15-213: Final Exam Review

Your Tas

Final Exam Logistics

- **May 6th from 1:00 pm - 4:00 pm**
- Rooms in Gates
- **ON GRADESCOPE, IN PERSON**
- Physical Cheat sheets - 2 double sided 8.5 x 11 in.
- Show ID and cheatsheet to TA
- You will receive an email with more detailed logistics soon

Final Exam Topics

- Low-level C (structs, alignment)
- Bits, Bytes, Ints (datalab)
- Assembly (bomblab)
- Stacks (attacklab)
- Caches (cachelab)
- Malloc and Dynamic Memory Allocation (malloclab)
- Virtual Memory
- Processes, Signals, IO (tshlab)
- Proxy, Threads, Synchronization (proxylab)

Assembly

Assembly

- Typical questions asked
  - Given a function, look at assembly to fill in missing portions
  - Given assembly of a function, intuit the behavior of the program
  - (More rare) Compare different chunks of assembly, which one implements the function given?

- Important things to remember/put on your cheat sheet:
  - Memory Access formula: D(Rb,Ri,S)
  - Distinguish between mov/lea instructions
  - Callee/Caller save regs
  - Condition codes and corresponding eflags

Assembly

Consider the following x86-64 code (Recall that `%cl` is the low-order byte of `%rcx`):

```
# On entry:
#   %rdi = x
#   %rsi = y
#   %rdx = z

4004f0 <mysterious>:
  4004f0:   mov    $0x0,%eax
  4004f5:   lea    -0x1(%rsi),%r9d
  4004f9:   jmp    400510 <mysterious+0x20>
  4004fb:   lea    0x2(%rdx),%r8d
  4004ff:   mov    %esi,%ecx
  400501:   shl    %cl,%r8d
  400504:   mov    %r9d,%ecx
  400507:   sar    %cl,%r8d
  40050a:   add    %r8d,%eax
  40050d:   add    $0x1,%edx
  400510:   cmp    %edx,%edi
  400512:   ja     4004fb <mysterious+0xb>
  400514:   retq
```

Assembly

1) Please fill in the corresponding blanks below to make the C source equivalent to the assembly.

```
int mysterious(int x, int y, int z){
  unsigned i;
  int d = 0;
  int e;
  for(i = z ; ____ ; ____ ){
    e = i + 2;
    e = ____ ;
    e = ____ ;
    d = ____ ;
  }
  return ____ ;
}
```

```
# On entry:
#   %rdi = x
#   %rsi = y
#   %rdx = z

4004f0 <mysterious>:
  4004f0:   mov    $0x0,%eax
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int mysterious(int x, int y, int z){
  unsigned i;
  int d = 0;
  int e;
  for(i = z ; ; ){
    e = i + 2;
    e = ;
    e = ;
    d = ;
  }
  return ;
}
```

e = %r8d

```
# On entry:
#   %rdi = x
#   %rsi = y
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4004f0 <mysterious>:
  4004f0:   mov    $0x0,%eax
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int mysterious(int x, int y, int z){
  unsigned i;
  int d = 0;
  int e;
  for(i = z ; ; i++ ){
    e = i + 2;
    e =      ;
    e =      ;
    d =      ;
  }
  return     ;
}
```

```
# On entry:
#   %rdi = x
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4004f0 <mysterious>:
  4004f0:   mov    $0x0,%eax
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  400514:   retq
```

Loop end: add 1, compare, iterate

Assembly

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```
int mysterious(int x, int y, int z){
  unsigned i;
  int d = 0;
  int e;
  for(i = z ; x > i ; i++ ){
    e = i + 2;
    e =      ;
    e =      ;
    d =      ;
  }
  return     ;
}
```

```
# On entry:
#   %rdi = x
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4004f0 <mysterious>:
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```

cmp %edx, %edi => (edi - edx > 0), same as x > i

Assembly

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```
int mysterious(int x, int y, int z){
  unsigned i;
  int d = 0;
  int e;
  for(i = [ z ] ; [ x > i ] ; [ i++ ] ){
    e = i + 2;
    e = [          ] ;
    e = [          ] ;
    d = [          ] ;
  }
  return [          ] ;
}
```

We know that e = %r8d...

```
# On entry:
#   %rdi = x
#   %rsi = y
#   %rdx = z

4004f0 <mysterious>:
  4004f0:   mov    $0x0,%eax
  4004f5:   lea    -0x1(%rsi),%r9d
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  unsigned i;
  int d = 0;
  int e;
  for(i = [ z ]; [ x > i ]; [ i++ ]){
    e = i + 2;
    e = [ e << y ];
    e = [          ];
    d = [          ];
  }
  return [          ];
}
```

```
# On entry:
#   %rdi = x
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4004f0 <mysterious>:
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Where did %cl come from?

%ecx	%cx	%ch	%cl

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    e = i + 2;
    e = e << y ;
    e =                ;
    d =                ;
  }
  return             ;
}
```

Again, e = %r8d...

```
# On entry:
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  unsigned i;
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    e = e << y ;
    e = e >> (y - 1) ;
    d = ____ ;
  }
  return ____ ;
}
```

What's left?

```
# On entry:
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    e = [ e << y ];
    e = [ e >> (y - 1) ];
    d = [ e + d ];
  }
  return [ d ];
}
```

```
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    d = e + d ;
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  return d ;
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```

C stuff

Structs

Padding and Alignment Rules:

Primitives:

- Char: 1-byte aligned (doesn’t matter)
- Short: 2-byte aligned
- Int: 4-byte aligned
- Word/Pointer/Long: 8-byte aligned

Structs

Padding and Alignment Rules:

Struct within a struct:
Uses the alignment of the biggest primitive within the struct. So if the struct has a pointer, it'll itself have 8 byte alignment in other structs.

Structs

```
struct foo {
    int *p;
    char b;
    char c;
    int x;
    short y;
    char[4] buf;
};
```

How would this be represented?

Structs

```
struct foo {
   int *p;
   char b;
   char c;
   int x;
   short y;
   char[4] buf;
};
```

p	p	p	p	p	p	p	p
b	c	-	-	x	x	x	x
y	y	buf	buf	buf	buf	-	-

Structs

```
struct foo {
    int *p;
    char b;
    char c;
    int x;
    short y;
    char[4] buf;
};
```

```
struct bar {
    char a;
    int b;
    struct foo c;
};
```

Now how do we represent bar?

Structs

```
struct foo {
   int *p;

   char b;
   char c;
   int x;
   short y;
   char[4] buf:
};
```

```
struct bar {
   char a;
   int b;
   struct foo c;

};
```

a	-	-	-	b	b	b	b
c	c	c	c	c	c	c	c
c	c	c	c	c	c	c	c
c	c	c	c	c	c	c	c

Structs

```
struct bar {
  char a;
  int b;
  struct foo c;
};
```

Here, we know from before that foo has a pointer as the largest element in it, so the largest primitive is 8-byte aligned. This means that for our struct bar in memory, we shall align the foo struct in it to match up to 8-byte alignments as well. Hence, we would want to start off “struct foo c” in a new line.

a	-	-	-	b	b	b	b
c	c	c	c	c	c	c	c
c	c	c	c	c	c	c	c
c	c	c	c	c	c	c	c

Arrays

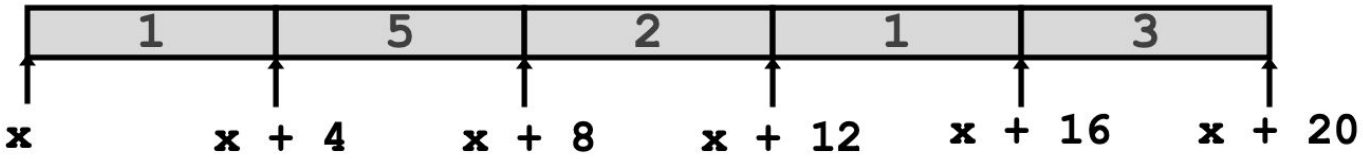
IMPORTANT POINTS + TIPS:

- ***Remember your indexing rules! They'll take you 95% of the way there.***
- **Be careful about addressing (&) vs. dereferencing (*)**
- ***You may be asked to look at assembly!***

Arrays

Good toy examples:

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

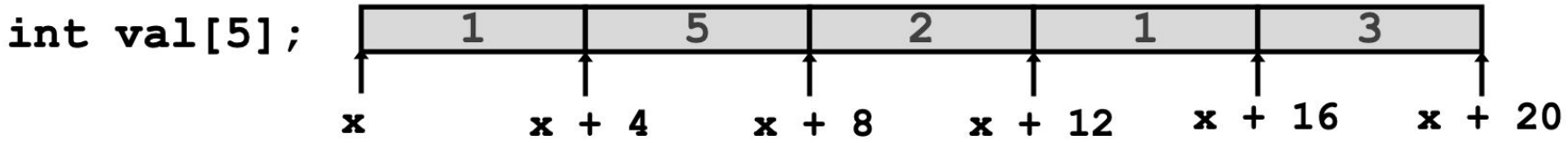


- A can be used as the pointer to the first array element: `A[0]`

	Type	Value
`val`		
`val[2]`		
`*(val + 2)`		
`&val[2]`		
`val + 2`		
`val + i`		

Arrays

Good toy examples:

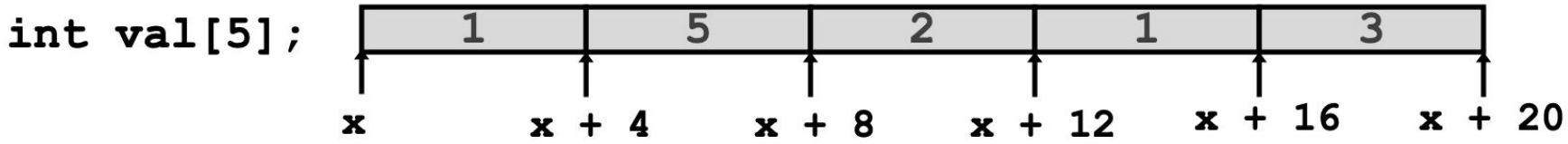


- A can be used as the pointer to the first array element: `A[0]`

	Type	Value
`val`	`int *`	`x`
`val[2]`	`int`	`2`
`*(val + 2)`	`int`	`2`
`&val[2]`	`int *`	`x + 8`
`val + 2`	`int *`	`x + 8`
`val + i`	`int *`	`x + (4 * i)`

Arrays

Good toy examples:



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	Type	Value
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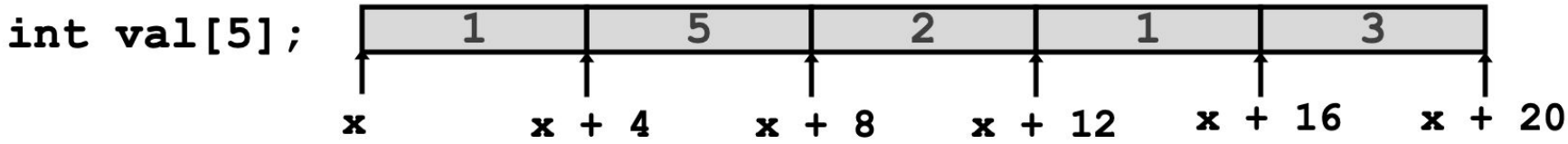
`&val[2]`	`int *`	`x + 8`
`val + 2`	`int *`	`x + 8`
`val + i`	`int *`	`x + (4 * i)`

Accessing methods:
- *val[index]*
- **(val + index)*

Arrays

Good toy examples:



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`val + 2`	`int *`	`x + 8`
`val + i`	`int *`	`x + (4 * i)`

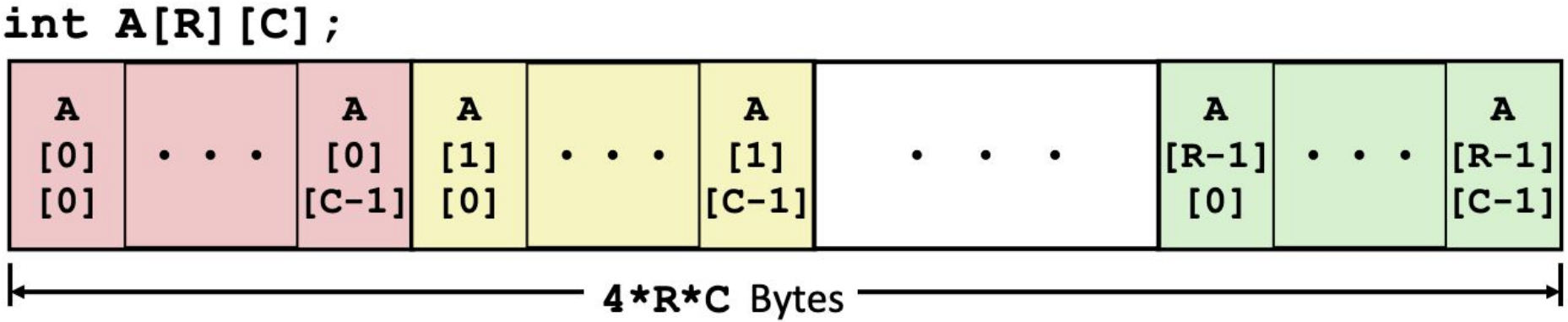
Accessing methods:
- *val[index]*
- **(val + index)*

Addressing methods:
- *&val[index]*
- *val + index*

Arrays

Nested indexing rules

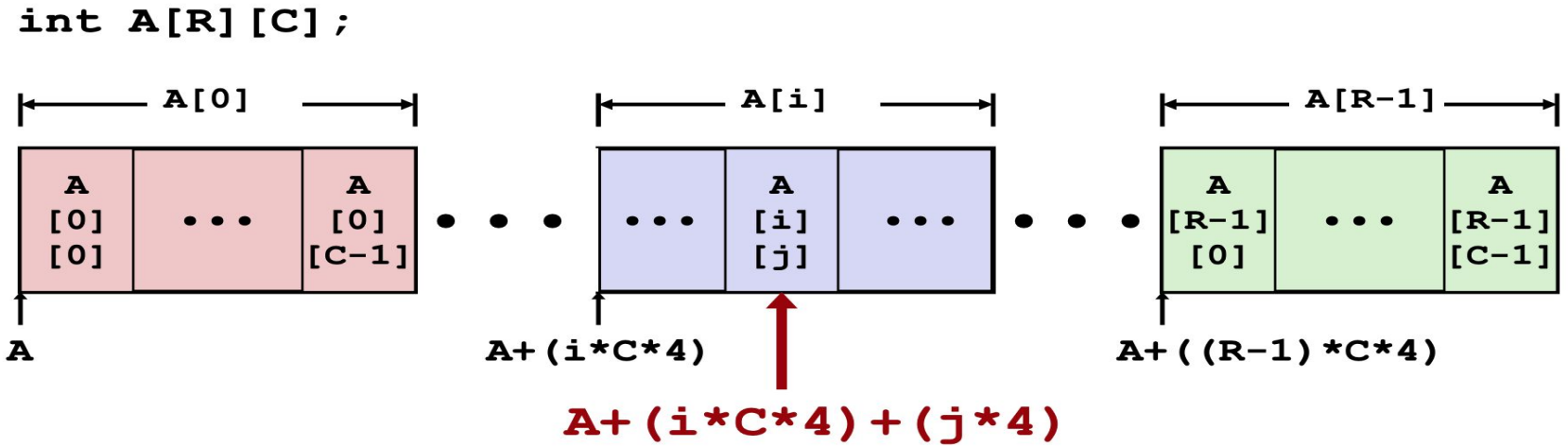
- Declared: `T A[R][C]`
- Contiguous chunk of space (think of multiple arrays lined up next to each other)



Arrays

Nested indexing rules:

- Arranged in ROW-MAJOR ORDER - think of row vectors
- `A[i]` is an array of C elements (“columns”) of type T



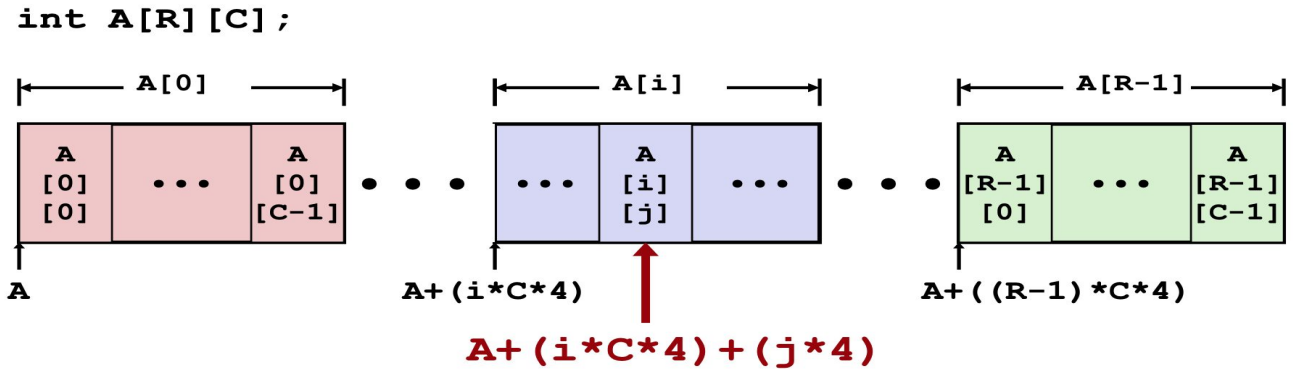
Arrays

Nested indexing rules:

A[i][j] is element of type *T*, which requires *K* bytes

Address **A + i * (C * K) + j * K**

= A + (i * C + j) * K



Arrays

Consider accessing elements of **A**....

	Compiles	Bad Deref?	Size (bytes)
`int A1[3][5]`			
`int *A2[3][5]`			
`int (*A3)[3][5]`			
`int *(A4[3][5])`			
`int (*A5[3])[5]`			

Arrays

Consider accessing elements of A....

	Compiles	Bad Deref?	Size (bytes)
`int A1[3][5]`	Y	N	3*5*(4) = 60
`int *A2[3][5]`			
`int (*A3)[3][5]`			
`int *(A4[3][5])`			
`int (*A5[3])[5]`			

Arrays

Consider accessing elements of A....

	Compiles	Bad Deref?	Size (bytes)
`int A1[3][5]`	Y	N	3*5*(4) = 60
`int *A2[3][5]`	Y	N	3*5*(8) = 120
`int (*A3)[3][5]`			
`int *(A4[3][5])`			
`int (*A5[3])[5]`			

Arrays

Consider accessing elements of A....

	Compiles	Bad Deref?	Size (bytes)
`int A1[3][5]`	Y	N	3*5*(4) = 60
`int *A2[3][5]`	Y	N	3*5*(8) = 120
`int (*A3)[3][5]`	Y	N	1*8 = 8
`int *(A4[3][5])`			
`int (*A5[3])[5]`			

Arrays

Consider accessing elements of A....

	Compiles	Bad Deref?	Size (bytes)
`int A1[3][5]`	Y	N	3*5*(4) = 60
`int *A2[3][5]`	Y	N	3*5*(8) = 120
`int (*A3)[3][5]`	Y	N	1*8 = 8
`int *(A4[3][5])`	Y	N	3*5*(8) = 120
`int (*A5[3])[5]`			

Arrays

Consider accessing elements of A....

	Compiles	Bad Deref?	Size (bytes)
`int A1[3][5]`	Y	N	3*5*(4) = 60
`int *A2[3][5]`	Y	N	3*5*(8) = 120
`int (*A3)[3][5]`	Y	N	1*8 = 8
`int *(A4[3][5])`	Y	N	3*5*(8) = 120
`int (*A5[3])[5]`	Y	N	3*8 = 24

Arrays

Decl	An			*An			**An		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3][5]`	Y	N	60	Y	N	20	Y	N	4
`int *A2[3][5]`	Y	N	120	Y	N	40	Y	N	8
`int (*A3)[3][5]`	Y	N	8	Y	Y	60	Y	Y	20
`int *(A4[3][5])`	Y	N	120	Y	N	40	Y	N	8
`int (*A5[3])[5]`	Y	N	24	Y	N	8	Y	Y	20

ex., A3: pointer to a 3x5 int array
*A3: BAD, 3x5 int array (3 * 5 elements * each 4 bytes = 60)
**A3: BAD, but means stepping inside one of 3 “rows” c

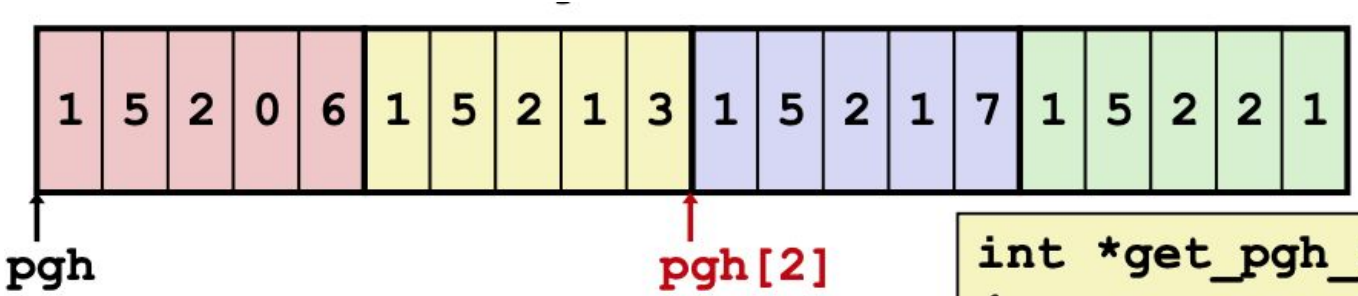
Arrays

Decl	An			*An			**An		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3][5]`	Y	N	60	Y	N	20	Y	N	4
`int *A2[3][5]`	Y	N	120	Y	N	40	Y	N	8
`int (*A3)[3][5]`	Y	N	8	Y	Y	60	Y	Y	20
`int *(A4[3][5])`	Y	N	120	Y	N	40	Y	N	8
`int (*A5[3])[5]`	Y	N	24	Y	N	8	Y	Y	20

ex., A5: array of 3 (int *) pointers
*A5: 1 (int *) pointer, points to an array of 5 ints
**A5: BAD, means accessing 5 individual ints of the pointer (stepping inside “row”)

Arrays

Sample assembly-type questions

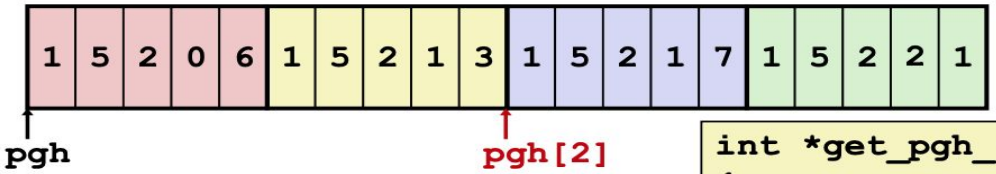



```
int *get_pgh_zip(int index)
{
  return pgh[index];
}
```

```
# %rdi = index
 leaq (%rdi,%rdi,4),%rax # 5 * index
 leaq pgh(,%rax,4),%rax  # pgh + (20 * index)
```

Arrays

Nested Array Row Access Code



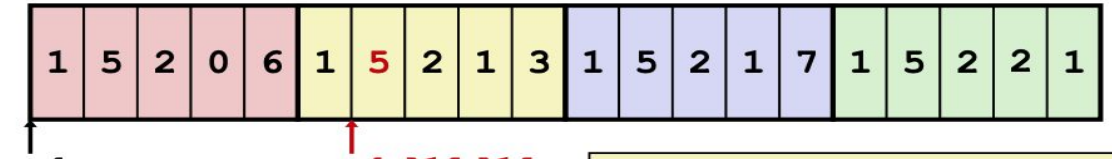

```
int *get_pgh_zip(int index)
{
  return pgh[index];
}
```

```
# %rdi = index
leaq (%rdi,%rdi,4),%rax # 5 * index
leaq pgh(,%rax,4),%rax  # pgh + (20 * index)
```

- **Row Vector**
  - `pgh[index]` is array of 5 `int`'s
  - Starting address `pgh+20*index`
- **Machine Code**
  - Computes and returns address
  - Compute as `pgh + 4*(index+4*index)`

Arrays

Nested Array Element Access Code




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

```
leaq   (%rdi,%rdi,4), %rax    # 5*index
addl   %rax, %rsi             # 5*index+dig
movl   pgh(,%rsi,4), %eax     # M[pgh + 4*(5*index+dig)]
```

- **Array Elements**
  - `pgh[index][dig]` is `int`
  - Address: `pgh + 20*index + 4*dig`
    `= pgh + 4*(5*index + dig)`

Stacks

Stack

- Important things to remember:
  - Stack grows towards lower addresses
  - %rsp = stack pointer, always point to “top” of stack
  - Push and pop, call and ret
  - Stack frames: how they are allocated and freed
  - Which registers used for arguments? Return values?
  - Little endianness

- ALWAYS helpful to draw a stack diagram!!
- Stack questions are like Assembly questions on steroids

Stack

- popq D instruction =
  - mov (%rsp), D
  - add $0x8, %rsp
- pushq S instruction =
  - sub $0x8, %rsp
  - mov S, (%rsp)
- ret instruction =
  - pop %rip
  - jmp %rip
- callq <func> instruction =
  - push %rip
  - jmp func

Stack

Consider the following code:

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
        call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0:
        .string "midtermexam"
```

Hints:

- `strcpy(char *dst, char *src)` copies the string at address src (including the terminating '\0' character) to address dst.
- Keep endianness in mind!
- Table of hex values of characters in `"midtermexam"`

Assumptions:

- `%rsp = 0x800100` just before `caller()` calls `foo()`
- `.LC0` is at address `0x400300`

Stack

Consider the following code:

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
        call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo             %rsp = 0x800100
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0:= 0x400300
        .string "midtermexam"
```

Hints:

- `strcpy(char *dst, char *src)` copies the string at address src (including the terminating '\0' character) to address dst.
- Keep endianness in mind!
- Table of hex values of characters in "midtermexam"

Assumptions:

- `%rsp = 0x800100` just before `caller()` calls `foo()`
- `.LC0` is at address `0x400300`

Stack

Question 1: What is the hex value of `%rsp` just ***before*** `strcpy()` is called for the first time in `foo()`?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
   End  call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
  Start call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

`%rsp = 0x800100`

Hints:

- Step through the program instruction by instruction from start to end
- Draw a stack diagram!!!
- Keep track of registers too

Stack

Arrow is instruction that will execute NEXT

Question 1: What is the hex value of `%rsp` just ***before*** `strcpy()` is called for the first time in `foo()`?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

%rsp	0x800100
%rdi	.LC0
%rsi	0x15213

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
   End  call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

%rsp = 0x800100

0x800100	
0x8000f8	
0x8000f0	
0x8000e8	
0x8000e0	
0x8000d8	
0x8000d0	
0x8000c8	
0x8000c0	
0x8000b8	

Stack

Question 1: What is the hex value of `%rsp` just ***before*** `strcpy()` is called for the first time in `foo()`?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

%rsp	0x8000f8
%rdi	.LC0
%rsi	0x15213

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
End     call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?
0x8000f8	ret address for `foo()`
0x8000f0	
0x8000e8	
0x8000e0	
0x8000d8	
0x8000d0	
0x8000c8	
0x8000c0	
0x8000b8	

Stack

Hint: `$24` in decimal = `0x18`

Question 1: What is the hex value of `%rsp` just ***before*** `strcpy()` is called for the first time in `foo()`?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

%rsp	0x8000e0
%rdi	.LC0
%rsi	0x15213

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
End     call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?
0x8000f8	ret address for `foo()`
0x8000f0	?
0x8000e8	?
0x8000e0	?
0x8000d8	
0x8000d0	
0x8000c8	
0x8000c0	
0x8000b8	

Stack

Question 1: What is the hex value of `%rsp` just ***before*** `strcpy()` is called for the first time in `foo()`?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

%rsp	0x8000e0
%rdi	.LC0
%rsi	0xdeadbeef

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
End     call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?
0x8000f8	ret address for `foo()`
0x8000f0	?
0x8000e8	?
0x8000e0	?
0x8000d8	
0x8000d0	
0x8000c8	
0x8000c0	
0x8000b8	

Stack

Question 1: What is the hex value of `%rsp` just ***before*** `strcpy()` is called for the first time in `foo()`?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

%rsp	0x8000d8
%rdi	.LC0
%rsi	0xdeadbeef

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
End     call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?
0x8000f8	ret address for `foo()`
0x8000f0	?
0x8000e8	?
0x8000e0	?
0x8000d8	ret address for `foo()`
0x8000d0	
0x8000c8	
0x8000c0	
0x8000b8	

Stack

Question 1: What is the hex value of `%rsp` just ***before*** `strcpy()` is called for the first time in `foo()`?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

%rsp	0x8000c0
%rdi	.LC0
%rsi	0xdeadbeef

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
End     call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?
0x8000f8	ret address for `foo()`
0x8000f0	?
0x8000e8	?
0x8000e0	?
0x8000d8	ret address for `foo()`
0x8000d0	?
0x8000c8	?
0x8000c0	?
0x8000b8	

Stack

Question 1: What is the hex value of `%rsp` just ***before*** `strcpy()` is called for the first time in `foo()`?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

%rsp	0x8000c0
%rdi	.LC0
%rsi	0xdeadbeef

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
End     call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?
0x8000f8	ret address for `foo()`
0x8000f0	?
0x8000e8	?
0x8000e0	?
0x8000d8	ret address for `foo()`
0x8000d0	?
0x8000c8	?
0x8000c0	?
0x8000b8	

Stack

Question 1: What is the hex value of `%rsp` just ***before*** `strcpy()` is called for the first time in `foo()`?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

Answer!

%rsp	0x8000c0
%rdi	0x8000c0
%rsi	.LC0

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
End     call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?
0x8000f8	ret address for `foo()`
0x8000f0	?
0x8000e8	?
0x8000e0	?
0x8000d8	ret address for `foo()`
0x8000d0	?
0x8000c8	?
0x8000c0	?
0x8000b8	

Stack

Question 2: What is the hex value of `buf[0]` when `strcpy()` **returns**?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

%rsp	0x8000c0
%rdi	0x8000c0
%rsi	.LC0

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
        call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?
0x8000f8	ret address for `foo()`
0x8000f0	?
0x8000e8	?
0x8000e0	?
0x8000d8	ret address for `foo()`
0x8000d0	?
0x8000c8	?
0x8000c0	?
0x8000b8	

Stack

%rsp	0x8000c0
%rdi	0x8000c0
%rsi	.LC0

Question 2: What is the hex value of `buf[0]` when `strcpy()` **returns**?

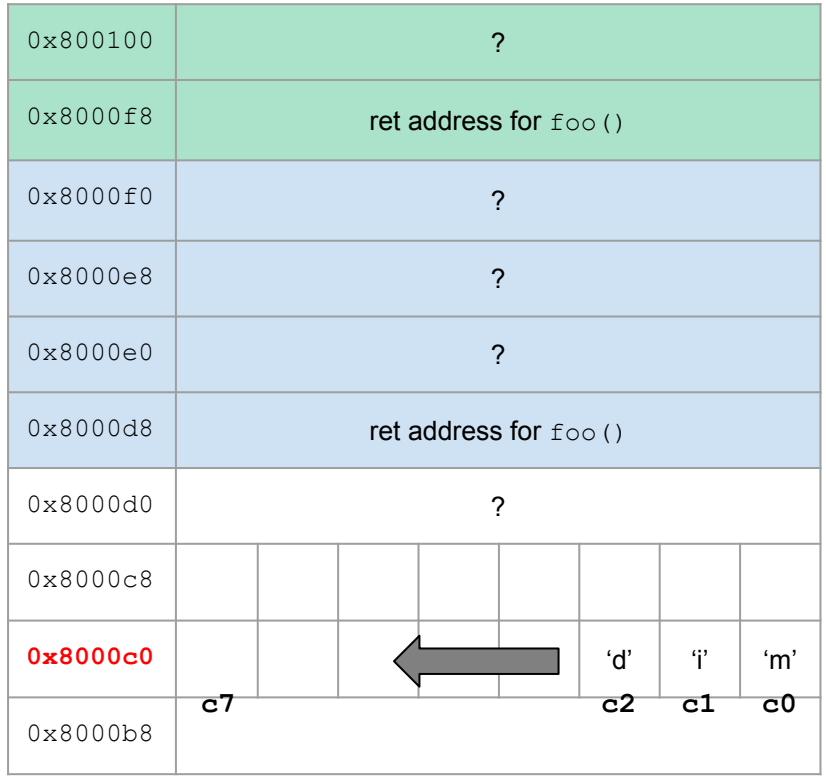
```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
        call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.s
.LC0: = 0x400300
        .string "midtermexam"
```



Stack

%rsp	0x8000c0
%rdi	0x8000c0
%rsi	.LC0

Question 2: What is the hex value of `buf[0]` when `strcpy()` **returns**?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
        call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.s
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?							
0x8000f8	ret address for `foo()`							
0x8000f0	?							
0x8000e8	?							
0x8000e0	?							
0x8000d8	ret address for `foo()`							
0x8000d0	?							
0x8000c8	?	?	?	?	'\0'	'm'	'a'	'x'
0x8000c0	'e'	'm'	'r'	'e'	't'	'd'	'i'	'm'
0x8000b8	**c7**					**c2**	**c1**	**c0**

Stack

Question 2: What is the hex value of `buf[0]` when `strcpy()` **returns**?

%rsp	0x8000c0
%rdi	0x8000c0
%rsi	.LC0

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
        call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.s
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?							
0x8000f8	ret address for `foo()`							
0x8000f0	?							
0x8000e8	?							
0x8000e0	?							
0x8000d8	ret address for `foo()`							
0x8000d0	?							
0x8000c8	?	?	?	?	'\0'	'm'	'a'	'x'
0x8000c0	'e'	'm'	'r'	'e'	't'	'd'	'i'	'm'
0x8000b8					**c3**	**buf[0]**		**c0**

Stack

`buf[0]` = | 't' | 'd' | 'i' | 'm' |

= | 74 | 64 | 69 | 6d |

`(as int)` = **0x7464696d**

Char	Hex	Char	Hex
a	61	m	6d
d	64	r	72
e	65	t	74
i	69	x	78

0x800100	?							
0x8000f8	ret address for `foo()`							
0x8000f0	?							
0x8000e8	?							
0x8000e0	?							
0x8000d8	ret address for `foo()`							
0x8000d0	?							
0x8000c8	?	?	?	?	'\0'	'm'	'a'	'x'
0x8000c0	'e'	'm'	'r'	'e'	't'	'd'	'i'	'm'
0x8000b8	**buf[0]**							

Stack

%rsp	0x8000c0
%rdi	0x8000c0
%rsi	.LC0

Question 3: What is the hex value of **`buf[1]`** when `strcpy()` **returns**?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
        call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.s
.LC0: = 0x400300
        .string "midtermexam"
```

0x800100	?							
0x8000f8	ret address for `foo()`							
0x8000f0	?							
0x8000e8	?							
0x8000e0	?							
0x8000d8	ret address for `foo()`							
0x8000d0	?							
0x8000c8	?	?	?	?	'\0'	'm'	'a'	'x'
0x8000c0	'e'	'm'	'r'	'e'	't'	'd'	'i'	'm'
0x8000b8	**c7**	**buf[1]**		**c4**	**buf[0]**			

Stack

`buf[1]` = | ‘e’ | ‘m’ | ‘r’ | ‘e’ |

= | 65 | 6d | 72 | 65 |

`(as int)` = **0x656d7265**

Char	Hex	Char	Hex
a	61	m	6d
d	64	r	72
e	65	t	74
i	69	x	78

0x800100	?							
0x8000f8	ret address for `foo()`							
0x8000f0	?							
0x8000e8	?							
0x8000e0	?							
0x8000d8	ret address for `foo()`							
0x8000d0	?							
0x8000c8	?	?	?	?	‘\0’	‘m’	‘a’	‘x’
0x8000c0	‘e’	‘m’	‘r’	‘e’	‘t’	‘d’	‘i’	‘m’
0x8000b8	**buf[1]**							

Stack

Question 4: What is the hex value of `%rdi` at the point where `foo()` is called recursively in the successful arm of the `if` statement?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

This is before the recursive call to `foo()`

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
        call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret

        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

Stack

Question 4: What is the hex value of `%rdi` at the point where `foo()` is called recursively in the successful arm of the `if` statement?

```
void foo(char *str, int a) {
   int buf[2];
   if (a != 0xdeadbeef) {
      foo(str, 0xdeadbeef);
      return;
   }
   strcpy((char*) buf, str);
}
```

```
void caller() {
   foo("midtermexam", 0x15213);
}
```

```
foo:
        subq    $24, %rsp
        cmpl    $0xdeadbeef, %esi
        je      .L2
        movl    $0xdeadbeef, %esi
        call    foo
        jmp     .L1
.L2:
        movq    %rdi, %rsi
        movq    %rsp, %rdi
        call    strcpy
.L1:
        addq    $24, %rsp
        ret
```

```
caller:
        subq    $8, %rsp
        movl    $86547, %esi
        movl    $.LC0, %edi
        call    foo
        addq    $8, %rsp
        ret
```

loaded %rdi

```
        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0: = 0x400300
        .string "midtermexam"
```

- This is before the recursive call to `foo()`
- Going backwards, `%rdi` was loaded in `caller()`
- `%rdi = $.LC0 =` **`0x400300`** (based on hint)

Stack

Question 5: What part(s) of the stack will be corrupted by invoking `caller()`? Check all that apply.

- return address from `foo()` to `caller()`
- return address from the recursive call to `foo()`
- `strcpy()`'s return address
- there will be no corruption

Stack

Question 5: What part(s) of the stack will be corrupted by invoking `caller()`? Check all that apply.

- return address from `foo()` to `caller()`
- return address from the recursive call to `foo()`
- `strcpy()`'s return address
- there will be no corruption

The strcpy didn't overwrite any return addresses, so there was no corruption!

0x800100	?							
0x8000f8	ret address for `foo()`							
0x8000f0	?							
0x8000e8	?							
0x8000e0	?							
0x8000d8	ret address for `foo()`							
0x8000d0	?							
0x8000c8	?	?	?	?	'\0'	'm'	'a'	'x'
0x8000c0	'e'	'm'	'r'	'e'	't'	'd'	'i'	'm'
0x8000b8								

Caches

Cache Concepts

- Key Points
  - Direct mapped vs. n-way associative vs. fully associative
  - Tag/Set/Block offset bits, how do they map depending on cache size?
  - LRU policies

(Spend time)

Bonus! Another Cache problem (will update)

- Consider you have the following cache:
  - 64-byte capacity
  - Directly mapped
  - You have an 8-bit address space

Bonus! (will update)

A. How many tag bits are there in the cache?

- Do we know how many set bits there are? What about offset bits? $2^6 = 64$
- If we have a 64-byte direct-mapped cache, we know the number of s + b bits there are total!
- Then $t + s + b = 8 \rightarrow t = 8 - (s + b)$
- Thus, we have 2 tag bits!

Problem 1: Cache

A. Assume you have a cache of the following structure:
   a. 32-byte blocks
   b. 2 sets
   c. Direct-mapped
   d. 8-bit address space
   e. The cache is cold prior to access

B. What does the address decomposition look like?

0 0 0 0 0 0 0 0

Problem 1: Cache

A. Assume you have a cache of the following structure:
   a. 32-byte blocks
   b. 2 sets
   c. Direct-mapped
   d. 8-bit address space
   e. The cache is cold prior to access

B. What does the address decomposition look like?

0 0 0 0 0 0 0 0

Problem 1: Cache

Address	Set	Tag	H/M	Evict? Y/N
0x56				
0x6D				
0x49				
0x3A				

Problem 1: Cache

Address	Set	Tag	H/M	Evict? Y/N
0101 0110				
0110 1101				
0100 1001				
0011 1010				

Problem 1: Cache

Address	Set	Tag	H/M	Evict? Y/N
0101 0110	0	01	M	N
0110 1101				
0100 1001				
0011 1010				

Problem 1: Cache

Address	Set	Tag	H/M	Evict? Y/N
0101 0110	0	01	M	N
0110 1101	1	01	M	N
0100 1001				
0011 1010				

Problem 1: Cache

Address	Set	Tag	H/M	Evict? Y/N
0101 0110	0	01	M	N
0110 1101	1	01	M	N
0100 1001	0	01	H	N
0011 1010				

Problem 1: Cache

Address	Set	Tag	H/M	Evict? Y/N
0101 0110	0	01	M	N
0110 1101	1	01	M	N
0100 1001	0	01	H	N
0011 1010	1	00	M	Y

Problem 1: Cache

A. Assume you have a cache of the following structure:
   a. 2-way associative
   b. 4 sets, 64-byte blocks

B. What does the address decomposition look like?

… 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

Problem 1: Cache

A. Assume you have a cache of the following structure:
   a. 2-way associative
   b. 4 sets, 64-byte blocks

B. What does the address decomposition look like?

... 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

Problem 1: Cache

B. Assume A and B are 128 ints and cache-aligned.

a. What is the miss rate of pass 1?

b. What is the miss rate of pass 2?

```
int get prod and copy(int *A, int *B) {
    int length = 64;
    int prod = 1;
    // pass 1
    for (int i = 0; i < length; i+=4) {
        prod*=A[i];
    }
    // pass 2
    for (int j = length-1; j > 0; j-=4) {
        A[j] = B[j];
    }
    return prod;
}
```

Problem 1: Cache

B. Pass 1: Only going through 64 ints with step size 4. Each miss loads 16 ints into a cache line, giving us 3 more hits before loading into a new line.

```
int get prod and copy(int *A, int *B) {
    int length = 64;
    int prod = 1;
    // pass 1
    for (int i = 0; i < length; i+=4) {
        prod*=A[i];
    }
    // pass 2
    for (int j = length-1; j > 0; j-=4) {
        A[j] = B[j];
    }
    return prod;
}
```

Problem 1: Cache

B. Pass 1: 25% miss

```
int get prod and copy(int *A, int *B) {
    int length = 64;
    int prod = 1;
    // pass 1
    for (int i = 0; i < length; i+=4) {
        prod*=A[i];
    }
    // pass 2
    for (int j = length-1; j > 0; j-=4) {
        A[j] = B[j];
    }
    return prod;
}
```

Problem 1: Cache

B. Pass 2: Our cache is the same size as our working set! Due to cache alignment, we won't evict anything from A, but still get a 1:3 miss:hit ratio for B.

```
int get prod and copy(int *A, int *B) {
    int length = 64;
    int prod = 1;
    // pass 1
    for (int i = 0; i < length; i+=4) {
        prod*=A[i];
    }
    // pass 2
    for (int j = length-1; j > 0; j-=4) {
        A[j] = B[j];
    }
    return prod;
}
```

Problem 1: Cache

B. Pass 2: For every 4 loop iterations, we get all hits for accessing A and 1 miss for accessing B, which gives us ⅛ miss.

```
int get prod and copy(int *A, int *B) {
    int length = 64;
    int prod = 1;
    // pass 1
    for (int i = 0; i < length; i+=4) {
        prod*=A[i];
    }
    // pass 2
    for (int j = length-1; j > 0; j-=4) {
        A[j] = B[j];
    }
    return prod;
}
```

Problem 1: Cache

B. Pass 2: 12.5% miss

```
int get prod and copy(int *A, int *B) {
    int length = 64;
    int prod = 1;
    // pass 1
    for (int i = 0; i < length; i+=4) {
        prod*=A[i];
    }
    // pass 2
    for (int j = length-1; j > 0; j-=4) {
        A[j] = B[j];
    }
    return prod;
}
```

Virtual Memory

Virtual Memory

Virtual Memory

Virtual Address - 18 Bits

Physical Address - 12 Bits

Page Size - 512 Bytes

TLB is 8-way set associative

Cache is 2-way set associative

[Final S-02 (#5)]

[Lecture 17: VM - Systems]

Page Table

VPN	PPN	Valid	VPN	PPN	Valid
000	7	0	010	1	0
001	5	0	011	3	0
002	1	1	012	3	0
003	5	0	013	0	0
004	0	0	014	6	1
005	5	0	015	5	0
006	2	0	016	7	0
007	4	1	017	2	1
008	7	0	018	0	0
009	2	0	019	2	0
00A	3	0	01A	1	0
00B	0	0	01B	3	0
00C	0	0	01C	2	0
00D	3	0	01D	7	0
00E	4	0	01E	5	1
00F	7	1	01F	0	0

TLB

Index	Tag	PPN	Valid
0	55	6	0
	48	F	1
	00	A	0
	32	9	1
	6A	3	1
	56	1	0
	60	4	1
	78	9	0
1	71	5	1
	31	A	1
	53	F	0
	87	8	0
	51	D	0
	39	E	1
	43	B	0
	73	2	1

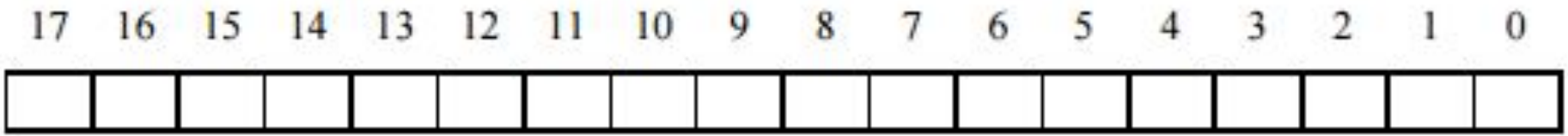
2-way Set Associative Cache

Index	Tag	Valid	Byte 0	Byte 1	Byte 2	Byte 3	Tag	Valid	Byte 0	Byte 1	Byte 2	Byte 3
0	7A	1	09	EE	12	64	00	0	99	04	03	48
1	02	0	60	17	18	19	7F	1	FF	BC	0B	37
2	55	1	30	EB	C2	0D	0B	0	8F	E2	05	BD
3	07	1	03	04	05	06	5D	1	7A	08	03	22

Virtual Memory

Label the following:

(A) *VPO:* Virtual Page Offset
(B) *VPN:* Virtual Page Number
(C) *TLBI:* TLB Index
(D) *TLBT:* TLB Tag

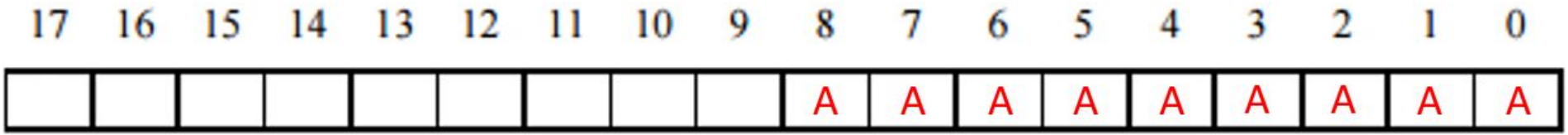


Virtual Memory

Label the following:

(A) *VPO:* Virtual Page Offset - Location in the page

Page Size = 512 Bytes = 2^9 → Need 9 bits

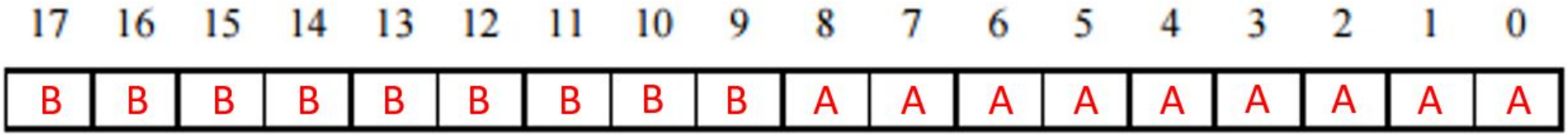


Virtual Memory

Label the following:

(A) *VPO:* Virtual Page Offset

(B) *VPN:* Virtual Page Number - Everything Else



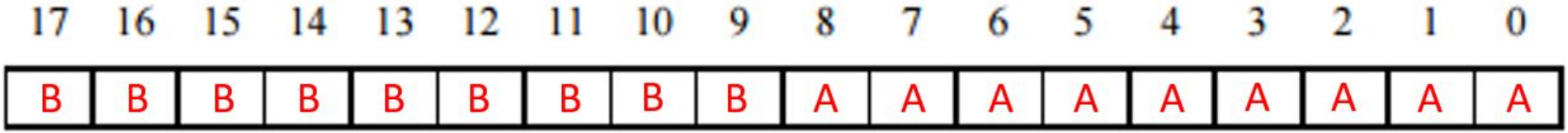
Virtual Memory

Label the following:

(A) *VPO:* Virtual Page Offset

(B) *VPN:* Virtual Page Number

(C) *TLBI:* TLB Index - Location in the TLB Cache



Virtual Memory

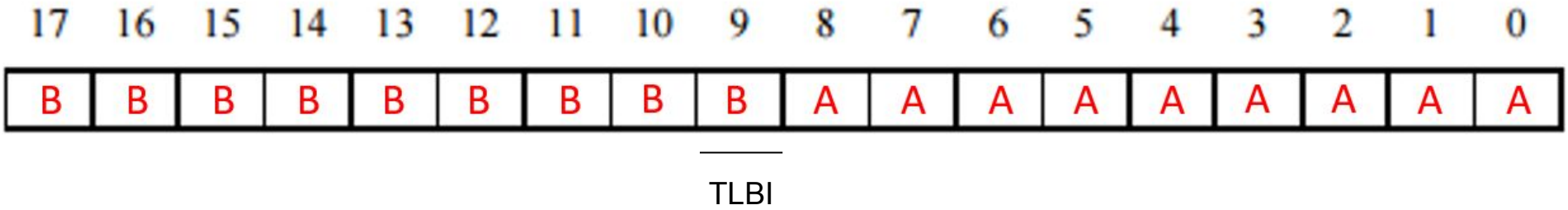
Label the following:

(A) *VPO:* Virtual Page Offset

(B) *VPN:* Virtual Page Number

(C) *TLBI:* TLB Index - Location in the TLB Cache

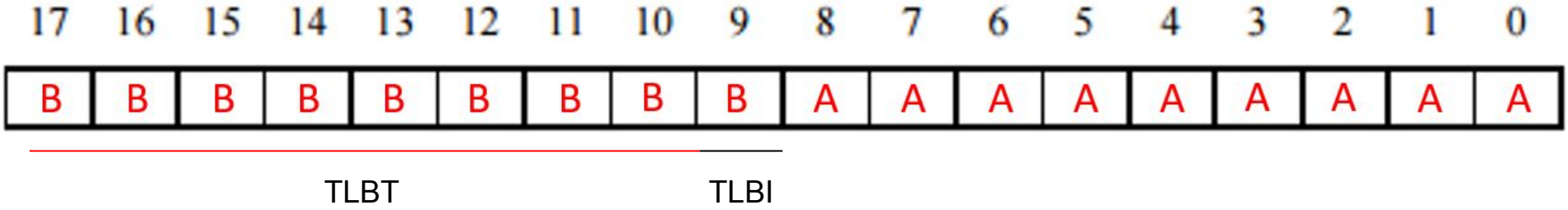
2 Indices → 1 Bit



Virtual Memory

Label the following:

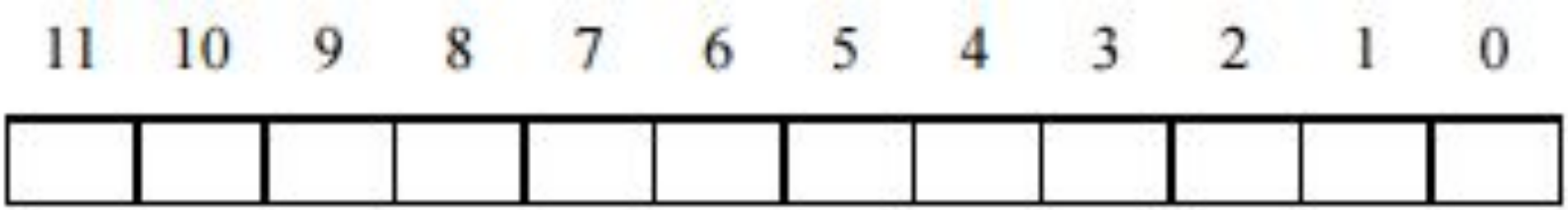
(A) *VPO:* Virtual Page Offset
(B) *VPN:* Virtual Page Number
(C) *TLBI:* TLB Index
(D) TLBT: TLB Tag - Everything Else



Virtual Memory

Label the following:

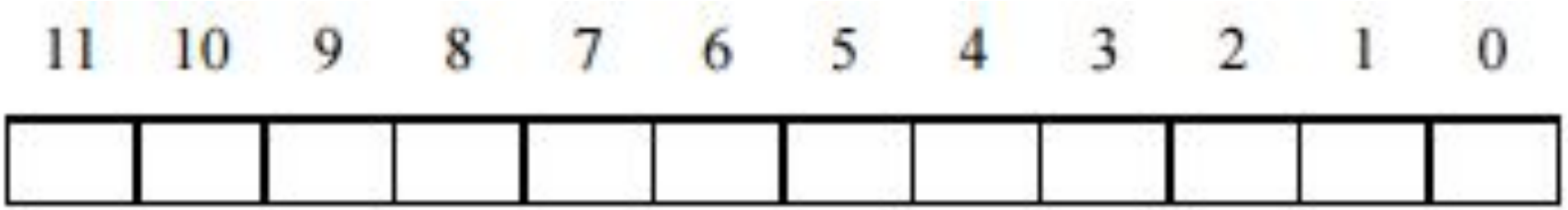
(A) *PPO:* Physical Page Offset
(B) *PPN:* Physical Page Number
(C) *CO:* Cache Offset
(D) *CI:* Cache Index
(E) *CT:* Cache Tag



Virtual Memory

Label the following:

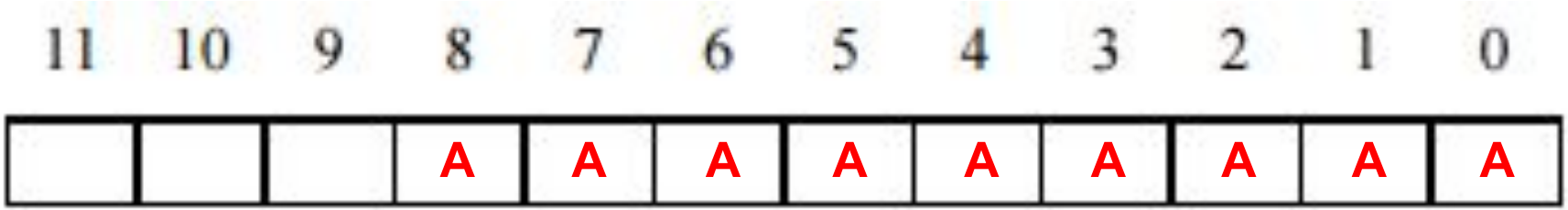
(A) *PPO:* Physical Page Offset



Virtual Memory

Label the following:

(A) *PPO:* Physical Page Offset - Same as VPO

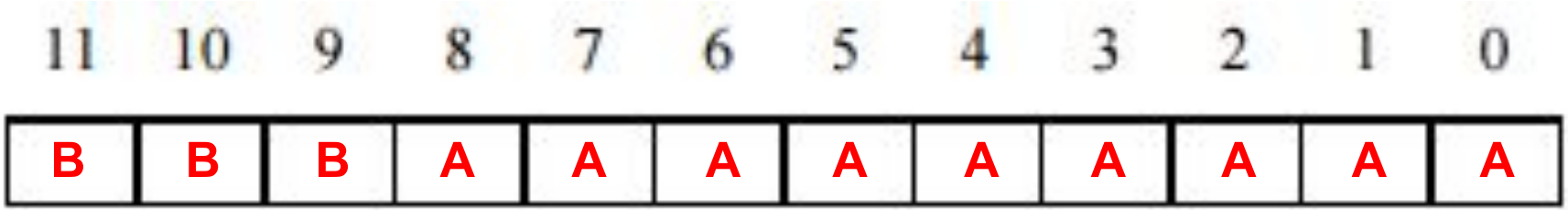


Virtual Memory

Label the following:

(A) *PPO:* Physical Page Offset - Same as VPO

(B) *PPN:* Physical Page Number - Everything Else



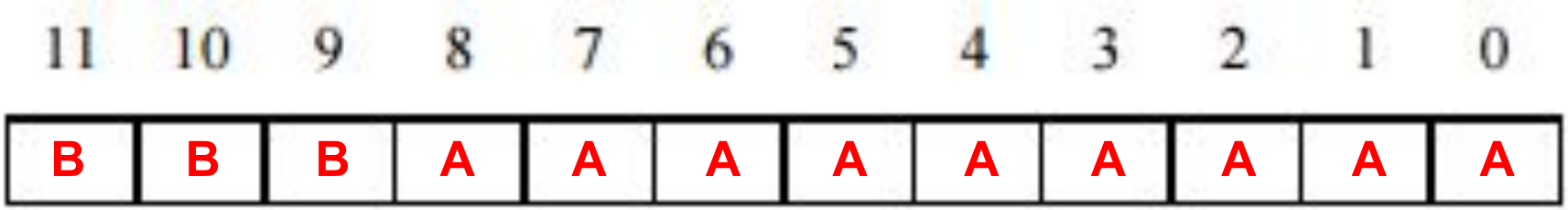
Virtual Memory

Label the following:

(A) *PPO:* Physical Page Offset - Same as VPO

(B) *PPN:* Physical Page Number - Everything Else

(C) *CO:* Cache Offset - Offset in Block



Virtual Memory

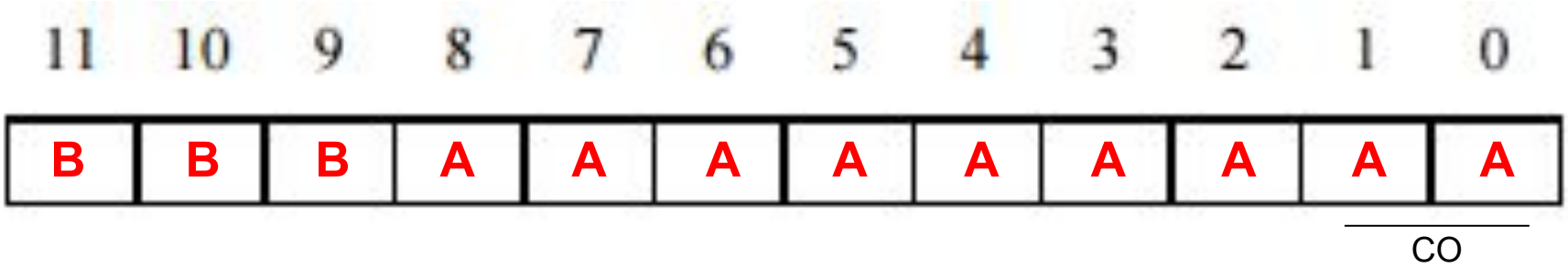
Label the following:

(A) *PPO:* Physical Page Offset - Same as VPO

(B) *PPN:* Physical Page Number - Everything Else

(C) *CO:* Cache Offset - Offset in Block

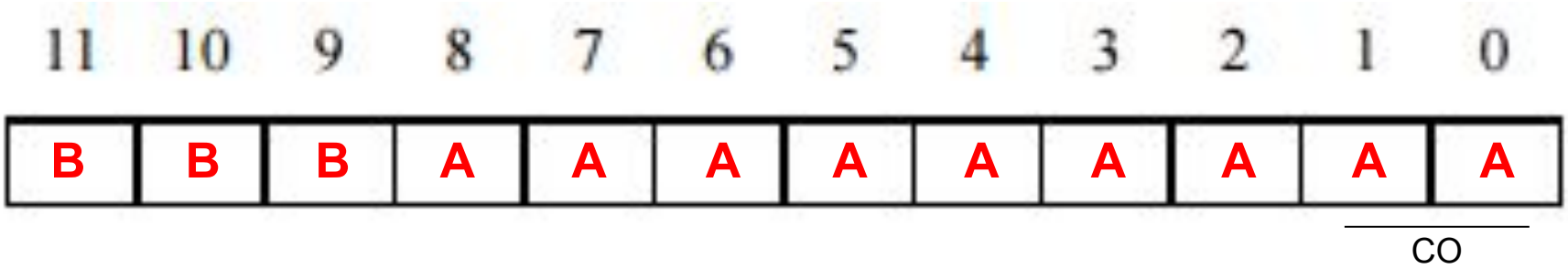
4 Byte Blocks → 2 Bits



Virtual Memory

Label the following:

(A) *PPO:* Physical Page Offset - Same as VPO
(B) *PPN:* Physical Page Number - Everything Else
(C) *CO:* Cache Offset - Offset in Block
(D) *CI:* Cache Index



Virtual Memory

Label the following:

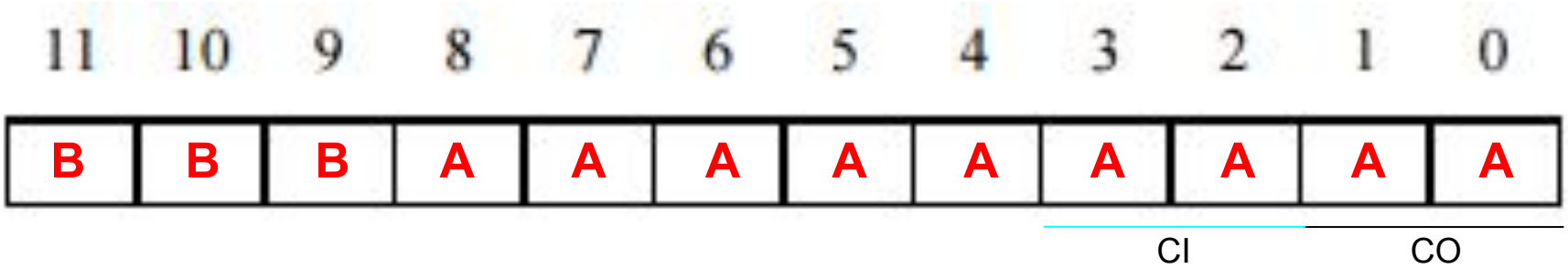
(A) *PPO:* Physical Page Offset - Same as VPO

(B) *PPN:* Physical Page Number - Everything Else

(C) *CO:* Cache Offset - Offset in Block

(D) *CI:* Cache Index

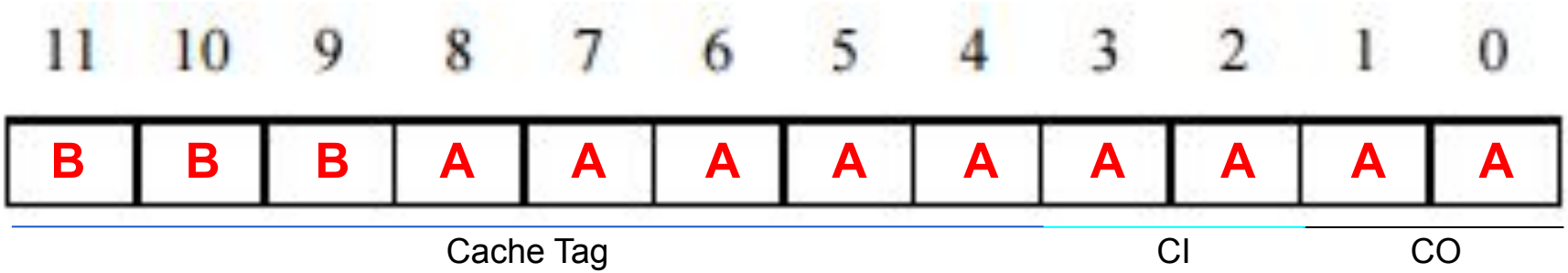
4 Indices → 2 Bits



Virtual Memory

Label the following:

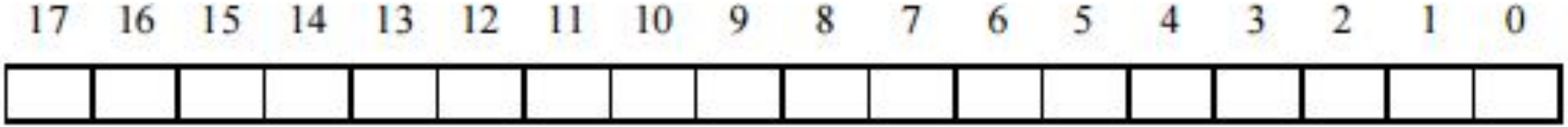
(A) *PPO:* Physical Page Offset - Same as VPO
(B) *PPN:* Physical Page Number - Everything Else
(C) *CO:* Cache Offset - Offset in Block
(D) *CI:* Cache Index
(E) *CT:* Cache Tag - Everything Else



Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**



Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation

1 = 0001 A = 1010 9 = 1001 F = 1111 4 = 0100

Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation
2. Extract Information:

VPN: 0x?? TLBI: 0x?? TLBT: 0x??

TLB Hit: Y/N? Page Fault: Y/N? PPN: 0x??

Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation
2. Extract Information:

VPN: 0xD4 TLBI: 0x?? TLBT: 0x??

TLB Hit: Y/N? Page Fault: Y/N? PPN: 0x??

Virtual Memory

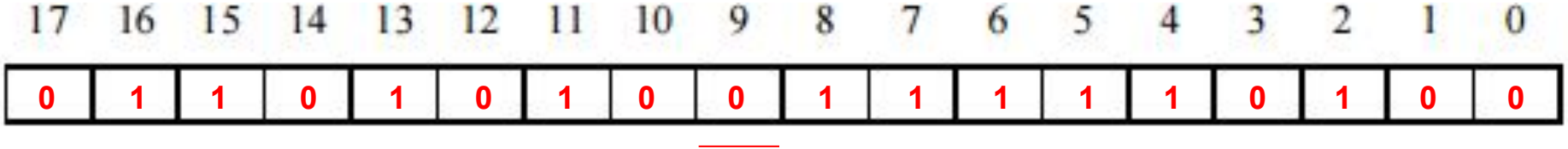
Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation
2. Extract Information:

VPN: 0xD4 TLBI: 0x00 TLBT: 0x??

TLB Hit: Y/N? Page Fault: Y/N? PPN: 0x??



Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation
2. Extract Information:

VPN: 0xD4 TLBI: 0x00 TLBT: 0x6A

TLB Hit: Y/N? Page Fault: Y/N? PPN: 0x??

TLB			
Index	Tag	PPN	Valid
0	55	6	0
	48	F	1
	00	A	0
	32	9	1
	6A	3	1
	56	1	0
	60	4	1
	78	9	0
1	71	5	1
	31	A	1
	53	F	0
	87	8	0
	51	D	0
	39	E	1
	43	B	0
	73	2	1

17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	0	1	0	0	1	1	1	1	1	0	1	0	0

Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation
2. Extract Information:

VPN: 0xD4 TLBI: 0x00 TLBT: 0x6A

TLB Hit: Y! Page Fault: Y/N? PPN: 0x??

TLB			
Index	Tag	PPN	Valid
0	55	6	0
	48	F	1
	00	A	0
	32	9	1
	6A	3	1
	56	1	0
	60	4	1
	78	9	0
1	71	5	1
	31	A	1
	53	F	0
	87	8	0
	51	D	0
	39	E	1
	43	B	0
	73	2	1

17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	0	1	0	0	1	1	1	1	1	0	1	0	0

Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation
2. Extract Information:

VPN: 0xD4 TLBI: 0x00 TLBT: 0x6A

TLB Hit: Y! Page Fault: N! PPN: 0x??

TLB			
Index	Tag	PPN	Valid
0	55	6	0
	48	F	1
	00	A	0
	32	9	1
	6A	3	1
	56	1	0
	60	4	1
	78	9	0
1	71	5	1
	31	A	1
	53	F	0
	87	8	0
	51	D	0
	39	E	1
	43	B	0
	73	2	1

17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	0	1	0	0	1	1	1	1	1	0	1	0	0

Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation
2. Extract Information:

VPN: 0xD4 TLBI: 0x00 TLBT: 0x6A

TLB Hit: Y! Page Fault: N! PPN: 0x3

TLB			
Index	Tag	PPN	Valid
0	55	6	0
	48	F	1
	00	A	0
	32	9	1
	6A	3	1
	56	1	0
	60	4	1
	78	9	0
1	71	5	1
	31	A	1
	53	F	0
	87	8	0
	51	D	0
	39	E	1
	43	B	0
	73	2	1

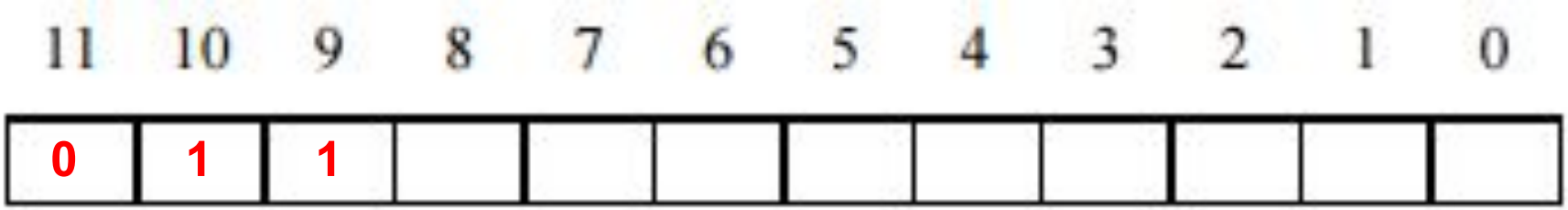
17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	0	1	0	1	0	0	1	1	1	1	1	0	1	0	0

Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation
2. Extract Information
3. Put it all together: PPN: 0x3, PPO = 0x??



Virtual Memory

Now to the actual question!

Q) **Translate the following address: 0x1A9F4**

1. Write down bit representation
2. Extract Information
3. Put it all together: PPN: 0x3, PPO = VPO = 0x1F4

Virtual Memory

Q) **What is the value of the address?**

CO: 0x?? CI: 0x?? CT: 0x?? Cache Hit: Y/N? Value:0x??

Virtual Memory

Q) **What is the value of the address?**

1. Extract more information

CO: 0x00 CI: 0x?? CT: 0x?? Cache Hit: Y/N? Value:0x??

Virtual Memory

Q) **What is the value of the address?**

1. Extract more information

CO: 0x00 CI: 0x01 CT: 0x?? Cache Hit: Y/N? Value:0x??

Virtual Memory

Q) **What is the value of the address?**

1. Extract more information
2. Go to Cache Table

CO: 0x00 CI: 0x01 CT: 0x7F Cache Hit: Y/N? Value:0x??

2-way Set Associative Cache

Index	Tag	Valid	Byte 0	Byte 1	Byte 2	Byte 3	Tag	Valid	Byte 0	Byte 1	Byte 2	Byte 3
0	7A	1	09	EE	12	64	00	0	99	04	03	48
1	02	0	60	17	18	19	7F	1	FF	BC	0B	37
2	55	1	30	EB	C2	0D	0B	0	8F	E2	05	BD
3	07	1	03	04	05	06	5D	1	7A	08	03	22

Virtual Memory

Q) **What is the value of the address?**

1. Extract more information
2. Go to Cache Table

CO: 0x00 CI: 0x01 CT: 0x7F Cache Hit: Y Value:0x??

2-way Set Associative Cache

Index	Tag	Valid	Byte 0	Byte 1	Byte 2	Byte 3	Tag	Valid	Byte 0	Byte 1	Byte 2	Byte 3
0	7A	1	09	EE	12	64	00	0	99	04	03	48
1	02	0	60	17	18	19	7F	1	FF	BC	0B	37
2	55	1	30	EB	C2	0D	0B	0	8F	E2	05	BD
3	07	1	03	04	05	06	5D	1	7A	08	03	22

Virtual Memory

Q) **What is the value of the address?**

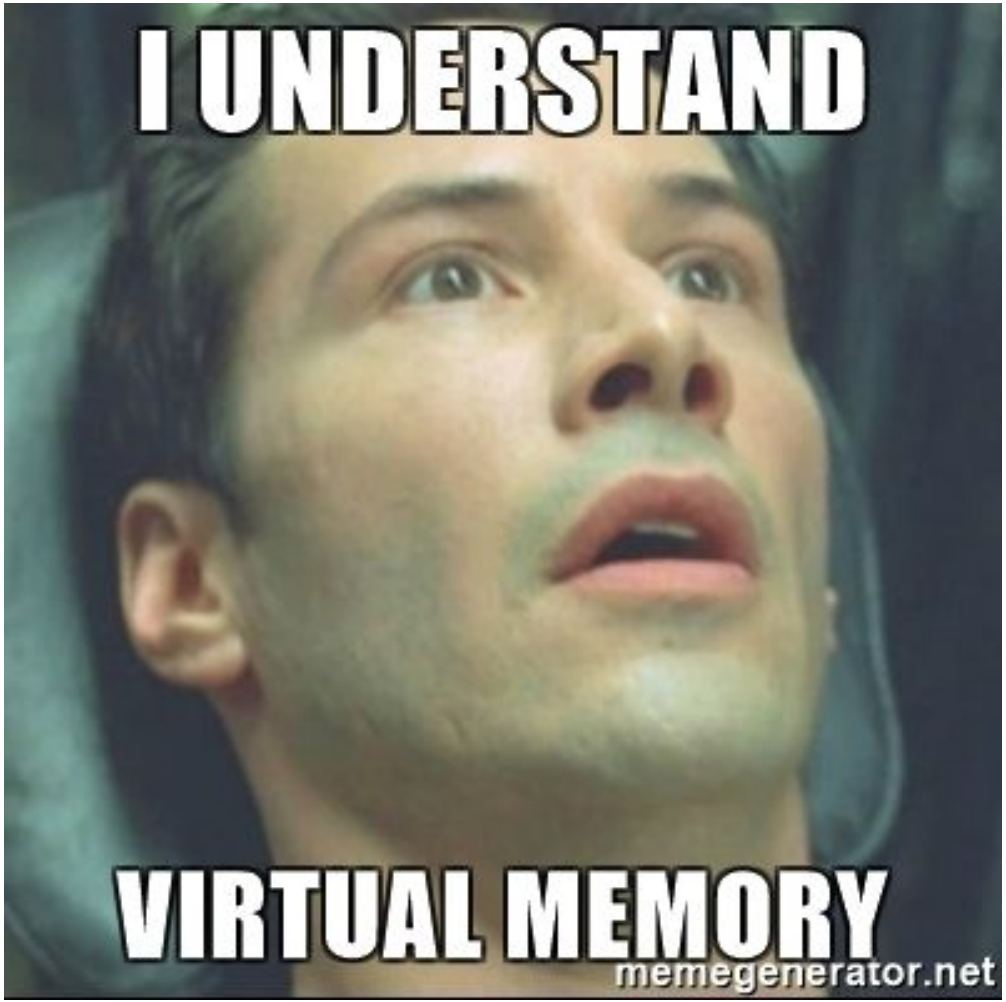
1. Extract more information
2. Go to Cache Table

CO: 0x00 CI: 0x01 CT: 0x7F Cache Hit: Y Value:0xFF

2-way Set Associative Cache

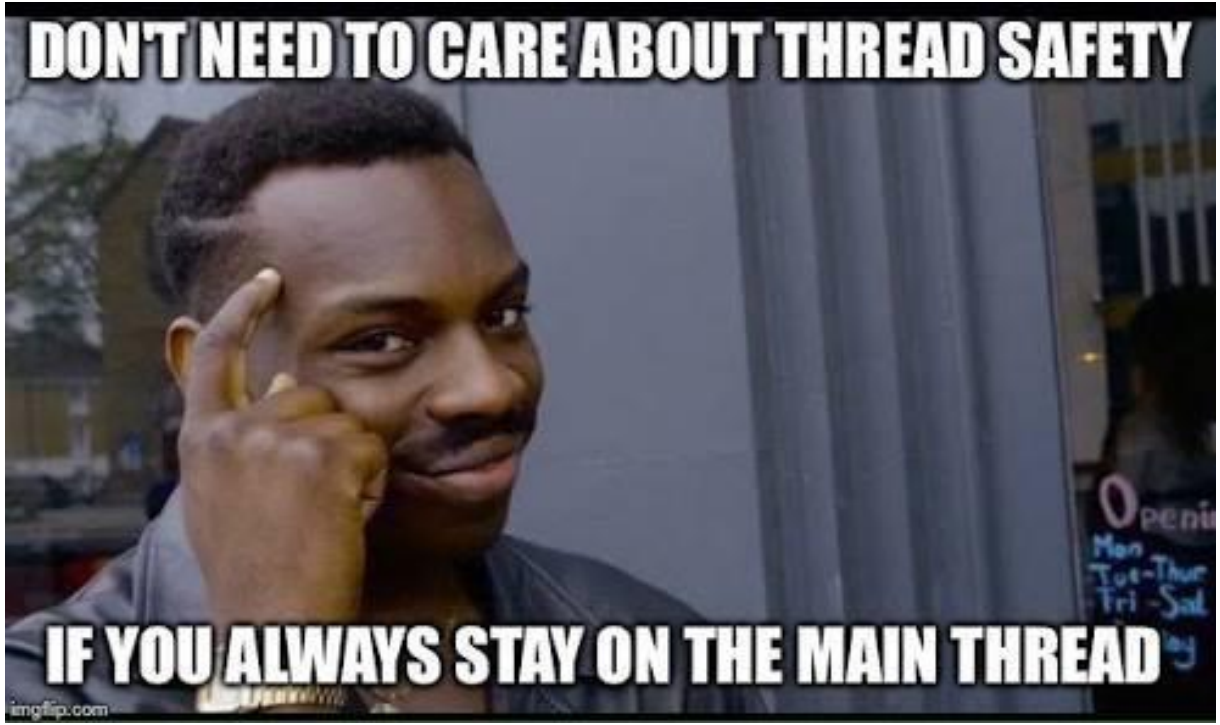
Index	Tag	Valid	Byte 0	Byte 1	Byte 2	Byte 3	Tag	Valid	Byte 0	Byte 1	Byte 2	Byte 3
0	7A	1	09	EE	12	64	00	0	99	04	03	48
1	02	0	60	17	18	19	7F	1	FF	BC	0B	37
2	55	1	30	EB	C2	0D	0B	0	8F	E2	05	BD
3	07	1	03	04	05	06	5D	1	7A	08	03	22

Virtual Memory



Threads

Threads


DON'T NEED TO CARE ABOUT THREAD SAFETY
IF YOU ALWAYS STAY ON THE MAIN THREAD
imgflip.com

Threads

Given this code, what variables do you think are shared?

```
#include <stdio.h>
#include <pthread.h>

#define NUM_THREADS 2
int balance = 10;


 int main() {
     int i;
     pthread_t tid[NUM_THREADS];
     pthread_create(&tid[0], NULL, threadA, (void*)0);
     pthread_create(&tid[1], NULL, threadB, (void*)0);
     for (i = 0; i < NUM_THREADS; i++) {
         pthread_join(tid[i], NULL);
     }
     printf("balance: %d\n", balance); // What is balance?
     return 0;
 }
```

```
void *threadA(void *vargp) {
    long instance = (long)vargp;
    static int cnt = 0;
    deposit(4);
    withdraw(11);
    return NULL;
}

void *threadB() {
    withdraw(6);
    deposit(3);
    withdraw(7);
    return NULL;
}
```

Threads (Contd.)

Which variables can be shared by multiple threads simultaneously in this program?

(A) i
(B) balance
(C) instance
(D) cnt
(E) None of the above

Threads (Contd.)

Which variables can be shared by multiple threads simultaneously in this program?

(A) i
(B) balance
(C) instance
(D) cnt
(E) None of the above

Answer: B

Threads (Contd.)

(A) i is a local variable so it isn't shared.

(A) balance is a global variable so it's shared.

(A) instance is local to threadA() so it isn't shared.

(A) cnt is a static variable, so it retains its value even outside the scope in which it was defined, so it isn't shared.

Threads (Contd.)

Given the withdraw() and deposit() functions, what are the possible outputs? (balance = 10 initially)

```
int withdraw(int amt) {
    if (balance >= amt) {
        balance = balance - amt;
        return 0;
    } else {
        return -1;
    }
}

int deposit(int amt) {
    balance = balance + amt;
    sleep(2);
    return 0;
}
```

```
void *threadA(void *vargp) {
    long instance = (long)vargp;
    static int cnt = 0;
    deposit(4);
    withdraw(11);
    return NULL;
}

void *threadB() {
    withdraw(6);
    deposit(3);
    withdraw(7);
    return NULL;
}
```

Threads (Contd.)

What can be the value of balance?

(A) balance: 0
(B) balance: -3
(C) balance: 14
(D) balance: 6
(E) balance: 17
(F) balance: 4

Threads (Contd.)

What can be printed at the indicated line?

(A) balance: 0
(B) balance: -3
(C) balance: 14
(D) balance: 6
(E) balance: 17
(F) balance: 4

Answer: ABDF

Threads (Contd.)

The following is one interleaving that leads to output 0:

- Thread A executes deposit(4), balance = 14
- Thread B executes withdraw(6), balance = 8
- Thread B executes deposit(3), balance = 11
- Thread A executes withdraw(11), balance = 0
- Thread B executes withdraw(7), balance = 0

Threads (Contd.)

The following is one interleaving that leads to output -3:

- Thread A executes deposit(4), balance = 14
- Thread A starts to execute withdraw(11) and enters the if condition
- Thread B executes withdraw(6), balance = 8
- Thread A computes RHS for withdraw(11) = -3
- Thread B executes deposit(3), balance = 11
- Thread A completes withdraw(11), balance = -3
- Thread B executes withdraw(7), balance = -3

Threads (Contd.)

The following is one interleaving that leads to output 6:

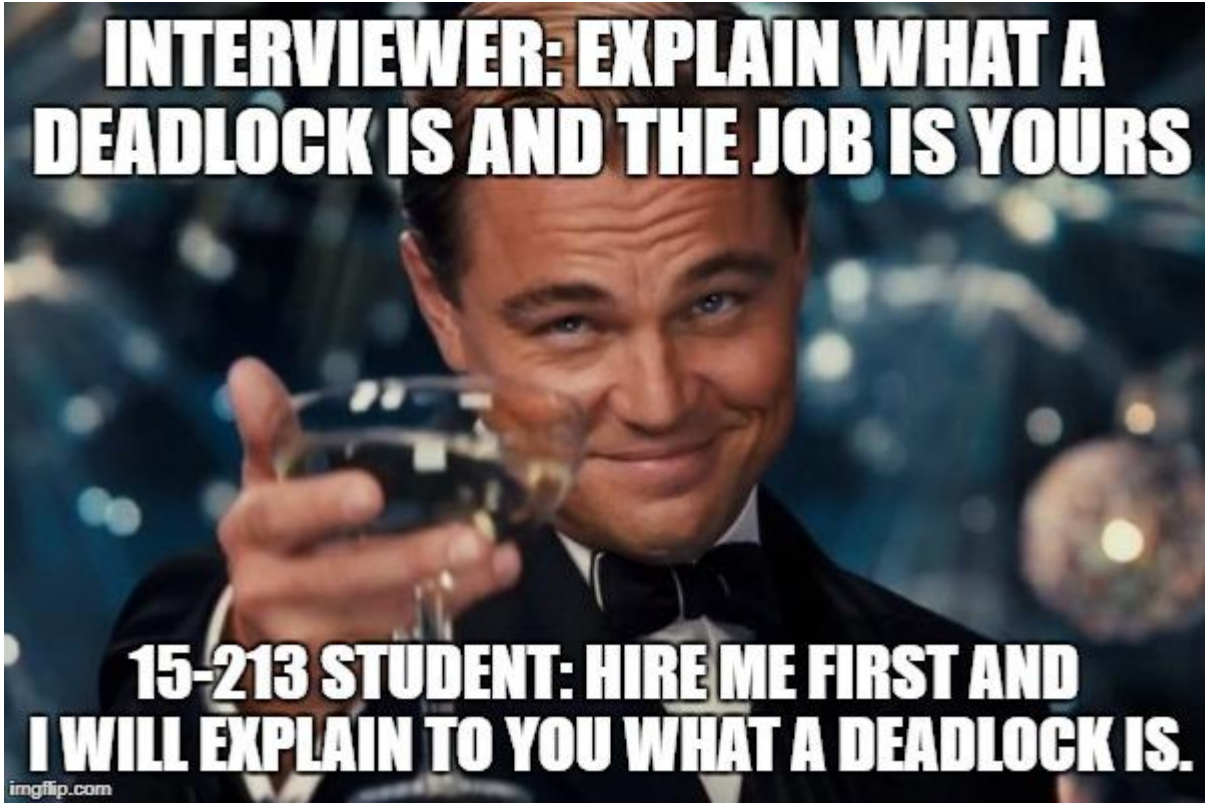
- Thread A executes deposit(4), balance = 14
- Thread A executes withdraw(11), balance = 3
- Thread B executes withdraw(6), balance = 3
- Thread B executes deposit(3), balance = 6
- Thread B executes withdraw(7), balance = 6

Threads (Contd.)

The following is one interleaving that leads to output 4:

- Thread B executes withdraw(6), balance = 4
- Thread A executes deposit(4), balance = 8
- Thread A executes withdraw(11), balance = 8
- Thread B executes deposit(3), balance = 11
- Thread B executes withdraw(7), balance = 4

Synchronization



Thread Synchronization

How many potential deadlock situations are present?

```
void *thread1(void *vargp) {
    V(&add_sem);
    V(&rem_sem);

    remove();

    P(&add_sem);
    P(&rem_sem);

    add();

    V(&add_sem);
    V(&rem_sem);

    remove();
    add();
}

sem_t add_sem;
sem_t rem_sem;
```

```
void *thread2(void *vargp) {
    P(&rem_sem);
    P(&add_sem);

    add();
    remove();
}

 int main() {
     pthread_t tid1, tid2;

     sem_init(&add_sem,0,0);
     sem_init(&rem_sem,0,0);

     pthread_create(&tid1, NULL, thread1, NULL);
     pthread_create(&tid2, NULL, thread2, NULL);

     pthread_join(tid1, NULL);
     pthread_join(tid2, NULL);

     return 0;
 }
```

Thread Synchronization (Contd.)

Situation 1:

tid1 executes V(&add_sem) and V(&rem_sem). Then, tid2 executes P(&rem_sem) and P(&add_sem). In this situation, tid1 can never execute P(&add_sem) since the value of add_sem = 0. As a result, this is a deadlock, since after the execution of thread 2, thread 1 can't resume. Thus, there's a deadlock.

Thread Synchronization (Contd.)

Situation 2:

tid1 executes V(&add_sem) and V(&rem_sem). Then, tid2 executes P(&rem_sem). Next, tid1 executes P(&add_sem). Thread 2 wants to execute P(&add_sem) but it can't since add_sem has value 0. Thread 1 wants to execute P(&rem_sem) but it can't since rem_sem has value 0. Thus, there's a deadlock.

Thread Synchronization (Contd.)

For lengths 0-6, indicate the number of outcomes of that length that can be produced.

```
sem_t add_sem;
sem_t rem_sem;

void add() {
    printf("A");
}

void remove() {
    printf("R");
}

void *thread2(void *vargp)
    P(&rem_sem);
    P(&add_sem);

    add();
    remove();
}
```

```
void *thread1(void *vargp) {
    V(&add_sem);
    V(&rem_sem);

    remove();

    P(&add_sem);
    P(&rem_sem);

    add();

    V(&add_sem);
    V(&rem_sem);

    remove();
    add();
}
```

```
int main() {
    pthread_t tid1, tid2;

    sem_init(&add_sem,0,0);
    sem_init(&rem_sem,0,0);

    pthread_create(&tid1, NULL, thread1, NULL);
    pthread_create(&tid2, NULL, thread2, NULL);

    pthread_join(tid1, NULL);
    pthread_join(tid2, NULL);

    return 0;
}
```

Thread Synchronization (Contd.)

Response length 0: None

This is because at least ‘R’ must get printed due to the call to remove() in thread1(). Even if there is a deadlock, at least that statement gets executed by tid1 before any sort of deadlock from the above situations.

Thread Synchronization (Contd.)

Response length 1: 1 (R)

In the deadlock scenario 2, where thread 1 executes P(&add_sem) and thread 2 executes P(&rem_sem), neither of the threads can proceed past that. Thus, no print statements are executed in either thread after that point. The only print statement that gets executed is due to the call to remove() before the calls to P() in thread 1.

Thread Synchronization (Contd.)

Response length 2: None

We noticed that ‘R’ due to the call to remove() in thread1() gets printed no matter what. From the code, we notice that it’s not possible for only one other print statement to get executed.

Thread Synchronization (Contd.)

Response length 3: 2 (RAR, ARR)

This happens due to deadlock scenario 1 above, where thread2() executes completely but thread1() can't execute P(&add_sem) and the statements after that.

- RAR: Thread 1 executes remove(), followed by thread 2 executing add() and remove().
- ARR: Thread 2 executes add(), followed by any ordering of the 2 calls to remove() by threads 1 and 2.

Thread Synchronization (Contd.)

Response length 4: None

For any length greater than 3, it means that there was no deadlock, since thread 2 could run to completion and thread 1 could get past the calls to P(), which means it would run to completion as well. Thus, no responses of length greater than 3 and less than 6 are possible.

Thread Synchronization (Contd.)

Response length 5: None

For any length greater than 3, it means that there was no deadlock, since thread 2 could run to completion and thread 1 could get past the calls to P(), which means it would run to completion as well. Thus, no responses of length greater than 3 and less than 6 are possible.

Thread Synchronization (Contd.)

Response length 6: 4
(RARAAR, RARARA, RAARRA, RAARAR)

Since there are no deadlocks, it means that the initial calls to V() and P() get executed by thread 1. Thus, ‘R’ and ‘A’ definitely get printed. After this, the calls to V() get executed by thread 1 and then, thread 2 can execute its calls to P(). After this, based on the interleavings between the threads, there are 4 possible outputs.

Thread Synchronization (Contd.)

- RARAAR: Thread 1 executes remove(), threads 1 and 2 execute the add() statements in any order, and then thread 2 executes remove().

- RARARA: Thread 1 executes remove(), thread 2 executes add() and remove(), then thread 1 executes add().

Thread Synchronization (Contd.)

- RAARRA: Thread 2 executes add(), threads 1 and 2 execute the remove() statements in any order, and then thread 1 executes add().

- RAARAR: Thread 2 executes add(), thread 1 executes remove() and add(), then thread 2 executes remove().

Processes

1. Logical control flow
2. Private address space

Important system calls

1. Fork
2. Execve
3. Wait
4. Waitpid

Processes

Draw a Process Graph!!!

(it does not have to be like mine)

Processes

```
int main() {
   int count = 1;
   int pid1 = fork();
   int pid2 = fork();

   if(pid1 == 0)
    count++;
   else{
    if(pid2 == 0)
          count--;
    else
          count += 2;
   }
   printf("%d", count);
}
```

What is printed?

Assume printf is atomic, and all system calls succeed.

Processes

```
int main() {
   int count = 1;
   int pid1 = fork();
   int pid2 = fork();

   if(pid1 == 0)
    count++;
   else{
    if(pid2 == 0)
          count--;
    else
          count += 2;
   }
   printf("%d", count);
}
```

How many processes?

Processes

```
int main() {
   int count = 1;
   int pid1 = fork();
   int pid2 = fork();

   if(pid1 == 0)
    count++;
   else{
    if(pid2 == 0)
          count--;
    else
          count += 2;
   }
   printf("%d", count);
}
```

How many processes?

Parent: forks child

Parent and child: each fork another child

Total: 4 processes

Processes

```
int main() {
   int count = 1;
   int pid1 = fork();
   int pid2 = fork();

   if(pid1 == 0)
    count++;
   else{
    if(pid2 == 0)
          count--;
    else
          count += 2;
   }
   printf("%d", count);
}
```

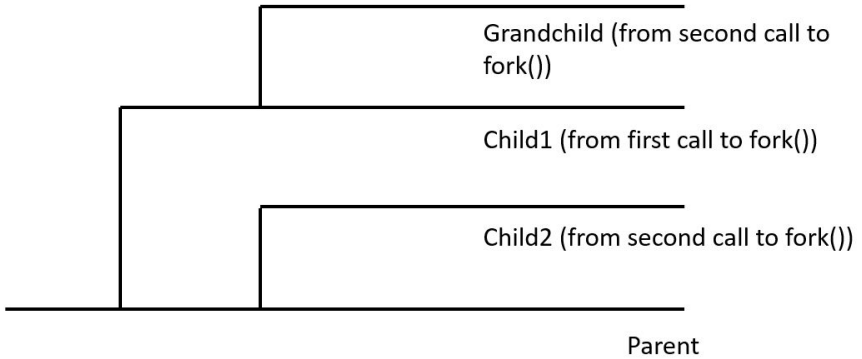
What does the process diagram look like?

Processes

```
int main() {
   int count = 1;
   int pid1 = fork();
   int pid2 = fork();

   if(pid1 == 0)
    count++;
   else{
    if(pid2 == 0)
          count--;
    else
          count += 2;
   }
   printf("%d", count);
}
```

What does the process diagram look like?



Processes

```
int main() {
   int count = 1;
   int pid1 = fork();
   int pid2 = fork();

   if(pid1 == 0)
    count++;
   else{
    if(pid2 == 0)
          count--;
    else
          count += 2;
   }
   printf("%d", count);
}
```

What does count look like?

Parent: pid1 != 0 and pid2 != 0
Child1: pid1 == 0 and pid2 != 0
Child2: pid1 != 0 and pid2 == 0
Grandchild: pid1 == 0 and pid2 == 0

Processes

```
int main() {
   int count = 1;
   int pid1 = fork();
   int pid2 = fork();

   if(pid1 == 0)
    count++;
   else{
    if(pid2 == 0)
          count--;
    else
          count += 2;
   }
   printf("%d", count);
}
```

What does count look like?

Parent: pid1 != 0 and pid2 != 0

- count = 3

Child1: pid1 == 0 and pid2 != 0

- count = 2

Child2: pid1 != 0 and pid2 == 0

- count = 0

Grandchild: pid1 == 0 and pid2 == 0

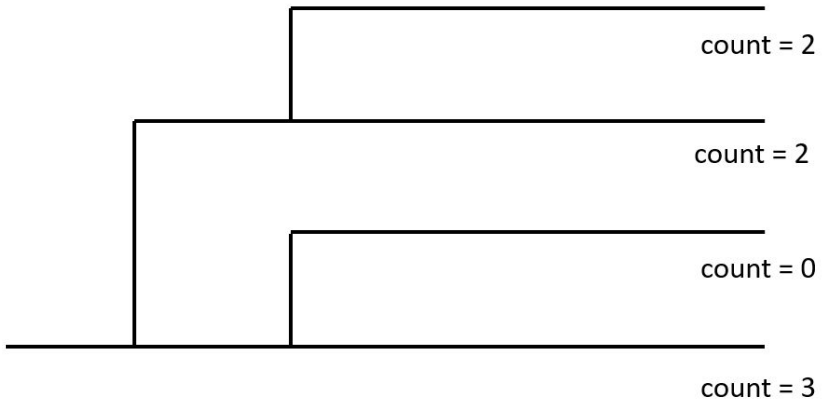
- count = 2

Processes

```
int main() {
   int count = 1;
   int pid1 = fork();
   int pid2 = fork();

   if(pid1 == 0)
    count++;
   else{
    if(pid2 == 0)
          count--;
    else
          count += 2;
   }
   printf("%d", count);
}
```

Given the process diagram, what are the different permutations that can be printed out?

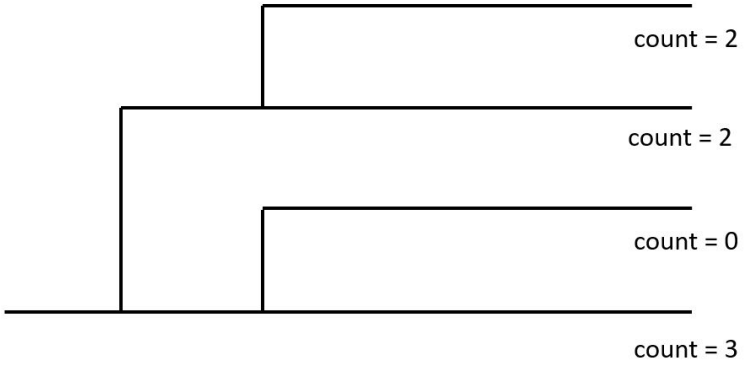


Processes

```
int main() {
   int count = 1;
   int pid1 = fork();
   int pid2 = fork();

   if(pid1 == 0)
    count++;
   else{
    if(pid2 == 0)
          count--;
    else
          count += 2;
   }
   printf("%d", count);
}
```

Given the process diagram, what are the different permutations that can be printed out?



Math! 4! / 2 = 12 different possible outcomes

Processes

Remember:

- Processes can occur in any order
- Watch out for a `wait` or a `waitpid`!
  - What if I included a `wait(NULL)` before I printed out count?
- Good luck!

Signals

who would win?

several hundred lines of tshlab code

```
 7 void
 6 exec_cmdline(char *cmdline, char **argv, sigset_t *set,
 5         int bg, int fd_in, int fd_out)
 4 {
 3     pid_t pid = 0;
 2     if ((pid = Fork()) == 0) {
 1         // Child process; restore mask and execute job.
314         Sigprocmask(SIG_SETMASK, set, NULL);
```

one asynchronous boi

Signals

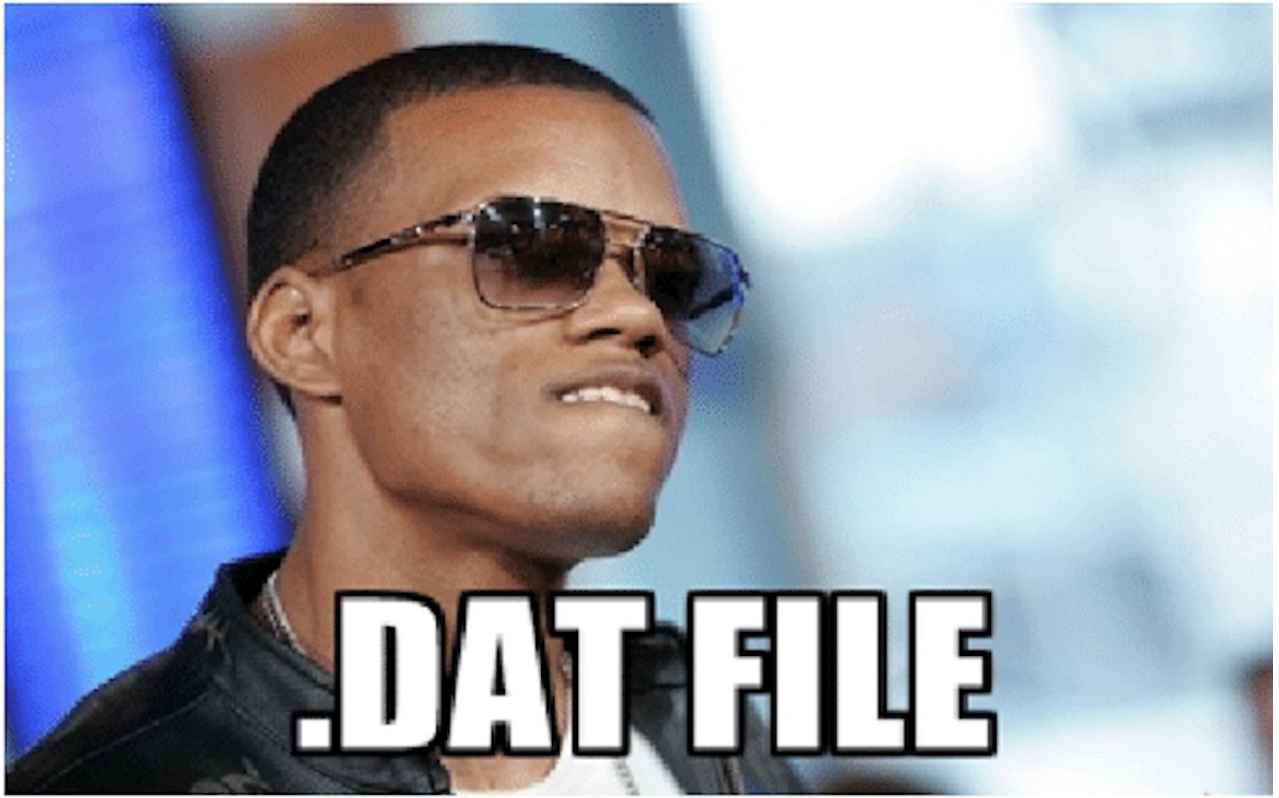
- Child calls kill(parent, SIGUSR{1,2}) between 2-4 times.
  What sequence of kills may print 1?
  Can you guarantee printing 2?
  What is the range of values printed?

```
int counter = 0;
void handler (int sig) {
  atomically {counter++;}
}
int main(int argc, char** argv) {
  signal(SIGUSR1, handler);
  signal(SIGUSR2, handler);
  int parent = getpid();   int child = fork();
  if (child == 0) {
    /* insert code here */
    exit(0);
  }
  sleep(1);   waitpid(child, NULL, 0);
  printf("Received %d USR{1,2} signals\n", counter);
}
```

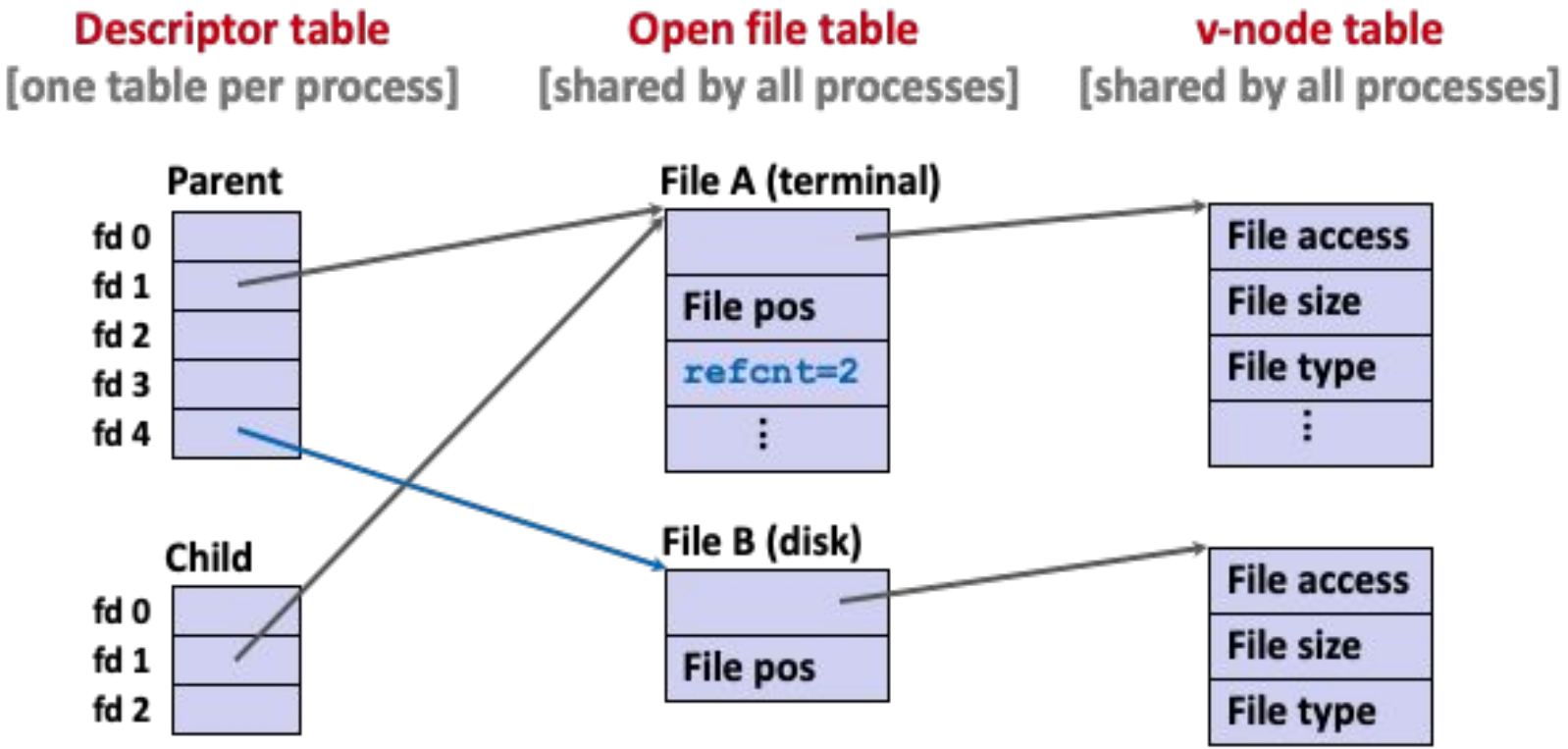
Signals (Contd.)

- Sending the same signal to the parent in all the calls to kill() may print 1 since there would be no queuing of signals.
- We can guarantee printing 2 if we send precisely one SIGUSR1 and one SIGUSR2.
- We can print 1-4 depending on the manner in which signals are sent and received.

File IO



How the Unix Kernel Represents Open Files



File IO

```
foo.txt: abcdefgh...xyz
int main() {
     int fd1, fd2, fd3;
     char c;
     pid_t pid;
     fd1 = open("foo.txt", O_RDONLY);
     fd2 = open("foo.txt", O_RDONLY);
     fd3 = open("foo.txt", O_RDONLY);
     read(fd1, &c, sizeof(c));          // c = ?
     read(fd2, &c, sizeof(c));          // c = ?
     dup2(fd2, fd3);
     read(fd3, &c, sizeof(c));          // c = ?
     read(fd2, &c, sizeof(c));          // c = ?
```

Main ideas:

- How does read offset?
- How does dup2 work?
  - What is the order of arguments?
  - Does fd3 share offset with fd2?

File IO

```
foo.txt: abcdefgh...xyz
int main() {
     int fd1, fd2, fd3;
     char c;
     pid_t pid;
     fd1 = open("foo.txt", O_RDONLY);
     fd2 = open("foo.txt", O_RDONLY);
     fd3 = open("foo.txt", O_RDONLY);
     read(fd1, &c, sizeof(c));          // c = a
     read(fd2, &c, sizeof(c));          // c = a
     dup2(fd2, fd3);
     read(fd3, &c, sizeof(c));          // c = b
     read(fd2, &c, sizeof(c));          // c = c
```

- How does read offset?
  - Incremented by number of bytes read
- How does dup2 work?
  - Any read/write from fd3 now happen from fd2
  - All file offsets are shared

File IO

```
read(fd1, &c, sizeof(c)); // a
read(fd2, &c, sizeof(c)); // a
dup2(fd2, fd3);
read(fd3, &c, sizeof(c)); // b
read(fd2, &c, sizeof(c)); // c
```

```
pid = fork();
if (pid==0) {
     read(fd1, &c, sizeof(c));
     printf("c = %c\n", c);
     dup2(fd1, fd2);
     read(fd3, &c, sizeof(c));
     printf("c = %c\n", c);
}
read(fd2, &c, sizeof(c));
printf("c = %c\n", c);
read(fd1, &c, sizeof(c));
printf("c = %c\n", c);
```

Main ideas:

- How are fd shared between processes?
- How does dup2 work from parent to child?
- How are file offsets shared between processes?

File IO

```
read(fd1, &c, sizeof(c)); // a
read(fd2, &c, sizeof(c)); // a
dup2(fd2, fd3);
read(fd3, &c, sizeof(c)); // b
read(fd2, &c, sizeof(c)); // c

pid = fork();
if (pid==0) {
     read(fd1, &c, sizeof(c));
     printf("c = %c\n", c);
     dup2(fd1, fd2);
     read(fd3, &c, sizeof(c));
     printf("c = %c\n", c);
}
read(fd2, &c, sizeof(c));
printf("c = %c\n", c);
read(fd1, &c, sizeof(c));
printf("c = %c\n", c);
```

What would this program print?

Just ignore the possible outcomes due to interleaving … try two simple cases :

1. First child executes to the end
2. First parent executes to the end.

File IO

```
read(fd1, &c, sizeof(c)); // a
read(fd2, &c, sizeof(c)); // a
dup2(fd2, fd3);
read(fd3, &c, sizeof(c)); // b
read(fd2, &c, sizeof(c)); // c

pid = fork();
if (pid==0) {
     read(fd1, &c, sizeof(c));
     printf("c = %c\n", c);
     dup2(fd1, fd2);
     read(fd3, &c, sizeof(c));
     printf("c = %c\n", c);
}
read(fd2, &c, sizeof(c));
printf("c = %c\n", c);
read(fd1, &c, sizeof(c));
printf("c = %c\n", c);
```

Possible output 1:

c = b // in child

c = d // in child

c = c // in child

c = d // in child

c = e // in parent

c = e // in parent

File IO

```
read(fd1, &c, sizeof(c)); // a
read(fd2, &c, sizeof(c)); // a
dup2(fd2, fd3);
read(fd3, &c, sizeof(c)); // b
read(fd2, &c, sizeof(c)); // c

pid = fork();
if (pid==0) {
     read(fd1, &c, sizeof(c));
     printf("c = %c\n", c);
     dup2(fd1, fd2);
     read(fd3, &c, sizeof(c));
     printf("c = %c\n", c);
}
read(fd2, &c, sizeof(c));
printf("c = %c\n", c);
read(fd1, &c, sizeof(c));
printf("c = %c\n", c);
```

Possible output 2:

c = d // in parent
c = b // in parent
c = c // in child from fd1
c = e // in child from fd3
c = d // in child
c = e // in child

File IO

```
    .
    .
    pid = fork();
    if (pid==0) {
        read(fd1, &c, sizeof(c));
        printf("c = %c\n", c);
        dup2(fd1, fd2);
        read(fd3, &c, sizeof(c));
        printf("c = %c\n", c);
    }
    if (pid!=0) waitpid(-1, NULL, 0);
    read(fd2, &c, sizeof(c));
    printf("c = %c\n", c);
    read(fd1, &c, sizeof(c));
    printf("c = %c\n", c);
    return 0;
}
```

What are the possible outputs now?

File IO

```
    .
    .
    pid = fork();
    if (pid==0) {
        read(fd1, &c, sizeof(c));
        printf("c = %c\n", c);
        dup2(fd1, fd2);
        read(fd3, &c, sizeof(c));
        printf("c = %c\n", c);
    }
    if (pid!=0) waitpid(-1, NULL, 0);
    read(fd1, &c, sizeof(c));
    printf("c = %c\n", c);
    read(fd2, &c, sizeof(c));
    printf("c = %c\n", c);
    return 0;
}
```

Possible output:

c = b // in child

c = d // in child

c = c // in child

c = d // in child

c = e // in parent

c = e // in parent

File IO

```
read(fd1, &c, sizeof(c)); // a
read(fd2, &c, sizeof(c)); // a
dup2(fd2, fd3);
read(fd3, &c, sizeof(c)); // b
read(fd2, &c, sizeof(c)); // c

pid = fork();
if (pid==0) {
     read(fd1, &c, sizeof(c));
     dup2(fd1, fd2);
     read(fd3, &c, sizeof(c));
}else{
     close(fd1)
}
if (pid!=0) waitpid(-1, NULL, 0);
read(fd2, &c, sizeof(c));
read(fd1, &c, sizeof(c));
```

- Child creates a copy of the parent fd table
  - dup2/open/close in parent affect the child
  - dup2/open/close in child do NOT affect the parent
- File descriptors across process share the same file offset.

Malloc

Malloc

- Fit algorithms - first/next/best/good
- Fragmentation
  - Internal - inside blocks
  - External - between blocks
- Organization
  - Implicit
  - Explicit
  - Segregated

Malloc - First fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)						
b = malloc(16)						
c = malloc(16)						
d = malloc(40)						
free(c)						
free(a)						
e = malloc(16)						
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)						
c = malloc(16)						
d = malloc(40)						
free(c)						
free(a)						
e = malloc(16)						
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

- 16 byte align
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- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)						
d = malloc(40)						
free(c)						
free(a)						
e = malloc(16)						
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

- 16 byte align
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- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)						
free(c)						
free(a)						
e = malloc(16)						
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)						
free(a)						
e = malloc(16)						
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

- 16 byte align
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- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)						
e = malloc(16)						
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

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- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)						
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

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- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48a	32a	32f [0]	48a		
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48a	32a	32f [0]	48a		
free(d)	48a	32a	80f [0]			
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48a	32a	32f [0]	48a		
free(d)	48a	32a	80f [0]			
f = malloc(48)	48a	32a	80a			
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - First fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48a	32a	32f [0]	48a		
free(d)	48a	32a	80f [0]			
f = malloc(48)	48a	32a	80a			
free(b)	48a	32f [0]	80a			

final-f01.pdf: Problem 10 Part A

Malloc - First fit

- 16 byte align
- coalesced
- footerless
- 32 min size
- fragmentation?
  - internal?

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48a	32a	32f [0]	48a		
free(d)	48a	32a	80f [0]			
f = malloc(48)	48a	32a	80a			
free(b)	48a	32f [0]	80a			

Malloc - First fit

- 16 byte align
- coalesced
- footerless
- 32 min size
- fragmentation?
  - internal
  - (48-16) + (80-48) = 64
  - external?

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48a	32a	32f [0]	48a		
free(d)	48a	32a	80f [0]			
f = malloc(48)	48a	32a	80a			
free(b)	48a	32f [0]	80a			

Malloc - First fit

- 16 byte align
- coalesced
- footerless
- 32 min size
- fragmentation?
  - internal
  - (48-16) + (80-48) = 64
  - external
  - 32

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48a	32a	32f [0]	48a		
free(d)	48a	32a	80f [0]			
f = malloc(48)	48a	32a	80a			
free(b)	48a	32f [0]	80a			

Malloc - Best fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)						
b = malloc(16)						
c = malloc(16)						
d = malloc(40)						
free(c)						
free(a)						
e = malloc(16)						
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - Best fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)						
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - Best fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48f [0]	32a	32a	48a		
free(d)						
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - Best fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48f [0]	32a	32a	48a		
free(d)	48f [1]	32a	32a	48f [0]		
f = malloc(48)						
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - Best fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48f [0]	32a	32a	48a		
free(d)	48f [1]	32a	32a	48f [0]		
f = malloc(48)	48f [0]	32a	32a	64a		
free(b)						

final-f01.pdf: Problem 10 Part A

Malloc - Best fit

- 16 byte align
- coalesced
- footerless
- 32 min size

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48f [0]	32a	32a	48a		
free(d)	48f [1]	32a	32a	48f [0]		
f = malloc(48)	48f [0]	32a	32a	64a		
free(b)	80f [0]		32a	64a		

final-f01.pdf: Problem 10 Part A

Malloc - Best fit

- 16 byte align
- coalesced
- footerless
- 32 min size
- fragmentation?
  - internal?

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48f [0]	32a	32a	48a		
free(d)	48f [1]	32a	32a	48f [0]		
f = malloc(48)	48f [0]	32a	32a	64a		
free(b)	80f [0]		32a	64a		

Malloc - Best fit

- 16 byte align
- coalesced
- footerless
- 32 min size
- fragmentation?
  - internal
  - (32-16) + (64-48) = 32
  - external?

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48f [0]	32a	32a	48a		
free(d)	48f [1]	32a	32a	48f [0]		
f = malloc(48)	48f [0]	32a	32a	64a		
free(b)	80f [0]		32a	64a		

Malloc - Best fit

- 16 byte align
- coalesced
- footerless
- 32 min size
- fragmentation?
  - internal
  - (32-16) + (64-48) = 32
  - external
  - 80

	#1	#2	#3	#4	#5	#6
a = malloc(32)	48a					
b = malloc(16)	48a	32a				
c = malloc(16)	48a	32a	32a			
d = malloc(40)	48a	32a	32a	48a		
free(c)	48a	32a	32f [0]	48a		
free(a)	48f [0]	32a	32f [1]	48a		
e = malloc(16)	48f [0]	32a	32a	48a		
free(d)	48f [1]	32a	32a	48f [0]		
f = malloc(48)	48f [0]	32a	32a	64a		
free(b)	80f [0]		32a	64a		

Good luck!