

How to Write Fast Numerical Code

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Lecture: Optimization for Instruction-Level Parallelism

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Organizational

- Midterm: April 14th
- Office hours fixed
- Projects

How To Make Code Faster?

- It depends!
- **Memory bound: Reduce memory traffic**
 - Reduce cache misses, register spills
 - Compress data
- **Compute bound: Keep floating point units busy**
 - Reduce cache misses, register spills
 - Instruction level parallelism (ILP)
 - Vectorization
- **Next: Optimizing for ILP (an example)**

Chapter 5 in *Computer Systems: A Programmer's Perspective*, 2nd edition,
Randal E. Bryant and David R. O'Hallaron, Addison Wesley 2010

Part of these slides are adapted from the course associated with this book

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Superscalar Processor

- **Definition:** A superscalar processor can issue and execute *multiple instructions in one cycle*. The instructions are retrieved from a sequential instruction stream and are usually scheduled dynamically.
- **Benefit:** Superscalar processors can take advantage of *instruction level parallelism (ILP)* that many programs have
- Most CPUs since about 1998 are superscalar
- Intel: since Pentium Pro

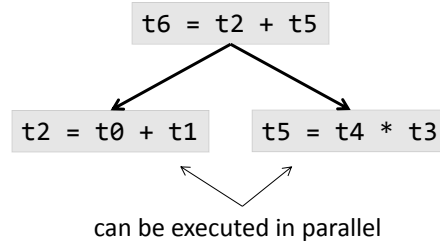
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ILP

Code

```
t2 = t0 + t1
t5 = t4 * t3
t6 = t2 + t5
```

Dependencies



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Hard Bounds: Pentium 4 vs. Core 2

■ Pentium 4 (Nocona)

<i>Instruction</i>	<i>Latency</i>	<i>1/Throughput = Cycles/Issue</i>
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

} black-board

■ Core 2

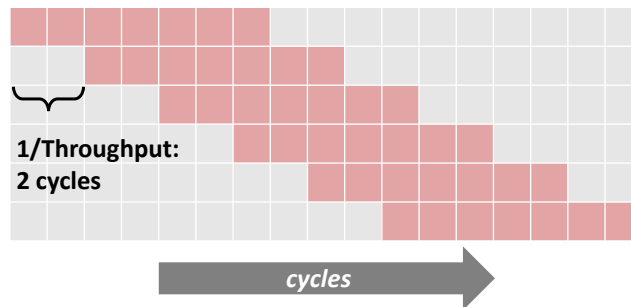
<i>Instruction</i>	<i>Latency</i>	<i>Cycles/Issue</i>
Load / Store	5	1
Integer Multiply	3	1
Integer/Long Divide	18/50	18/50
Single/Double FP Multiply	4/5	1
Single/Double FP Add	3	1
Single/Double FP Divide	18/32	18/32

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Single/Double FP Multiply

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Hard Bounds (cont'd)

- How many cycles at least if
 - Function requires n float adds?
 - Function requires n int mults?

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Example Computation (on Pentium 4)

```
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;
}
```

$d[0]$ OP $d[1]$ OP $d[2]$ OP ... OP $d[\text{length}-1]$

data_t: float or double or int

OP: + or *

IDENT: 0 or 1

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Runtime of Combine4 (Pentium 4)

■ Use cycles/OP

```
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;
}
```

■ Questions:

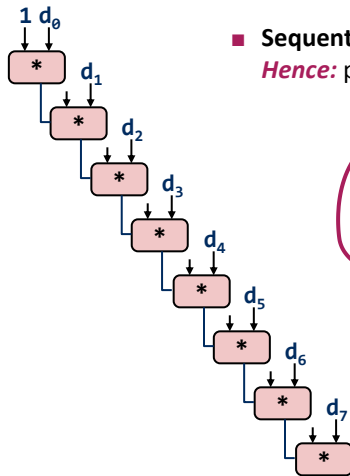
- Explain red row
- Explain gray row

Cycles per OP

Method	Int (add/mult)	Float (add/mult)	Int (add/mult)	Float (add/mult)
combine4	2.2	10.0	5.0	7.0
bound	1.0	1.0	2.0	2.0

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Combine4 = Serial Computation (OP = *)



- Sequential dependence = no ILP!
Hence: performance determined by latency of OP!

Cycles per element (or per OP)

Method	Int (add/mult)		Float (add/mult)	
combine4	2.2	10.0	5.0	7.0
bound	1.0	1.0	2.0	2.0

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Loop Unrolling

```
void unroll2(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

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Effect of Loop Unrolling

Method	Int (add/mult)		Float (add/mult)	
combine4	2.2	10.0	5.0	7.0
unroll2	1.5	10.0	5.0	7.0
bound	1.0	1.0	2.0	2.0



- Helps integer sum
- Others don't improve. *Why?*
 - Still sequential dependency

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

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Loop Unrolling with Reassociation

```
void unroll2_ra(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;
}
```

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

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Effect of Reassociation

Method	Int (add/mult)		Float (add/mult)	
combine4	2.2	10.0	5.0	7.0
unroll2	1.5	10.0	5.0	7.0
unroll2-ra	1.56	5.0	2.75	3.62
bound	1.0	1.0	2.0	2.0

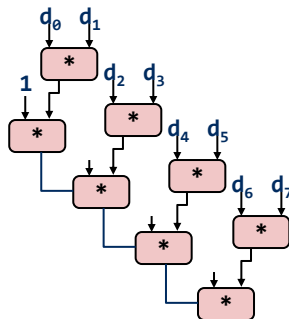


- Nearly 2x speedup for Int *, FP +, FP *
 - Why is that? (next slide)

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Reassociated Computation

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



- Breaks sequential dependency
- Overall Performance
 - N elements, D cycles latency/op
 - Should be $(N/2+1)*D$ cycles:
cycle per OP $\approx D/2$
 - Measured is slightly worse for FP

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Loop Unrolling with Separate Accumulators

```
void unroll2_sa(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

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Effect of Separate Accumulators

Method	Int (add/mult)		Float (add/mult)	
combine4	2.2	10.0	5.0	7.0
unroll2	1.5	10.0	5.0	7.0
unroll2-ra	1.56	5.0	2.75	3.62
unroll2-sa	1.50	5.0	2.5	3.5
bound	1.0	1.0	2.0	2.0

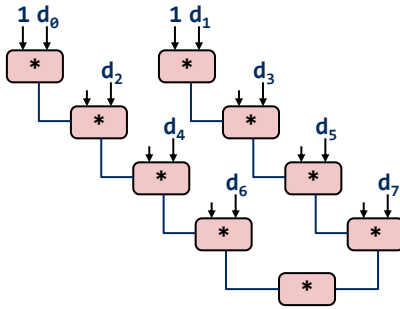
- Almost exact 2x speedup (over unroll2) for Int *, FP +, FP *
 - Breaks sequential dependency in a “cleaner,” more obvious way

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

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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:
cycles per OP $\approx D/2$

What Now?

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Unrolling & Accumulating

■ Idea

- Use K accumulators
- Increase K until best performance reached
- Need to unroll by L, K divides L

■ Limitations

- Diminishing returns:
Cannot go beyond throughput limitations of execution units
- Large overhead for short lengths: Finish off iterations sequentially

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Unrolling & Accumulating: Intel FP *

- Case
 - Pentium 4
 - FP Multiplication
 - Theoretical Limit: 2.00

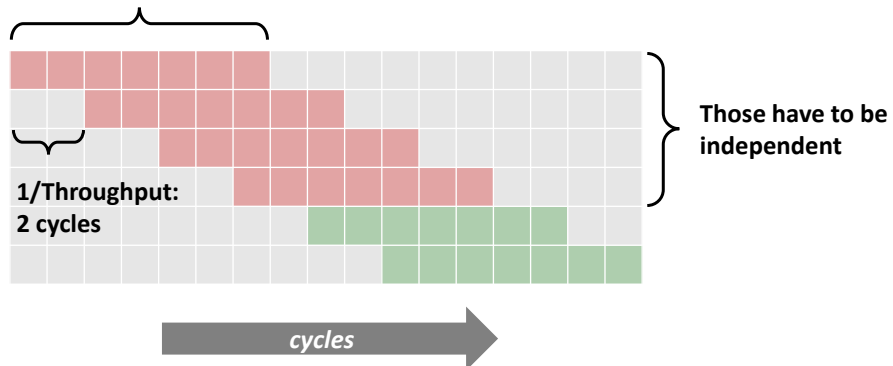
Accumulators	FP *	Unrolling Factor L							
	K	1	2	3	4	6	8	10	12
1	7.00	7.00			7.01		7.00		
2		3.50			3.50		3.50		
3				2.34					
4					2.01		2.00		
6						2.00			2.01
8							2.01		
10								2.00	
12									2.00

Why 4?

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Why 4?

Latency: 7 cycles



Based on this insight: $K = \text{\#accumulators} = \text{ceil}(\text{latency}/\text{cycles per issue})$

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Unrolling & Accumulating: Intel FP +

■ Case

- Pentium 4
- FP Addition
- Theoretical Limit: 2.00

FP +	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	5.0	5.0		5.0		5.0		
2		2.5		2.5		2.5		
3			2.0					
4				2.0		2.00		
6					2.0			2.0
8						2.0		
10							2.0	
12								2.0

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Unrolling & Accumulating: Intel Int *

■ Case

- Pentium 4
- Integer Multiplication
- Theoretical Limit: 1.00

Int *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	10.0	10.0		10.0		10.0		
2		5.0		5.0		5.0		
3			3.3					
4				2.5		2.5		
6					1.67			1.67
8						1.25		
10							1.1	
12								1.14

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Unrolling & Accumulating: Intel Int +

■ **Case**

- Pentium 4
- Integer addition
- Theoretical Limit: 1.00

Int +	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	2.2	1.5		1.1		1.0		
2		1.5		1.1		1.0		
3			1.34					
4				1.1		1.03		
6					1.0			1.0
8						1.03		
10							1.04	
12								1.1

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FP *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	7.0	7.0		7.0		7.0		
2		3.5		3.5		3.5		
3			2.34					
4				2.0		2.0		
6					2.0			2.0
8						2.0		
10							2.0	
12								2.0

Pentium 4

FP *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	4.0	4.0		4.0		4.0		
2		2.0		2.0		2.0		
3			1.34					
4				1.0		1.0		
6					1.0			1.0
8						1.0		
10							1.0	
12								1.0

Core 2
FP * is fully pipelined

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Summary (ILP)

- **Instruction level parallelism may have to be made explicit in program**
- **Potential blockers for compilers**
 - Reassociation changes result (FP)
 - Too many choices, no good way of deciding
- **Unrolling**
 - By itself does often nothing (branch prediction works usually well)
 - But may be needed to enable additional transformations (here: reassociation)
- **How to program this example?**
 - Solution 1: program generator generates alternatives and picks best
 - Solution 2: use model based on latency and throughput

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