15-213

"The course that gives CMU its Zip!"

Code Optimization
Sept. 25, 2003

Topics

- Machine-Independent Optimizations
- Machine Dependent Optimizations
- Code Profiling

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**

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

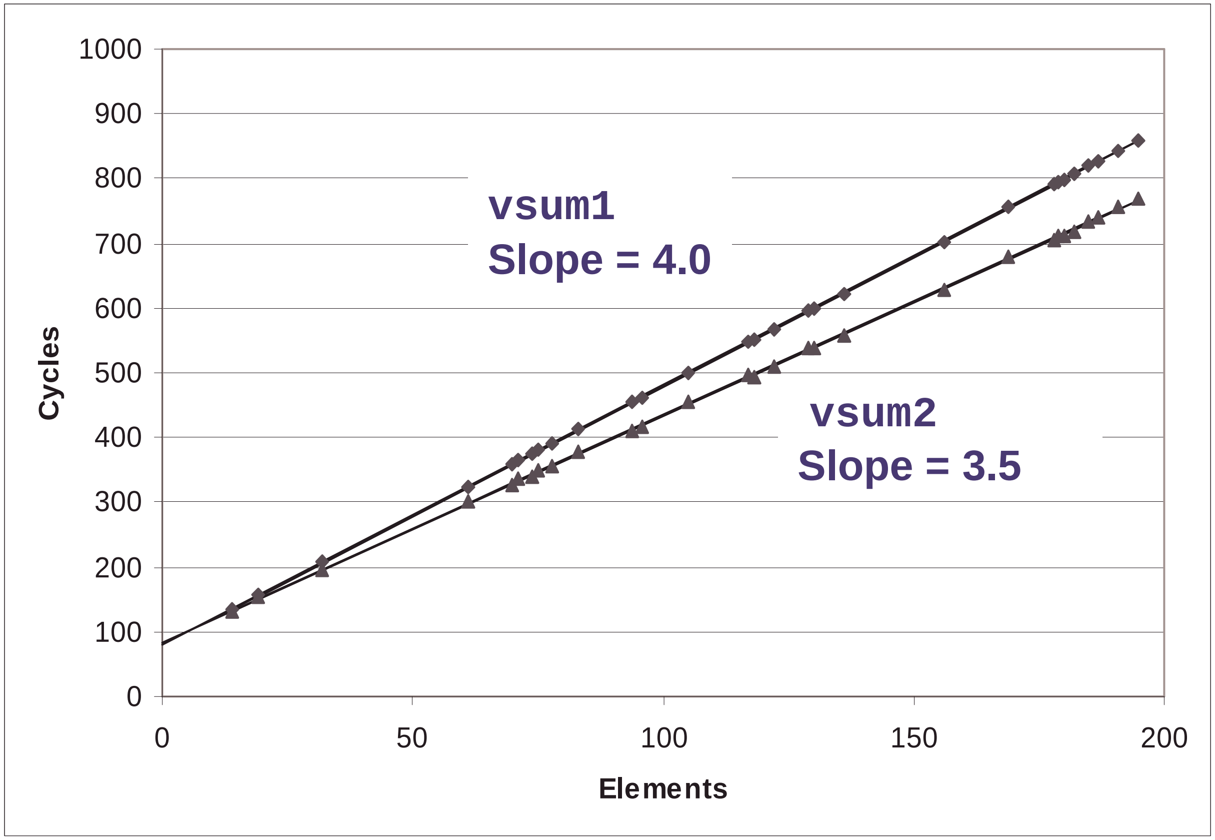
- Typically use nanoseconds
  - 10^{-9} seconds
- Time scale of computer instructions

Clock Cycles

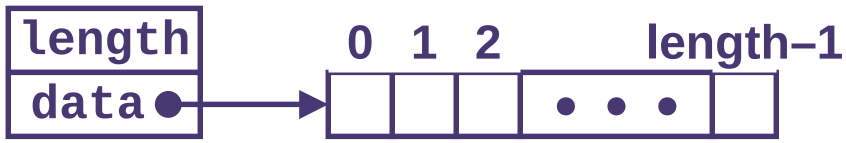
- Most computers controlled by high frequency clock signal
- Typical Range
  - 100 MHz
    - » 10^8 cycles per second
    - » Clock period = 10ns
  - 2 GHz
    - » 2 X 10^9 cycles per second
    - » Clock period = 0.5ns
- Fish machines: 550 MHz (1.8 ns clock period)

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 II/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;
    if (i >= vec_length(v))
      goto done;
  loop:
    get_vec_element(v, i, &val);
    *dest += val;
    i++;
    if (i < vec_length(v))
      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

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**

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

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*

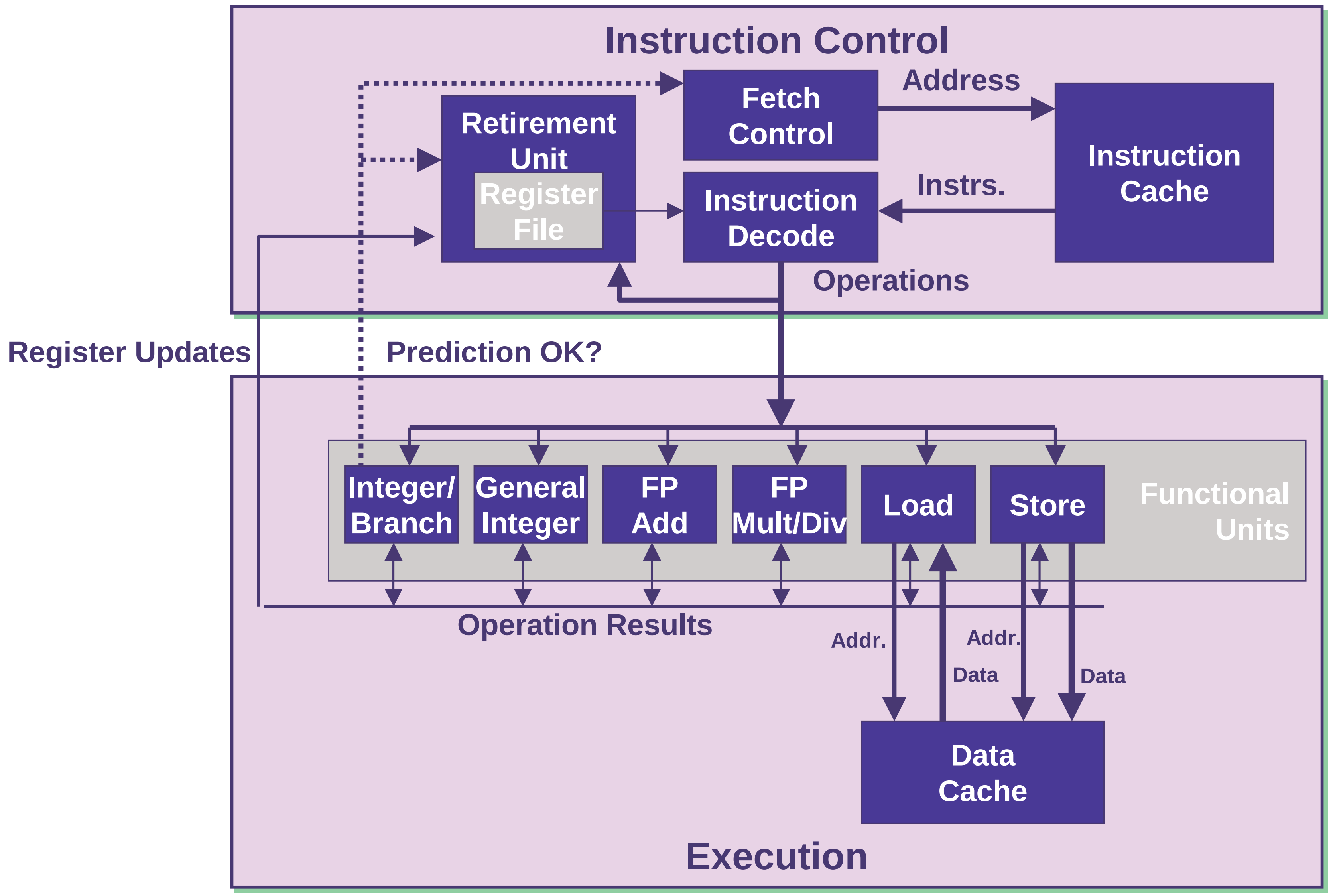
Reduction in Strength

- **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***

Share Common Subexpressions

- *compilers have limited algebraic reasoning capabilities*

Modern CPU Design



CPU Capabilities of Pentium III

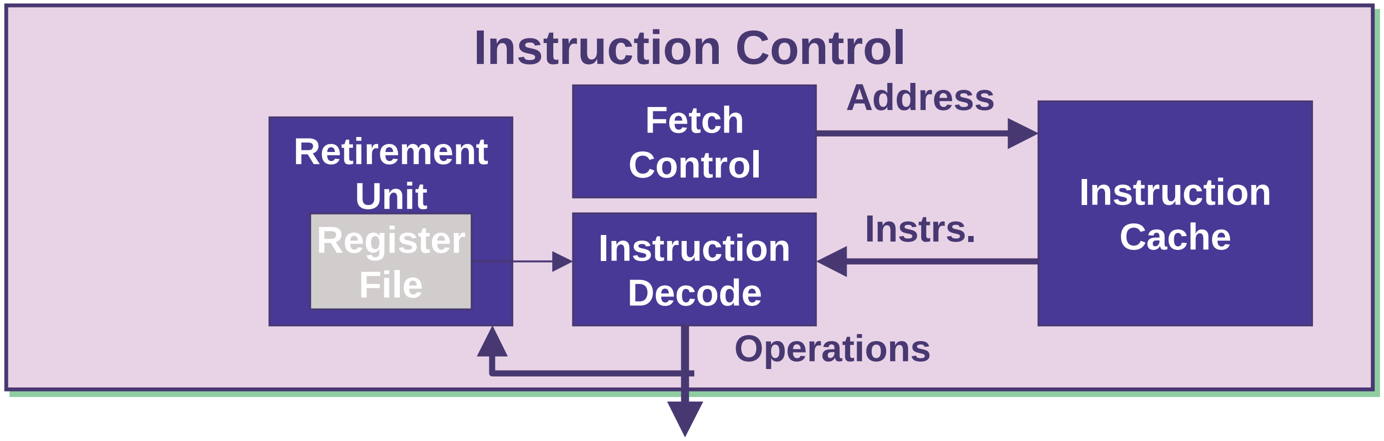
Multiple Instructions Can Execute in Parallel

- 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



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*

- 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

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
```

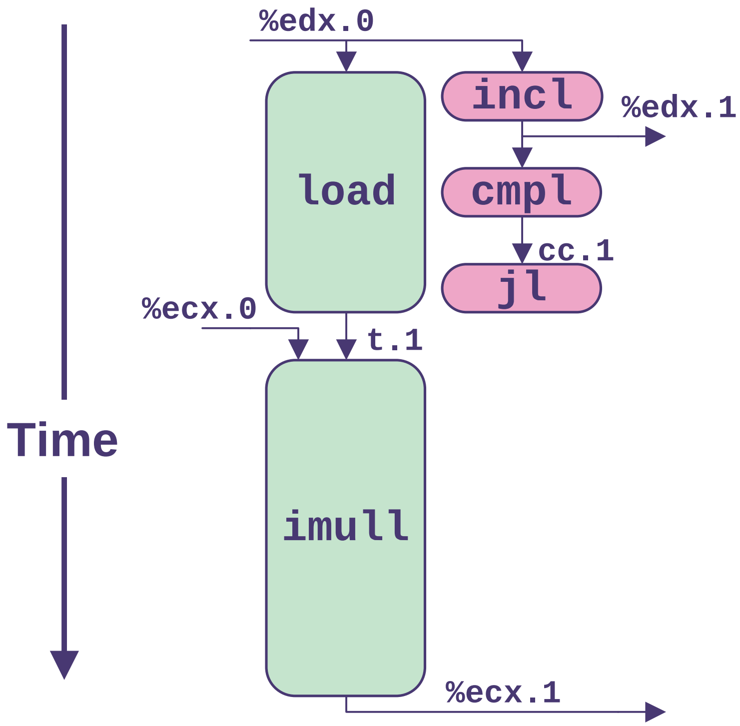
- Condition codes are treated similar to registers
- Assign tag to define connection between producer and consumer

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




```
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
```

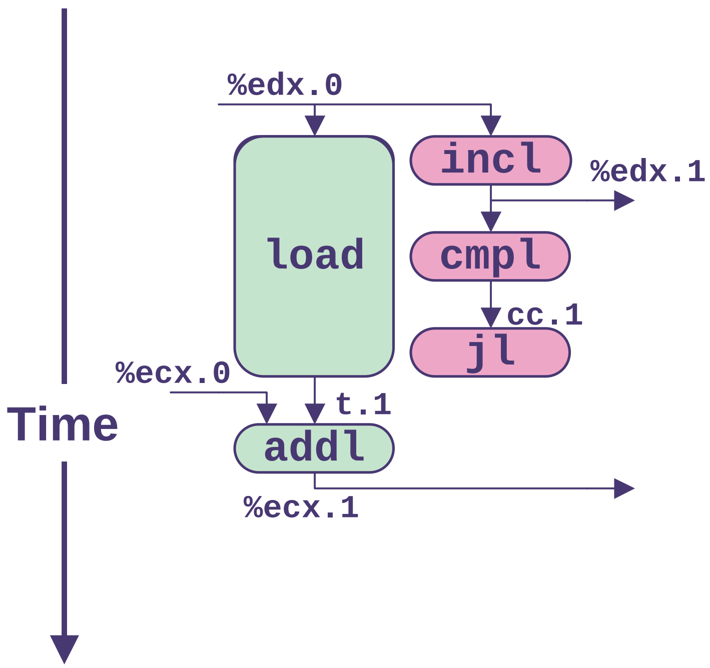
Operations

- 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.)

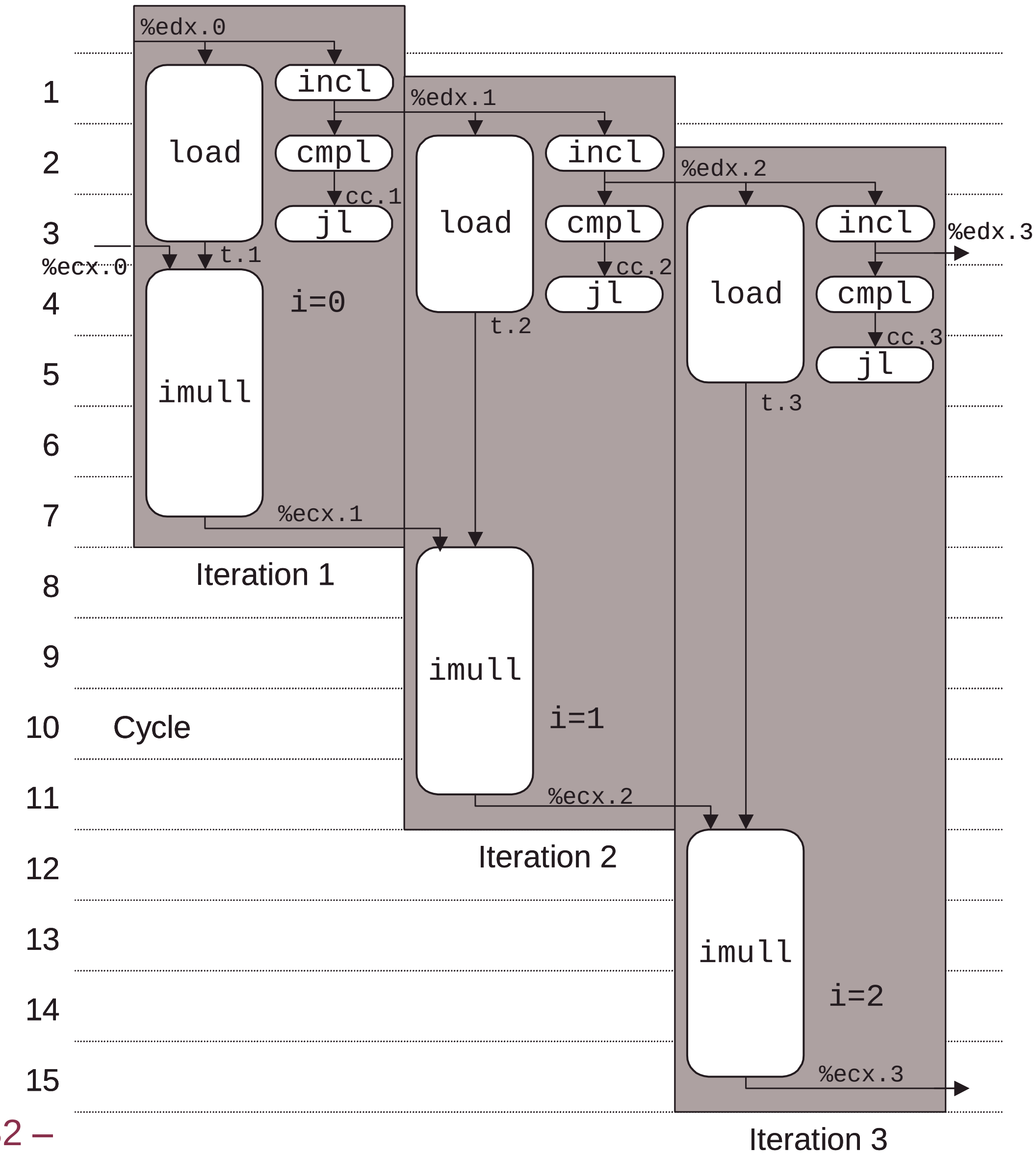



```
load (%eax,%edx,4)  → t.1
iaddl t.1, %ecx.0   → %ecx.1
incl %edx.0          → %edx.1
cmpl %esi, %edx.1   → cc.1
jl-taken cc.1
```

Operations

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

3 Iterations of Combining Product



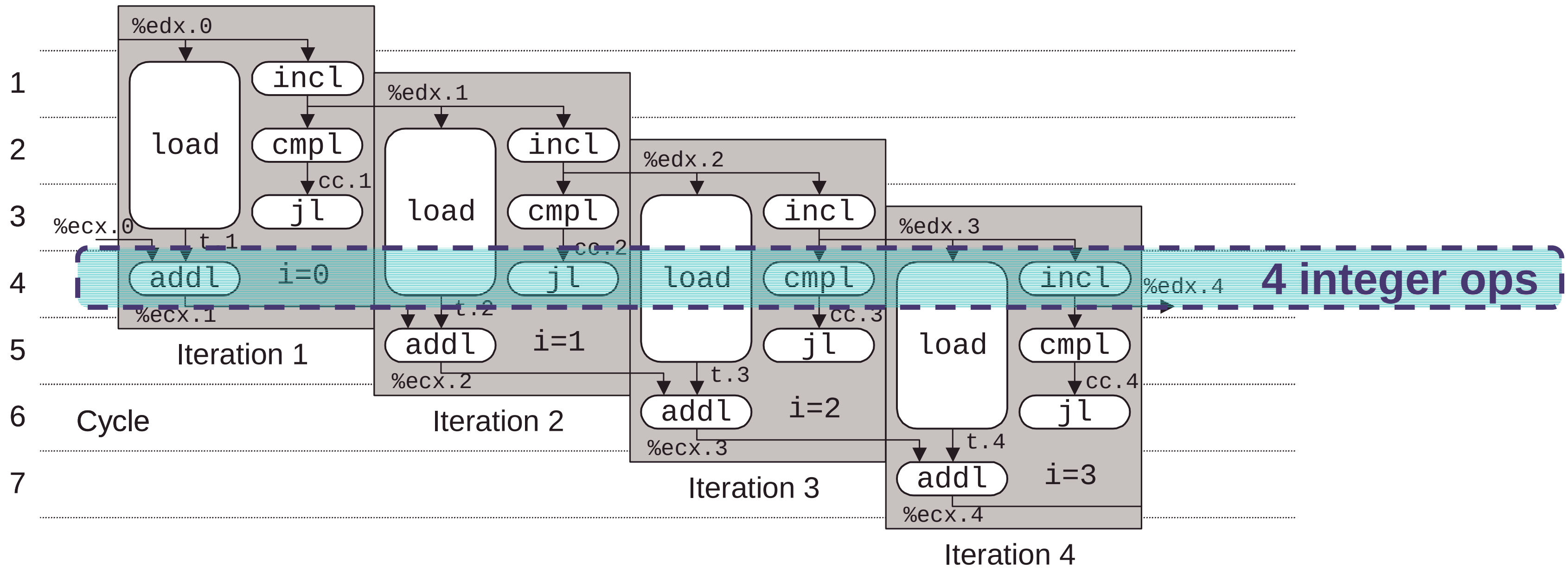
Unlimited Resource Analysis

- 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

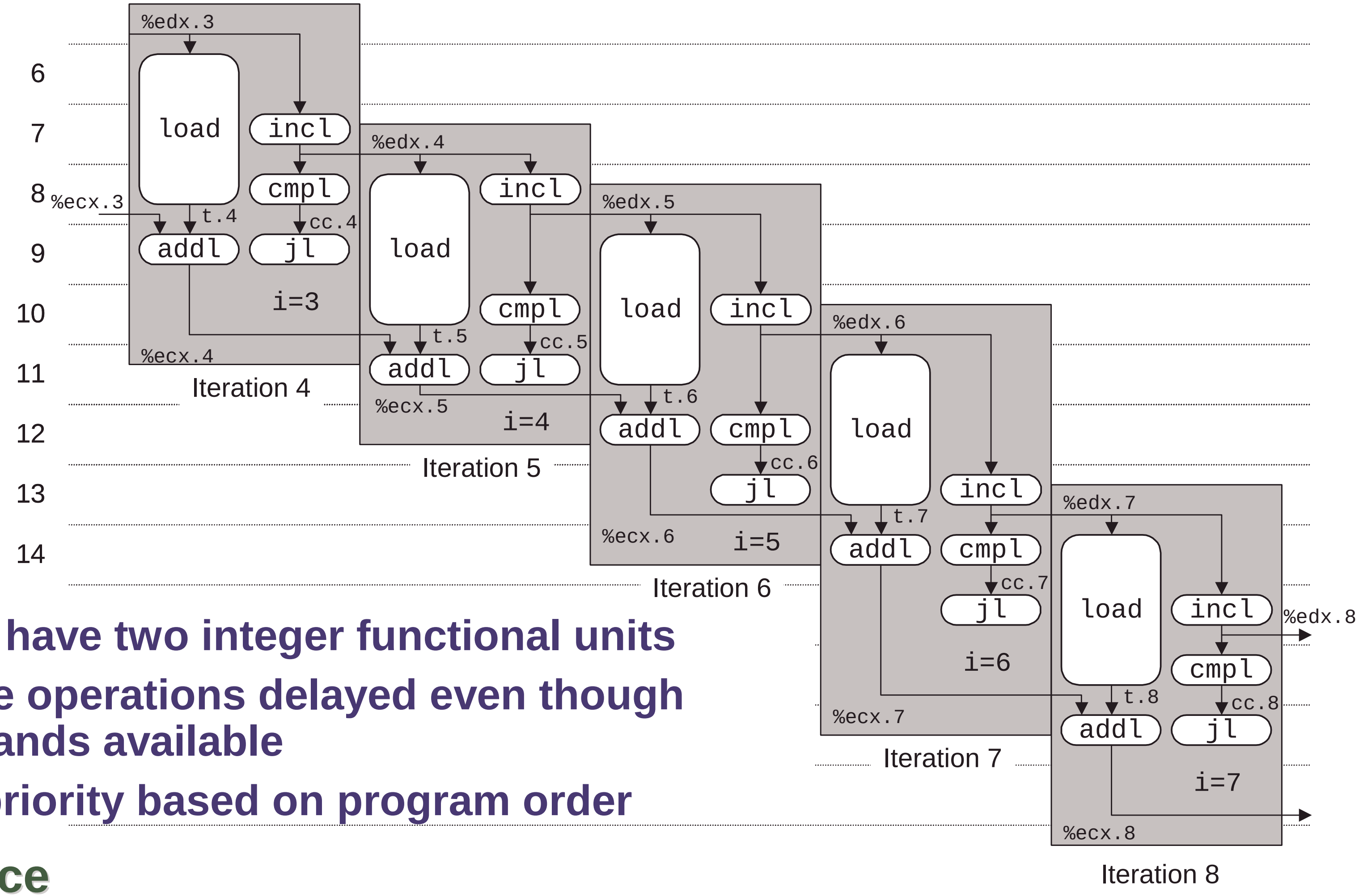


Unlimited Resource Analysis

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



- 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

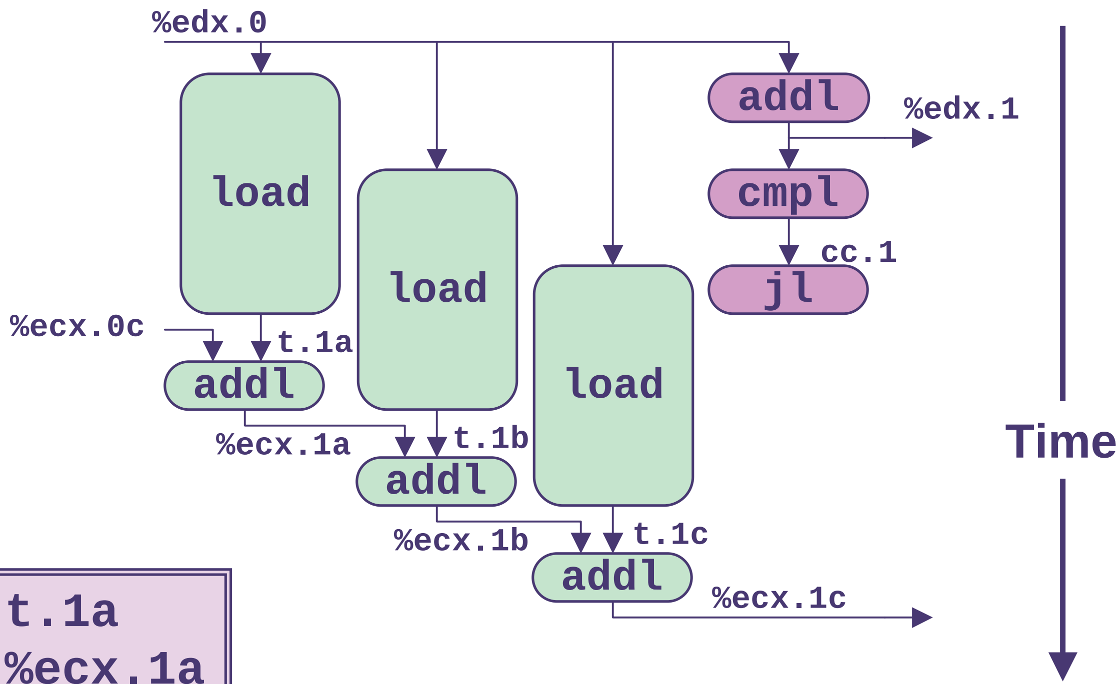
```
void combine5(vec_ptr v, int *dest)
{
  int length = vec_length(v);
  int limit = length-2;
  int *data = get_vec_start(v);
  int sum = 0;
  int i;
  /* Combine 3 elements at a time */
  for (i = 0; i < limit; i+=3) {
    sum += data[i] + data[i+2]
           + data[i+1];
  }
  /* Finish any remaining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

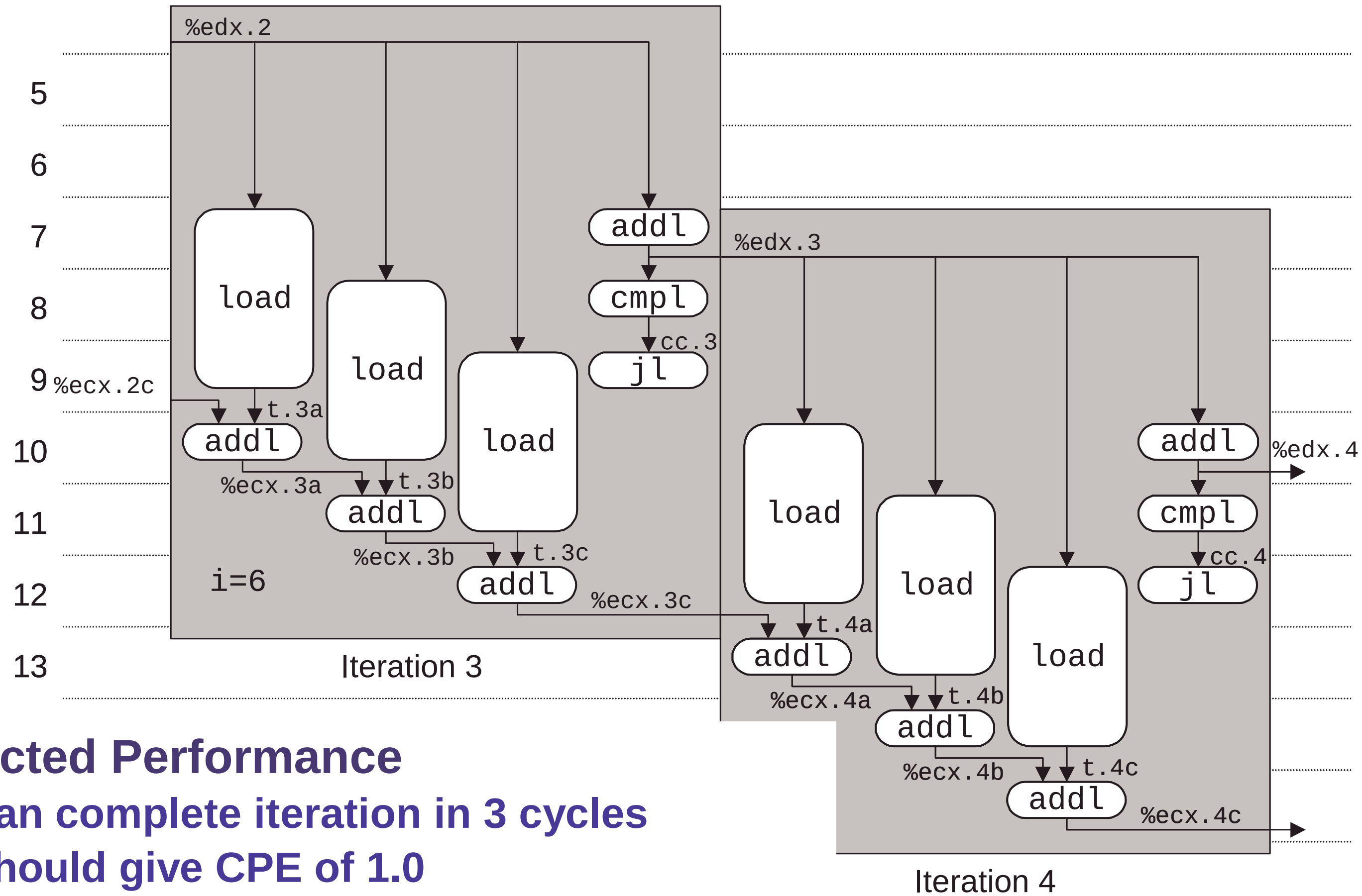
Visualizing Unrolled Loop

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




```
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



- **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

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

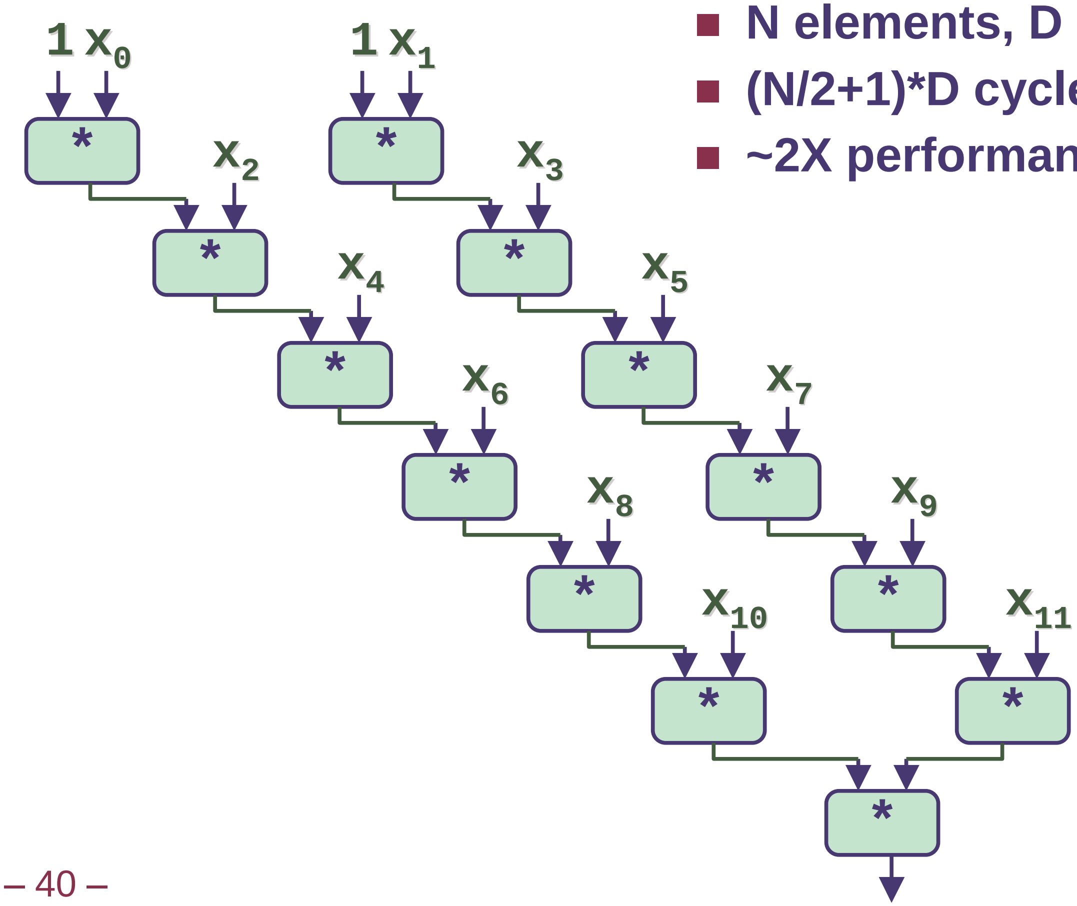
Dual Product Computation

Computation

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

Performance

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



Requirements for Parallel Computation

Mathematical

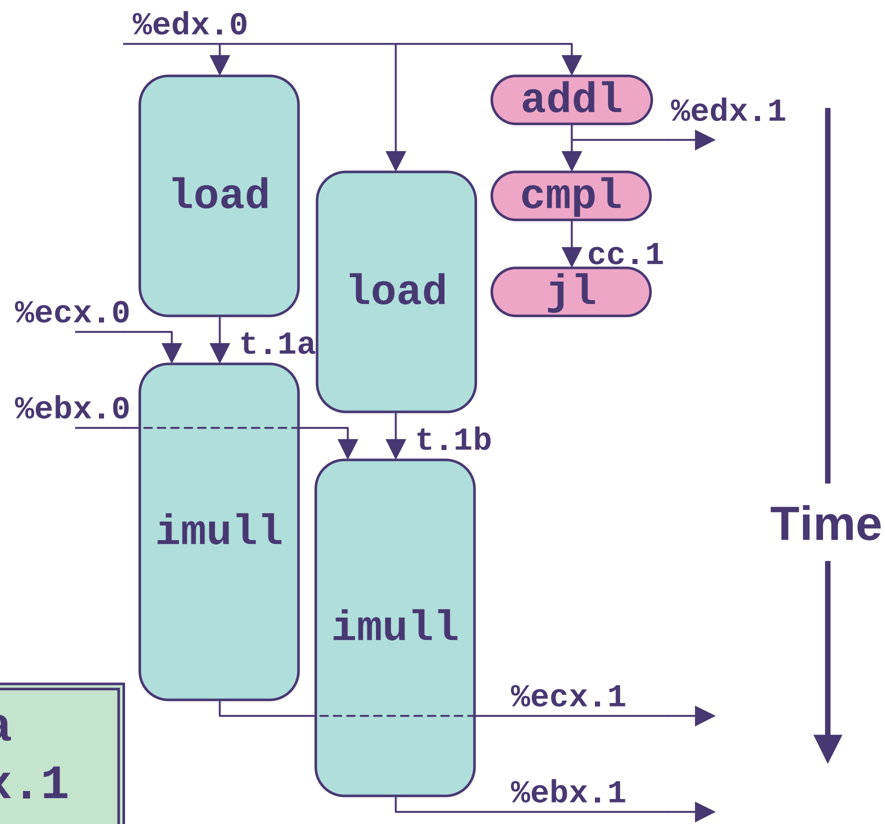
- Combining operation must be associative & commutative
  - OK for integer multiplication
  - Not strictly true for floating point
    - » OK for most applications

Hardware

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

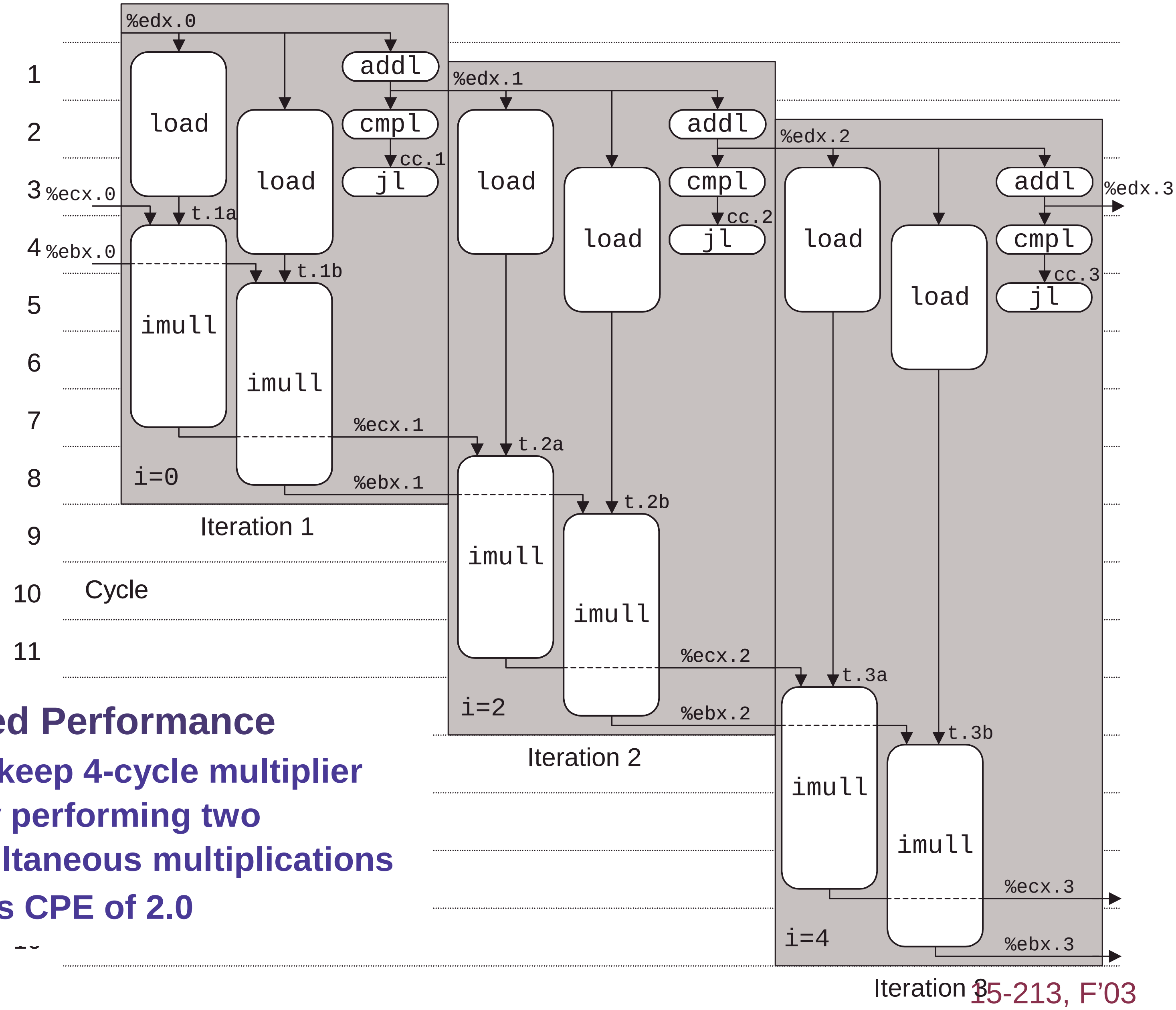
Visualizing Parallel Loop

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




```
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



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

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*

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

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
```

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

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

% time	cumulative seconds	self seconds	calls	self ms/call	total 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

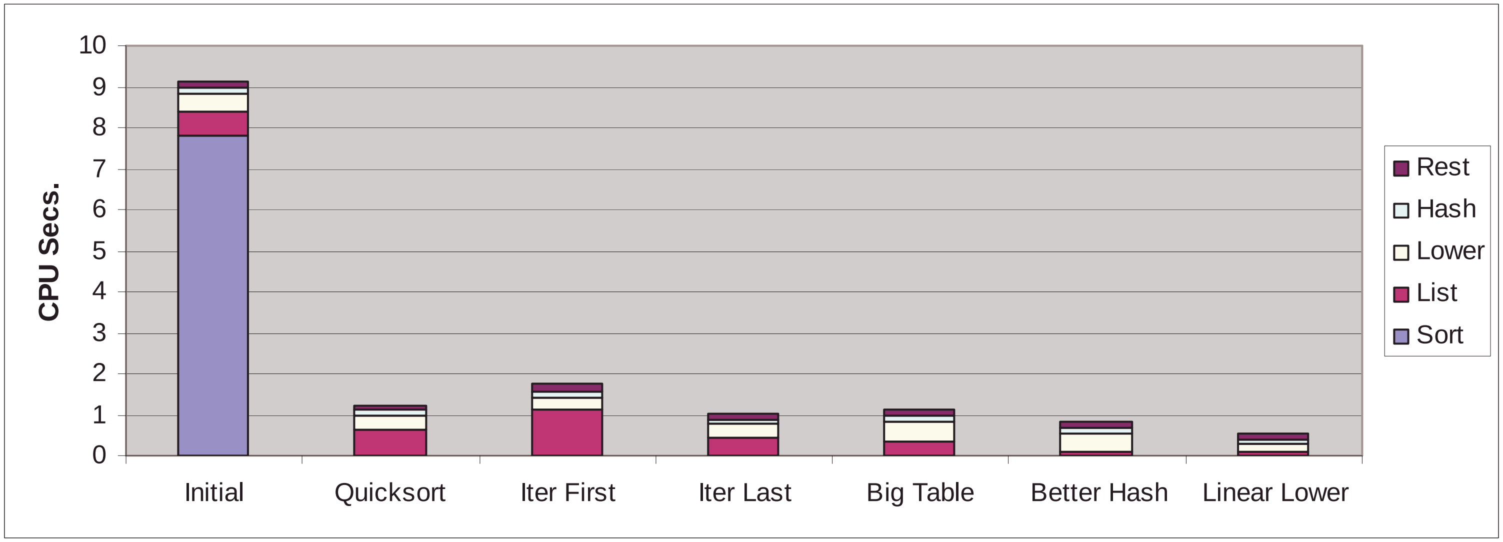
Call Statistics

- Number of calls and cumulative time for each function

Performance Limiter

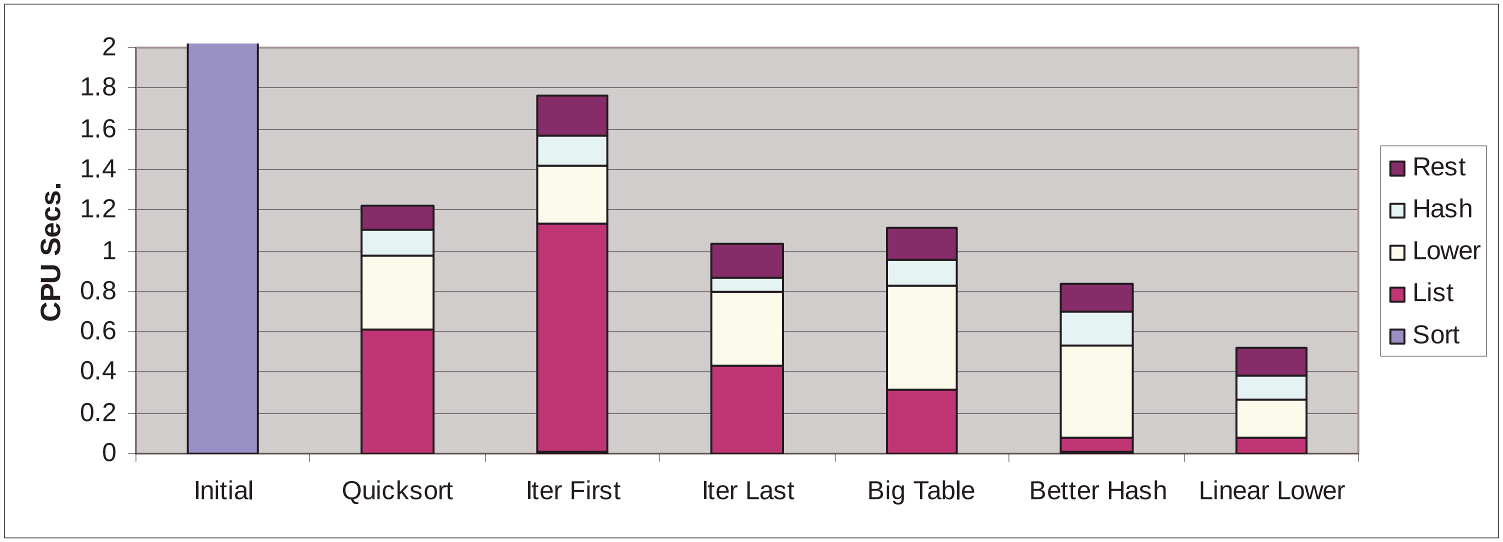
- Using inefficient sorting algorithm
- Single call uses 87% of CPU time

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

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