Lecture 1:

Why Parallelism? Why Efficiency?

Parallel Computer Architecture and Programming
CMU 15-418/15-618, Spring 2016

Tunes

Leela James

"Long Time Coming"

(A Change is Gonna Come)

"I'd heard about parallelism in 213. And they kept telling me about in 210. And so I was really excited when got the chance to roll up my sleeves and tune some parallel code for a bunch of cores."

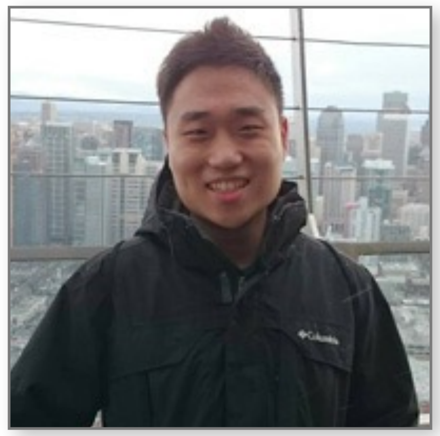
- Leela James, on the inspiration for "Long Time Coming"

Hi!

Prof. Kayvon

Prof. Bryant

Greg



Kevin

Karima

Oguz

Josh

One common definition

A parallel computer is a collection of processing elements that cooperate to solve problems quickly

We care about performance *
We care about efficiency

We're going to use multiple processors to get it

* Note: different motivation from "concurrent programming" using pthreads in 15-213

DEMO 1

(15-418 Spring 2016‘s first parallel program)

Speedup

One major motivation of using parallel processing: achieve a speedup

For a given problem:

$$\text{speedup(using P processors)} = \frac{\text{execution time (using 1 processor)}}{\text{execution time (using P processors)}}$$

Class observations from demo 1

- Communication limited the maximum speedup achieved
    - In the demo, the communication was telling each other the partial sums

- Minimizing the cost of communication improved speedup
    - Moved students (“processors”) closer together (or let them shout)

DEMO 2

(scaling up to four “processors”)

Class observations from demo 2

- Imbalance in work assignment limited speedup
  - Some students ("processors") ran out work to do (went idle), while others were still working on their assigned task

- Improving the distribution of work improved speedup

DEMO 3

(massively parallel execution)

Class observations from demo 3

- The problem I just gave you has a significant amount of communication compared to computation

- Communication costs can dominate a parallel computation, severely limiting speedup

Course theme 1:

Designing and writing parallel programs ... that scale!

- **Parallel thinking**
  1. Decomposing work into pieces that can safely be performed in parallel
  2. Assigning work to processors
  3. Managing communication/synchronization between the processors so that it does not limit speedup

- **Abstractions/mechanisms for performing the above tasks**
  - Writing code in popular parallel programming languages

Course theme 2:

Parallel computer hardware implementation: how parallel computers work

- Mechanisms used to implement abstractions efficiently
  - Performance characteristics of implementations
  - Design trade-offs: performance vs. convenience vs. cost

- Why do I need to know about hardware?
  - Because the characteristics of the machine really matter
(recall speed of communication issues in earlier demos)
  - Because you care about efficiency and performance
(you are writing parallel programs after all!)

Course theme 3:
Thinking about efficiency

- FAST != EFFICIENT

- Just because your program runs faster on a parallel computer, it does not mean it is using the hardware efficiently
  - Is 2x speedup on computer with 10 processors a good result?

- Programmer's perspective: make use of provided machine capabilities

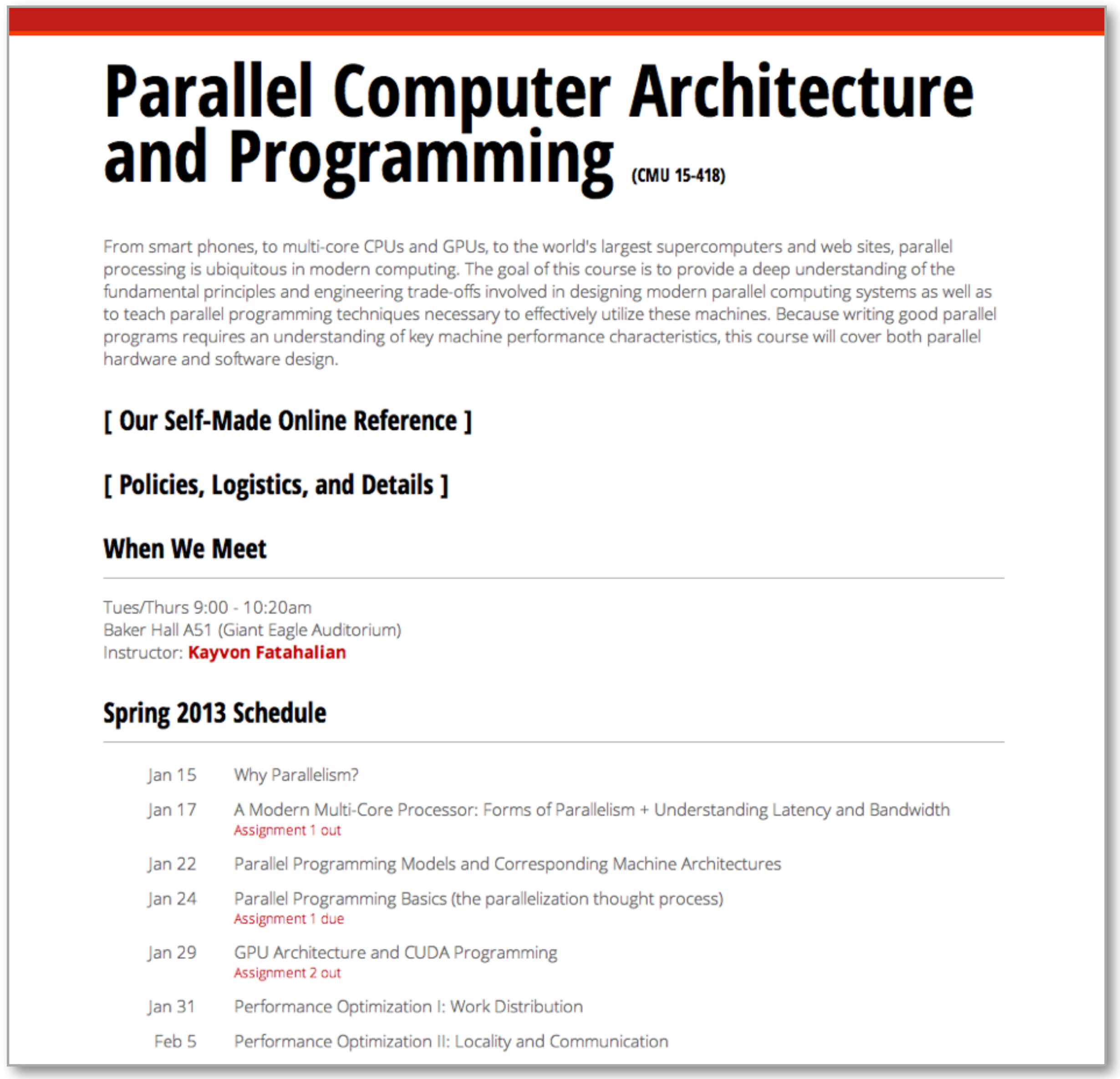
- HW designer's perspective: choosing the right capabilities to put in system (performance/cost, cost = silicon area?, power?, etc.)

Course logistics

Getting started

- **Create an account on the course web site**
  - **http://15418.courses.cs.cmu.edu**

- **Sign up for the course on Piazza**
  - **http://piazza.com/cmu/spring2016/15418618/home**



Parallel Computer Architecture and Programming (CMU 15-418)

From smart phones, to multi-core CPUs and GPUs, to the world's largest supercomputers and web sites, parallel processing is ubiquitous in modern computing. The goal of this course is to provide a deep understanding of the fundamental principles and engineering trade-offs involved in designing modern parallel computing systems as well as to teach parallel programming techniques necessary to effectively utilize these machines. Because writing good parallel programs requires an understanding of key machine performance characteristics, this course will cover both parallel hardware and software design.

[Our Self-Made Online Reference]

[Policies, Logistics, and Details]

When We Meet

Tues/Thurs 9:00 - 10:20am
Baker Hall A51 (Giant Eagle Auditorium)
Instructor: **Kayvon Fatahalian**

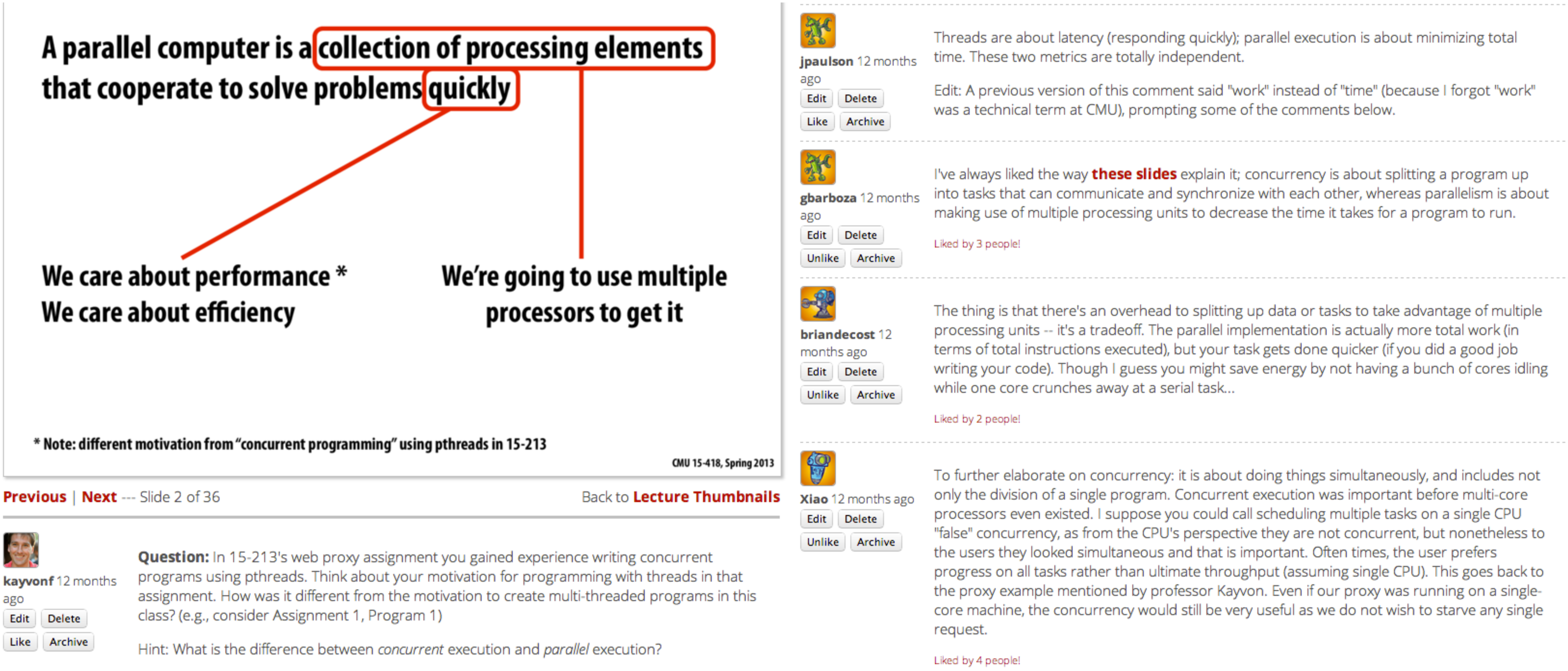
Spring 2013 Schedule

Jan 15	Why Parallelism?
Jan 17	A Modern Multi-Core Processor: Forms of Parallelism + Understanding Latency and Bandwidth Assignment 1 out
Jan 22	Parallel Programming Models and Corresponding Machine Architectures
Jan 24	Parallel Programming Basics (the parallelization thought process) Assignment 1 due
Jan 29	GPU Architecture and CUDA Programming Assignment 2 out
Jan 31	Performance Optimization I: Work Distribution
Feb 5	Performance Optimization II: Locality and Communication

- **Textbook**
  - **There is no course textbook, but please see web site for suggested references**

Commenting and contributing to lectures

- We have no textbook for this class and so the lecture slides are the primary course reference



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CMU 15-418, Spring 2013

Previous | **Next** --- Slide 2 of 36   Back to **Lecture Thumbnails**

kayvonf 12 months ago

Question: In 15-213's web proxy assignment you gained experience writing concurrent programs using pthreads. Think about your motivation for programming with threads in that assignment. How was it different from the motivation to create multi-threaded programs in this class? (e.g., consider Assignment 1, Program 1)

Hint: What is the difference between *concurrent* execution and *parallel* execution?

jpaulson 12 months ago

Threads are about latency (responding quickly); parallel execution is about minimizing total time. These two metrics are totally independent.

Edit: A previous version of this comment said "work" instead of "time" (because I forgot "work" was a technical term at CMU), prompting some of the comments below.

gbarboza 12 months ago

I've always liked the way **these slides** explain it; concurrency is about splitting a program up into tasks that can communicate and synchronize with each other, whereas parallelism is about making use of multiple processing units to decrease the time it takes for a program to run.

Liked by 3 people!

briandecost 12 months ago

The thing is that there's an overhead to splitting up data or tasks to take advantage of multiple processing units -- it's a tradeoff. The parallel implementation is actually more total work (in terms of total instructions executed), but your task gets done quicker (if you did a good job writing your code). Though I guess you might save energy by not having a bunch of cores idling while one core crunches away at a serial task...

Liked by 2 people!

Xiao 12 months ago

To further elaborate on concurrency: it is about doing things simultaneously, and includes not only the division of a single program. Concurrent execution was important before multi-core processors even existed. I suppose you could call scheduling multiple tasks on a single CPU "false" concurrency, as from the CPU's perspective they are not concurrent, but nonetheless to the users they looked simultaneous and that is important. Often times, the user prefers progress on all tasks rather than ultimate throughput (assuming single CPU). This goes back to the proxy example mentioned by professor Kayvon. Even if our proxy was running on a single-core machine, the concurrency would still be very useful as we do not wish to starve any single request.

Liked by 4 people!

Participation requirement (comments)

- You are required to submit one well-thought-out comment per lecture (only two comments per week)

- It counts if you answer a TA's question if randomly prompted:
  - My TAs will be randomly seeding the site with questions (and asking specific students to respond!)

- Why do we write?
  - Because writing is a way many good architects and systems designers force themselves to think (explaining clearly and thinking clearly are highly correlated!)

What we are looking for in comments

- Try to explain the slide (as if you were trying to teach your classmate while studying for an exam)
  - "Kayvon said this, but if you think about it this way instead it makes much more sense... "
- Explain what is confusing to you:
  - "What I'm totally confused by here was..."
- Challenge classmates with a question
  - For example, make up a question you think might be on an exam.
- Provide a link to an alternate explanation
  - "This site has a really good description of how multi-threading works..."
- Mention real-world examples
  - For example, describe all the parallel hardware components in the XBox One
- Constructively respond to another student's comment or question
  - "@segfault21, are you sure that is correct? I thought that Kayvon said..."
- It is OKAY (and even encouraged) to address the same topic (or repeat someone else's summary, explanation or idea) in your own words
  - "@funkysenior16's point is that the overhead of communication..."

Quizzes

- Every two-weeks ON THURSDAY we will have a take-home quiz
  - You must complete the quiz on your own
  - Distributed Wednesday night, due 10:00am on Friday
  - We will grade your work to give you feedback, but only a participation grade will go into the gradebook

Assignments

- Four programming assignments
  - First assignment is done individually, the rest may be done in pairs
  - Each uses a different parallel programming environment

Assignment 1: ISPC programming on Intel quad-core CPU (and Xeon Phi)

Assignment 2: CUDA programming on NVIDIA GPUs

Assignment 3: to be announced (but will involve many-core programming on Xeon Phis)

Assignment 4: Create an elastic web server that scales with load

Final project

- 6-week self-selected final project
- May be completed in pairs
- Start thinking about your project ideas TODAY!
- Announcing: the FIFTH annual 418 parallelism competition!
  - Held during the final exam slot
  - Non-CMU judges... (previous years: from Intel, Apple, NVIDIA)
  - Expect non-trivial prizes... (e.g., high-end GPUs, drones, iPads, solid state disks) and most importantly fame, glory, and respect from your peers.

Check out last year's projects!

http://15418.courses.cs.cmu.edu/spring2015/competition

Grades

39%	Programming assignments (4)
28%	Exams (2)
28%	Final project
5%	Participation (quizzes and lecture comments)

Each student (or group) gets up to five late days on programming assignments (see web site for details)

Why parallelism?

Why parallel processing?

- **The answer 10-15 years ago**
  - To realize performance improvements that exceeded what CPU performance improvements could provide
  - Because if you just waited until next year, your application would run faster on a new CPU
- **Implication: working to parallelize your code was often not worth the time**
  - Software developer does nothing: CPU performance doubles ~ every 18 months. Woot!

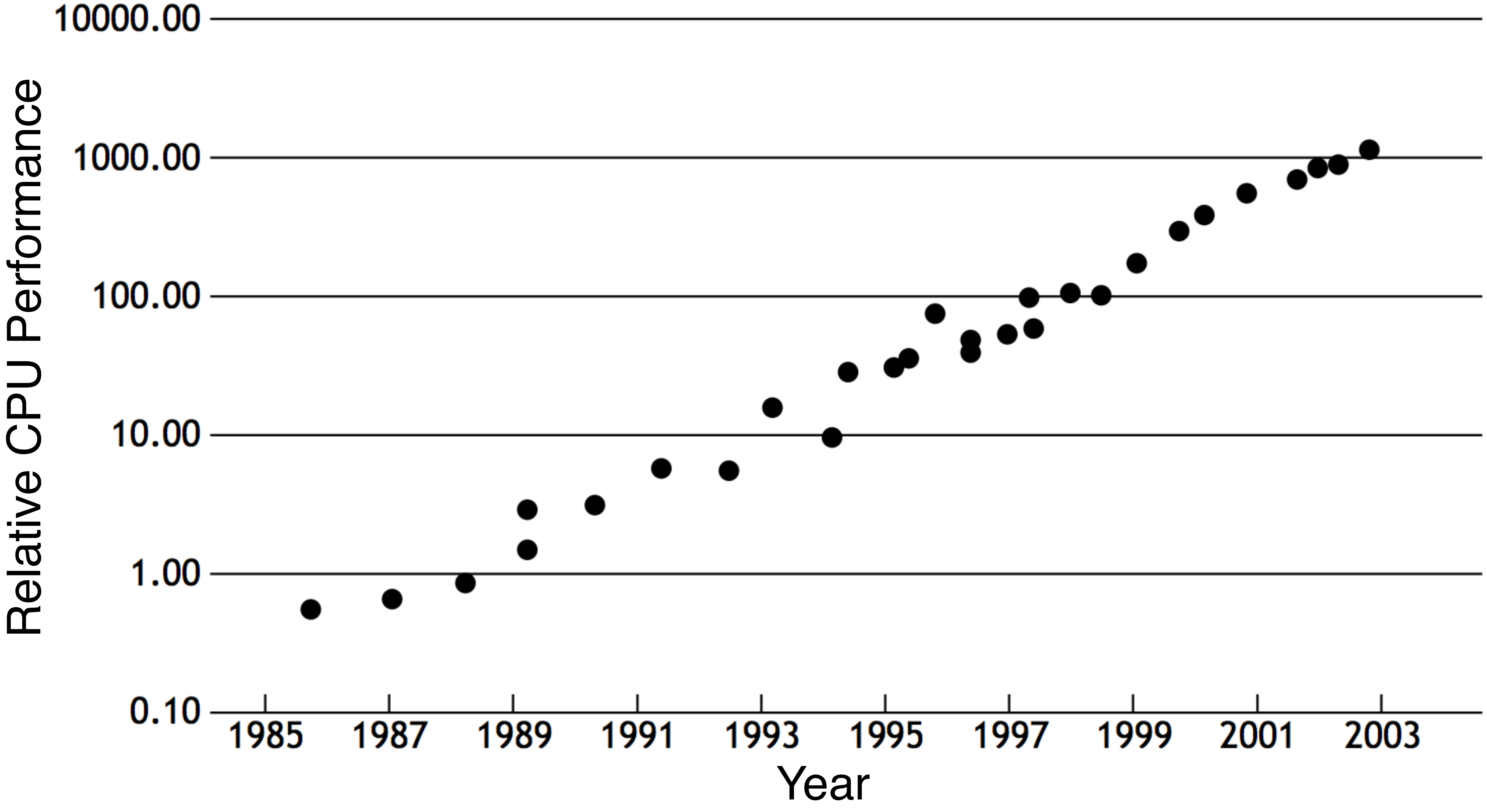


Image credit: Olukutun and Hammond, ACM Queue 2005

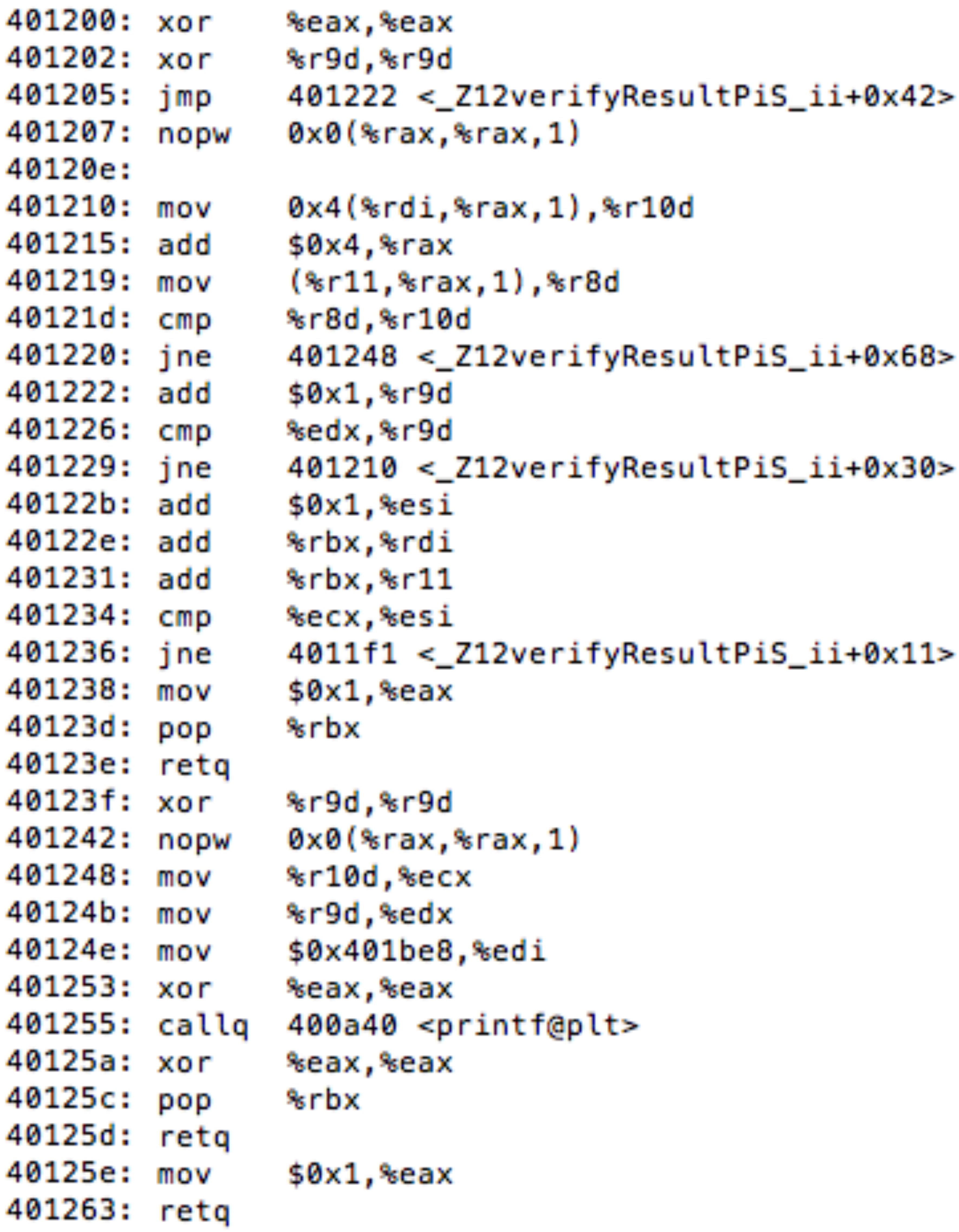
Until 10 years ago: two significant reasons for processor performance improvement

1. Increasing clock frequency

2. Exploiting instruction-level parallelism (superscalar execution)

Review: what is a program?

From a processor's perspective, a program is a sequence of instructions.



```
401200: xor    %eax,%eax
401202: xor    %r9d,%r9d
401205: jmp    401222 <_Z12verifyResultPiS_ii+0x42>
401207: nopw   0x0(%rax,%rax,1)
40120e:
401210: mov    0x4(%rdi,%rax,1),%r10d
401215: add    $0x4,%rax
401219: mov    (%r11,%rax,1),%r8d
40121d: cmp    %r8d,%r10d
401220: jne    401248 <_Z12verifyResultPiS_ii+0x68>
401222: add    $0x1,%r9d
401226: cmp    %edx,%r9d
401229: jne    401210 <_Z12verifyResultPiS_ii+0x30>
40122b: add    $0x1,%esi
40122e: add    %rbx,%rdi
401231: add    %rbx,%r11
401234: cmp    %ecx,%esi
401236: jne    4011f1 <_Z12verifyResultPiS_ii+0x11>
401238: mov    $0x1,%eax
40123d: pop    %rbx
40123e: retq
40123f: xor    %r9d,%r9d
401242: nopw   0x0(%rax,%rax,1)
401248: mov    %r10d,%ecx
40124b: mov    %r9d,%edx
40124e: mov    $0x401be8,%edi
401253: xor    %eax,%eax
401255: callq  400a40 <printf@plt>
40125a: xor    %eax,%eax
40125c: pop    %rbx
40125d: retq
40125e: mov    $0x1,%eax
401263: retq
```

Review: what does a processor do?

It runs programs!

Execute instruction referenced by the program counter (PC)

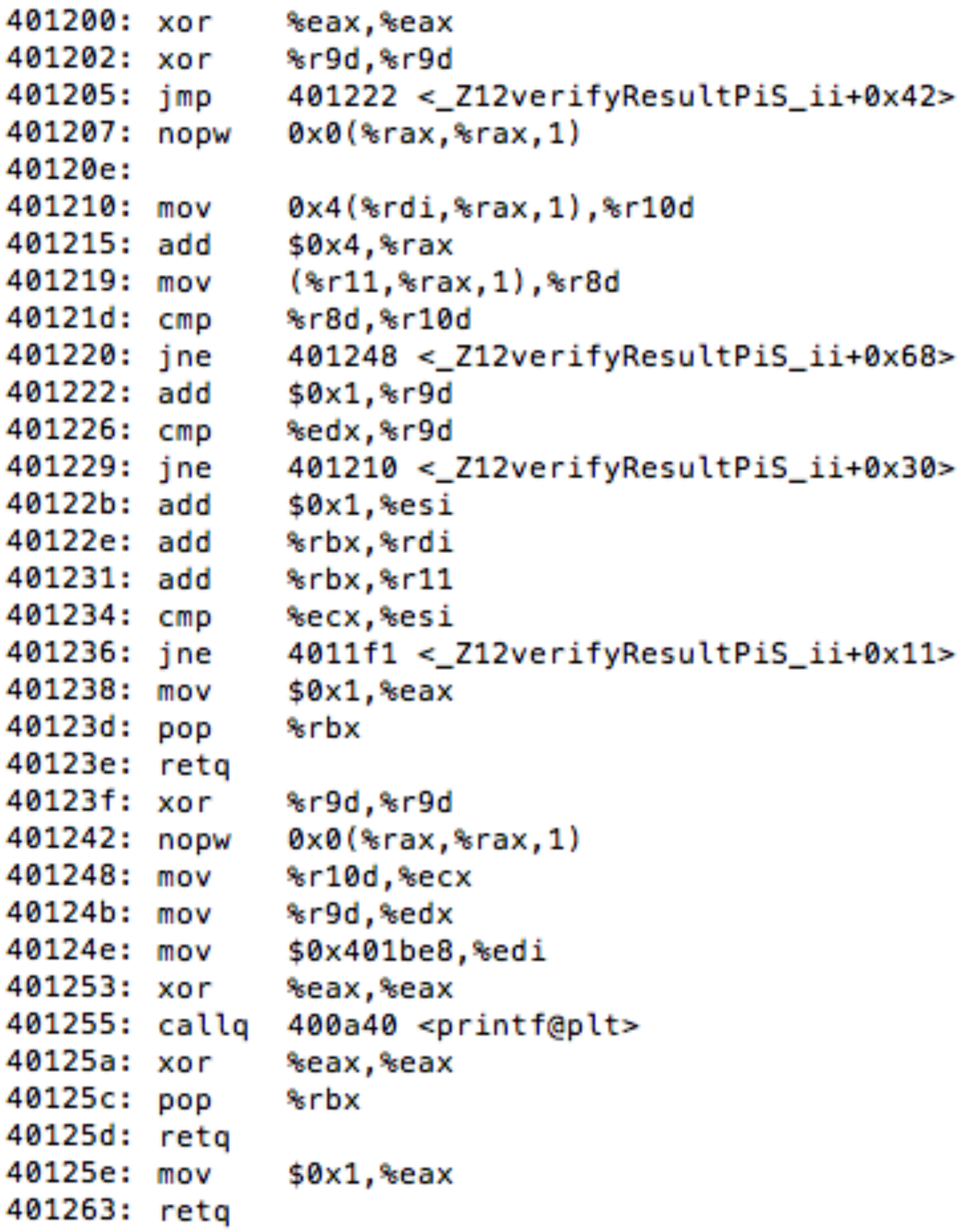
(executing the instruction will modify machine state: contents of registers, memory, CPU state, etc.)

Move to next instruction …

Then execute it…

PC

And so on…



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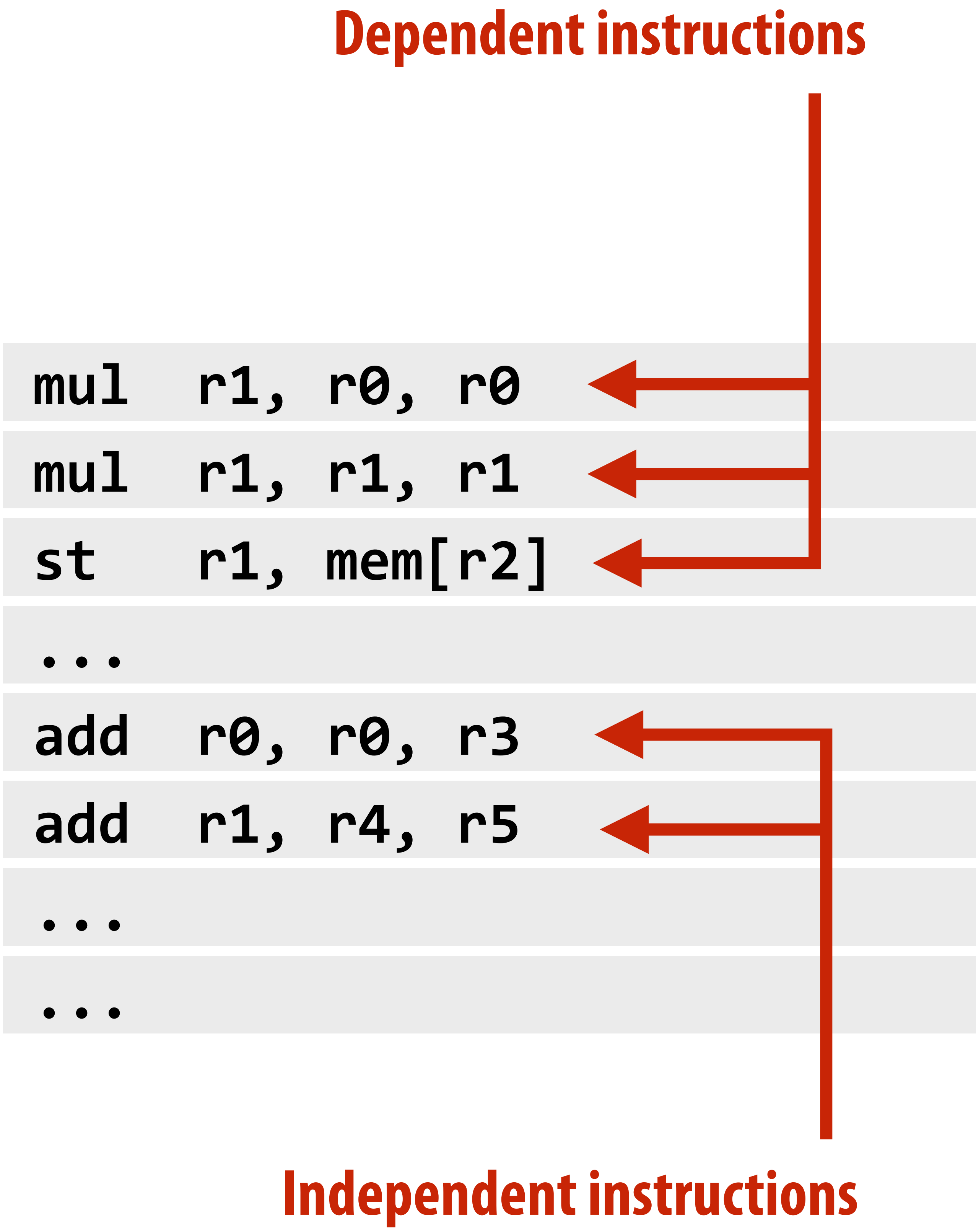
Instruction level parallelism (ILP)

- Processors did in fact leverage parallel execution to make programs run faster, it was just invisible to the programmer

- Instruction level parallelism (ILP)
  - Idea: Instructions must appear to be executed in program order. BUT <u>independent</u> instructions can be executed simultaneously by a processor without impacting program correctness
  - <u>Superscalar execution</u>: processor dynamically finds independent instructions in an instruction sequence and executes them in parallel



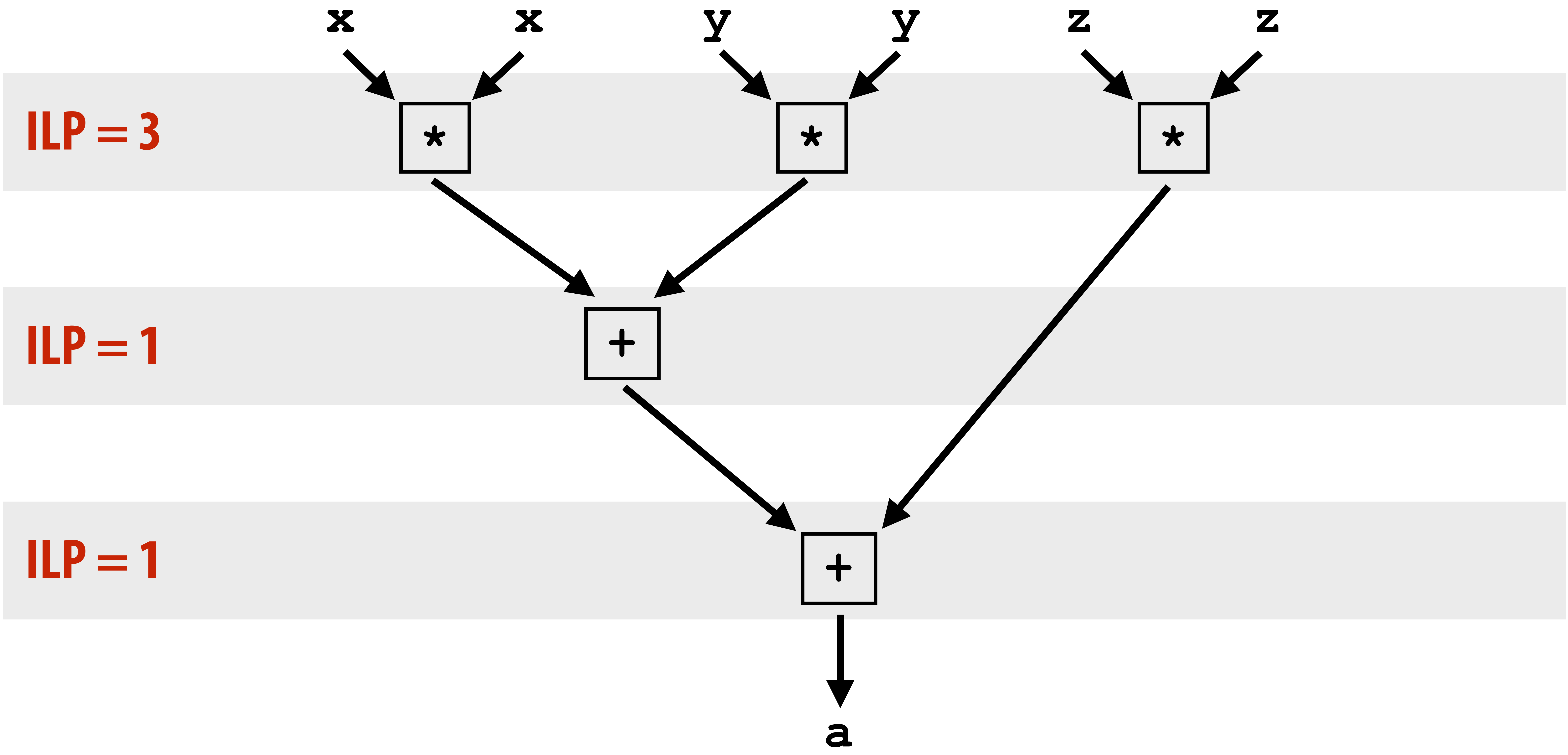
Dependent instructions

```
mul  r1, r0, r0
mul  r1, r1, r1
st   r1, mem[r2]
...
add  r0, r0, r3
add  r1, r4, r5
...
...
```

Independent instructions

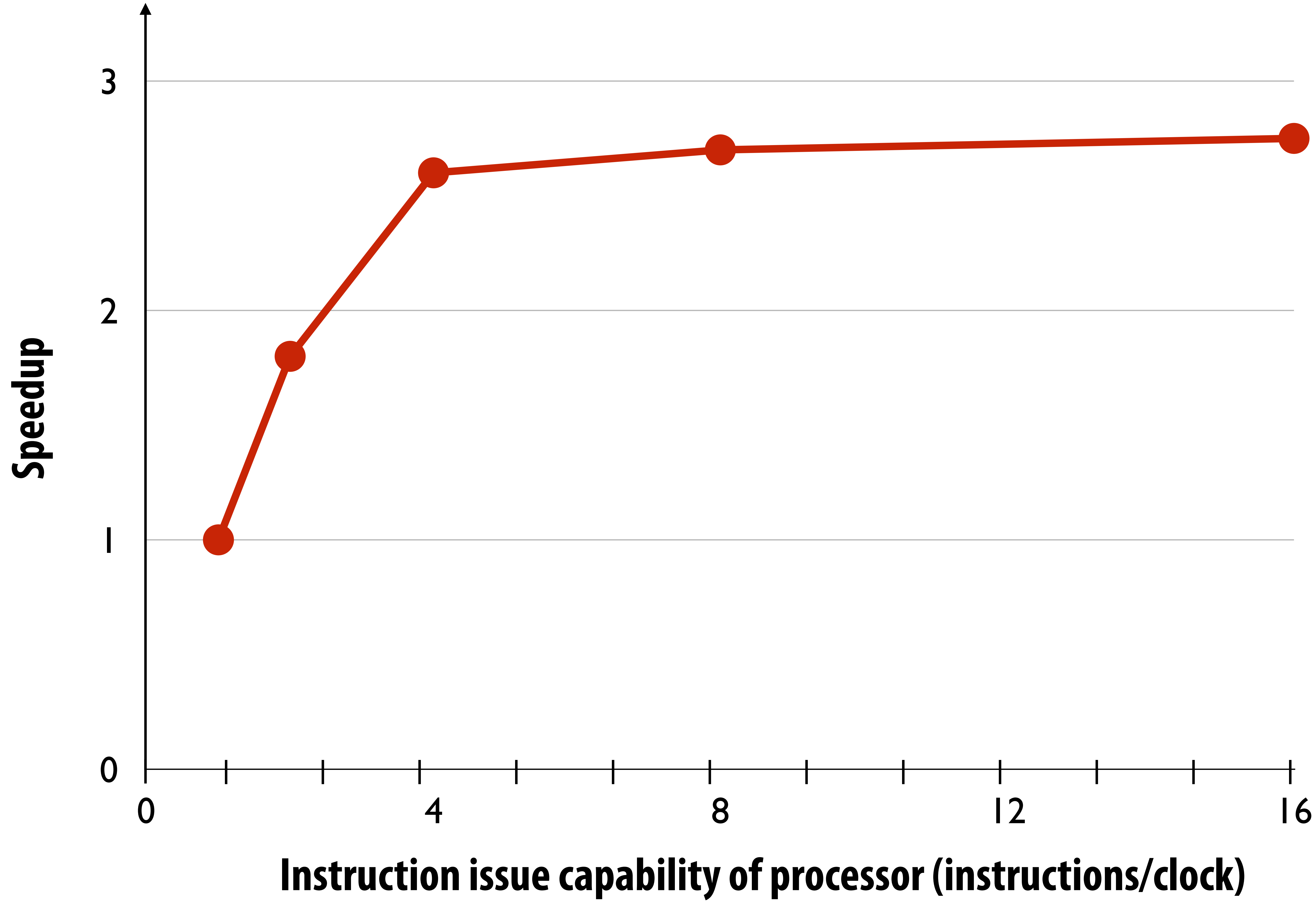
ILP example

```
a = x*x + y*y + z*z
```



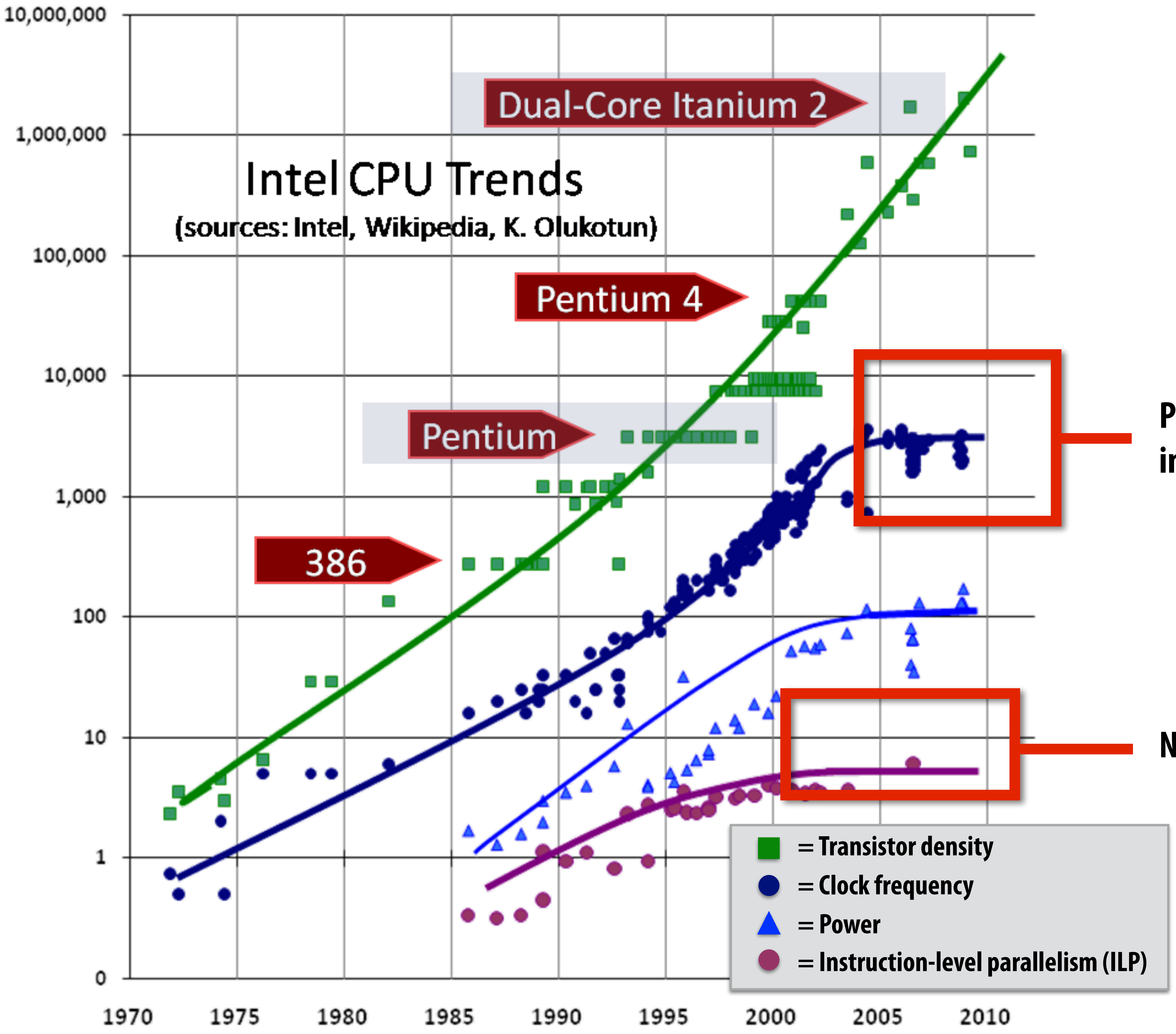
Diminishing returns of superscalar execution

Most available ILP is exploited by a processor capable of issuing four instructions per clock
(Little performance benefit from building a processing that can issue more)



Source: Culler & Singh (data from Johnson 1991)

ILP tapped out + end of frequency scaling



Processor clock rate stops increasing

No further benefit from ILP

Image credit: "The free Lunch is Over" by Herb Sutter, Dr. Dobbs 2005

The “power wall”

Power consumed by a transistor:

Dynamic power $\propto$ capacitive load $\times$ voltage^2 $\times$ frequency

Static power: transistors burn power even when inactive due to leakage

High power = high heat

Power is a critical design constraint in modern processors

	TDP
Intel Core i7 (in this laptop):	45W
Intel Core i7 2700K (fast desktop CPU):	95W
NVIDIA GTX 780 GPU	250W
Mobile phone processor	$^1/_2$ - 2W
World’s fastest supercomputer	megawatts
Standard microwave oven	700W

Source: Intel, NVIDIA, Wikipedia, Top500.org

Power draw as a function of frequency

Dynamic power ∝ capacitive load × voltage^2 × frequency

Static power: transistors burn power even when inactive due to leakage

Maximum allowed frequency determined by processor's core voltage

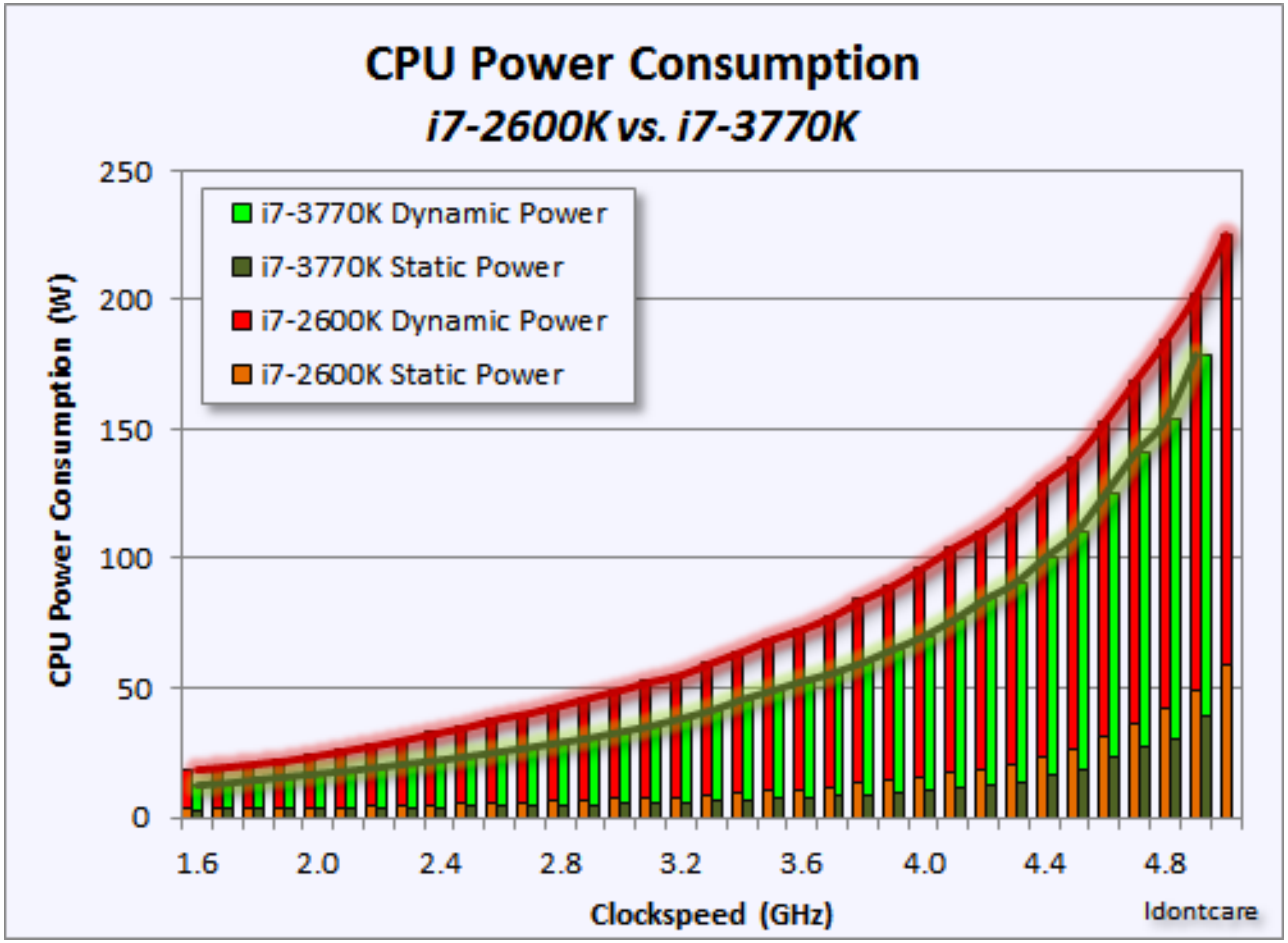


Image credit: "Idontcare": posted at: http://forums.anandtech.com/showthread.php?t=2281195

Single-core performance scaling

The rate of single-instruction stream performance scaling has decreased (almost to zero)

1. Frequency scaling limited by power
2. ILP scaling tapped out

Architects are now building faster processors by adding more execution units that run in parallel.

Software must be written to be parallel to see performance gains. No more free lunch for software developers!

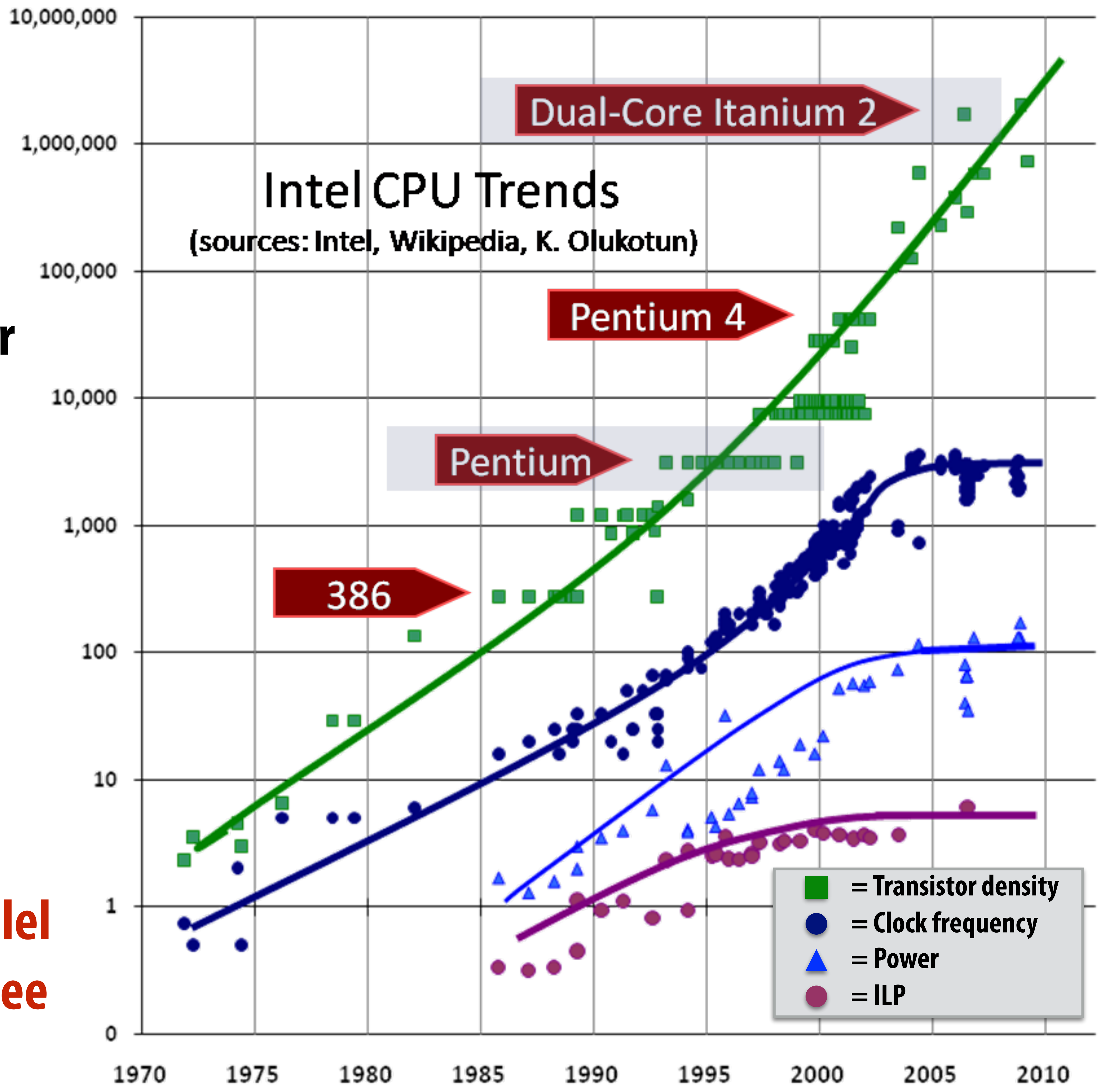


Image credit: "The free Lunch is Over" by Herb Sutter, Dr. Dobbs 2005

Recap: why parallelism?

- **The answer 15 years ago**
  - To realize performance improvements that exceeded what CPU performance improvements could provide

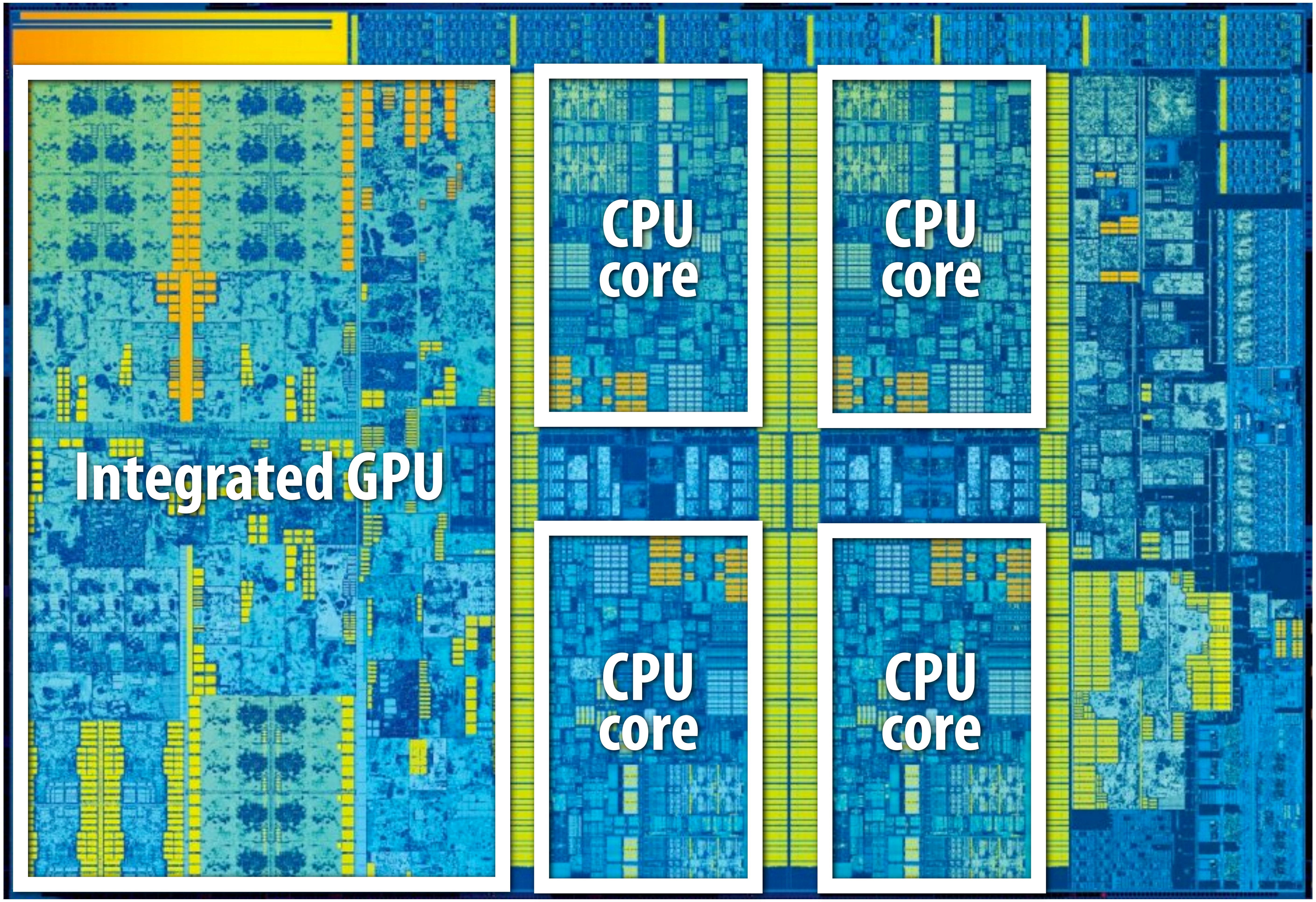
    (specifically, in the early 2000's, what clock frequency scaling could provide)
  - Because if you just waited until next year, your code would run faster on the next generation CPU

- **The answer today:**
  - Because it is <u>the primary way</u> to achieve significantly higher application performance for the foreseeable future *

* We'll revisit this comment later in the heterogeneous processing lecture

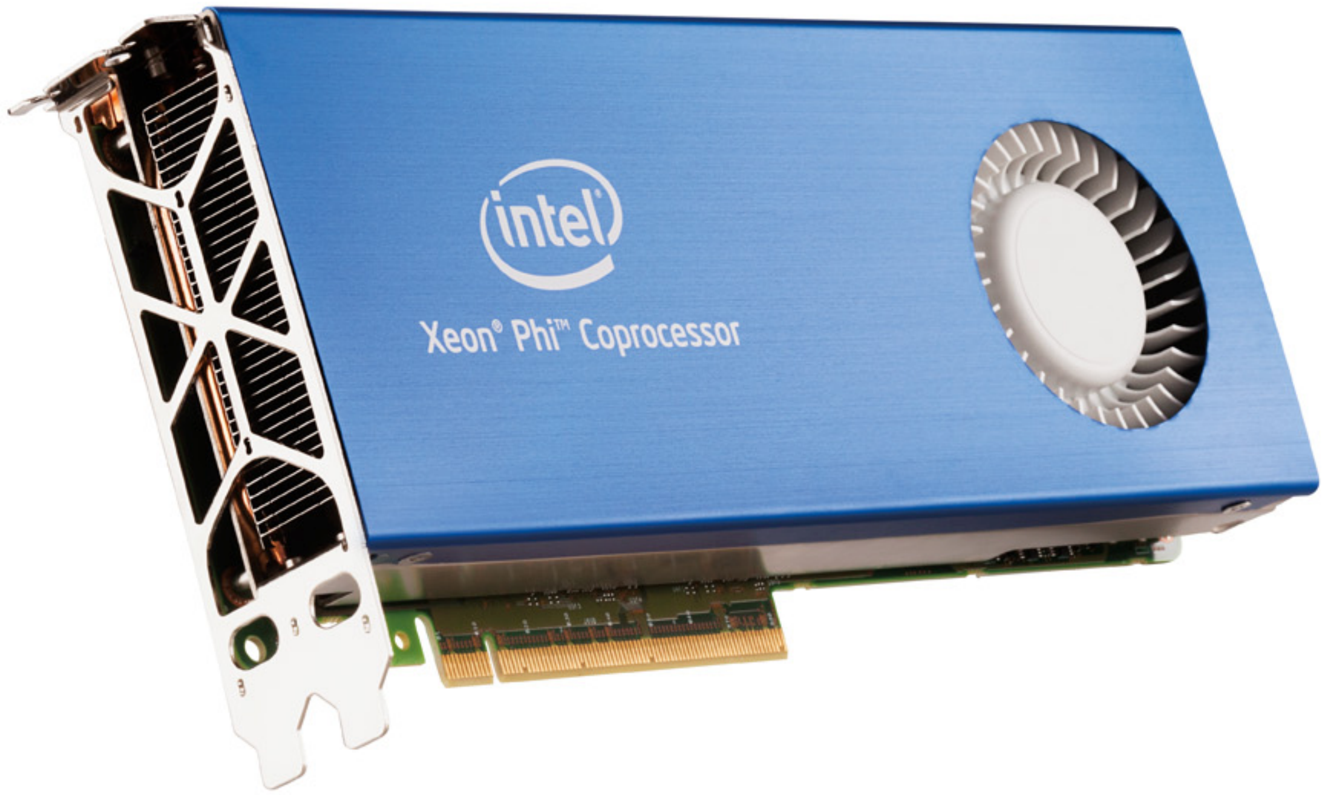
Intel Skylake (2015) (aka "6th generation Core i7")

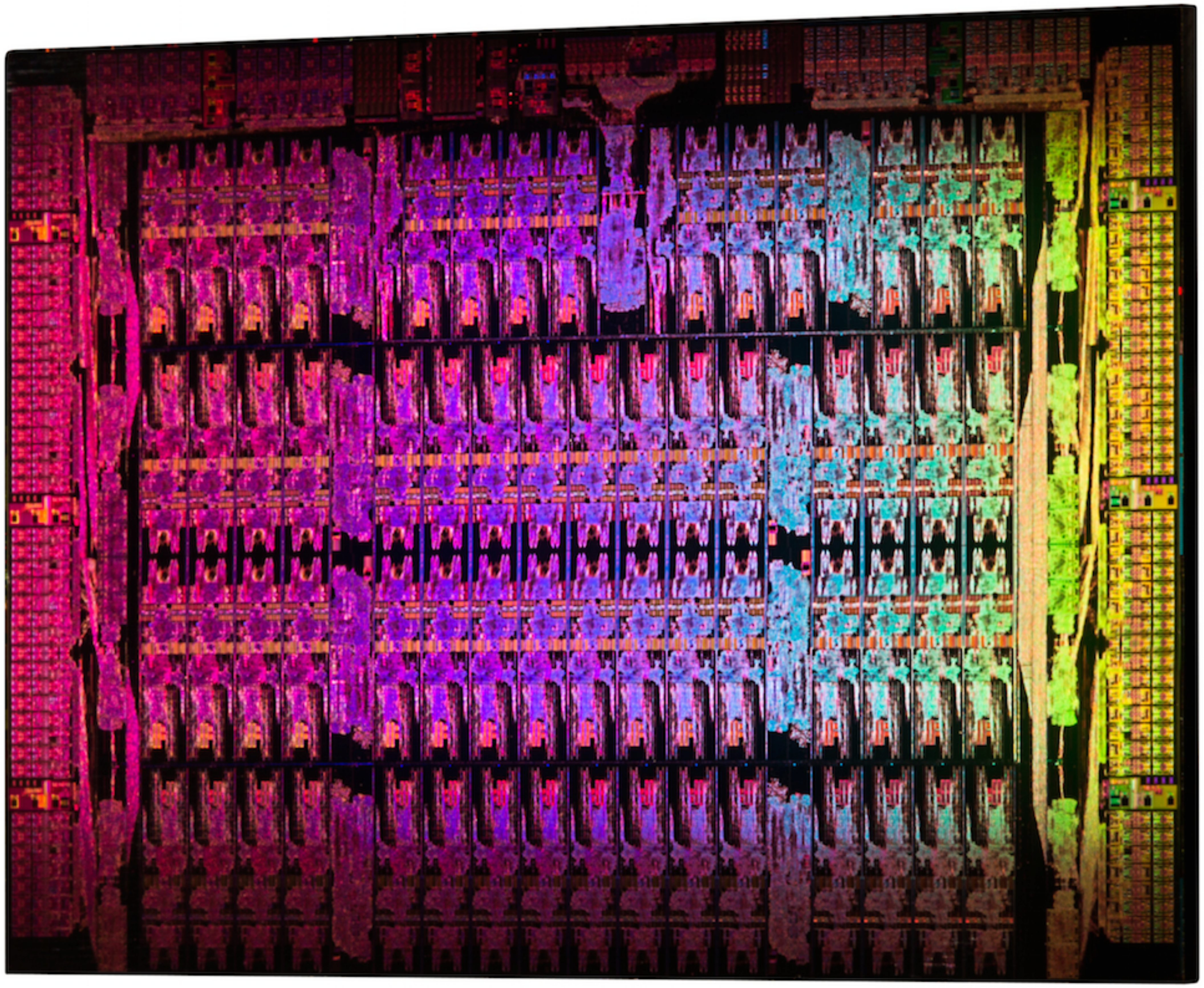
Quad-core CPU + multi-core GPU integrated on one chip



Intel Xeon Phi 7120A "coprocessor"

- 61 "simple" x86 cores (1.3 Ghz, derived from Pentium)
- Targeted as an accelerator for supercomputing applications

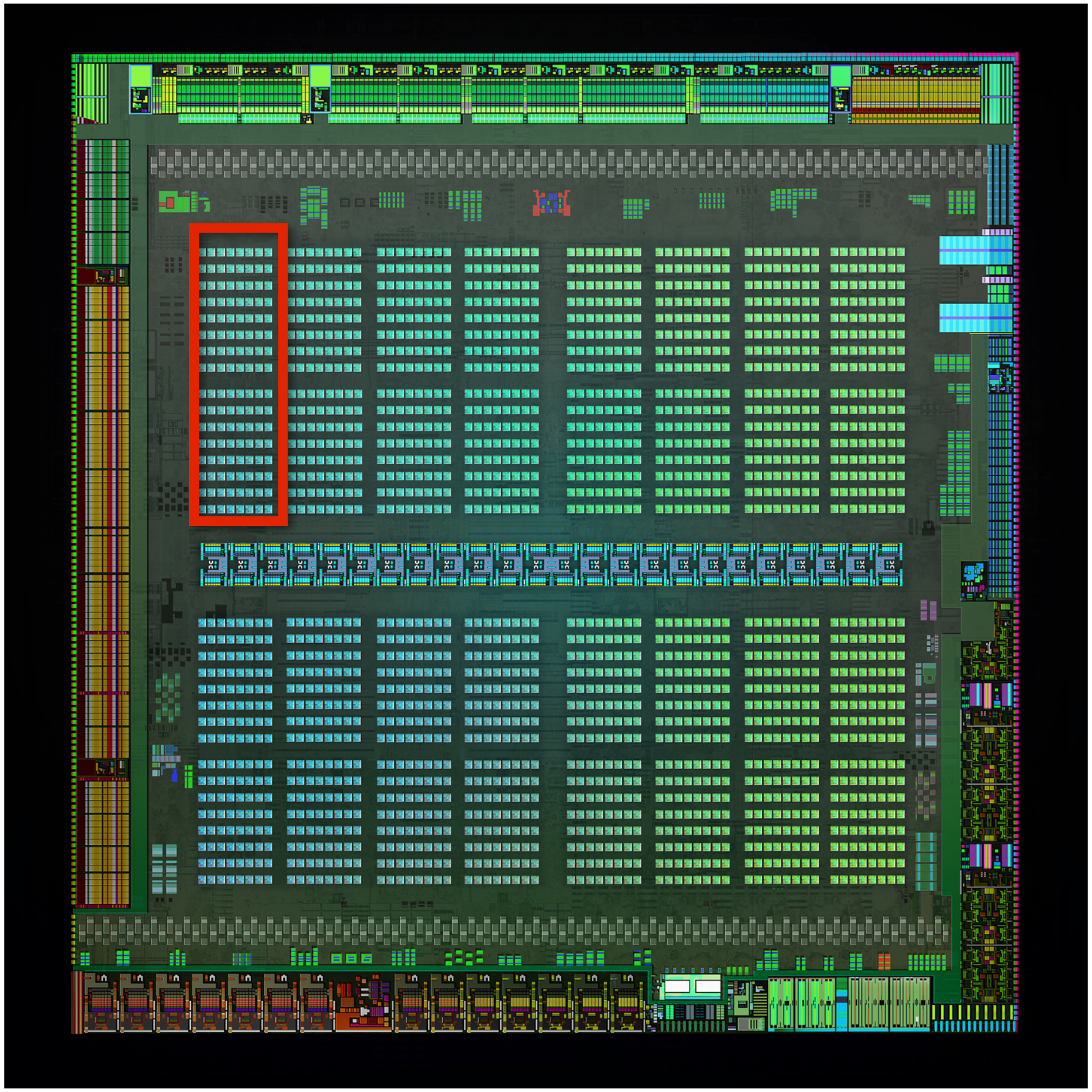




NVIDIA Maxwell GTX 980 GPU (2014)

Sixteen major processing blocks

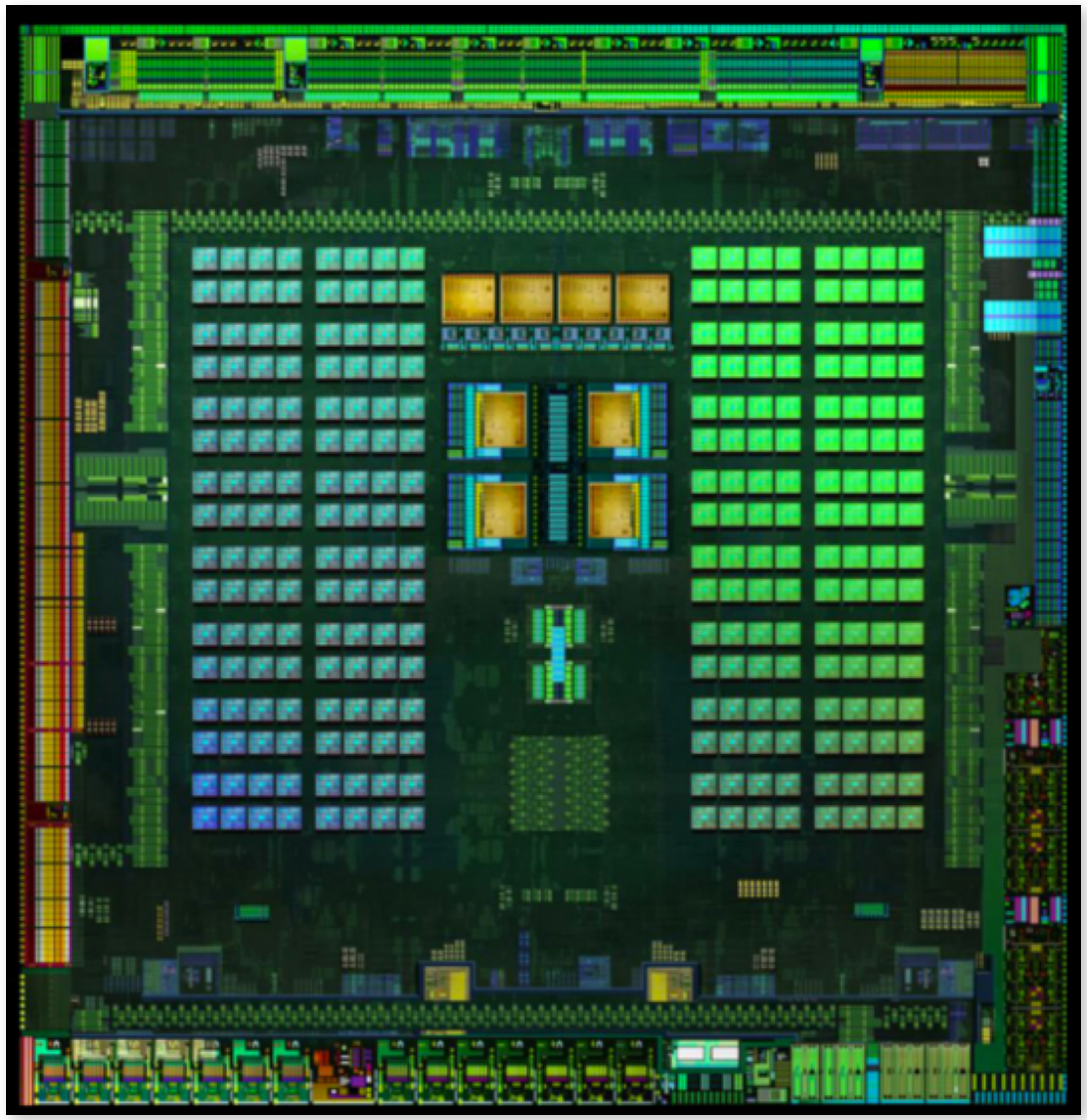
(but much, much more parallelism available... details coming next class)



Mobile parallel processing

Power constraints heavily influence design of mobile systems

Apple A9: (in iPhone 6s)
Dual-core CPU + GPU + image processor
and more on one chip



NVIDIA Tegra K1:
Quad-core ARM A57 CPU + 4 ARM A53 CPUs +
NVIDIA GPU + image processor...

Supercomputing

- Today: clusters of multi-core CPUs + GPUs
- Oak Ridge National Laboratory: Titan (#2 supercomputer in world)
    - 18,688 x 16 core AMD CPUs + 18,688 NVIDIA K20X GPUs

Summary

- Today, single-thread-of-control performance is improving very slowly
    - To run programs significantly faster, programs must utilize multiple processing elements
    - Which means you need to know how to write parallel code

- Writing parallel programs can be challenging
    - Requires problem partitioning, communication, synchronization
    - Knowledge of machine characteristics is important

- I suspect you will find that modern computers have tremendously more processing power than you might realize, if you just use it!

- Welcome to 15-418!