Advanced Systems Lab
Spring 2023
Lecture: Compiler Limitations

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Last Time: ILP

Coffee Lake

<table>
<thead>
<tr>
<th></th>
<th>latency</th>
<th>1/throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP Add</td>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>FP Mul</td>
<td>4</td>
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<tr>
<td>Int Add</td>
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<td>0.5</td>
</tr>
<tr>
<td>Int Mul</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Deep (long) pipelines require ILP

Twice as fast
Last Time: How Many Accumulators?

Based on this insight:
\[ K = \#\text{accumulators} = \text{ceil}(\text{latency}/\text{cycles per issue}) \]
\[ = \text{ceil}(\text{latency} \times \text{throughput}) \]

Coffee Lake, FP mult:
\[ K = \text{ceil}(4/0.5) = 8 \]
\[ 8x \text{speedup} \]

Those have to be independent

Compiler Limitations

void reduce(vec_ptr v, data_t *dest)
{
    int i;
    int 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;
    }
}

void unroll2_sa(vec_ptr v, data_t *dest)
{
    int length = vec_length(v);
    int limit = length-1;
    data_t *d = get_vec_start(v);
    data_t x0 = IDENT;
    data_t x1 = IDENT;
    int 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];
        x1 = x1 OP d[i+1];
    }
    *dest = x0 OP x1;
}

Associativity law does not hold for floats: illegal transformation

No good way of handling choices (e.g., number of accumulators)

More examples of limitations today
Today

Optimizing compilers and optimization blockers

- Overview
- Code motion
- Strength reduction
- Sharing of common subexpressions
- Removing unnecessary procedure calls
- Optimization blocker: Procedure calls
- Optimization blocker: Memory aliasing
- Summary


Part of these slides are adapted from the course associated with this book

Optimizing Compilers

Always use optimization flags:

- gcc: default is no optimization (-O0)
- icc: some optimization is turned on

Good choices for gcc/icc: -O2, -O3, -march=xxx, -mAVX, -m64

- Read in manual what they do
- Understand the differences

Experiment: Try different flags and maybe different compilers
Example (On Skylake)

double a[4][4];
double b[4][4];
double c[4][4];

/* Multiply 4 x 4 matrices c = a*b + c */
void mmm(double *a, double *b, double *c) {
    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 (gcc):
~1000 cycles

Compiled with -O3 -march=native -fno-tree-vectorize
~100 cycles

Prevents use of vector instructions

---

**Intel x86**

<table>
<thead>
<tr>
<th></th>
<th>Processors (subset)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>x86-16</strong></td>
<td>8086 286</td>
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<td><strong>x86-32</strong></td>
<td>386 486 Pentium</td>
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<td></td>
<td>Pentium MMX</td>
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<td>Pentium III</td>
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<td>Pentium 4E</td>
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<td>Core i3/5/7 Sandy Bridge</td>
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<td>Haswell</td>
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<td>Skylake-X Icelake</td>
</tr>
</tbody>
</table>

**MMX:** Multimedia extension

**SSE:** Streaming SIMD extension

**AVX:** Advanced vector extensions

Use architecture flags
Optimizing Compilers

Compilers are good at: mapping program to machine
- register allocation
- instruction scheduling
- dead code elimination
- eliminating minor inefficiencies

Compilers are not good at: algorithmic restructuring
- for example to increase ILP, locality, etc.
- cannot deal with choices

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 that would only affect behavior under pathological conditions

Most analysis is performed only within procedures
- Whole-program analysis is too expensive in many cases

Most analysis is based only on static information (C/C++)
- Compiler has difficulty anticipating run-time inputs
- Not good at evaluating or dealing with choices
Organization

Optimizing compilers and optimization blockers

- Overview
- Code motion
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- Optimization blocker: Memory aliasing
- Summary

Code Motion

Reduce frequency with which computation is performed

- If it will always produce same result
- Especially moving code out of loop (loop-invariant code motion)

A form of precomputation

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

Compiler is likely to do
**Strength Reduction**

Replace costly operation with simpler one

Example: Shift/add instead of multiply or divide $16 \times x \to x << 4$

- Benefit is machine dependent

Example:

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

Compiler is likely to do

**Share Common Subexpressions**

Reuse portions of expressions

Compilers often not very sophisticated in exploiting arithmetic properties

3 mults: $i*n$, $(i-1)*n$, $(i+1)*n$

```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;
```

1 mult: $i*n$

```c
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;
```

In simple cases compiler is likely to do
Organization

Instruction level parallelism (ILP): an example

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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

```c
/* sum elements of vector */
double sum_elements(vec *v, double *res)
{
    int i;
    int n = vec_length(v);
    *res = 0.0;
    double t;
    for (i = 0; i < n; i++) {
        get_vec_element(v, i, &t);
        *res += t;
    } 
    return *res;
}
```  

Overhead for every fp +:
• One fct call
• One <
• One >=
• One ||
• One memory variable access

Potential big performance loss

Removing Procedure Call

```c
/* sum elements of vector */
double sum_elements(vec *v, double *res)
{
    int i;
    int n = vec_length(v);
    *res = 0.0;
    double t;
    for (i = 0; i < n; i++) {
        get_vec_element(v, i, &t);
        *res += t;
    } 
    return *res;
}
```
Removing Procedure Calls

Procedure calls can be very expensive

Bound 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

Further Inspection of the Example

vector.c // vector data type
sum.c    // sum
sum_opt.c // optimized sum
main.c   // timing

$(CC) -c -o vector.o vector.c
$(CC) -c -o sum.o sum.c
$(CC) -c -o main.o main.c
$(CC) -o vector vector.o sum.o main.o

Intel Xeon E3-1535M (Skylake)
CC=gcc -w -std=c99 -03 -march=native

Intel Atom D2550
CC=gcc -w -std=c99 -03 -march=atom

Xeon: 9.1 cycles/add
Atom: 28 cycles/add

Xeon: 4 cycles/add
Atom: 6 cycles/add

Xeon: 4 cycles/add
Atom: 6 cycles/add

What's happening here?
Function Inlining

Compilers may be able to do function inlining

- Replace function call with body of function
- Usually requires that source code is compiled together

Enables other optimizations

Problem:

- code size can increase dramatically
- performance libraries distributed as binary

```
/* sum elements of vector */
double sum_elements(vec *v, double *res)
{
    int i;
    n = vec_length(v);
    *res = 0.0;
    double t;
    for (i = 0; i < n; i++) {
        get_vec_element(v, i, &t);
        *res += t;
    }
    return res;
}
```

```
/* 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;
}
```

```
/* sum elements of vector */
int sum_elements(vec *v, double *res)
{
    int i;
    n = vec_length(v);
    *res = 0.0;
    double t;
    for (i = 0; i < n; i++) {
        get_vec_element(v, i, &t);
        *res += t;
    }
    return res;
}
```

Optimization Blocker #1: 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');
}
```

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

\[O(n^2)\] instead of \[O(n)\]
Improving Performance

```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');
}
```

Move call to `strlen` outside of loop

Form of code motion/precomputation

Optimization Blocker: Procedure Calls

Why couldn’t compiler move `strlen` out of inner loop?
- Procedure may have side effects

Compiler usually treats procedure call as a black box that cannot be analyzed
- Consequence: conservative in optimizations

In this case the compiler may actually do it if `strlen` is recognized as built-in function whose properties are known
```c
/* Sums rows of n x n matrix a and stores in vector b */
void sum_rows1(double *a, double *b, int n) {
    int i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

Code updates $b[i]$ (= memory access) on every iteration

```c
/* Sums rows of n x n matrix a and stores in vector b */
void sum_rows2(double *a, double *b, int n) {
    int 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;
    }
}
```

Why does the compiler not optimize as shown?
Reason: Possible Memory Aliasing

If memory is accessed, compiler assumes the possibility of side effects

```c
/* Sums rows of n x n matrix a and stores in vector b */
void sum_rows1(double *a, double *b, int n) {
    int i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

**Example:**

double A[9] = 
{ 1, 2, 3,
  2, 4, 6,
  3, 6, 9 };
sum_rows1(A, B, 3);

---

Removing Aliasing

```c
/* Sums rows of n x n matrix a and stores in vector b */
void sum_rows2(double *a, double *b, int n) {
    int 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;
    }
}
```

**Scalar replacement:**

- Assumes no memory aliasing (otherwise likely an incorrect transformation)
- Copy array elements **that are reused** into temporary variables
- Perform computation on those variables
- Enables better register allocation and instruction scheduling by the compiler
Optimization Blocker: Memory Aliasing

Memory aliasing: Two different memory references write to the same location

Easy to have happen in C
- Address arithmetic is allowed
- Direct access to storage structures

Hard to analyze = compiler cannot figure it out
- Hence is conservative

Prevents many performance optimizations

Solution: Scalar replacement (by programmer) in innermost loop
- Copy memory variables that are reused into local variables
- Basic scheme:
  Load: \( t_1 = a[i], t_2 = b[i+1], ... \)
  Compute: \( t_4 = t_1 * t_2; ... \)
  Store: \( a[i] = t_1, b[i+1] = t_7, ... \)

Example: MMM

Which array elements are reused? All of them! But how to take advantage?

```c
void mmm(double const * A, double const * B, double * C, size_t N) {
    for(size_t k = 0; k < N; k++)
        for(size_t i = 0; i < N; i++)
            for(size_t j = 0; j < N; j++)
}
```

Tile each loop (= blocking MMM)

```c
void mmm(double const * A, double const * B, double * C, size_t N) {
    for(size_t i = 0; i < N; i+=2)
        for(size_t j = 0; j < N; j+=2)
            for(size_t k = 0; k < N; k+=2)
                for(size_t ii = 0; ii < 2; ii++)
                    for(size_t jj = 0; jj < 2; jj++)
                        C[N*i + N*ii + j + jj] = C[N*i + N*ii + j + jj] +
                            A[N*i + N*ii + k + kk] * B[j + jj + N*k + N*kk];
}
```

Unroll inner three loops
void mmm(double const * A, double const * B, double * C, size_t N) {
    for(size_t i = 0; i < N; i+=2 )
        for(size_t j = 0; j < N; j+=2 )
            for(size_t k = 0; k < N; k+=2 ) {
            }
}
```c
void mm(double const * A, double const * B, double * C, size_t N) {
    for (size_t i = 0; i < N; i+=2) {
        for (size_t j = 0; j < N; j+=2) {
            for (size_t k = 0; k < N; k+=2) {
                double t0, t1, t2, t3, t4, t5, t6, t7, t8, t9, t10, t11, t12;
                t7 = A[N*i + k];
                t6 = A[N*i + k + 1];
                t5 = A[N*i + N + k];
                t4 = A[N*i + N + k + 1];
                t3 = B[j + N*k];
                t2 = B[j + N*k + 1];
                t1 = B[j + N*k + N];
                t0 = B[j + N*k + N + 1];
                t8 = C[N*i + j];
                t9 = C[N*i + j + 1];
                t10 = C[N*i + N + j];
                t11 = C[N*i + N + j + 1];
                t12 = t7 * t3;
                t8  = t8 + t12;
                t12 = t7 * t2;
                t9  = t9 + t12;
                t12 = t5 * t3;
                t10 = t10 + t12;
                t12 = t5 * t2;
                t11 = t11 + t12;
                t12 = t6 * t1;
                t8  = t8 + t12;
                t12 = t6 * t0;
                t9  = t9 + t12;
                t12 = t4 * t1;
                t10 = t10 + t12;
                t12 = t4 * t0;
                t11 = t11 + t12;
                C[N*i + j] + t8;
                C[N*i + j + 1] + t9;
                C[N*i + N + j] + t10;
                C[N*i + N + j + 1] = t11;
            }
        }
    }
}
```

**Effect on Runtime?**

**Intel Xeon E-2176M (Coffee Lake)**
**compiler:** gcc 9.4.0
**flags:** -O3 -ffast-math -march=native

<table>
<thead>
<tr>
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<tr>
<td>Triple loop</td>
<td>181</td>
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*As usual, unrolling by itself does nothing*
Effect on Runtime?

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<tr>
<td>Six-fold loop</td>
<td>158</td>
<td>2.4M</td>
</tr>
<tr>
<td>+ Inner three unrolled</td>
<td>160</td>
<td>2.4M</td>
</tr>
<tr>
<td>+ Scalar replacement</td>
<td>90</td>
<td>1.5M</td>
</tr>
</tbody>
</table>

30–45% speedup for smallish sizes

and we did not experiment yet with the block size ...

Can Compiler Remove Aliasing?

for (i = 0; i < n; i++)
  a[i] = a[i] + b[i];

Potential aliasing: Can compiler do something about it?

Compiler can insert runtime check:

if (a + n < b || b + n < a)
  /* further optimizations may be possible now */
  ... 
else
  /* aliased case */
  ...
Removing Aliasing With Compiler

Globally with compiler flag:
- `-fno-alias, /Oa`
- `-fargument-noalias, /Qalias-args- (function arguments only)`

For one loop: `pragma`

```c
void add(float *a, float *b, int n) {
    #pragma ivdep
    for (i = 0; i < n; i++)
        a[i] = a[i] + b[i];
}
```

For specific arrays: `restrict` (needs compiler flag `-restrict, /Qrestrict`)

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

Organization

Instruction level parallelism (ILP): an example

Optimizing compilers and optimization blockers
- **Overview**
- **Code motion**
- **Sharing of common subexpressions**
- **Strength reduction**
- Removing unnecessary procedure calls
- Optimization blocker: Procedure calls
- Optimization blocker: Memory aliasing

**Compiler is likely to do**

**Summary**
Summary

One can easily lose 10x or even more

What matters besides operation count:
- Code style (unnecessary procedure calls, no aliasing, scalar replacement, …)
- Algorithm structure (instruction level parallelism, locality, …)
- Data representation (complicated structs or simple arrays)

Summary: Optimize at Multiple Levels

Algorithm:
- Evaluate different algorithm choices
- Restructuring may be needed (ILP, locality)

Data representations:
- Careful with overhead of complicated data types
- Best are arrays

Procedures:
- Careful with overhead
- They are black boxes for the compiler

Loops:
- Often need to be restructured (ILP, locality)
- Unrolling often necessary to enable other optimizations
- Watch the innermost loop bodies
Numerical Functions

Use arrays, avoid linked data structures, if possible

Unroll to some extent

▪ To restructure computation to make ILP explicit
▪ To enable scalar replacement and hence better register allocation for variables that are reused