Lecture 13: Optimization

CS 105 Spring 2024

Under the Abstraction Barrier

```c
#include<stdio.h>

int main(int argc,
         char ** argv){

  printf("Hello world!\n");
  return 0;
}
```

```
pushq   %rbp
movq    %rsp, %rbp
subq  $32, %rsp
leaq  L_.str(%rip), %rax
movl  $0, -4(%rbp)
movl  %edi, -8(%rbp)
movq  %rsi, -16(%rbp)
movq  %rax, %rdi
movb  $0, %al
callq _printf
xorl  %ecx, %ecx
movl  %eax, -20(%rbp)
movl  %ecx, %eax
addq  $32, %rsp
popq  %rbp
retq
```

```
55
48 89 e5
48 83 ec 20
48 8d 05 25 00 00 00
c7 45 fc 00 00 00 00
89 7d f8
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 code
  - 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)

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

```
dead_code:
    movl    %edi, %eax
    ret
```

```
int dead_code(int input){

    return input;




}
```

Code Motion (-O1)

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

```
void set_row(int* a, int* b,
             int i,  int n) {

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

```
set_row:
        testl   %ecx, %ecx
        jle     .L1
        imull   %ecx, %edx
        addl    %edx, %ecx
.L3:
        movl    (%rsi), %r8d
        movslq  %edx, %rax
        movl    %r8d, (%rdi,%rax,4)
        addl    $1, %edx
        addq    $4, %rsi
        cmpl    %ecx, %edx
        jne     .L3
.L1:
        rep ret
```

```
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

```
/* 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;
```

3 multiplications

```
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;
```

1 multiplication

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

Loop Elimination (-O1)

```
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;
}
```

```
loop_while:
        leal    -24(,%rdi,4), %eax
        ret
```

```
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

```
void set_matrix(long* a, long* b,
                long n){

  for (long i = 0;
    long ni = n*i;
    for (long j = 0
      a[ni + j] = b
    }

  }
}
```

```
set_matrix:
        xorl    %
        testq   %
        leaq    0
        jle     .
.L6:    xorl    %
.L3:    movq    (
        movq    %
        addq    $
        cmpq    %rax, %rdx
        jne     .L3
        addq    $1, %r8
        addq    %r9, %rdi
        cmpq    %r8, %rdx
        jne     .L6
.L1:    rep ret
```

```
void set_matrix(long* a, long* b,
                long n){
  int ni = 0;
  for (long i = 0; i < n; i++) {

    for (long j = 0; j < n; j++){
      a[ni + j] = b[j];
    }
    ni += n;
  }
}
```

Machine Independent Optimization

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

Case Study: Vector Data Type

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

`data_t` will vary by example

- `int`
- `long`
- `float`
- `double`

```
/* get length of vector */
long vec_length(vec* v) {

    return v->len;
}
```

```
/* get address of vector element */
data_t* get_vec_elem(vec* v, long idx) {

    if (idx >= v->len){
        return NULL;
    }
    return &(v->data[idx]);
}
```

Benchmark Computation

```
void combine1(vec* v, data_t* dest){

  *dest = IDENT;

  for(long 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

```
void combine1(vec* v, data_t* dest){

  *dest = IDENT;

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

Method	Integer		Double FP	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 –O0	22.68	20.02	19.98	20.18
Combine1 –O1	10.12	10.12	10.17	11.14

Question: how could you optimize this code to get even better performance?

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

Limitations of Optimizing Compilers

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

?

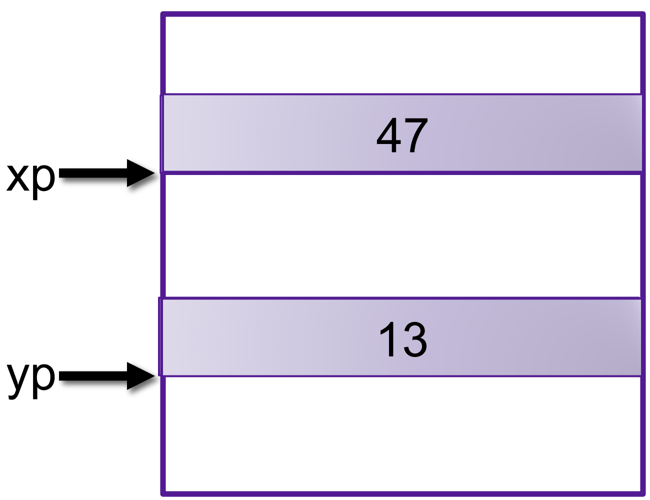
```
void mystery2(int* xp,
              int* yp){
  int temp = *xp;
  *xp = *yp;
  *yp = temp;
}
```

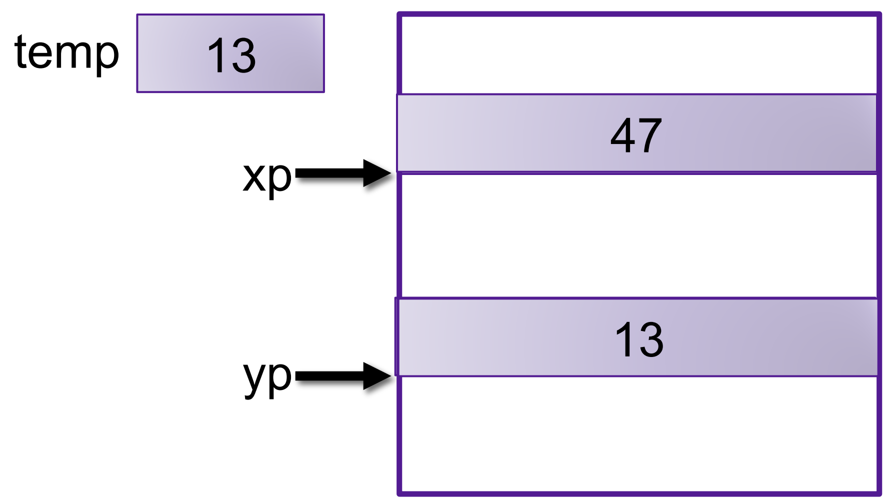
Exercise: What do each of these programs do?
Do they do the same thing?

Comparing Programs

```
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;
}
```

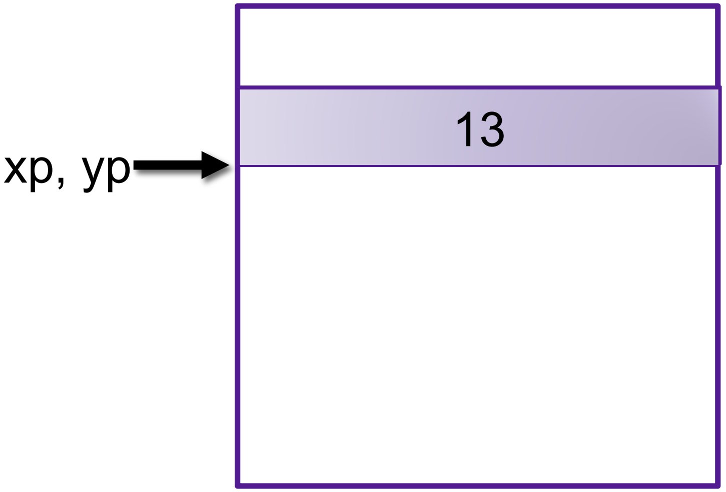


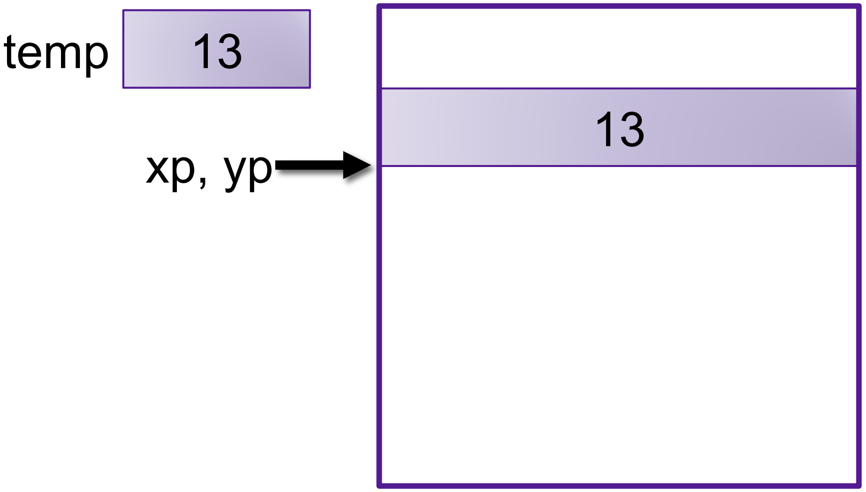


Comparing Programs

```
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;
}
```





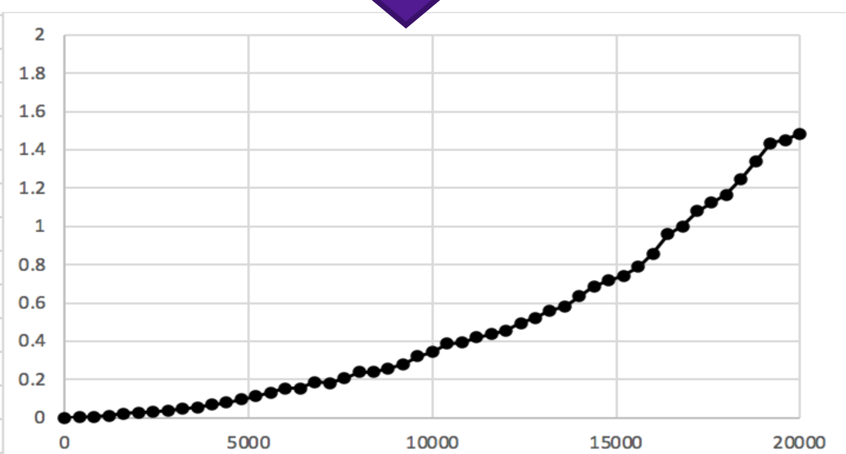
Optimization Blocker 1

- 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

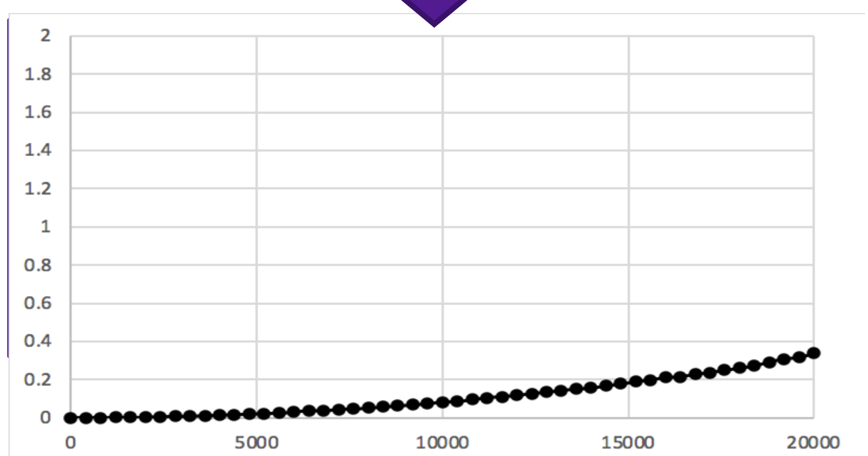
Example: Summing Matrix Rows

```
/* 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;
  }
}
```



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 inter-procedural analysis within files

Exercise 2: Procedure Calls

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

```
long f1();

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

?

```
long f1();

long f2(){
  return 2*f1();
}
```

Optimization Blocker 2

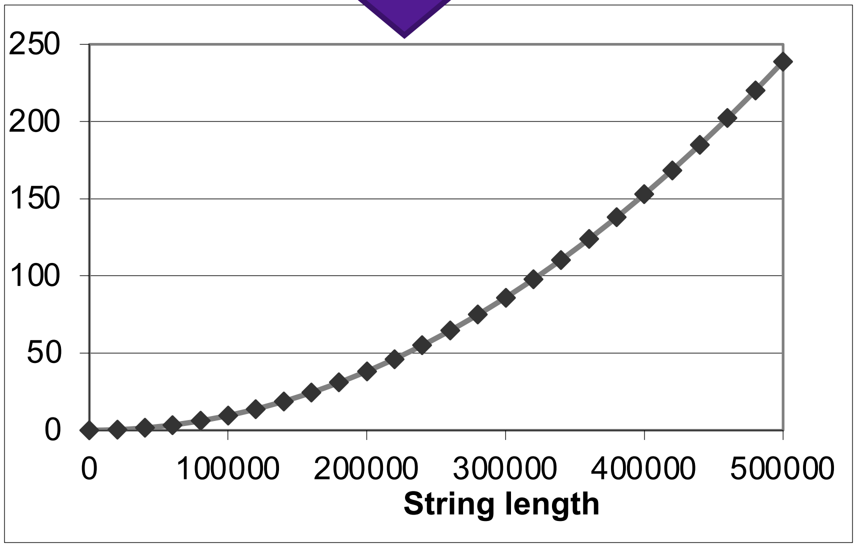
- Compiler treats procedure calls as black boxes
  - Unknown side-effects
  - **`strlen`** may not always return the same value

- Alternatives:
  - Do your own code motion (necessary here)
  - Use inline keyword when declaring functions
    - **`gcc`** will optimize within a single file with **`–O1`**

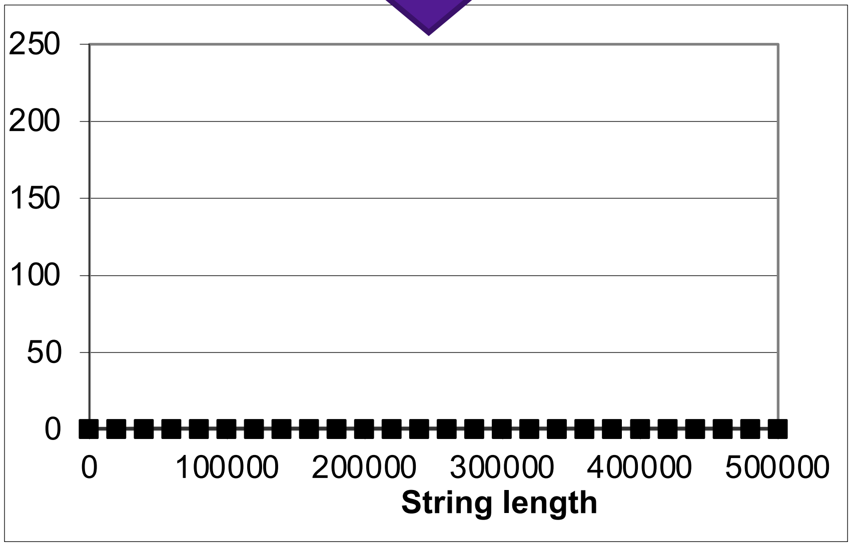
Example: Lowering Case

```
void lower(char* s){
  int i;

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




```
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

Exercise: Code-Level Optimizations

```
void combine1(vec* v, data_t* dest){

  *dest = IDENT;

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

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 –O0	22.68	20.02	19.98	20.18
Combine1 –O1	10.12	10.12	10.17	11.14

Exercise: how could you optimize this code to get even better performance?

Exercise: Code-Level Optimizations

```
void combine1(vec* v, data_t*
              dest){

  *dest = IDENT;


  for(long i=0;i<vec_length(v);
      i++){
    data_t* val=get_vec_elem(v,i);
    *dest = *dest OP *val;
  }

}
```

Code-Level Optimizations

```
void combine2(vec* v, data_t* dest){

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

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 –O0	22.68	20.02	19.98	20.18
Combine1 –O1	10.12	10.12	10.17	11.14
Combine2	1.27	3.01	3.01	5.01

Loop Unrolling

```
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 sums[],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];
  }
}
```

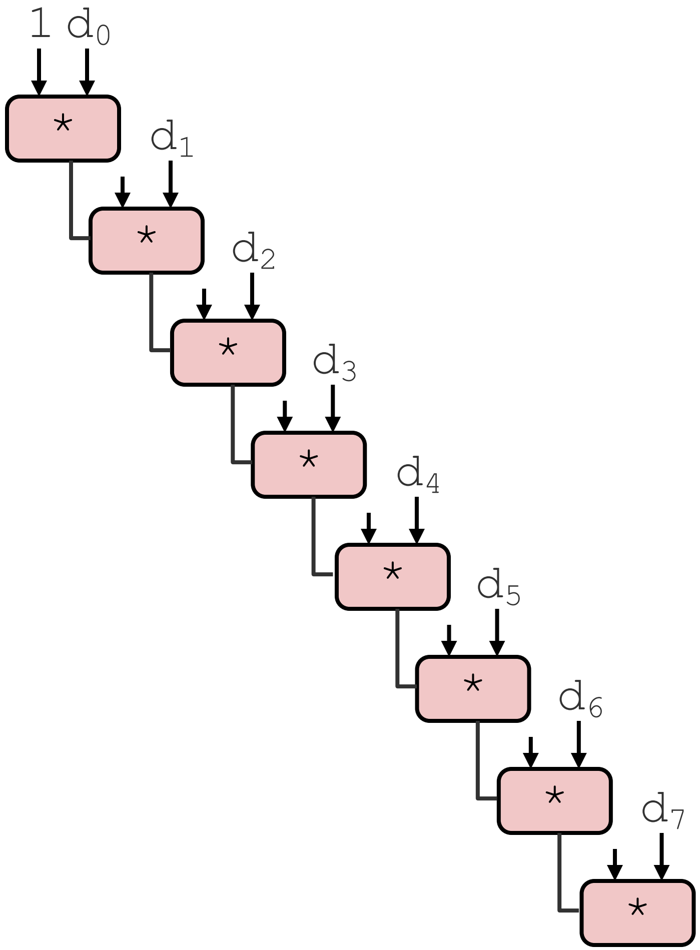
Combine with Unrolling

```
void unroll2_combine(vec* 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;
    /* Combine 2 elements at a time */
    for(long i = 0; i < limit; i+=2) {
        x = (x OP d[i]) OP d[i+1];
    }
    /* Finish any remaining elements */
```

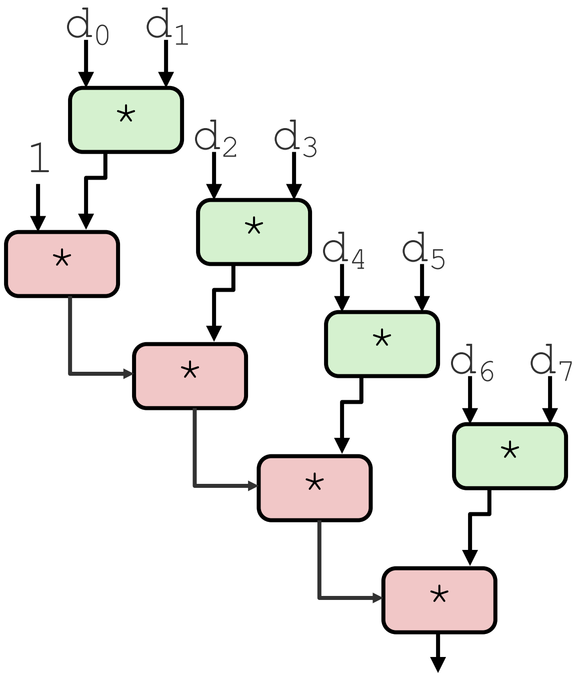
Method	Integer		Double FP	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 –O0	22.68	20.02	19.98	20.18
Combine1 –O1	10.12	10.12	10.17	11.14
Combine2	1.27	3.01	3.01	5.01
Unroll 2	1.01	3.01	3.01	5.01
Latency Bound	1.00	3.00	3.00	5.00

Reassociation

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



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



Effect of Reassociation

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 –O0	22.68	20.02	19.98	20.18
Combine1 –O1	10.12	10.12	10.17	11.14
Combine2	1.27	3.01	3.01	5.01
Unroll 2	1.01	3.01	3.01	5.01
Unroll 2a	1.01	1.51	1.51	2.51
Latency Bound	1.00	3.00	3.00	5.00
Throughput Bound	0.50	1.00	1.00	0.50

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

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

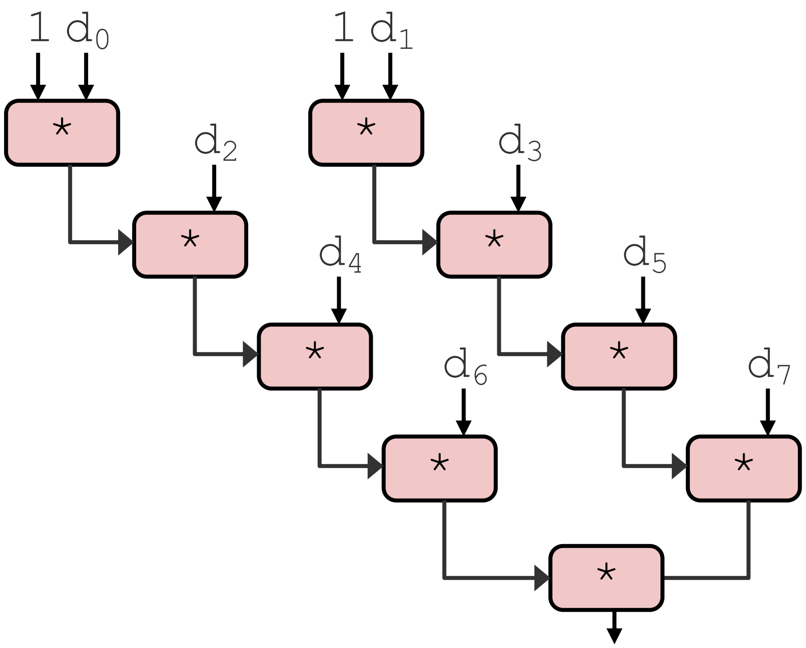
2 func. units for FP *
2 func. units for load

pipelined processor

4 func. units for int +
2 func. units for load

Separate Accumulators

```
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

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 –O0	22.68	20.02	19.98	20.18
Combine1 –O1	10.12	10.12	10.17	11.14
Combine2	1.27	3.01	3.01	5.01
Unroll 2	1.01	3.01	3.01	5.01
Unroll 2a	1.01	1.51	1.51	2.51
Unroll 2x2	0.81	1.51	1.51	2.51
Latency Bound	1.00	3.00	3.00	5.00
Throughput Bound	0.50	1.00	1.00	0.50

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

- Int + makes use of two load units
- for Int *, FP +, FP *, speedup similar to unroll with reassociation

Machine-Dependent Optimization

Integer Addition

Accumulators

FP *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	1.27	1.01	1.01	1.01	1.01	1.01	1.01	
2		0.81		0.69		0.54		
3			0.74					
4				0.69		1.24		
6					0.56			0.56
8						0.54		
10							0.54	
12								0.56

Float Multiplication

Accumulators

FP *	Unrolling Factor L							
K	1	2	3	4	6	8	10	12
1	5.01	5.01	5.01	5.01	5.01	5.01	5.01	
2		2.51		2.51		2.51		
3			1.67					
4				1.25		1.26		
6					0.84			0.88
8						0.63		
10							0.51	
12								0.52

Machine-Dependent Optimization

Method	Integer		Double FP	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 –O0	22.68	20.02	19.98	20.18
Combine1 –O1	10.12	10.12	10.17	11.14
Combine2	1.27	3.01	3.01	5.01
Unroll 2	1.01	3.01	3.01	5.01
Unroll 2a	1.01	1.51	1.51	2.51
Unroll 2x2	0.81	1.51	1.51	2.51
Optimal Unrolling	0.54	1.01	1.01	0.51
Latency Bound	1.00	3.00	3.00	5.00
Throughput Bound	0.50	1.00	1.00	0.50

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