CSC 252: Computer Organization
Spring 2023: Lecture 26

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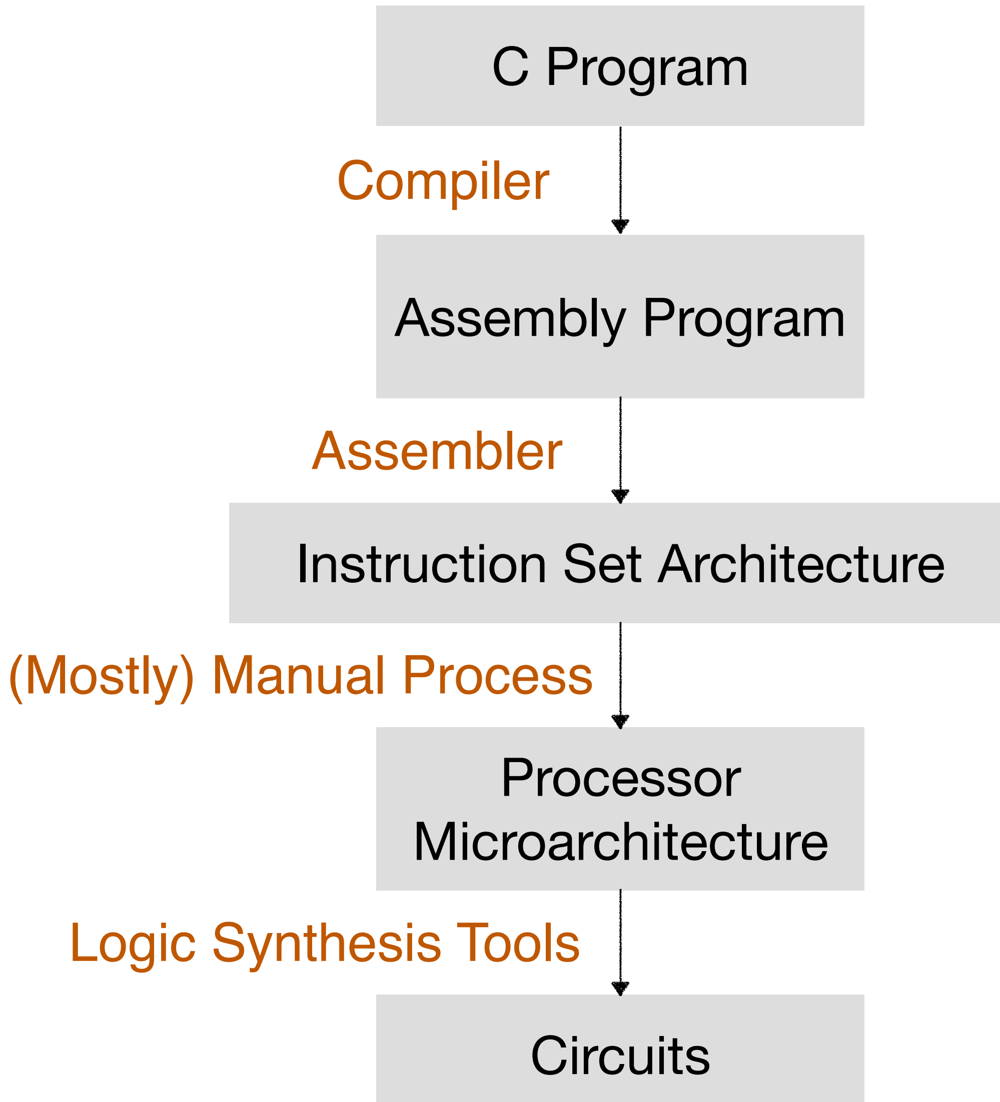
Announcements

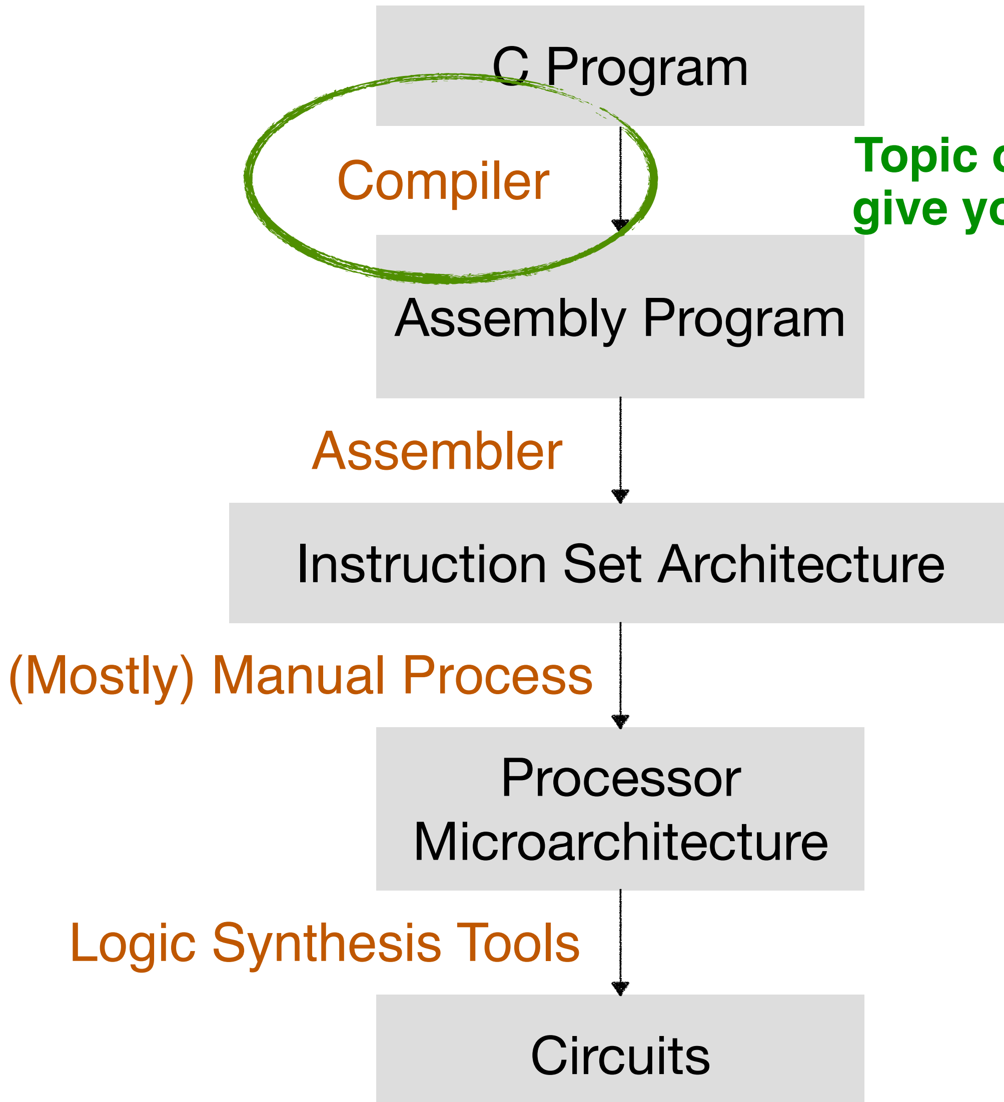
- Virtual Memory problem set: https://www.cs.rochester.edu/courses/252/spring2023/handouts.html
  - Not to be turned in. Won’t be graded.
- Assignment 5 due April 28 (Extended).

9	10	11	12	13	14	15
16	17	18	19 Today	20	21	22
23	24	25	26 Last Class	27	28 Due	29
30	May 1 Final	2	3	4	5	6

So far in 252…


C Program
Compiler
Assembly Program
Assembler
Instruction Set Architecture
(Mostly) Manual Process
Processor Microarchitecture
Logic Synthesis Tools
Circuits

So far in 252…



Topic of CSC 255, but we will give you some intuition here.

Code Optimization Overview

- Three entities can optimize the program: programmer, compiler, and hardware
- The best thing to speed up a program is to pick a good algorithm. Compilers/hardware can't do that in general.
  - Quicksort: O(n log n) = K * n * log(n)
  - Bubblesort: O(n^2) = K * n^2
- Algorithm choice decides overall complexity (big O), compiler/hardware decides the constant factor in the big O notation
- Compiler and hardware implementations decide the K.
- Programmers can write code that makes it easier to compiler and hardware to improve performance.

Optimizing Code Transformation

- Hardware/Microarchitecture Independent Optimizations
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
- Optimization Blockers
  - Procedure calls
  - Memory aliasing
- Exploit Hardware Microarchitecture

Generally Useful Optimizations

- Optimizations that you or the compiler should do regardless of processor

- 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;
    int ni = n*i;
    for (j = 0; j < n; j++)
          a[ni+j] = 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`
  - Depends on cost of multiply or divide instruction
  - On Intel Nehalem, integer multiply requires 3 CPU cycles. Division takes even more cycles. Shift can generally be done in 1 cycle.
- Use the `lea` instruction

Reduction in Strength

- Replace costly operation with simpler one
- Shift, add instead of multiply or divide
  - `16*x      -->     x << 4`
  - Depends on cost of multiply or divide instruction
  - On Intel Nehalem, integer multiply requires 3 CPU cycles. Division takes even more cycles. Shift can generally be done in 1 cycle.
- Use the `lea` instruction

```
long m12(long x)
{
  return x*12;
}
```

```
leaq (%rdi,%rdi,2), %rax # t <- x+x*2
salq $2, %rax            # return t<<2
```

Common Subexpression Elimination

- Reuse portions of expressions
- GCC will do this with –O1

3 multiplications: 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 multiplication: i*n

```
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;
```

```
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
```

Today: Optimizing Code Transformation

- Hardware/Microarchitecture Independent Optimizations
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
- Optimization Blockers
  - Procedure calls
  - Memory aliasing
- Exploit Hardware Microarchitecture

Optimization Blocker #1: Procedure Calls

- 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');
}
```

Calling Strlen

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

- Strlen performance
  - Has to scan the entire length of a string, looking for null character.
  - O(N) complexity
- Overall performance
  - N calls to strlen
  - Overall $O(N^2)$ performance

Improving Performance

- Move call to `strlen` outside of loop
- Since result does not change from one iteration to another
- Form of code motion

```
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');
}
```

Optimization Blocker: Procedure Calls

```
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');
}

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

Why couldn't compiler move `strlen` out of loop?

- Procedure may have side effects, e.g., alters global state each time called
- Function may not return same value for given arguments

Optimization Blocker: Procedure Calls

- Most compilers treat procedure call as a black box
  - Assume the worst case, weak optimizations near them
  - There are interprocedural optimizations (IPO), but they are expensive
  - Sometimes the compiler doesn't have access to source code of other functions because they are object files in a library. Link-time optimizations (LTO) comes into play, but are expensive as well.

Optimization Blocker: Procedure Calls

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  - Sometimes the compiler doesn’t have access to source code of other functions because they are object files in a library. Link-time optimizations (LTO) comes into play, but are expensive as well.
- Remedies:
  - Use of inline functions
  - Do your own code motion

Optimization Blocker: Procedure Calls

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  - Sometimes the compiler doesn't have access to source code of other functions because they are object files in a library. Link-time optimizations (LTO) comes into play, but are expensive as well.
- Remedies:
  - Use of inline functions
  - Do your own code motion

```
inline void swap(int *m, int *n) {
 int tmp = *m;
 *m = *n;
 *n = tmp;
}

void foo () {
  swap(&x, &y);
}
```

→

```
void foo () {
  int tmp = x;
  x = y;
  y = tmp;
}
```

Optimization Blocker #2: Memory Aliasing

```
/* 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];
    }
}
```

Value of `a`:

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

Value of `b`:

```
init:  [x, x, x]
```

Optimization Blocker #2: Memory Aliasing

```
/* 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];
    }
}
```

Value of `a`:

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

Value of `b`:

```
init:   [x, x, x]
```

```
i = 0: [3, x, x]
```

Optimization Blocker #2: Memory Aliasing

```
/* 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];
    }
}
```

Value of `a`:

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

Value of `b`:

```
init:   [x, x, x]
```

```
i = 0: [3, x, x]
```

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

Optimization Blocker #2: Memory Aliasing

```
/* 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];
    }
}
```

Value of `a`:

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

Value of `b`:

```
init:   [x, x, x]
```

```
i = 0: [3, x, x]
```

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

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

A Potential Optimization

```
/* 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];
    }
}
```

Every iteration updates memory location b[i]. Memory accesses are slow, so…

A Potential Optimization

```
/* 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];
    }
}
```

Every iteration updates memory location b[i]. Memory accesses are slow, so…

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

Every iteration updates `val`, which could stay in register. Update memory only once.

A Potential Optimization

```
/* 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];
    }
}
```

Every iteration updates memory location b[i]. Memory accesses are slow, so…

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

Every iteration updates `val`, which could stay in register. Update memory only once.

Why can't a compiler perform this optimization?

Memory Aliasing

```
/* 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];
    }
}
```

Value of a:

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

double b[3] = a+3;

sum_rows1(a, b, 3);
```

b

Value of b:

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

Memory Aliasing

```
/* 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];
    }
}
```

Value of a:

b

```
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]
```

Memory Aliasing

```
/* 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];
    }
}
```

Value of a:

```
double a[9] =
  { 0,   1,   2,
    3,   8,  16,
   32,  64, 128};

double b[3] = a+3;

sum_rows1(a, b, 3);
```

b

Value of b:

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

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

Memory Aliasing

```
/* 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];
    }
}
```

Value of a:

```
double a[9] =
  { 0,   1,   2,
    3,   0,  16,
   32,  64, 128};

double b[3] = a+3;

sum_rows1(a, b, 3);
```

b

Value of b:

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

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

Memory Aliasing

```
/* 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];
    }
}
```

Value of a:

```
double a[9] =
  { 0,   1,   2,
b  3,   3,  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]
```

Memory Aliasing

```
/* 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];
    }
}
```

Value of a:

```
double a[9] =
  { 0,   1,   2,
    3,   6,  16,
   32,  64, 128};

double b[3] = a+3;

sum_rows1(a, b, 3);
```

b

Value of b:

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

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

Memory Aliasing

```
/* 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];
    }
}
```

Value of a:

b

```
double a[9] =
  { 0,   1,   2,
    3,  22,  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]
```

Memory Aliasing

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

Value of a:

```
double a[9] =
  { 0,   1,   2,
    3,  22,  16,
   32,  64, 128};

double b[3] = a+3;

sum_rows1(a, b, 3);
```

b

Value of b:

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

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

```
i = 1: [3, 22, 16]
```

Memory Aliasing

```
/* 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];
    }
}
```

Value of a:

b

```
double a[9] =
  { 0,   1,   2,
    3 ,  22 ,  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, 22, 16]
```

```
i = 2: [3, 22, 224]
```

Optimization Blocker: Memory Aliasing

- Aliasing
  - Two different memory references (array elements or pointers) specify the same memory location
  - Easy to have in C
    - Since C allows address/pointer 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

Today: Optimizing Code Transformation

- Hardware/Microarchitecture Independent Optimizations
  - Code motion/precomputation
  - Strength reduction
  - Sharing of common subexpressions
- Optimization Blockers
  - Procedure calls
  - Memory aliasing
- Exploit Hardware Microarchitecture

Exploiting Instruction-Level Parallelism (ILP)

- Hardware can execute multiple instructions in parallel
  - Pipeline is a classic technique. Multiple instructions are being executed at the same time
- Performance limited by control/data dependencies
- Simple transformations can yield dramatic performance improvement
  - Compilers often cannot make these transformations
  - Lack of associativity and distributivity in floating-point arithmetic

Baseline Code

```
for (i = 0; i < length; i++) {
  t = t * d[i];
  *dest = t;
}
```

```
.L519:
  imulq (%rax,%rdx,4), %ecx
  addq  $1, %rdx           # i++
  cmpq  %rdx, %rbp         # Compare length:i
  jg    .L519              # If >, goto Loop
```

Real work

Overhead

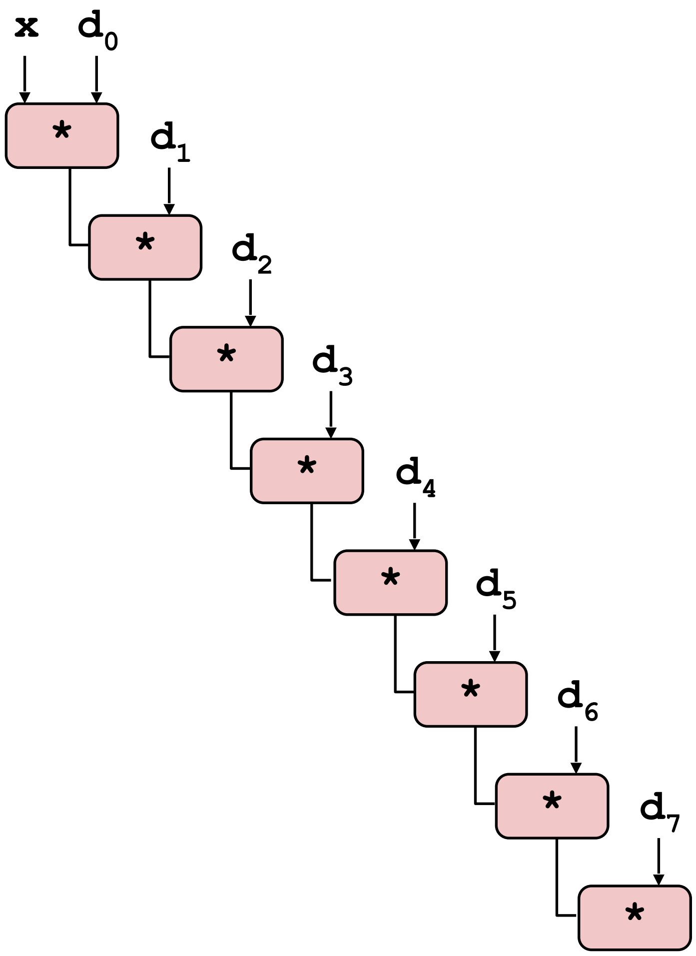
Loop Unrolling (2x1)

```
long limit = length-1;
long i;
/* Combine 2 elements at a time */
for (i = 0; i < limit; i+=2) {
    x = (x * d[i]) * d[i+1];
}

/* Finish any remaining elements */
for (; i < length; i++) {
    x = x * d[i];
}
*dest = x;
```

- Perform 2x more useful work per iteration
- Reduce loop overhead (comp, jmp, index dec, etc.)
- What’s the trade-off here?

DFG of This Implementation



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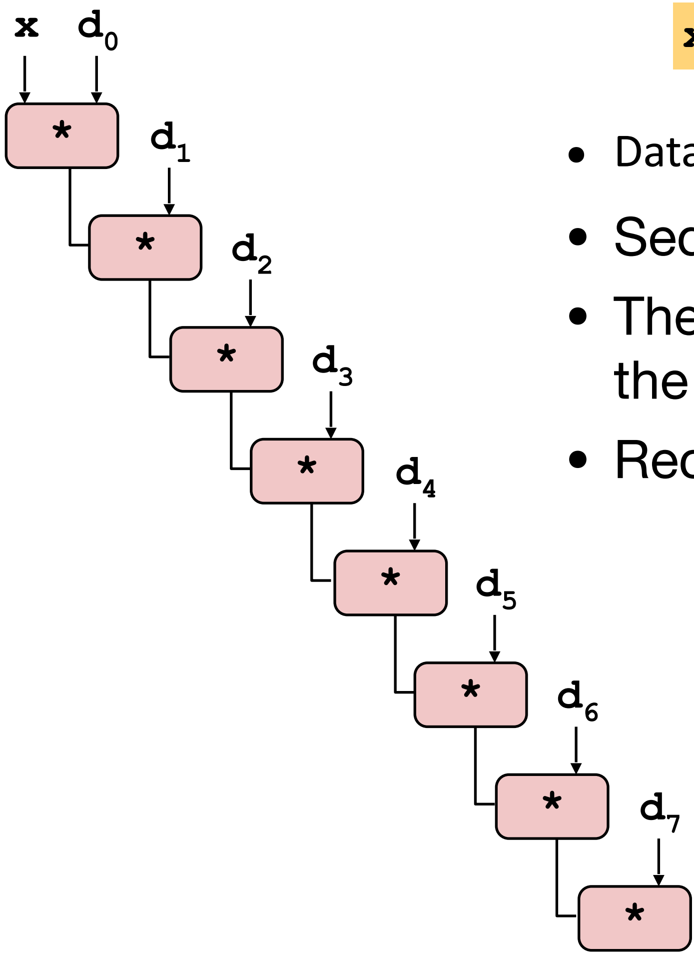



```
x = (x OP d[i]) OP d[i+1];
```

- Data dependency graph
- Sequential dependence
- The performance of the code is dictated by the the latency of OP
- Recall the read-after-write dependency

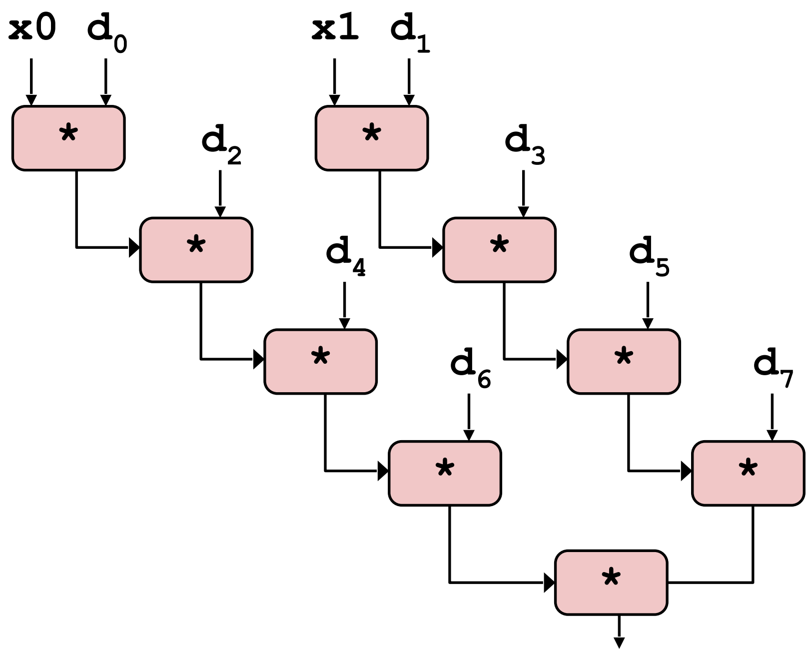
Loop Unrolling with Separate Accumulators

```
long limit = length-1;
long i;
/* Combine 2 elements at a time */
for (i = 0; i < limit; i+=2) {
    x0 = x0 * d[i];
    x1 = x1 * d[i+1];
}

/* Finish any remaining elements */
for (; i < length; i++) {
    x0 = x0 * d[i];
}
*dest = x0 * x1;
```

Data-Flow Graph (DFG)

```
x0 = x0 * d[i];
x1 = x1 * d[i+1];
```

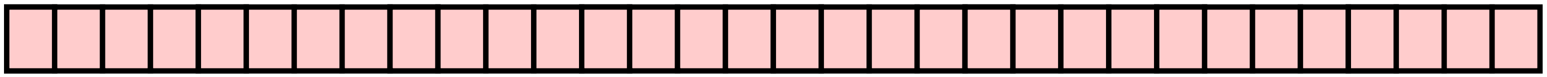


- What changed:
  - Two independent “streams” of operations
  - Reduce data dependency

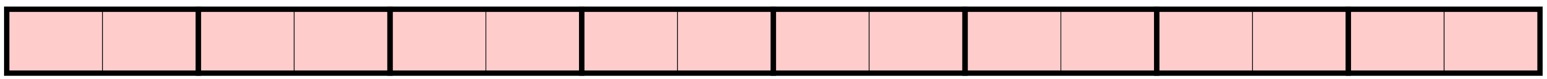
Aside: Vector Registers and Instructions

A single 32-byte register; can be used differently

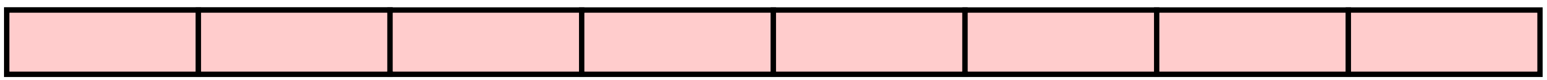
32 single-byte integers



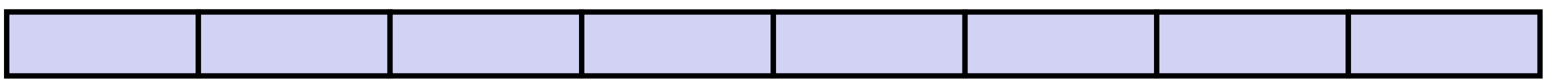
16 2-byte integers



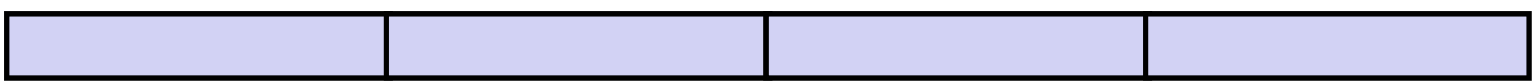
8 4-byte integers



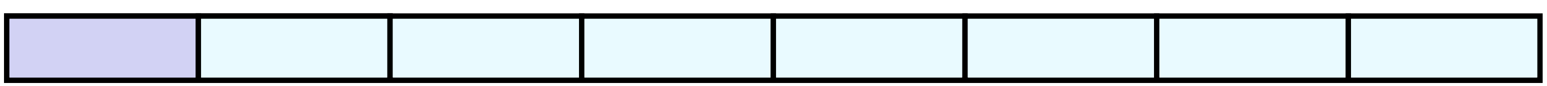
8 single-precision floats



4 double-precision floats



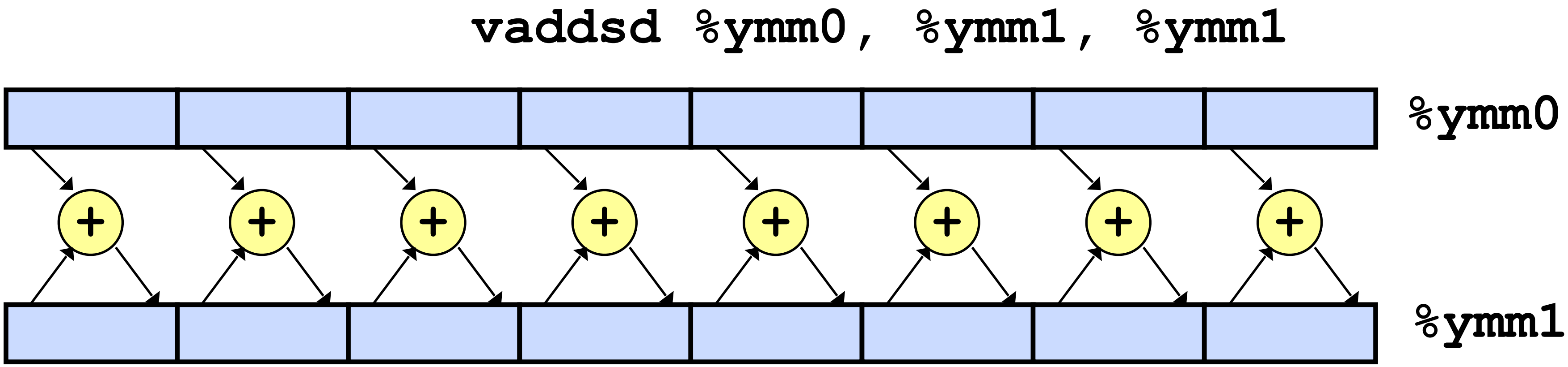
1 single-precision floats

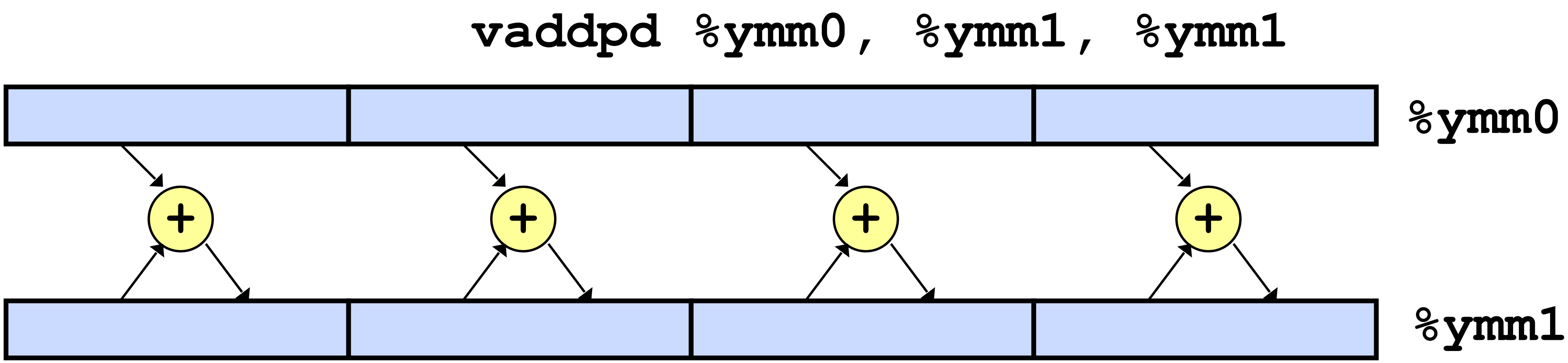


1 double-precision floats

Aside: SIMD Operations

Single Instruction Multiple Data





Can manually write assembly code that uses SIMD/vector instructions; some compilers will automatically vectorize your code. Hard problem!

Aside: Profile-Guided Optimization

```
float foo(int x, int y)
{
    return pow(x, y) * 100 / log(x) * sqrt(y);
}
```

Aside: Profile-Guided Optimization

- As a programmer, if you know what `x` and `y` will be, say 5, you could direct return the results 23769.8 without having to the computation

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}
```

```
float foo(int x, int y)
{
  if (x == 2 && y == 5) return 23769.8;
  else return pow(x, y) * 100 / log(x) * sqrt(y);
}
```

Code Optimization Summary

- From a programmer's perspective:
  - What you know: the functionality/intention of your code; the inputs to the program; all the code in the program
  - What you might not know: the hardware details.
- From a compiler's perspective:
  - What you know: all the code in the program; (maybe) the hardware details.
  - What you might not know: the inputs to the program; the intention of the code
- From the hardware's perspective:
  - What you know: the hardware details; some part of the code
  - What you might not know: the inputs to the program; the intention of the code
- The different perspectives indicate that different entities have different responsibilities, limitations, and advantages in optimizing the code