# 15-213

*"The course that gives CMU its Zip!"*

# Code Optimization
# Sept. 25, 2003

## Topics

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

`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



# 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;
```

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

```
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;
```

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

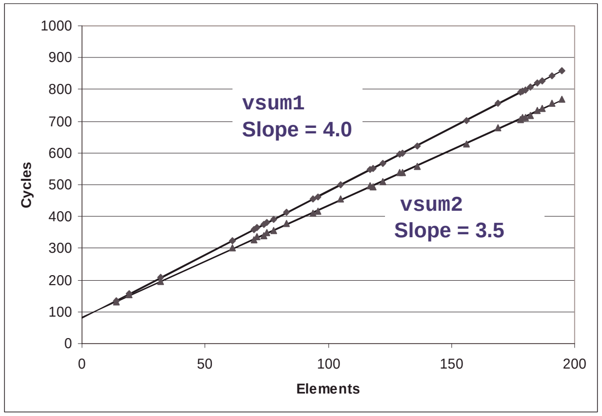
- Typically use nanoseconds
  - $10^{-9}$ seconds
- Time scale of computer instructions

## 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)

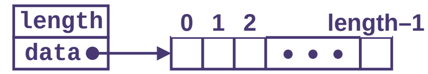
# Cycles Per Element

- 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

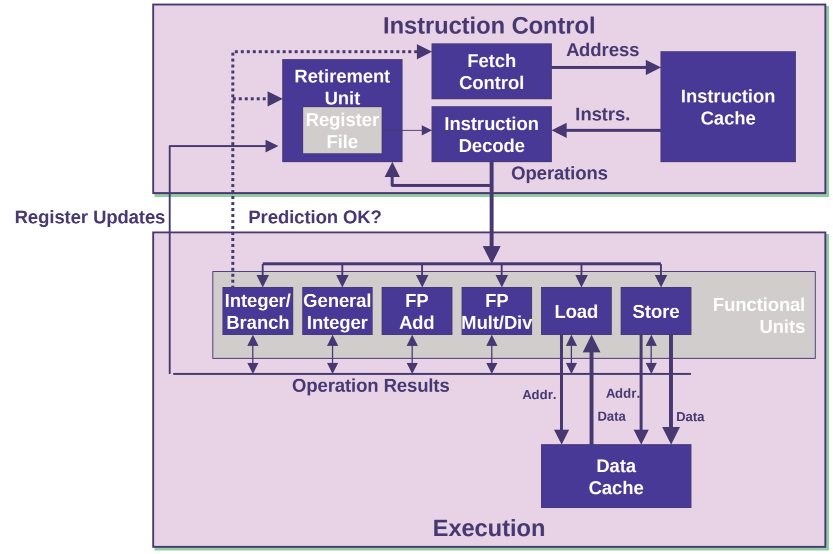
- **Shift, add instead of multiply or divide**
  - ***compilers are (generally) good at this***
  - ***Exact trade-offs machine-dependent***
- **Keep data in registers rather than memory**
  - ***compilers are not good at this, since concerned with aliasing***

## Share Common Subexpressions

- *compilers have limited algebraic reasoning capabilities*



# Modern CPU Design






# CPU Capabilities of Pentium III

## Multiple Instructions Can Execute in Parallel

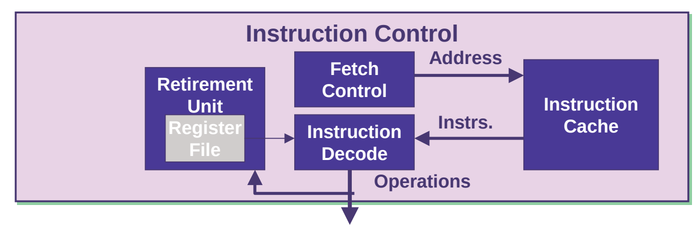
- **1 load**
- **1 store**
- **2 integer (one may be branch)**
- **1 FP Addition**
- **1 FP Multiplication or Division**

## 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

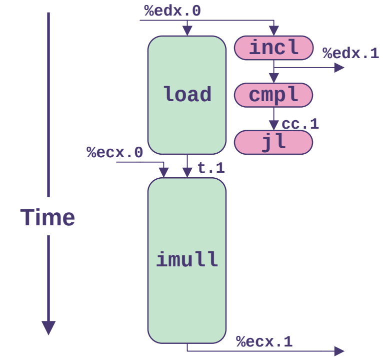
```
jl .L24
```

```
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

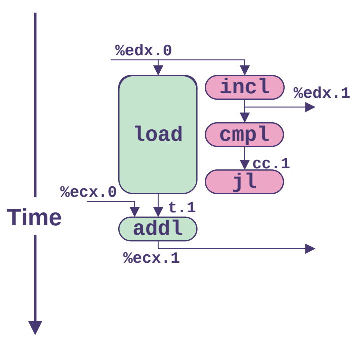
- Vertical position denotes time at which executed
  - Cannot begin operation until operands available
- Height denotes latency

### Operands

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



# Visualizing Operations (cont.)



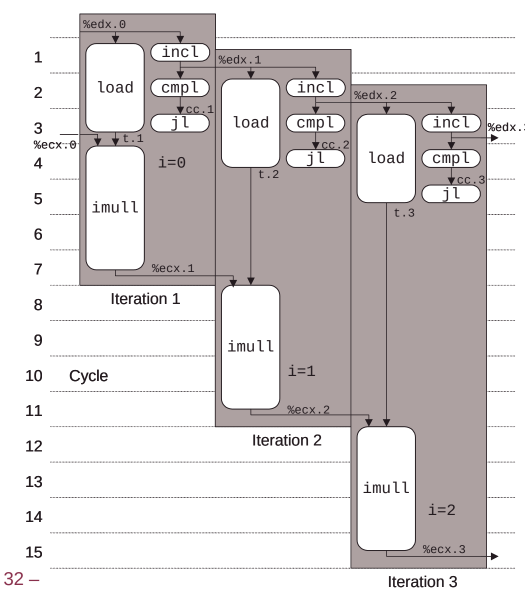

```
load (%eax,%edx,4)  → t.1
iaddl t.1, %ecx.0   → %ecx.1
incl %edx.0          → %edx.1
cmpl %esi, %edx.1   → cc.1
jl-taken cc.1
```

### Operations

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



# 3 Iterations of Combining Product



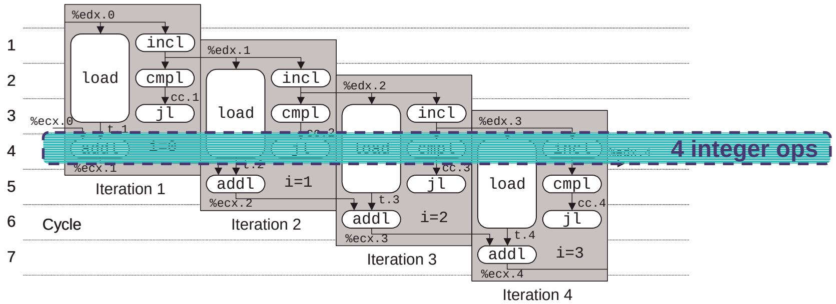

### Unlimited Resource Analysis

- 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



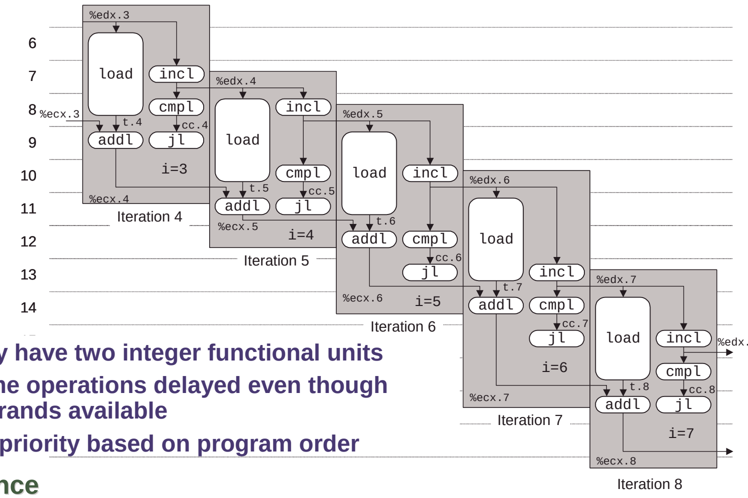

## Unlimited Resource Analysis

## 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;
}
```

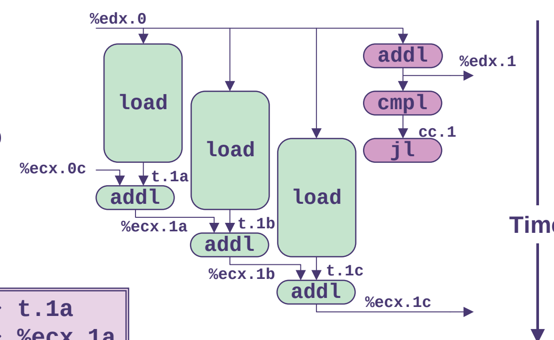
## Optimization

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



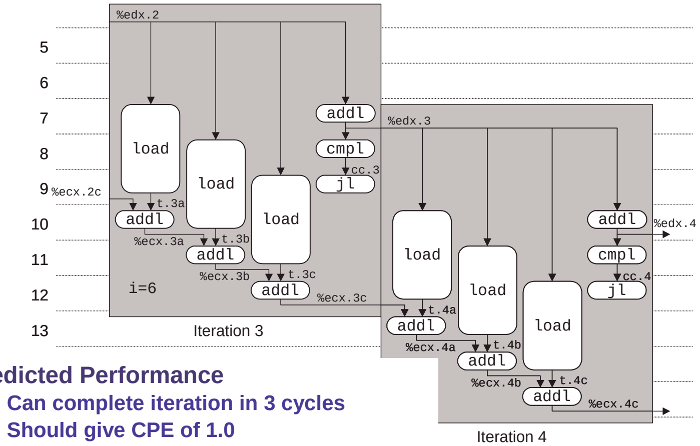
# Visualizing Unrolled Loop

- 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

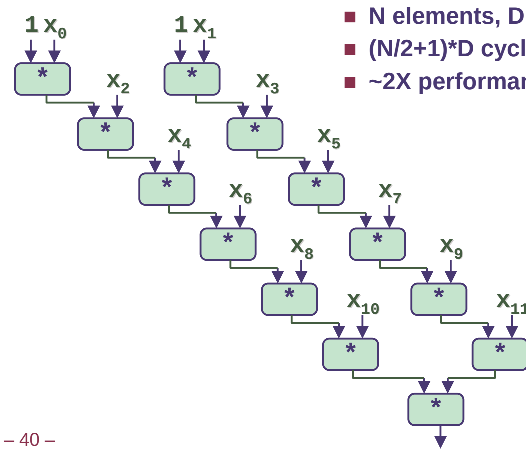


# Dual Product Computation

**Computation**

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

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



# 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

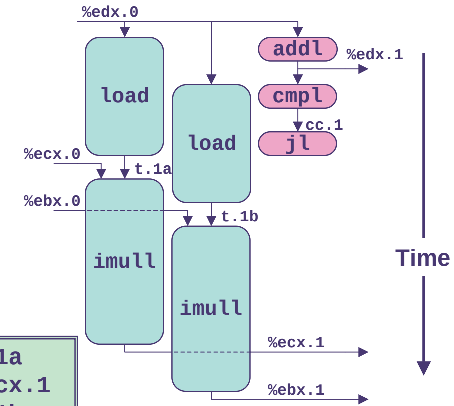
## Hardware

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



# Visualizing Parallel Loop

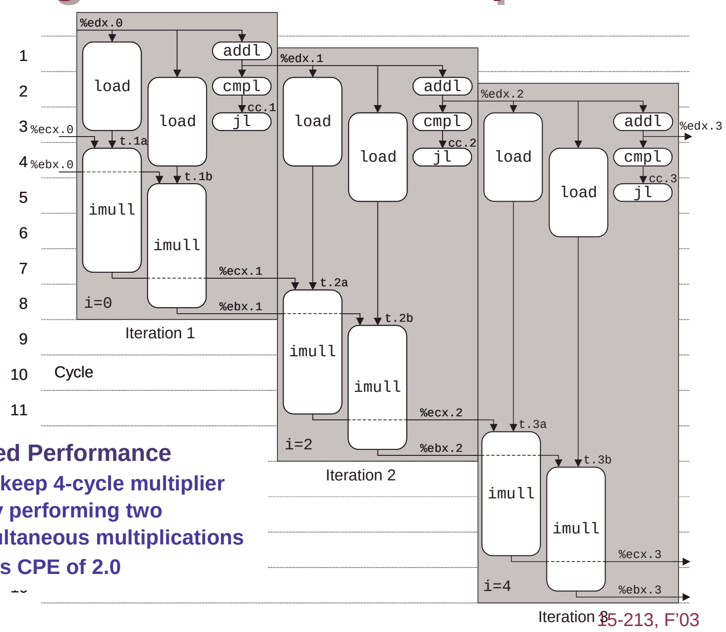
- Two multiplies within loop no longer have data depency
- Allows them to pipeline




```
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

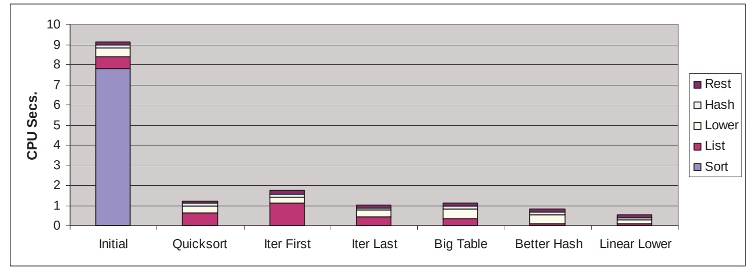
- Number of calls and cumulative time for each function

## Performance Limiter

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



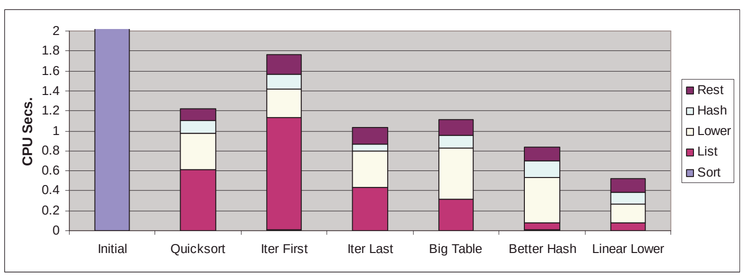
# Code Optimizations




- 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