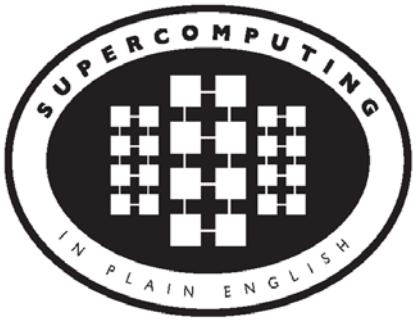
Supercomputing in Plain English

Instruction Level Parallelism

Henry Neeman, Director
OU Supercomputing Center for Education & Research (OSCER)
University of Oklahoma
Tuesday February 5 2013



This is an experiment!

It's the nature of these kinds of videoconferences that **FAILURES ARE GUARANTEED TO HAPPEN! NO PROMISES!**

So, please bear with us. Hopefully everything will work out well enough.

If you lose your connection, you can retry the same kind of connection, or try connecting another way.

Remember, if all else fails, you always have the toll free phone bridge to fall back on.

H.323 (Polycom etc) #1

If you want to use H.323 videoconferencing – for example, Polycom – then:

- If you AREN'T registered with the OneNet gatekeeper (which is probably the case), then:
  - Dial **`164.58.250.47`**
  - Bring up the virtual keypad.
    On some H.323 devices, you can bring up the virtual keypad by typing: #

    (You may want to try without first, then with; some devices won't work with the #, but give cryptic error messages about it.)
  - When asked for the conference ID, or if there's no response, enter: **`0409`**
  - On most but not all H.323 devices, you indicate the end of the ID with: **#**

H.323 (Polycom etc) #2

If you want to use H.323 videoconferencing – for example, Polycom – then:

- If you ARE already registered with the OneNet gatekeeper (most institutions aren't), dial:

  2500409

Many thanks to Skyler Donahue and Steven Haldeman of OneNet for providing this.

Wowza #1

You can watch from a Windows, MacOS or Linux laptop using Wowza from either of the following URLs:

http://www.onenet.net/technical-resources/video/sipe-stream/

OR

https://vcenter.njvid.net/videos/livestreams/page1/

Wowza behaves a lot like YouTube, except live.

Many thanks to Skyler Donahue and Steven Haldeman of OneNet and Bob Gerdes of Rutgers U for providing this.

Wowza #2

Wowza has been tested on multiple browsers on each of:

- Windows (7 and 8): IE, Firefox, Chrome, Opera, Safari
- MacOS X: Safari, Firefox
- Linux: Firefox, Opera

We've also successfully tested it on devices with:

- Android
- iOS

However, we make no representations on the likelihood of it working on your device, because we don't know which versions of Android or iOS it might or might not work with.

Wowza #3

If one of the Wowza URLs fails, try switching over to the other one.

If we lose our network connection between OU and OneNet, then there may be a slight delay while we set up a direct connection to Rutgers.

Toll Free Phone Bridge

IF ALL ELSE FAILS, you can use our toll free phone bridge:

800-832-0736

* 623 2847 #

Please mute yourself and use the phone to listen.

Don't worry, we'll call out slide numbers as we go.

Please use the phone bridge **ONLY** if you cannot connect any other way: the phone bridge can handle only 100 simultaneous connections, and we have over 350 participants.

Many thanks to OU CIO Loretta Early for providing the toll free phone bridge.

Please Mute Yourself

No matter how you connect, please mute yourself, so that we cannot hear you.

(For Wowza, you don't need to do that, because the information only goes from us to you, not from you to us.)

At OU, we will turn off the sound on all conferencing technologies.

That way, we won't have problems with echo cancellation.

Of course, that means we cannot hear questions.

So for questions, you'll need to send e-mail.

Questions via E-mail Only

Ask questions by sending e-mail to:

sipe2013@gmail.com

All questions will be read out loud and then answered out loud.

TENTATIVE Schedule

Tue Jan 29: Inst Level Par: What the Heck is Supercomputing?
Tue Jan 29: The Tyranny of the Storage Hierarchy
Tue Feb 5: Instruction Level Parallelism
Tue Feb 12: Stupid Compiler Tricks
Tue Feb 19: Shared Memory Multithreading
Tue Feb 26: Distributed Multiprocessing
Tue March 5: Applications and Types of Parallelism
Tue March 12: Multicore Madness
Tue March 19: NO SESSION (OU's Spring Break)
Tue March 26: High Throughput Computing
Tue Apr 2: GPGPU: Number Crunching in Your Graphics Card
Tue Apr 9: Grab Bag: Scientific Libraries, I/O Libraries, Visualization

Supercomputing Exercises #1

Want to do the "Supercomputing in Plain English" exercises?

- The 3rd exercise will be posted soon at:

  http://www.oscer.ou.edu/education/

- If you don't yet have a supercomputer account, you can get a temporary account, just for the "Supercomputing in Plain English" exercises, by sending e-mail to:

  hneeman@ou.edu

Please note that this account is for doing the **exercises only**, and will be shut down at the end of the series. It's also available only to those at institutions in the USA.

- This week's Introductory exercise will teach you how to compile and run jobs on OU's big Linux cluster supercomputer, which is named Boomer.

Supercomputing Exercises #2

You'll be doing the exercises on your own (or you can work with others at your local institution if you like).

These aren't graded, but we're available for questions:

hneeman@ou.edu

Thanks for helping!

- OU IT
  - OSCER operations staff (Brandon George, Dave Akin, Brett Zimmerman, Josh Alexander, Patrick Calhoun)
  - Horst Severini, OSCER Associate Director for Remote & Heterogeneous Computing
  - Debi Gentis, OU Research IT coordinator
  - Kevin Blake, OU IT (videographer)
  - Chris Kobza, OU IT (learning technologies)
  - Mark McAvoy
- Kyle Keys, OU National Weather Center
- James Deaton, Skyler Donahue and Steven Haldeman, OneNet
- Bob Gerdes, Rutgers U
- Lisa Ison, U Kentucky
- Paul Dave, U Chicago

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Coming in 2013!

From Computational Biophysics to Systems Biology, May 19-21, Norman OK

Great Plains Network Annual Meeting, May 29-31, Kansas City

XSEDE2013, July 22-25, San Diego CA

IEEE Cluster 2013, Sep 23-27, Indianapolis IN

OKLAHOMA SUPERCOMPUTING SYMPOSIUM 2013, Oct 1-2, Norman OK

SC13, Nov 17-22, Denver CO

OK Supercomputing Symposium 2013

2003 Keynote:
Peter Freeman
NSF
Computer & Information Science & Engineering
Assistant Director

2004 Keynote:
Sangtae Kim
NSF Shared Cyberinfrastructure Division Director

2005 Keynote:
Walt Brooks
NASA Advanced Supercomputing Division Director

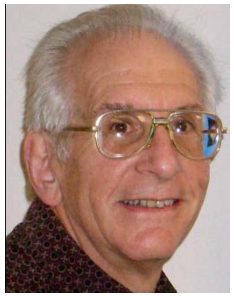
2006 Keynote:
Dan Atkins
Head of NSF's Office of Cyberinfrastructure

2007 Keynote:
Jay Boisseau
Director
Texas Advanced Computing Center
U. Texas Austin

2008 Keynote:
José Munoz
Deputy Office Director/ Senior Scientific Advisor
NSF Office of Cyberinfrastructure

2009 Keynote:
Douglass Post
Chief Scientist
US Dept of Defense HPC Modernization Program

2010 Keynote:
Horst Simon
Deputy Director
Lawrence Berkeley National Laboratory



2011 Keynote:
Barry Schneider
Program Manager
National Science Foundation

2012 Keynote:
Thom Dunning
Director
National Center for Supercomputing Applications

2013 Keynote
to be announced!

FREE! Wed Oct 2 2013 @ OU

http://symposium2013.oscer.ou.edu/

Reception/Poster Session
Tue Oct 1 2013 @ OU
Symposium Wed Oct 2 2013 @ OU

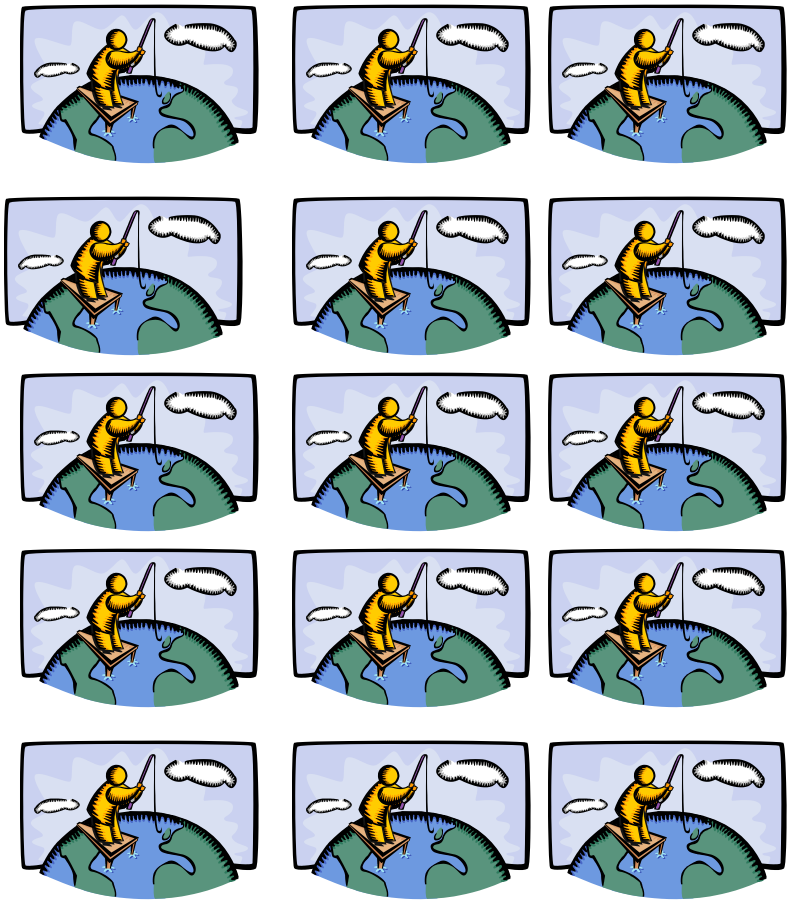
Outline

- What is Instruction-Level Parallelism?
- Scalar Operation
- Loops
- Pipelining
- Loop Performance
- Superpipelining
- Vectors
- A Real Example

Parallelism

Parallelism means doing multiple things at the same time: You can get more work done in the same time.

Less fish …



More fish!

What Is ILP?

Instruction-Level Parallelism (ILP) is a set of techniques for **executing multiple instructions at the same time within the same CPU core**.

(Note that ILP has **nothing to do with multicore**.)

The problem: A CPU core has lots of circuitry, and at any given time, most of it is idle, which is wasteful.

The solution: Have different parts of the CPU core work on different operations at the same time:

If the CPU core has the ability to work on 10 operations at a time, then the program can, in principle, run as much as 10 times as fast (although in practice, not quite so much).

DON'T PANIC!

Why You Shouldn't Panic

In general, the compiler and the CPU will do most of the heavy lifting for instruction-level parallelism.

BUT:

You need to be aware of ILP, because how your code is structured affects how much ILP the compiler and the CPU can give you.

Kinds of ILP

- ***Superscalar***: Perform multiple operations at the same time (for example, simultaneously perform an add, a multiply and a load).
- ***Pipeline***: Start performing an operation on one piece of data while finishing the same operation on another piece of data – perform different ***stages*** of the same operation on different sets of operands at the same time (like an assembly line).
- ***Superpipeline***: A combination of superscalar and pipelining – perform multiple pipelined operations at the same time.
- ***Vector***: Load multiple pieces of data into special registers and perform the same operation on all of them at the same time.

What's an Instruction?

- ***Memory***: For example, load a value from a specific address in main memory into a specific register, or store a value from a specific register into a specific address in main memory.
- ***Arithmetic***: For example, add two specific registers together and put their sum in a specific register – or subtract, multiply, divide, square root, etc.
- ***Logical***: For example, determine whether two registers both contain nonzero values ("**AND**").
- ***Branch***: Jump from one sequence of instructions to another (for example, function call).
- … and so on ….

What's a Cycle?

You've heard people talk about having a 2 GHz processor or a 3 GHz processor or whatever. (For example, consider a laptop with a 2.0 GHz i3.)

Inside every CPU is a little clock that ticks with a fixed frequency.

We call each tick of the CPU clock a ***clock cycle*** or a ***cycle***.

So a 2 GHz processor has 2 billion clock cycles per second.

Typically, a primitive operation (for example, add, multiply, divide) takes a fixed number of cycles to execute (assuming no pipelining).

What's the Relevance of Cycles?

Typically, a primitive operation (for example, add, multiply, divide) takes a fixed number of cycles to execute (assuming no pipelining).

- IBM POWER4 [1]
  - Multiply or add: 6 cycles (64 bit floating point)
  - Load: 4 cycles from L1 cache
    14 cycles from L2 cache

- Intel Sandy Bridge (4 x 64 bit floating point vector) [5]
  - Add: 3 cycles
  - Subtract: 3 cycles
  - Multiply: 5 cycles
  - Divide: 21-45 cycles
  - Square root: 21-45 cycles
  - Tangent:147 – 300 cycles

Scalar Operation

DON'T PANIC!

Scalar Operation

```
z = a * b + c * d;
```

How would this statement be executed?

1. Load **a** into register **R0**
2. Load **b** into **R1**
3. Multiply **R2** = **R0** * **R1**
4. Load **c** into **R3**
5. Load **d** into **R4**
6. Multiply **R5** = **R3** * **R4**
7. Add **R6** = **R2** + **R5**
8. Store **R6** into **z**

Does Order Matter?

```
z = a * b + c * d;
```

1. Load **a** into **R0**	1. Load **d** into **R0**
2. Load **b** into **R1**	2. Load **c** into **R1**
3. Multiply **R2 = R0 * R1**	3. Multiply **R2 = R0 * R1**
4. Load **c** into **R3**	4. Load **b** into **R3**
5. Load **d** into **R4**	5. Load **a** into **R4**
6. Multiply **R5 = R3 * R4**	6. Multiply **R5 = R3 * R4**
7. Add **R6 = R2 + R5**	7. Add **R6 = R2 + R5**
8. Store **R6** into **z**	8. Store **R6** into **z**

In the cases where order doesn't matter, we say that the operations are ***independent*** of one another.

Superscalar Operation

```
z = a * b + c * d;
```

1. Load **a** into **R0** **AND**
   load **b** into **R1**
2. Multiply **R2** = **R0** * **R1** **AND**
   load **c** into **R3** **AND**
   load **d** into **R4**
3. Multiply **R5** = **R3** * **R4**
4. Add **R6** = **R2** + **R5**
5. Store **R6** into **z**

If order doesn't matter,
then things can happen **simultaneously**.
So, we go from 8 operations down to 5.
(Note: there are lots of simplifying assumptions here.)

Loops

Loops Are Good

Most compilers are very good at optimizing **loops**, and not very good at optimizing other constructs.

Why?

```
DO index = 1, length
    dst(index) = src1(index) + src2(index)
END DO

for (index = 0; index < length; index++) {
    dst[index] = src1[index] + src2[index];
}
```

Why Loops Are Good

- Loops are **very common** in many programs.
- Also, it's easier to optimize loops than more arbitrary sequences of instructions: when a program does **the same thing over and over**, it's **easier to predict** what's likely to happen next.

So, hardware vendors have designed their products to be able to execute loops quickly.

DON'T PANIC!

Superscalar Loops (C)

```
for (i = 0; i < length; i++) {
  z[i] = a[i] * b[i] + c[i] * d[i];
}
```

Each of the iterations is **completely independent** of all of the other iterations; for example,

```
z[0] = a[0] * b[0] + c[0] * d[0]
```

has nothing to do with

```
z[1] = a[1] * b[1] + c[1] * d[1]
```

Operations that are independent of each other can be performed in **parallel**.

Superscalar Loops (F90)

```
DO i = 1, length
   z(i) = a(i) * b(i) + c(i) * d(i)
END DO
```

Each of the iterations is **completely independent** of all of the other iterations; for example,

```
z(1) = a(1) * b(1) + c(1) * d(1)
```

has nothing to do with

```
z(2) = a(2) * b(2) + c(2) * d(2)
```

Operations that are independent of each other can be performed in **parallel**.

Superscalar Loops

```
for (i = 0; i < length; i++) {
   z[i] = a[i] * b[i] + c[i] * d[i];
}
```

1. Load **a[i]** into **R0** **AND** load **b[i]** into **R1**
2. Multiply **R2 = R0 * R1** **AND** load **c[i]** into **R3** **AND** load **d[i]** into **R4**
3. Multiply **R5 = R3 * R4** **AND** load **a[i+1]** into **R0** **AND** load **b[i+1]** into **R1**
4. Add **R6 = R2 + R5** **AND** load **c[i+1]** into **R3** **AND** load **d[i+1]** into **R4**
5. Store **R6** into **z[i]** **AND** multiply **R2 = R0 * R1**
6. etc etc etc

Once this loop is "in flight," each iteration adds only 2 operations to the total, not 8.

Example: IBM POWER4

8-way Superscalar: can execute up to 8 operations at the same time[1]

- 2 integer arithmetic or logical operations, and
- 2 floating point arithmetic operations, and
- 2 memory access (load or store) operations, and
- 1 branch operation, and
- 1 conditional operation

Pipelining

Pipelining

Pipelining is like an assembly line or a bucket brigade.

- An operation consists of multiple stages.
- After a particular set of operands

```
z(i) = a(i) * b(i) + c(i) * d(i)
```

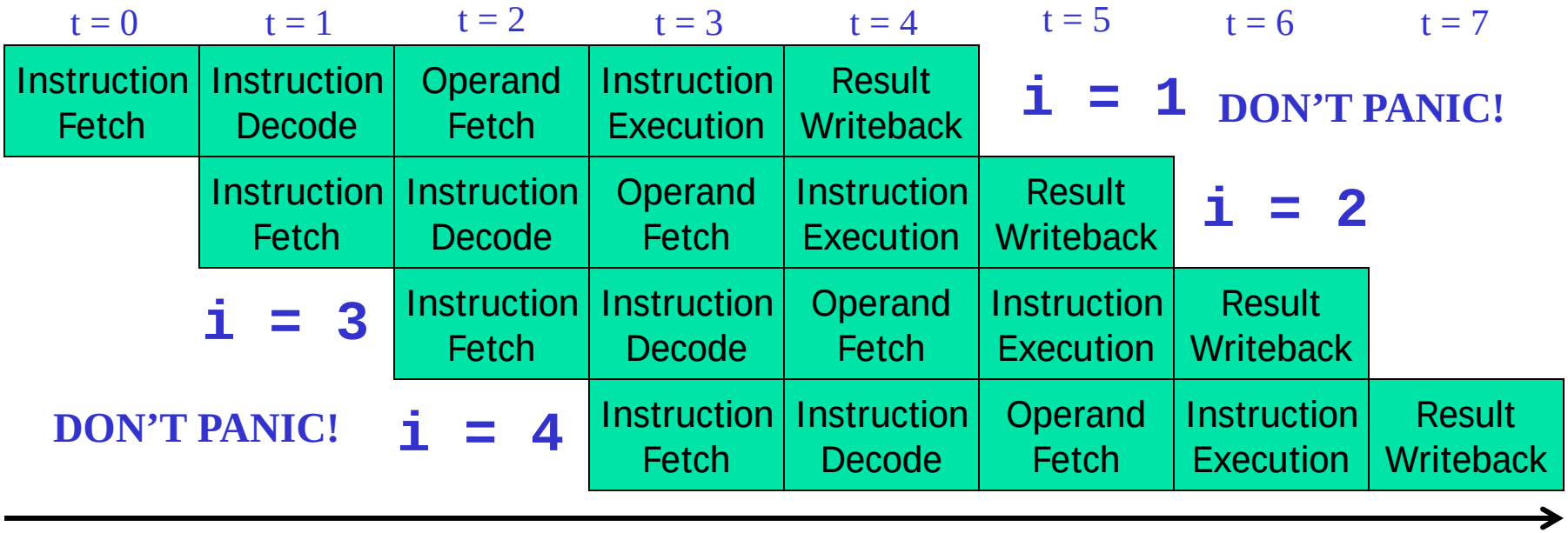
  completes a particular stage, they move into the next stage.
- Then, another set of operands

```
z(i+1) = a(i+1) * b(i+1) + c(i+1) * d(i+1)
```

  can move into the stage that was just abandoned by the previous set.

DON'T PANIC!

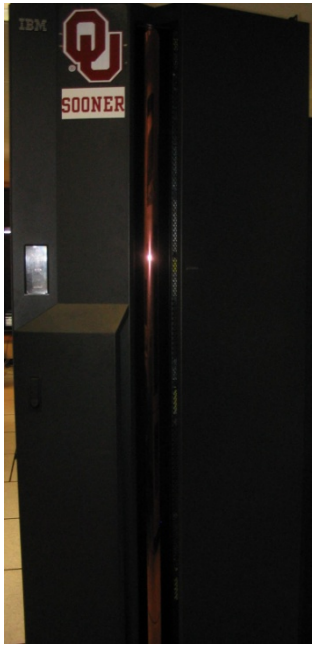
Pipelining Example



If each stage takes, say, one CPU cycle, then once the loop gets going, each iteration of the loop increases the total time by only one cycle. So a loop of length 1000 takes only 1004 cycles. [3]

Pipelines: Example

- IBM POWER4: pipeline length ≅ 15 stages [1]



Some Simple Loops (F90)

```
DO index = 1, length
  dst(index) = src1(index) + src2(index)
END DO

DO index = 1, length
  dst(index) = src1(index) - src2(index)
END DO

DO index = 1, length
  dst(index) = src1(index) * src2(index)
END DO

DO index = 1, length
  dst(index) = src1(index) / src2(index)
END DO

DO index = 1, length
  sum = sum + src(index)
END DO
```

Reduction: convert array to scalar

Some Simple Loops (C)

```
for (index = 0; index < length; index++) {
  dst[index] = src1[index] + src2[index];
}

for (index = 0; index < length; index++) {
  dst[index] = src1[index] - src2[index];
}

for (index = 0; index < length; index++) {
  dst[index] = src1[index] * src2[index];
}

for (index = 0; index < length; index++) {
  dst[index] = src1[index] / src2[index];
}

for (index = 0; index < length; index++) {
  sum = sum + src[index];
}
```

Slightly Less Simple Loops (F90)

```
DO index = 1, length
  dst(index) = src1(index) ** src2(index) !! src1 ^ src2
END DO

DO index = 1, length
  dst(index) = MOD(src1(index), src2(index))
END DO

DO index = 1, length
  dst(index) = SQRT(src(index))
END DO

DO index = 1, length
  dst(index) = COS(src(index))
END DO

DO index = 1, length
  dst(index) = EXP(src(index))
END DO

DO index = 1, length
  dst(index) = LOG(src(index))
END DO
```

Slightly Less Simple Loops (C)

```
for (index = 0; index < length; index++) {
  dst[index] = pow(src1[index], src2[index]);
}

for (index = 0; index < length; index++) {
  dst[index] = src1[index] % src2[index];
}

for (index = 0; index < length; index++) {
  dst[index] = sqrt(src[index]);
}

for (index = 0; index < length; index++) {
  dst[index] = cos(src[index]);
}

for (index = 0; index < length; index++) {
  dst[index] = exp(src[index]);
}

for (index = 0; index < length; index++) {
  dst[index] = log(src[index]);
}
```

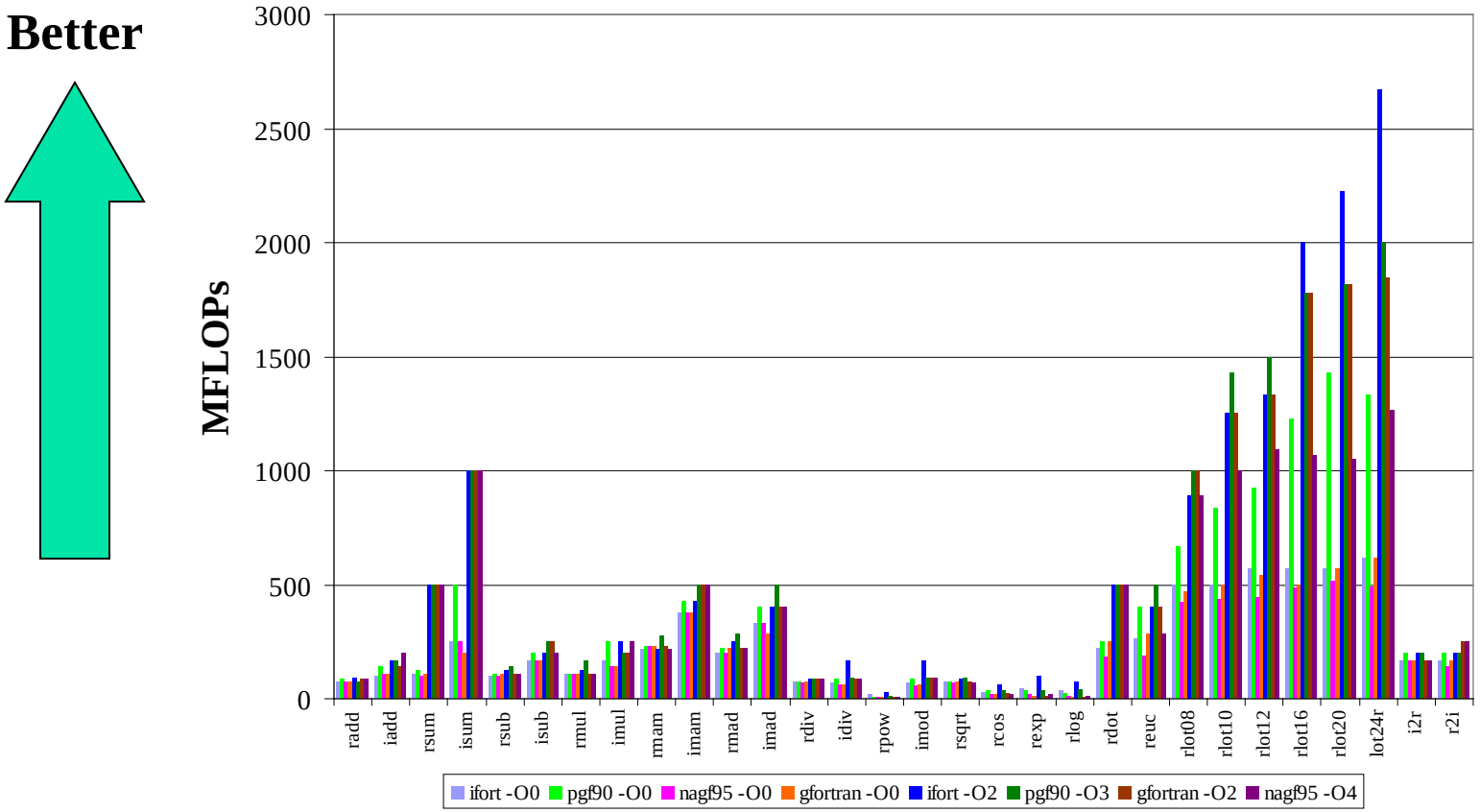
Loop Performance

Performance Characteristics

- Different operations take different amounts of time.
- Different processor types have different performance characteristics, but there are some characteristics that many platforms have in common.
- Different compilers, even on the same hardware, perform differently.
- On some processors, floating point and integer speeds are similar, while on others they differ.

Arithmetic Operation Speeds

Arithmetic Performance on Pentium4 EM64T
(Irwindale 3.2 GHz)



Fast and Slow Operations

- **Fast**: sum, add, subtract, multiply
- **Medium**: divide, mod (that is, remainder), sqrt
- **Slow**: transcendental functions (sin, exp)
- **Incredibly slow**: power x^y for real x and y

On most platforms, divide, mod and transcendental functions are not pipelined, so a code will run faster if most of it is just adds, subtracts and multiplies.

For example, solving an N x N system of linear equations by LU decomposition uses on the order of N^3 additions and multiplications, but only on the order of N divisions.

What Can Prevent Pipelining?

Certain events make it very hard (maybe even impossible) for compilers to pipeline a loop, such as:

- array elements accessed in **random order**
- loop body **too complicated**
- **`if` statements** inside the loop (on some platforms)
- premature **loop exits**
- function/subroutine **calls**
- **I/O**

How Do They Kill Pipelining?

- **Random access order**: Ordered array access is common, so pipelining hardware and compilers tend to be designed under the assumption that most loops will be ordered. Also, the pipeline will constantly ***stall*** because data will come from main memory, not cache.
- **Complicated loop body**: The compiler gets too overwhelmed and can't figure out how to schedule the instructions.

How Do They Kill Pipelining?

- **`if` statements** in the loop: On some platforms (but not all), the pipelines need to perform exactly the same operations over and over; **`if`** statements make that impossible.

However, many CPUs can now perform ***speculative execution***: both branches of the **`if`** statement are executed while the condition is being evaluated, but only one of the results is retained (the one associated with the condition's value).

Also, many CPUs can now perform ***branch prediction*** to head down the most likely compute path.

How Do They Kill Pipelining?

- **Function/subroutine calls** interrupt the flow of the program even more than `if` statements. They can take execution to a completely different part of the program, and pipelines aren't set up to handle that.
- **Loop exits** are similar. Most compilers can't pipeline loops with premature or unpredictable exits.
- **I/O**: Typically, I/O is handled in subroutines (above). Also, I/O instructions can take control of the program away from the CPU (they can give control to I/O devices).

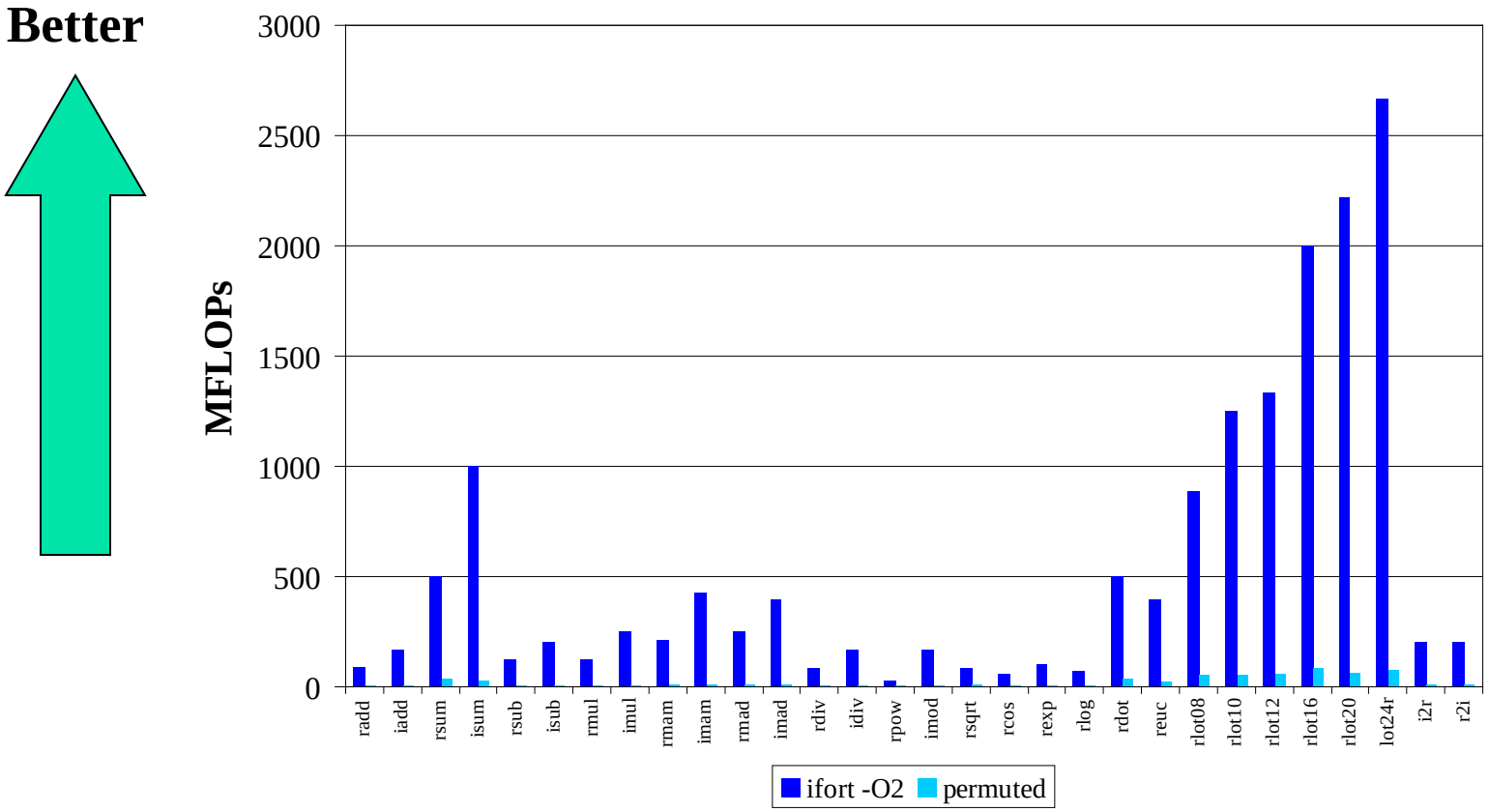
What If No Pipelining?

SLOW!

(on most platforms)

Randomly Permuted Loops

Arithmetic Performance: Ordered vs Random
(Irwindale 3.2 GHz)



Superpipelining

Superpipelining

Superpipelining is a combination of superscalar and pipelining.

So, a superpipeline is a collection of multiple pipelines that can operate simultaneously.

In other words, several different operations can execute simultaneously, and each of these operations can be broken into stages, each of which is filled all the time.

So you can get multiple operations per CPU cycle.

For example, a IBM Power4 can have over 200 different operations "in flight" at the same time.[1]

More Operations At a Time

- If you put more operations into the code for a loop, you can get better performance:
  - more operations can execute at a time (use more pipelines), and
  - you get better register/cache reuse.
- On most platforms, there's a limit to how many operations you can put in a loop to increase performance, but that limit varies among platforms, and can be quite large.

Some Complicated Loops

```
DO index = 1, length
  dst(index) = src1(index) + 5.0 * src2(index)
END DO
```

madd (or FMA): mult then add (2 ops)

```
dot = 0
DO index = 1, length
  dot = dot + src1(index) * src2(index)
END DO
```

dot product (2 ops)

```
DO index = 1, length
  dst(index) = src1(index) * src2(index) + &
 &             src3(index) * src4(index)
END DO
```

from our example (3 ops)

```
DO index = 1, length
  diff12 = src1(index) - src2(index)
  diff34 = src3(index) - src4(index)
  dst(index) = SQRT(diff12 * diff12 + diff34 * diff34)
END DO
```

Euclidean distance (6 ops)

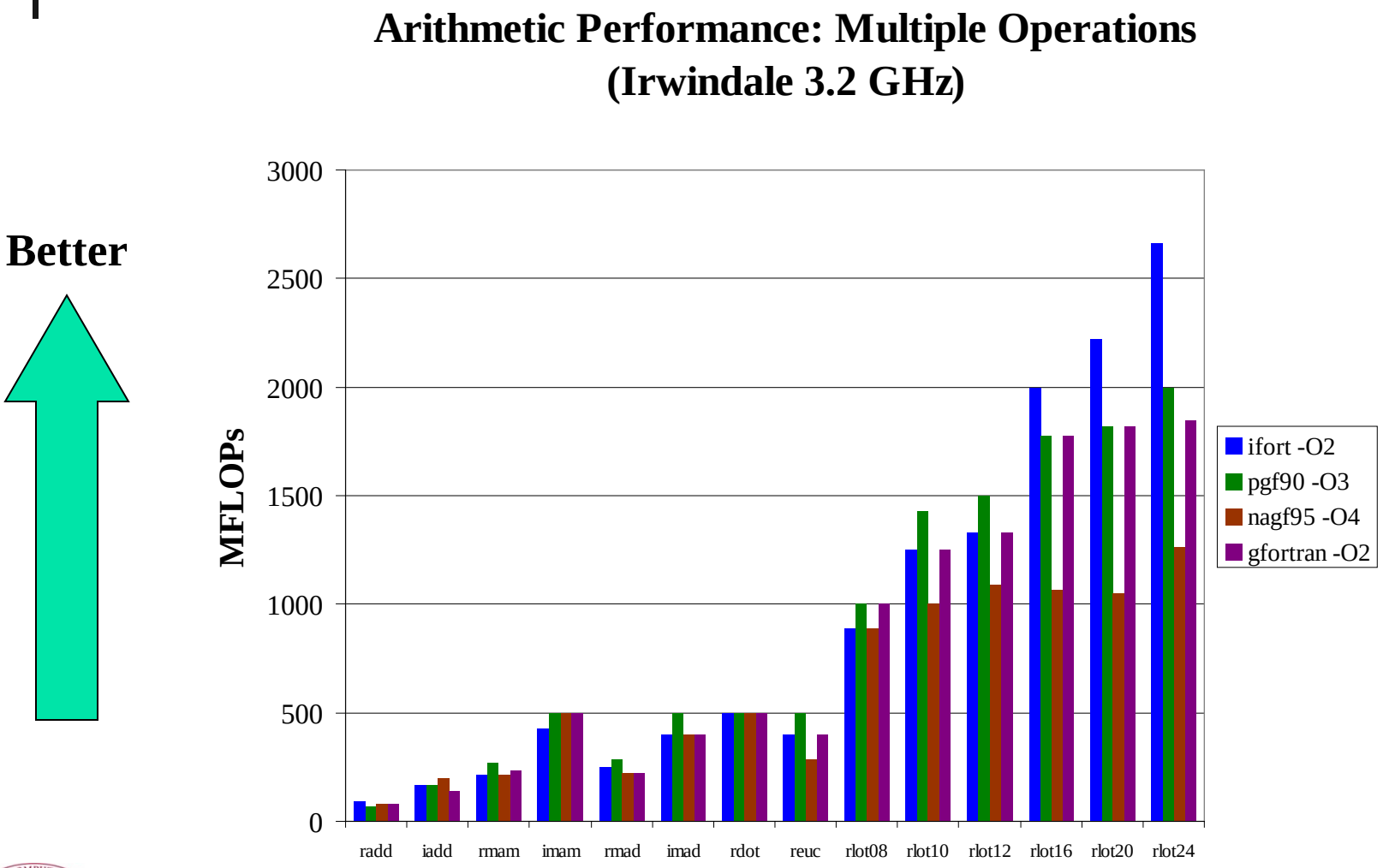
A Very Complicated Loop

```
lot = 0.0
DO index = 1, length
    lot = lot +                              &
 &    src1(index) * src2(index) +            &
 &    src3(index) * src4(index) +            &
 &    (src1(index) + src2(index)) *          &
 &    (src3(index) + src4(index)) *          &
 &    (src1(index) - src2(index)) *          &
 &    (src3(index) - src4(index)) *          &
 &    (src1(index) - src3(index) +           &
 &     src2(index) - src4(index)) *          &
 &    (src1(index) + src3(index) -           &
 &     src2(index) + src4(index)) +          &
 &    (src1(index) * src3(index)) +          &
 &    (src2(index) * src4(index))
END DO
```

24 arithmetic ops per iteration

4 memory/cache loads per iteration

Multiple Ops Per Iteration



Vectors

What Is a Vector?

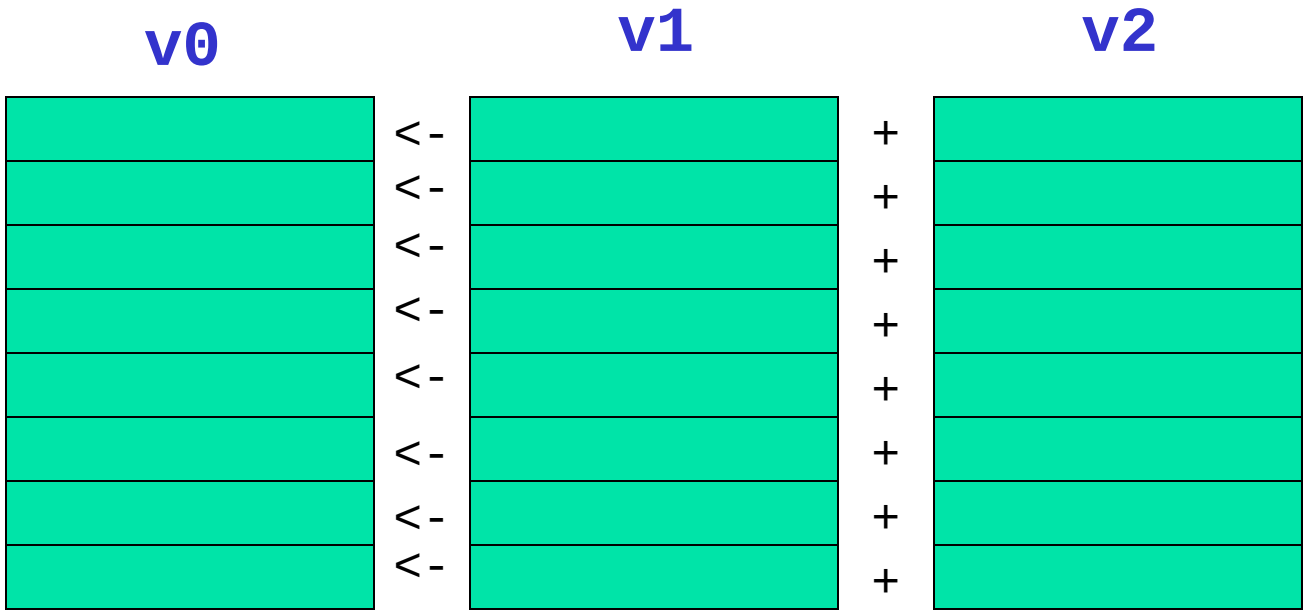
A ***vector*** is a giant register that behaves like a collection of regular registers, except these registers all simultaneously perform the same operation on multiple sets of operands, producing multiple results.

In a sense, vectors are like operation-specific cache.

A ***vector register*** is a register that's actually made up of many individual registers.

A ***vector instruction*** is an instruction that performs the same operation simultaneously on all of the individual registers of a vector register.

Vector Register




```
v0 <- v1 + v2
```

Vectors Are Expensive

Vectors were very popular in the 1980s, because they're very fast, often faster than pipelines.

In the 1990s, though, they weren't very popular. Why?

Well, vectors aren't used by many commercial codes (for example, MS Word). So most chip makers didn't bother with vectors.

So, if you wanted vectors, you had to pay a lot of **extra money** for them.

Pentium III Intel reintroduced very small integer vectors (2 operations at a time). Pentium4 added floating point vector operations, also of size 2. The Core family doubled the vector size to 4, and Sandy Bridge (2011) added "Fused Mutiply-Add," which allows 8 calculations at a time (vector length 4).

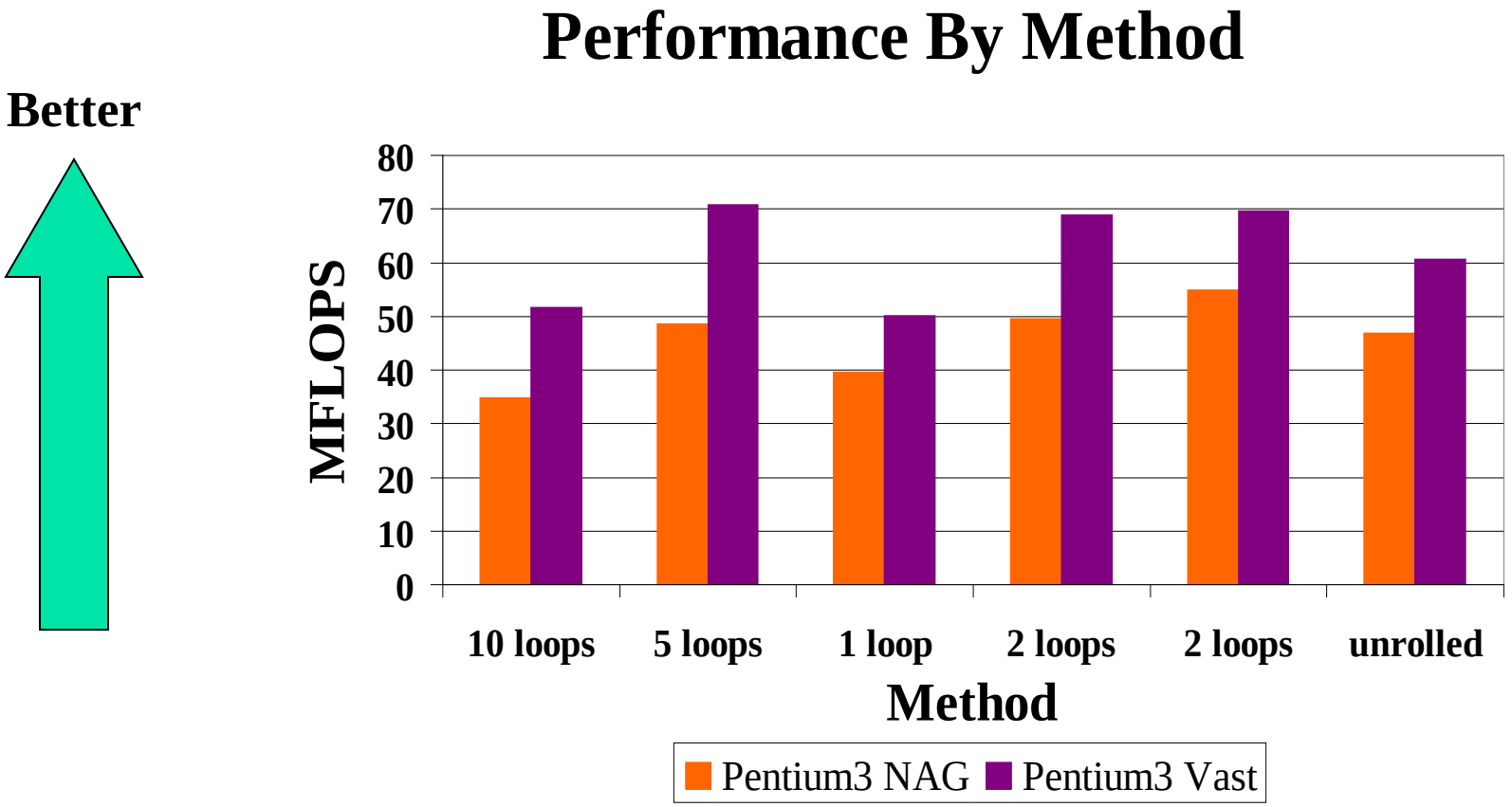
A Real Example

A Real Example[4]

```
DO k=2,nz-1
  DO j=2,ny-1
    DO i=2,nx-1
      tem1(i,j,k) = u(i,j,k,2)*(u(i+1,j,k,2)-u(i-1,j,k,2))*dxinv2
      tem2(i,j,k) = v(i,j,k,2)*(u(i,j+1,k,2)-u(i,j-1,k,2))*dyinv2
      tem3(i,j,k) = w(i,j,k,2)*(u(i,j,k+1,2)-u(i,j,k-1,2))*dzinv2
    END DO
  END DO
END DO
DO k=2,nz-1
  DO j=2,ny-1
    DO i=2,nx-1
      u(i,j,k,3) = u(i,j,k,1) -    &
 &                 dtbig2*(tem1(i,j,k)+tem2(i,j,k)+tem3(i,j,k))
    END DO
  END DO
END DO

. . .
```

Real Example Performance



DON'T PANIC!

Why You Shouldn't Panic

In general, the compiler and the CPU will do most of the heavy lifting for instruction-level parallelism.

BUT:

You need to be aware of ILP, because how your code is structured affects how much ILP the compiler and the CPU can give you.

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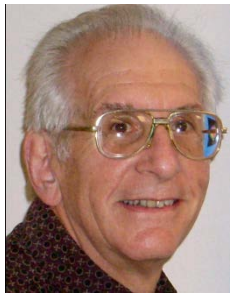

2011 Keynote:
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Thanks for your attention!

Questions?

www.oscer.ou.edu

References

[1] Steve Behling et al, *The POWER4 Processor Introduction and Tuning Guide*, IBM, 2001.

[2] *Intel® 64 and IA-32 Architectures Optimization Reference Manual*, Order Number: 248966-015, May 2007.
http://www.intel.com/design/processor/manuals/248966.pdf

[3] Kevin Dowd and Charles Severance, *High Performance Computing*, 2nd ed. O'Reilly, 1998.

[4] Code courtesy of Dan Weber, 2001.

[5] Intel® 64 and IA-32 Architectures Optimization Reference Manual
http://www.intel.com/content/dam/doc/manual/64-ia-32-architectures-optimization-manual.pdf