Evaluating Computers: Bigger, better, faster, more?

What do you want in a computer?

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- Low latency -- one unit of work in minimum time
  - 1/latency = responsiveness
- High throughput -- maximum work per time
  - High bandwidth (BW)
- Low cost
- Low power -- minimum jules per time
- Low energy -- minimum jules per work
- Reliability -- Mean time to failure (MTTF)
- Derived metrics
  - responsiveness/dollar
  - BW/$
  - BW/Watt
  - Work/Jule
  - Energy * latency -- Energy delay product
  - MTTF/$

Latency

- This is the simplest kind of performance
- How long does it take the computer to perform a task?
  - The task at hand depends on the situation.
- Usually measured in seconds
- Also measured in clock cycles
  - Caution: if you are comparing two different system, you must ensure that the cycle times are the same.

Measuring Latency

- Stop watch!
- System calls
  - `gettimeofday()`
  - `System.currentTimeMillis()`
- Command line
  - `time <command>`

Where latency matters

- Application responsiveness
  - Any time a person is waiting.
  - GUIs
  - Games
  - Internet services (from the users perspective)
- “Real-time” applications
  - Tight constraints enforced by the real world
  - Anti-lock braking systems
  - Manufacturing control
  - Multi-media applications
- The cost of poor latency
  - If you are selling computer time, latency is money.

Latency and Performance

- By definition:
- Performance = 1/Latency
- If Performance(X) > Performance(Y), X is faster.
- If Perf(X)/Perf(Y) = S, X is S times faster than Y.
- Equivalently: Latency(Y)/Latency(X) = S

- When we need to talk about specifically about other kinds of "performance" we must be more specific.

The Performance Equation

- We would like to model how architecture impacts performance (latency)
- This means we need to quantify performance in terms of architectural parameters.
  - Instructions -- this is the basic unit of work for a processor
  - Cycle time -- these two give us a notion of time.
  - Cycles

- The first fundamental theorem of computer architecture:

Latency = Instructions * Cycles/Instruction * Seconds/Cycle

The Performance Equation

Latency = Instructions * Cycles/Instruction * Seconds/Cycle

- The units work out! Remember your dimensional analysis!
- Cycles/Instruction == CPI
- Seconds/Cycle == 1/hz
- Example:
  - 1GHz clock
  - 1 billion instructions
  - CPI = 4
  - What is the latency?

Examples

Latency = Instructions * Cycles/Instruction * Seconds/Cycle

- gcc runs in 100 sec on a 1 GHz machine
  - How many cycles does it take?

100G cycles

- gcc runs in 75 sec on a 600 MHz machine
  - How many cycles does it take?

45G cycles

How can this be?

Latency = Instructions * Cycles/Instruction * Seconds/Cycle

- Different Instruction count?
  - Different ISAs ?
  - Different compilers ?
- Different CPI?
  - underlying machine implementation
  - Microarchitecture
- Different cycle time?
  - New process technology
  - Microarchitecture

Computing Average CPI

- Instruction execution time depends on instruction time (we'll get into why this is so later on)
  - Integer +, -, <<, |, & -- 1 cycle
  - Integer *, /, -- 5-10 cycles
  - Floating point +, - -- 3-4 cycles
  - Floating point *, /, sqrt() -- 10-30 cycles
  - Loads/stores -- variable
  - All theses values depend on the particular implementation, not the ISA
- Total CPI depends on the workload's Instruction mix -- how many of each type of instruction executes
  - What program is running?
  - How was it compiled?

The Compiler’s Role

- Compilers affect CPI…
  - Wise instruction selection
    - “Strength reduction”: x*2n -> x << n
    - Use registers to eliminate loads and stores
  - More compact code -> less waiting for instructions
- …and instruction count
  - Common sub-expression elimination
  - Use registers to eliminate loads and stores

Stupid Compiler

```
int i, sum = 0;
for(i=0;i<10;i++)
    sum += i;
```

Type	CPI	Static #	dyn #
mem	5	6	42
int	1	3	30
br	1	2	20
Total	2.8	11	92

(5*42 + 1*30 + 1*20)/92 = 2.8

```
sw   0($sp), $0 #sum = 0
sw   4($sp), $0 #i = 0
loop:
lw   $1, 4($sp)
sub  $3, $1, 10
beq  $3, $0, end
lw   $2, 0($sp)
add  $2, $2, $1
st   0($sp), $2
addi $1, $1, 1
st   4($sp), $1
b    loop
end:
```

Smart Compiler

```
int i, sum = 0;
for(i=0;i<10;i++)
    sum += i;
```

```
add  $1, $0, $0 # i
add  $2, $0, $0 # sum
loop:
sub  $3, $1, 10
beq  $3, $0, end
add  $2, $2, $1
addi $1, $1, 1
b    loop
end:
sw   0($sp), $2
```

Type	CPI	Static #	dyn #
mem	5	1	1
int	1	5	32
br	1	2	20
Total	1.01	8	53

$(5*1 + 1*32 + 1*20)/53 = 2.8$

Live demo

Program inputs affect CPI too!

```
int rand[1000] = {random 0s and 1s }
for(i=0;i<1000;i++)
   if(rand[i]) sum -= i;
   else sum *= i;

int ones[1000] = {1, 1, ...}
for(i=0;i<1000;i++)
   if(ones[i]) sum -= i;
   else sum *= i;
```

- Data-dependent computation
- Data-dependent micro-architectural behavior
  - Processors are faster when the computation is predictable (more later)

Live demo

Making Meaningful Comparisons

Latency = Instructions * Cycles/Instruction * Seconds/Cycle

- Meaningful CPI exists only:
  - For a particular program with a particular compiler
  - ....with a particular input.
- You MUST consider all 3 to get accurate latency estimations or machine speed comparisons
  - Instruction Set
  - Compiler
  - Implementation of Instruction Set (386 vs Pentium)
  - Processor Freq (600 Mhz vs 1 GHz)
  - Same high level program with same input
- “wall clock” measurements are always comparable.
  - If the workloads (app + inputs) are the same

The Performance Equation

Latency = Instructions * Cycles/Instruction * Seconds/Cycle

- Clock rate =
- Instruction count =
- Latency =
- Find the CPI!

Today

- DRAM
- Quiz 1 recap
- HW 1 recap
- Questions about ISAs
- More about the project?
- Amdahl's law

Key Points

- Amdahl's law and how to apply it in a variety of situations
- It's role in guiding optimization of a system
- It's role in determining the impact of localized changes on the entire system
-

Limits on Speedup: Amdahl's Law

- "The fundamental theorem of performance optimization"
- Coined by Gene Amdahl (one of the designers of the IBM 360)
- Optimizations do not (generally) uniformly affect the entire program
  - The more widely applicable a technique is, the more valuable it is
  - Conversely, limited applicability can (drastically) reduce the impact of an optimization.

Always heed Amdahl's Law!!!

It is central to many many optimization problems

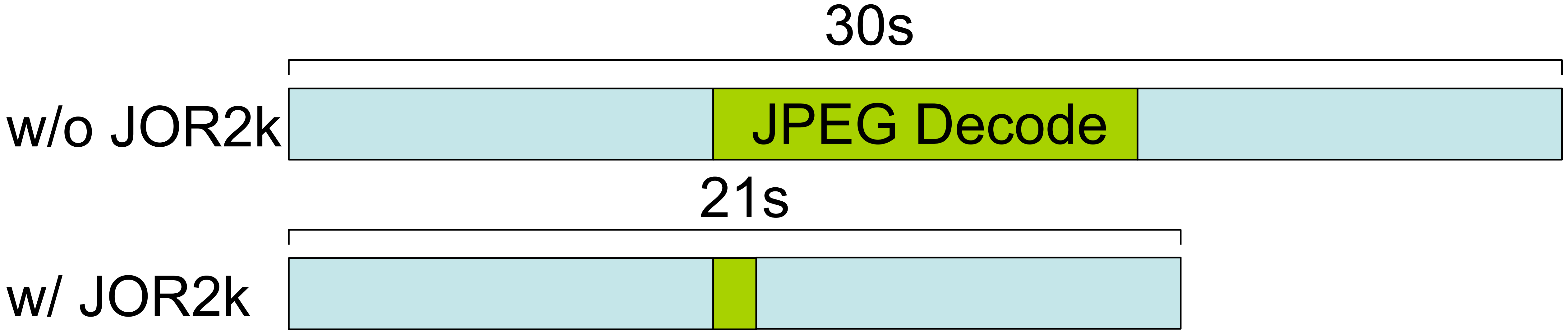
Amdahl's Law in Action

- SuperJPEG-O-Rama2000 ISA extensions **
  - Speeds up JPEG decode by 10x!!!
  - Act now! While Supplies Last!

** Increases processor cost by 45%

Amdahl's Law in Action

- SuperJPEG-O-Rama2000 in the wild
- PictoBench spends 33% of it's time doing JPEG decode
- How much does JOR2k help?



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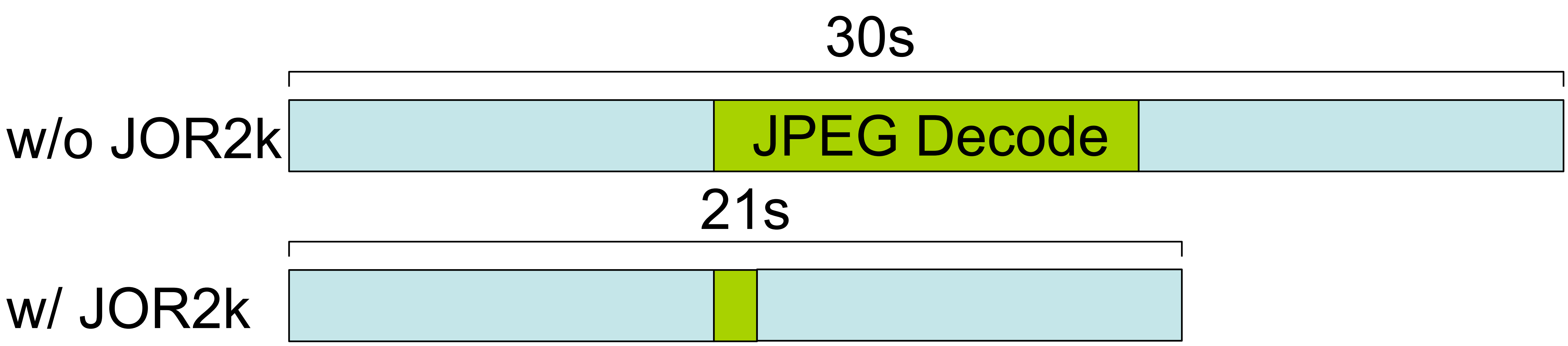

Performance: 30/21 = 1.4x Speedup != 10x

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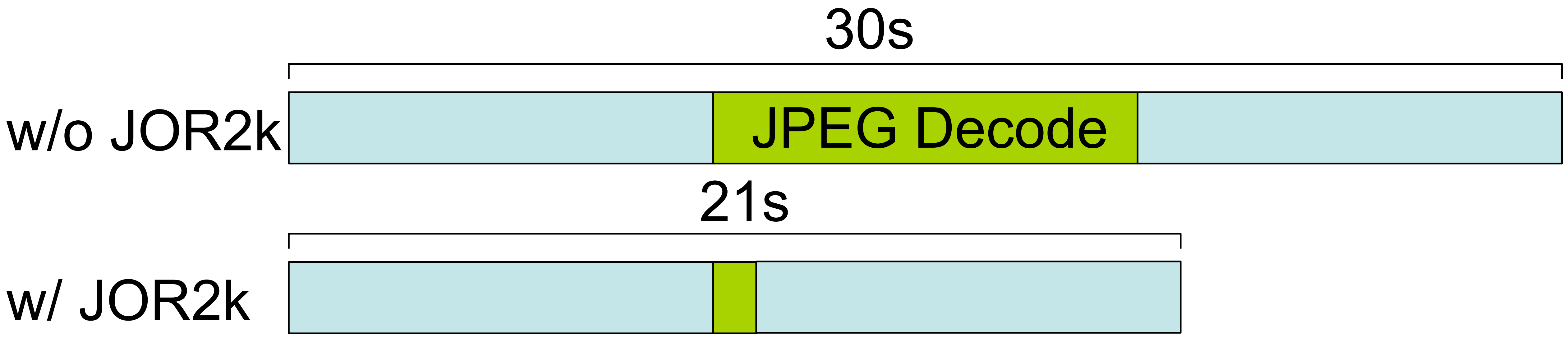

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Is this worth the 45% increase in cost?

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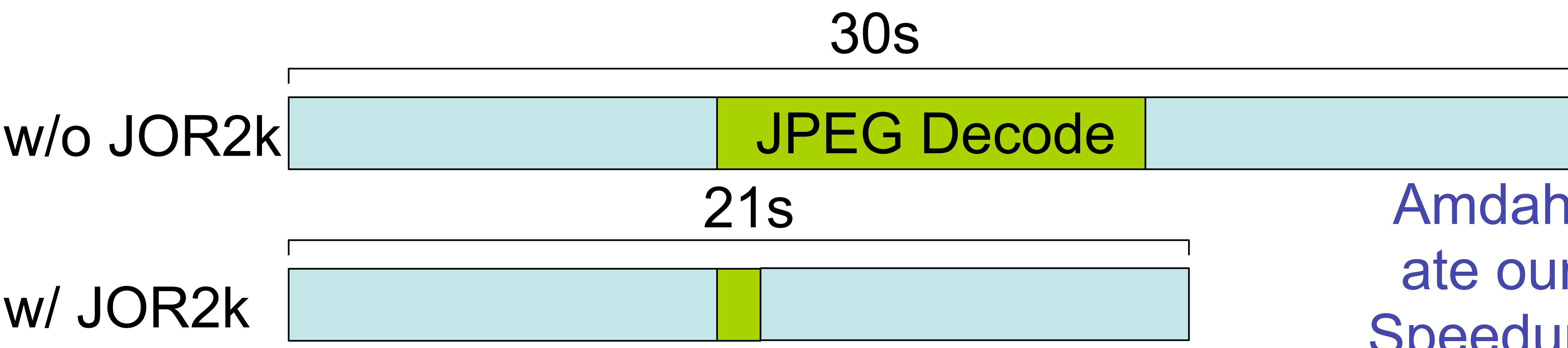

Amdahl ate our Speedup!

Performance: 30/21 = 1.4x Speedup != 10x

Is this worth the 45% increase in cost?

Amdahl's Law

- The second fundamental theorem of computer architecture.
- If we can speed up *X* of the program by *S* times
- Amdahl's Law gives the total speed up, S_{tot}

$$S_{tot} = \frac{1}{(x/S + (1-x))}.$$

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Sanity check:

$$x = 1 \Rightarrow S_{tot} = \frac{1}{(1/S + (1-1))} = \frac{1}{1/S} = S$$

Amdahl's Corollary #1

- Maximum possible speedup, S_{max}

$$S = \mathit{infinity}$$

$$S_{max} = \frac{1}{(1-x)}$$

Amdahl's Law Practice

- Protein String Matching Code
  - 200 hours to run on current machine, spends 20% of time doing integer instructions
  - How much faster must you make the integer unit to make the code run 10 hours faster?
  - How much faster must you make the integer unit to make the code run 50 hours faster?

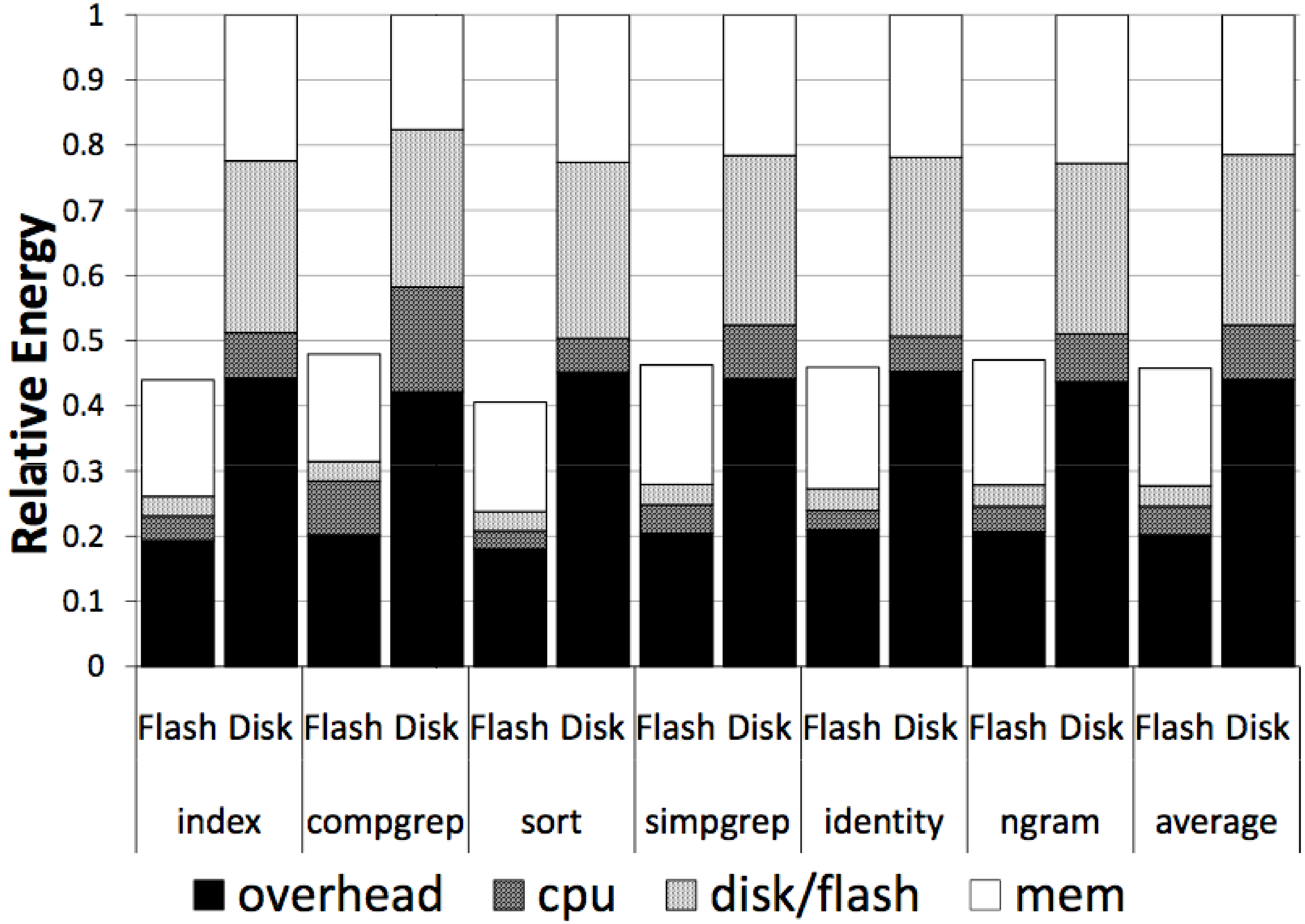
A) 1.1
B) 1.25
C) 1.75
D) 1.33

E) 10.0
F) 50.0
G) 1 million times
H) Other

Amdahl's Law Practice

- Protein String Matching Code
  - 4 days ET on current machine
    - 20% of time doing integer instructions
    - 35% percent of time doing I/O
  - Which is the better economic tradeoff?
    - Compiler optimization that reduces number of integer instructions by 25% (assume each integer inst takes the same amount of time)
    - Hardware optimization that makes I/O run 20% faster?

Amdahl's Law Applies All Over

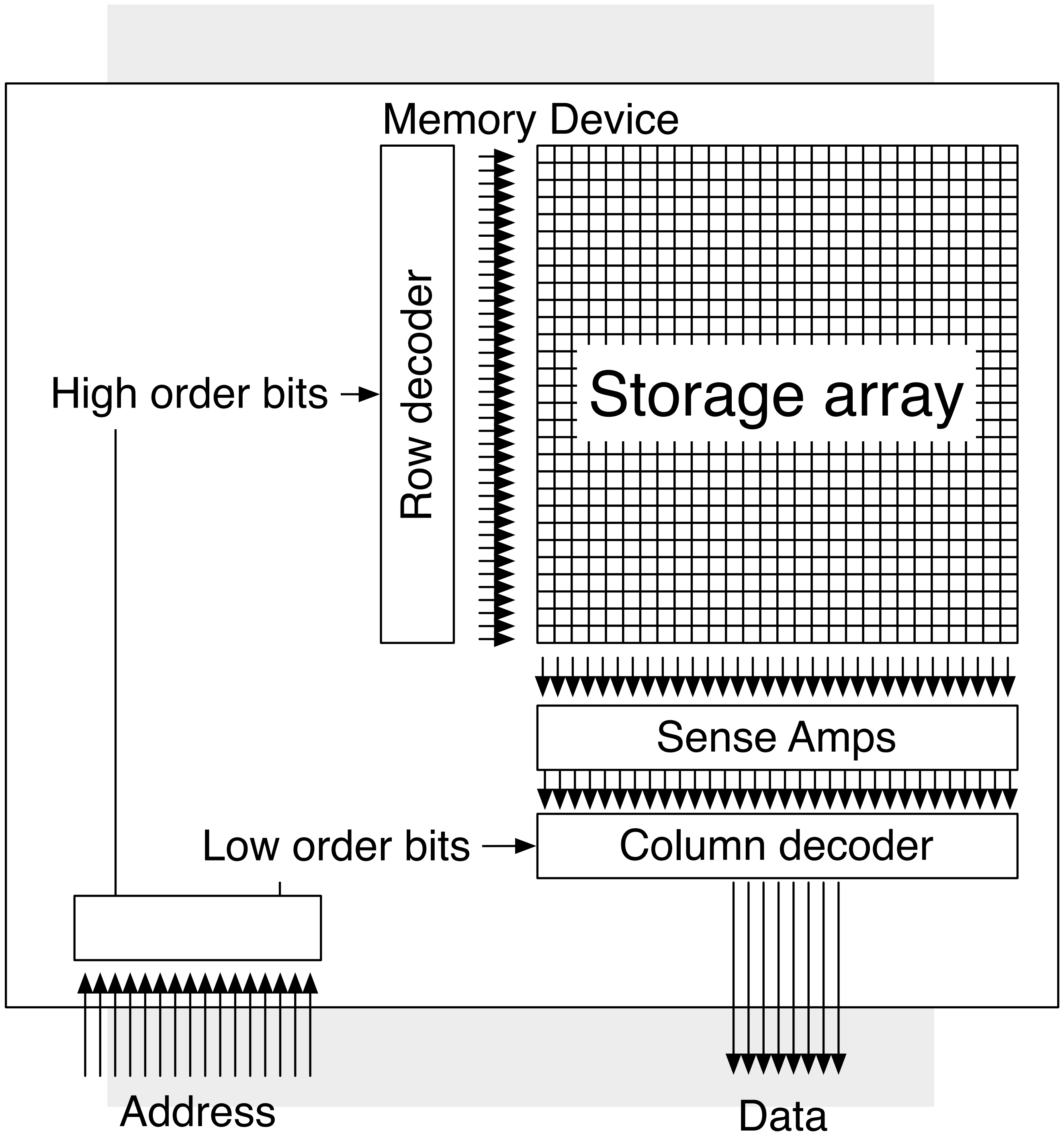


- SSDs use 10x less power than HDs
- But they only save you ~50% overall.

Amdahl's Law in Memory

- Storage array 90% of area
- Row decoder 4%
- Column decode 2%
- Sense amps 4%

- What's the benefit of reducing bit size by 10%?
- Reducing column decoder size by 90%?



Amdahl's Corollary #2

- Make the common case fast (i.e., *x* should be large)!
  - Common == "most time consuming" not necessarily "most frequent"
  - The uncommon case doesn't make much difference
  - Be sure of what the common case is
  - The common case changes.
- Repeat…
  - With optimization, the common becomes uncommon and vice versa.

Amdahl's Corollary #2: Example

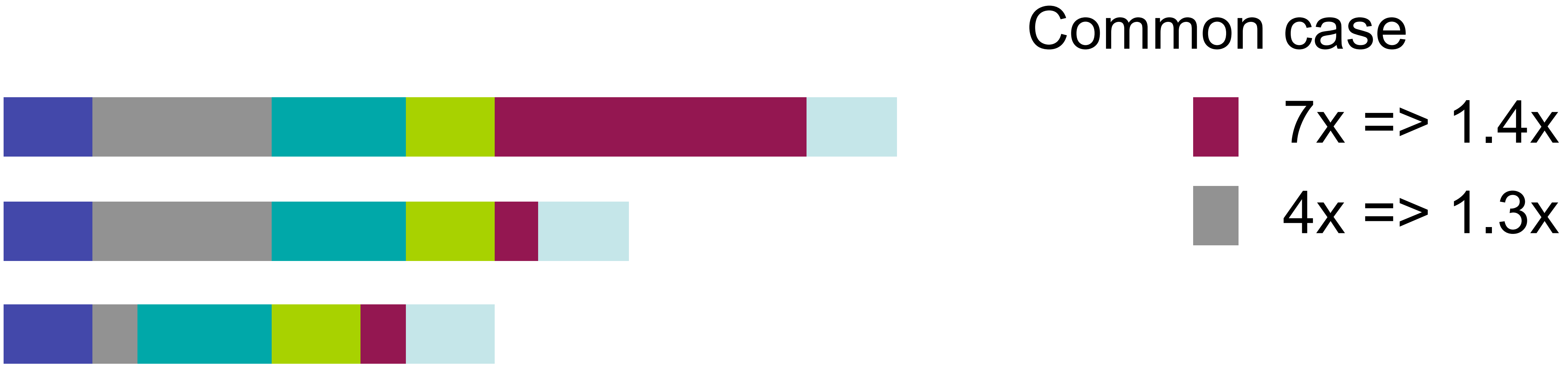
Common case

Amdahl's Corollary #2: Example

Common case

7x => 1.4x

Amdahl's Corollary #2: Example



Amdahl’s Corollary #2: Example

Common case

7x => 1.4x

4x => 1.3x

1.3x => 1.1x

Total = 20/10 = 2x

Amdahl's Corollary #2: Example

Common case

7x => 1.4x

4x => 1.3x

1.3x => 1.1x

Total = 20/10 = 2x

- In the end, there is no common case!
- Options:
  - Global optimizations (faster clock, better compiler)
  - Find something common to work on (i.e. memory latency)
  - War of attrition
  - Total redesign (You are probably well-prepared for this)

Amdahl's Corollary #3

- Benefits of parallel processing
- *p* processors
- *x*% is *p*-way parallizable
- maximum speedup, S_{par}

$$S_{par} = \frac{1}{(x/p + (1-x))}$$

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x is pretty small for desktop applications, even for p = 2

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Does Intel's 80-core processor make much sense?

Amdahl's Corollary #4

- Amdahl's law for latency (L)

$$L_{new} = L_{base} *1/Speedup$$
$$L_{new} = L_{base} *(x/S + (1-x))$$
$$L_{new} = (L_{base} /S)*x + ET_{base}*(1-x)$$

- If you can speed up y% of the remaining (1-x), you can apply Amdahl's law recursively

$$L_{new} = (L_{base} /S_1)*x + (S_{base}*(1-x)/S_2*y + L_{base}*(1-x)*(1-y))$$

- This is how we will analyze memory system performance

Amdahl's Non-Corollary

- Amdahl's law does not bound slowdown

  $L_{new} = (L_{base}/S)*x + L_{base}*(1-x)$
- L_{new} is linear in 1/S
- Example: x = 0.01 of execution, $L_{base} = 1$
  - S = 0.001;
    - $E_{new} = 1000*L_{base}*0.01 + L_{base}*(0.99) \sim 10*L_{base}$
  - S = 0.00001;
    - $E_{new} = 100000*L_{base}*0.01 + L_{base}*(0.99) \sim 1000*L_{base}$
- Things can only get so fast, but they can get arbitrarily slow.
  - Do not hurt the non-common case too much!

Benchmarks: Standard Candles for Performance

- It's hard to convince manufacturers to run *your* program (unless you're a BIG customer)
- A benchmark is a set of programs that are representative of a class of problems.
- To increase predictability, collections of benchmark applications, called *benchmark suites*, are popular
  - "Easy" to set up
  - Portable
  - Well-understood
  - Stand-alone
  - Standardized conditions
  - These are all things that real software is not.

Classes of benchmarks

- Microbenchmark – measure one feature of system
  - e.g. memory accesses or communication speed
- Kernels – most compute-intensive part of applications
  - e.g. Linpack and NAS kernel b'marks (for supercomputers)
- Full application:
  - SpecInt / SpecFP (int and float) (for Unix workstations)
  - Other suites for databases, web servers, graphics,...

Bandwidth

- The amount of work (or data) per time
  - MB/s, GB/s -- network BW, disk BW, etc.
  - Frames per second -- Games, video transcoding
    - (why are games under both latency and BW?)
- Also called "throughput"

Measuring Bandwidth

- Measure how much work is done
- Measure latency
- Divide

Latency-BW Trade-offs

- Often, increasing latency for one task and increase BW for many tasks.
  - Think of waiting in line for one of 4 bank tellers
  - If the line is empty, your response time is minimized, but throughput is low because utilization is low.
  - If there is always a line, you wait longer (your latency goes up), but there is always work available for tellers.
- Much of computer performance is about scheduling work onto resources
  - Network links.
  - Memory ports.
  - Processors, functional units, etc.
  - IO channels.
  - Increasing contention for these resources generally increases throughput but hurts latency.

Stationwagon Digression

- IPv6 Internet 2: 272,400 terabit-meters per second
  - 585GB in 30 minutes over 30,000 Km
  - 9.08 Gb/s

- Subaru outback wagon
  - Max load = 408Kg
  - 21Mpg
- MHX2 BT 300 Laptop drive
  - 300GB/Drive
  - 0.135Kg
- 906TB
- Legal speed: 75MPH (33.3 m/s)
- BW = 8.2 Gb/s
- Latency = 10 days
- 241,535 terabit-meters per second

Prius Digression

- IPv6 Internet 2: 272,400 terabit-meters per second
  - 585GB in 30 minutes over 30,000 Km
  - 9.08 Gb/s

- My Toyota Prius
  - Max load = 374Kg
  - 44Mpg (2x power efficiency)
- MHX2 BT 300
  - 300GB/Drive
  - 0.135Kg
- 831TB
- Legal speed: 75MPH (33.3 m/s)
- BW = 7.5 Gb/s
- Latency = 10 days
- 221,407 terabit-meters per second (13% performance hit)