# Parallel Programming & Cluster Computing

## Instruction Level Parallelism

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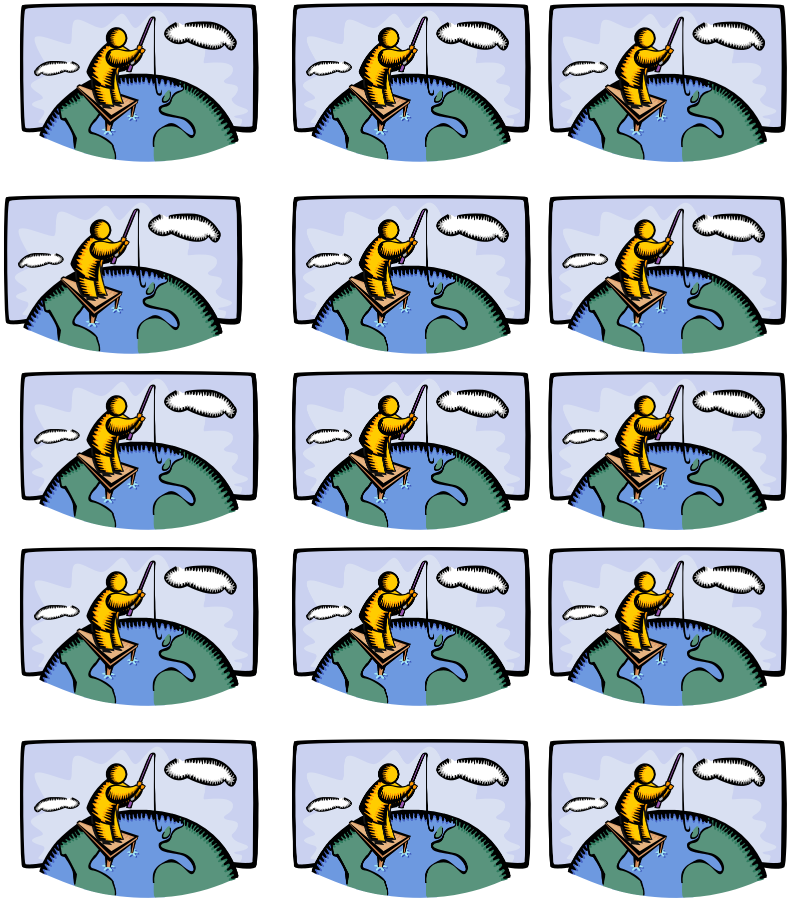
# Outline

- 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**: The CPU 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 work on different operations at the same time: If the CPU 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, Henry's laptop has a 1.83 GHz Pentium4 Centrino Duo.)

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 Pentium4 EM64T (Core) [2]
  - Multiply: 7 cycles (64 bit floating point)
  - Add, subtract: 5 cycles (64 bit floating point)
  - Divide: 38 cycles (64 bit floating point)
  - Square root: 39 cycles (64 bit floating point)
  - Tangent: 240-300 cycles (64 bit floating point)

# 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
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

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

```
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

| t = 0 | t = 1 | t = 2 | t = 3 | t = 4 | t = 5 | t = 6 | t = 7 |
|---|---|---|---|---|---|---|---|
| Instruction Fetch | Instruction Decode | Operand Fetch | Instruction Execution | Result Writeback | `i = 1` | **DON'T PANIC!** | |
| | Instruction Fetch | Instruction Decode | Operand Fetch | Instruction Execution | Result Writeback | `i = 2` | |
| | `i = 3` | Instruction Fetch | Instruction Decode | Operand Fetch | Instruction Execution | Result Writeback | |
| **DON'T PANIC!** | | `i = 4` | Instruction Fetch | Instruction Decode | Operand Fetch | Instruction Execution | Result Writeback |

Computation time

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

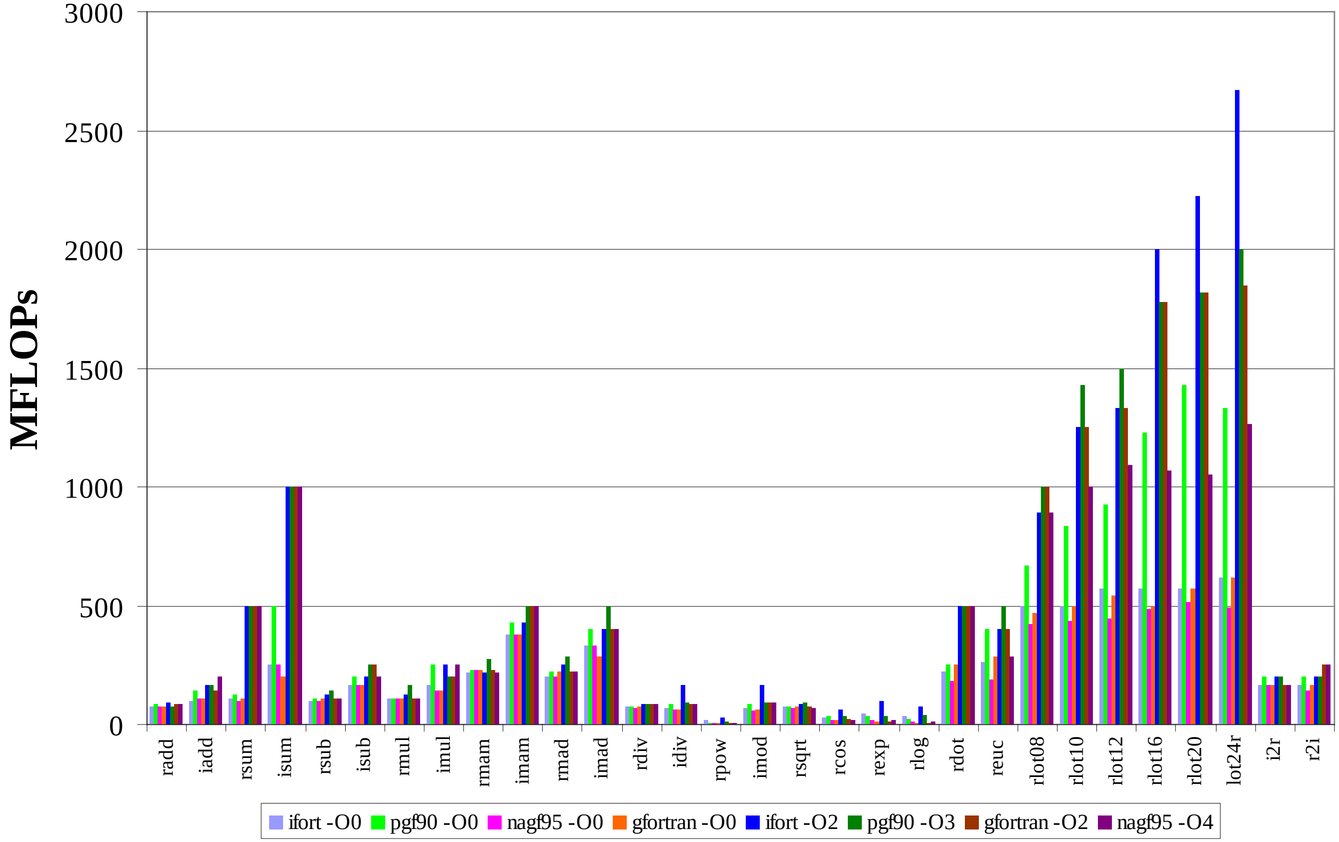
# Performance Characteristics

- 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)**

**Better**



# Fast and Slow Operations

- **Fast**: sum, add, subtract, multiply
- **Medium**: divide, mod (that is, remainder)
- **Slow**: transcendental functions (sqrt, 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?

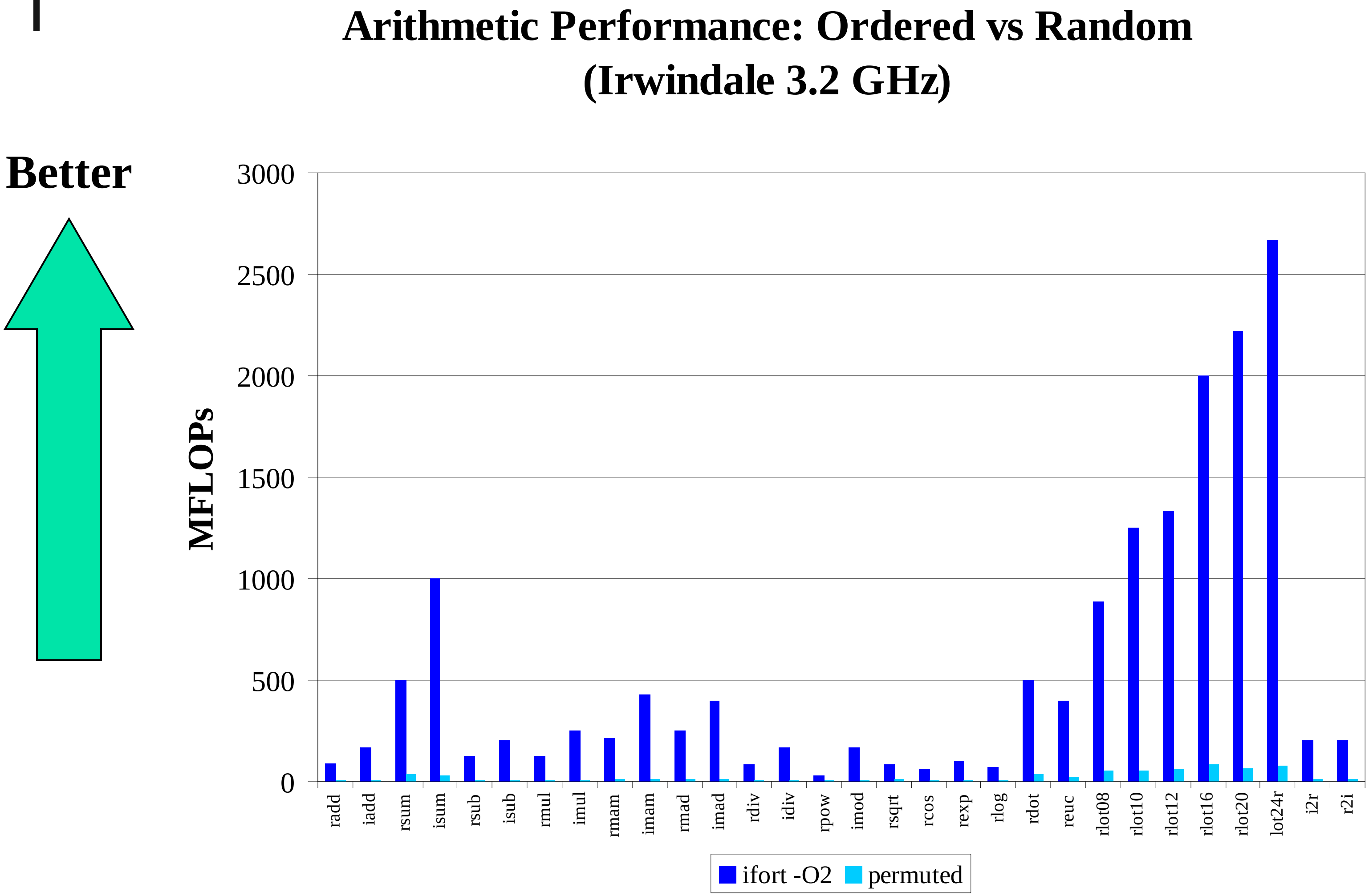
- **Function/subroutine calls** interrupt the flow of the program even more than `if` statements. They can take execution to a completely different part of the program, and pipelines aren’t set up to handle that.
- **Loop exits** are similar. Most compilers can’t pipeline loops with premature or unpredictable 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



# 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
```

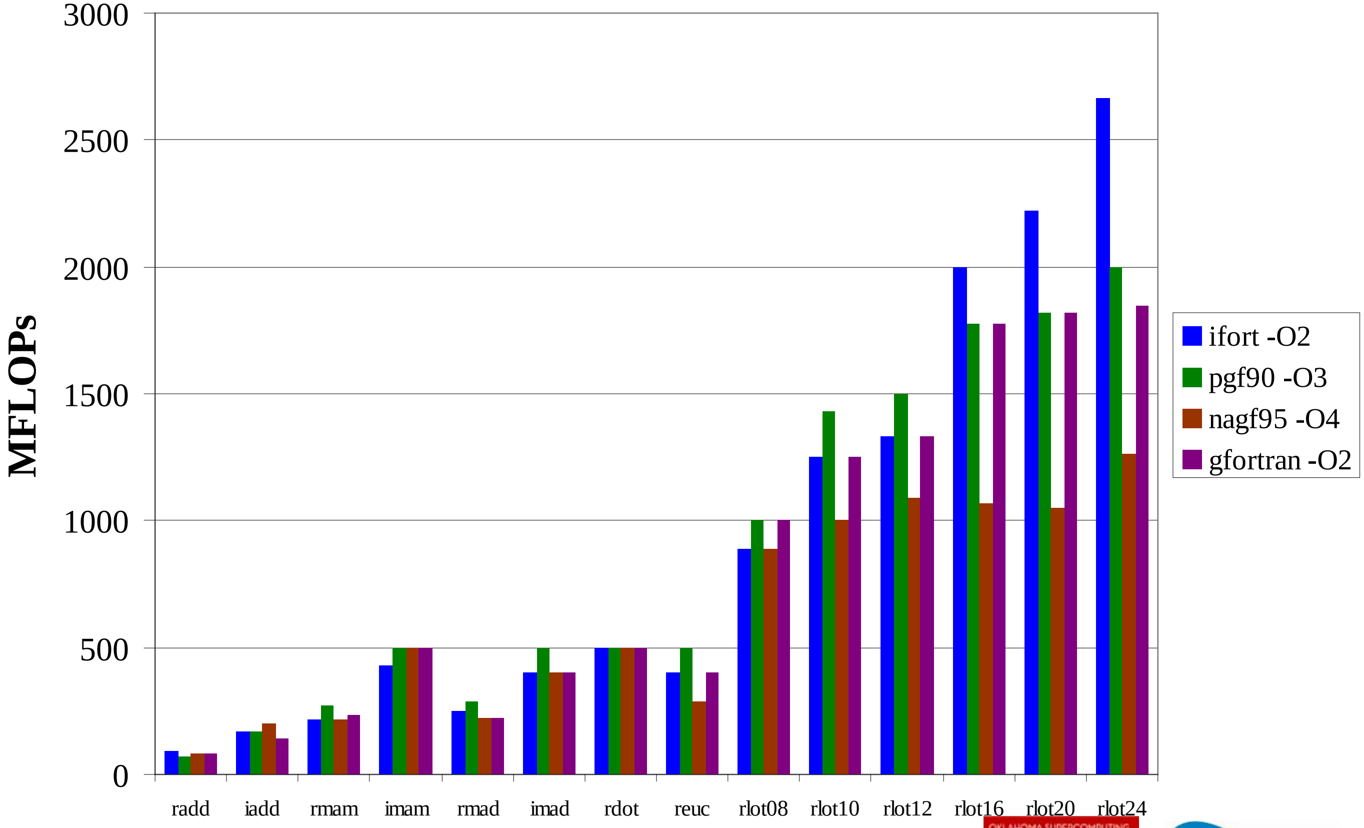
24 arithmetic ops per iteration

4 memory/cache loads per iteration

# Multiple Ops Per Iteration

**Arithmetic Performance: Multiple Operations (Irwindale 3.2 GHz)**

**Better**



# Vectors

# What Is a Vector?

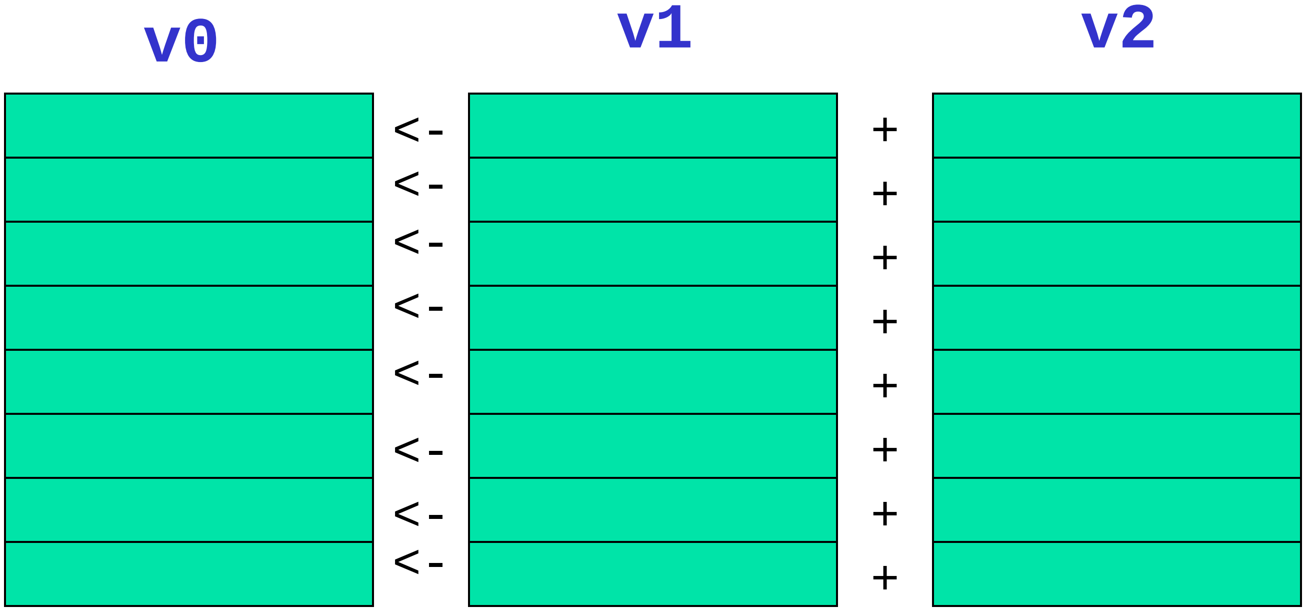
A ***vector*** is a giant register that behaves like a collection of regular registers, except these registers all simultaneously perform the same operation on multiple sets of operands, producing multiple results.

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.

However, with the Pentium III Intel reintroduced very small vectors (2 operations at a time), for integer operations only. The Pentium4 added floating point vector operations, also of size 2. Now, the Core family has doubled the vector size to 4.

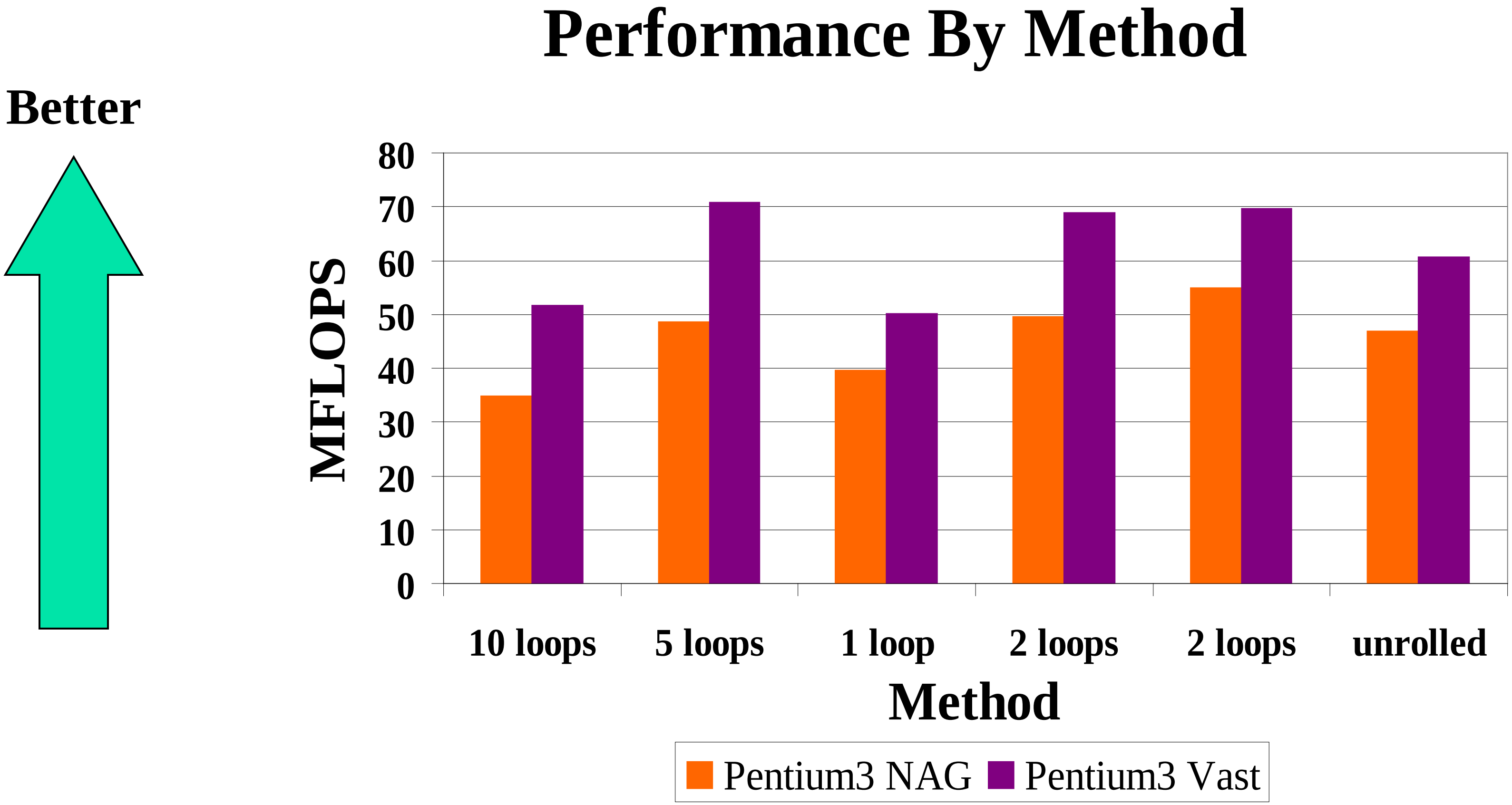
# A Real Example

# 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



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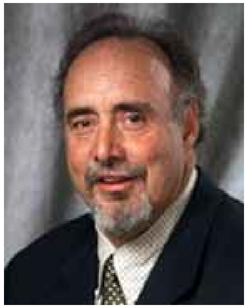

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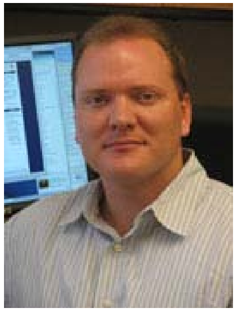

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# Thanks for your attention!

# Questions?

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

[4] Code courtesy of Dan Weber, 2001.