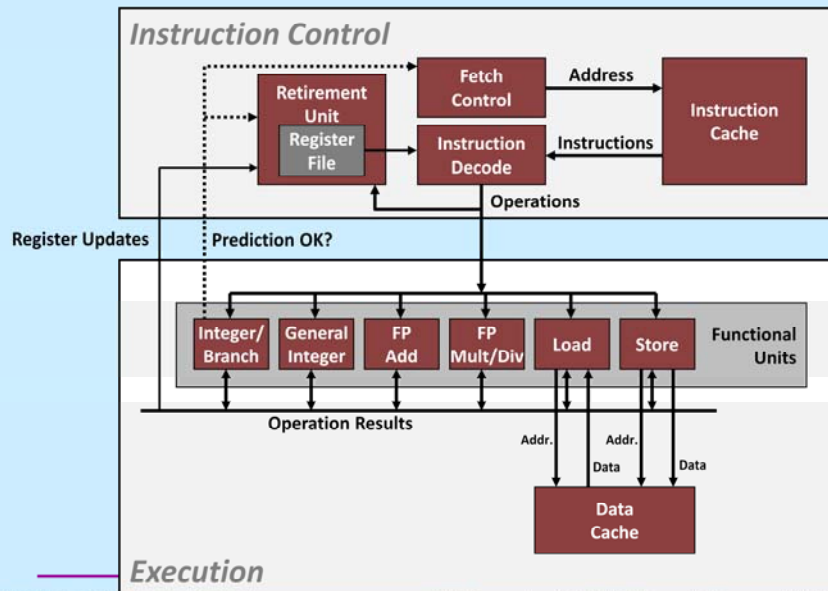


CS 33

Architecture and Optimization (2)

Most of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook “Computer Systems: A Programmer’s Perspective,” 2nd Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O’Hallaron in Fall 2010. These slides are indicated “Supplied by CMU” in the notes section of the slides.

Modern CPU Design



Supplied by CMU.

Superscalar Processor

- **Definition:** A superscalar processor can issue and execute *multiple instructions in one cycle*
 - instructions are retrieved from a sequential instruction stream and are usually scheduled dynamically
 - » instructions are executed *out of order*
- **Benefit:** without programming effort, superscalar processor can take advantage of the *instruction-level parallelism* that most programs have
- Most CPUs since about 1998 are superscalar
- Intel: since Pentium Pro (1995)

Supplied by CMU.

Multiple Operations per Instruction

- `addl %eax, %edx`
 - a single operation
- `addl %eax, 4(%edx)`
 - three operations
 - » load value from memory
 - » add to it the contents of `%eax`
 - » store result in memory

Instruction-Level Parallelism

- `addl 4(%eax), %eax`
`addl %ebx, %edx`
 - can be executed simultaneously: completely independent
- `addl 4(%eax), %ebx`
`addl %ebx, %edx`
 - can also be executed simultaneously, but some coordination is required

Out-of-Order Execution

```
• movss    (%rbp), %xmm0
  mulss    (%rax, %rdx, 4), %xmm0
  movss    %xmm0, (%rbp)
  addq     %r8d, %r9d
  imulq    %rcx, %r12d
  addq     $1, %rdx
```

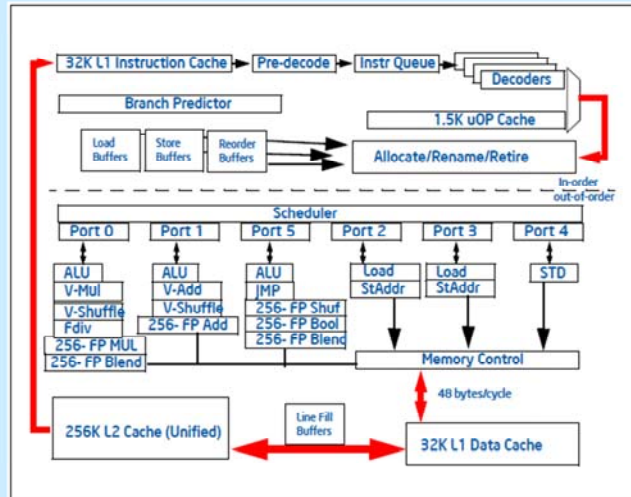
} these can be
executed without
waiting for the first
three to finish

Speculative Execution

```
80489f3:  movl    $0x1,%ecx
80489f8:  xorl    %edx,%edx
80489fa:  cmpl    %esi,%edx
80489fc:  jnl     8048a25
80489fe:  movl    %esi,%esi
8048a00:  imull   (%eax,%edx,4),%ecx
```

} perhaps execute these instructions

Sandy-Bridge Microarchitecture



This is Figure 2-1 from *Intel® 64 and IA-32 Architectures Optimization Reference Manual*, published in April 2012. The document can be found at <http://www.intel.com/content/dam/doc/manual/64-ia-32-architectures-optimization-manual.pdf>. It shows the microarchitecture of Intel's "Sandy Bridge" architecture, the successor to the Nehalem architecture.

Nehalem CPU

- **Multiple instructions can execute in parallel**

- 1 load, with address computation
- 1 store, with address computation
- 2 simple integer (one may be branch)
- 1 complex integer (multiply/divide)
- 1 FP Multiply
- 1 FP Add

- **Some instructions take > 1 cycle, but can be pipelined**

<i>Instruction</i>	<i>Latency</i>	<i>Cycles/Issue</i>
Load / Store	4	1
Integer Add	1	.33
Integer Multiply	3	1
Integer/Long Divide	11–21	11–21
Single/Double FP Multiply	4/5	1
Single/Double FP Add	3	1
Single/Double FP Divide	10–23	10–23

Supplied by CMU.

“Nehalem” is Intel’s code name for its Core I7 processor design.

x86-64 Compilation of Combine4

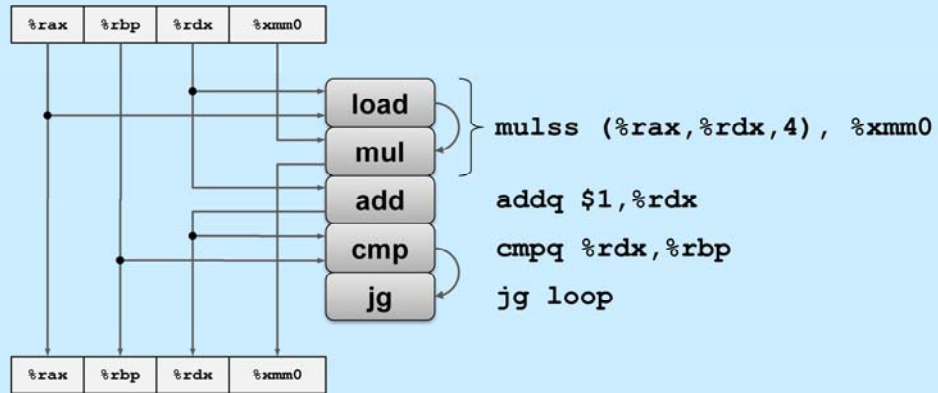
- Inner loop (case: integer multiply)

```
.L519:                # Loop:
    imull (%rax,%rdx,4), %ecx  # t = t * d[i]
    addq $1, %rdx             # i++
    cmpq %rdx, %rbp           # Compare length:i
    jg .L519                  # If >, goto Loop
```

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine4	2.0	3.0	3.0	5.0
Latency bound	1.0	3.0	3.0	5.0
Throughput bound	1.0	1.0	1.0	1.0

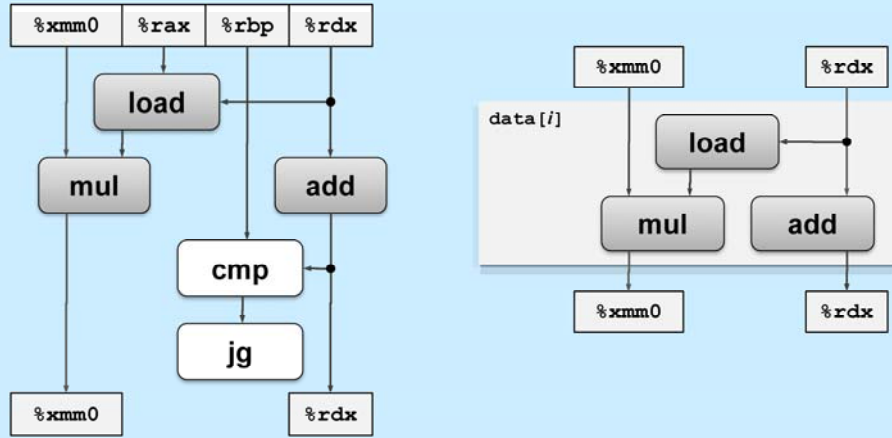
Supplied by CMU.

Inner Loop



This is Figure 5.13 of Bryant and O'Hallaron.

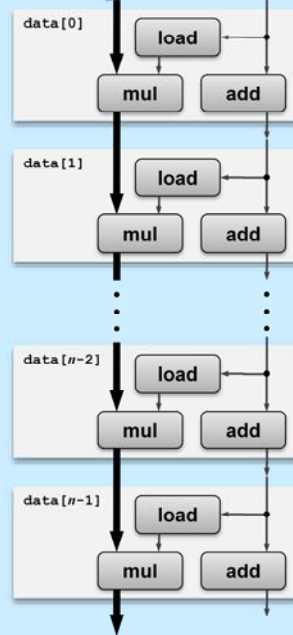
Data-Flow Graphs of Inner Loop



These are Figures 5.14 a and b of Bryant and O'Hallaron.

Data Flow Over Multiple Iterations

Critical path



This is Figure 5.15 of Bryant and O'Hallaron.

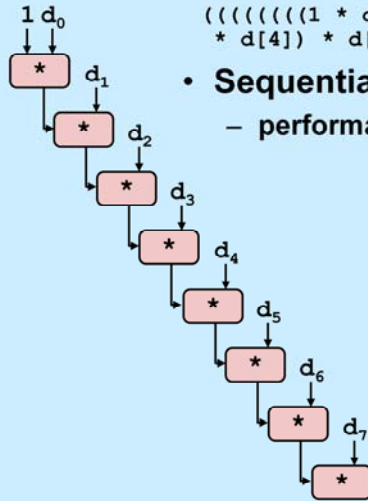
Combine4 = Serial Computation (OP = *)

- **Computation (length=8)**

$(((((1 * d[0]) * d[1]) * d[2]) * d[3]) * d[4]) * d[5]) * d[6]) * d[7])$

- **Sequential dependence**

– performance: determined by latency of OP



Supplied by CMU.

Loop Unrolling

```
void unroll2a_combine(vec_ptr v, data_t *dest)
{
    int length = vec_length(v);
    int limit = length-1;
    data_t *d = get_vec_start(v);
    data_t x = IDENT;
    int i;
    /* Combine 2 elements at a time */
    for (i = 0; i < limit; i+=2) {
        x = (x OP d[i]) OP d[i+1];
    }
    /* Finish any remaining elements */
    for (; i < length; i++) {
        x = x OP d[i];
    }
    *dest = x;
}
```

- Perform 2x more useful work per iteration

Supplied by CMU.

Effect of Loop Unrolling

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine4	2.0	3.0	3.0	5.0
Unroll 2x	2.0	1.5	3.0	5.0
Latency bound	1.0	3.0	3.0	5.0
Throughput bound	1.0	1.0	1.0	1.0

- **Helps integer multiply**
 - below latency bound
 - compiler does clever optimization
- **Others don't improve. *Why?***
 - still sequential dependency

```
x = (x OP d[i]) OP d[i+1];
```

Supplied by CMU.

What the compiler does for the case of integer multiplication is to apply reassociation, discussed in the next slide.

Loop Unrolling with Reassociation

```
void unroll2aa_combine(vec_ptr v, data_t *dest)
{
    int length = vec_length(v);
    int limit = length-1;
    data_t *d = get_vec_start(v);
    data_t x = IDENT;
    int i;
    /* Combine 2 elements at a time */
    for (i = 0; i < limit; i+=2) {
        x = x OP (d[i] OP d[i+1]);
    }
    /* Finish any remaining elements */
    for (; i < length; i++) {
        x = x OP d[i];
    }
    *dest = x;
}
```

Compare to before

x = (x OP d[i]) OP d[i+1];

- Can this change the result of the computation?
- Yes, for FP. *Why?*

Supplied by CMU.

Effect of Reassociation

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine4	2.0	3.0	3.0	5.0
Unroll 2x	2.0	1.5	3.0	5.0
Unroll 2x, reassociate	2.0	1.5	1.5	3.0
Latency bound	1.0	3.0	3.0	5.0
Throughput bound	1.0	1.0	1.0	1.0

- Nearly 2x speedup for int *, FP +, FP *
 - reason: breaks sequential dependency

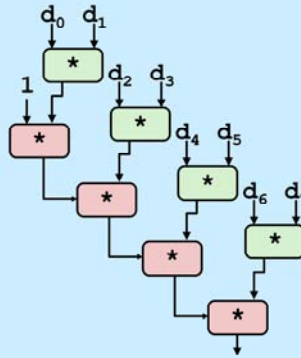
```
x = x OP (d[i] OP d[i+1]);
```

- why is that? (next slide)

Supplied by CMU.

Reassociated Computation

```
x = x OP (d[i] OP d[i+1]);
```



- **What changed:**

- ops in the next iteration can be started early (no dependency)

- **Overall Performance**

- N elements, D cycles latency/op
- should be $(N/2+1)*D$ cycles:
CPE = D/2
- measured CPE slightly worse for FP mult

Supplied by CMU.

Loop Unrolling with Separate Accumulators

```
void unroll2a_combine(vec_ptr v, data_t *dest)
{
    int length = vec_length(v);
    int limit = length-1;
    data_t *d = get_vec_start(v);
    data_t x0 = IDENT;
    data_t x1 = IDENT;
    int i;
    /* Combine 2 elements at a time */
    for (i = 0; i < limit; i+=2) {
        x0 = x0 OP d[i];
        x1 = x1 OP d[i+1];
    }
    /* Finish any remaining elements */
    for (; i < length; i++) {
        x0 = x0 OP d[i];
    }
    *dest = x0 OP x1;
}
```

- Different form of reassociation

Supplied by CMU.

Effect of Separate Accumulators

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine4	2.0	3.0	3.0	5.0
Unroll 2x	2.0	1.5	3.0	5.0
Unroll 2x, reassociate	2.0	1.5	1.5	3.0
Unroll 2x parallel 2x	1.5	1.5	1.5	2.5
Latency bound	1.0	3.0	3.0	5.0
Throughput bound	1.0	1.0	1.0	1.0

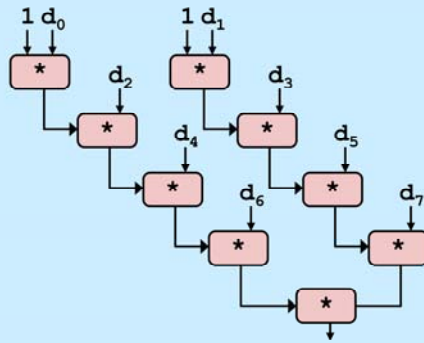
- 2x speedup (over unroll2) for int *, FP +, FP *
 - breaks sequential dependency in a “cleaner,” more obvious way

```
x0 = x0 OP d[i];
x1 = x1 OP d[i+1];
```

Supplied by CMU.

Separate Accumulators

```
x0 = x0 OP d[i];  
x1 = x1 OP d[i+1];
```



- **What changed:**

- two independent “streams” of operations

- **Overall Performance**

- N elements, D cycles latency/op
- should be $(N/2+1)*D$ cycles:
CPE = D/2
- CPE matches prediction!

What Now?

Supplied by CMU.

Unrolling & Accumulating

- **Idea**

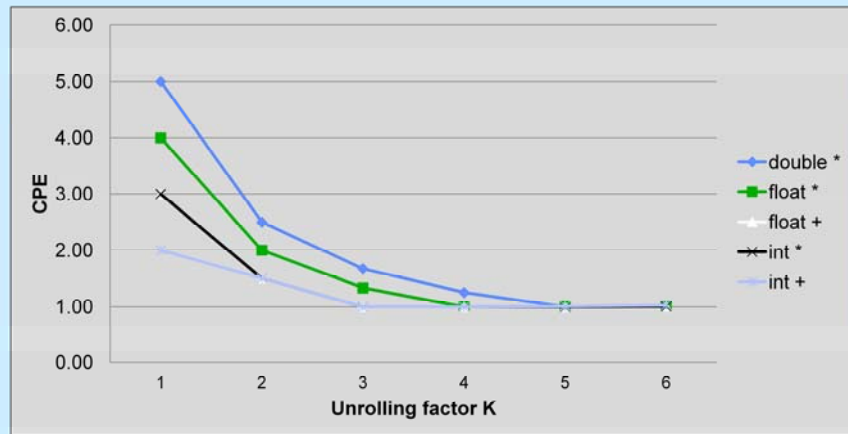
- can unroll to any degree L
- can accumulate K results in parallel
- L must be multiple of K

- **Limitations**

- diminishing returns
 - » cannot go beyond throughput limitations of execution units
- large overhead for short lengths
 - » finish off iterations sequentially

Supplied by CMU.

Performance



- K-way loop unrolling with K accumulators

Achievable Performance

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Scalar optimum	1.00	1.00	1.00	1.00
Latency bound	1.00	3.00	3.00	5.00
Throughput bound	1.00	1.00	1.00	1.00

- Limited only by throughput of functional units
- Up to 29X improvement over original, unoptimized code

Supplied by CMU.

Using Vector Instructions

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Scalar optimum	1.00	1.00	1.00	1.00
Vector optimum	0.25	0.53	0.53	0.57
Latency bound	1.00	3.00	3.00	5.00
Throughput bound	1.00	1.00	1.00	1.00
Vec throughput bound	0.25	0.50	0.50	0.50

- **Make use of SSE Instructions**
 - parallel operations on multiple data elements
 - see Web Aside OPT:SIMD on CS:APP web page

Supplied by CMU.

What About Branches?

- Challenge

– **instruction control unit** must work well ahead of **execution unit** to generate enough operations to keep EU busy

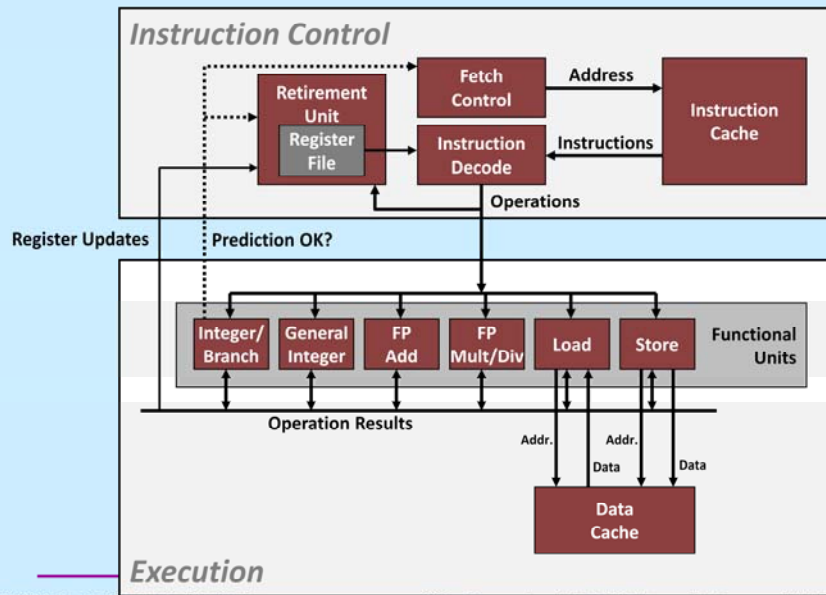
```
80489f3: movl    $0x1,%ecx
80489f8: xorl    %edx,%edx
80489fa: cmpl    %esi,%edx
80489fc: jnl     8048a25
80489fe: movl    %esi,%esi
8048a00: imull   (%eax,%edx,4),%ecx
```

} Executing

← How to continue?

– when it encounters conditional branch, cannot reliably determine where to continue fetching

Modern CPU Design



Supplied by CMU.

Branch Outcomes

- When encounter conditional branch, cannot determine where to continue fetching
 - branch taken: transfer control to branch target
 - branch not-taken: continue with next instruction in sequence
- Cannot resolve until outcome determined by branch/integer unit

```
80489f3: movl    $0x1,%ecx
80489f8: xorl    %edx,%edx
80489fa: cmpl    %esi,%edx
80489fc: jnl     8048a25
80489fe: movl    %esi,%esi
8048a00: imull   (%eax,%edx,4),%ecx
```

Branch not-taken

Branch taken

```
8048a25: cmpl    %edi,%edx
8048a27: jl      8048a20
8048a29: movl    0xc(%ebp),%eax
8048a2c: leal    0xffffffff8(%ebp),%esp
8048a2f: movl    %ecx,(%eax)
```

Supplied by CMU.

Branch Prediction

- Idea

- guess which way branch will go
- begin executing instructions at predicted position
 - » but don't actually modify register or memory data

```
80489f3: movl    $0x1,%ecx
80489f8: xorl    %edx,%edx
80489fa: cmpl    %esi,%edx
80489fc: jnl     8048a25
. . .
```

Predict taken

```
8048a25: cmpl    %edi,%edx
8048a27: jl      8048a20
8048a29: movl    0xc(%ebp),%eax
8048a2c: leal    0xffffffff8(%ebp),%esp
8048a2f: movl    %ecx,(%eax)
```

} Begin
execution

Supplied by CMU.

Branch Prediction Through Loop

```
80488b1: movl    (%ecx,%edx,4),%eax
80488b4: addl    %eax, (%edi)
80488b6: incl    %edx
80488b7: cmpl    %esi,%edx    i = 98
80488b9: j1l     80488b1
```

Assume
vector length = *100*

Predict taken (OK)

```
80488b1: movl    (%ecx,%edx,4),%eax
80488b4: addl    %eax, (%edi)
80488b6: incl    %edx
80488b7: cmpl    %esi,%edx    i = 99
80488b9: j1l     80488b1
```

Predict taken
(oops)

```
80488b1: movl    (%ecx,%edx,4),%eax
80488b4: addl    %eax, (%edi)
80488b6: incl    %edx
80488b7: cmpl    %esi,%edx    i = 100
80488b9: j1l     80488b1
```

Read
invalid
location

```
80488b1: movl    (%ecx,%edx,4),%eax
80488b4: addl    %eax, (%edi)
80488b6: incl    %edx
80488b7: cmpl    %esi,%edx    i = 101
80488b9: j1l     80488b1
```

Executed

Fetches

Supplied by CMU.

Branch Misprediction Invalidation

```
80488b1: movl    (%ecx,%edx,4),%eax
80488b4: addl    %eax, (%edi)
80488b6: incl    %edx
80488b7: cmpl    %esi, %edx    i = 98
80488b9: jnl     80488b1
```

Assume
vector length = **100**

Predict taken (OK)

```
80488b1: movl    (%ecx,%edx,4),%eax
80488b4: addl    %eax, (%edi)
80488b6: incl    %edx
80488b7: cmpl    %esi, %edx    i = 99
80488b9: jnl     80488b1
```

Predict taken (oops)

```
80488b1: movl    (%ecx,%edx,4),%eax
80488b4: addl    %eax, (%edi)
80488b6: incl    %edx
80488b7: cmpl    %esi, %edx    i = 100
80488b9: jnl     80488b1
```

Invalidate

```
80488b1: movl    (%ecx,%edx,4),%eax
80488b4: addl    %eax, (%edi)
80488b6: incl    %edx    i = 101
```

Supplied by CMU.

Branch Misprediction Recovery

```
80488b1: movl    (%ecx,%edx,4),%eax
80488b4: addl    %eax,(%edi)
80488b6: incl    %edx
80488b7: cmpl    %esi,%edx
80488b9: jl      80488b1
80488bb: leal    0xffffffff(%ebp),%esp
80488be: popl    %ebx
80488bf: popl    %esi
80488c0: popl    %edi
```

i = 99

Definitely not taken

- **Performance Cost**

- multiple clock cycles on modern processor
- can be a major performance limiter

Conditional Moves

```
void minmax1(int *a, int *b, int n) {  
    int i;  
    for (i=0; i<n; i++) {  
        if (a[i] > b[i]) {  
            int t = a[i];  
            a[i] = b[i];  
            b[i] = t;  
        }  
    }  
}
```

```
void minmax2(int *a, int *b, int n) {  
    int i;  
    for (i=0; i<n; i++) {  
        int min = a[i] < b[i] ?  
            a[i] : b[i];  
        int max = a[i] < b[i] ?  
            b[i] : a[i];  
        a[i] = min;  
        b[i] = max;  
    }  
}
```

- **Compiled code uses conditional branch**
 - 14.5 CPE for random data
 - 2.0 – 4.0 CPE for predictable data

- **Compiled code uses conditional move instruction**
 - 5.0 CPE regardless of data's pattern

This example is from the textbook.

Getting High Performance

- **Good compiler and flags**
- **Don't do anything stupid**
 - watch out for hidden algorithmic inefficiencies
 - write compiler-friendly code
 - » watch out for optimization blockers:
procedure calls & memory references
 - look carefully at innermost loops (where most work is done)
- **Tune code for machine**
 - exploit instruction-level parallelism
 - avoid unpredictable branches
 - make code cache friendly (covered soon)

Supplied by CMU.