Program Optimization

Instructors:

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Today

- **Overview**
- **Generally Useful Optimizations**
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
  - Removing unnecessary procedure calls
- **Optimization Blockers**
  - Procedure calls
  - Memory aliasing
- **Exploiting Instruction-Level Parallelism**
- **Dealing with Conditionals**

Performance Realities

- ***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 modern processors + memory systems operate
  - 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

Generally Useful Optimizations

- **Optimizations that you or the 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

```
void set_row(double *a, double *b,
   long i, long n)
{
    long j;
    for (j = 0; j < n; j++)
         a[n*i+j] = b[j];
}
```

→

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

Compiler-Generated Code Motion (-O1)

```
void set_row(double *a, double *b,
   long i, long n)
{
    long j;
    for (j = 0; j < n; j++)
         a[n*i+j] = b[j];
}
```

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

```
set_row:
        testq    %rcx, %rcx               # Test n
        jle      .L1                      # If 0, goto done
        imulq    %rcx, %rdx               # ni = n*i
        leaq     (%rdi,%rdx,8), %rdx      # rowp = A + ni*8
        movl     $0, %eax                 # j = 0
.L3:                                      # loop:
        movsd    (%rsi,%rax,8), %xmm0     # t = b[j]
        movsd    %xmm0, (%rdx,%rax,8)     # M[A+ni*8 + j*8] = t
        addq     $1, %rax                 # j++
        cmpq     %rcx, %rax               # j:n
        jne      .L3                      # if !=, goto loop
.L1:                                      # done:
        rep ; ret
```

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 Intel Nehalem, integer multiply requires 3 CPU cycles
- Recognize sequence of products

```
for (i = 0; i < n; i++) {
  int ni = n*i;
  for (j = 0; j < n; j++)
    a[ni + 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
- GCC will do this with –O1

```
/* 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;
```

```
long 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

```
leaq   1(%rsi), %rax   # i+1
leaq   -1(%rsi), %r8   # i-1
imulq  %rcx, %rsi      # i*n
imulq  %rcx, %rax      # (i+1)*n
imulq  %rcx, %r8       # (i-1)*n
addq   %rdx, %rsi      # i*n+j
addq   %rdx, %rax      # (i+1)*n+j
addq   %rdx, %r8       # (i-1)*n+j
```

```
imulq    %rcx, %rsi   # i*n
addq     %rdx, %rsi   # i*n+j
movq     %rsi, %rax   # i*n+j
subq     %rcx, %rax   # i*n+j-n
leaq     (%rsi,%rcx), %rcx # i*n+j+n
```

Limitations of Optimizing Compilers

- **Operate under fundamental constraint**
  - Must not cause any change in program behavior
- **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
  - Newer versions of GCC do interprocedural analysis within individual files
    - But, not between code in different files
- **Most analysis is based only on *static* information**
  - Compiler has difficulty anticipating run-time inputs
- **When in doubt, the compiler must be conservative**

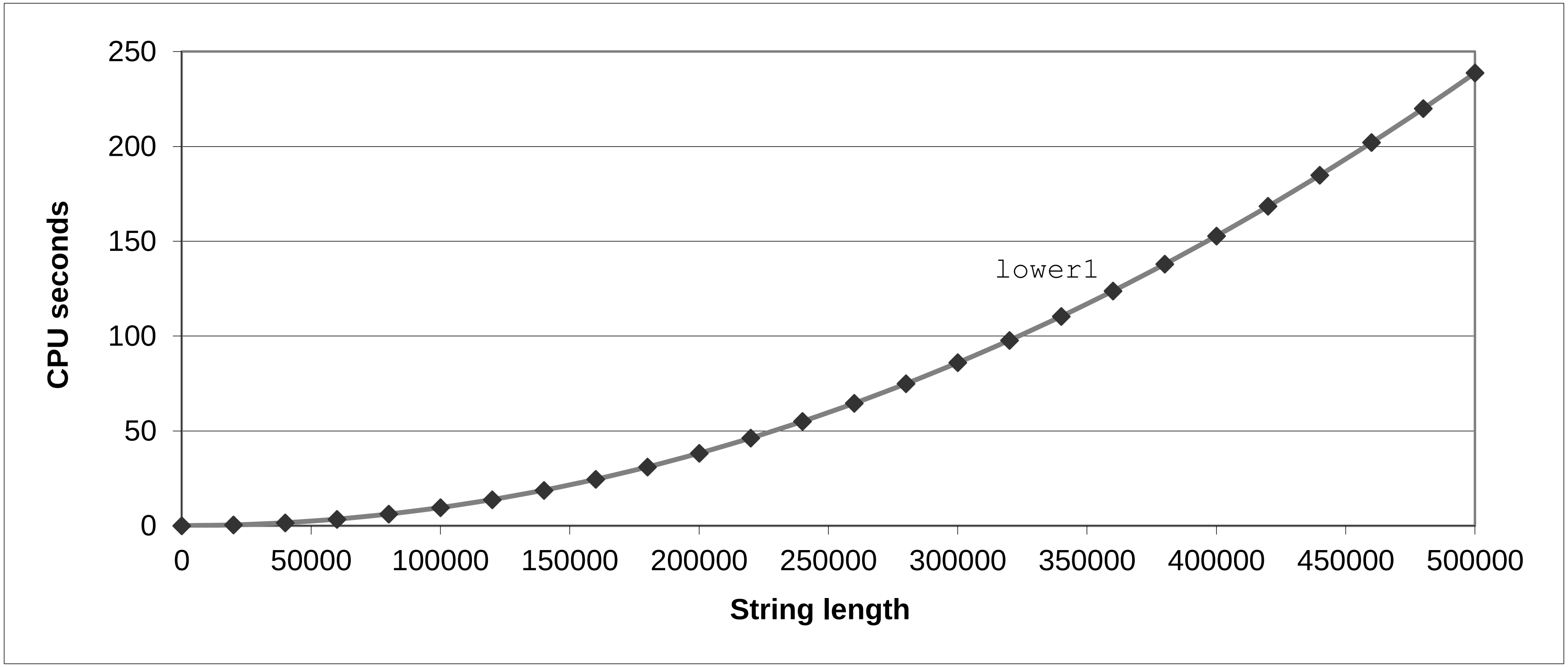
Optimization Blocker #1:

- **Procedure to Convert String to Lower Case**

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

Lower Case Conversion Performance

- Time quadruples when double string length
- Quadratic performance



Convert Loop To Goto Form

```
void lower(char *s)
{
   size_t 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

Calling Strlen

```
/* My version of strlen */
size_t strlen(const char *s)
{
    size_t length = 0;
    while (*s != '\0') {
        s++;
        length++;
    }
    return length;
}
```

- **Strlen performance**
  - Only way to determine length of string is to scan its entire length, looking for null character.
- **Overall performance, string of length N**
  - N calls to strlen
  - Require times N, N-1, N-2, …, 1
  - Overall $O(N^2)$ performance

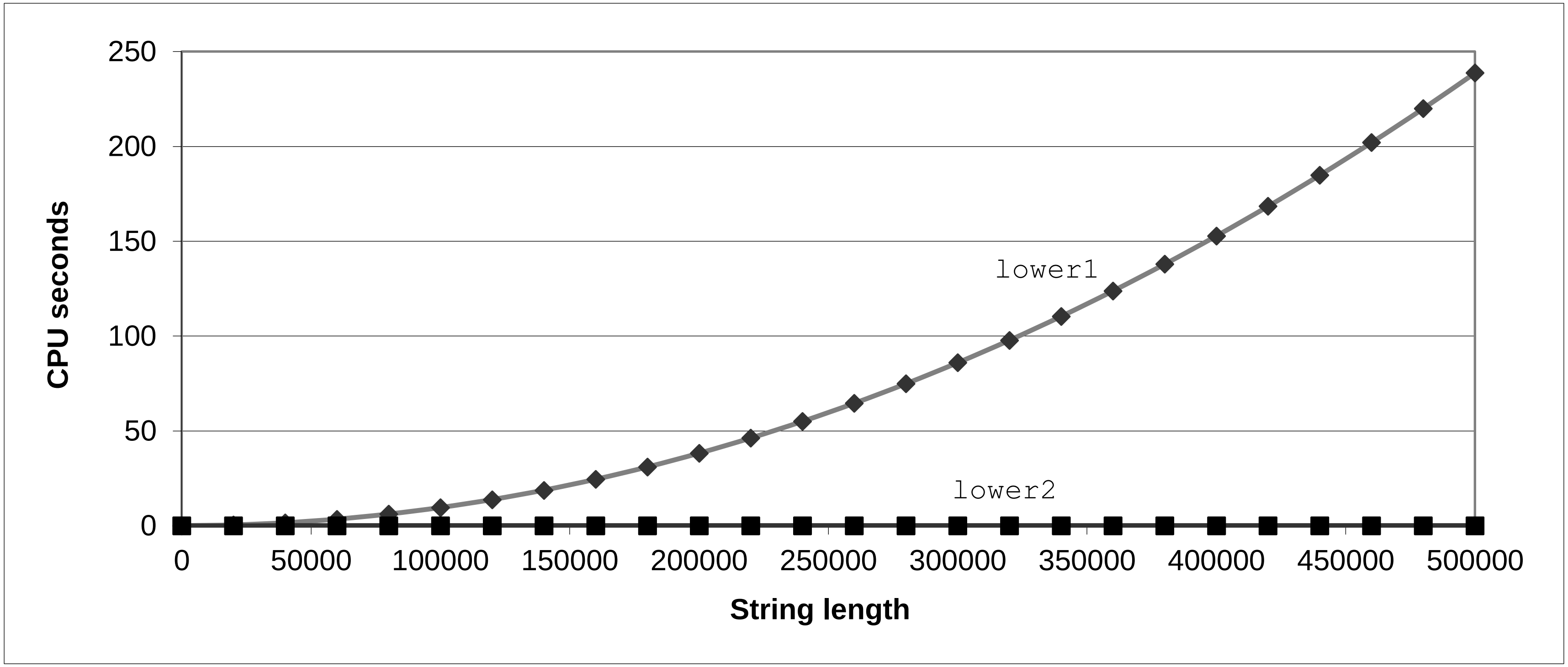
Improving Performance

```
void lower(char *s)
{
  size_t i;
  size_t 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 `strlen` 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`
- **Warning:**
  - Compiler treats procedure call as a black box
  - Weak optimizations near them
- **Remedies:**
  - Use of inline functions
    - GCC does this with –O1
      - Within single file
  - Do your own code motion

```
size_t lencnt = 0;
size_t strlen(const char *s)
{
    size_t length = 0;
    while (*s != '\0') {
       s++; length++;
    }
    lencnt += length;
    return length;
}
```

Memory Matters

```
/* Sum rows of n X n matrix a
   and store in vector b  */
void sum_rows1(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

```
# sum_rows1 inner loop
.L4:
        movsd   (%rsi,%rax,8), %xmm0        # FP load
        addsd   (%rdi), %xmm0               # FP add
        movsd   %xmm0, (%rsi,%rax,8)        # FP store
        addq    $8, %rdi
        cmpq    %rcx, %rdi
        jne     .L4
```

- Code updates `b[i]` on every iteration
- Why couldn't compiler optimize this away?

```
void twiddle1(long *xp, long *yp)
{
    *xp += *yp;
    *xp += *yp;
}

void twiddle2(long *xp, long *yp)
{
    *xp += 2* *yp;
}
```

At first glance, both procedures seem to have identical behavior. They both add twice the value stored at the location designated by pointer yp to that designated by pointer xp. On the other hand, function `twiddle2` is more efficient. It requires only three memory references (read *xp, read *yp, write *xp), whereas `twiddle1` requires six (two reads of *xp, two reads of *yp, and two writes of *xp). Hence, if a compiler is given procedure `twiddle1` to compile, one might think it could generate more efficient code based on the computations performed by `twiddle2`.

Consider, however, the case in which xp and yp are equal. Then function `twiddle1` will perform the following computations:

```
    *xp += *xp;  /* Double value at xp */
    *xp += *xp;  /* Double value at xp */
```

The result will be that the value at xp will be increased by a factor of 4. On the other hand, function `twiddle2` will perform the following computation:

```
    *xp += 2* *xp;  /* Triple value at xp */
```

Memory Aliasing

```
/* Sum rows is of n X n matrix a
   and store in vector b  */
void sum_rows1(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

```
double A[9] =
  { 0,   1,   2,
    4,   8,  16},
   32,  64, 128};

double B[3] = A+3;

sum_rows1(A, B, 3);
```

Value of B:

```
init:   [4, 8, 16]
```

```
i = 0: [3, 8, 16]
```

```
i = 1: [3, 28, 16]
```

```
i = 2: [3, 28, 224]
```

- Code updates `b[i]` on every iteration
- Must consider possibility that these updates will affect program behavior

Removing Aliasing

```
/* Sum rows is of n X n matrix a
   and store in vector b  */
void sum_rows2(double *a, double *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        double val = 0;
        for (j = 0; j < n; j++)
            val += a[i*n + j];
        b[i] = val;
    }
}
```

Optimization Blocker: Memory Aliasing

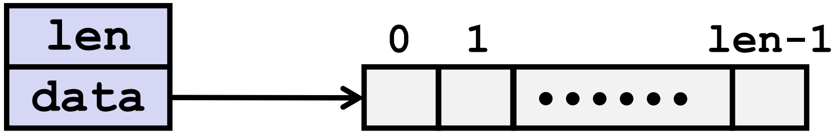
- **Aliasing**
  - Two different memory references specify single location
  - Easy to have happen in C
    - Since allowed to do address arithmetic
    - Direct access to storage structures
  - Get in habit of introducing local variables
    - Accumulating within loops
    - Your way of telling compiler not to check for aliasing

Exploiting Instruction-Level Parallelism

- **Need general understanding of modern processor design**
  - Hardware can execute multiple instructions in parallel
- **Performance limited by data dependencies**
- **Simple transformations can yield dramatic performance improvement**
  - Compilers often cannot make these transformations
  - Lack of associativity and distributivity in floating-point arithmetic

Benchmark Example: Data Type for Vectors

```
/* data structure for vectors */
typedef struct{
    size_t len;
    data_t *data;
} vec;
```



Data Types

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

```
/* retrieve vector element
   and store at val */
int get_vec_element
  (*vec v, size_t idx, data_t *val)
{
    if (idx >= v->len)
        return 0;
    *val = v->data[idx];
    return 1;
}
```

Benchmark Computation

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

Compute sum or product of vector elements

Data Types

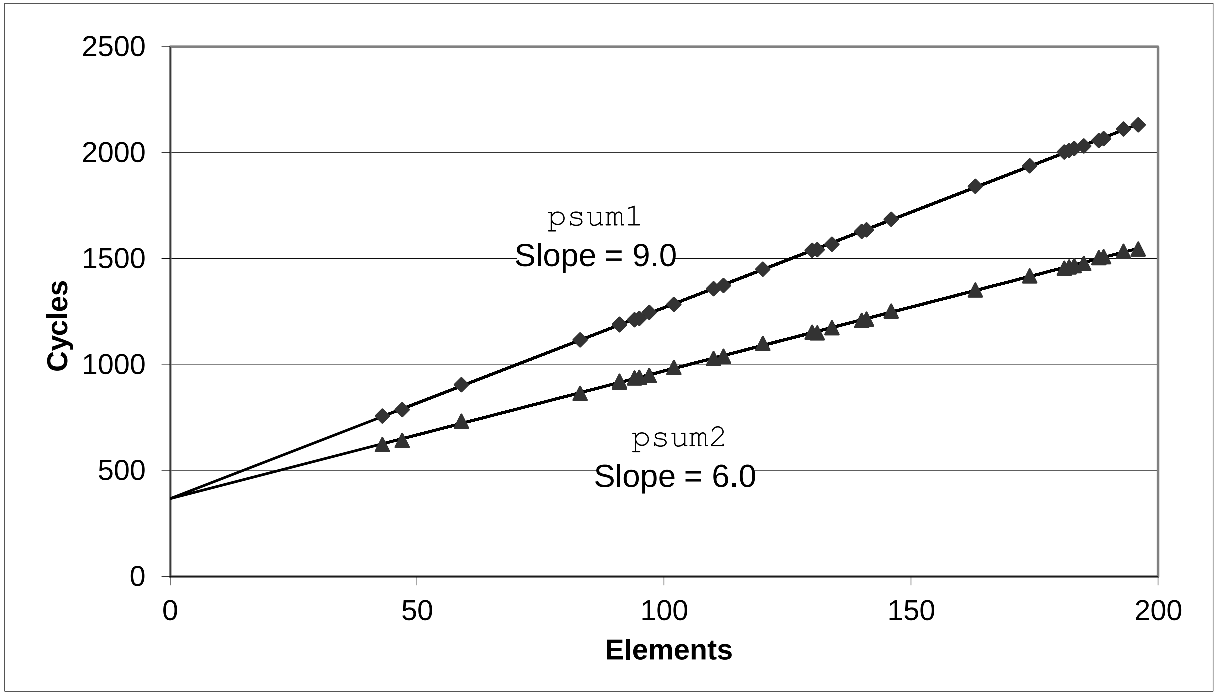
- Use different declarations for `data_t`
- `int`
- `long`
- `float`
- `double`

Operations

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

Cycles Per Element (CPE)

- **Convenient way to express performance of program that operates on vectors or lists**
- **Length = n**
- **In our case: CPE = cycles per OP**
- **T = CPE*n + Overhead**
  - CPE is slope of line



Benchmark Performance

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

Compute sum or product of vector elements

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 –O1	10.12	10.12	10.17	11.14

O1. Eliminating Loop Inefficiencies

Code Motion

```
/* Implementation with maximum use of data abstraction */
void combine1(vec_ptr v, data_t *dest)
{
    long i;

    *dest = IDENT;
    for (i = 0; i < vec_length(v); i++) {
        data_t val;
        get_vec_element(v, i, &val);
        *dest = *dest OP val;
    }
}
```

```
/* Move call to vec_length out of loop */
void combine2(vec_ptr v, data_t *dest)
{
    long i;
    long length = vec_length(v);

    *dest = IDENT;
    for (i = 0; i < length; i++) {
        data_t val;
        get_vec_element(v, i, &val);
        *dest = *dest OP val;
    }
```

			Integer		Floating point	
Function	Page	Method	+	*	+	*
combine1	543	Abstract -O1	10.12	10.12	10.17	11.14
combine2	545	Move vec_length	7.02	9.03	9.02	11.03

O2. Reducing Procedure Calls

code/opt/vec.c

```
data_t *get_vec_start(vec_ptr v)
{
    return v->data;
}
```

code/opt/vec.c

```
/* Direct access to vector data */
void combine3(vec_ptr v, data_t *dest)
{
    long i;
    long length = vec_length(v);
    data_t *data = get_vec_start(v);

    *dest = IDENT;
    for (i = 0; i < length; i++) {
        *dest = *dest OP data[i];
    }
}
```

Function	Page	Method	Integer +	Integer *	Floating point +	Floating point *
combine2	545	Move vec_length	7.02	9.03	9.02	11.03
combine3	549	Direct data access	7.17	9.02	9.02	11.03

Surprisingly, there is no apparent performance improvement. Indeed, the performance for integer sum has gotten slightly worse.

Evidently, other operations in the inner loop are forming a bottleneck that limits the performance more than the call to get_vec_element. We will return to this function later and see why the repeated bounds checking by combine2 does not incur a performance penalty.

For now, we can view this transformation as one of a series of steps that will ultimately lead to greatly improved performance.

O3. Eliminating Unneeded Memory References

```
/* Accumulate result in local variable */
void combine4(vec_ptr v, data_t *dest)
{
    long i;
    long length = vec_length(v);
    data_t *data = get_vec_start(v);
    data_t acc = IDENT;

    for (i = 0; i < length; i++) {
        acc = acc OP data[i];
    }
    *dest = acc;
}
```

Function	Page	Method	Integer		Floating point	
			+	*	+	*
combine3	549	Direct data access	7.17	9.02	9.02	11.03
combine4	551	Accumulate in temporary	1.27	3.01	3.01	5.01

Basic Optimizations

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

- **Move vec_length out of loop**
- **Avoid bounds check on each cycle**
- **Accumulate in temporary**

Effect of Basic Optimizations

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

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 –O1	10.12	10.12	10.17	11.14
Combine4	1.27	3.01	3.01	5.01

- Eliminates sources of overhead in loop