Under the Abstraction Barrier

```c
#include<stdio.h>

int main(int argc, char ** argv){
    printf("Hello world!\n");
    return 0;
}
```

```
55 48 89 e5
48 83 ec 20
48 8d 05 25 00 00 00
48 8d 05 25 00 00 00
48 89 75 f0
48 89 c7
b0 00
e8 00 00 00 00
31 c9
89 45 ec
89 c8
48 83 c4 20
5d
c3
```
Techniques for Improving Performance

1. Use better algorithms/data structures
2. Compile to efficient byte code
3. Write code that compiles to efficient byte code
4. Parallelize your execution
Optimizing Compilers

- Provide efficient mapping of program to machine
  - register allocation
  - code selection and ordering (scheduling)
  - eliminating minor inefficiencies

- Compiler optimization flags
  - `-O0`, `-O1`, `-O2`, `-O3`, `-Os`, `-Og`

- Seldom 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
Eliminating Dead Code (-O0)

```c
int dead_code(int input){
    if(47 > 0){
        return input;
    } else {
        return -1 *input;
    }
}
```

```c
int dead_code(int input){
    return input;
}
```

dead_code:
    movl %edi, %eax
    ret
Code Motion (-O1)

- Reduce frequency with which computation is performed
- For example, move code out of a loop

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

```c
void set_row(int *a, int *b, int i, int n) {
    int ni = n*i;
    for (int j = 0; j < n; j++) {
        a[ni+j] = b[j];
    }
}
```
Factoring out Subexpressions (-O1)

• Share common subexpressions
  • Gcc will do this with –O1

```c
/* 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

```assembly
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
```

1 multiplication
int loop_while(int a)
{
    int b = 4;
    int i = 0;
    int result = 0;
    while (i < 16) {
        result += a;
        a -= b;
        i += b;
    }
    return result;
}

int loop_while(int a)
{
    return 4*a-24;
}
Reduction in Strength (-O2)

- Replace costly operation with simpler one
- For example, replace multiplication with shift or addition

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

```assembly
set_matrix:
    xorl %r8d, %r8d
    testq %rdx, %rdx
    leaq 0(,%rdx,8), %r9
    jle .L1
.L6:
    xorl %eax, %eax
.L3:
    movq %rcx, (%rsi,%rax,8)
    movq %rcx, (%rdi,%rax,8)
    addq $1, %rax
    cmpq %rax, %rdx
    jne .L3
.L1:
    rep ret
```
Limitations of Optimizing Compilers

1. Must not cause any change in program behavior
   • Often prevents optimizations that would only affect behavior under pathological conditions.
     • Data ranges may be more limited than variable type suggests
     • Compiler cannot know run-time inputs
   • When in doubt, the compiler must be conservative
Exercise 1: Aliasing

Consider the following two functions. What do each of these programs do? Do they do the same thing?

```c
void mystery1(int *xp, int *yp){
    *xp = *xp + *yp;
    *yp = *xp - *yp;
    *xp = *xp - *yp;
}

void mystery2(int *xp, int *yp){
    int temp = *xp;
    *xp = *yp;
    *yp = temp;
}
```
Exercise 1: Aliasing

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}

void mystery2(int *xp, int *yp){
    int temp = *xp;
    *xp = *yp;
    *yp = temp;
}
```
void mystery1(int *xp,  
               int *yp) {  
    *xp = *xp + *yp;  
    *yp = *xp - *yp;  
    *xp = *xp - *yp;  
}
Optimization Blocker 1

• Aliasing: Two different references to a single location
  • Easy to happen in C

• Develop habit of introducing local variables
  • To accumulate within loops, for example
  • Your way of telling the compiler not to check for aliasing
Case Study 1: Summing Matrix Rows

/* Sum rows of nxn matrix a, store in vector sums */
void sum_rows1(int *a, int *sums, int n) {
    for (int i = 0; i < n; i++) {
        sums[i] = 0;
        for (long j = 0; j < n; j++){
            sums[i] += a[i*n + j];
        }
    }
}

/* Sum rows of nxn matrix a, store in vector sums */
void sum_rows2(int *a, int *sums, int n) {
    for (int i = 0; i < n; i++) {
        int val = 0;
        for (long j = 0; j < n; j++){
            val += a[i*n + j];
        }
        sums[i] = val;
    }
}
Exercise 2: Procedure Calls

Consider the following two functions. What do each of these programs do? Do they do the same thing?

```cpp
long f1();
long f2(){
    return f1() + f1();
}
```

```cpp
long f1();
long f2(){
    return 2*f1();
}
```
Limitations of Optimizing Compilers

1. **Must not cause any change in program behavior**
   - Often prevents optimizations that would only affect behavior under pathological conditions.
     - Data ranges may be more limited than variable type suggests
     - Compiler cannot know run-time inputs
   - When in doubt, the compiler must be conservative

2. **Most analysis is performed only within procedures**
   - Whole-program analysis is too expensive in most cases
   - Newer versions of **gcc** do interprocedural analysis within files
Limitations of Optimizing Compilers

long f1();
long f2(){
    return f1() + f1();
}

long f1();
long f2(){
    return 2*f1();
}
Optimization Blocker 2

- Compiler treats procedure calls as black boxes
  - Unknown side-effects
  - `strlen` may not always return the same value

- Alternatives:
  - Do your own code motion (necessary here)
  - Use inline keyword when declaring functions
    - `gcc` will optimize within a single file with `-01`
Case Study 2: Lowering Case

```c
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');
        }
    }
}
```
Machine Independent Optimization

- Compilers optimize assembly code
  - Dead code elimination
  - Code motion
  - Factoring out common subexpressions
  - Loop elimination
  - Reduction in Strength

- Optimization blockers:
  - Aliasing
    - Use local variables
  - Procedure calls
    - Move them yourself
Case Study 3: Vector Data Type

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

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

data_t will vary by example
- int
- long
- float
- double
Benchmark Computation

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_elem(v, i);
        *dest = *dest OP *val;
    }
}

Sum or product of vector elements

IDENT/OP may be 0/+ or 1/*

Metric: CPE, cycles per element

Time = CPE * n + Overhead
### Benchmark Performance

```c
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_elem(v, i);
        *dest = *dest OP *val;
    }
}
```

<table>
<thead>
<tr>
<th>Method</th>
<th>Integer</th>
<th>Double FP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
<td>Add</td>
<td>Mult</td>
</tr>
<tr>
<td>Combine1 –O0</td>
<td>22.68</td>
<td>20.02</td>
</tr>
<tr>
<td>Combine1 –O1</td>
<td>10.12</td>
<td>10.12</td>
</tr>
</tbody>
</table>

Exercise: how could you optimize this code to get even better performance?
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_elem(v, i);
        *dest = *dest OP *val;
    }
}

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Exercise: how could you optimize this code to get even better performance?
Exercise 3: Code-Level Optimizations

- Accumulate in temporary variable
- Move `vec_length` out of loop
- Avoid extra bounds check on each cycle
**Code-Level Optimizations**

```c
void combine2(vec_ptr v, data_t *dest){
    long i;
    data_t x = IDENT;
    long length = vec_length(v);
    data_t *d = get_vec_element(v,0);
    for (i = 0; i < length; i++){
        x = x OP d[i];
    }
    *dest = x;
}
```

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<tr>
<td>Combine2</td>
<td>1.27</td>
<td>3.01</td>
</tr>
</tbody>
</table>
Loop Unrolling

```c
int psum1(int a[], int sums[], int n){
    int i;
    sums[0] = a[0];
    for(i = 1; i < n; i++){
        sums[i] = sums[i-1] + a[i];
    }
}

int psum2(int a[], int p[], int n){
    int i;
    sums[0] = a[0];
    for(i = 1; i < n-1; i+=2){
        sums[i] = sums[i-1] + a[i];
        sums[i+1] = sums[i] + a[i+1];
    }
    if (i < n){ // handle odd #iterations
        sums[i] = sum[i-1] + a[i];
    }
}
```
Combine with Unrolling

```c
void unroll2_combine(vec_ptr v, data_t *dest){
  long length = vec_length(v);
  long limit = length-1;
  data_t *d = get_vec_element(v,0);
  data_t x = IDENT;
  long i;
  /* Combine 2 elements at a time */
  for (i = 0; i < limit; i+=2) {
    x = (x OP d[i]) OP d[i+1];
  }
  /* Finish any remaining elements */
  for (; i < length; i++) {
    x = x OP d[i];
  }
  *dest = x;
}
```

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</tr>
<tr>
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<td>3.00</td>
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</table>
Reassociation

\[ x = (x \text{ OP } d[i]) \text{ OP } d[i+1]; \]

\[ x = x \text{ OP } (d[i] \text{ OP } d[i+1]); \]
## Effect of Reassociation

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<td>Unroll 2</td>
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<td>Unroll 2a</td>
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</tr>
<tr>
<td>Throughput Bound</td>
<td>0.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>

- Nearly 2x speedup for Int *, FP +, FP *
- Reason: Breaks sequential dependency

\[ x = x \text{ OP } (d[i] \text{ OP } d[i+1]); \]
Separate Accumulators

```c
void unroll2a_combine(vec_ptr v, data_t *dest)
{
    long length = vec_length(v);
    long limit = length - 1;
    data_t *d = get_vec_element(v, 0);
    data_t x0 = IDENT;
    data_t x1 = IDENT;
    long i;
    /* Combine 2 elements at a time */
    for (i = 0; i < limit; i+=2) {
        x0 = x0 OP d[i];
        x1 = x1 OP d[i+1];
    }
    /* Finish any remaining elements */
    for (; i < length; i++) {
        x0 = x0 OP d[i];
    }
    *dest = x0 OP x1;
}
```

- Two independent streams of operation
Effect of Separate Accumulators

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<td>Unroll 2x2</td>
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- Int + makes use of two load units
- 2x speedup (over unroll2) for Int *, FP +, FP *
### Machine-Dependent Optimization

#### Integer Addition

<table>
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<td>K</td>
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#### Float Multiplication

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- Limited only by throughput of hardware
- Up to 42X improvement over original, unoptimized code
Exercise 3: Feedback

1. Rate how well you think this recorded lecture worked
   1. Better than an in-person class
   2. About as well as an in-person class
   3. Less well than an in-person class, but you still learned something
   4. Total waste of time, you didn't learn anything

2. How much time did you spend on this video lecture (including time spent on exercises)?

3. Do you have any questions that you would like me to address in this week's problem session?

4. Do you have any other comments or feedback?