15-213

"The course that gives CMU its Zip!"

Code Optimization
September 30, 2004

Topics

- Machine-Independent Optimizations
- Machine Dependent
  - Understanding Processor
  - Branches and Branch Prediction
- Code Profiling & Tuning

`class10.ppt`

Harsh Reality

There's more to performance than asymptotic complexity

Constant factors matter too!

- Easily see 10:1 performance range depending on how code is written
- Must optimize at multiple levels:
  - algorithm, data representations, procedures, and loops

Must understand system to optimize performance

- How programs are compiled and executed
- How to measure program performance and identify bottlenecks
- How to improve performance without destroying code modularity and generality

Optimizing Compilers

Provide efficient mapping of program to machine

- register allocation
- code selection and ordering (scheduling)
- dead code elimination
- eliminating minor inefficiencies

Don’t (usually) improve asymptotic efficiency

- up to programmer to select best overall algorithm
- big-O savings are (often) more important than constant factors
  - but constant factors also matter

Have difficulty overcoming “optimization blockers”

- potential memory aliasing
- potential procedure side-effects

Limitations of Optimizing Compilers

Operate under fundamental constraint

- Must not cause any change in program behavior under any possible condition
- Often prevents it from making optimizations when would only affect behavior under pathological conditions.

Behavior that may be obvious to the programmer can be obfuscated by languages and coding styles

- e.g., Data ranges may be more limited than variable types suggest

Most analysis is performed only within procedures

- Whole-program analysis is too expensive in most cases

Most analysis is based only on *static* information

- Compiler has difficulty anticipating run-time inputs

When in doubt, the compiler must be conservative

Machine-Independent Optimizations

Optimizations that you or compiler should do regardless of processor / compiler

Code Motion

- Reduce frequency with which computation performed
  - If it will always produce same result
  - Especially moving code out of loop

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

→

```
for (i = 0; i < n; i++) {
  int ni = n*i;
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
}
```

Compiler-Generated Code Motion

- Most compilers do a good job with array code + simple loop structures

Code Generated by GCC

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

```
for (i = 0; i < n; i++) {
  int ni = n*i;
  int *p = a+ni;
  for (j = 0; j < n; j++)
    *p++ = b[j];
}
```

```
  imull %ebx,%eax          # i*n
  movl 8(%ebp),%edi        # a
  leal (%edi,%eax,4),%edx # p = a+i*n (scaled by 4)
# Inner Loop
.L40:
  movl 12(%ebp),%edi       # b
  movl (%edi,%ecx,4),%eax # b+j  (scaled by 4)
  movl %eax,(%edx)         # *p = b[j]
  addl $4,%edx             # p++  (scaled by 4)
  incl %ecx                # j++
  jl .L40                  # loop if j<n
```

Reduction in Strength

- Replace costly operation with simpler one
- Shift, add instead of multiply or divide

  `16*x    -->    x << 4`

  - Utility machine dependent
  - Depends on cost of multiply or divide instruction
  - On Pentium II or III, integer multiply only requires 4 CPU cycles
- Recognize sequence of products

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

→

```
int ni = 0;
for (i = 0; i < n; i++) {
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
  ni += n;
}
```

Share Common Subexpressions

- Reuse portions of expressions
- Compilers often not very sophisticated in exploiting arithmetic properties

```
/* Sum neighbors of i,j */
up =    val[(i-1)*n + j];
down =  val[(i+1)*n + j];
left =  val[i*n   + j-1];
right = val[i*n   + j+1];
sum = up + down + left + right;
```

```
int inj = i*n + j;
up =    val[inj - n];
down =  val[inj + n];
left =  val[inj - 1];
right = val[inj + 1];
sum = up + down + left + right;
```

3 multiplications: i*n, (i–1)*n, (i+1)*n

1 multiplication: i*n

```
  leal -1(%edx),%ecx  # i-1
  imull %ebx,%ecx     # (i-1)*n
  leal 1(%edx),%eax   # i+1
  imull %ebx,%eax     # (i+1)*n
  imull %ebx,%edx     # i*n
```

Time Scales

Absolute Time

- Typically use nanoseconds
  - 10^{-9} seconds
- Time scale of computer instructions

Clock Cycles

- Most computers controlled by high frequency clock signal
- Typical Range
  - 100 MHz
    - » 10^{8} cycles per second
    - » Clock period = 10ns
  - 2 GHz
    - » 2 X 10^{9} cycles per second
    - » Clock period = 0.5ns
- Fish machines: 550 MHz (1.8 ns clock period)

Measuring Performance

For many programs, cycles per element (CPE)

- Especially true of programs that work on lists/vectors
- Total time = fixed overhead + CPE * length-of-list

```
void vsum1(int n)
{
  int i;

  for (i = 0; i<n; i++)
    c[i] = a[i] + b[i];
}
```

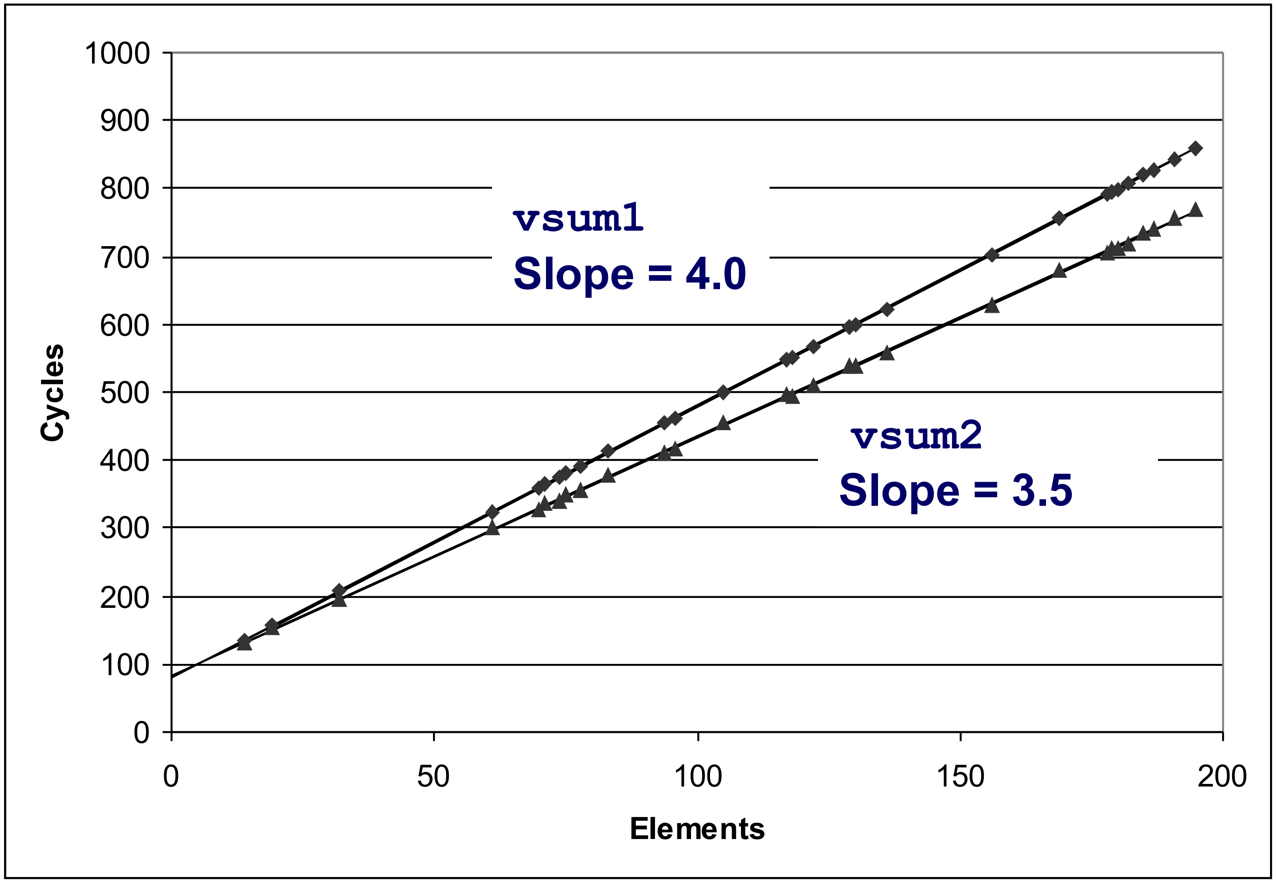
```
void vsum2(int n)
{
  int i;

  for (i = 0; i<n; i+=2){
    c[i] = a[i] + b[i];
    c[i+1] = a[i+1] + b[i+1];
  }
}
```

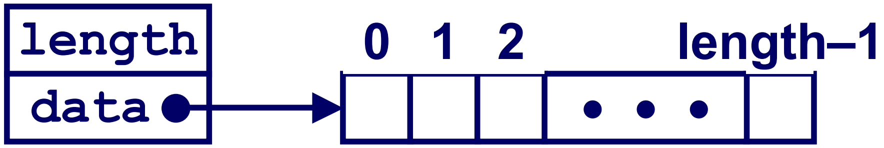
- vsum2 only works on even n.
- vsum2 is an example of loop unrolling.

Cycles Per Element

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



Vector Abstract Data Type (ADT)



Procedures

`vec_ptr new_vec(int len)`

- Create vector of specified length

`int get_vec_element(vec_ptr v, int index, int *dest)`

- Retrieve vector element, store at *dest
- Return 0 if out of bounds, 1 if successful

`int *get_vec_start(vec_ptr v)`

- Return pointer to start of vector data

- Similar to array implementations in Pascal, ML, Java
  - E.g., always do bounds checking

Optimization Example

```
void combine1(vec_ptr v, int *dest)
{
  int i;
  *dest = 0;
  for (i = 0; i < vec_length(v); i++) {
    int val;
    get_vec_element(v, i, &val);
    *dest += val;
  }
}
```

Procedure

- Compute sum of all elements of integer vector
- Store result at destination location
- Vector data structure and operations defined via abstract data type

Pentium III Performance: Clock Cycles / Element

- 42.06 (Compiled -g) 31.25 (Compiled -O2)

Understanding Loop

```
void combine1-goto(vec_ptr v, int *dest)
{
    int i = 0;
    int val;
    *dest = 0;
loop:
    if (i >= vec_length(v))
      goto done;
    get_vec_element(v, i, &val);
    *dest += val;
    i++;
    goto loop;
done:
}
```

1 iteration

Inefficiency

- Procedure vec_length called every iteration
- Even though result always the same

Move `vec_length` Call Out of Loop

```
void combine2(vec_ptr v, int *dest)
{
  int i;
  int length = vec_length(v);
  *dest = 0;
  for (i = 0; i < length; i++) {
    int val;
    get_vec_element(v, i, &val);
    *dest += val;
  }
}
```

Optimization

- Move call to `vec_length` out of inner loop
  - Value does not change from one iteration to next
  - Code motion
- CPE: 20.66 (Compiled -O2)
  - `vec_length` requires only constant time, but significant overhead

Code Motion Example #2

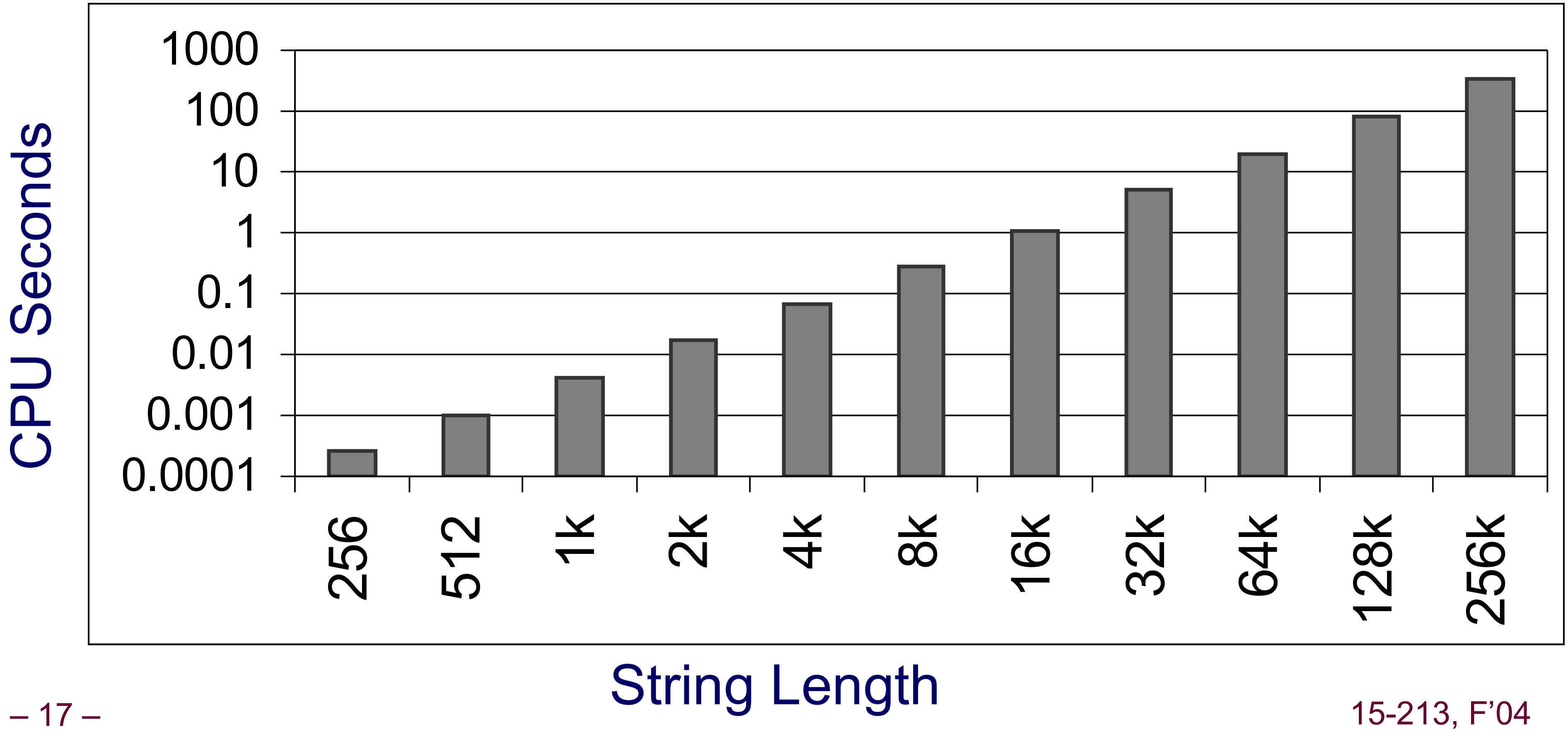
Procedure to Convert String to Lower Case

```
void lower(char *s)
{
  int i;
  for (i = 0; i < strlen(s); i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

- **Extracted from 213 lab submissions, Fall, 1998**

Lower Case Conversion Performance

- **Time quadruples when double string length**
- **Quadratic performance of lower**



Convert Loop To Goto Form

```
void lower(char *s)
{
   int i = 0;
   if (i >= strlen(s))
     goto done;
 loop:
   if (s[i] >= 'A' && s[i] <= 'Z')
       s[i] -= ('A' - 'a');
   i++;
   if (i < strlen(s))
     goto loop;
 done:
}
```

- `strlen` **executed every iteration**
- `strlen` **linear in length of string**
  - **Must scan string until finds** `'\0'`
- **Overall performance is quadratic**

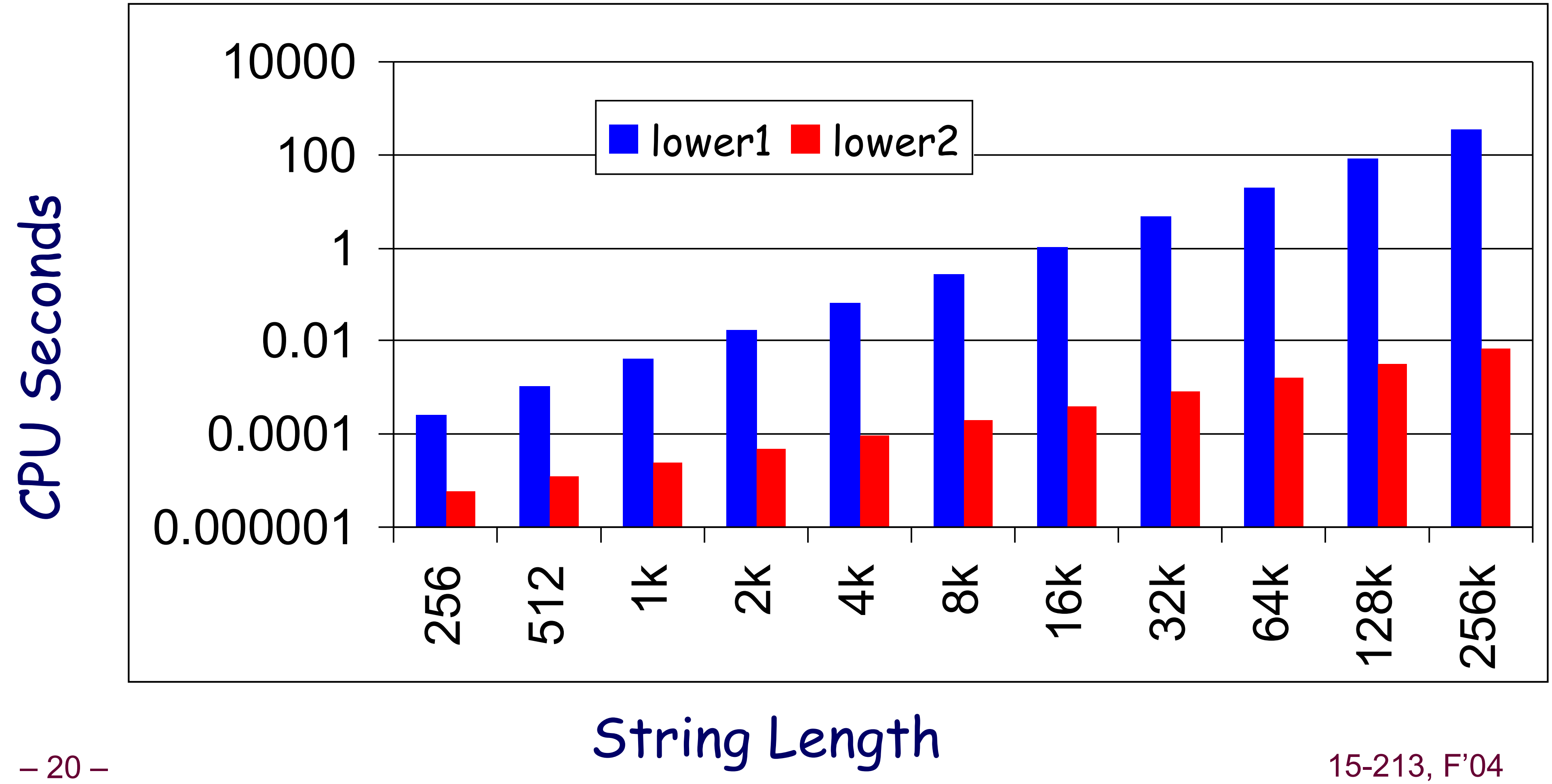
Improving Performance

```
void lower(char *s)
{
  int i;
  int len = strlen(s);
  for (i = 0; i < len; i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

- Move call to `strlen` outside of loop
- Since result does not change from one iteration to another
- Form of code motion

Lower Case Conversion Performance

- Time doubles when double string length
- Linear performance of lower2



Optimization Blocker: Procedure Calls

Why couldn't compiler move `vec_len` out of inner loop?

- Procedure may have side effects
  - Alters global state each time called
- Function may not return same value for given arguments
  - Depends on other parts of global state
  - Procedure `lower` could interact with `strlen`

Why doesn't compiler look at code for `vec_len`?

- Interprocedural optimization is not used extensively due to cost

Warning:

- Compiler treats procedure call as a black box
- Weak optimizations in and around them

Remedies:

- Use of `inline` functions
- Use of macros (careful: can obfuscate code!)

Reduction in Strength

```
void combine3(vec_ptr v, int *dest)
{
  int i;
  int length = vec_length(v);
  int *data = get_vec_start(v);
  *dest = 0;
  for (i = 0; i < length; i++) {
    *dest += data[i];
}
```

Optimization

- Avoid procedure call to retrieve each vector element
  - Get pointer to start of array before loop
  - Within loop just do pointer reference
  - Not as clean in terms of data abstraction
- CPE: 6.00 (Compiled -O2)
  - Procedure calls are expensive!
  - Bounds checking is expensive

Eliminate Unneeded Memory Refs

```
void combine4(vec_ptr v, int *dest)
{
  int i;
  int length = vec_length(v);
  int *data = get_vec_start(v);
  int sum = 0;
  for (i = 0; i < length; i++)
    sum += data[i];
  *dest = sum;
}
```

Optimization

- Don’t need to store in destination until end
- Local variable `sum` held in register
- Avoids 1 memory read, 1 memory write per cycle
- CPE: 2.00 (Compiled -O2)
  - Memory references are expensive!

Detecting Unneeded Memory Refs.

Combine3

```
.L18:
        movl  (%ecx,%edx,4),%eax
        addl  %eax,(%edi)
        incl  %edx
        cmpl  %esi,%edx
        jl  .L18
```

Combine4

```
.L24:
        addl  (%eax,%edx,4),%ecx

        incl  %edx
        cmpl  %esi,%edx
        jl  .L24
```

Performance

- Combine3
  - 5 instructions in 6 clock cycles
  - `addl` must read and write memory
- Combine4
  - 4 instructions in 2 clock cycles

Optimization Blocker: Memory Aliasing

Aliasing

- Two different memory references specify single location

Example

- `v: [3, 2, 17]`
- `combine3(v, get_vec_start(v)+2)   --> ?`
- `combine4(v, get_vec_start(v)+2)   --> ?`

Observations

- Easy to have happen in C
  - Since allowed to do address arithmetic
  - Direct access to storage structures
- Get in habit of introducing local variables
  - Accumulating within loops
  - Your way of telling compiler not to check for aliasing

General Forms of Combining

```
void abstract_combine4(vec_ptr v, data_t *dest)
{
  int i;
  int length = vec_length(v);
  data_t *data = get_vec_start(v);
  data_t t = IDENT;
  for (i = 0; i < length; i++)
    t = t OP data[i];
  *dest = t;
}
```

Data Types

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

Operations

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

Machine Independent Opt. Results

Optimizations

- Reduce function calls and memory references within loop

Method	Integer		Floating Point	
	+	*	+	*
Abstract -g	42.06	41.86	41.44	160.00
Abstract -O2	31.25	33.25	31.25	143.00
Move vec_length	20.66	21.25	21.15	135.00
data access	6.00	9.00	8.00	117.00
Accum. in temp	2.00	4.00	3.00	5.00

Performance Anomaly

- Computing FP product of all elements exceptionally slow.
- Very large speedup when accumulate in temporary
- Caused by quirk of IA32 floating point
  - Memory uses 64-bit format, register use 80
  - Benchmark data caused overflow of 64 bits, but not 80

Pointer Code

```
void combine4p(vec_ptr v, int *dest)
{
  int length = vec_length(v);
  int *data = get_vec_start(v);
  int *dend = data+length;
  int sum = 0;
  while (data < dend) {
    sum += *data;
    data++;
  }
  *dest = sum;
}
```

Optimization

- Use pointers rather than array references
- CPE: 3.00 (Compiled -O2)
  - Oops! We're not making progress here!

Warning: Some compilers do better job optimizing array code

Pointer vs. Array Code Inner Loops

Array Code

```
.L24:                     # Loop:
  addl (%eax,%edx,4),%ecx # sum += data[i]
  incl %edx               # i++
  cmpl %esi,%edx          # i:length
  jl .L24                 # if < goto Loop
```

Pointer Code

```
.L30:              # Loop:
  addl (%eax),%ecx #  sum += *data
  addl $4,%eax     #  data ++
  cmpl %edx,%eax   #  data:dend
  jb .L30          #  if < goto Loop
```

Performance

- Array Code: 4 instructions in 2 clock cycles
- Pointer Code: Almost same 4 instructions in 3 clock cycles

Machine-Independent Opt. Summary

Code Motion

- Compilers are good at this for simple loop/array structures
- Don't do well in presence of procedure calls and memory aliasing

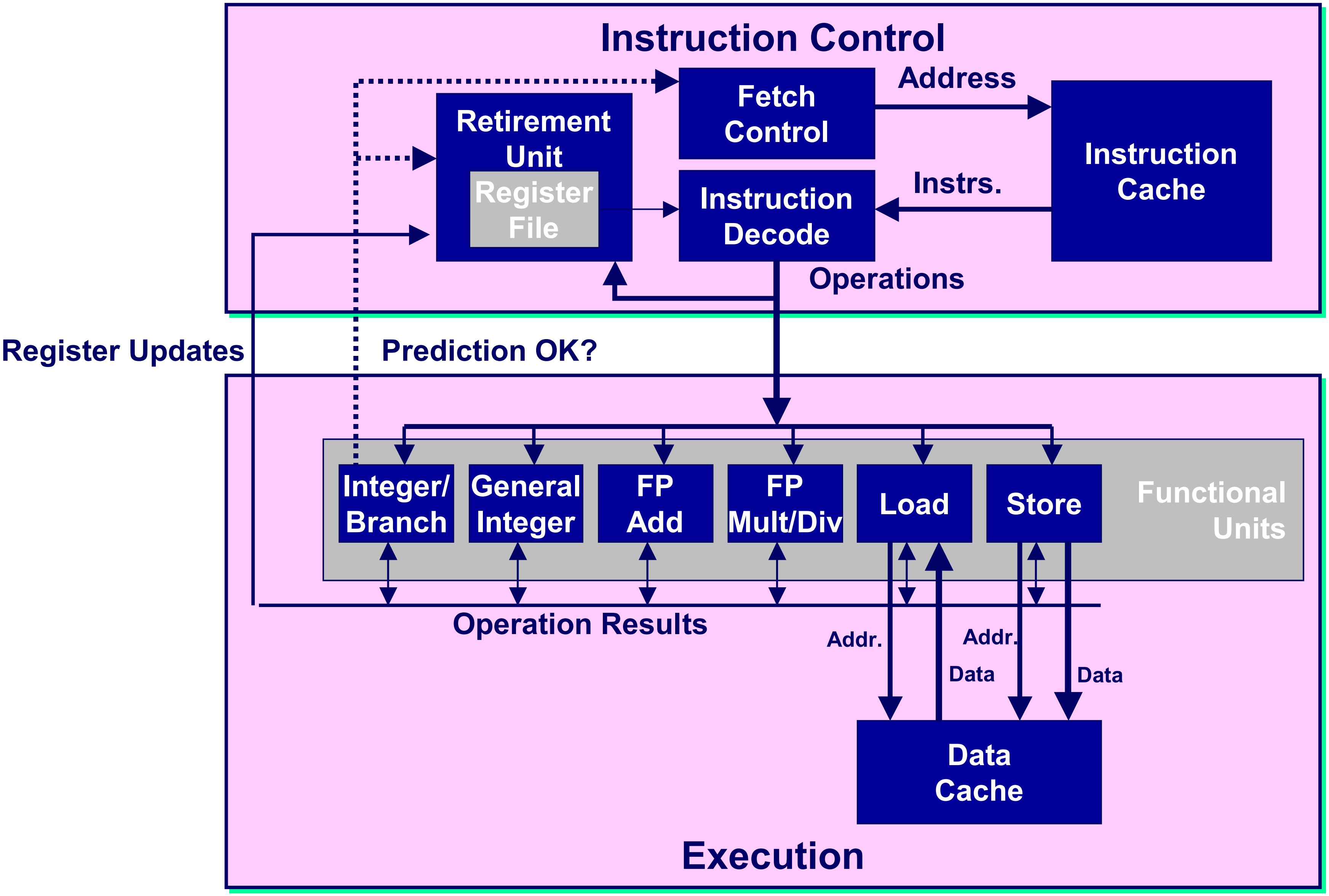
Reduction in Strength

- Shift, add instead of multiply or divide
  - *Compilers are (generally) good at this*
  - *Exact trade-offs machine-dependent*
- Keep data in registers rather than memory
  - *Compilers are not good at this, since concerned with aliasing*
  - *Compilers do know how to allocate registers (no need for* `register` *declaration)*

Share Common Subexpressions

- Compilers have limited algebraic reasoning capabilities

Modern CPU Design


Instruction Control
Fetch Control
Address
Instruction Cache
Retirement Unit
Register File
Instruction Decode
Instrs.
Operations
Register Updates
Prediction OK?
Integer/ Branch
General Integer
FP Add
FP Mult/Div
Load
Store
Functional Units
Operation Results
Addr.
Addr.
Data
Data
Data Cache
Execution

CPU Capabilities of Pentium III

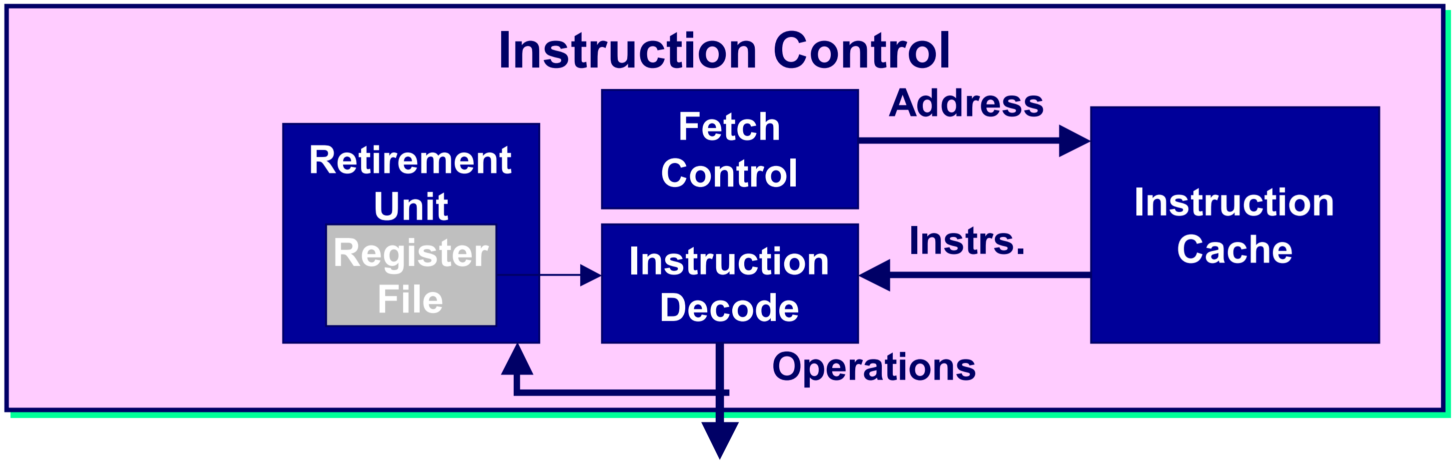
Multiple Instructions Can Execute in Parallel

- 1 load
- 1 store
- 2 integer (one may be branch)
- 1 FP Addition
- 1 FP Multiplication or Division

Some Instructions Take > 1 Cycle, but Can be Pipelined

Instruction	Latency	Cycles/Issue
Load / Store	3	1
Integer Multiply	4	1
Integer Divide	36	36
Double/Single FP Multiply	5	2
Double/Single FP Add	3	1
Double/Single FP Divide	38	38

Instruction Control


Instruction Control
Retirement Unit
Register File
Fetch Control
Address
Instruction Cache
Instrs.
Instruction Decode
Operations

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

Translation Example

Version of Combine4

- Integer data, multiply operation

```
.L24:                           # Loop:
  imull (%eax,%edx,4),%ecx      # t *= data[i]
  incl %edx                     # i++
  cmpl %esi,%edx                # i:length
  jl .L24                       # if < goto Loop
```

Translation of First Iteration

```
.L24:
  imull (%eax,%edx,4),%ecx

  incl %edx
  cmpl %esi,%edx
  jl .L24
```

```

load (%eax,%edx.0,4)  → t.1
imull t.1, %ecx.0     → %ecx.1
incl %edx.0           → %edx.1
cmpl %esi, %edx.1     → cc.1
jl-taken cc.1
```

Translation Example #1

```
imull (%eax,%edx,4),%ecx
```

```
load (%eax,%edx.0,4)  → t.1
imull t.1, %ecx.0     → %ecx.1
```

- Split into two operations
  - `load` reads from memory to generate temporary result `t.1`
  - Multiply operation just operates on registers
- Operands
  - Register `%eax` does not change in loop. Values will be retrieved from register file during decoding
  - Register `%ecx` changes on every iteration. Uniquely identify different versions as `%ecx.0`, `%ecx.1`, `%ecx.2`, …
    - » Register *renaming*
    - » Values passed directly from producer to consumers (bypass hardware)

Translation Example #2

```
incl %edx
```

```
incl %edx.0              →  %edx.1
```

- Register `%edx` changes on each iteration. Rename as `%edx.0`, `%edx.1`, `%edx.2`, …

Translation Example #3

```
cmpl %esi,%edx
```

```
cmpl %esi, %edx.1  → cc.1
```

- Condition codes are treated similar to registers
- Assign tag to define connection between producer and consumer

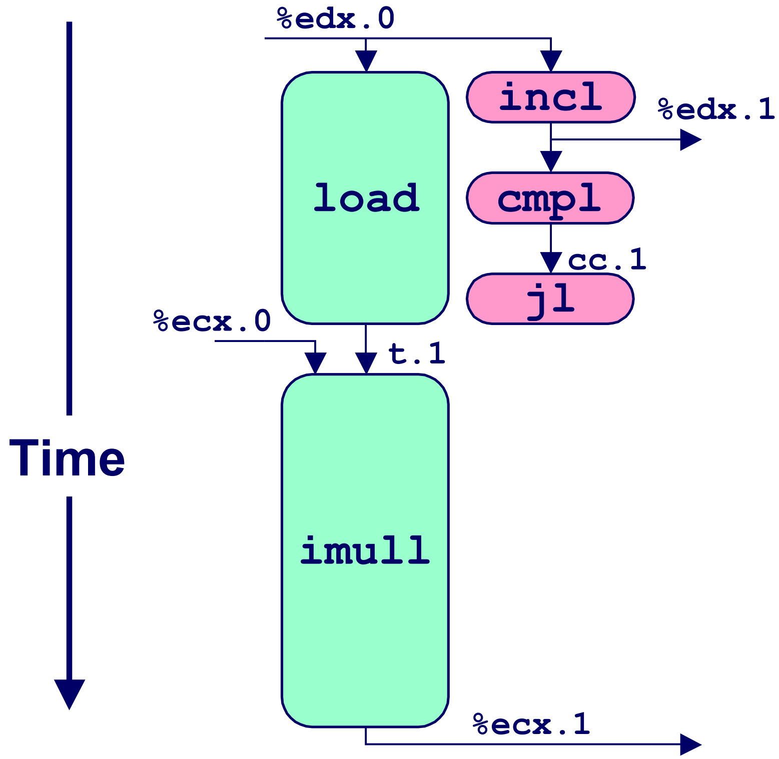
Translation Example #4

```
  jl .L24
```

```
jl-taken cc.1
```

- Instruction control unit determines destination of jump
- Predicts whether will be taken and target
- Starts fetching instruction at predicted destination
- Execution unit simply checks whether or not prediction was OK
- If not, it signals instruction control
  - Instruction control then "invalidates" any operations generated from misfetched instructions
  - Begins fetching and decoding instructions at correct target

Visualizing Operations


%edx.0
incl
%edx.1
load
cmpl
cc.1
jl
%ecx.0
t.1
Time
imull
%ecx.1

```
load (%eax,%edx,4)  ➔  t.1
imull t.1, %ecx.0   ➔  %ecx.1
incl %edx.0          ➔  %edx.1
cmpl %esi, %edx.1   ➔  cc.1
jl-taken cc.1
```

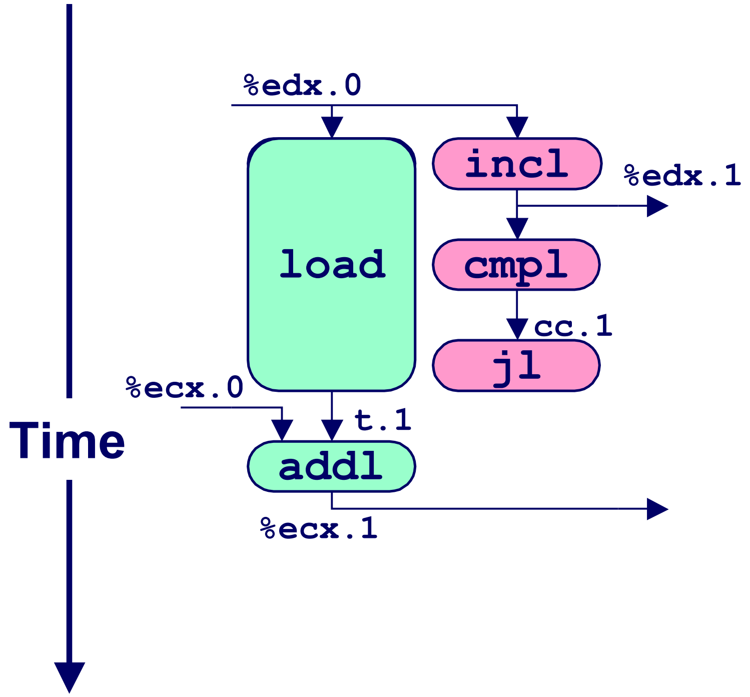
Operations

- Vertical position denotes time at which executed
  - Cannot begin operation until operands available
- Height denotes latency

Operands

- Arcs shown only for operands that are passed within execution unit

Visualizing Operations (cont.)

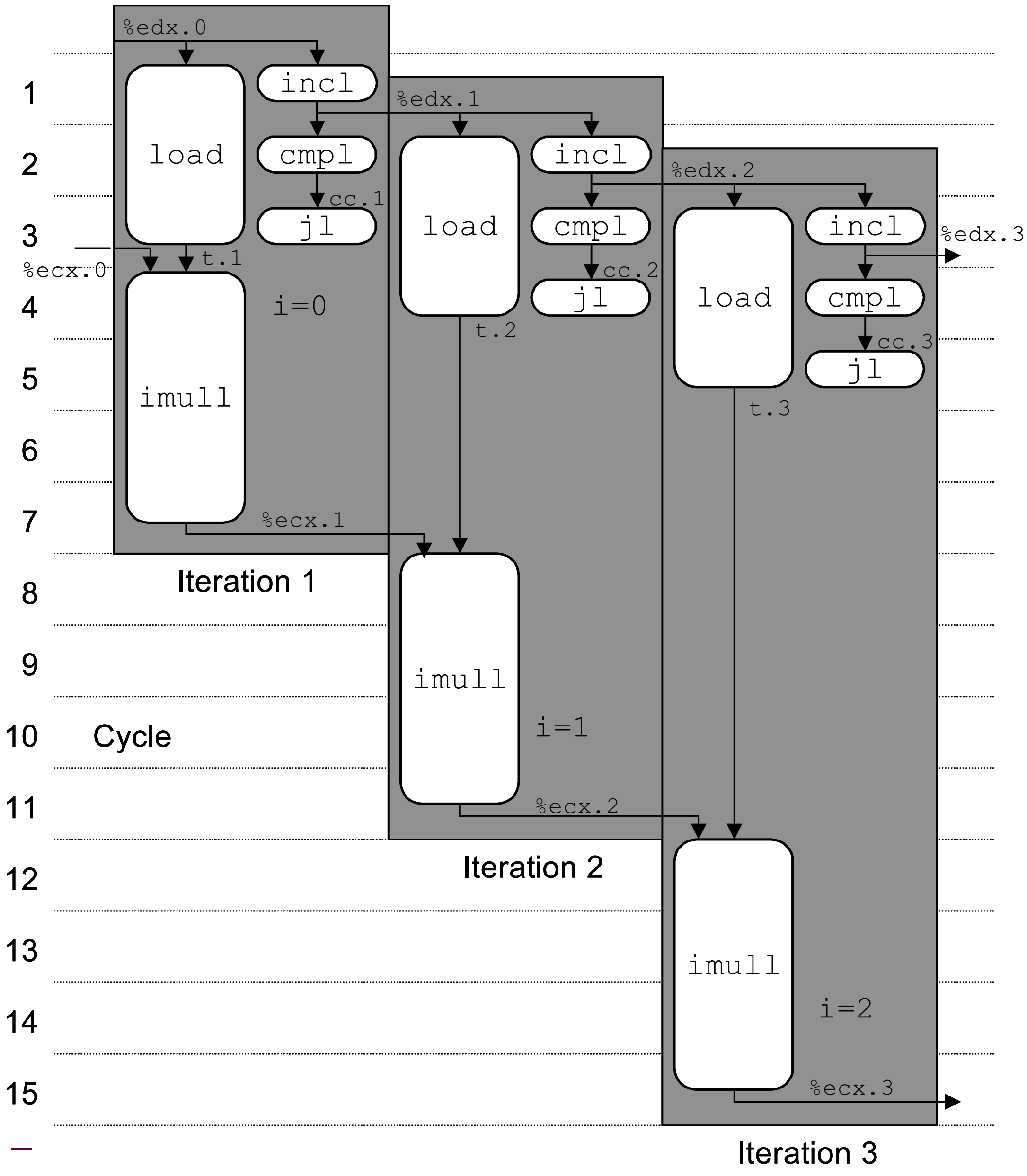

%edx.0
incl
%edx.1
load
cmpl
cc.1
jl
%ecx.0
t.1
Time
addl
%ecx.1

```
load (%eax,%edx,4)  ➔ t.1
iaddl t.1, %ecx.0   ➔ %ecx.1
incl %edx.0          ➔ %edx.1
cmpl %esi, %edx.1   ➔ cc.1
jl-taken cc.1
```

Operations

- Same as before, except that add has latency of 1

3 Iterations of Combining Product


%edx.0
incl
load
cmpl
cc.1
jl
t.1
%ecx.0
i=0
imull
%ecx.1
Iteration 1
%edx.1
incl
load
cmpl
cc.2
jl
t.2
imull
i=1
%ecx.2
Iteration 2
%edx.2
incl
load
cmpl
cc.3
jl
%edx.3
t.3
imull
i=2
%ecx.3
Iteration 3
1
2
3
4
5
6
7
8
9
10
Cycle
11
12
13
14
15

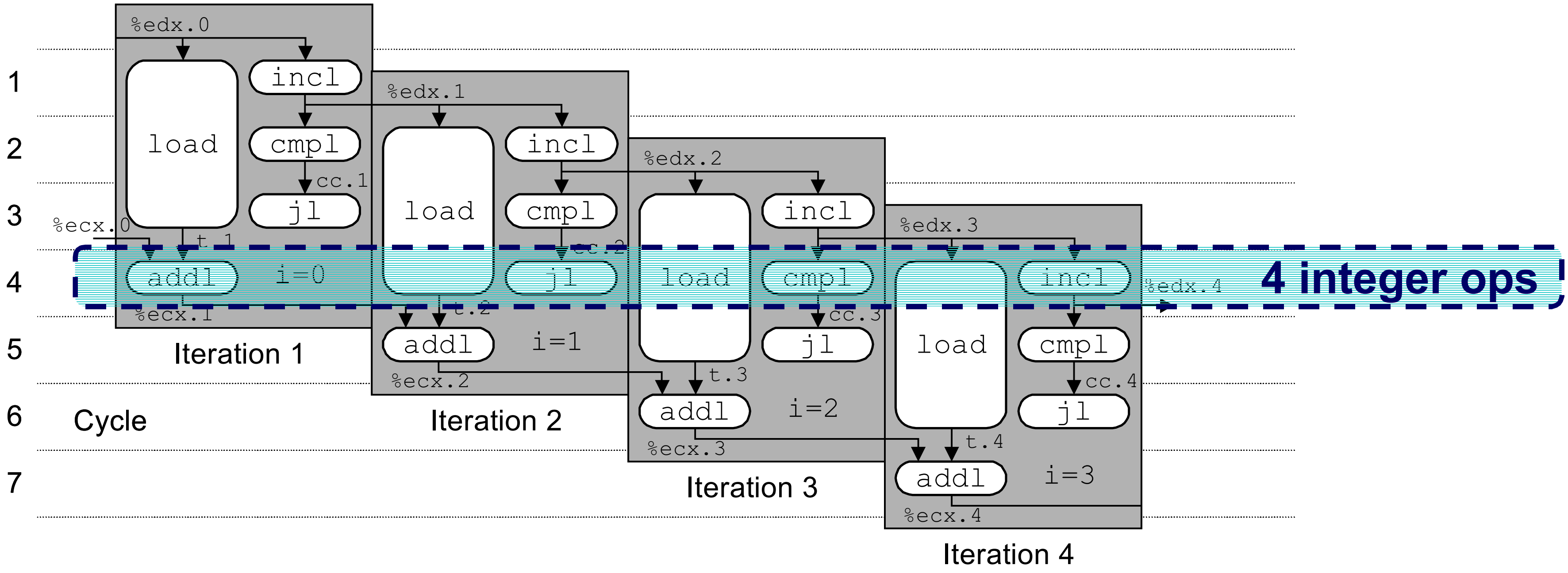
Unlimited Resource Analysis

- Assume operation can start as soon as operands available
- Operations for multiple iterations overlap in time

Performance

- Limiting factor becomes latency of integer multiplier
- Gives CPE of 4.0

4 Iterations of Combining Sum



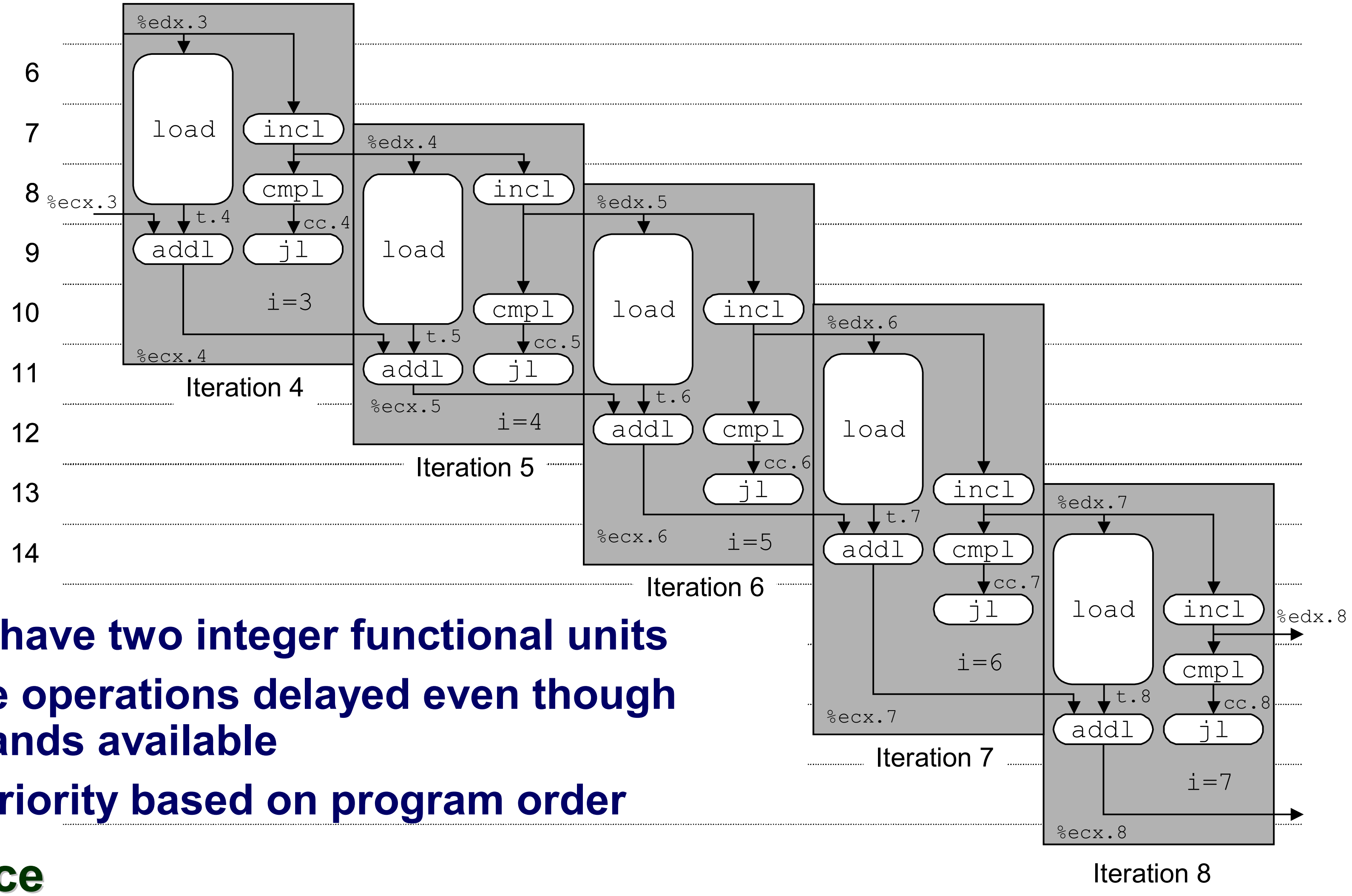
1
2
3
4
5
6
7
Cycle
%edx.0
load
incl
cmpl
cc.1
jl
%ecx.0
t.1
addl
i=0
%ecx.1
Iteration 1
%edx.1
load
incl
cmpl
cc.2
jl
t.2
addl
i=1
%ecx.2
Iteration 2
%edx.2
load
incl
cmpl
cc.3
jl
t.3
addl
i=2
%ecx.3
Iteration 3
%edx.3
load
incl
cmpl
cc.4
jl
t.4
addl
i=3
%ecx.4
Iteration 4
%edx.4
4 integer ops

Unlimited Resource Analysis

Performance

- **Can begin a new iteration on each clock cycle**
- **Should give CPE of 1.0**
- **Would require executing 4 integer operations in parallel**

Combining Sum: Resource Constraints


6
7
8
9
10
11
12
13
14
%edx.3
load
incl
cmpl
%ecx.3
t.4
cc.4
addl
jl
i=3
%ecx.4
Iteration 4
%edx.4
load
incl
cmpl
t.5
cc.5
addl
jl
%ecx.5
i=4
Iteration 5
%edx.5
load
incl
cmpl
t.6
cc.6
addl
jl
%ecx.6
i=5
Iteration 6
%edx.6
load
incl
cmpl
t.7
cc.7
addl
jl
i=6
%ecx.7
Iteration 7
%edx.7
load
incl
%edx.8
cmpl
t.8
cc.8
addl
jl
i=7
%ecx.8
Iteration 8

- Only have two integer functional units
- Some operations delayed even though operands available
- Set priority based on program order

Performance

- Sustain CPE of 2.0

Loop Unrolling

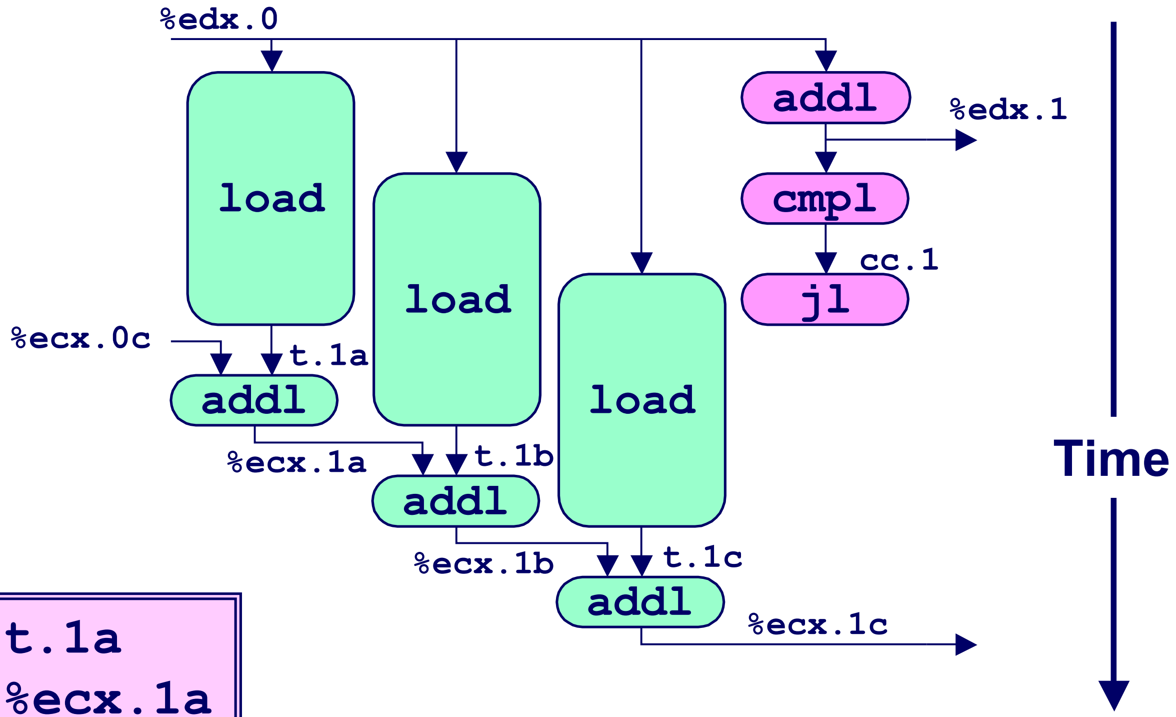
```
void combine5(vec_ptr v, int *dest)
{
  int length = vec_length(v);
  int limit = length-2;
  int *data = get_vec_start(v);
  int sum = 0;
  int i;
  /* Combine 3 elements at a time */
  for (i = 0; i < limit; i+=3) {
    sum += data[i] + data[i+2]
           + data[i+1];
  }
  /* Finish any remaining elements */
  for (; i < length; i++) {
    sum += data[i];
  }
  *dest = sum;
}
```

Optimization

- Combine multiple iterations into single loop body
- Amortizes loop overhead across multiple iterations
- Finish extras at end
- Measured CPE = 1.33

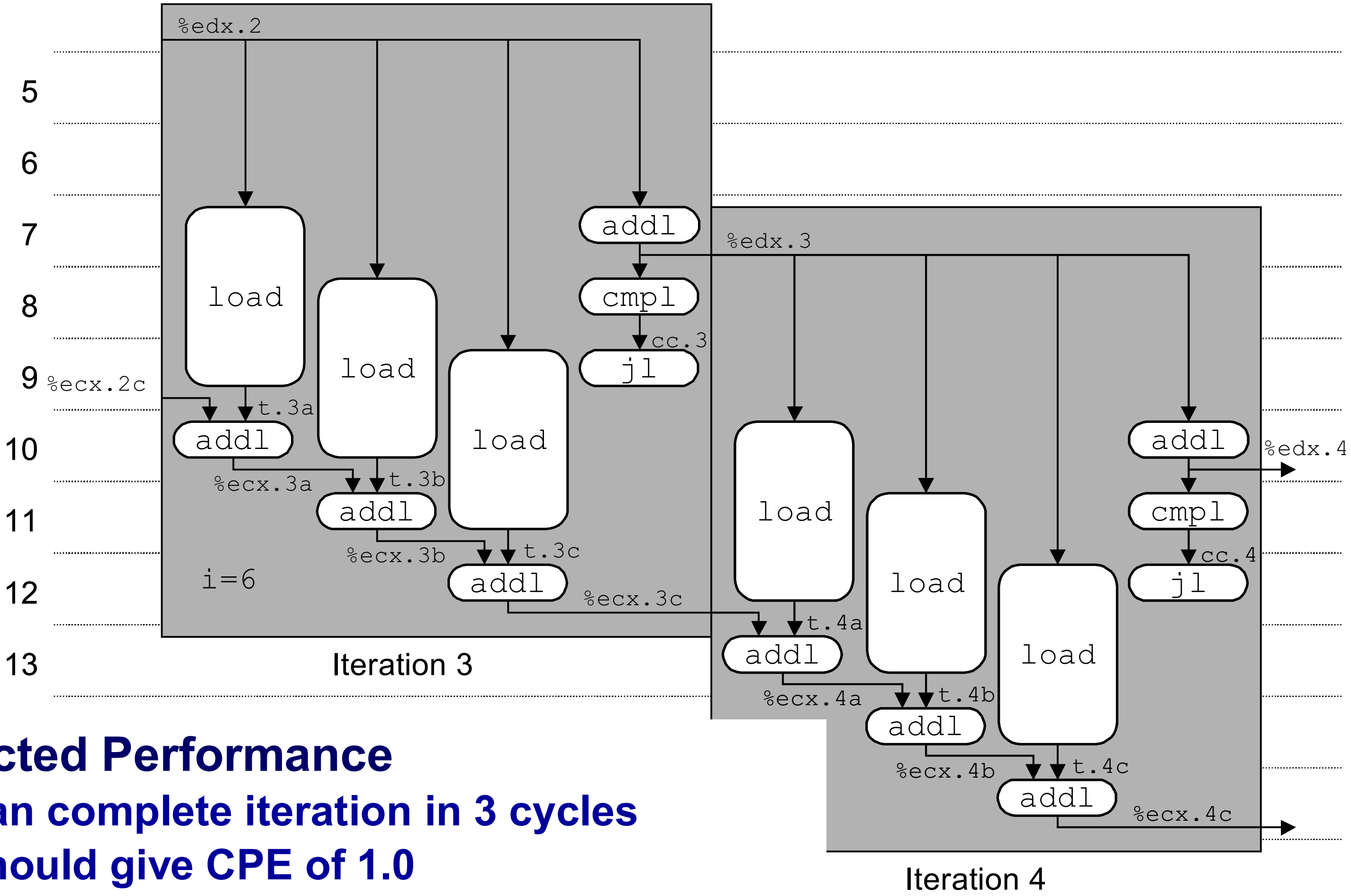
Visualizing Unrolled Loop

- Loads can pipeline, since don’t have dependencies
- Only one set of loop control operations


%edx.0
load
load
load
addl
%edx.1
cmpl
cc.1
jl
%ecx.0c
t.1a
addl
%ecx.1a
t.1b
addl
%ecx.1b
t.1c
addl
%ecx.1c
Time

```
load (%eax,%edx.0,4)    → t.1a
iaddl t.1a, %ecx.0c     → %ecx.1a
load 4(%eax,%edx.0,4)   → t.1b
iaddl t.1b, %ecx.1a     → %ecx.1b
load 8(%eax,%edx.0,4)   → t.1c
iaddl t.1c, %ecx.1b     → %ecx.1c
iaddl $3,%edx.0         → %edx.1
cmpl %esi, %edx.1       → cc.1
jl-taken cc.1
```

Executing with Loop Unrolling


%edx.2
5
6
7
8
9
10
11
12
13
load
load
load
addl
cmpl
cc.3
jl
%ecx.2c
t.3a
addl
%ecx.3a
t.3b
addl
%ecx.3b
t.3c
addl
%ecx.3c
i=6
Iteration 3
%edx.3
load
load
load
addl
%edx.4
cmpl
cc.4
jl
t.4a
addl
%ecx.4a
t.4b
addl
%ecx.4b
t.4c
addl
%ecx.4c
Iteration 4

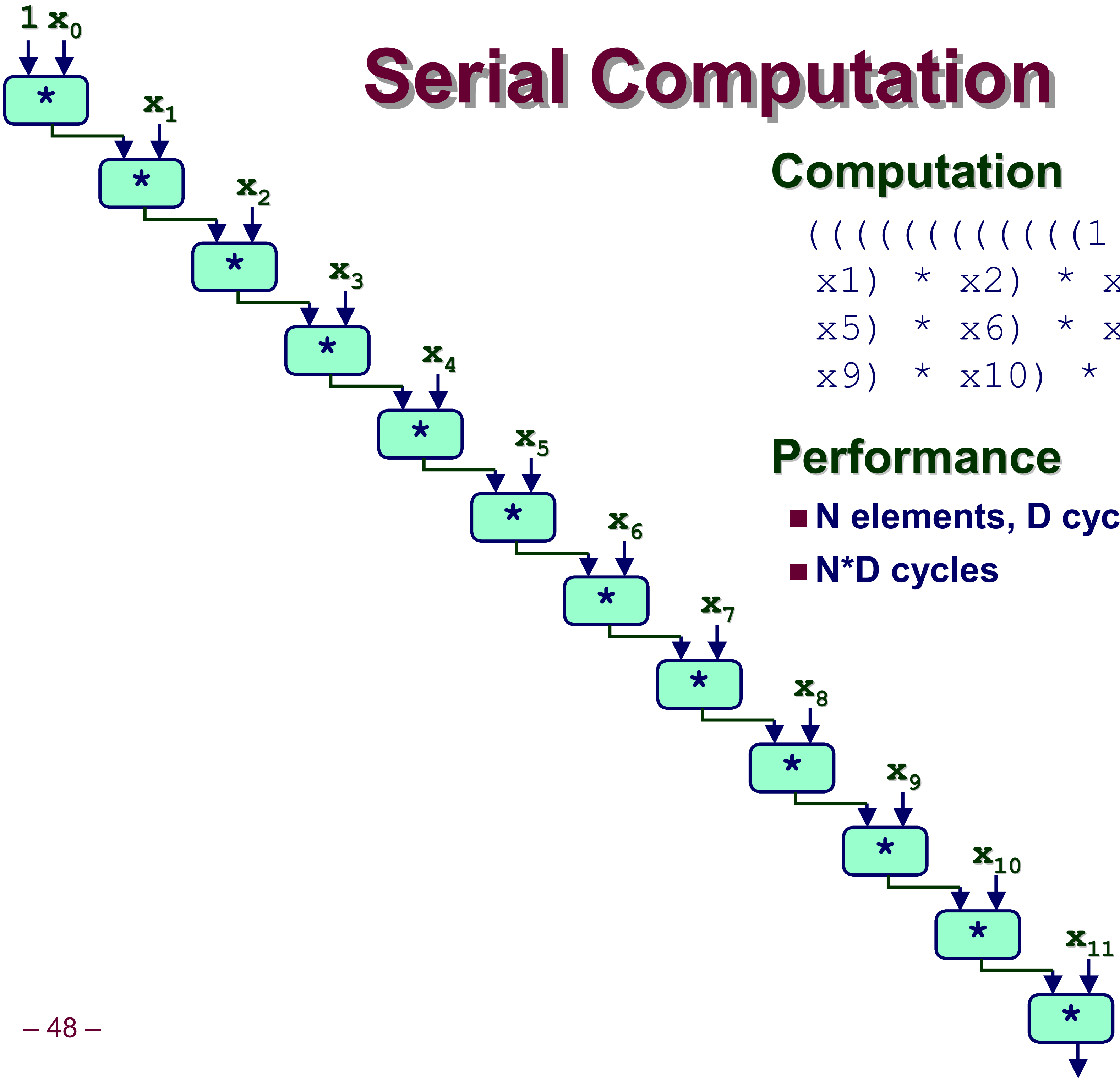
- **Predicted Performance**
  - **Can complete iteration in 3 cycles**
  - **Should give CPE of 1.0**
- **Measured Performance**
  - **CPE of 1.33**
  - **One iteration every 4 cycles**

Effect of Unrolling

Unrolling Degree		1	2	3	4	8	16
Integer	Sum	2.00	1.50	1.33	1.50	1.25	1.06
Integer	Product	4.00					
FP	Sum	3.00					
FP	Product	5.00					

- Only helps integer sum for our examples
  - Other cases constrained by functional unit latencies
- Effect is nonlinear with degree of unrolling
  - Many subtle effects determine exact scheduling of operations

Serial Computation


1
x_0
*
x_1
*
x_2
*
x_3
*
x_4
*
x_5
*
x_6
*
x_7
*
x_8
*
x_9
*
x_{10}
*
x_{11}
*

Computation

```
((((((((((((1 * x0) *
 x1) * x2) * x3) * x4) *
 x5) * x6) * x7) * x8) *
 x9) * x10) * x11)
```

Performance

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

Parallel Loop Unrolling

```
void combine6(vec_ptr v, int *dest)
{
  int length = vec_length(v);
  int limit = length-1;
  int *data = get_vec_start(v);
  int x0 = 1;
  int x1 = 1;
  int i;
  /* Combine 2 elements at a time */
  for (i = 0; i < limit; i+=2) {
    x0 *= data[i];
    x1 *= data[i+1];
  }
  /* Finish any remaining elements */
  for (; i < length; i++) {
    x0 *= data[i];
  }
  *dest = x0 * x1;
}
```

Code Version

- Integer product

Optimization

- Accumulate in two different products
  - Can be performed simultaneously
- Combine at end
- *2-way parallism*

Performance

- CPE = 2.0
- 2X performance

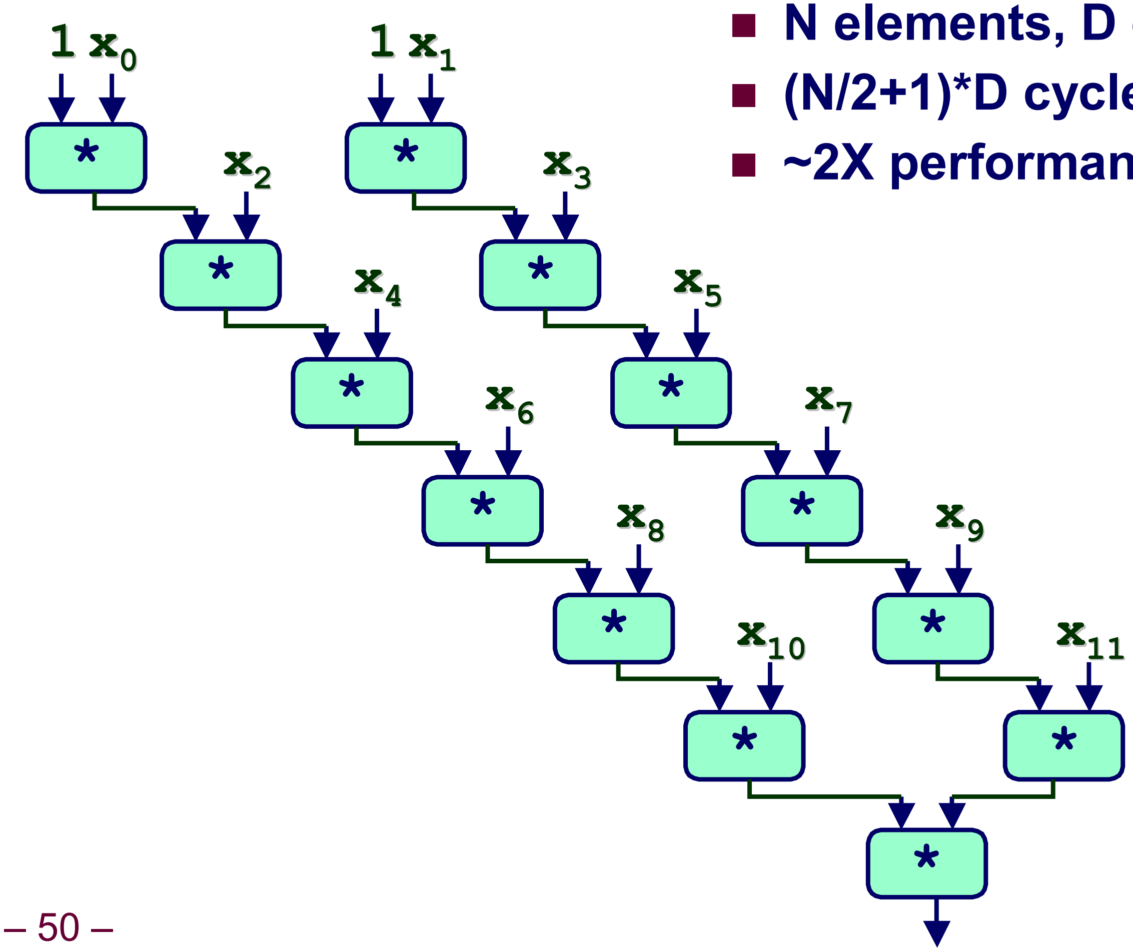
Dual Product Computation

Computation

$$((((((1 * x_0) * x_2) * x_4) * x_6) * x_8) * x_{10}) *$$
$$((((((1 * x_1) * x_3) * x_5) * x_7) * x_9) * x_{11})$$

Performance

- N elements, D cycles/operation
- (N/2+1)*D cycles
- ~2X performance improvement



1 x_0
1 x_1
x_2
x_3
x_4
x_5
x_6
x_7
x_8
x_9
x_{10}
x_{11}
*

Requirements for Parallel Computation

Mathematical

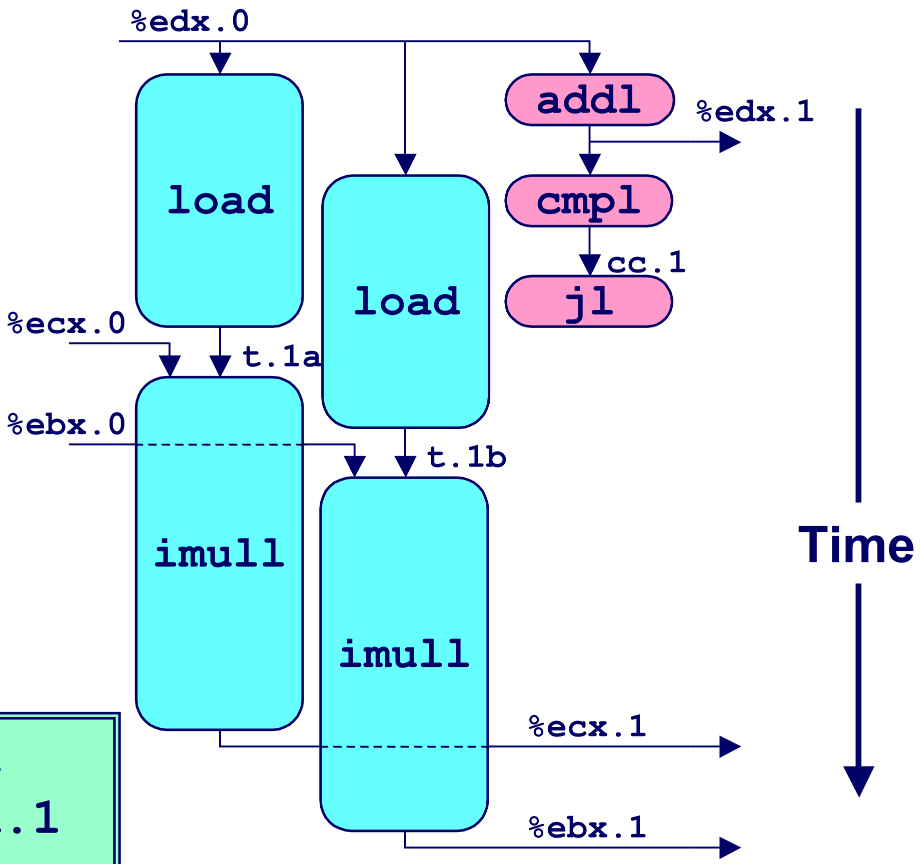
- Combining operation must be associative & commutative
  - OK for integer multiplication
  - Not strictly true for floating point
    - » OK for most applications

Hardware

- Pipelined functional units
- Ability to dynamically extract parallelism from code

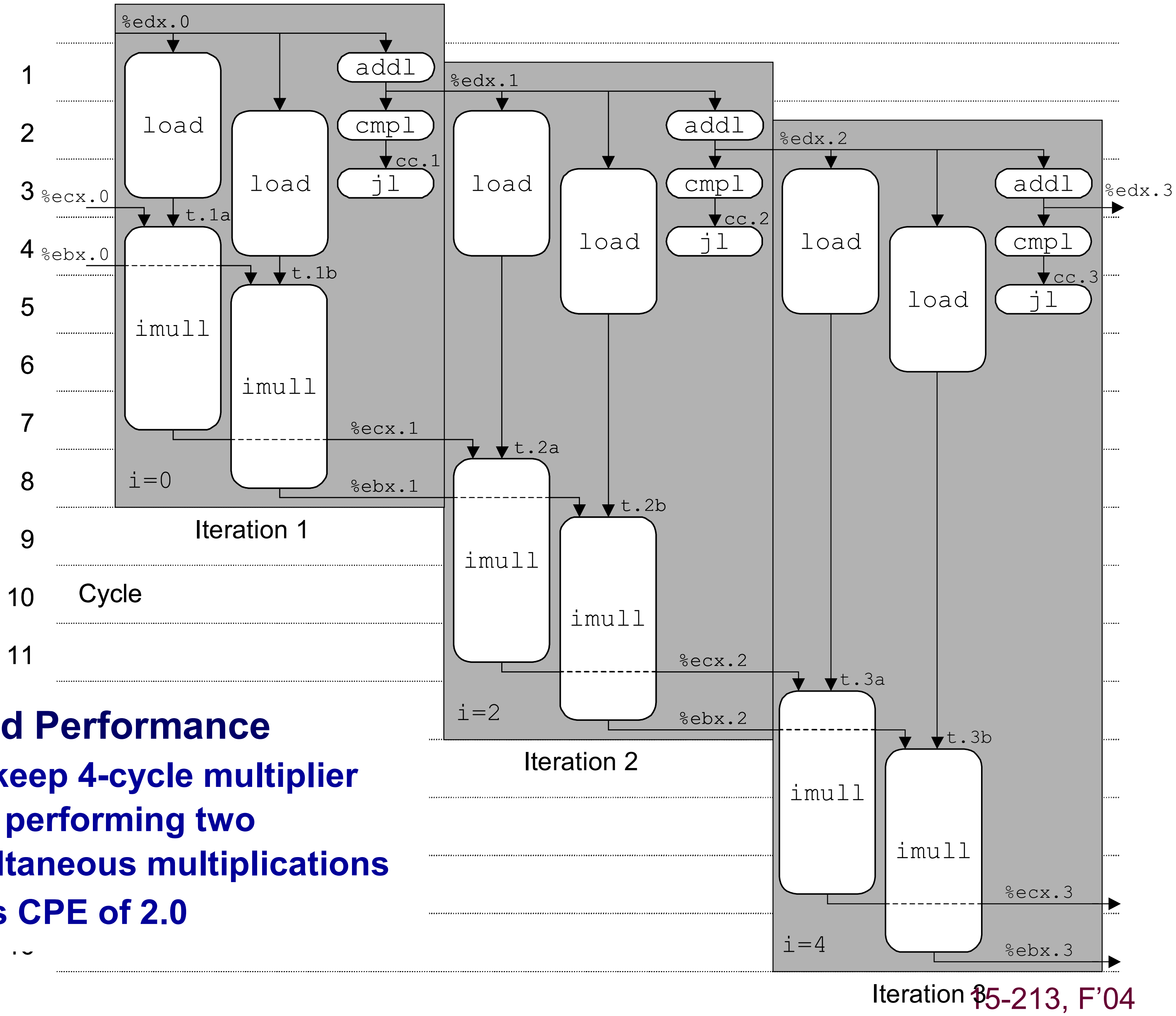
Visualizing Parallel Loop

- Two multiplies within loop no longer have data depency
- Allows them to pipeline


%edx.0
load
addl
%edx.1
cmpl
load
cc.1
jl
%ecx.0
t.1a
%ebx.0
t.1b
imull
imull
%ecx.1
%ebx.1
Time

```
load (%eax,%edx.0,4)   ➔ t.1a
imull t.1a, %ecx.0     ➔ %ecx.1
load 4(%eax,%edx.0,4)  ➔ t.1b
imull t.1b, %ebx.0     ➔ %ebx.1
iaddl $2,%edx.0        ➔ %edx.1
cmpl %esi, %edx.1      ➔ cc.1
jl-taken cc.1
```

Executing with Parallel Loop


%edx.0
1
2
3
4
5
6
7
8
9
10
11
Cycle
load
load
addl
cmpl
cc.1
jl
%ecx.0
%ebx.0
t.1a
t.1b
imull
imull
%ecx.1
%ebx.1
i=0
Iteration 1
%edx.1
load
load
addl
cmpl
cc.2
jl
t.2a
t.2b
imull
imull
%ecx.2
%ebx.2
i=2
Iteration 2
%edx.2
load
load
addl
cmpl
cc.3
jl
%edx.3
t.3a
t.3b
imull
imull
%ecx.3
%ebx.3
i=4
Iteration 3

- **Predicted Performance**
  - **Can keep 4-cycle multiplier busy performing two simultaneous multiplications**
  - **Gives CPE of 2.0**

Parallel Unrolling: Method #2

```
void combine6aa(vec_ptr v, int *dest)
{
  int length = vec_length(v);
  int limit = length-1;
  int *data = get_vec_start(v);
  int x = 1;
  int i;
  /* Combine 2 elements at a time */
  for (i = 0; i < limit; i+=2) {
    x *= (data[i] * data[i+1]);
  }
  /* Finish any remaining elements */
  for (; i < length; i++) {
    x *= data[i];
  }
  *dest = x;
}
```

Code Version

- Integer product

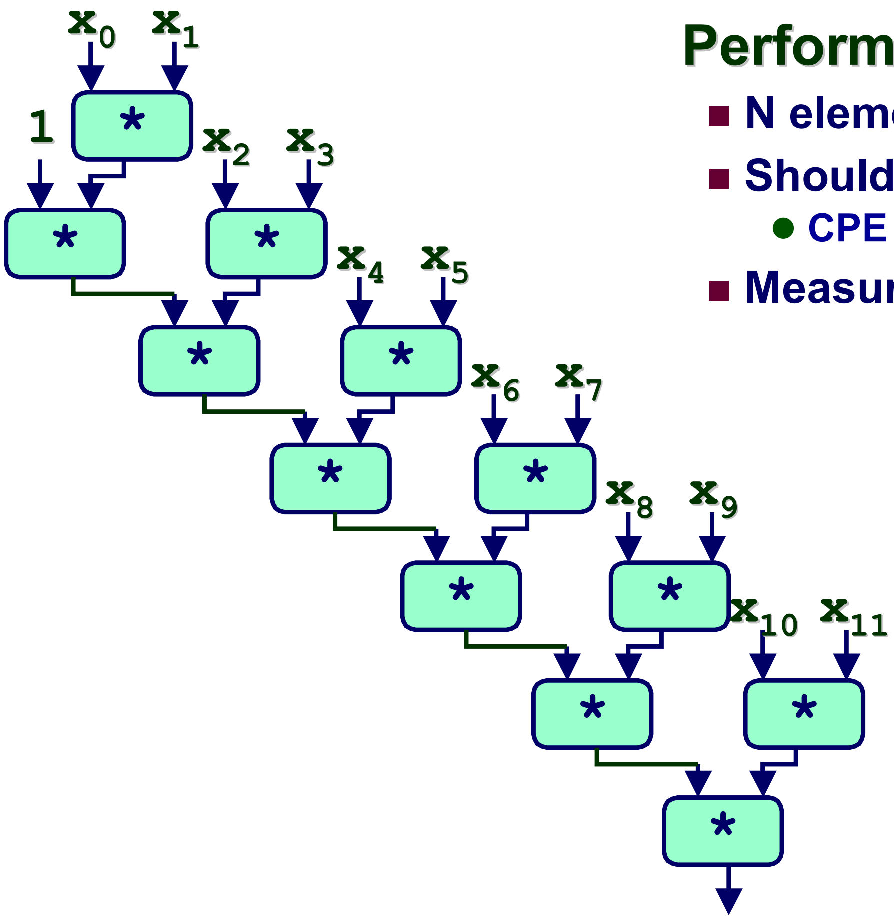
Optimization

- Multiply pairs of elements together
- And then update product
- “Tree height reduction”

Performance

- CPE = 2.5

Method #2 Computation


x_0
x_1
*
1
x_2
x_3
*
*
x_4
x_5
*
*
x_6
x_7
*
*
x_8
x_9
*
*
x_{10}
x_{11}
*
*
*

Computation

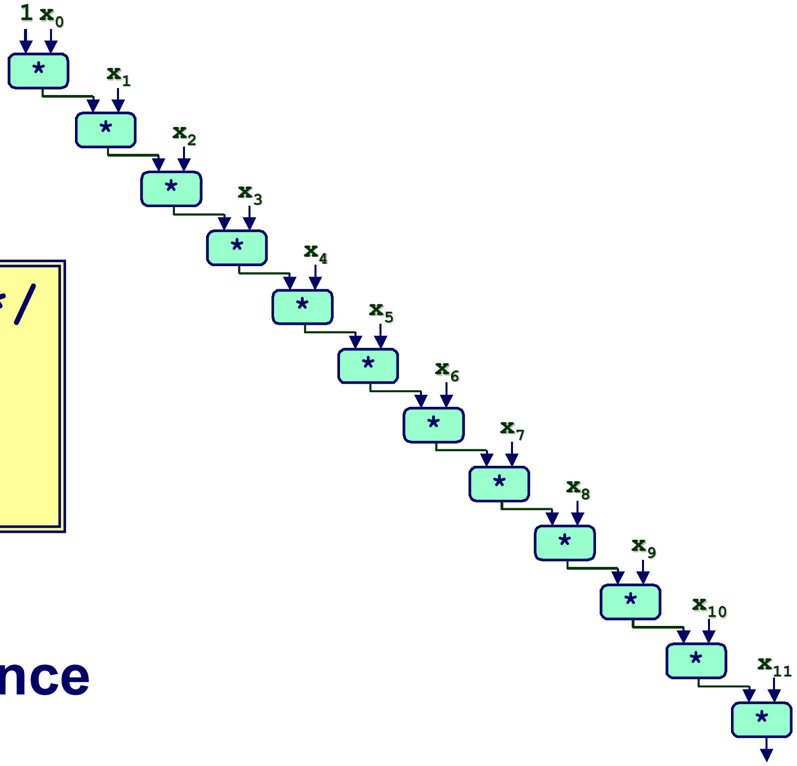
```
((((((1 * (x0 * x1)) * (x2 * x3)) * (x4
* x5)) * (x6 * x7)) * (x8 * x9)) * (x10
* x11))
```

Performance

- N elements, D cycles/operation
- Should be (N/2+1)*D cycles
  - CPE = 2.0
- Measured CPE worse

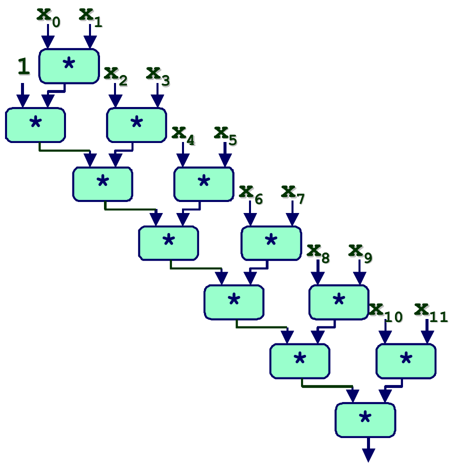
Unrolling	CPE (measured)	CPE (theoretical)
2	2.50	2.00
3	1.67	1.33
4	1.50	1.00
6	1.78	1.00

Understanding Parallelism


1
x_0
x_1
x_2
x_3
x_4
x_5
x_6
x_7
x_8
x_9
x_{10}
x_{11}
*

```
/* Combine 2 elements at a time */
for (i = 0; i < limit; i+=2) {
  x = (x * data[i]) * data[i+1];
}
```

- CPE = 4.00
- All multiplies perfomed in sequence


x_0
x_1
1
x_2
x_3
x_4
x_5
x_6
x_7
x_8
x_9
x_{10}
x_{11}
*

```
/* Combine 2 elements at a time */
for (i = 0; i < limit; i+=2) {
  x = x * (data[i] * data[i+1]);
}
```

- CPE = 2.50
- Multiplies overlap

Limitations of Parallel Execution

Need Lots of Registers

- To hold sums/products
- Only 6 usable integer registers
  - Also needed for pointers, loop conditions
- 8 FP registers
- When not enough registers, must spill temporaries onto stack
  - Wipes out any performance gains
- Not helped by renaming
  - Cannot reference more operands than instruction set allows
  - Major drawback of IA32 instruction set architecture, partially alleviated by recent extensions like SSE, …

Register Spilling Example

Example

- 8 X 8 integer product
- 7 local variables share 1 register
- See that are storing locals on stack
- E.g., at `-8(%ebp)`

```
.L165:
      imull  (%eax),%ecx
      movl  -4(%ebp),%edi
      imull  4(%eax),%edi
      movl  %edi,-4(%ebp)
      movl  -8(%ebp),%edi
      imull  8(%eax),%edi
      movl  %edi,-8(%ebp)
      movl  -12(%ebp),%edi
      imull  12(%eax),%edi
      movl  %edi,-12(%ebp)
      movl  -16(%ebp),%edi
      imull  16(%eax),%edi
      movl  %edi,-16(%ebp)
    …
      addl  $32,%eax
      addl  $8,%edx
      cmpl  -32(%ebp),%edx
      jl  .L165
```

Summary: Results for Pentium III

Method	Integer		Floating Point	
	+	*	+	*
Abstract -g	42.06	41.86	41.44	160.00
Abstract -O2	31.25	33.25	31.25	143.00
Move vec_length	20.66	21.25	21.15	135.00
data access	6.00	9.00	8.00	117.00
Accum. in temp	2.00	4.00	3.00	5.00
Pointer	3.00	4.00	3.00	5.00
Unroll 4	1.50	4.00	3.00	5.00
Unroll 16	*1.06*	4.00	3.00	5.00
2 X 2	1.50	2.00	2.00	2.50
4 X 4	1.50	*2.00*	*1.50*	2.50
8 X 4	1.25	*1.25*	1.50	*2.00*
Theoretical Opt.	1.00	1.00	1.00	2.00
Worst : Best	*39.7*	*33.5*	*27.6*	*80.0*

Results for Alpha Processor

Method	Integer		Floating Point	
	+	*	+	*
Abstract -g	40.14	47.14	52.07	53.71
Abstract -O2	25.08	36.05	37.37	32.02
Move vec_length	19.19	32.18	28.73	32.73
data access	6.26	12.52	13.26	13.01
Accum. in temp	1.76	9.01	8.08	8.01
Unroll 4	1.51	9.01	6.32	6.32
Unroll 16	1.25	9.01	6.33	6.22
4 X 2	1.19	4.69	4.44	4.45
8 X 4	1.15	*4.12*	*2.34*	*2.01*
8 X 8	*1.11*	4.24	2.36	2.08
Worst : Best	*36.2*	*11.4*	*22.3*	*26.7*

- Overall trends very similar to those for Pentium III.
- Even though very different architecture and compiler

Results for Pentium 4 Processor

Method	Integer		Floating Point	
	+	*	+	*
Abstract -g	35.25	35.34	35.85	38.00
Abstract -O2	26.52	30.26	31.55	32.00
Move vec_length	18.00	25.71	23.36	24.25
data access	3.39	31.56	27.50	28.35
Accum. in temp	2.00	14.00	5.00	7.00
Unroll 4	1.01	14.00	5.00	7.00
Unroll 16	1.00	14.00	5.00	7.00
4 X 2	1.02	7.00	2.63	3.50
8 X 4	1.01	*3.98*	*1.82*	*2.00*
8 X 8	1.63	4.50	2.42	2.31
Worst : Best	*35.2*	*8.9*	*19.7*	*19.0*

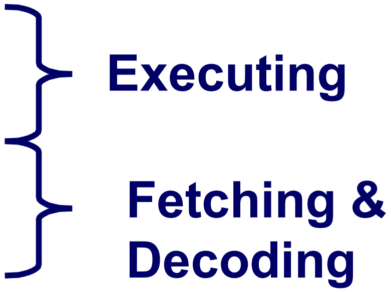
- Higher latencies (int * = 14, fp + = 5.0, fp * = 7.0)
  - Clock runs at 2.0 GHz
  - Not an improvement over 1.0 GHz P3 for integer *
- Avoids FP multiplication anomaly

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
```



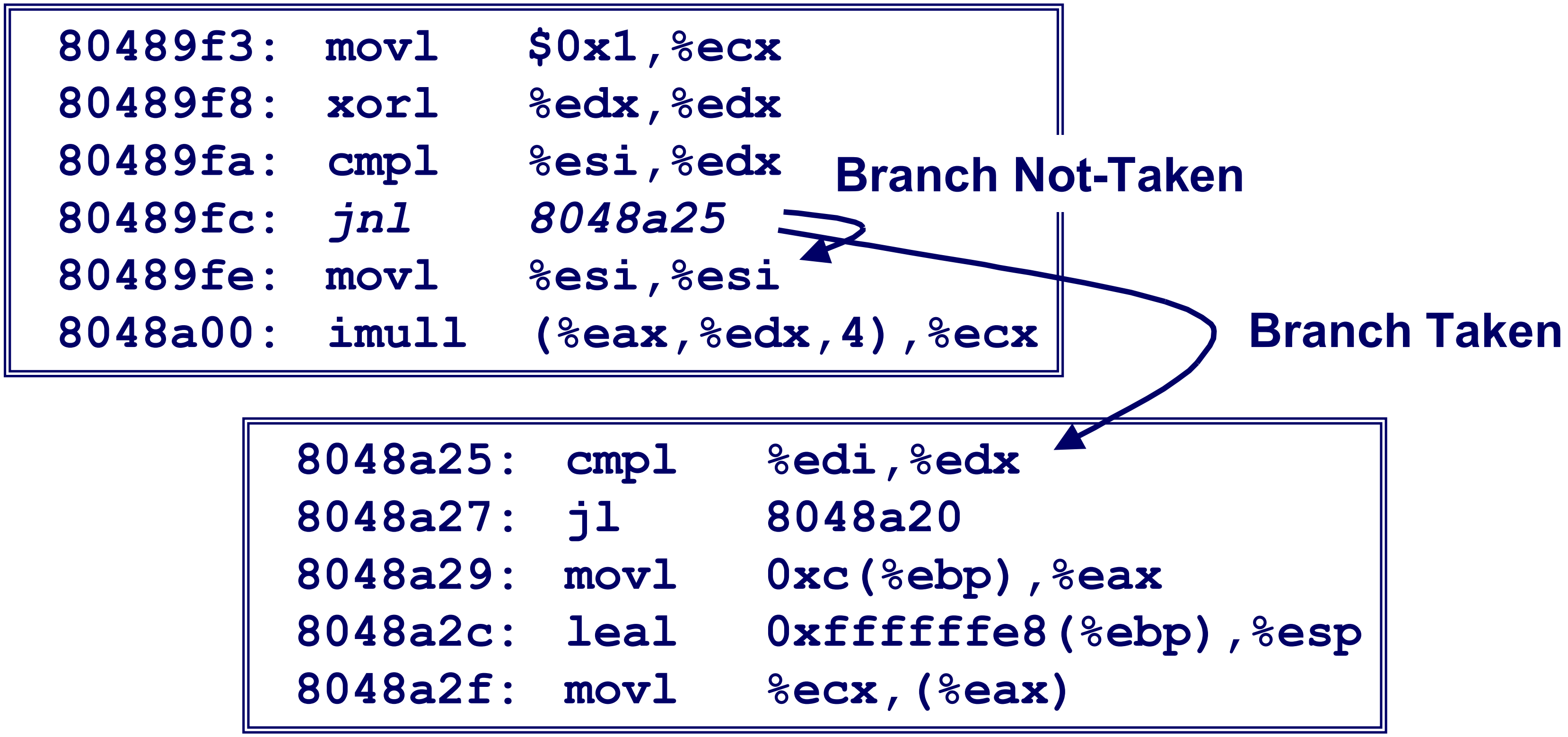
Executing

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

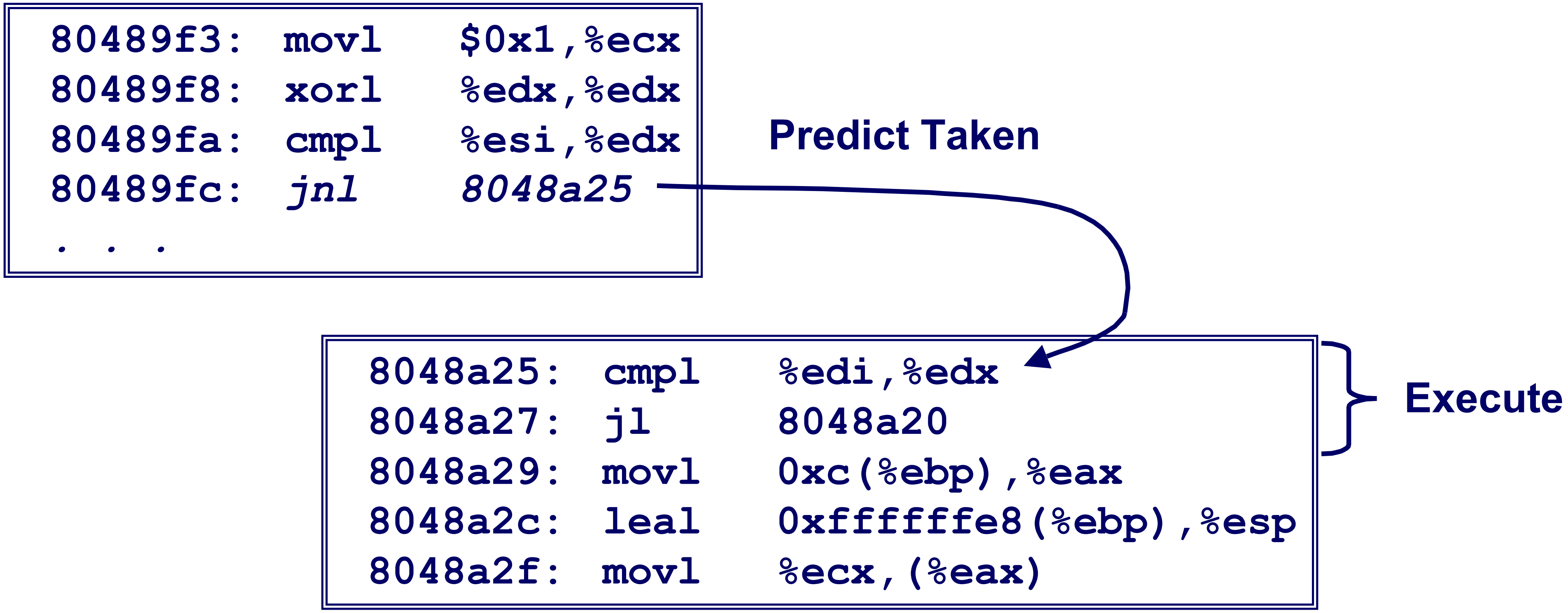
Branch Taken

```
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



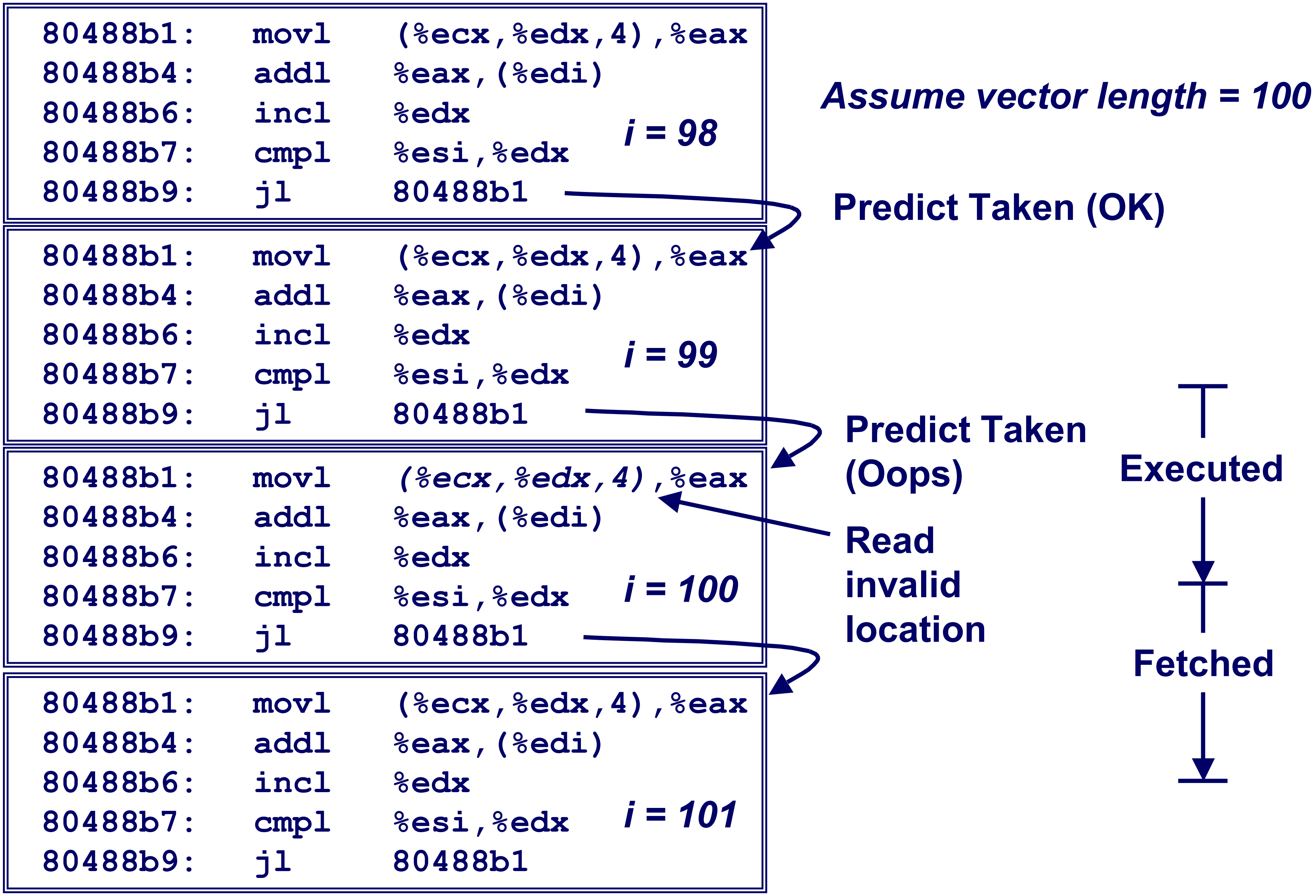
```
80489f3:  movl    $0x1,%ecx
80489f8:  xorl    %edx,%edx
80489fa:  cmpl    %esi,%edx
80489fc:  jnl     8048a25
. . .
```

Predict Taken

```
8048a25:  cmpl    %edi,%edx
8048a27:  jl      8048a20
8048a29:  movl    0xc(%ebp),%eax
8048a2c:  leal    0xffffffe8(%ebp),%esp
8048a2f:  movl    %ecx,(%eax)
```

Execute

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
80488b9:    jl      80488b1
```

i = 98

Predict Taken (OK)

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

i = 99

Predict Taken (Oops)

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

i = 100

Read invalid location

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

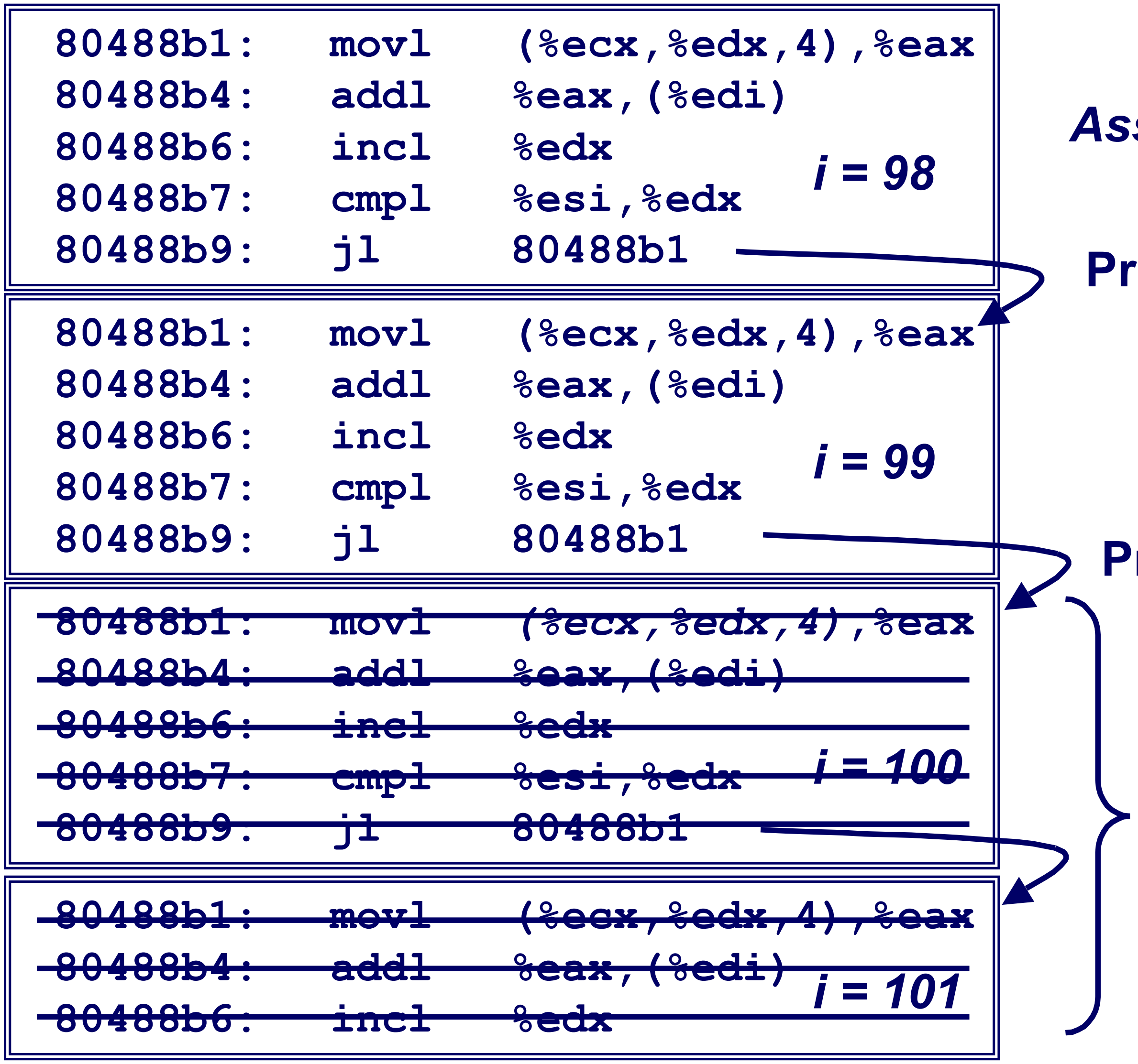
i = 101

Executed

Fetched

Branch Misprediction Invalidation

Assume vector length = 100



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

i = 98

Predict Taken (OK)

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

i = 99

Predict Taken (Oops)

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

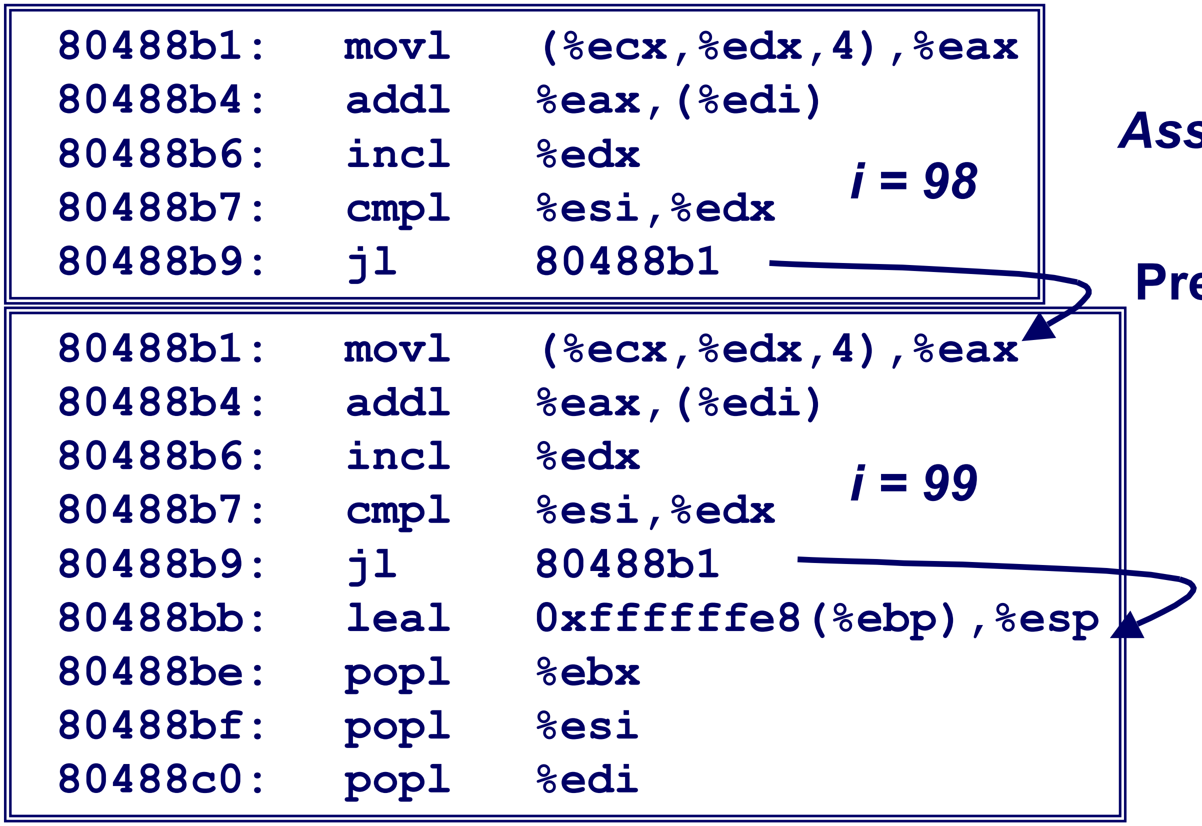
~~*i = 100*~~

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

i = 101

Invalidate

Branch Misprediction Recovery



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

i = 98

Assume vector length = 100

Predict Taken (OK)

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

i = 99

Definitely not taken

Performance Cost

- Misprediction on Pentium III wastes ~14 clock cycles
- That’s a lot of time on a high performance processor

Avoiding Branches

On Modern Processor, Branches Very Expensive

- Unless prediction can be reliable
- When possible, best to avoid altogether

Example

- Compute maximum of two values
  - 14 cycles when prediction correct
  - 29 cycles when incorrect

```
int max(int x, int y)
{
  return (x < y) ? y : x;
}
```

```
  movl 12(%ebp),%edx   # Get y
  movl 8(%ebp),%eax    # rval=x
  cmpl %edx,%eax       # rval:y
  jge L11              # skip when >=
  movl %edx,%eax       # rval=y
L11:
```

Avoiding Branches with Bit Tricks

- In style of Lab #1
- Use masking rather than conditionals

```
int bmax(int x, int y)
{
  int mask = -(x>y);
  return (mask & x) | (~mask & y);
}
```

- Compiler still uses conditional
  - 16 cycles when predict correctly
  - 32 cycles when mispredict

```
  xorl %edx,%edx      # mask = 0
  movl 8(%ebp),%eax
  movl 12(%ebp),%ecx
  cmpl %ecx,%eax
  jle L13             # skip if x<=y
  movl $-1,%edx       # mask = -1
L13:
```

Avoiding Branches with Bit Tricks

- Force compiler to generate desired code

```
int bvmax(int x, int y)
{
    volatile int t = (x>y);
    int mask = -t;
    return (mask & x) |
           (~mask & y);
}
```

```
movl 8(%ebp),%ecx   # Get x
movl 12(%ebp),%edx  # Get y
cmpl %edx,%ecx      # x:y
setg %al            # (x>y)
movzbl %al,%eax     # Zero extend
movl %eax,-4(%ebp)  # Save as t
movl -4(%ebp),%eax  # Retrieve t
```

- `volatile` declaration forces value to be written to memory
  - Compiler must therefore generate code to compute `t`
  - Simplest way is `setg/movzbl` combination
- Not very elegant!
  - A hack to get control over compiler
- 22 clock cycles on all data
  - Better than misprediction

Conditional Move

- Added with P6 microarchitecture (PentiumPro onward)
- `cmovXXl %edx, %eax`
  - If condition `XX` holds, copy `%edx` to `%eax`
  - Doesn't involve any branching
  - Handled as operation within Execution Unit

```
  movl 8(%ebp),%edx   # Get x
  movl 12(%ebp),%eax  # rval=y
  cmpl %edx, %eax     # rval:x
   cmovll %edx,%eax   # If <, rval=x
```

- Current version of GCC won't use this instruction
  - Thinks it's compiling for a 386
- Performance
  - 14 cycles on all data

Machine-Dependent Opt. Summary

Loop Unrolling

- Some compilers do this automatically
- Generally not as clever as what can achieve by hand

Exposing Instruction-Level Parallelism

- Generally helps, but extent of improvement is machine dependent

Warning:

- Benefits depend heavily on particular machine
- Best if performed by compiler
  - But GCC on IA32/Linux is not very good
- Do only for performance-critical parts of code

Important Tools

Observation

- Generating assembly code
  - Lets you see what optimizations compiler can make
  - Understand capabilities/limitations of particular compiler

Measurement

- Accurately compute time taken by code
  - Most modern machines have built in cycle counters
  - Using them to get reliable measurements is tricky
    - » Chapter 9 of the CS:APP textbook
- Profile procedure calling frequencies
  - Unix tool `gprof`

Code Profiling Example

Task

- Count word frequencies in text document
- Produce sorted list of words from most frequent to least

Steps

- Convert strings to lowercase
- Apply hash function
- Read words and insert into hash table
  - Mostly list operations
  - Maintain counter for each unique word
- Sort results

Data Set

- Collected works of Shakespeare
- 946,596 total words, 26,596 unique
- Initial implementation: 9.2 seconds

Shakespeare's most frequent words

29,801	the
27,529	and
21,029	I
20,957	to
18,514	of
15,370	a
14010	you
12,936	my
11,722	in
11,519	that

Code Profiling

Augment Executable Program with Timing Functions

- Computes (approximate) amount of time spent in each function
- Time computation method
  - Periodically (~ every 10ms) interrupt program
  - Determine what function is currently executing
  - Increment its timer by interval (e.g., 10ms)
- Also maintains counter for each function indicating number of times called

Using

```
gcc –O2 –pg prog. –o prog
./prog
```

- Executes in normal fashion, but also generates file `gmon.out`

```
gprof prog
```

- Generates profile information based on `gmon.out`

Profiling Results

```
%    cumulative   self              self     total
time    seconds   seconds    calls  ms/call  ms/call  name
86.60       8.21      8.21        1  8210.00  8210.00  sort_words
 5.80       8.76      0.55   946596     0.00     0.00  lower1
 4.75       9.21      0.45   946596     0.00     0.00  find_ele_rec
 1.27       9.33      0.12   946596     0.00     0.00  h_add
```

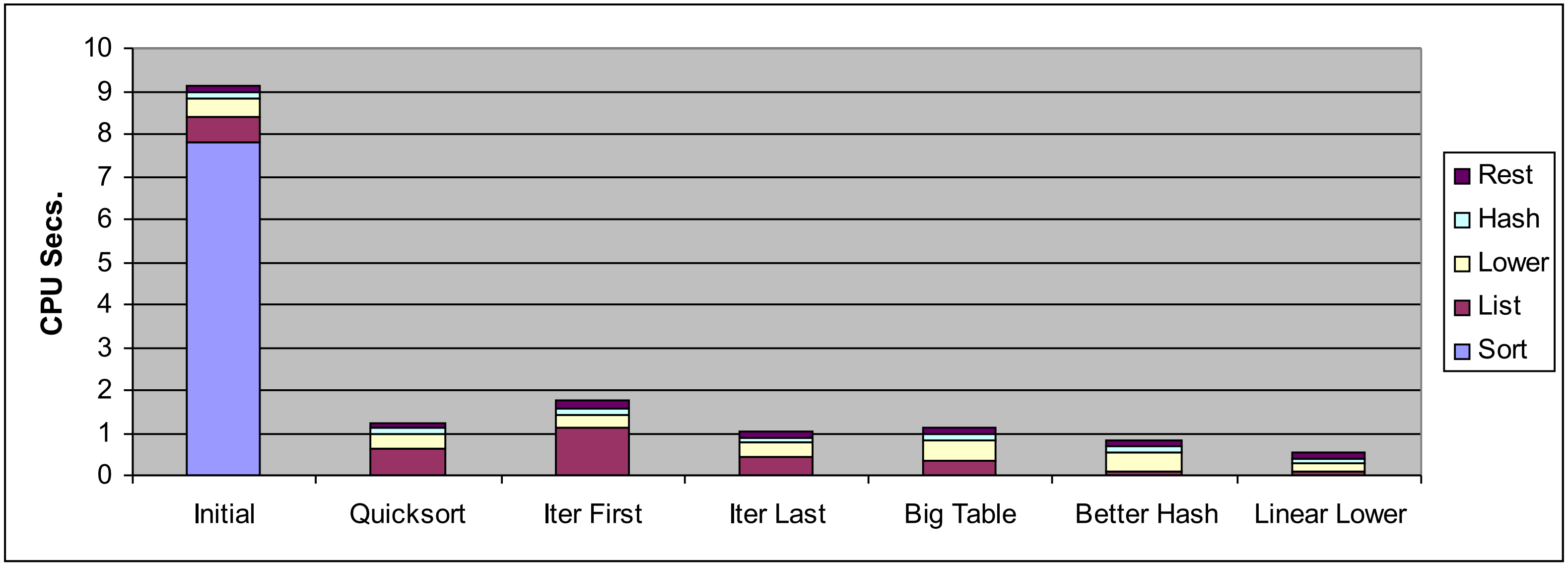
Call Statistics

- Number of calls and cumulative time for each function

Performance Limiter

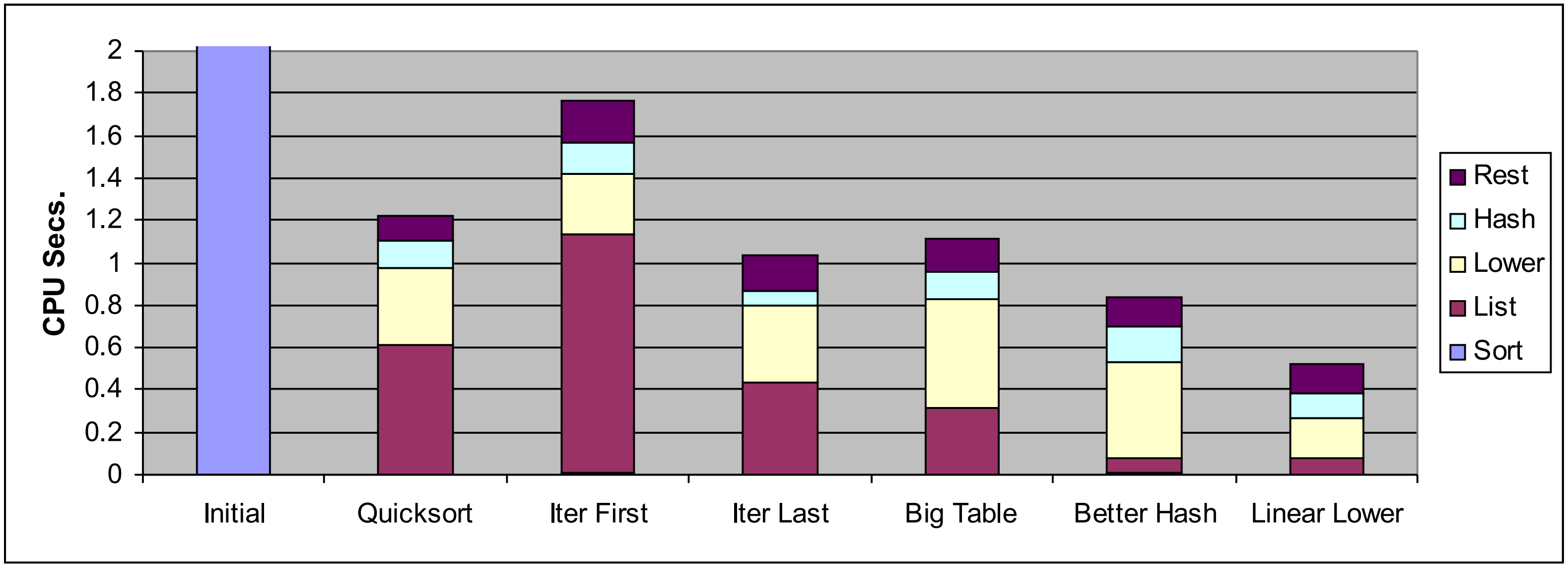
- Using inefficient sorting algorithm
- Single call uses 87% of CPU time

Code Optimizations



- **First step: Use more efficient sorting function**
- **Library function `qsort`**

Further Optimizations



- **Iter first:** Use iterative function to insert elements into linked list
  - Causes code to slow down
- **Iter last:** Iterative function, places new entry at end of list
  - Tend to place most common words at front of list
- **Big table:** Increase number of hash buckets
- **Better hash:** Use more sophisticated hash function
- **Linear lower:** Move `strlen` out of loop

Profiling Observations

Benefits

- Helps identify performance bottlenecks
- Especially useful when have complex system with many components

Limitations

- Only shows performance for data tested
- E.g., linear lower did not show big gain, since words are short
  - Quadratic inefficiency could remain lurking in code
- Timing mechanism fairly crude
  - Only works for programs that run for > 3 seconds

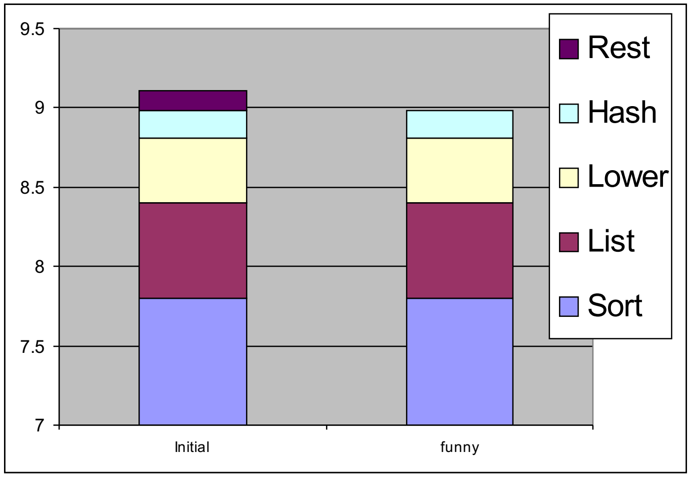
How Much Effort Should we Expend?

Amdahl's Law:

Overall performance improvement is a combination

- How much we sped up a piece of the system
- How important that piece is!

Example, suppose Chose to optimize "rest" & you succeed! It goes to ZERO seconds!



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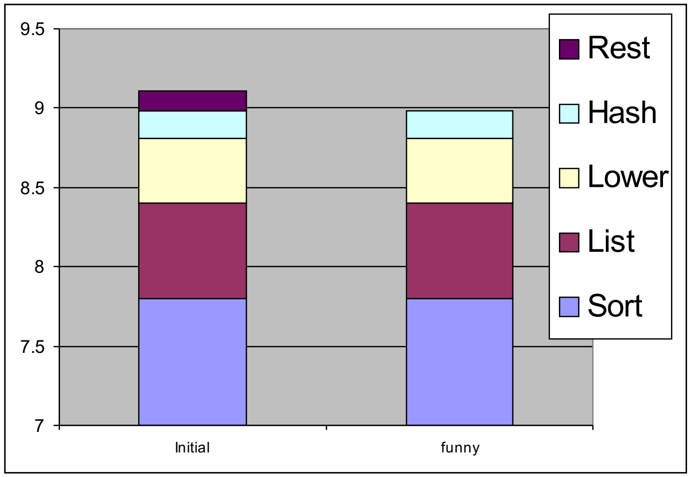

Amdahl’s Law

- Total time = $(1-\alpha)T + \alpha T$
- Component optimizing takes αT time.
- Improvement is factor of k, then:
- $T_{new} = T_{old}[(1-\alpha) + \alpha/k]$
- Speedup = $T_{old}/T_{new} = 1/ [(1-\alpha) + \alpha/k]$
- Maximum Achievable Speedup ($k = \infty$) = $1/(1-\alpha)$

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