Writing high performance code

CS448h
Nov. 3, 2015

Overview

Is it slow?	deciding when to optimize
Where is it slow?	identifying bottlenecks
How slow is it?	estimating potential
Why is it slow?	reasons for bottlenecks
How can I make it faster?	levers you have

Is it slow?

deciding when to optimize

Yes.*

* but you should only care if:

- it’s a critical path
- you have real-time constraints
- you will make new things feasible
- someone will pay you $$$

Where is it slow?

identifying bottlenecks

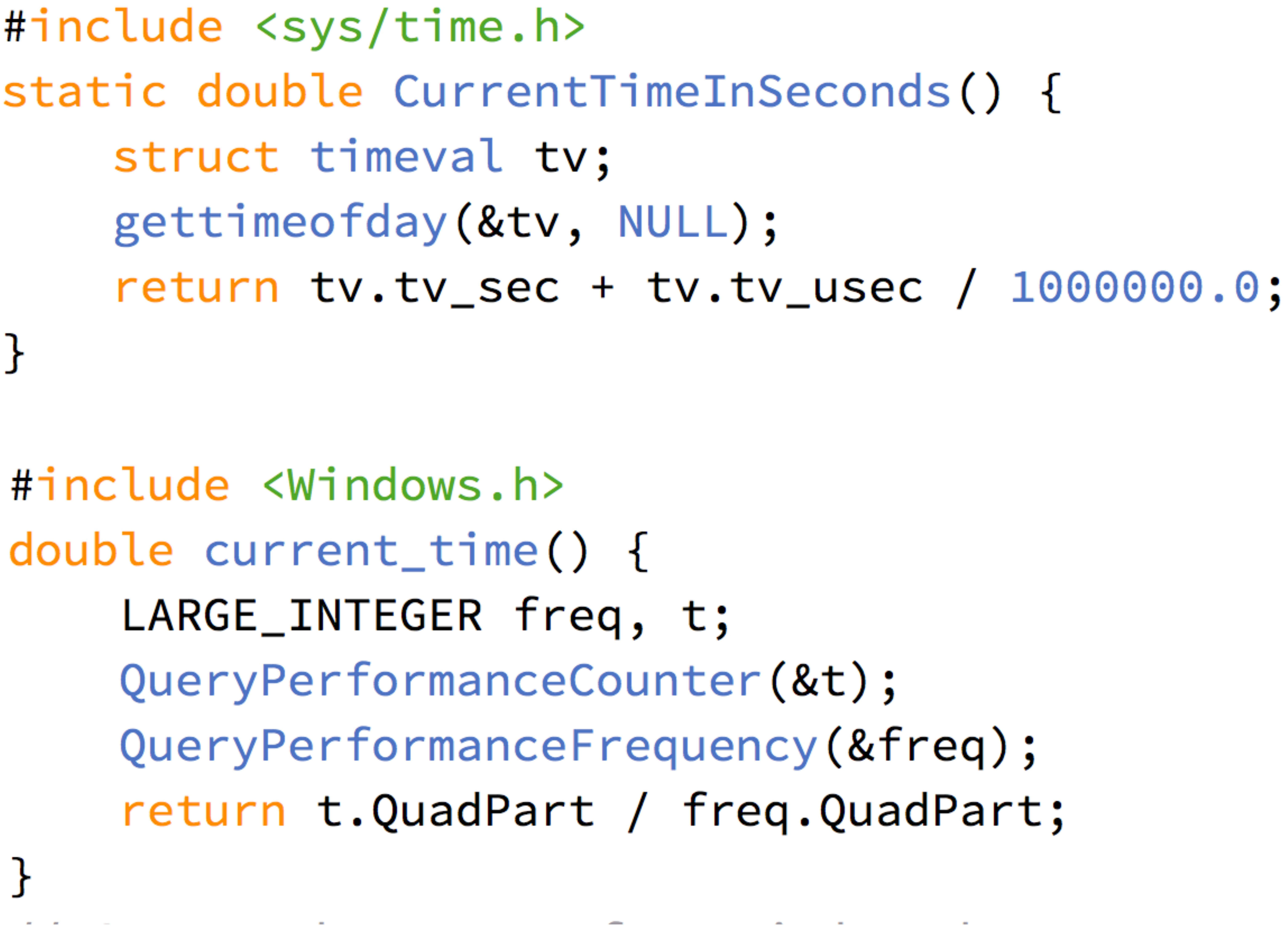
Tools for analysis

Timers

Profilers

Reading generated code (assembly)

Tool #1: Timers



```
#include <sys/time.h>
static double CurrentTimeInSeconds() {
    struct timeval tv;
    gettimeofday(&tv, NULL);
    return tv.tv_sec + tv.tv_usec / 1000000.0;
}

#include <Windows.h>
double current_time() {
    LARGE_INTEGER freq, t;
    QueryPerformanceCounter(&t);
    QueryPerformanceFrequency(&freq);
    return t.QuadPart / freq.QuadPart;
}
```

SCIENCE!

(demo time)

Tool #2: Profiling - Performance Counters

Each core has performance counters for key events:

e.g elapsed cycles, instructions executed, L1-cache hit, L2-cache miss, branch mis-predict

Can be configured to interrupt the CPU when the counter >= threshold.

Used to *sample* the execution of the program

Very low overhead (often < 5%)

perf-tools on linux, Instruments on Mac

Perf-Tools

Install (ubuntu)

```
$ apt-get install linux-tools-common linux-base

$ perf

perf_<version> not found

You may need to install linux-tools-<version>

$ apt-get install linux-tools-<version>
```

Print common counters

```
$ perf stat <your cmd>
```

Record profiling info

```
$ perf record -g <your cmd>
```

Display profiling results

```
$ perf report -M intel
```

EXAMPLE

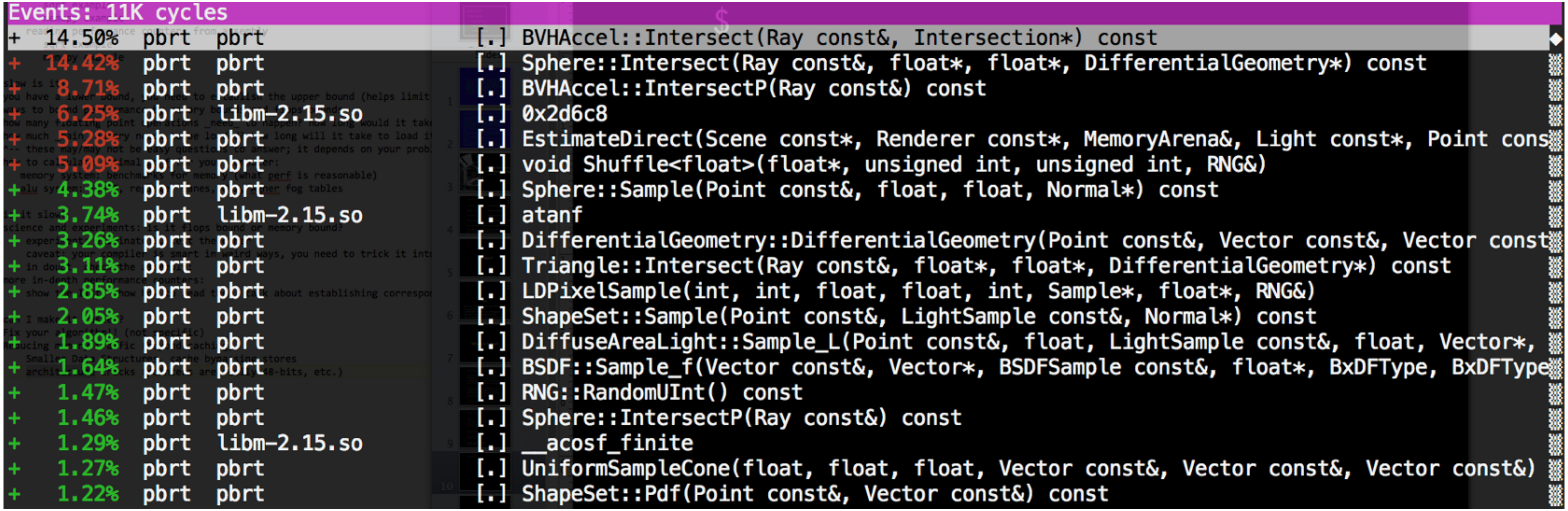
```
$ perf stat my/binary --arg 1
 Performance counter stats for ‘my/binary --arg 1’:
      82627.485530 task-clock                #    7.858 CPUs utilized
             9,158 context-switches          #    0.000 M/sec
                15 CPU-migrations            #    0.000 M/sec
            11,847 page-faults               #    0.000 M/sec
   305,027,996,924 cycles                    #    3.692 GHz
   321,979,156,613 instructions              #    1.06  insns per cycle
    29,568,248,179 branches                  #  357.850 M/sec
       379,261,417 branch-misses             #    1.28% of all branches
      10.515014818 seconds time elapsed
$ perf stat -e r20D1 my/binary --arg 1
           725,894 r20D1
      10.607431962 seconds time elapsed
```

Code for specific counter
(man perf list for details)

EXAMPLE

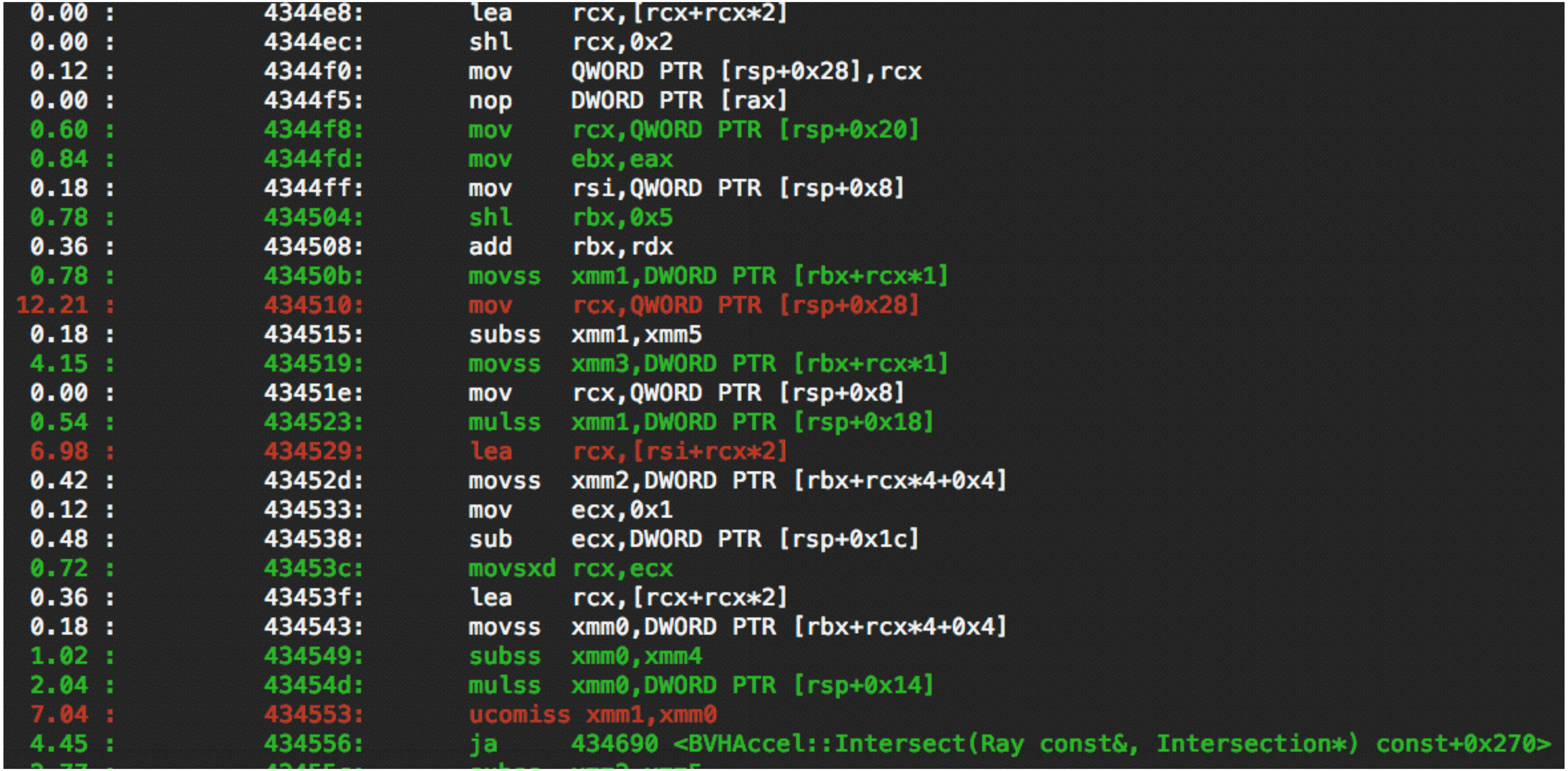
```
$ perf record -g ../src/bin/pbrt --ncores 1 killeroo-simple.pbrt
```

```
$ perf report -M intel
```



```
Events: 11K cycles
+  14.50%  pbrt  pbrt          [.] BVHAccel::Intersect(Ray const&, Intersection*) const
+  14.42%  pbrt  pbrt          [.] Sphere::Intersect(Ray const&, float*, float*, DifferentialGeometry*) const
+   8.71%  pbrt  pbrt          [.] BVHAccel::IntersectP(Ray const&) const
+   6.25%  pbrt  libm-2.15.so  [.] 0x2d6c8
+   5.28%  pbrt  pbrt          [.] EstimateDirect(Scene const*, Renderer const*, MemoryArena&, Light const*, Point cons
+   5.09%  pbrt  pbrt          [.] void Shuffle<float>(float*, unsigned int, unsigned int, RNG&)
+   4.38%  pbrt  pbrt          [.] Sphere::Sample(Point const&, float, float, Normal*) const
+   3.74%  pbrt  libm-2.15.so  [.] atanf
+   3.26%  pbrt  pbrt          [.] DifferentialGeometry::DifferentialGeometry(Point const&, Vector const&, Vector const
+   3.11%  pbrt  pbrt          [.] Triangle::Intersect(Ray const&, float*, float*, DifferentialGeometry*) const
+   2.85%  pbrt  pbrt          [.] LDPixelSample(int, int, float, float, int, Sample*, float*, RNG&)
+   2.05%  pbrt  pbrt          [.] ShapeSet::Sample(Point const&, LightSample const&, Normal*) const
+   1.89%  pbrt  pbrt          [.] DiffuseAreaLight::Sample_L(Point const&, float, LightSample const&, float, Vector*,
+   1.64%  pbrt  pbrt          [.] BSDF::Sample_f(Vector const&, Vector*, BSDFSample const&, float*, BxDFType, BxDFType
+   1.47%  pbrt  pbrt          [.] RNG::RandomUInt() const
+   1.46%  pbrt  pbrt          [.] Sphere::IntersectP(Ray const&) const
+   1.29%  pbrt  libm-2.15.so  [.] __acosf_finite
+   1.27%  pbrt  pbrt          [.] UniformSampleCone(float, float, float, Vector const&, Vector const&, Vector const&)
+   1.22%  pbrt  pbrt          [.] ShapeSet::Pdf(Point const&, Vector const&) const
```

EXAMPLE



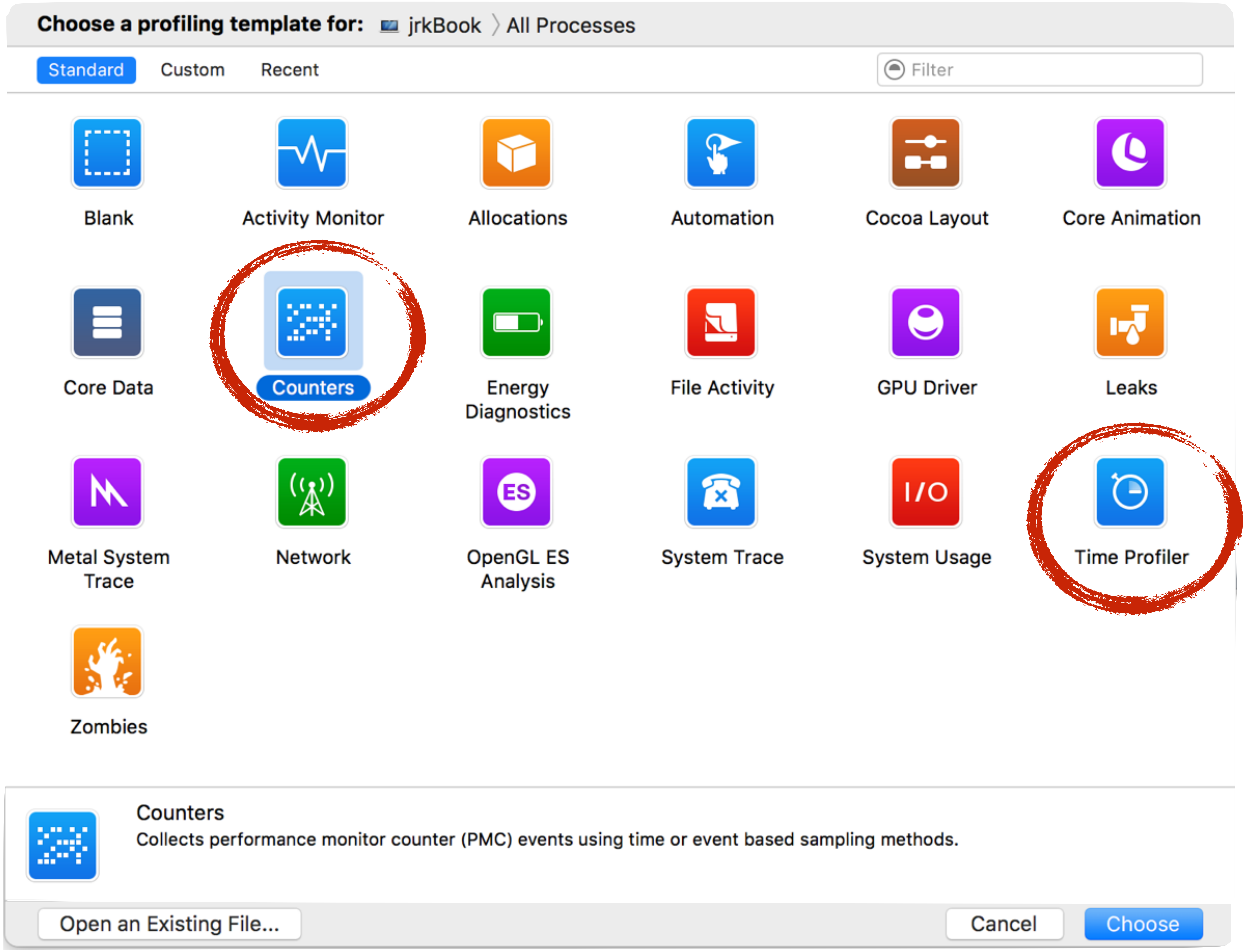
```
 0.00 :          4344e8:       lea    rcx,[rcx+rcx*2]
 0.00 :          4344ec:       shl    rcx,0x2
 0.12 :          4344f0:       mov    QWORD PTR [rsp+0x28],rcx
 0.00 :          4344f5:       nop    DWORD PTR [rax]
 0.60 :          4344f8:       mov    rcx,QWORD PTR [rsp+0x20]
 0.84 :          4344fd:       mov    ebx,eax
 0.18 :          4344ff:       mov    rsi,QWORD PTR [rsp+0x8]
 0.78 :          434504:       shl    rbx,0x5
 0.36 :          434508:       add    rbx,rdx
 0.78 :          43450b:       movss  xmm1,DWORD PTR [rbx+rcx*1]
12.21 :          434510:       mov    rcx,QWORD PTR [rsp+0x28]
 0.18 :          434515:       subss  xmm1,xmm5
 4.15 :          434519:       movss  xmm3,DWORD PTR [rbx+rcx*1]
 0.00 :          43451e:       mov    rcx,QWORD PTR [rsp+0x8]
 0.54 :          434523:       mulss  xmm1,DWORD PTR [rsp+0x18]
 6.98 :          434529:       lea    rcx,[rsi+rcx*2]
 0.42 :          43452d:       movss  xmm2,DWORD PTR [rbx+rcx*4+0x4]
 0.12 :          434533:       mov    ecx,0x1
 0.48 :          434538:       sub    ecx,DWORD PTR [rsp+0x1c]
 0.72 :          43453c:       movsxd rcx,ecx
 0.36 :          43453f:       lea    rcx,[rcx+rcx*2]
 0.18 :          434543:       movss  xmm0,DWORD PTR [rbx+rcx*4+0x4]
 1.02 :          434549:       subss  xmm0,xmm4
 2.04 :          43454d:       mulss  xmm0,DWORD PTR [rsp+0x14]
 7.04 :          434553:       ucomiss xmm1,xmm0
 4.45 :          434556:       ja     434690 <BVHAccel::Intersect(Ray const&, Intersection*) const+0x270>
```

Instruments

Part of Xcode

Very easy to use

Pick a template, *attach* to a process


Choose a profiling template for: jrkBook 〉 All Processes

Counters
Collects performance monitor counter (PMC) events using time or event based sampling methods.

Profilers are cool, but don’t be seduced by tools

For most analysis, timers + printf are all you need, and give you total control over your experiments.

Tool #3: reading the assembly

Good idea: look at the assembly of whatever you’re timing to sanity check what it’s doing, spot anything suspicious.

x86 isn’t MIPS, but it’s *not that hard* to learn to skim.

READING X86 ASSEMBLY

Two syntaxes exist:

intel: `movss   xmm1,DWORD PTR [rbx+rcx*1]`

at&t: `movss   (%rbx,%rcx,1),%xmm1`

Intel's manual uses Intel syntax (surprise!), Linux by default uses AT&T, but tools have options

Recommendation: use Intel syntax

documented by the manuals

may be easier to read

X86 REGISTERS

16 64-bit general purpose reg (for integers and pointers):

```
RAX RBX RCX RDX RSI RDI RBP RSP <- stack pointer
R8  R9  R10 R11 R12 R13 R14 R15
```

16 General Purpose 128/256-bit SSE/AVX registers (for floating point and vectors):

```
XMM0/YMM0 through XMM15/YMM15
```

```
RIP <- instruction pointer, used to address constants
```

Smaller registers have different names (e.g. lower 32-bits of RAX is EAX)

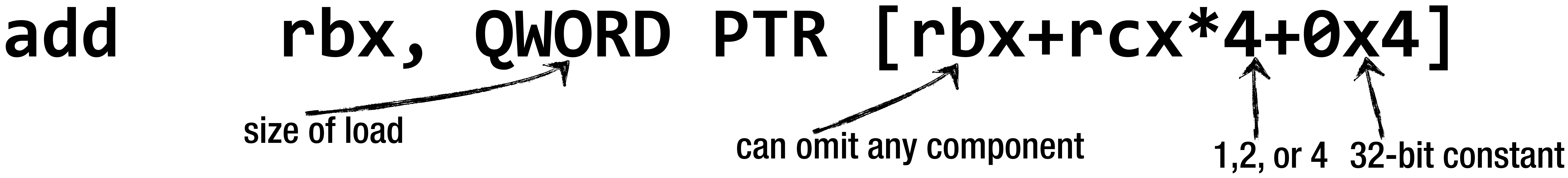
There are other registers, we don’t need to talk about them

AN X86 INSTRUCTION

dest, src; 2-Op rather than 3-Op:

```
add     rbx,rdx     rbx = rbx + rdx
```

most instructions can take a memory location as the source (but not the dest):



```
add     rbx, QWORD PTR [rbx+rcx*4+0x4]
```

size of load

can omit any component

1,2, or 4

32-bit constant

```
rbx = rbx + MEMORY[rbx+rcx*4 + 0x4]
```

STORES AND LOADS

Load Constant:

```
mov     ecx,0x1    ecx = 0x1
```

Store:

```
mov     QWORD PTR [rsp+0x20],rsi
MEMORY[rsp + 0x20] = rsi
```

Load:

```
mov     rsi, QWORD PTR [rsp+0x20]
rsi = MEMORY[rsp + 0x20]
```

BRANCHING

```
cmp     rax, rbp    //sets comparison flags
je      434610      //examines flags to decide
```

```
if(rax == rbp) goto address 434610
```

Knowing how instructions sets the flags is basically black magic (i.e. you look it up in the manual if you need to know)

How slow is it?

estimating peak performance potential

BOUNDING PEAK PERFORMANCE

Before optimizing, we want to get an idea of how much faster we can make something. Is it even worth pursuing?

We have a lower bound: our current code

We want to estimate an optimistic upper bound.*

*many people don’t do this (even in academic papers!) and don’t know when to stop trying

Key concept: *bottlenecks*

Compute

FLOPS, IPC

Bandwidth

to memory, caches, of ports, …

UPPER BOUND ON PERFORMANCE

Based on fundamental limits in the hardware

Throughput of main mem

~25GB/s peak*

Memory bound

Throughput of instructions (i ons-per-clock)

~1-5 IPC / core, dep truction mix*

Compute bound

*for an i7-3770K with a dual channel memory controller

MEMORY LIMITS

cache	layout	latency	measured bw
L1 code	32 kB, 8 way, 64 B line size, per core	4 cycles	~100 GB/s
L1 data	32 kB, 8 way, 64 B line size, per core	4 cycles	~100 GB/s
L2	256 kB, 8 way, 64 B line size, per core	~12 cycles	~50 GB/s
L3	up to 16 MB, 12 way, 64 B line size, shared	~20 cycles	~33 GB/s
Main		hundreds of cycles	~20 GB/s

From: http://www.agner.org/optimize/microarchitecture.pdf

OP LIMITS

Port	type	op	max size	latency
1	float	fp add	256	**3**
0	float	fp mul	256	**5**
0	float	fp div and sqrt	128	**10--22**
5	float	fp mov, shuffle	256	1
5	float	fp boolean	256	1
2	load	memory read	128	*
3	load	memory read	128	*
4	store	memory write	128	*

From:
http://www.agner.org/optimize/microarchitecture.pdf

Port	type	op	max size	latency
0	int	move	128	1
1	int	move	128	1
5	int	move	128	1
0	int	add	128	1
1	int	add	64	1
5	int	add	128	1
0	int	Boolean	128	1
1	int	Boolean	128	1
5	int	Boolean	128	1
1	int	multiply	128	**3**
0	int	shift	64	1
1	int	shift	128	1
5	int	shift	64	1
0	int	pack	128	1
5	int	pack	128	1
0	int	shuffle	128	1
5	int	shuffle	128	1
5	int	jump	64	1

EXAMPLE: MEMCPY

```
void mymemcpy1(void *destv,
               void *srcv, int nbytes) {
   char *dest = (char*)destv;
   char *src = (char*)srcv;
   for(int i = 0; i < nbytes; i++)
      dest[i] = src[i];
}
```

Compute bound?

not clear how many instructions we need to execute...

Memory Bound?

the copy cannot be faster than the time it takes to read nbytes from memory and then write nbytes to memory

Memory bandwidth is:

~~`2*nbytes/elapsed_time`~~

`3*nbytes/elapsed_time`

writing a byte requires reading the entire cache-line from main memory so it counts as 1 read + 1 write!

MEASURING OUR LOWER BOUND

```
__attribute__((__noinline__)) //force it not to inline so it can’t optimize away
void mymemcpy1(void * destv, void * srcv, int bytes) { ... }

int main() {
  double * src = new double[N];
  double * dest = new double[N];
  for(int i = 0; i < N; i++) {
   src[i] = i;
   dest[i] = 0;//TOUCH ALL THE MEMORY BEFORE YOU START TIMING!!!!!
               // the OS will only actually give you the memory
               // when you write to it
  }

  double start = current_time();
  //sample multiple runs to cover timer inaccuracy/noise
  for (int i = 0; i < 10; i++) mymemcpy1(dest,src,N*sizeof(double));
  double end = current_time();
  printf(“Throughput: %f GB/sec”, (10*N/(1024*1024*1024))/(end-start));
}
```

MEMCPY 1 RESULT:

1.79 GB/s copied

5.37 GB/s effective memory bandwidth

Out of a possible 20GB/s!

Why is it slow?

reasons for bottlenecks

TECHNIQUE 1: PERFORMANCE EXPERIMENTS

Is your code compute or memory bound?

Experiment 1

Halve core compute (e.g., FLOPS), fix memory access

Perf increases → probably compute bound

Experiment 2

Halve memory access, keep compute the same

Perf increases → probably memory bound

EXAMPLE EXPERIMENT

```
void sqrtv(double *dest,
           double *src, int N) {
   for(int i = 0; i < N; i++) {
     dest[i] = sqrt(src[i]);
   }
}
```

```
//Experiment 1: FLOPS
control1:
            dest[i] = sqrt(src[i]);       // 0.22 GHz
experimental1:
            dest[i] = i % 2 == 0 ? src[i] // 0.43 GHz
                        : sqrt(src[i])

//Experiment 2: Memory
control2:
            dest[i] = sqrt(src[i])        // 0.22 GHz
experimental2:
            dest[i/2] = sqrt(src[i/2])    // 0.22 GHz
```

TECHNIQUE 2: ESTIMATE

Recall mymemcpy1 results:

- 1.79 GB/s copied
- **5.37 GB/s effective** memory bandwidth
- **20 GB/s possible** bandwidth

It’s not memory bound, how many ops is it calculating? Let’s estimate it!

ESTIMATE OPS

```
(gdb) disas mymemcpy1(void*, void*, int)
Dump of assembler code for function _Z9mymemcpy1PvS_i:
   0x0000000000400720 <+0>:   test   edx,edx
   0x0000000000400722 <+2>:   jle    0x40073e <_Z9mymemcpy1PvS_i+30>
   0x0000000000400724 <+4>:   data32 data32 nop WORD PTR cs:[rax+rax*1+0x0]
   0x0000000000400730 <+16>:  mov    al,BYTE PTR [rsi]
   0x0000000000400732 <+18>:  mov    BYTE PTR [rdi],al
   0x0000000000400734 <+20>:  inc    rdi
   0x0000000000400737 <+23>:  inc    rsi
   0x000000000040073a <+26>:  dec    edx
   0x000000000040073c <+28>:  jne    0x400730 <_Z9mymemcpy1PvS_i+16>
   0x000000000040073e <+30>:  ret
```

ESTIMATE OPS

```
(gdb) disas mymemcpy1(void*, void*, int)
Dump of assembler code for function _Z9mymemcpy1PvS_i:
   0x0000000000400720 <+0>:    test   edx,edx
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   0x0000000000400734 <+20>:   inc    rdi
   0x0000000000400737 <+23>:   inc    rsi
   0x000000000040073a <+26>:   dec    edx
   0x000000000040073c <+28>:   jne    0x400730 <_Z9mymemcpy1PvS_i+16>
   0x000000000040073e <+30>:   ret
```

`6 Ops/iteration * niterations / elapsed_time`

`10.77 effective GOPS`

Note: it is much harder to estimate a realistic maximum IPC since it depends on how these instructions will get scheduled.

How can I make it faster?

levers you have for improving performance

Major levers for performance

Parallelism

threads/cores, vectors/SIMD, ILP

Locality

caches, registers, reuse

other*

* amount of work,
“code quality”

TRICKS FOR COMPUTE-BOUND CODE

- **Vectorize! 4/8-wide vectors will give you 4/8x FLOPS**
- **Parallelize! FLOPS scale linearly with *n* cores**
  - Threads don't have to be scary!
  - Use simple work queues, or just `#pragma omp parallel for`
- **Intel and AMD ship faster versions of math functions** (log, cos, exp)
  - Up to 2x faster!
  - Intel MKL (normally comes with ICC), AMD ACML

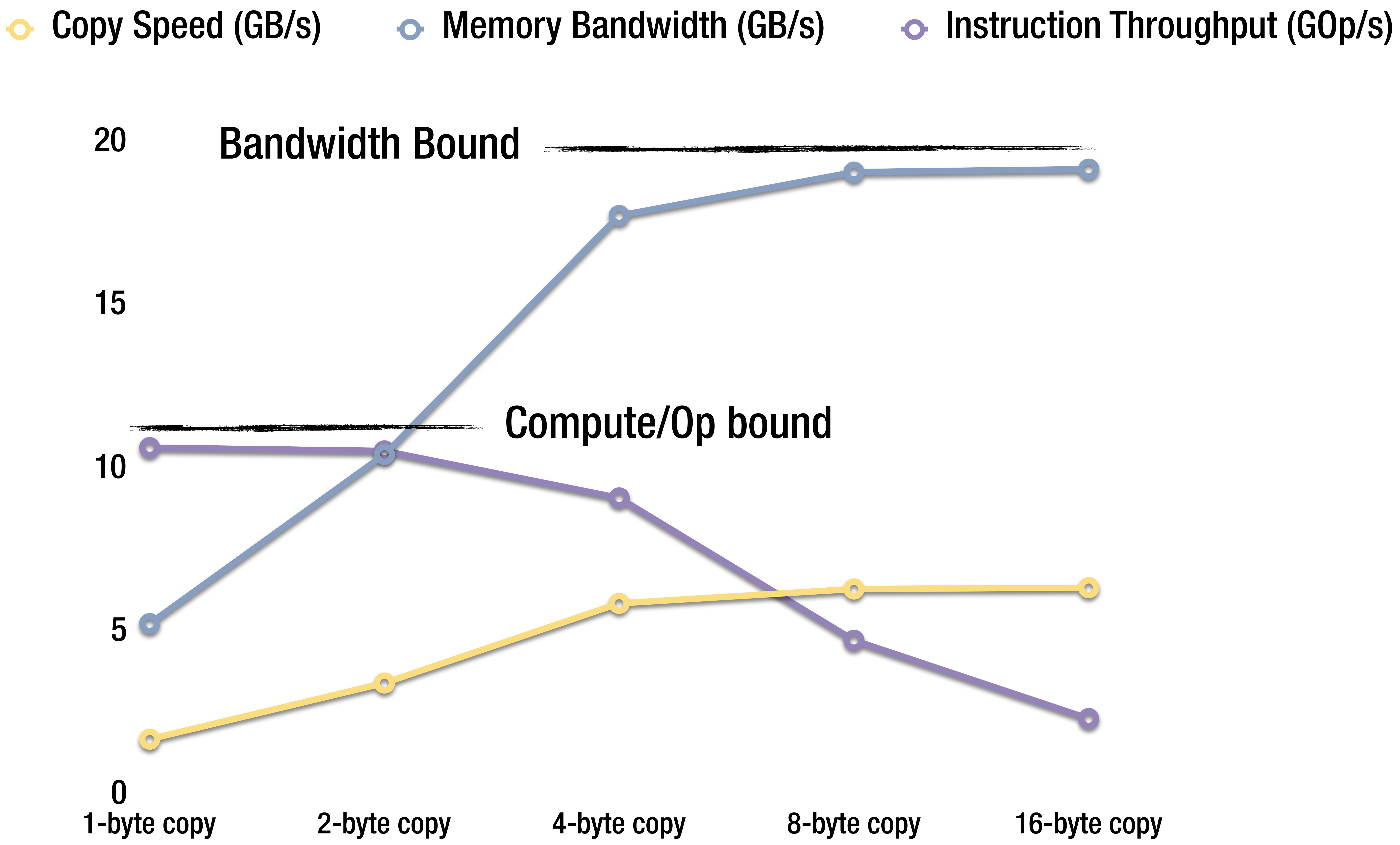
COMPUTE BOUND: REDUCE THE OPS

Process 2 bytes
in parallel

```
__attribute__((__noinline__))
void mymemcpy2(void * destv, void * srcv, int bytes) {
    short * dest = (short*) destv;
    short * src = (short*) srcv;
    bytes /= sizeof(short);
    for(int i = 0; i < bytes; i++)
        dest[i] = src[i];
}
```

Process *16 bytes*
in parallel

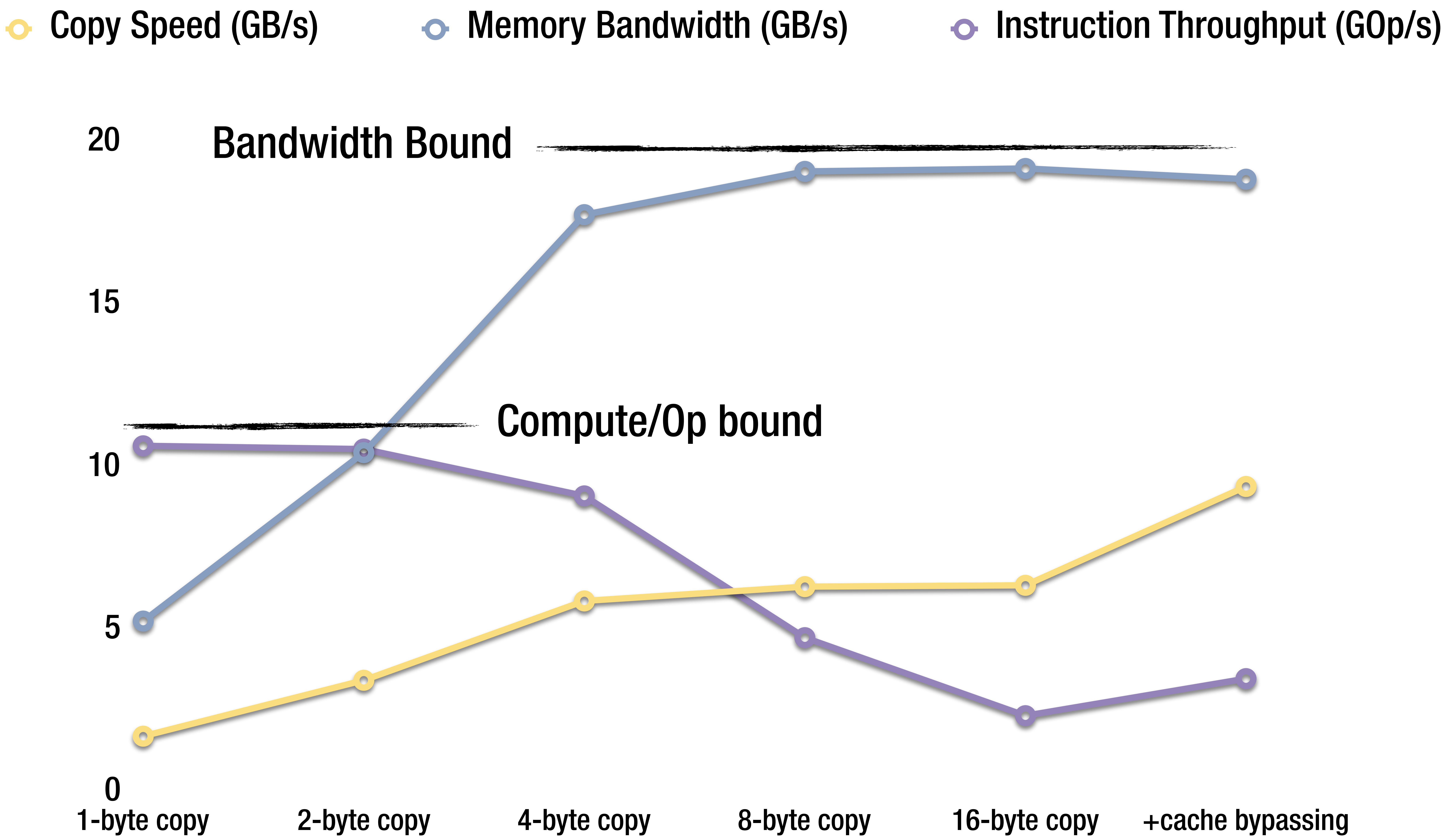
```
__attribute__((__noinline__))
void mymemcpy5(void * destv, void * srcv, int bytes) {
    float * dest = (float*) destv;
    float * src = (float*) srcv;
    bytes /= sizeof(float);
    for(int i = 0; i < bytes; i += 4) {
        _mm_store_ps(&dest[i],_mm_load_ps(&src[i]));
    }
}
```


Copy Speed (GB/s)
Memory Bandwidth (GB/s)
Instruction Throughput (GOp/s)
20
15
10
5
0
Bandwidth Bound
Compute/Op bound
1-byte copy
2-byte copy
4-byte copy
8-byte copy
16-byte copy

BANDWIDTH BOUND: REDUCE THE BANDWIDTH

```
__attribute__((__noinline__))
void mymemcpy5(void * destv, void * srcv, int bytes) {
   float * dest = (float*) destv;
   float * src = (float*) srcv;
   bytes /= sizeof(float);
   for(int i = 0; i < bytes; i += 4) {
      //_mm_store_ps(&dest[i],_mm_load_ps(&src[i]));
     _mm_stream_ps(&dest[i],_mm_load_ps(&src[i]));
 }
}
```

`_mm_stream_ps` is a cache-bypassing write.
If you write the entire cache line together it can skip the read
making the total bandwidth `2.0*nbytes/elapsed_time`



Bandwidth Bound

Compute/Op bound

TRICKS TO IMPROVE MEMORY BOUND CODE (CONT.)

Standard cache-blocking techniques

Cache-bypassing writes (where appropriate)

Parallelize: each core has its own L1 and L2, which makes blocking techniques more effective. However, this will *not* scale *main memory bandwidth* (usually/much).

Putting it all together…

let’s optimize something real!

Summary

Is it slow?	yes (but you might not care)
Where is it slow?	timers + profiling *(science!)*
How slow is it?	estimate peak potential
Why is it slow?	experiment, estimate costs
How can I make it faster?	parallelism, locality