CS 33 – Discussion 1A
Computer System Organization

Week 5

Questions before we start?

Logistics

- Lab 1 - Bomblab due tonight 11:59pm
- Lab 2 – Attack lab will be released May 5th – Due Friday May 18th 11:55pm
- HW 3 will be released soon, due May 10th
- Please submit suggestions on CCLE TA-site on how to improve OH or DISC
  - Please fill out LA survey on CCLE

Agenda

10am-11am PST:

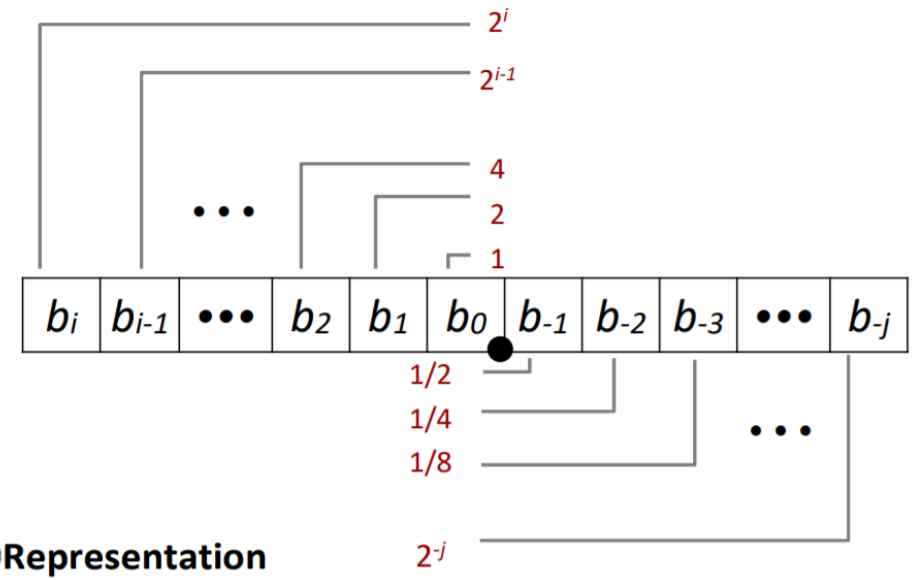
- Go through midterm together?
- Floating point
- Stack overflow attacks
- Optimization

11am-11:50am PST:

- LA worksheet

x86-64 Basics – Floating point

Fractional Binary Numbers



- **Representation**
  - Bits to right of "binary point" represent fractional powers of 2
  - Represents rational number: $\sum_{k=-j}^{i} b_k \times 2^k$

x86-64 Basics – Floating point

Floating Point Representation

- **Numerical Form:**

$$(-1)^s\ M\ 2^E$$

  - **Sign bit** ***s*** determines whether number is negative or positive
  - **Significand** ***M*** normally a fractional value in range [1.0,2.0).
  - **Exponent** ***E*** weights value by power of two

- **Encoding**
  - MSB s is sign bit ***s***
  - exp field encodes ***E*** (but is not equal to E)
  - frac field encodes ***M*** (but is not equal to M)

x86-64 Basics – Floating point

Precision options

- **Single precision: 32 bits**

- **Double precision: 64 bits**

- **Extended precision: 80 bits (Intel only)**

- **Conversions/Casting**
  - Casting between `int`, `float`, and `double` changes bit representation
  - `double/float` → `int`
    - Truncates fractional part
    - Like rounding toward zero
    - Not defined when out of range or NaN: Generally sets to TMin
  - `int` → `double`
    - Exact conversion, as long as `int` has ≤ 53 bit word size
  - `int` → `float`
    - Will round according to rounding mode

x86-64 Basics – Floating point

"Normalized" Values

$v = (-1)^s M 2^E$

- **When: exp ≠ 000…0 and exp ≠ 111…1**
- **Exponent coded as a *biased* value: *E* = *Exp* – *Bias***
  - *Exp*: unsigned value of exp field
  - *Bias* = $2^{k-1} - 1$, where *k* is number of exponent bits
    - Single precision: 127 (Exp: 1…254, E: -126…127)
    - Double precision: 1023 (Exp: 1…2046, E: -1022…1023)
- **Significand coded with implied leading 1: *M* = 1.xxx…x_2**
  - xxx…x: bits of frac field
  - Minimum when frac=000…0 (M = 1.0)
  - Maximum when frac=111…1 (M = 2.0 – ε)
  - Get extra leading bit for "free"

x86-64 Basics – Floating point

Denormalized Values

$$v = (-1)^s M 2^E$$
$$E = 1 - Bias$$

- **Condition: exp = 000…0**

- **Exponent value: *E* = 1 – Bias (instead of *E* = 0 – *Bias*)**
- **Significand coded with implied leading 0: *M* = 0.xxx…x_2**
  - **`xxx…x`**: bits of **`frac`**
- **Cases**
  - **`exp`** = 000…0, **`frac`** = 000…0
    - Represents zero value
    - Note distinct values: +0 and –0
  - **`exp`** = 000…0, **`frac`** ≠ 000…0
    - Numbers closest to 0.0
    - Equispaced

x86-64 Basics – Floating point

Special Values

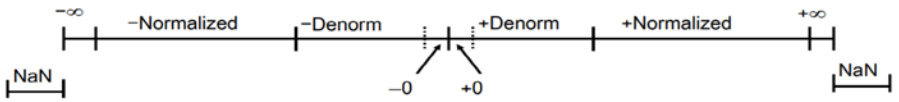
- **Condition: `exp` = `111…1`**

- **Case: `exp` = `111…1`, `frac` = `000…0`**
  - Represents value ∞ (infinity)
  - Operation that overflows
  - Both positive and negative
  - E.g., 1.0/0.0 = −1.0/−0.0 = +∞, 1.0/−0.0 = −∞

- **Case: `exp` = `111…1`, `frac` ≠ `000…0`**
  - Not-a-Number (NaN)
  - Represents case when no numeric value can be determined
  - E.g., sqrt(–1), ∞ − ∞, ∞ × 0

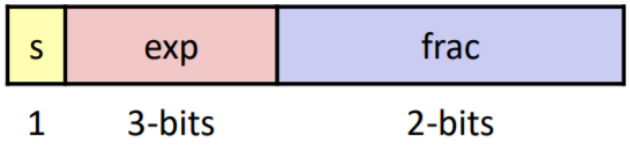
x86-64 Basics – Floating point

Visualization: Floating Point Encodings

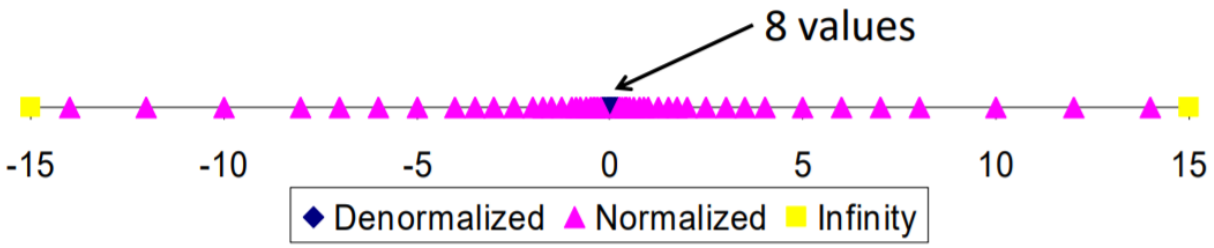


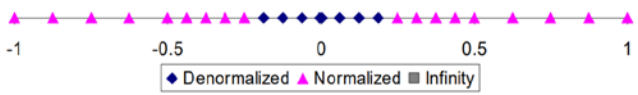
Distribution of Values

- 6-bit IEEE-like format
  - e = 3 exponent bits
  - f = 2 fraction bits
  - Bias is $2^{3-1}-1 = 3$



- Notice how the distribution gets denser toward zero.





x86-64 Basics – Floating point

Special Properties of the IEEE Encoding

- **FP Zero Same as Integer Zero**
  - All bits = 0
- **Can (Almost) Use Unsigned Integer Comparison**
  - Must first compare sign bits
  - Must consider −0 = 0
  - NaNs problematic
    - Will be greater than any other values
    - What should comparison yield?
  - Otherwise OK
    - Denorm vs. normalized
    - Normalized vs. infinity

Floating Point Operations: Basic Idea

- $x +_f y = \text{Round}(x + y)$
- $x \times_f y = \text{Round}(x \times y)$
- **Basic idea**
  - First compute exact result
  - Make it fit into desired precision
    - Possibly overflow if exponent too large
    - Possibly round to fit into `frac`

x86-64 Basics – Floating point

Rounding Binary Numbers

- **Binary Fractional Numbers**
  - "Even" when least significant bit is 0
  - "Half way" when bits to right of rounding position = $100\ldots_2$

- **Examples**
  - Round to nearest 1/4 (2 bits right of binary point)

Value	Binary	Rounded	Action	Rounded Value
2 3/32	10.00011_2	10.00_2	(<1/2—down)	2
2 3/16	10.00110_2	10.01_2	(>1/2—up)	2 1/4
2 7/8	10.11100_2	11.00_2	(1/2—up)	3
2 5/8	10.10100_2	10.10_2	(1/2—down)	2 1/2

x86-64 Basics – Floating point

FP Multiplication

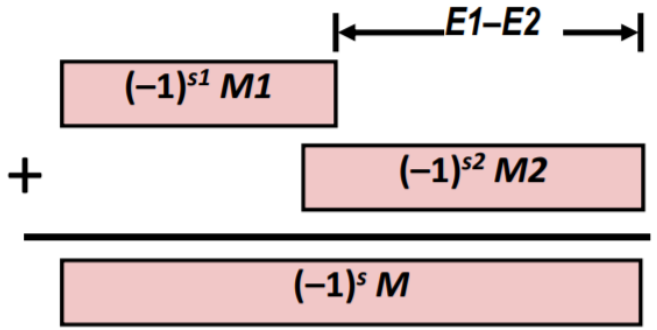
- $(-1)^{s1}\ M1\ \ 2^{E1}$ x $(-1)^{s2}\ M2\ \ 2^{E2}$
- **Exact Result:** $(-1)^{s}\ M\ \ 2^{E}$
  - Sign *s*: *s1* ^ *s2*
  - Significand *M*: *M1* x *M2*
  - Exponent *E*: *E1* + *E2*
- **Fixing**
  - If *M* ≥ 2, shift *M* right, increment *E*
  - If *E* out of range, overflow
  - Round *M* to fit `frac` precision
- **Implementation**
  - Biggest chore is multiplying significands

x86-64 Basics – Floating point

Floating Point Addition

- $(-1)^{s1}\ M1\ \ 2^{E1}\ \ +\ \ (-1)^{s2}\ M2\ \ 2^{E2}$
  - Assume $E1 > E2$
- **Exact Result: $(-1)^{s}\ M\ \ 2^{E}$**
  - Sign s, significand M:
    - Result of signed align & add
  - Exponent E: $E1$

Get binary points lined up



- **Fixing**
  - If $M \geq 2$, shift M right, increment E
  - if $M < 1$, shift M left k positions, decrement E by k
  - Overflow if E out of range
  - Round M to fit `frac` precision

x86-64 Basics – Floating point

Floating Point Addition

- $(-1)^{s1}\ M1\ \ 2^{E1}\ \ +\ \ (-1)^{s2}\ M2\ \ 2^{E2}$
  - Assume $E1 > E2$
- **Exact Result: $(-1)^{s}\ M\ \ 2^{E}$**
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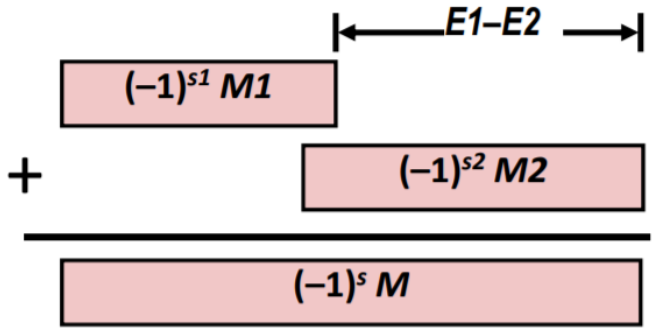
Get binary points lined up



- **Fixing**
  - If $M \geq 2$, shift M right, increment E
  - if $M < 1$, shift M left k positions, decrement E by k
  - Overflow if E out of range
  - Round M to fit `frac` precision

x86-64 Basics – Stack attacks

- Stack overflow attacks

- Inject code on stack to execute on stack
  - Through buffer overflow into local variables
    - e.g. int buffer[LIMIT] with |input| > LIMIT
  - Stick byte-code that corresponds to your ins
  - When it returns from function, pops ret val
    - Ret val overwritten to beginning of stack

- Return oriented programming
  - Find desired byte code sequences for ins in text memory
    - Must end with c3 – for retq
  - Stick pointer to code on stack beginning at overwritten ret addr (address)

x86-64 Basics – Stack attacks

- Stack overflow attack protections

- For first type:
  - make stack non-executeable
    - Permission bits on pages, can be hardware check
  - Randomize stack location

- For ROP: use stack canaries
  - Special hidden value placed on stack after ret addr
    - See if ret addr overwritten with canary check
    - Then return from function else raise fault

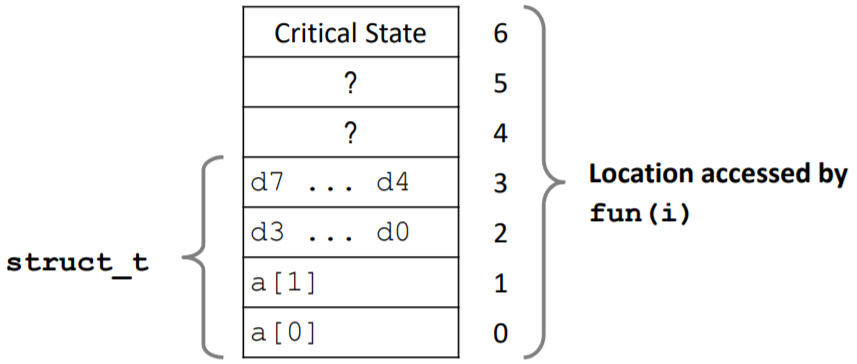
x86-64 Basics – Stack attacks

Recall: Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;

double fun(int i) {
  volatile struct_t s;
  s.d = 3.14;
  s.a[i] = 1073741824; /* Possibly out of bounds */
  return s.d;
}
```

Explanation:




```
fun(0)  ↬  3.14
fun(1)  ↬  3.14
fun(2)  ↬  3.1399998664856
fun(3)  ↬  2.00000061035156
fun(4)  ↬  3.14
fun(6)  ↬  Segmentation fault
```

x86-64 Basics – Stack attacks

Vulnerable Buffer Code

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

← btw, how big is big enough?

```
void call_echo() {
    echo();
}
```

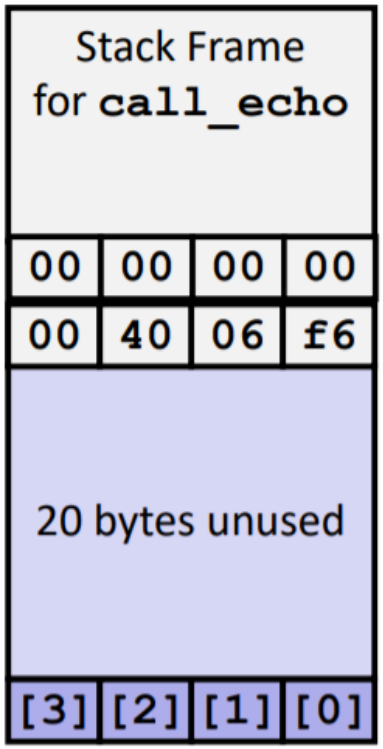
```
unix>./bufdemo-nsp
Type a string:012345678901234567890123
012345678901234567890123
```

```
unix>./bufdemo-nsp
Type a string:012345678901234567890123
Segmentation Fault
```

x86-64 Basics – Stack attacks

Buffer Overflow Stack Example

Before call to gets




```
void echo()
{
    char buf[4];
    gets(buf);
    . . .
}
```

```
echo:
   subq   $24, %rsp
   movq   %rsp, %rdi
   call   gets
   . . .
```

call_echo:

```
   . . .
4006f1:  callq  4006cf <echo>
4006f6:  add    $0x8,%rsp
   . . .
```

x86-64 Basics – Stack attacks

```
unix>./bufdemo-nsp
Type a string:0123456789012345678901
0123456789012345678901
```

```
unix>./bufdemo-nsp
Type a string:012345678901234567890123
Segmentation Fault
```

After call to gets

Stack Frame for `call_echo`			
00	00	00	00
00	40	06	f6
00	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

Could overwrite stack to jump to address that doesn't cause seg fault

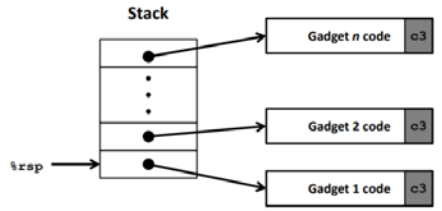
After call to gets

Stack Frame for `call_echo`			
00	00	00	00
00	40	00	34
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

x86-64 Basics – Stack attacks ROP

- **Construct program from *gadgets***
  - Sequence of instructions ending in `ret`
    - Encoded by single byte `0xc3`
  - Code positions fixed from run to run
  - Code is executable

ROP Execution



- Trigger with `ret` instruction
  - Will start executing Gadget 1
- Final `ret` in each gadget will start next one

Gadget Example #2

```
void setval(unsigned *p) {
    *p = 3347663060u;
}
```

Encodes `movq %rax, %rdi`

```
<setval>:
  4004d9:  c7 07 d4 48 89 c7   movl   $0xc78948d4,(%rdi)
  4004df:  c3                  retq
```

rdi ← rax

Gadget address = 0x4004dc

- Repurpose byte codes

Gadget Example #1

```
long ab_plus_c
  (long a, long b, long c)
{
   return a*b + c;
}
```

```
00000000004004d0 <ab_plus_c>:
  4004d0:  48 0f af fe     imul %rsi,%rdi
  4004d4:  48 8d 04 17     lea (%rdi,%rdx,1),%rax
  4004d8:  c3              retq
```

rax ← rdi + rdx

Gadget address = 0x4004d4

- Use tail end of existing functions

x86-64 Basics – Optimization

Basic types of optimization:

- Code motion
- Reduction in Strength
- Share common Subexpressions
- Loop unrolling

Optimization blockers:

- Procedure calls
  - Fix by doing own code motion
  - Inline functions
- Memory Aliasing
  - Pointers can point to same object
    - Makes it so you have to access memory everytime to mutate object
      - Keep a local copy to amortize reads/writes
        - Accumulate in loop

x86-64 Basics – Code motion

- **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];
```

x86-64 Basics – Code motion

- **Code Motion**
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}
```

→

```
    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;
    long ni = n*i;
    double *rowp = a+ni;
    for (j = 0; j < n; j++)
        *rowp++ = 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
```

x86-64 Basics – share calculation

Share Common Subexpressions

- Reuse portions of expressions
- 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: i*n, (i–1)*n, (i+1)*n

```
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
```

```
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: i*n

```
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
```

x86-64 Basics – Loop unrolling

Loop Unrolling (2x1)

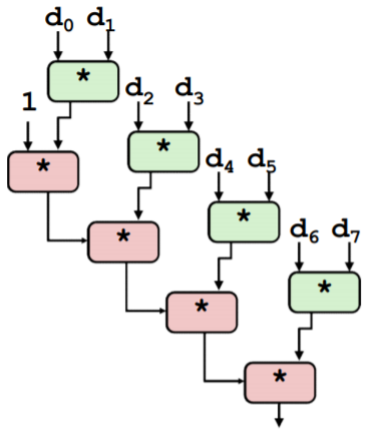
```
void unroll2a_combine(vec_ptr v, data_t *dest)
{
    long length = vec_length(v);
    long limit = length-1;
    data_t *d = get_vec_start(v);
    data_t x = IDENT;
    long i;
    /* Combine 2 elements at a time */
    for (i = 0; i < limit; i+=2) {
        x = (x OP d[i]) OP d[i+1];
    }
    /*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

- Perform 2x more useful work per iteration

x86-64 Basics – Loop unrolling

Loop Unrolling with Reassociation (2x1a)

```
void unroll2aa_combine(vec_ptr v, data_t *dest)
{
    long length = vec_length(v);
    long limit = length-1;
    data_t *d = get_vec_start(v);
    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;
}
```



Compare to before

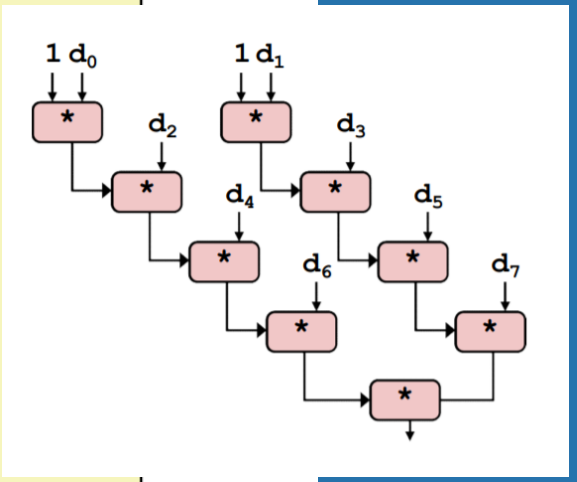
```
x = (x OP d[i]) OP d[i+1];
```

- Can this change the result of the computation?

x86-64 Basics – Loop unrolling

Loop Unrolling with Separate Accumulators (2x2)

```
void unroll2a_combine(vec_ptr v, data_t *dest)
{
    long length = vec_length(v);
    long limit = length-1;
    data_t *d = get_vec_start(v);
    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;
}
```



x86-64 Basics – Optimization block

Optimization Blocker: Procedure Calls

- ***Why couldn't compiler move*** `strlen` ***out of inner loop?***
  - Procedure may have side effects
    - Alters global state each time called
  - Function may not return same value for given arguments
    - Depends on other parts of global state
    - Procedure `lower` could interact with `strlen`
- **Warning:**
  - Compiler treats procedure call as a black box
  - Weak optimizations near them
- **Remedies:**
  - Use of inline functions
    - GCC does this with –O1
      - Within single file
  - Do your own code motion

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

x86-64 Basics – Optimization block

Memory Aliasing

```
/* Sum rows is 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];
    }
}
```

FIX:

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

- **Aliasing**
  - Two different memory references specify single location
  - Easy to have happen in C
    - Since allowed to do address 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

```
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]
i = 1: [3, 22, 16]
i = 2: [3, 22, 224]
```

- Code updates `b[i]` on every iteration
- Must consider possibility that these updates will affect program behavior

Questions before we start worksheet?

Resources used

- Professor Reinman's slides (CCLE)
- **Credit for compilation: Attiano Purpura-Pontoniere**