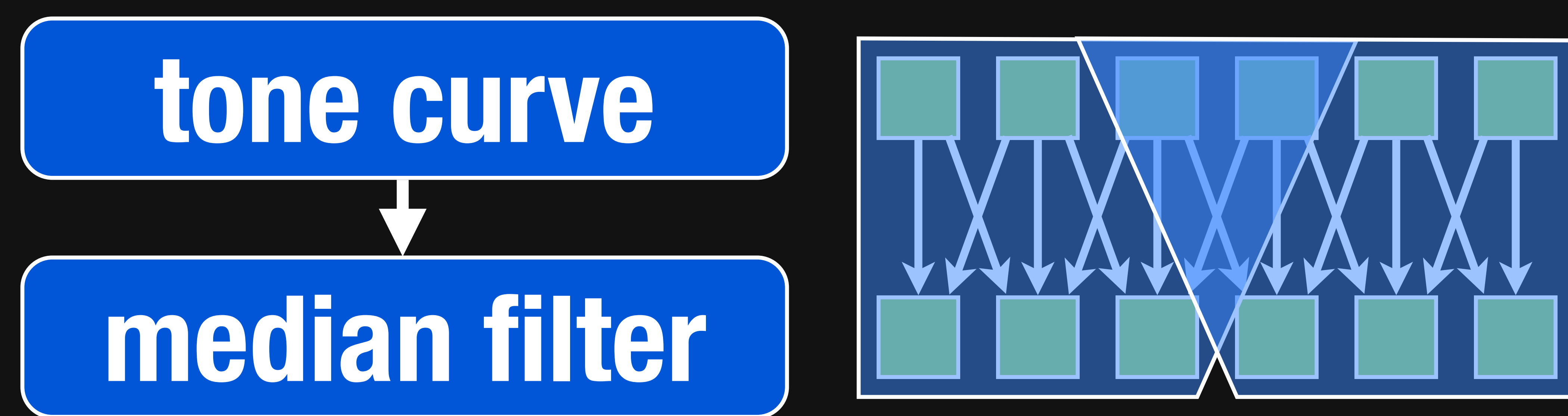

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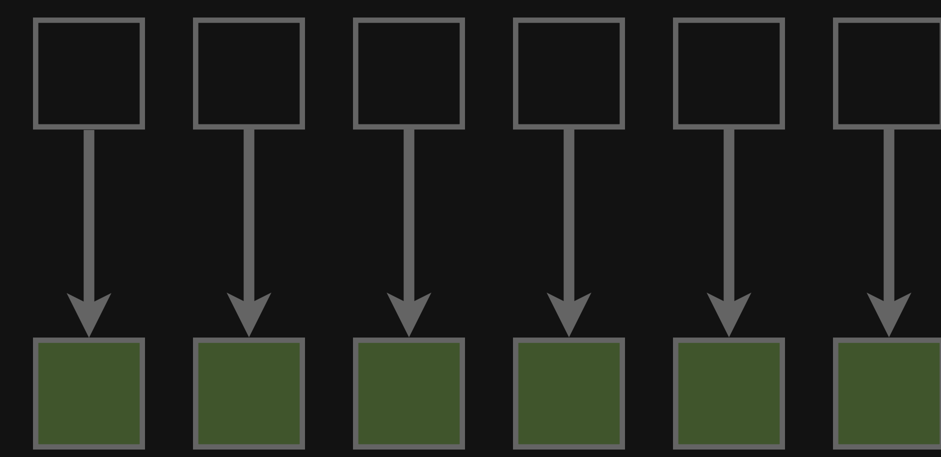
tone curve → color correct



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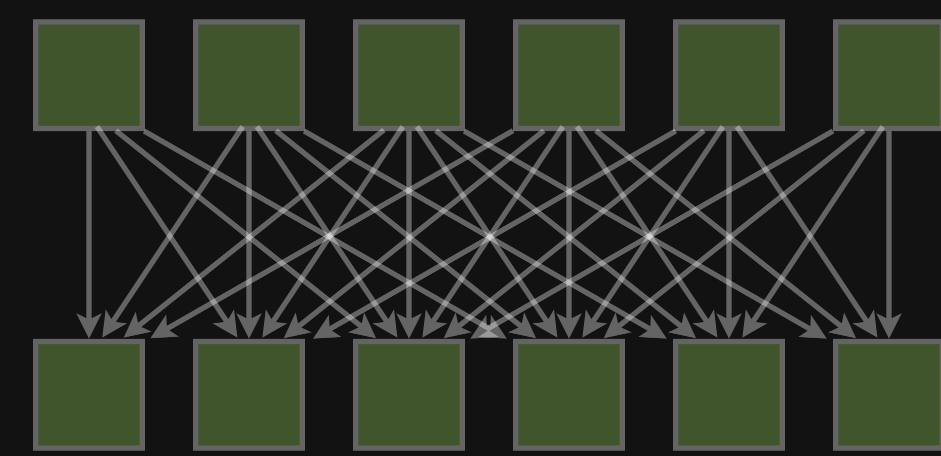
tone curve → gaussian blur



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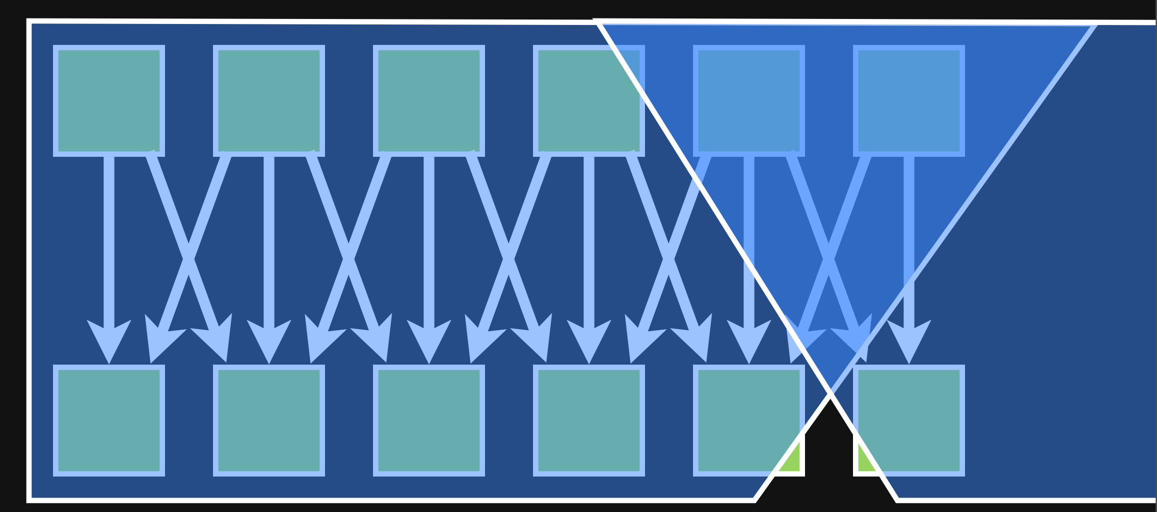
tone curve → median filter



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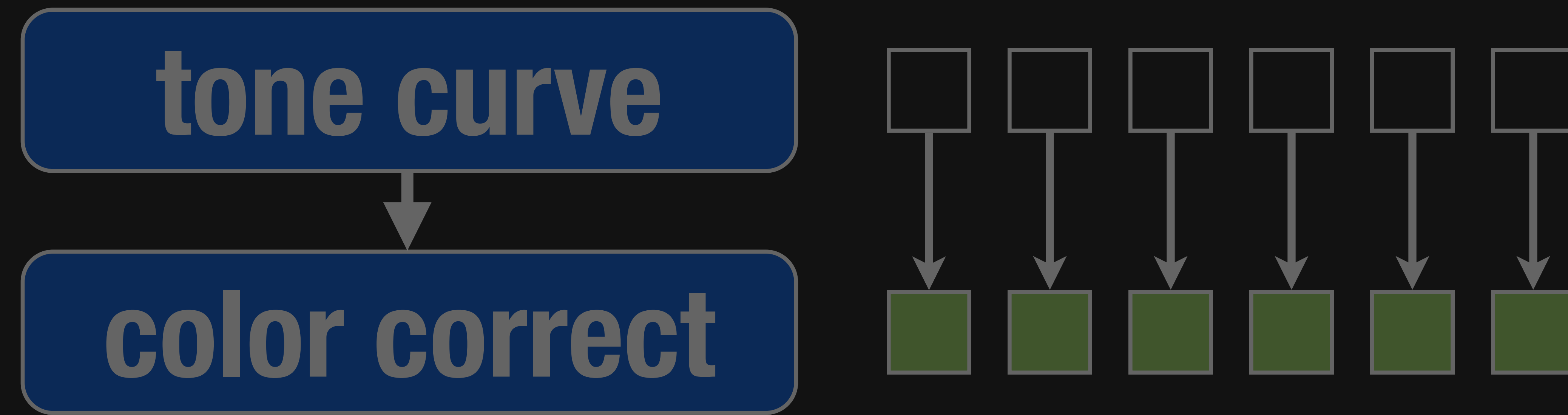

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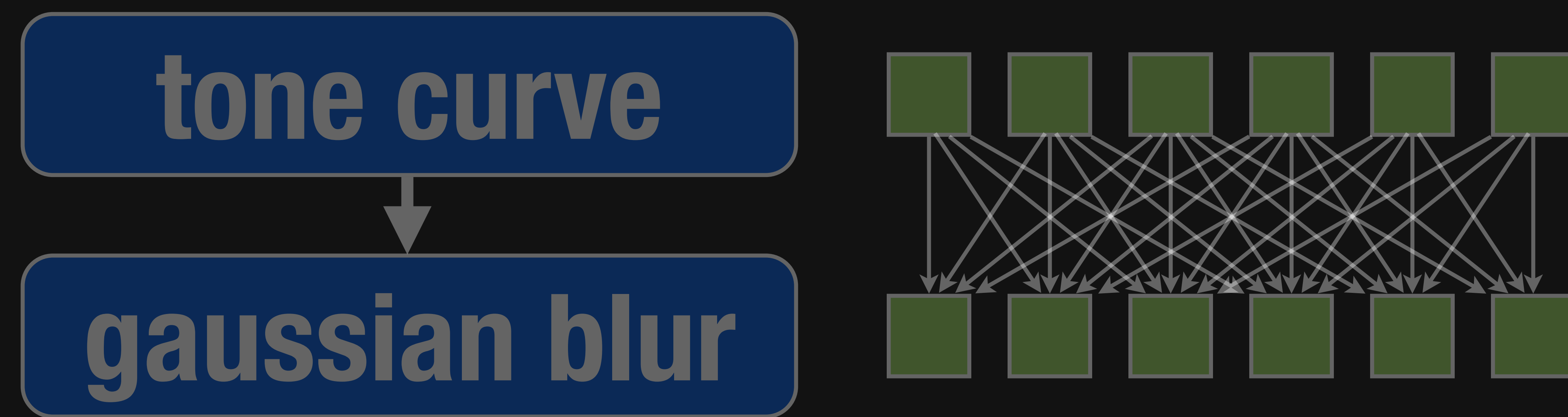

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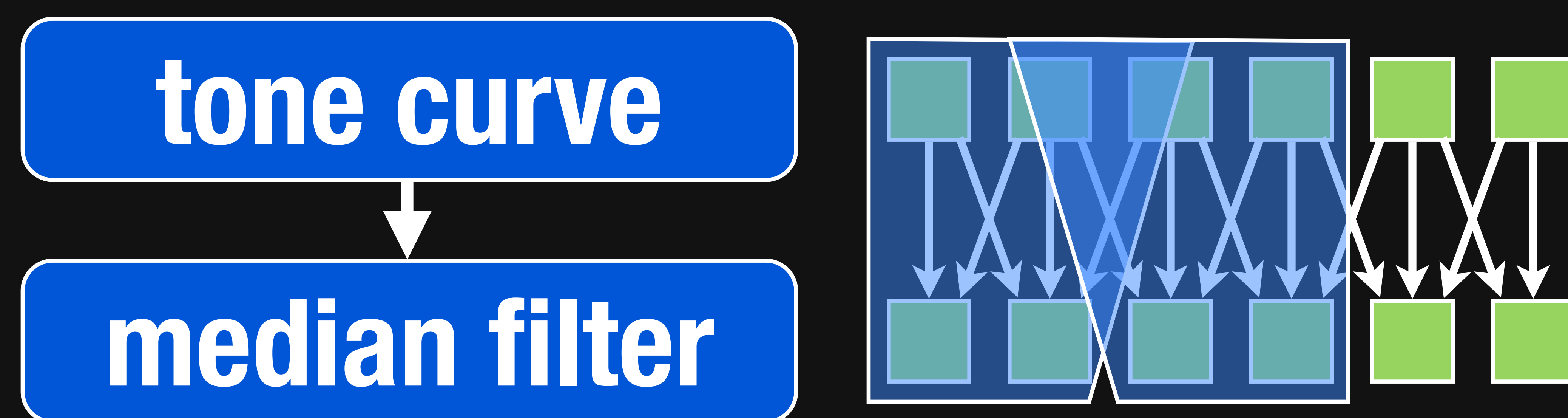

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