15-213

"The course that gives CMU its Zip!"

Code Optimization II
September 27, 2006

Topics

- Machine Dependent Optimizations
  - Understanding Processor Operations
  - Branches and Branch Prediction

`class09.ppt`

Getting High Performance

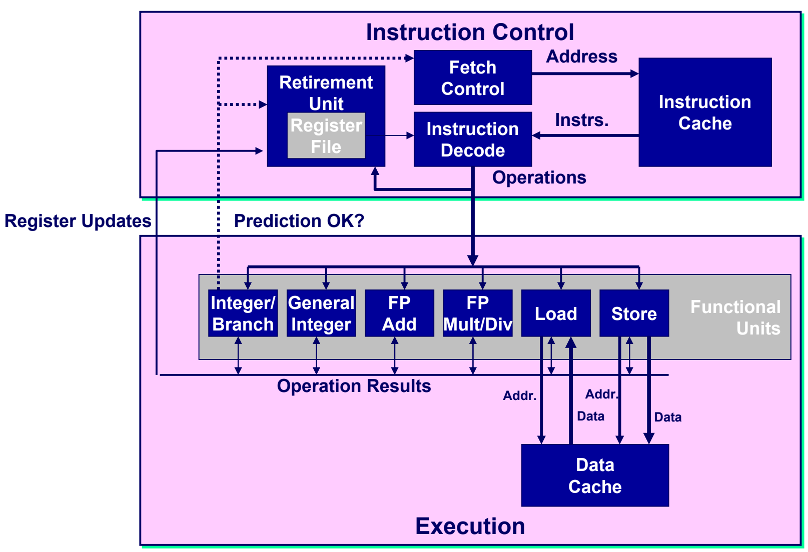
Don't Do Anything Stupid

- Watch out for hidden algorithmic inefficiencies
- Write compiler-friendly code
  - Help compiler past optimization blockers: function calls & memory refs.

Tune Code For Machine

- Exploit instruction-level parallelism
- Avoid unpredictable branches
- Make code cache friendly
  - Covered later in course

Modern CPU Design



CPU Capabilities of Pentium IV

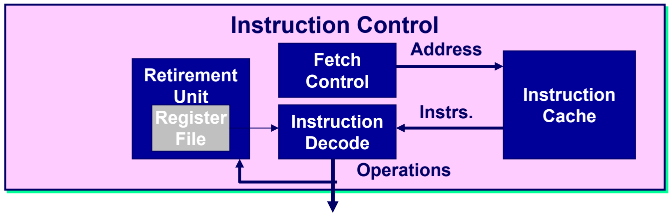
Multiple Instructions Can Execute in Parallel

- 1 load, with address computation
- 1 store, with address computation
- 2 simple integer (one may be branch)
- 1 complex integer (multiply/divide)
- 1 FP/SSE3 unit
- 1 FP move (does all conversions)

Some Instructions Take > 1 Cycle, but Can be Pipelined

Instruction	Latency	Cycles/Issue
Load / Store	5	1
Integer Multiply	10	1
Integer/Long Divide	36/106	36/106
Single/Double FP Multiply	7	2
Single/Double FP Add	5	2
Single/Double FP Divide	32/46	32/46

Instruction Control



Grabs Instruction Bytes From Memory

- Based on current PC + predicted targets for predicted branches
- Hardware dynamically guesses whether branches taken/not taken and (possibly) branch target

Translates Instructions Into *Operations* (for CISC style CPUs)

- Primitive steps required to perform instruction
- Typical instruction requires 1–3 operations

Converts Register References Into *Tags*

- Abstract identifier linking destination of one operation with sources of later operations

Translating into Operations

Goal: Each Operation Utilizes Single Functional Unit

```
addq %rax, 8(%rbx,%rdx,4)
```

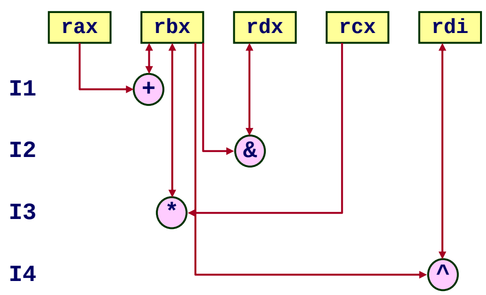
- Requires: Load, Integer arithmetic, Store

```
load 8(%rbx,%rdx,4)      ➔    temp1
imull %rax, temp1        ➔    temp2
store temp2, 8(%rbx,%rdx,4)
```

- Exact form and format of operations is trade secret
- Operations: split up instruction into simpler pieces
- Devise temporary names to describe how result of one operation gets used by other operations

Traditional View of Instruction Execution

```
addq %rax, %rbx   # I1
andq %rbx, %rdx   # I2
mulq %rcx, %rbx   # I3
xorq %rbx, %rdi   # I4
```

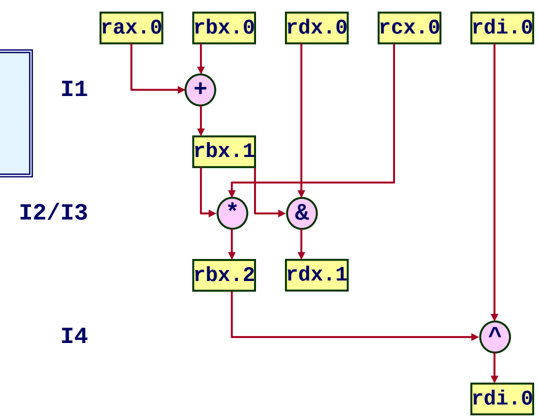


Imperative View

- Registers are fixed storage locations
  - Individual instructions read & write them
- Instructions must be executed in specified sequence to guarantee proper program behavior

Dataflow View of Instruction Execution

```
addq %rax, %rbx   # I1
andq %rbx, %rdx   # I2
mulq %rcx, %rbx   # I3
xorq %rbx, %rdi   # I4
```



Functional View

- View each write as creating new instance of value
- Operations can be performed as soon as operands available
- No need to execute in original sequence

Example Computation

```
void combine4(vec_ptr v, data_t *dest)
{
  int i;
  int length = vec_length(v);
  data_t *d = get_vec_start(v);
  data_t t = IDENT;
  for (i = 0; i < length; i++)
    t = t OP d[i];
  *dest = t;
}
```

Data Types

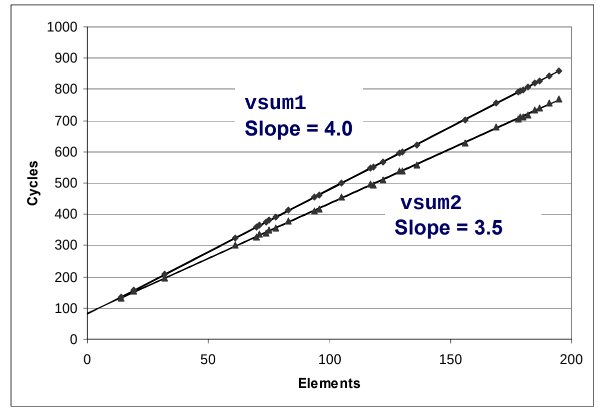
- Use different declarations for `data_t`
- `int`
- `float`
- `double`

Operations

- Use different definitions of `OP` and `IDENT`
- `+ / 0`
- `* / 1`

Cycles Per Element

- Convenient way to express performance of program that operators on vectors or lists
- Length = n
- T = CPE*n + Overhead



x86-64 Compilation of Combine4

Inner Loop (Integer Multiply)

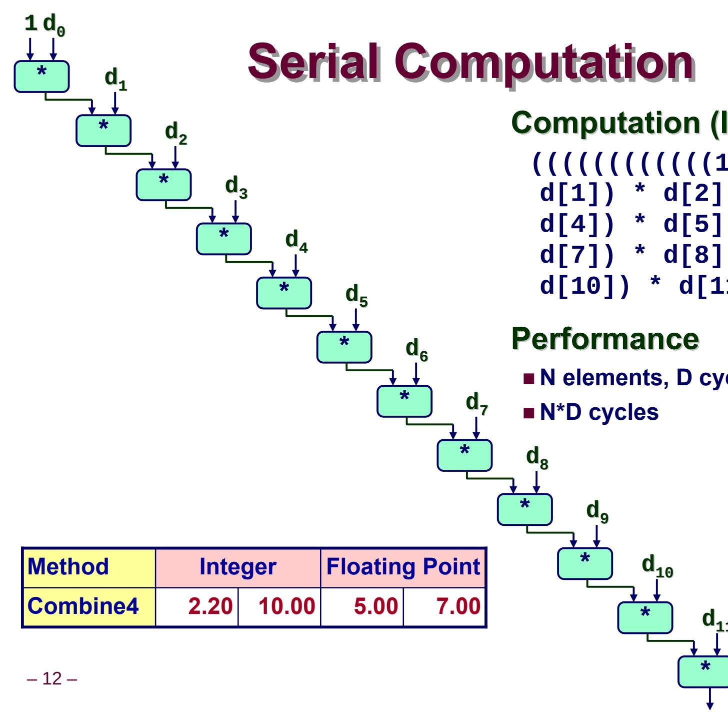
```
L33:                          # Loop:
  movl  (%eax,%edx,4), %ebx   # temp = d[i]
  incl  %edx                  # i++
  imull %ebx, %ecx            # x *= temp
  cmpl  %esi, %edx            # i:length
  jl    L33                   # if < goto Loop
```

Performance

- 5 instructions in 2 clock cycles

Method	Integer		Floating Point	
Combine4	2.20	10.00	5.00	7.00

Serial Computation



Computation (length=12)

```
((((((((((((1 * d[0]) *
 d[1]) * d[2]) * d[3]) *
 d[4]) * d[5]) * d[6]) *
 d[7]) * d[8]) * d[9]) *
 d[10]) * d[11])
```

Performance

- N elements, D cycles/operation
- N*D cycles

Method	Integer		Floating Point	
Combine4	2.20	10.00	5.00	7.00

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 OPER d[i]) OPER d[i+1];
    }
    /* Finish any remaining elements */
    for (; i < length; i++) {
       x = x OPER d[i];
    }
    *dest = x;
}
```

- Perform 2x more useful work per iteration

Effect of Loop Unrolling

Method	Integer		Floating Point	
Combine4	2.20	10.00	5.00	7.00
Unroll 2	1.50	10.00	5.00	7.00

Helps Integer Sum

- Before: 5 operations per element
- After: 6 operations per 2 elements
  - = 3 operations per element

Others Don't Improve

- Sequential dependency
  - Each operation must wait until previous one completes

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


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 OPER (d[i] OPER d[i+1]);
    }
    /* Finish any remaining elements */
    for (; i < length; i++) {
       x = x OPER d[i];
    }
    *dest = x;
}
```

- Could change numerical results for FP

Effect of Reassociation

Method	Integer		Floating Point	
Combine4	2.20	10.00	5.00	7.00
Unroll 2	1.50	10.00	5.00	7.00
2 X 2 reassociate	1.56	5.00	2.75	3.62

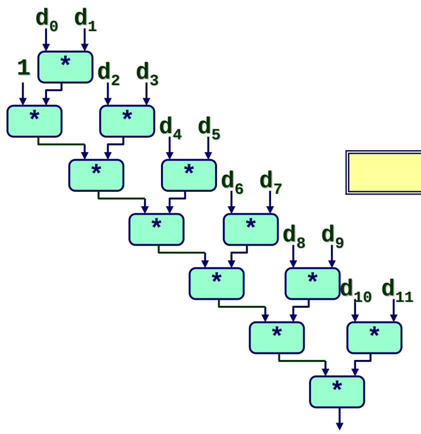
Nearly 2X speedup for Int *, FP +, FP *

- Breaks sequential dependency

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

- While computing result for iteration i, can precompute `d[i+2]*d[i+3]` for iteration i+2

Reassociated Computation



Performance

- N elements, D cycles/operation
- Should be (N/2+1)*D cycles
  - CPE = D/2
- Measured CPE slightly worse for FP

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


Loop Unrolling with Separate Accum.

```
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 OPER d[i];
       x1 = x1 OPER d[i+1];
    }
    /* Finish any remaining elements */
    for (; i < length; i++) {
       x0 = x0 OPER d[i];
    }
    *dest = x0 OPER x1;
}
```

- Different form of reassociation

Effect of Reassociation

Method	Integer		Floating Point	
Combine4	2.20	10.00	5.00	7.00
Unroll 2	1.50	10.00	5.00	7.00
2 X 2 reassociate	1.56	5.00	2.75	3.62
2 X 2 separate accum.	1.50	5.00	2.50	3.50

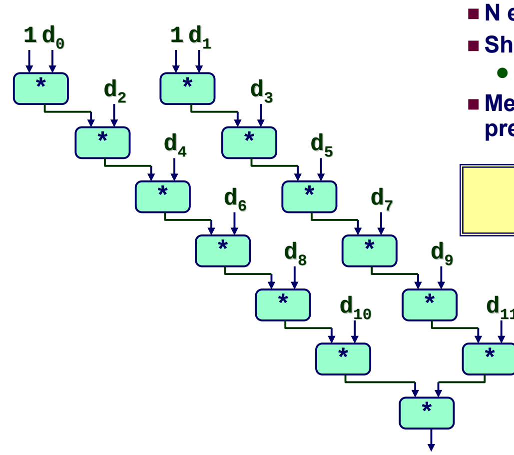
Nearly 2X speedup for Int *, FP +, FP *

- Breaks sequential dependency

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

- Computation of even elements independent of odd ones

Separate Accum. Computation



Performance

- N elements, D cycles/operation
- Should be (N/2+1)*D cycles
  - CPE = D/2
- Measured CPE matches prediction!

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

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 pipelining limitations of execution units
- Large overhead
  - Finish off iterations sequentially
  - Especially for shorter lengths

Unrolling & Accumulating: Intel FP *

Case

- Intel Nocoma (Saltwater fish machines)
- FP Multiplication
- Theoretical Limit: 2.00

FP *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	7.00	7.00		7.01		7.00		
2		3.50		3.50		3.50		
3			2.34					
4				2.01		2.00		
6					2.00			2.01
8						2.01		
10							2.00	
12								2.00

Unrolling & Accumulating: Intel FP +

Case

- Intel Nocoma (Saltwater fish machines)
- FP Addition
- Theoretical Limit: 2.00

FP +	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	5.00	5.00		5.02		5.00		
2		2.50		2.51		2.51		
3			2.00					
4				2.01		2.00		
6					2.00			1.99
8						2.01		
10							2.00	
12								2.00

Unrolling & Accumulating: Intel Int *

Case

- Intel Nocoma (Saltwater fish machines)
- Integer Multiplication
- Theoretical Limit: 1.00

Int *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	10.00	10.00		10.00		10.01		
2		5.00		5.01		5.00		
3			3.33					
4				2.50		2.51		
6					1.67			1.67
8						1.25		
10							1.09	
12								1.14

Unrolling & Accumulating: Intel Int +

Case

- Intel Nocoma (Saltwater fish machines)
- Integer addition
- Theoretical Limit: 1.00 (unrolling enough)

Int +	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	2.20	1.50		1.10		1.03		
2		1.50		1.10		1.03		
3			1.34					
4				1.09		1.03		
6					1.01			1.01
8						1.03		
10							1.04	
12								1.11

Intel vs. AMD FP *

FP *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	7.00	7.00		7.01		7.00		
2		3.50		3.50		3.50		
3			2.34					
4				2.01		2.00		
6					2.00			2.01
8						2.01		
10							2.00	
12								2.00

FP *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	4.00	4.00		4.00		4.01		
2		2.00		2.00		2.00		
3			1.34					
4				1.00		1.00		
6					1.00			1.00
8						1.00		
10							1.00	
12								1.00

Machines

- Intel Nocomoa
  - 3.2 GHz
- AMD Opteron
  - 2.0 GHz

Performance

- AMD lower latency & better pipelining
- But slower clock rate

Intel vs. AMD Int *

Int *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	10.00	10.00		10.00		10.01		
2		5.00		5.01		5.00		
3			3.33					
4				2.50		2.51		
6					1.67			1.67
8						1.25		
10							1.09	
12								1.14

Int *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	3.00	3.00		3.00		3.00		
2		2.33		2.0		1.35		
3			2.00					
4				1.75		1.38		
6					1.50			1.50
8						1.75		
10							1.30	
12								1.33

Performance

- AMD multiplier much lower latency
- Can get high performance with less work
- Doesn't achieve as good an optimum

Intel vs. AMD Int +

Int +	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	2.20	1.50		1.10		1.03		
2		1.50		1.10		1.03		
3			1.34					
4				1.09		1.03		
6					1.01			1.01
8						1.03		
10							1.04	
12								1.11

Int +	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	2.32	1.50		0.75		0.63		
2		1.50		0.83		0.63		
3			1.00					
4				1.00		0.63		
6					0.83			0.67
8						0.63		
10							0.60	
12								0.85

Performance

- AMD gets below 1.0
- Even just with unrolling

Explanation

- Both Intel & AMD can "double pump" integer units
- Only AMD can load two elements / cycle

Can We Go Faster?

Fall 2005 Lab #4

Performance Lab Class Status Page

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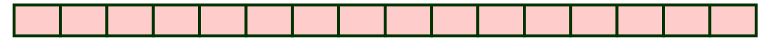
#	Nickname	Handin Version	Submission Date	ACPE	Grade Points
1	Anton	4	Sun Oct 23 21:10	1.69	100
2	edanaher	1	Thu Oct 13 22:41	2.37	100
3	mjrosenb	4	Tue Oct 18 08:40	2.37	100
4	Old Prof	3	Tue Oct 18 13:38	2.42	100
5	mcwillia	4	Thu Oct 20 01:17	2.46	100

- Floating-point addition & multiplication gives theoretical optimum CPE of 2.00
- What did Anton do?

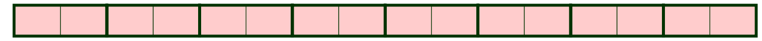
Programming with SSE3

XMM Registers

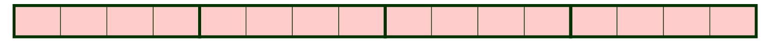
- 16 total, each 16 bytes
- 16 single-byte integers



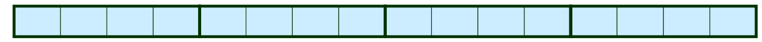
- 8 16-bit integers



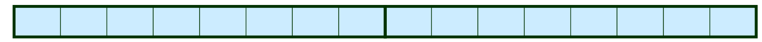
- 4 32-bit integers



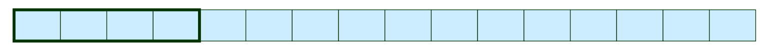
- 4 single-precision floats



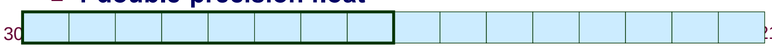
- 2 double-precision floats



- 1 single-precision float

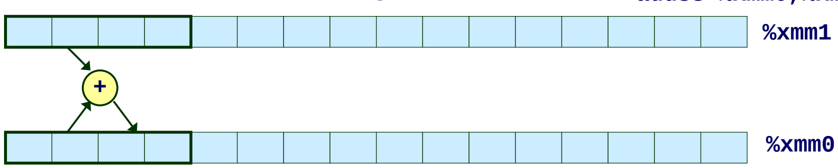


- 1 double-precision float

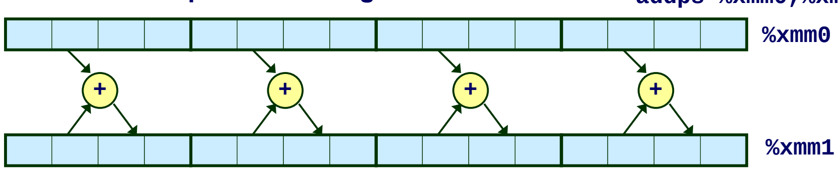


Scalar & SIMD Operations

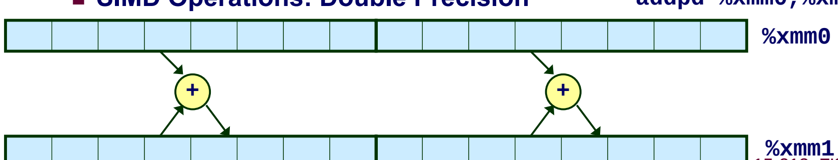
- Scalar Operations: Single Precision `addss %xmm0,%xmm1`



- SIMD Operations: Single Precision `addps %xmm0,%xmm1`



- SIMD Operations: Double Precision `addpd %xmm0,%xmm1`



Getting GCC to Use SIMD Operations

Declarations

```
typedef float vec_t __attribute__ ((mode(V4SF)));
typedef union {
    vec_t v;
    float d[4];
} pack_t
```

Accessing Vector Elements

```
    pack_t xfer;
    vec_t accum;
    for (i = 0; i < 4; i++)
      xfer.d[i] = IDENT;
    accum = xfer.v;
```

Invoking SIMD Operations

```
      vec_t chunk = *((vec_t *) d);
      accum = accum OPER chunk;
```

Implementing Combine

```
void SSEx1_combine(vec_ptr v, float *dest)
{
    pack_t xfer;
    vec_t accum;
    float *d = get_vec_start(v);
    int cnt = vec_length(v);
    float result = IDENT;

    /* Initialize vector of 4 accumulators */

    /* Step until d aligned to multiple of 16 */

    /* Use packed operations with 4X parallelism */

    /* Single step to finish vector */

    /* Combine accumulators */
}
```


Getting Started

Create Vector of 4 Accumulators

```
/* Initialize vector of 4 accumulators */
int i;
for (i = 0; i < 4; i++)
   xfer.d[i] = IDENT;
accum = xfer.v;
```

Single Step to Meet Alignment Requirements

- Memory address of vector must be multiple of 16

```
/* Step until d aligned to multiple of 16 */
while (((long) d)%16 && cnt) {
   result = result OPER *d++;
   cnt--;
}
```


SIMD Loop

- Similar to 4-way loop unrolling
- Express with single arithmetic operation
  - Translates into single `addps` or `mulps` instruction

```
/* Use packed operations with 4X parallelism */
while (cnt >= 4) {
   vec_t chunk = *((vec_t *) d);
   accum = accum OPER chunk;
   d += 4;
   cnt -= 4;
}
```


Completion

Finish Off Final Elements

- Similar to standard unrolling

```
/* Single step to finish vector */
while (cnt) {
   result = result OPER *d++;
   cnt--;
}
```

Combine Accumulators

- Use union to reference individual elements

```
/* Combine accumulators */
xfer.v = accum;
for (i = 0; i < 4; i++)
   result = result OPER xfer.d[i];
*dest = result;
```

SIMD Results

Intel Nocoma

	Unrolling Factor L			
	4	8	16	32
FP +	1.25	0.82	0.50	0.58
FP *	1.90	1.24	0.90	0.57
Int +	0.84	0.70	0.51	0.58
Int *	39.09	37.65	36.75	37.44

AMD Opteron

	Unrolling Factor L			
	4	8	16	32
FP +	1.00	0.50	0.50	0.50
FP *	1.00	0.50	0.50	0.50
Int +	0.75	0.38	0.28	0.27
Int *	9.40	8.63	9.32	9.12

Results

- FP approaches theoretical optimum of 0.50
- Int + shows speed up
- For int *, compiler does not generate SIMD code

Portability

- GCC can target other machines with this code
  - Altivec instructions for PowerPC

What About Branches?

Challenge

- Instruction Control Unit must work well ahead of Exec. 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

Fetching & Decoding

- When encounters conditional branch, cannot reliably determine where to continue fetching

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   0xffffffe8(%ebp),%esp
8048a2f:  movl   %ecx,(%eax)
```


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   0xffffffe8(%ebp),%esp
8048a2f:  movl   %ecx,(%eax)
```

Begin Execution

Branch Prediction Through Loop

Assume vector length = 100

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

Predict Taken (OK)

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

Predict Taken (Oops)

Executed

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

Read invalid location

Fetched

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


Branch Misprediction Invalidation

Assume vector length = 100

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

Predict Taken (OK)

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

Predict Taken (Oops)

Invalidate

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

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


Branch Misprediction Recovery

Assume vector length = 100

```
80488b1:   movl   (%ecx,%edx,4),%eax
80488b4:   addl   %eax,(%edi)
80488b6:   incl   %edx
80488b7:   cmpl   %esi,%edx        i = 99
80488b9:   jl     80488b1
80488bb:   leal   0xffffffe8(%ebp),%esp
80488be:   popl   %ebx
80488bf:   popl   %esi
80488c0:   popl   %edi
```

Definitely not taken

Performance Cost

- Multiple clock cycles on modern processor
- One of the major performance limiters

Determining Misprediction Penalty

```
int cnt_gt = 0;
int cnt_le = 0;
int cnt_all = 0;

int choose_cmov(int x, int y)
{
    int result;
    if (x > y) {
        result = cnt_gt;
    } else {
        result = cnt_le;
    }
    ++cnt_all;
    return result;
}
```

GCC/x86-64 Tries to Minimize Use of Branches

- Generates conditional moves when possible/sensible

```
choose_cmov:
  cmpl   %esi, %edi          # x:y
  movl   cnt_le(%rip), %eax  # r = cnt_le
  cmovg  cnt_gt(%rip), %eax  # if >= r=cnt_gt
  incl   cnt_all(%rip)       # cnt_all++
  ret                        # return r
```

Forcing Conditional

```
int cnt_gt = 0;
int cnt_le = 0;

int choose_cond(int x, int y)
{
    int result;
    if (x > y) {
        result = ++cnt_gt;
    } else {
        result = ++cnt_le;
    }
    return result;
}
```

```
choose_cond:
  cmpl  %esi, %edi          # If
  jle   .L8                 # If
  movl  cnt_gt(%rip), %eax  # Then
  incl  %eax                # Then
  movl  %eax, cnt_gt(%rip)  # Then
  ret                       # Then
.L8:
  movl  cnt_le(%rip), %eax  # Else
  incl  %eax                # Else
  movl  %eax, cnt_le(%rip)  # Else
  ret                       # Else
```

- Cannot use conditional move when either outcome has side effect

Testing Methodology

Idea

- Measure procedure under two different prediction probabilities
  - P = 1.0: Perfect prediction
  - P = 0.5: Random data

Test Data

- x = 0, y = ±1

Case +1: y = [+1, +1, +1, …, +1, +1]

Case −1: y = [−1, −1, −1, …, −1, −1]

Case A: y = [+1, −1, +1, …, +1, −1]

Case R: y = [+1, −1, −1, …, −1, +1] (Random)

Testing Outcomes

Intel Nocoma

Case	cmov	cond
+1	12.3	18.2
−1	12.3	12.2
A	12.3	15.2
R	12.3	31.2

AMD Opteron

Case	cmov	cond
+1	8.05	10.1
−1	8.05	8.1
A	8.05	9.2
R	8.05	15.7

Observations:

- Conditional move insensitive to data
- Perfect prediction for regular patterns
  - But, else case requires 6 (Intel) or 2 (AMD) additional cycles
  - Averages to 15.2
- Branch penalties:
  - Intel 2 * (31.2-15.2) = 32 cycles
  - AMD 2 * (15.7-9.2) = 13 cycles

Role of Programmer

How should I write my programs, given that I have a good, optimizing compiler?

Don't: Smash Code into Oblivion

- Hard to read, maintain, & assure correctness

Do:

- Select best algorithm
- Write code that's readable & maintainable
  - Procedures, recursion, without built-in constant limits
  - Even though these factors can slow down code
- Eliminate optimization blockers
  - Allows compiler to do its job

Focus on Inner Loops

- Do detailed optimizations where code will be executed repeatedly
- Will get most performance gain here
- Understand how enough about machine to tune effectively