High-Performance Image Processing

Frédo Durand
most slides by Jonathan Ragan-Kelley
MIT CSAIL

Speed

Our code is slow

Often minutes of computation for small images

Simple box blur

```
def box_x(im):
    w,h=im.shape[1],im.shape[0]
    out = numpy.empty([h, w])
    for y in xrange(1,h-1):
        for x in xrange(1,w-1):
            out[y,x]=(im[y,x-1]+im[y,x]+im[y,x+1])/3.0
    return out
def box_y(im):
    w,h=im.shape[1],im.shape[0]
    out = numpy.empty([h, w])
    for y in xrange(1,h-1):
        for x in xrange(1,w-1):
            out[y,x]=(im[y-1,x]+im[y,x]+im[y+1,x])/3.0
    return out
def blur(im):
    return box_y(box_x(im))
```

6.4 seconds
per megapixel

Speed

Our code is slow
Often minutes of computation for small images

Professional code is very fast
e.g. Lightroom processes megapixels images in real time

Why?

4D lightfields: orders of magnitude from “good enough”

Current Lytro

10 Mrays

<1 Mpixels

5 secs

(on desktop PC)

Scale to 4k video

100 Mrays

8 Mpixels

1 min/*frame*

(on desktop PC)

[Ng 2005; Ng et al. 2006]
images by Ren Ng, Lytro

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(on desktop PC)

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100 Mrays

8 Mpixels

1 min/*frame*

(on desktop PC)

1 hour to process 1 second of video

[Ng 2005; Ng et al. 2006]
images by Ren Ng, Lytro

Rendering: orders of magnitude from “good enough”

10 ms

5 hrs

6 orders of magnitude more computation

images by Valve, Weta

Modern game:
Team Fortress 2

2 Mpixels

0.5 Mpolys

10 ms/frame

CG movie:
Tintin, Avatar

8 Mpixels

5 Gpolys

5 hrs/frame

3D printing: orders of magnitude from “good enough”

1500 cm³ shoe,
10 µm detail,
16 materials

2500³ DPI

10^{12} voxels

25 terabytes

10 shoes/hour = 4B voxels/sec

Pervasive sensing: orders of magnitude from “good enough”

Sensor + Read out

5 Mpixels

~1 mJ/frame

Eulerian Video Magnification [Wu et al. 2012]

Pervasive sensing: orders of magnitude from “good enough”

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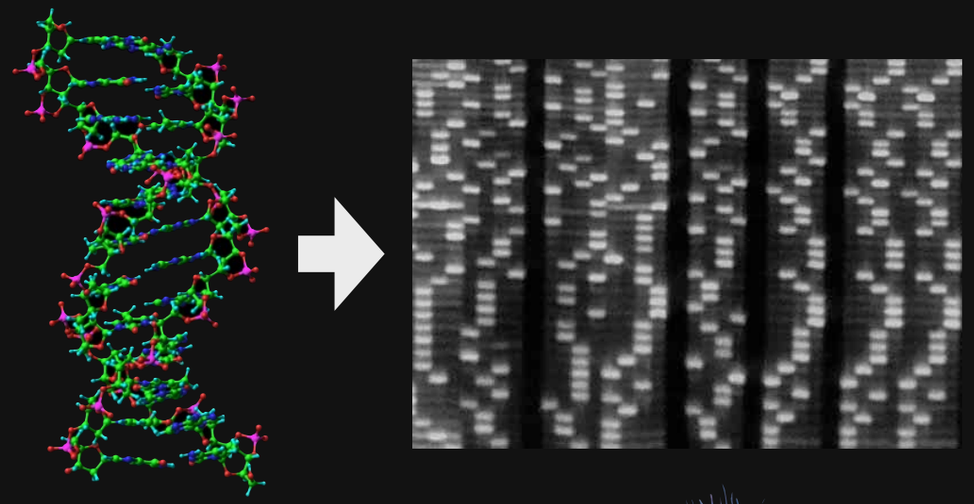
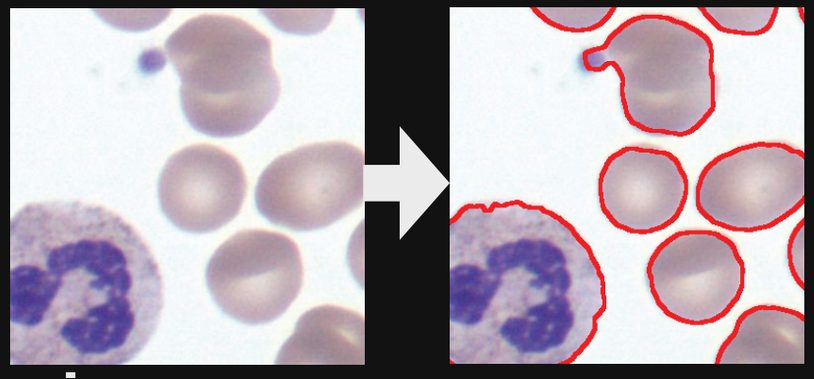
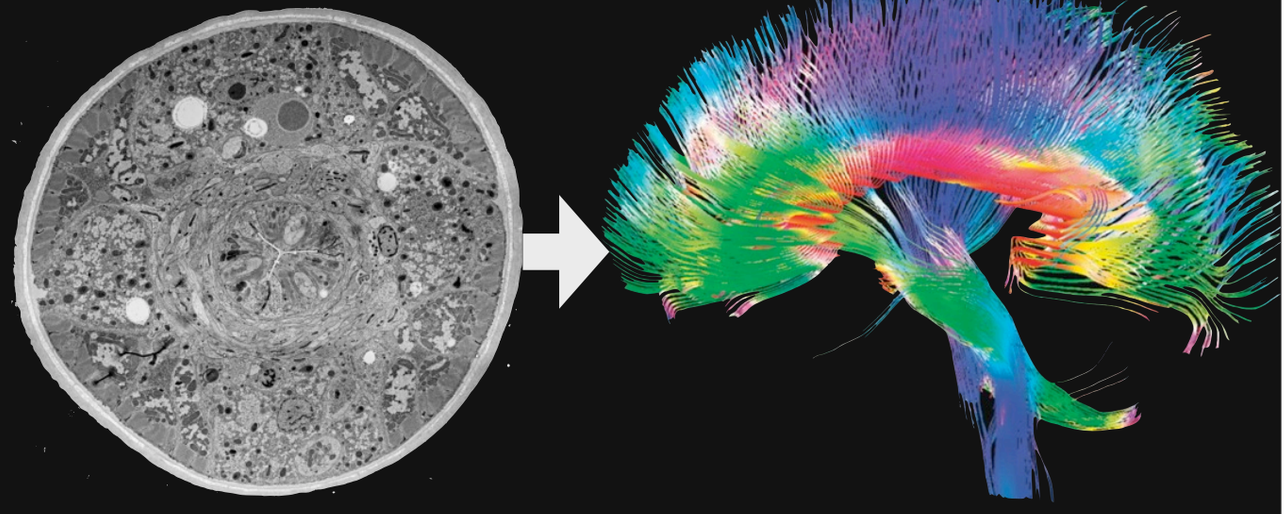
Eulerian Video Magnification [Wu et al. 2012]

High throughput imaging: orders of magnitude from “good enough”

most sensing is “imaging”







Your data-intensive problem here…

Making image processing faster

Faster algorithms

Faster programming language

Faster Hardware

Parallelism

Memory bheavior

Algorithmic acceleration (not today's topic though)

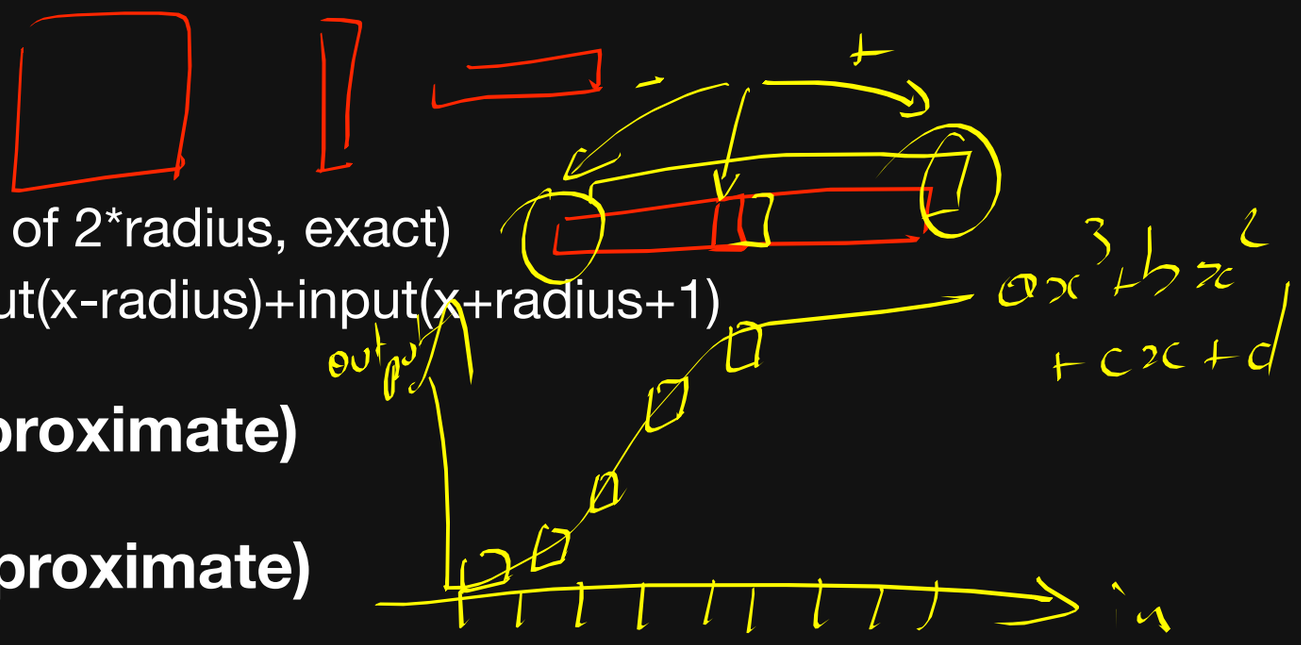
Sometimes exact, sometimes approximate

e.g. Fast box blur

Separable (exact)

Incremental (3 taps instead of 2*radius, exact)

(box(x+1)=box(x)+input(x-radius)+input(x+radius+1)



e.g. Bilateral Grid (approximate)

e.g. lookup tables (approximate)

See e.g. Andrew Adams' slides http://www.stanford.edu/class/cs448f/lectures/2.2/Fast%20Filtering.pdf

Algorithmic acceleration (not today's topic though)

e.g. Fast Gaussian blur

Separable (exact)

Recursive (approximate)

Iterated Box (approximate)

FFT (exact up to wraparound)

See e.g. Andrew Adams' slides

http://www.stanford.edu/class/cs448f/lectures/2.2/Fast%20Filtering.pdf

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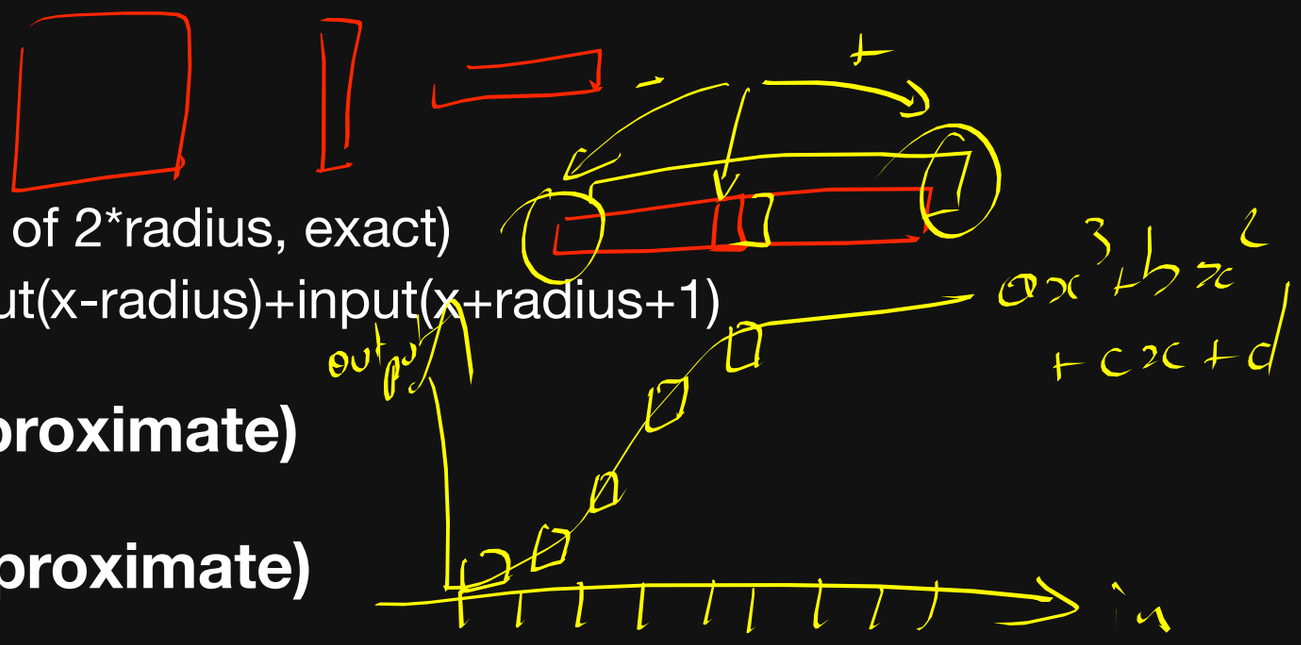

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Making image processing faster

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Faster programming language

Faster Hardware

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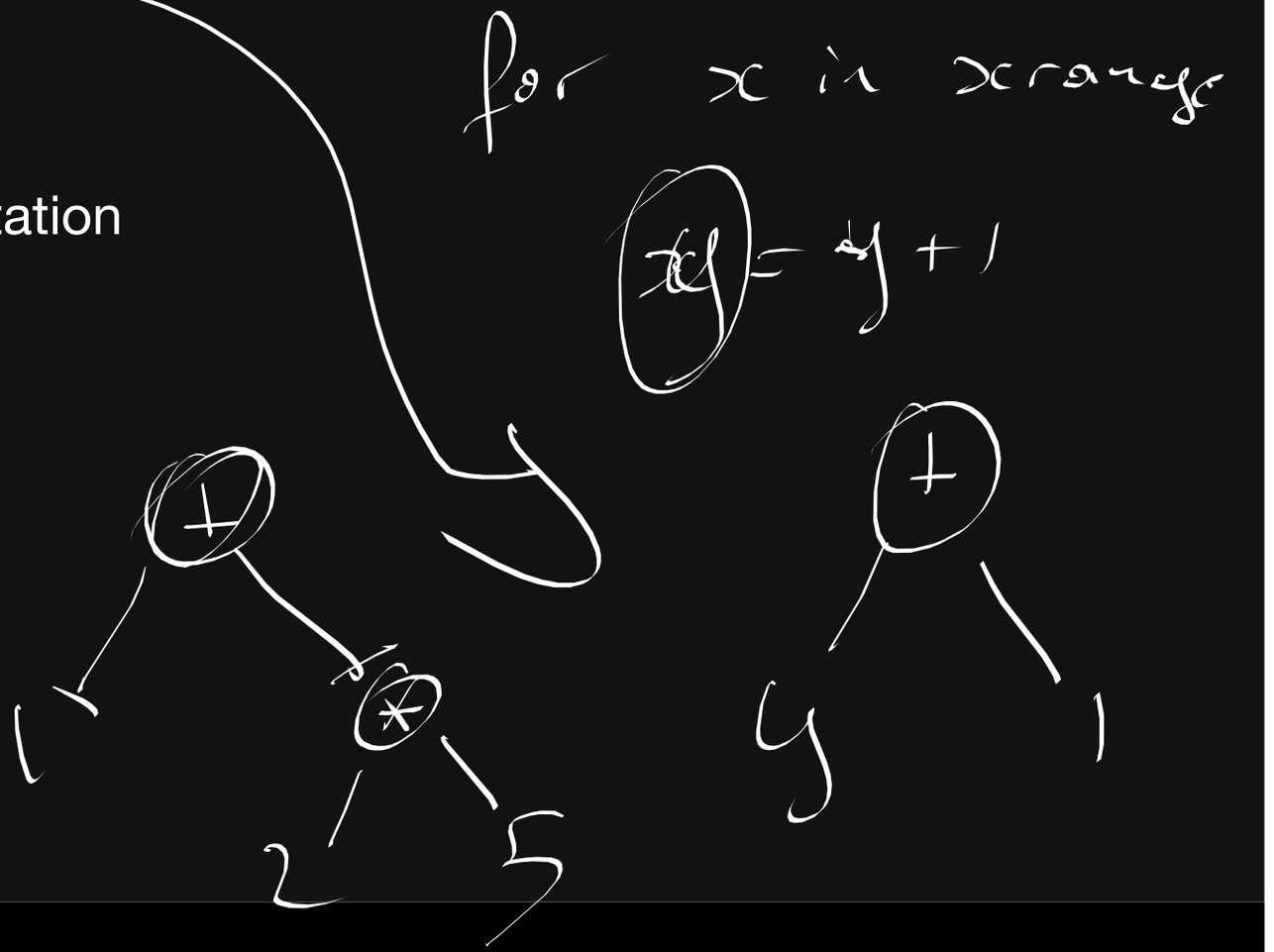
Faster programming language

Python is slow because it's interpreted:

Parse (syntax)
verify syntax
translate into internal representation

Execute (semantics)

All this takes time!
for us, mostly execution



e.g. Norvig's (very concise) scheme interpreter

```
def eval(x, env=global_env):
 "Evaluate an expression in an environment."
 if isa(x, Symbol):              # variable reference
     return env.find(x)[x]
 elif not isa(x, list):          # constant literal
     return x
 elif x[0] == 'quote':           # (quote exp)
     (_, exp) = x
     return exp
 elif x[0] == 'if':              # (if test conseq alt)
     (_, test, conseq, alt) = x
     return eval((conseq if eval(test, env) else alt), env)
 elif x[0] == 'set!':            # (set! var exp)
     (_, var, exp) = x
     env.find(var)[var] = eval(exp, env)
 elif x[0] == 'define':          # (define var exp)
     (_, var, exp) = x
     env[var] = eval(exp, env)
 elif x[0] == 'lambda':          # (lambda (var*) exp)
     (_, vars, exp) = x
     return lambda *args: eval(exp, Env(vars, args, env))
 elif x[0] == 'begin':           # (begin exp*)
     for exp in x[1:]:
         val = eval(exp, env)
     return val
 else:                           # (proc exp*)
     exps = [eval(exp, env) for exp in x]
     proc = exps.pop(0)
     return proc(*exps)

isa = isinstance

Symbol = str
```

http://norvig.com/lispy.html

Some interpreters

http://norvig.com/lispy.html

http://www.jayconrod.com/posts/37/a-simple-interpreter-from-scratch-in-python-part-1

http://mitpress.mit.edu/sicp/full-text/book/book-Z-H-26.html#%%5Fsec%5F4.1

Faster programming language

Python is slow because it's interpreted

Switch to a compiled language

typically C, C++

Java is intermediate (just-in-time compilation)

There are compilers for Python, e.g. pypy

BTW, numpy code is compiled.

Box blur in C

```
void blur(const Image &in, Image &blurred) {
    Image tmp(in.width(), in.height());
    for (int y = 0; y < in.height(); y++)
        for (int x = 0; x < in.width(); x++)
            tmp(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++)
            blurred(x, y) = (tmp(x, y-1) + tmp(x, y) + tmp(x, y+1))/3;
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Recall Python: 6.4 s/ megapixel

Box blur in C

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}
```

Recall Python: 6.4 s/ megapixel

C: 0.015s/megapixel

Faster hardware

Faster CPU

More GHZ

More parallelism (multicore, SIMD vector-unit). But hard to program

Better memory bandwidth

Graphics Hardware

Lots of parallelism

Can be annoying to program and debug (CUDA)

the free lunch is over

Same Instruction Multiple Data

as opposed to MIMD

GPU

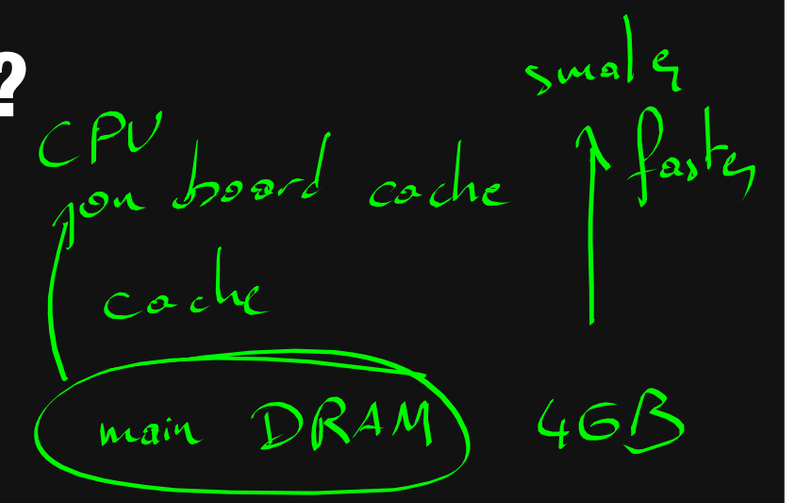
$\vec{v} + \vec{u}$

Can we do better?

Parallelism

Good cache coherence

Requires to reorganize computation!



smaller ↑ faster

cache

RAM 4GB

blur 1

for y

for x

out =

for each tile

for yo

for xo

hori

for yi

for xi

out...

merge two stages

verti

for yi

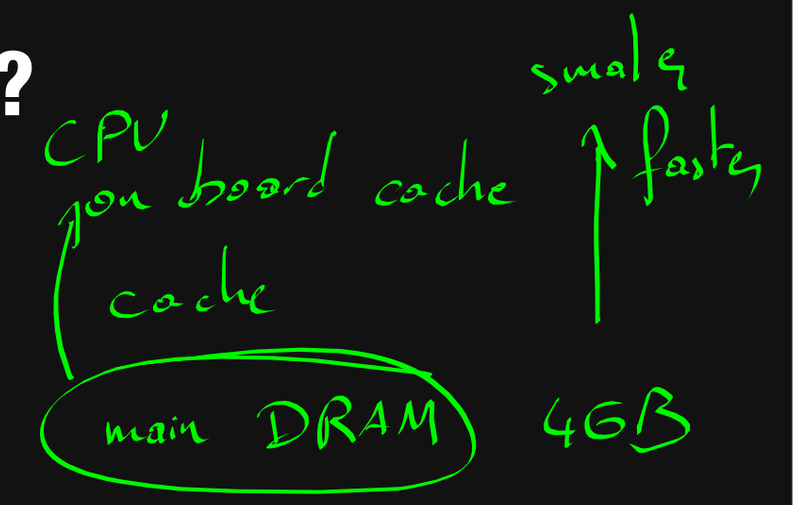
for xi

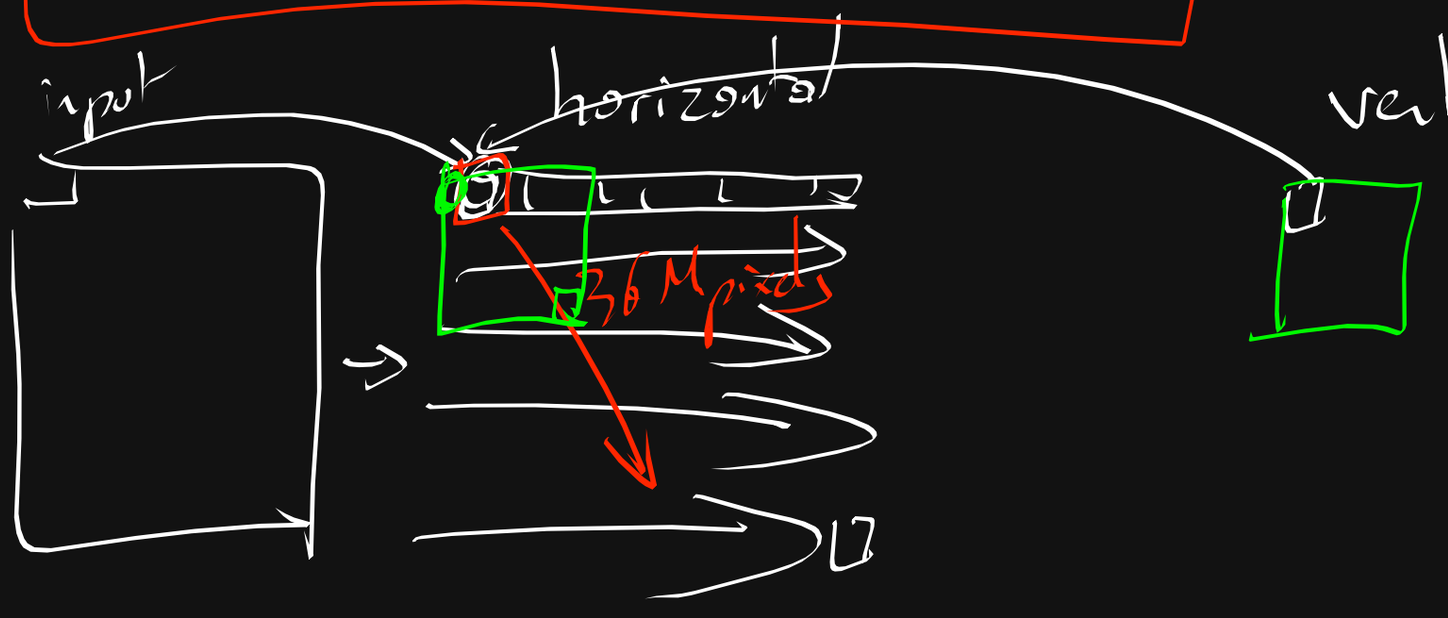
Can we do better?

Parallelism

Good cache coherence

Requires to reorganize computation!





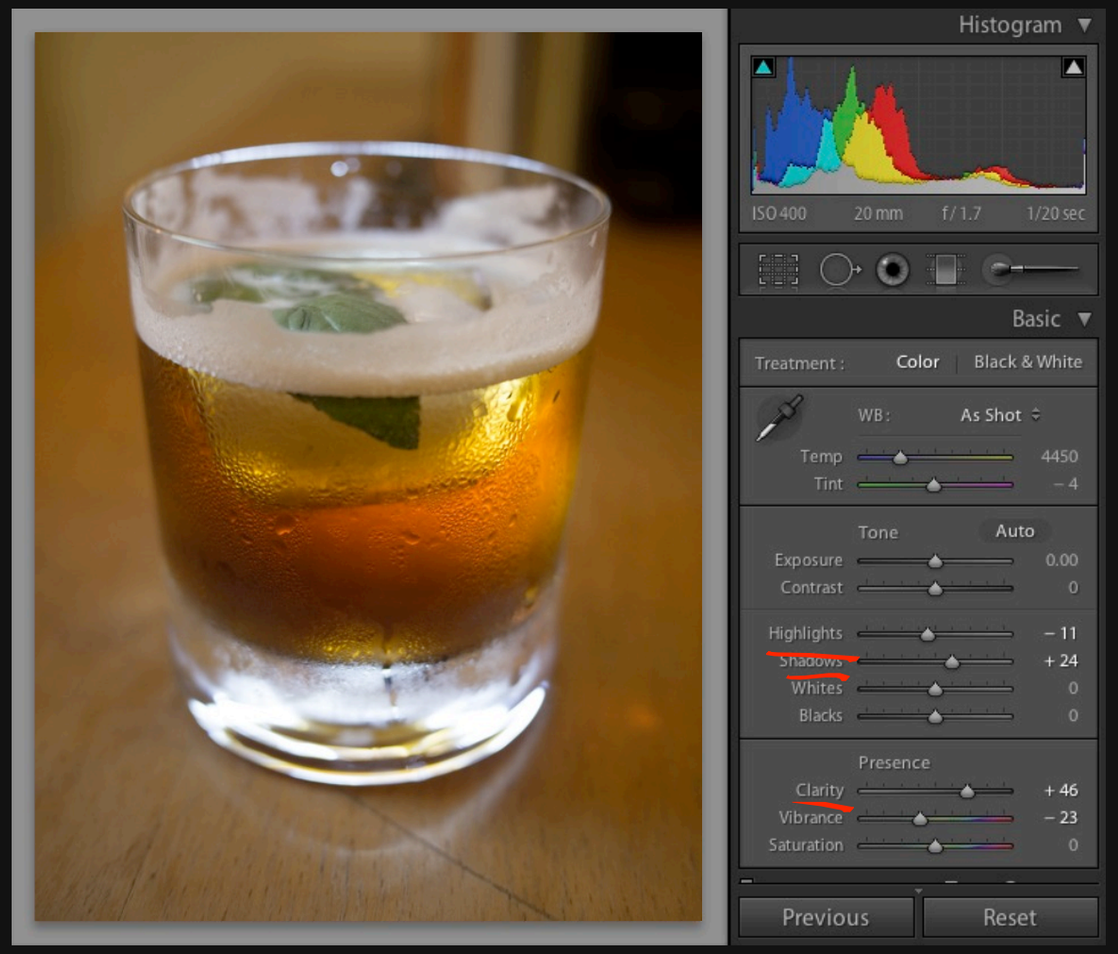
e.g. Local Laplacian Filtering

Reference: 300 lines C++

Adobe: 1500 lines

3 months of work

10x faster *(vs. reference)*



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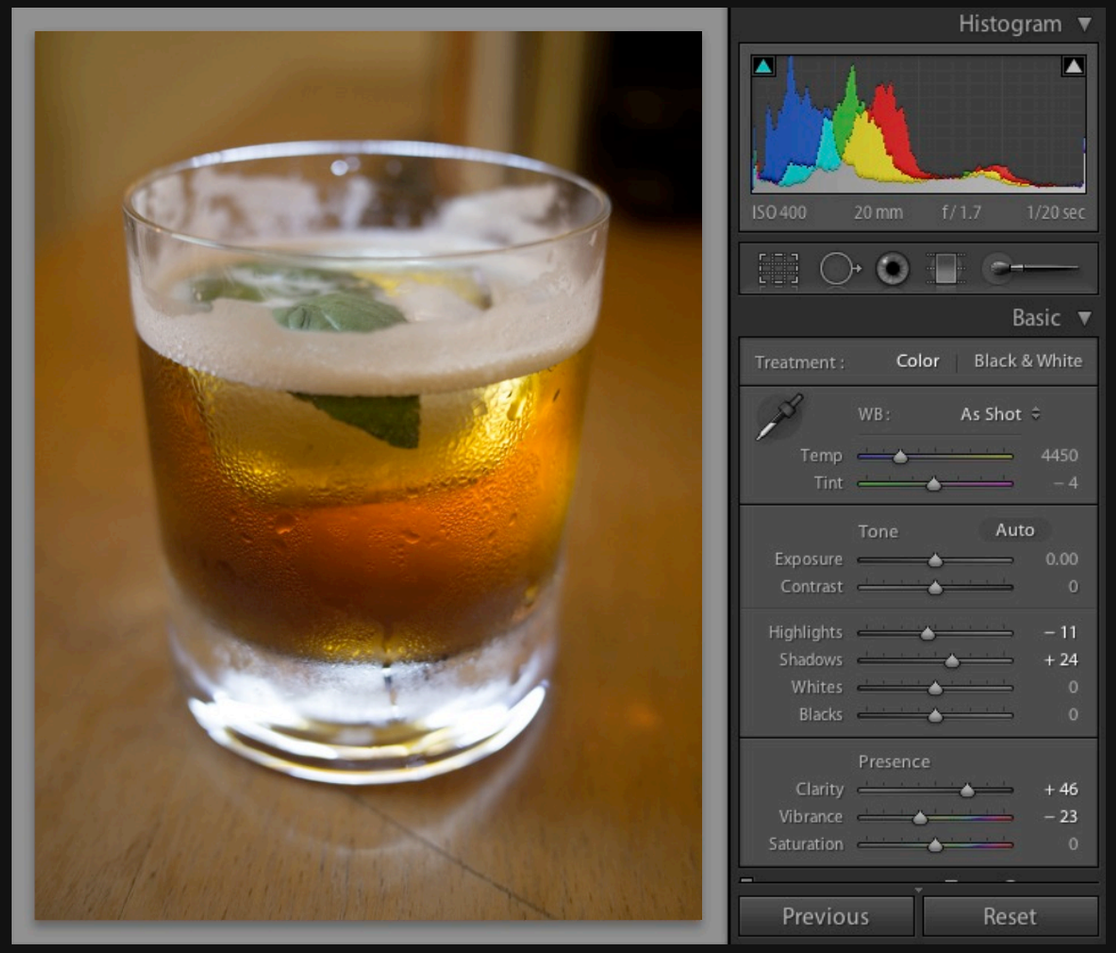
Parallelize (multicore)

Parallelize (SIMD vectorization)

Organized into tiles to maximize locality

Other tricks



Decoupling Algorithms from the Organization of Computation for High-Performance Graphics & Imaging

Jonathan Ragan-Kelley
MIT CSAIL

Graphics & Imaging are
orders of magnitude
from **“good enough”**

Simpler, Faster, Scalable

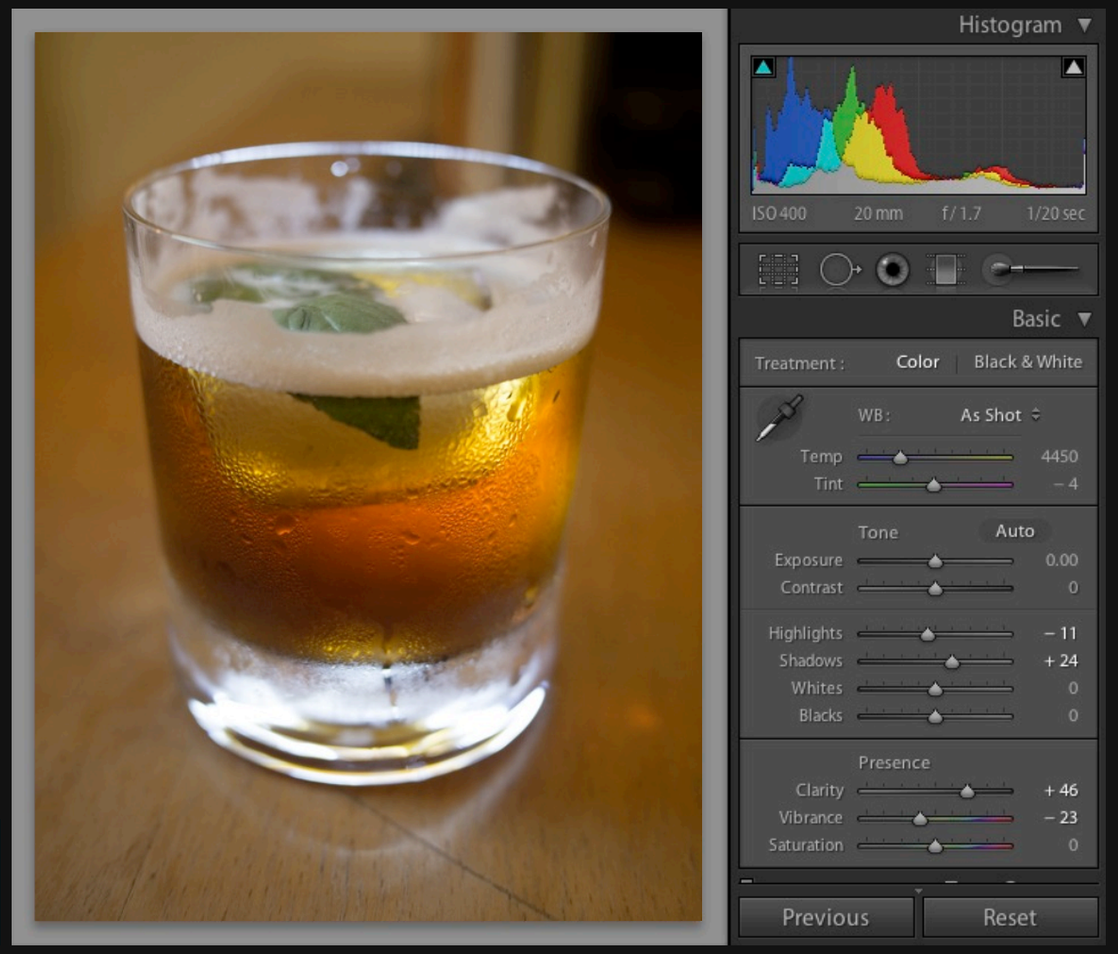
Reference: 300 lines C++

Adobe: 1500 lines
3 months of work
10x faster *(vs. reference)*

Halide: 60 lines
1 intern-day

20x faster (vs. reference)
2x faster (vs. Adobe)

GPU: 70x faster (vs. reference)



How can we get there?

Parallelism
“Moore’s law” growth will require exponentially more parallelism.

How can we get there?

Parallelism
“Moore’s law” growth will require exponentially more parallelism.

Locality
Data should move as little as possible.

Communication dominates computation
in both energy and time

Operation (32-bit operands)	**Energy/Op** (28 nm)	***Cost*** *(vs. ALU)*
ALU op	**1 pJ**	**-**
Load from SRAM	1-5 pJ	*5x*
Move 10mm on-chip	32 pJ	*32x*
Send off-chip	500 pJ	*500x*
Send to DRAM	1 nJ	*1,000x*
Send over LTE	>10 µJ	*10,000,000x*

data from John Brunhaver, Bill Dally, Mark Horowitz

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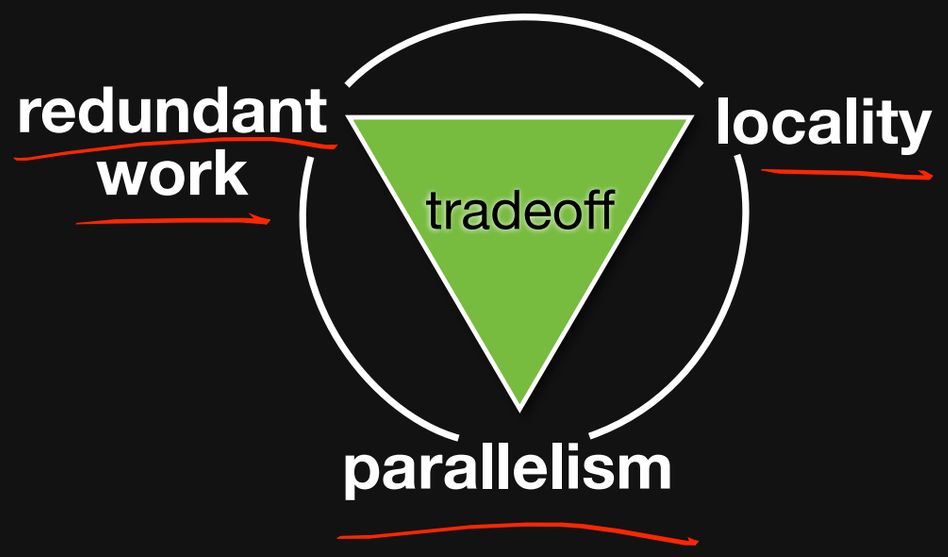
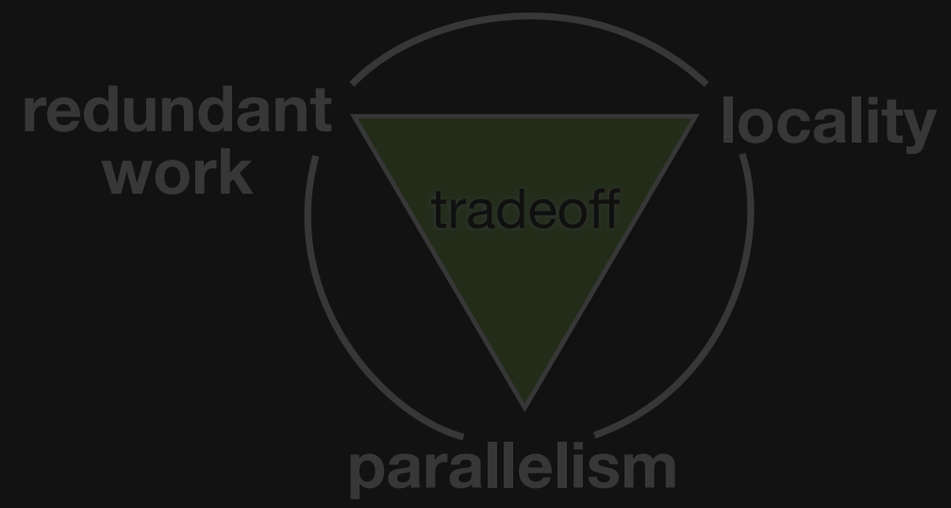
Message #1: Performance requires complex tradeoffs



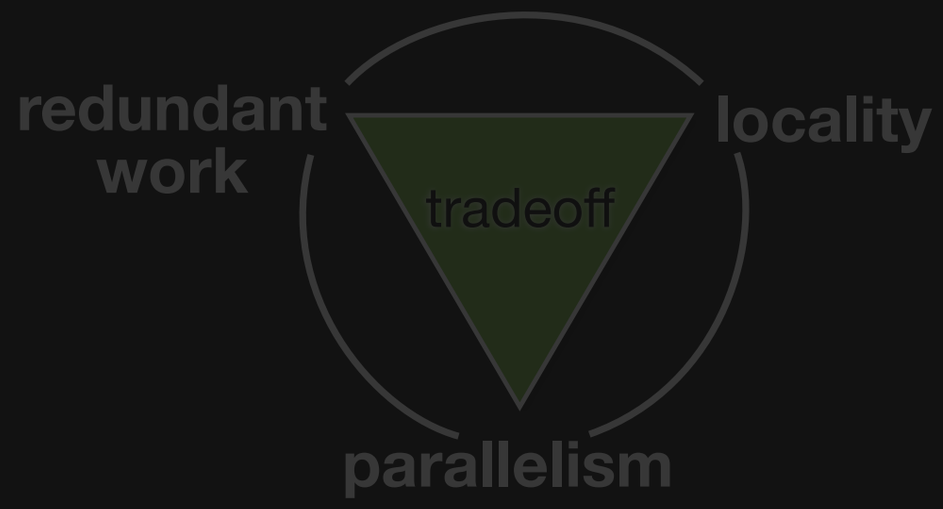
Where does performance come from?



Where does performance come from?

Program

Hardware

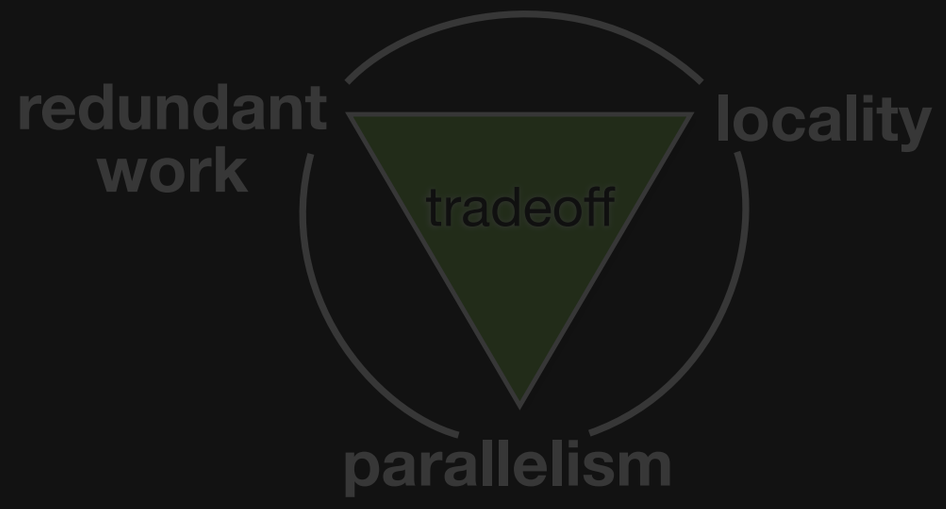


Message #2: organization of computation
is a first-class issue

Program:

Program

Hardware



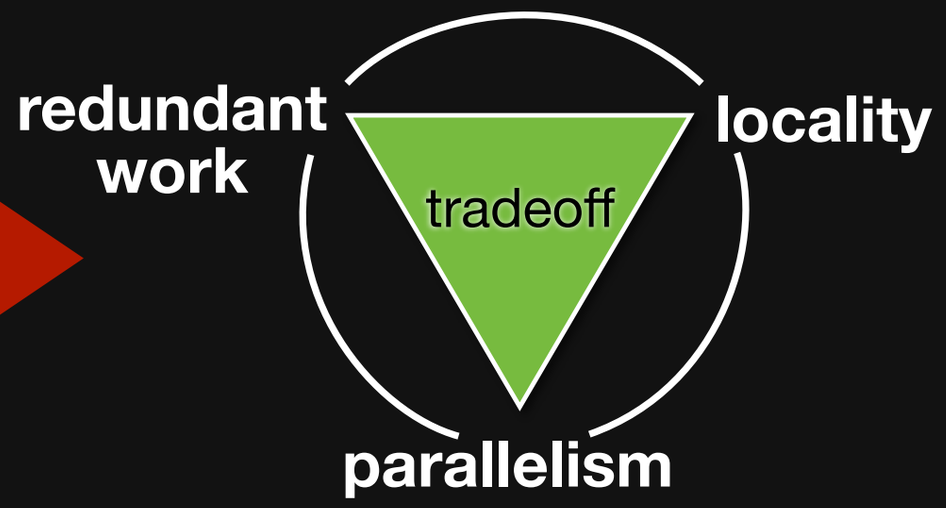
Message #2: organization of computation
is a first-class issue

Program:

Algorithm

Organization of computation

Hardware

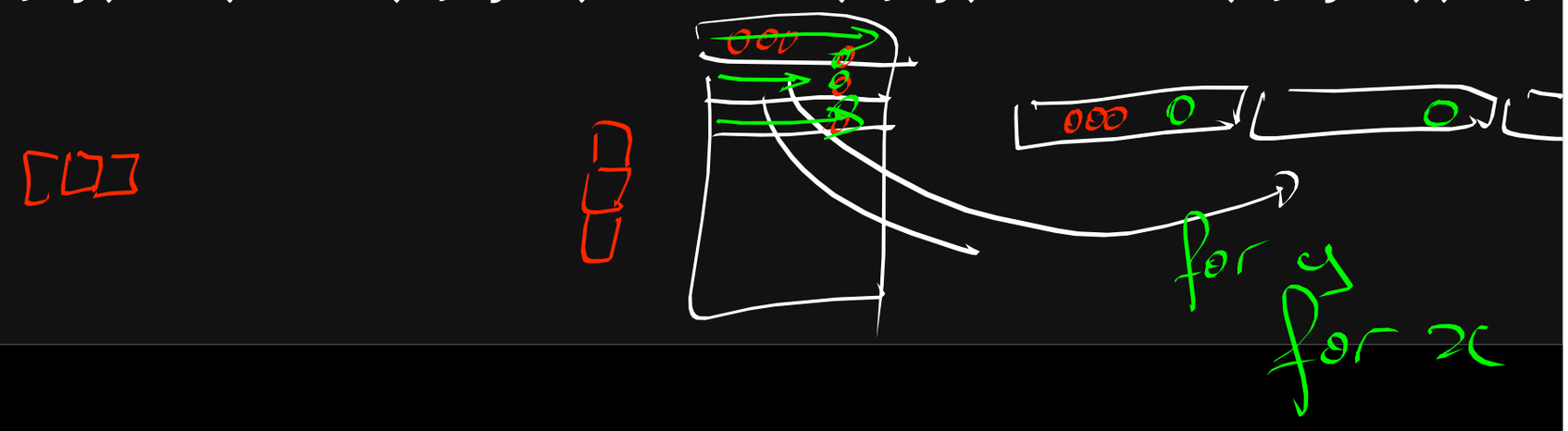


Algorithm vs. Organization: 3x3 blur

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



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  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;
}
```

Same algorithm, different organization

Algorithm vs. Organization: 3x3 blur

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      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;
}
```

Same algorithm, different organization

One of them is 15x faster

Why does swapping loops make things slower?

Why does swapping loops make things slower?

Memory behavior

Images are layed out linearly in memory.

More coherence along scanlines

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);
}}}}}
```

Tiled, fused

Vectorized

Multithreaded

Redundant computation

Near roof-line optimum

```
void box_filter_3x3(const Image &in, Image &blury) {
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      __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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          avg = _mm_mulhi_epi16(sum, one_third);
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        }}
      blurxPtr = blurx;
      for (int y = 0; y < 32; y++) {
        __m128i *outPtr = (__m128i *)(&(blury[yTile+y][xTile]));
        for (int x = 0; x < 256; x += 8) {
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```

parallism

hori

verti

redundant

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) {
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11x faster
(quad core x86)

Tiled, fused

Vectorized

Multithreaded

Redundant computation

Near roof-line optimum

(Re)organizing computation is hard

Optimizing parallelism, locality requires
transforming program & data structure.

What transformations are *legal?*

What transformations are *beneficial?*

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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);
```