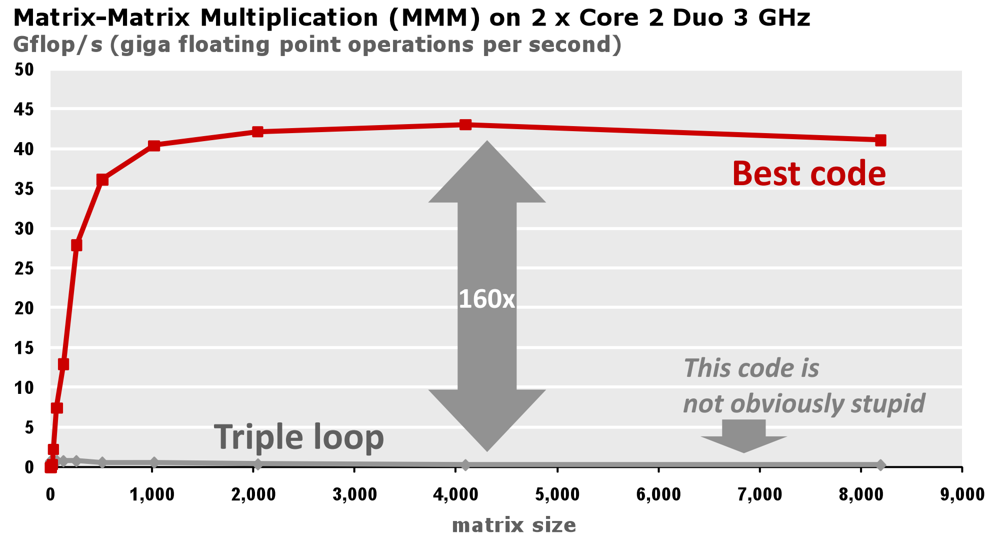
Today

- **Program optimization**
  - Removing unnecessary procedure calls
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
  - Optimization blocker: Procedure calls
  - Optimization blocker: Memory aliasing

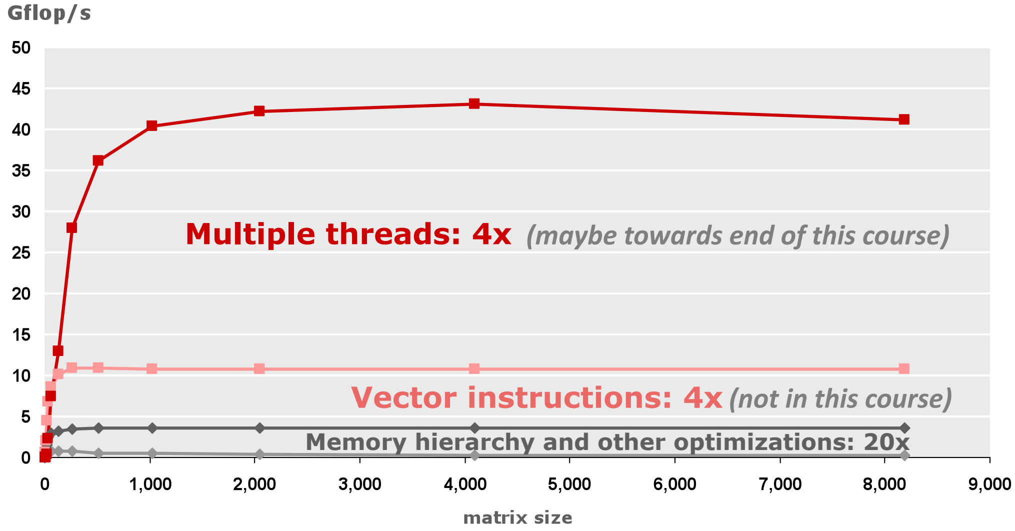
Example Matrix Multiplication



- **Standard desktop computer, compiler, using optimization flags**
- **Both implementations have exactly the same operations count ($2n^3$)**
- ***What is going on?***

MMM Plot: Analysis

Matrix-Matrix Multiplication (MMM) on 2 x Core 2 Duo 3 GHz



Multiple threads: 4x *(maybe towards end of this course)*

Vector instructions: 4x *(not in this course)*

Memory hierarchy and other optimizations: 20x

- Reason for 20x: Blocking or tiling, loop unrolling, array scalarization, instruction scheduling, search to find best choice
- *Effect: more instruction level parallelism, better register use, less L1/L2 cache misses, less TLB misses*

Harsh Reality

- *There's more to runtime performance than asymptotic complexity*
- *One can easily loose 10x, 100x in runtime or even more*
- What matters:
  - Constants (100n and 5n are both O(n), but ….)
  - Coding style (unnecessary procedure calls, unrolling, reordering, …)
  - Algorithm structure (locality, instruction level parallelism, …)
  - Data representation (complicated structs or simple arrays)

Harsh Reality

- **Must optimize at multiple levels:**
    - Algorithm
    - Data representations
    - Procedures
    - Loops

- **Must understand system to optimize performance**
    - How programs are compiled and executed
        - Execution units, memory hierarchy
    - How to measure program performance and identify bottlenecks
    - How to improve performance without destroying code modularity and generality

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Optimizing Compilers

-O

- **Use optimization flags, default is no optimization (-O0)!**
- **Good choices for gcc: -O2, -O3, -march=xxx, -m64**
- **Try different flags and maybe different compilers**

Example

```
double a[4][4];
double b[4][4];
double c[4][4]; # set to zero

/* Multiply 4 x 4 matrices a and b  */
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    for (i = 0; i < 4; i++)
        for (j = 0; j < 4; j++)
            for (k = 0; k < 4; k++)
                c[i*4+j] += a[i*4 + k]*b[k*4 + j];
}
```

- **Compiled without flags:**
  ~1300 cycles
- **Compiled with –O3 –m64 -march=… –fno-tree-vectorize**
  ~150 cycles
- **Core 2 Duo, 2.66 GHz**

Optimizing Compilers

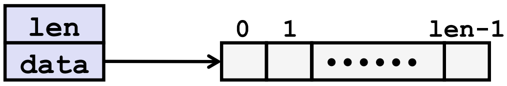
- **Compilers are good at: mapping program to machine**
  - register allocation
  - code selection and ordering (scheduling)
  - dead code elimination
  - eliminating minor inefficiencies
- **Compilers are not good at: improving asymptotic efficiency**
  - up to programmer to select best overall algorithm
  - big-O savings are (often) more important than constant factors
    - but constant factors also matter
- **Compilers are not good at: overcoming “optimization blockers”**
  - potential memory aliasing
  - potential procedure side-effects

Limitations of Optimizing Compilers

- *If in doubt, the compiler is conservative*
- **Operate under fundamental constraints**
  - Must not change 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

Example: Data Type for Vectors

```
/* data structure for vectors */
typedef struct{
        int len;
        double *data;
} vec;
```



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

Example: Summing Vector Elements

```
double get_vec_element(vec *v, int idx,
                                double *val)
{
  if (idx < 0 || idx >= v->len)
        return 0;
  *val = v->data[idx];
  return 1;
}
```

Bound check unnecessary in sum_elements
Why?

```
/* sum elements of vector */
double sum_elements(vec *v, double *res)
{
  int i;
  n = v->len;
  *res = 0.0;
  double val;

  for (i = 0; i < n; i++) {
    get_vec_element(v, i, &val);
         *res += val;
  }
  return res;
}
```

Overhead for every fp +:

- One fct call
- One <
- One >=
- One ||
- One memory variable access

Slowdown:
probably 10x or more

Removing Procedure Call

```
/* sum elements of vector */
double sum_elements(vec *v, double *res)
{
  int i;
  n = v->len;
  *res = 0.0;
  double val;

  for (i = 0; i < n; i++) {
    get_vec_element(v, i, &val);
          *res += val;
  }
  return res;
}
```

```
/* sum elements of vector */
double sum_elements(vec *v, double *res)
{
  int i;
  n = v->len;
  *res = 0.0;
  double *data = get_vec_start(v);

  for (i = 0; i < n; i++)
          *res += data[i];
  return res;
}
```

Removing Procedure Calls

- **Procedure calls can be very expensive**
- **Bounds checking can be very expensive**
- **Abstract data types can easily lead to inefficiencies**
  - Usually avoided in superfast numerical library functions

- **Watch your innermost loop!**

- **Get a feel for overhead versus actual computation being performed**

Code Motion

- **Reduce frequency with which computation is performed**
  - If it will always produce same result
  - Especially moving code out of loop
- **Sometimes also called pre-computation**

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

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

Compiler-Generated Code Motion

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

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

```
copy_row:
        xorl     %r8d, %r8d            #  j = 0
        cmpq     %rcx, %r8             #  j:n
        jge      .L7                   #  if >= goto done
        movq     %rcx, %rax            #  n
        imulq    %rdx, %rax            #  n*i outside of inner loop
        leaq     (%rdi,%rax,8), %rdx   #  rowp = A + n*i*8
.L5:                                   # loop:
        movq     (%rsi,%r8,8), %rax    #  t = b[j]
        incq     %r8                   #  j++
        movq     %rax, (%rdx)          #  *rowp = t
        addq     $8, %rdx              #  rowp++
        cmpq     %rcx, %r8             #  j:n
        jl       .L5                   #  if < goto loop
.L7:                                   # done:
        rep ; ret                       #  return
```

Strength Reduction

- **Replace costly operation with simpler one**
- **Example: Shift/add instead of multiply or divide**

  `16*x` → `x << 4`

  - Depends on cost of multiply or divide instruction
  - On Pentium IV, integer multiply requires 10 CPU cycles
- **Example: 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

*3 mults: i*n, (i–1)*n, (i+1)*n*

```
/* 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;
```

```
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
```

*1 mult: i*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;
```

```
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
```

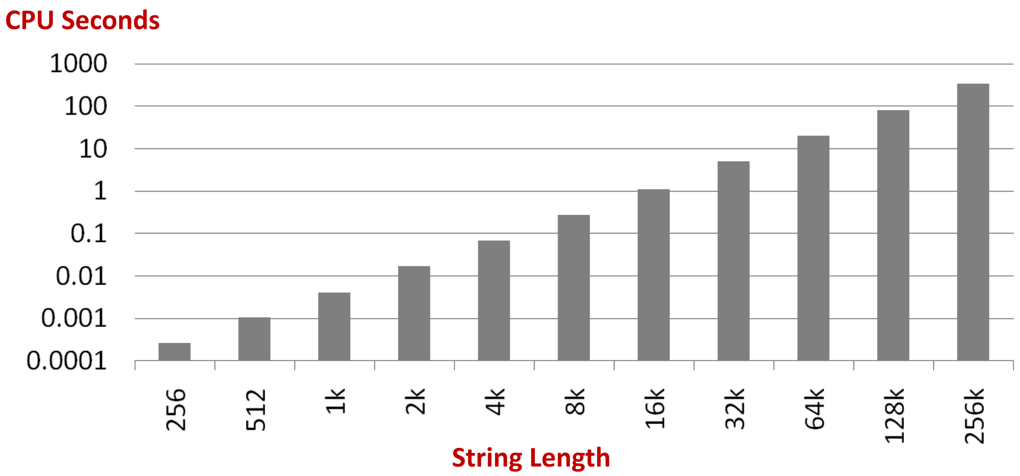
Optimization Blocker: Procedure Calls

- 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');
}
```

Performance

- Time quadruples when double string length
- Quadratic performance



Why is That?

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

- String length is called in every iteration!
  - And **`strlen`** is O(n), so **`lower`** is O(n^2)

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

Improving Performance

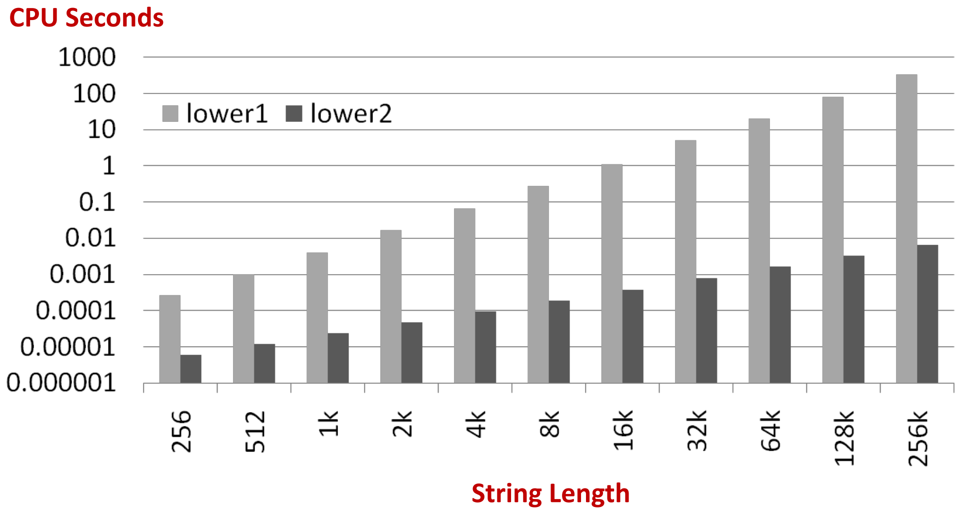
```
void lower(char *s)
{
  int i;
  for (i = 0; i < strlen(s); i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

```
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/precomputation**

Performance

- **Lower2: Time doubles when double string length**
- **Linear performance**



Optimization Blocker: Procedure Calls

- **Why couldn't compiler move `strlen` out of inner loop?**
  - Procedure may have side effects
  - Function may not return same value for given arguments
    - Could depend on other parts of global state
    - Procedure `lower` could interact with `strlen`
- **Compiler usually treats procedure call as a black box that cannot be analyzed**
  - Consequence: conservative in optimizations
- **Remedies:**
  - Inline the function if possible
  - Do your own code motion

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

Optimization Blocker: Memory Aliasing

```
// add twice the value stored at yp to the value stored at xp

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

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

- **twiddle1 appears to be less efficient**
  - 6 memory references: two reads each of *yp and *xp, two writes of *xp
- **twiddle2 appears to be more efficient**
  - 3 memory references: read *yp, read *xp, write *xp
- **Can a compiler come up with twiddle2 if given twiddle1?**

Optimization Blocker: Memory Aliasing

```
// add twice the value stored at yp to the value stored at xp
// *xp = *xp + 2 * *yp;

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

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

- **But what if xp == yp?**
  - twiddle1 quadruples value at xp
  - twiddle2 triples value at xp
- **Because of this 'aliasing', compiler does not optimize twiddle1**
  - Would lead to different result
  - Assume twiddle1 is programmer's intent

Optimization Blocker: Memory Aliasing

```
x = 1000;
y = 3000;
*q = y;
*p = x;
return *q;
```

- **What is the return value?**
- **Two cases:**
  - q and p are different addresses
  - q and p are aliases for the same address

Optimization Blocker: Memory Aliasing

- **Memory aliasing: Two different memory references write to the same location**
- **Can happen easily in C**
  - Since allowed to do address arithmetic
  - Direct access to storage structures
- **Hard to analyze = compiler cannot figure it out**
  - Hence the compiler is conservative

A Solution to Aliasing

- **Apply a programming style consistently**
  - Copy values for memory variables into local variables
  - Then assign local variables to final destinations

```
x = 1000;
y = 3000;
*q = y;
*p = x;
return *q;
```

```
x = 1000;
y = 3000;
temp1 = y;
temp2 = x;
*q = temp1;
*p = temp2;
return temp1;
```

A Final Thought

- **Source code optimization can muddle/destroy code clarity and program structure**
  - Certain optimizations are pretty easy and not too messy, so do them – e.g, move strlen(s) outside the loop
  - But it's not always that simple…
- **Worth doing when it actually buys you something**
  - Use profiling tools to find out where the code is spending its time
    (it's often not where you think!)
    (Alas, we probably won't see gprof and other tools in this course)

> **"Premature optimization is the root of all evil"**
>
> Donald Knuth