Topics

- Arrays
- Structs
- Unions

Basic Data Types

Integral

- Stored & operated on in general registers
- Signed vs. unsigned depends on instructions used

Intel	GAS	Bytes	C
byte	`b`	1	`[unsigned] char`
word	`w`	2	`[unsigned] short`
double word	`l`	4	`[unsigned] int`

Floating Point

- Stored & operated on in floating point registers

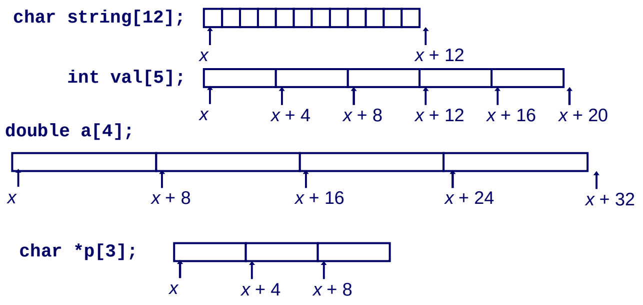
Intel	GAS	Bytes	C
Single	`s`	4	`float`
Double	`l`	8	`double`
Extended	`t`	10/12	`long double`

Array Allocation

Basic Principle

T `A[`*L*`];`

- Array of data type *T* and length *L*
- Contiguously allocated region of *L* * `sizeof(`*T*`)` bytes



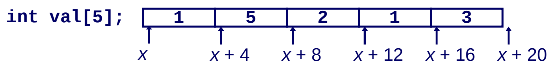
```
char string[12];
int val[5];
double a[4];
char *p[3];
```

Array Access

Basic Principle

T `A[`*L*`];`

- Array of data type *T* and length *L*
- Identifier A can be used as a pointer to array element 0

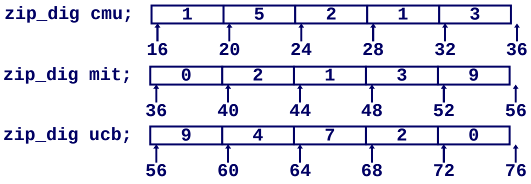


```
int val[5];
```

Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val +` *i*	`int *`	*x* + 4 *i*

Array Example

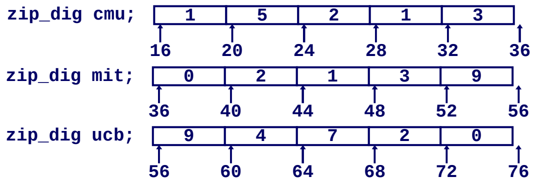
```
typedef int zip_dig[5];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```



Notes

- Declaration “`zip_dig cmu`” equivalent to “`int cmu[5]`”
- Example arrays were allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

Referencing Examples



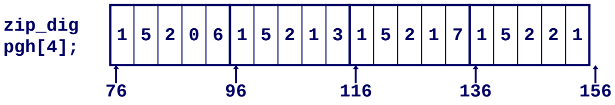
Code Does Not Do Any Bounds Checking!

Reference	Address	Value	Guaranteed?
`mit[3]`	`36 + 4* 3 = 48`	3	Yes
`mit[5]`	`36 + 4* 5 = 56`	9	No
`mit[-1]`	`36 + 4*-1 = 32`	3	No
`cmu[15]`	`16 + 4*15 = 76`	??	No

- Out of range behavior implementation-dependent
  - No guaranteed relative allocation of different arrays

Nested Array Example

```
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```



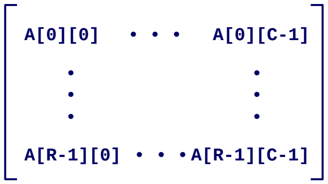
- Declaration “`zip_dig pgh[4]`” equivalent to “`int pgh[4][5]`”
  - Variable pgh denotes array of 4 elements
    - » Allocated contiguously
  - Each element is an array of 5 `int`’s
    - » Allocated contiguously
- “Row-Major” ordering of all elements guaranteed

Nested Array Allocation

Declaration

T `A[`*R*`][`*C*`];`

- Array of data type *T*
- *R* rows, *C* columns
- Type *T* element requires *K* bytes



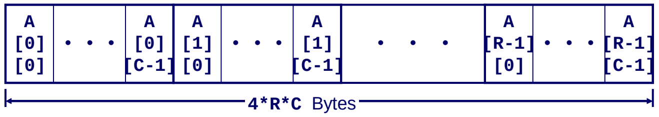
Array Size

- *R* * *C* * *K* bytes

Arrangement

- Row-Major Ordering

`int A[R][C];`

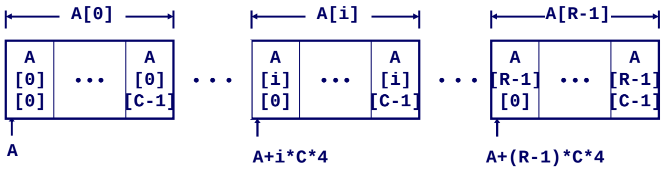


Nested Array Row Access

Row Vectors

- `A[i]` is array of *C* elements
- Each element of type *T*
- Starting address `A +` *i * C * K*

```
int A[R][C];
```

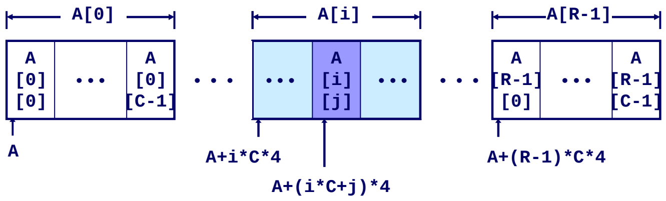


Nested Array Element Access

Array Elements

- `A[i][j]` is element of type *T*
- Address `A +` (*i * C + j*) * *K*

```
int A[R][C];
```

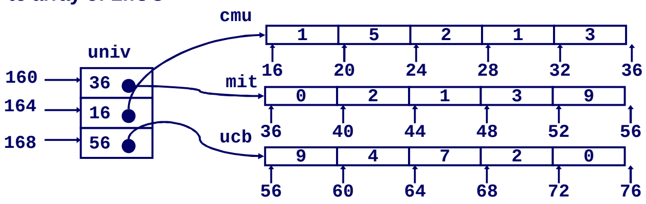


Multi-Level Array Example

- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 4 bytes
- Each pointer points to array of `int`'s

```
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

```
#define UCOUNT 3
int *univ[UCOUNT] = {mit, cmu, ucb};
```



Element Access in Multi-Level Array

```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```

Computation

- Element access `Mem[Mem[univ+4*index]+4*dig]`
- Must do two memory reads
  - First get pointer to row array
  - Then access element within array

```
  # %ecx = index
  # %eax = dig
  leal 0(,%ecx,4),%edx     # 4*index
  movl univ(%edx),%edx     # Mem[univ+4*index]
  movl (%edx,%eax,4),%eax  # Mem[...+4*dig]
```

Array Element Accesses

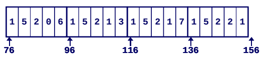
- Similar C references

Nested Array

```
int get_pgh_digit
  (int index, int dig)
{
  return pgh[index][dig];
}
```

- Element at

`Mem[pgh+20*index+4*dig]`



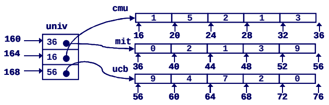
- Different address computation

Multi-Level Array

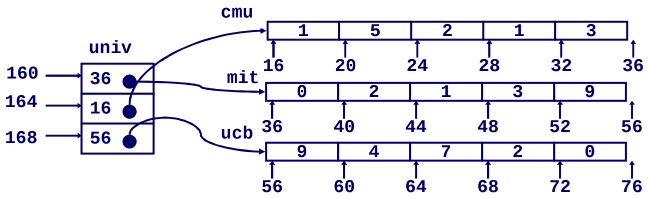
```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```

- Element at

`Mem[Mem[univ+4*index]+4*dig]`



Strange Referencing Examples



Reference	Address	Value	Guaranteed?
`univ[2][3]`	`56+4*3   = 68`	`2`	Yes
`univ[1][5]`	`16+4*5   = 36`	`0`	No
`univ[2][-1]`	`56+4*-1 = 52`	`9`	No
`univ[3][-1]`	`??`	`??`	No
`univ[1][12]`	`16+4*12 = 64`	`7`	No

- Code does not do bounds checking
- Ordering of elements in different arrays not guaranteed

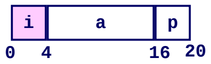
Structures

Concept

- Contiguously-allocated region of memory
- Refer to members within structure by names
- Members may be of different types

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

Memory Layout



Accessing Structure Member

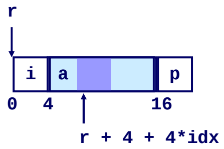
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

Assembly

```
# %eax = val
# %edx = r
movl %eax,(%edx)    # Mem[r] = val
```

Generating Pointer to Struct. Member

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```



Generating Pointer to Array Element

- Offset of each structure member determined at compile time

```
int *
find_a
 (struct rec *r, int idx)
{
  return &r->a[idx];
}
```

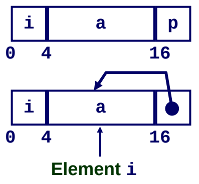
```
# %ecx = idx
# %edx = r
leal 0(,%ecx,4),%eax   # 4*idx
leal 4(%eax,%edx),%eax # r+4*idx+4
```

Structure Referencing (Cont.)

C Code

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

```
void
set_p(struct rec *r)
{
  r->p =
   &r->a[r->i];
}
```



```
 # %edx = r
movl (%edx),%ecx       # r->i
leal 0(,%ecx,4),%eax   # 4*(r->i)
leal 4(%edx,%eax),%eax # r+4+4*(r->i)
movl %eax,16(%edx)     # Update r->p
```

Alignment

Aligned Data

- Primitive data type requires K bytes
- Address must be multiple of K
- Required on some machines; advised on IA32
  - treated differently by Linux and Windows!

Motivation for Aligning Data

- Memory accessed by (aligned) double or quad-words
  - Inefficient to load or store datum that spans quad word boundaries
  - Virtual memory very tricky when datum spans 2 pages

Compiler

- Inserts gaps in structure to ensure correct alignment of fields

Specific Cases of Alignment

Size of Primitive Data Type:

- 1 byte (e.g., `char`)
  - no restrictions on address
- 2 bytes (e.g., `short`)
  - lowest 1 bit of address must be 0_2
- 4 bytes (e.g., `int`, `float`, `char *`, etc.)
  - lowest 2 bits of address must be 00_2
- 8 bytes (e.g., `double`)
  - Windows (and most other OS's & instruction sets):
    - » lowest 3 bits of address must be 000_2
  - Linux:
    - » lowest 2 bits of address must be 00_2
    - » i.e., treated the same as a 4-byte primitive data type
- 12 bytes (`long double`)
  - Linux:
    - » lowest 2 bits of address must be 00_2
    - » i.e., treated the same as a 4-byte primitive data type

Satisfying Alignment with Structures

Offsets Within Structure

- Must satisfy element's alignment requirement

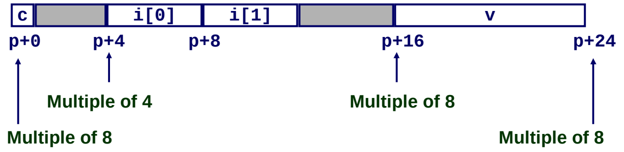
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

Overall Structure Placement

- Each structure has alignment requirement K
  - Largest alignment of any element
- Initial address & structure length must be multiples of K

Example (under Windows):

- K = 8, due to `double` element

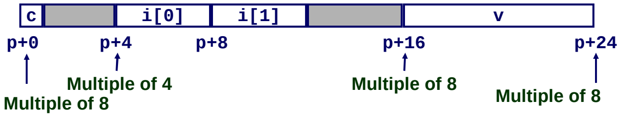


Linux vs. Windows

```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

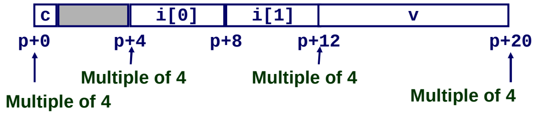
Windows (including Cygwin):

- K = 8, due to `double` element



Linux:

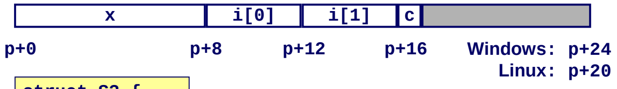
- K = 4; `double` treated like a 4-byte data type



Overall Alignment Requirement

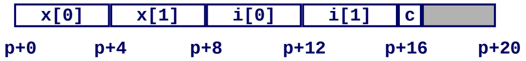
```
struct S2 {
  double x;
  int i[2];
  char c;
} *p;
```

p must be multiple of:
8 for Windows
4 for Linux



```
struct S3 {
  float x[2];
  int i[2];
  char c;
} *p;
```

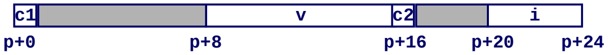
p must be multiple of 4 (in either OS)



Ordering Elements Within Structure

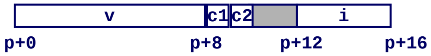
```
struct S4 {
  char c1;
  double v;
  char c2;
  int i;
} *p;
```

10 bytes wasted space in Windows



```
struct S5 {
  double v;
  char c1;
  char c2;
  int i;
} *p;
```

2 bytes wasted space

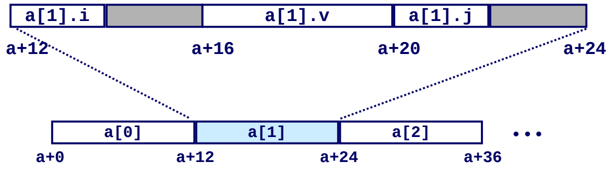


Arrays of Structures

Principle

- Allocated by repeating allocation for array type
- In general, may nest arrays & structures to arbitrary depth

```
struct S6 {
  short i;
  float v;
  short j;
} a[10];
```

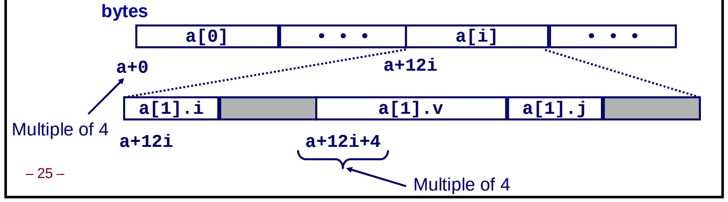


Satisfying Alignment within Structure

Achieving Alignment

- Starting address of structure array must be multiple of worst-case alignment for any element
  - a must be multiple of 4
- Offset of element within structure must be multiple of element's alignment requirement
  - v's offset of 4 is a multiple of 4
- Overall size of structure must be multiple of worst-case alignment for any element
  - Structure padded with unused space to be 12 bytes

```
struct S6 {
  short i;
  float v;
  short j;
} a[10];
```

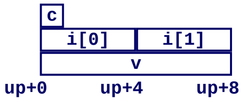


Union Allocation

Principles

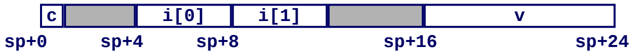
- Overlay union elements
- Allocate according to largest element
- Can only use one field at a time

```
union U1 {
  char c;
  int i[2];
  double v;
} *up;
```



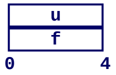
```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```

(Windows alignment)



Using Union to Access Bit Patterns

```
typedef union {
  float f;
  unsigned u;
} bit_float_t;
```



- Get direct access to bit representation of float
- `bit2float` generates float with given bit pattern
  - NOT the same as `(float) u`
- `float2bit` generates bit pattern from float
  - NOT the same as `(unsigned) f`

```
float bit2float(unsigned u)
{
  bit_float_t arg;
  arg.u = u;
  return arg.f;
}
```

```
unsigned float2bit(float f)
{
  bit_float_t arg;
  arg.f = f;
  return arg.u;
}
```

Byte Ordering Revisited

Idea

- Short/long/quad words stored in memory as 2/4/8 consecutive bytes
- Which is most (least) significant?
- Can cause problems when exchanging binary data between machines

Big Endian

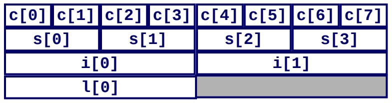
- Most significant byte has lowest address
- PowerPC, Sparc

Little Endian

- Least significant byte has lowest address
- Intel x86, Alpha

Byte Ordering Example

```
    union {
      unsigned char c[8];
      unsigned short s[4];
      unsigned int i[2];
      unsigned long l[1];
    } dw;
```



c[0] c[1] c[2] c[3] c[4] c[5] c[6] c[7]

s[0] s[1] s[2] s[3]

i[0] i[1]

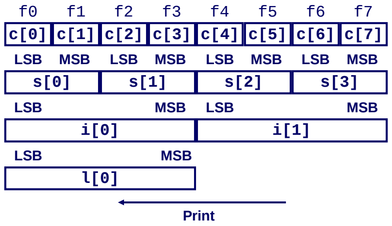
l[0]

Byte Ordering Example (Cont).

```
int j;
for (j = 0; j < 8; j++)
dw.c[j] = 0xf0 + j;

printf("Characters 0-7 ==
[0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x]\n",
    dw.c[0], dw.c[1], dw.c[2], dw.c[3],
    dw.c[4], dw.c[5], dw.c[6], dw.c[7]);

printf("Shorts 0-3 ==
[0x%x,0x%x,0x%x,0x%x]\n",
    dw.s[0], dw.s[1], dw.s[2], dw.s[3]);

printf("Ints 0-1 == [0x%x,0x%x]\n",
    dw.i[0], dw.i[1]);

printf("Long 0 == [0x%lx]\n",
    dw.l[0]);
```

Byte Ordering on x86

Little Endian



f0 f1 f2 f3 f4 f5 f6 f7

c[0] c[1] c[2] c[3] c[4] c[5] c[6] c[7]

LSB MSB LSB MSB LSB MSB LSB MSB

s[0] s[1] s[2] s[3]

LSB MSB LSB MSB

i[0] i[1]

LSB MSB

l[0]

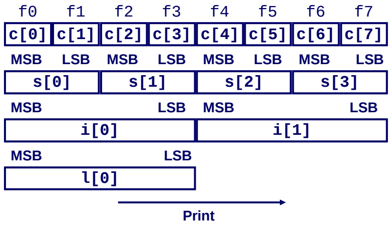
Print

Output on Pentium:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,0xf3f2,0xf5f4,0xf7f6]
Ints       0-1 == [0xf3f2f1f0,0xf7f6f5f4]
Long       0   == [f3f2f1f0]
```

Byte Ordering on Sun

Big Endian



f0 f1 f2 f3 f4 f5 f6 f7

c[0] c[1] c[2] c[3] c[4] c[5] c[6] c[7]

MSB LSB MSB LSB MSB LSB MSB LSB

s[0] s[1] s[2] s[3]

MSB LSB MSB LSB

i[0] i[1]

MSB LSB

l[0]

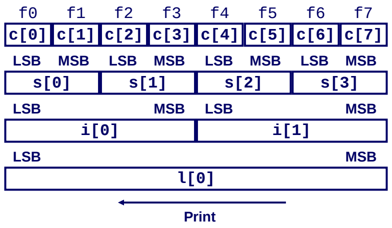
Print

Output on Sun:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf0f1,0xf2f3,0xf4f5,0xf6f7]
Ints       0-1 == [0xf0f1f2f3,0xf4f5f6f7]
Long       0   == [0xf0f1f2f3]
```

Byte Ordering on Alpha

Little Endian


f0 f1 f2 f3 f4 f5 f6 f7

c[0] c[1] c[2] c[3] c[4] c[5] c[6] c[7]

LSB MSB LSB MSB LSB MSB LSB MSB

s[0] s[1] s[2] s[3]

LSB MSB LSB MSB

i[0] i[1]

LSB MSB

l[0]

Print

Output on Alpha:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,0xf3f2,0xf5f4,0xf7f6]
Ints       0-1 == [0xf3f2f1f0,0xf7f6f5f4]
Long       0   == [0xf7f6f5f4f3f2f1f0]
```

Summary

Arrays in C

- Contiguous allocation of memory
- Pointer to first element
- No bounds checking

Compiler Optimizations

- Compiler often turns array code into pointer code (`zd2int`)
- Uses addressing modes to scale array indices
- Lots of tricks to improve array indexing in loops

Structures

- Allocate bytes in order declared
- Pad in middle and at end to satisfy alignment

Unions

- Overlay declarations
- Way to circumvent type system

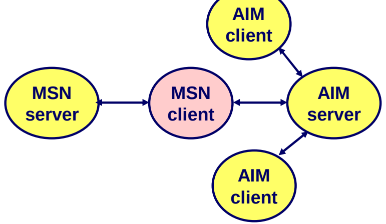
Internet Worm and IM War

November, 1988

- Internet Worm attacks thousands of Internet hosts.
- How did it happen?

July, 1999

- Microsoft launches MSN Messenger (instant messaging system).
- Messenger clients can access popular AOL Instant Messaging Service (AIM) servers


AIM client

MSN server

MSN client

AIM server

AIM client

Internet Worm and IM War (cont.)

August 1999

- Mysteriously, Messenger clients can no longer access AIM servers.
- Microsoft and AOL begin the IM war:
  - AOL changes server to disallow Messenger clients
  - Microsoft makes changes to clients to defeat AOL changes.
  - At least 13 such skirmishes.
- How did it happen?

The Internet Worm and AOL/Microsoft War were both based on *stack buffer overflow* exploits!

- many Unix functions do not check argument sizes.
- allows target buffers to overflow.

String Library Code

- Implementation of Unix function `gets`
  - No way to specify limit on number of characters to read

```
/* Get string from stdin */
char *gets(char *dest)
{
    int c = getc();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getc();
    }
    *p = '\0';
    return dest;
}
```

- Similar problems with other Unix functions
  - `strcpy`: Copies string of arbitrary length
  - `scanf`, `fscanf`, `sscanf`, when given `%s` conversion specification

Vulnerable Buffer Code

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

```
int main()
{
  printf("Type a string:");
  echo();
  return 0;
}
```

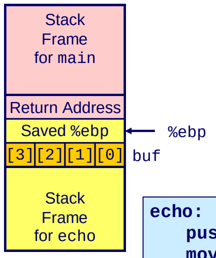
Buffer Overflow Executions

```
unix>./bufdemo
Type a string:123
123
```

```
unix>./bufdemo
Type a string:12345
Segmentation Fault
```

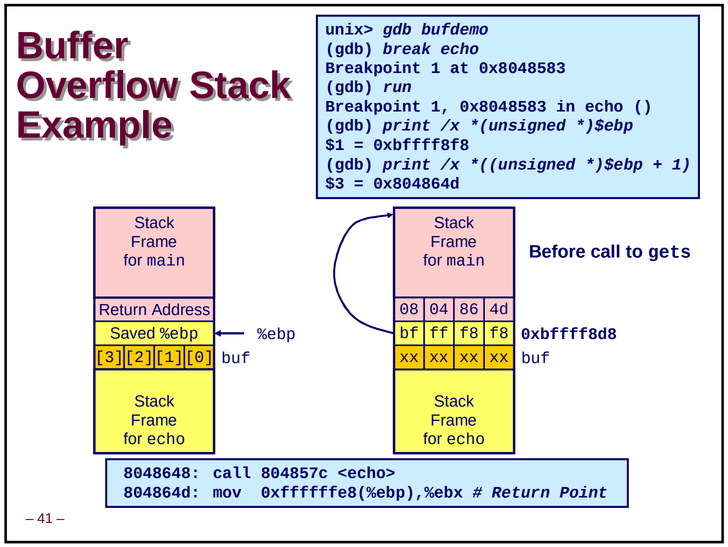
```
unix>./bufdemo
Type a string:12345678
Segmentation Fault
```

Buffer Overflow Stack



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

```
echo:
   pushl %ebp              # Save %ebp on stack
   movl %esp,%ebp
   subl $20,%esp           # Allocate space on stack
   pushl %ebx              # Save %ebx
   addl $-12,%esp          # Allocate space on stack
   leal -4(%ebp),%ebx      # Compute buf as %ebp-4
   pushl %ebx              # Push buf on stack
   call gets               # Call gets
   . . .
```



Buffer Overflow Stack Example

```
unix> gdb bufdemo
(gdb) break echo
Breakpoint 1 at 0x8048583
(gdb) run
Breakpoint 1, 0x8048583 in echo ()
(gdb) print /x *(unsigned *)$ebp
$1 = 0xbffff8f8
(gdb) print /x *((unsigned *)$ebp + 1)
$3 = 0x804864d
```

Stack Frame for main

Return Address

Saved %ebp ← %ebp

[3][2][1][0] buf

Stack Frame for echo

Stack Frame for main

08 | 04 | 86 | 4d

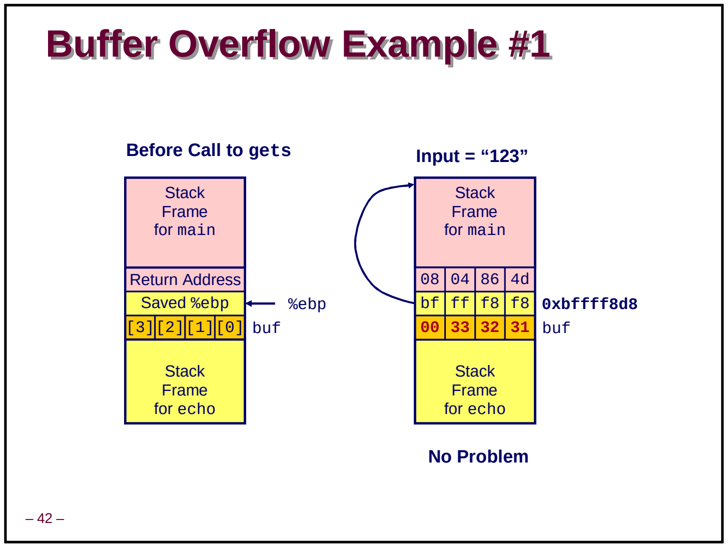
bf | ff | f8 | f8 0xbffff8d8

xx | xx | xx | xx buf

Stack Frame for echo

Before call to gets

```
8048648:  call 804857c <echo>
804864d:  mov  0xffffffe8(%ebp),%ebx # Return Point
```



Buffer Overflow Example #1

Before Call to gets

Stack Frame for main

Return Address

Saved %ebp ← %ebp

[3][2][1][0] buf

Stack Frame for echo

Input = “123”

Stack Frame for main

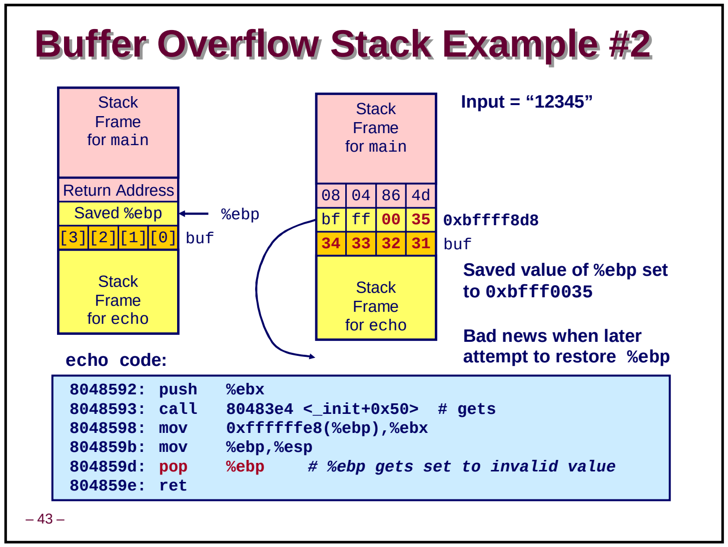
08 | 04 | 86 | 4d

bf | ff | f8 | f8 0xbffff8d8

00 | 33 | 32 | 31 buf

Stack Frame for echo

No Problem



Buffer Overflow Stack Example #2

Stack Frame for main

Return Address

Saved %ebp ← %ebp

[3][2][1][0] buf

Stack Frame for echo

Input = “12345”

Stack Frame for main

08 | 04 | 86 | 4d

bf | ff | 00 | 35 0xbffff8d8

34 | 33 | 32 | 31 buf

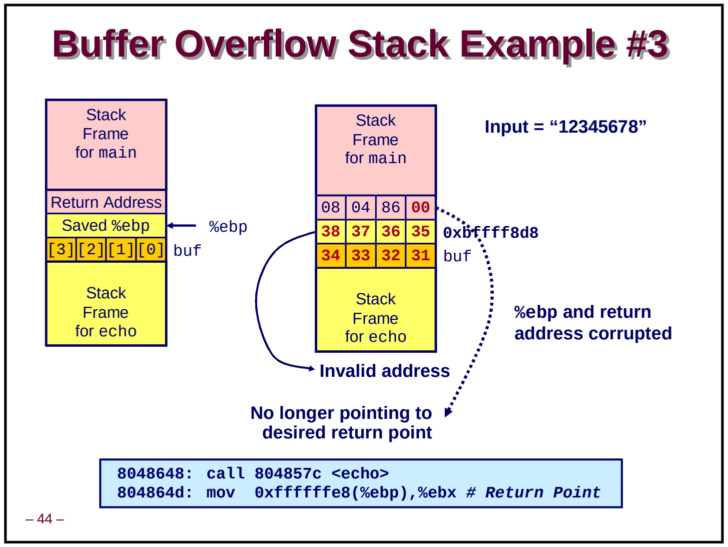
Stack Frame for echo

Saved value of %ebp set to 0xbfff0035

Bad news when later attempt to restore %ebp

echo code:

```
8048592:  push   %ebx
8048593:  call   80483e4 <_init+0x50>  # gets
8048598:  mov    0xffffffe8(%ebp),%ebx
804859b:  mov    %ebp,%esp
804859d:  pop    %ebp     # %ebp gets set to invalid value
804859e:  ret
```



Buffer Overflow Stack Example #3

Stack Frame for main

Return Address

Saved %ebp ← %ebp

[3][2][1][0] buf

Stack Frame for echo

Input = “12345678”

Stack Frame for main

08 | 04 | 86 | 00

38 | 37 | 36 | 35 0xbffff8d8

34 | 33 | 32 | 31 buf

Stack Frame for echo

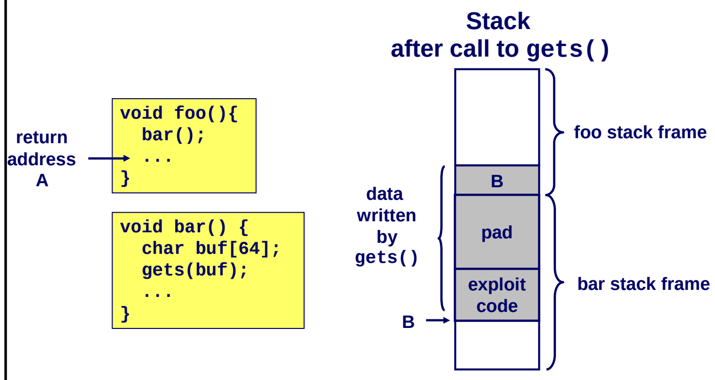
%ebp and return address corrupted

Invalid address

No longer pointing to desired return point

```
8048648:  call 804857c <echo>
804864d:  mov  0xffffffe8(%ebp),%ebx # Return Point
```

Malicious Use of Buffer Overflow



Stack after call to `gets()`

```
void foo(){
  bar();
  ...
}
```

```
void bar() {
  char buf[64];
  gets(buf);
  ...
}
```

- Input string contains byte representation of executable code
- Overwrite return address with address of buffer
- When `bar()` executes `ret`, will jump to exploit code

Exploits Based on Buffer Overflows

Buffer overflow bugs allow remote machines to execute arbitrary code on victim machines.

Internet worm

- Early versions of the finger server (fingerd) used `gets()` to read the argument sent by the client:
  - *`finger droh@cs.cmu.edu`*
- Worm attacked fingerd server by sending phony argument:
  - *`finger "exploit-code  padding  new-return-address"`*
  - exploit code: executed a root shell on the victim machine with a direct TCP connection to the attacker.

Exploits Based on Buffer Overflows

Buffer overflow bugs allow remote machines to execute arbitrary code on victim machines.

IM War

- AOL exploited existing buffer overflow bug in AIM clients
- exploit code: returned 4-byte signature (the bytes at some location in the AIM client) to server.
- When Microsoft changed code to match signature, AOL changed signature location.

Disclaimer

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