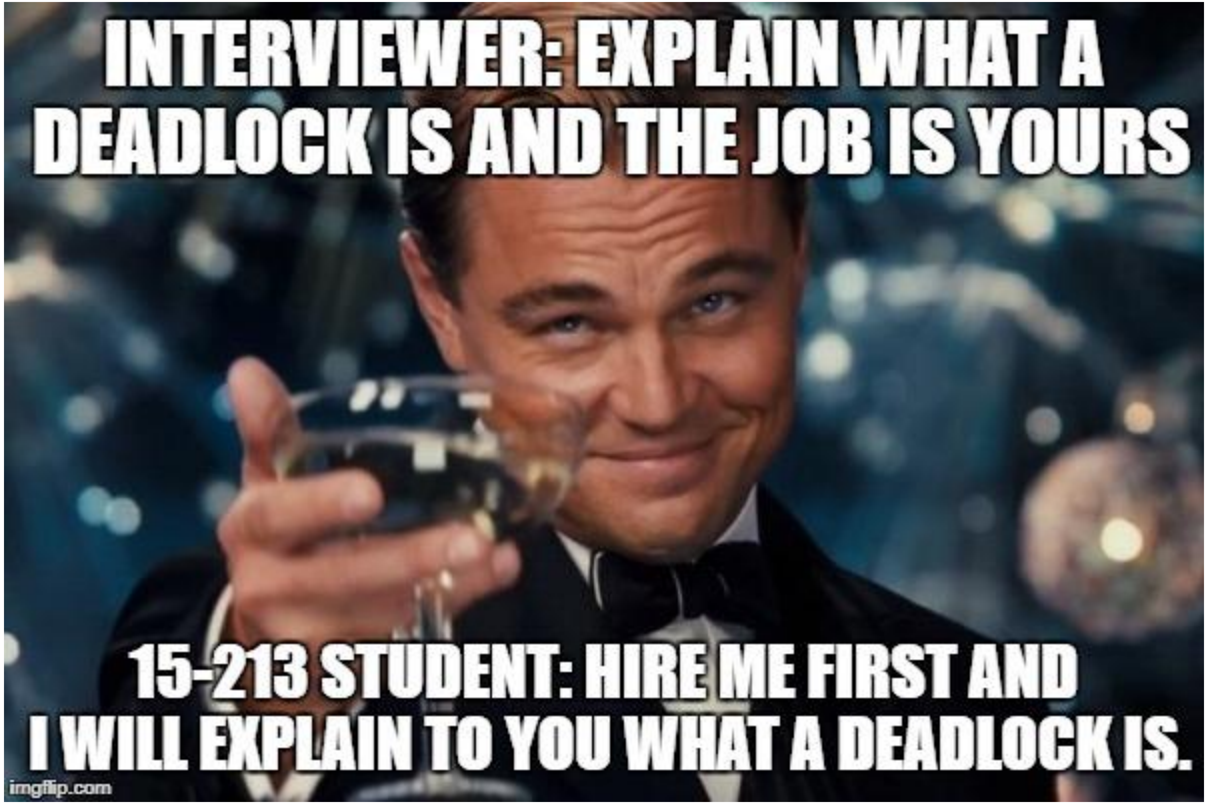
# 15-213: Final Exam Review

Minji, Harsha, and Ishita

# Threads and Synchronization



# Threads and Synchronization

Problem Statement:

- 15-213 TAs now want to begin a new procedure for daily office hours:
- When a student enters the room, he/she will see a table inside the room with several pens and several notebooks on it (if the pens and notebooks haven't been claimed by other students). TAs are inside the room waiting to help them.

# Threads and Synchronization

Procedure for students:

- Wait until you get called, claim a pen and a notebook.
- Use the pen to write your questions on the notebook.
- After you are done with question writing, release the pen.
- Hold the notebook and wait until a TA is free to help you.
- After you are done with talking to a TA about the question, go back to claim a pen and write the solutions on the notebook.
- Release the pen and the notebook and go home.

# Threads and Synchronization

Typical Code to launch threads and wait for them to finish:

```
sem_t pen;
sem_t notebook;
sem_t ta;

int main(int argc, char** argv)
{
    int P = 5, N = 5, T = 3, S = 50;
    sem_init(&pen, 0, P);
    sem_init(&notebook, 0, N);
    sem_init(&ta, 0, T);


    int* students = malloc(S * sizeof(int));
    launch_threads();
    reap_threads();
}
```

```
void launch_threads()
{
  for(int i = 0; i < S; i++)
  {
    students[s] =
          pthread_create(students+i,
                  NULL, student_fn, NULL);
  }
}
void reap_threads()
{
  for(int i = 0; i < S; i++)
  {
    pthread_join(students[i]);
  }
}
```

# Threads and Synchronization

A student writes the following worker thread to simulate the given procedure

```
void* student_fn(void* varp)
{
  P(&pen);
  P(&notebook);
  sleep(genrand() % 60); // Time for you to write questions

  V(&pen);
  P(&ta);
  sleep(genrand() % 900); // Time for you to ask TA

  V(&ta);
  P(&pen);
  sleep(genrand() % 60); // Time for you to write solutions

  V(&notebook);
  V(&pen);

  return 0;
}
```

- However, the code sometimes gets stuck by a deadlock. Which of the following is correct?
- A: The deadlock is caused by the pen and the notebook.
- B: The deadlock is caused by the notebook and the TA.
- C: The deadlock is caused by the TA and the pen.

# Threads and Synchronization

A student writes the following program to simulate the given procedures

```
void* student_fn(void* varp)
{
  P(&pen);
  P(&notebook);
  sleep(genrand() % 60); // Time for you to write questions

  V(&pen);
  P(&ta);
  sleep(genrand() % 900); // Time for you to ask TA

  V(&ta);
  P(&pen);
  sleep(genrand() % 60); // Time for you to write solutions

  V(&notebook);
  V(&pen);

  return 0;
}
```

Let us consider a simple example:

- Pens: 5
- Notebooks: 5
- TAs:
- Students: 50

# Threads and Synchronization

## Let's analyse the semaphores

S: Signal
W: Wait

```
void* student_fn(void* varp)
{
```

W:Get a pen

W:Get a Notebook

```
 P(&pen);
 P(&notebook);

 sleep(genrand() % 60); // Time for you to write questions
```

S: Give up pen

W:Get a TA

```
 V(&pen);
 P(&ta);

 sleep(genrand() % 900); // Time for you to ask TA
```

S:Give up TA

W:Get a pen

```
 V(&ta);
 P(&pen);

 sleep(genrand() % 60); // Time for you to write solutions
```

S:Give up Notebook

S: Give up pen

```
 V(&notebook);
 V(&pen);

 return 0;
}
```

## Case C: TAs and Pens

- There is no overlap
- There can't be a case where a student who is talking to a TA is waiting on a pen.
- There can't be a case where a student who is holding a pen is waiting on a TA

# Threads and Synchronization

## Let's analyse the semaphores

S: Signal
W: Wait

W:Get a pen
W:Get a Notebook
S: Give up pen
W:Get a TA
S:Give up TA
W:Get a pen
S:Give up Notebook
S: Give up pen

```
void* student_fn(void* varp)
{
    P(&pen);
    P(&notebook);

    sleep(genrand() % 60); // Time for you to write questions

    V(&pen);
    P(&ta);

    sleep(genrand() % 900); // Time for you to ask TA

    V(&ta);
    P(&pen);

    sleep(genrand() % 60); // Time for you to write solutions

    V(&notebook);
    V(&pen);

    return 0;
}
```

## Case B: TAs and Notebooks

- There is an overlap
- A student who is holding a notebook may be waiting on a TA
- But….A student who is talking to a TA will not be waiting on a notebook

# Threads and Synchronization

## Let's analyse the semaphores

S: Signal
W: Wait

W:Get a pen
W:Get a Notebook

```
void* student_fn(void* varp)
{
    P(&pen);
    P(&notebook);

    sleep(genrand() % 60); // Time for you to write questions

    V(&pen);
    P(&ta);

    sleep(genrand() % 900); // Time for you to ask TA

    V(&ta);
    P(&pen);

    sleep(genrand() % 60); // Time for you to write solutions

    V(&notebook);
    V(&pen);

    return 0;
}
```

S: Give up pen
W:Get a TA
S:Give up TA
W:Get a pen
S:Give up Notebook
S: Give up pen

## Case A: Pens and Notebooks

- There is an overlap
- A student who is holding a notebook may be waiting on a pen
- A student who is holding a pen may be waiting on a notebook

# Threads and Synchronization

## Let's analyse the semaphores

S: Signal
W: Wait

```
void* student_fn(void* varp)
{
  P(&pen);
  P(&notebook);

  sleep(genrand() % 60); // Time for you to write questions

  V(&pen);
  P(&ta);

  sleep(genrand() % 900); // Time for you to ask TA

  V(&ta);
  P(&pen);

  sleep(genrand() % 60); // Time for you to write solutions

  V(&notebook);
  V(&pen);

  return 0;
}
```

W:Get a pen

W:Get a Notebook

S: Give up pen

W:Get a TA

S:Give up TA

W:Get a pen

S:Give up Notebook

S: Give up pen

Case A: Pens and Notebooks

Consider this likely scenario:

- 5 Students (group A) enter the room
- They grab all 5 pens and all 5 notebooks on the table.
- Every student behind them is waiting on a pen and a notebook. (Group B)
- All 5 students in Group A give up their pens, but not their notebooks.
- 5 students in Group B immediately grab the 5 pens.
- Group B are now waiting on notebooks.
- After talking to the TAs, all students in Group A are now waiting on pens, which students in Group B have.
- Group B is waiting on the notebooks which students in Group A have.

DEADLOCK!!

# Threads and Synchronization

A student writes the following program to simulate the given procedures

```
void* student_fn(void* varp)
{
  P(&pen);
  P(&notebook);


  sleep(genrand() % 60); // Time for you to write questions


  V(&pen);
  P(&ta);

  sleep(genrand() % 900); // Time for you to ask TA


  V(&ta);
  P(&pen);

  sleep(genrand() % 60); // Time for you to write solutions


  V(&notebook);
  V(&pen);

  return 0;
}
```

- However, the code sometimes gets stuck by a deadlock. Which of the following is correct?
- A: The deadlock is caused by the pen and the notebook.
- B: The deadlock is caused by the notebook and the ta.
- C: The deadlock is caused by the ta and the pen.

ANSWER: A

# Threads and Synchronization

Can we fix this without changing the Office Hour procedure?

# Threads and Synchronization

Can we fix this without changing the Office Hour procedure?

YES!

# Threads and Synchronization

## Let's analyse the semaphores

S: Signal
W: Wait

W:Get a Notebook

W:Get a pen

S: Give up pen

W:Get a TA

S:Give up TA

W:Get a pen

S: Give up pen

S:Give up Notebook

```
void* student_fn(void* varp)
{
  P(&notebook);
  P(&pen);

  sleep(genrand() % 60); // Time for you to write questions

  V(&pen);
  P(&ta);

  sleep(genrand() % 900); // Time for you to ask TA

  V(&ta);
  P(&pen);

  sleep(genrand() % 60); // Time for you to write solutions

  V(&pen);
  V(&notebook);

  return 0;
}
```

Let's just re-order the locks and analyse it again.

- A student who is holding a notebook may wait on a pen or a TA

However...

- A student who is holding a pen will already have a notebook (and never wait on it).
- A student who is talking to a TA will already have a notebook (and never wait on it).

# Signals

## who would win?

several hundred lines of tshlab code

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

one asynchronous boi

SIGCHLD

# Signals

- Examples in these slides are important “gotchas”
  - **NOT** an all inclusive list
  - In particular, these do **NOT** go over signals sent **between multiple processes**
- Many more examples in:
  - Recitation slides
  - Lecture slides
  - Past exams
- Reminder: solve the questions **on your own** when studying **before** looking at the answer

# Signals

- Does the following code ever terminate?

```
void handler(int sig) {
    while(1);
}
int main() {
    Signal(SIGUSR1, handler);
    Kill(0, SIGUSR1);
    return 0;
}
```

# Signals

- Does the following code ever terminate?

```
void handler(int sig) {
    while(1);                // stuck here forever!
}
int main() {
    Signal(SIGUSR1, handler);
    // Spec says signal sent to self must be handled
    // before kill() returns
    Kill(0, SIGUSR1);
    return 0;
}
```

# Signals

- What about now?

```
void handler(int sig) {
    Kill(0, SIGUSR1);
}

int main() {
    Signal(SIGUSR1, handler);
    Kill(0, SIGUSR1);
    return 0;
}
```

# Signals

- What about now?

```
void handler(int sig) {
    Kill(0, SIGUSR1);
}

int main() {
    Signal(SIGUSR1, handler);
    Kill(0, SIGUSR1);
    return 0;
}
```

- Does not terminate:

`main: Kill(0, SIGUSR1);`

`<SIGUSR1` **`handler invoked`**`, SIGUSR1` **`blocked`** `in handler>`

`handler: Kill(0, SIGUSR1);`

`<SIGUSR1` **`pending`**`>`

`<handler returns>`

`<SIGUSR1 unblocked, SIGUSR1` **`handler invoked`**`, SIGUSR1` **`blocked`** `in handler>`

`handler: Kill(0, SIGUSR);`

`...repeat...`

# Processes

# 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);
}
```

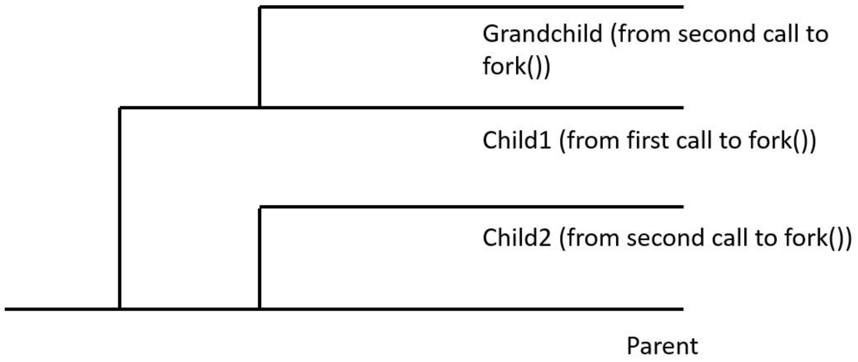
What does the process diagram look like?

# 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

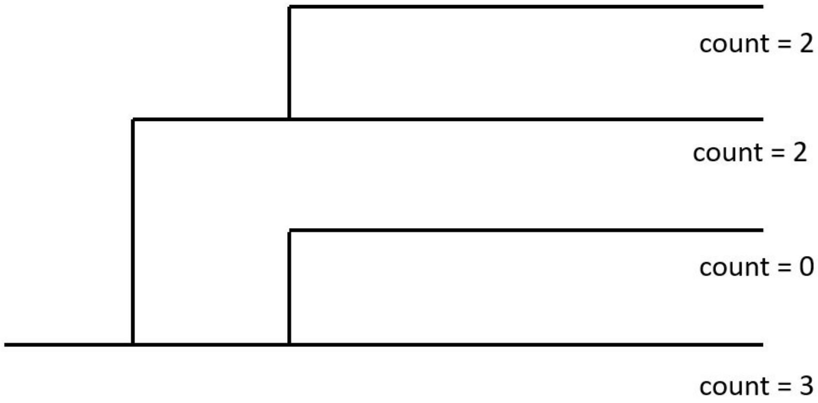
Grandchild: pid1 == 0 and pid2 == 0
- count = 2

# 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?

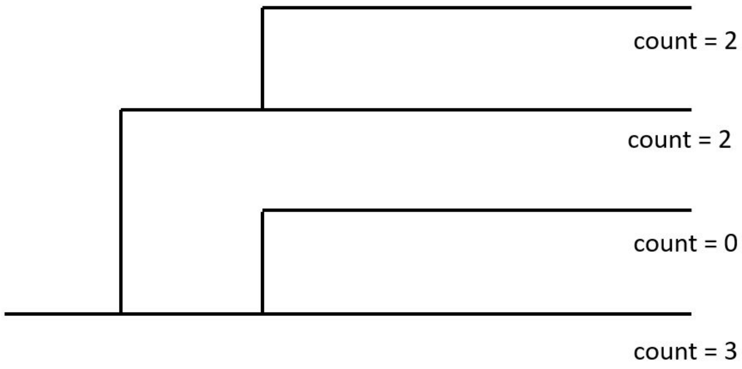


# Processes

```
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?



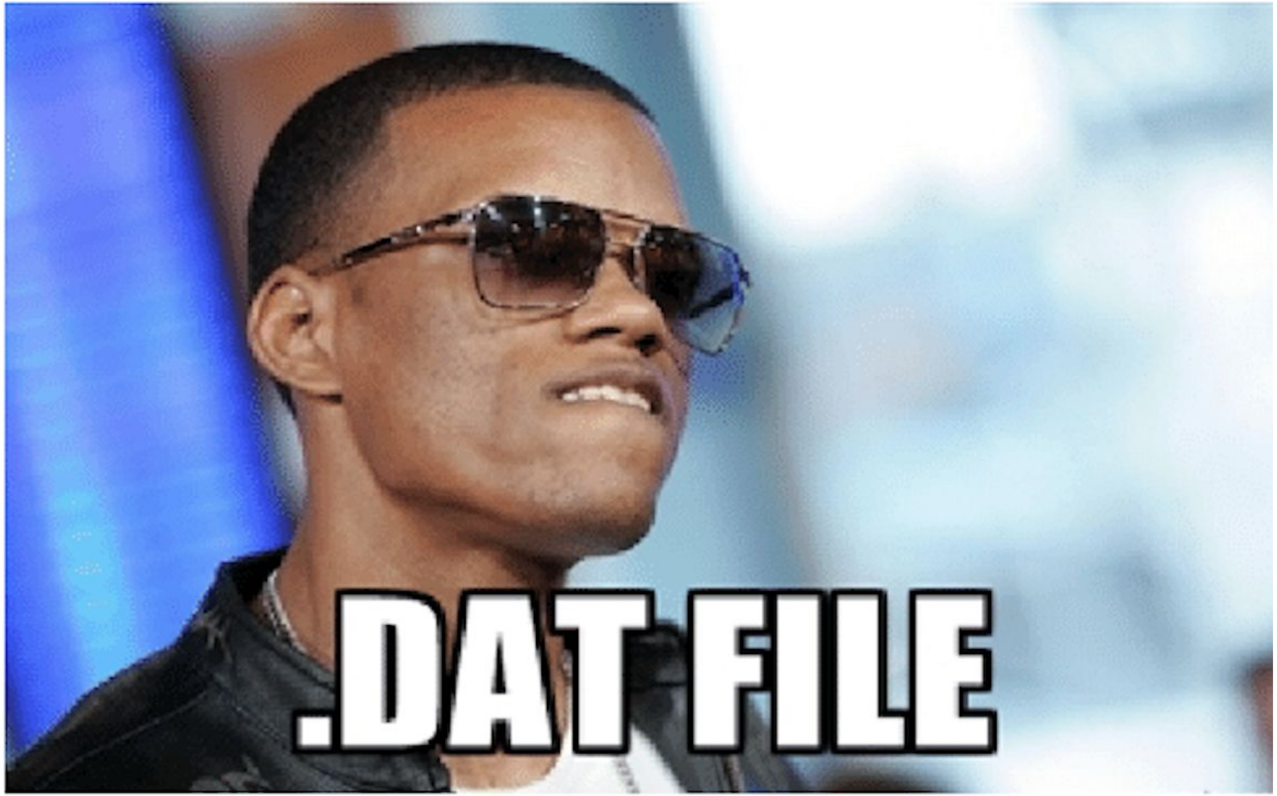

Math! 4! / 2 = 12 different possible outcomes

# 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!

# File IO



# 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?

# 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 = 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

```
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 = 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

```
    .
    .
    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));
}
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 only before fork() affect the child
  - dup2/open/close in child do NOT affect the parent
- File descriptors across process share the same file offset.

# 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 18: 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

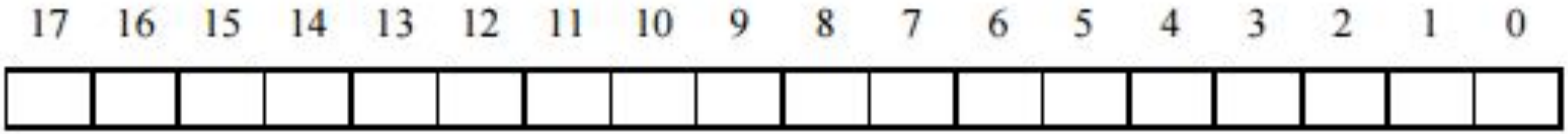
Label the following:

(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 = $2^9 \rightarrow$ Need 9 bits

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

# Virtual Memory

Label the following:

(A) *VPO:* Virtual Page Offset

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

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

# Virtual Memory

Label the following:

(A) *VPO:* Virtual Page Offset

(B) *VPN:* Virtual Page Number

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

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

# 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

| 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B | B | B | B | B | B | B | B | B | A | A | A | A | A | A | A | A | A |
| | | | | | | | | TLBI | | | | | | | | | |

# 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

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

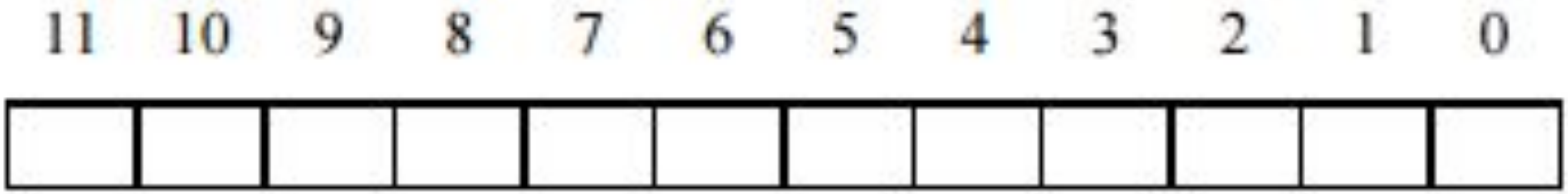
TLBT

TLBI

# Virtual Memory

Label the following:

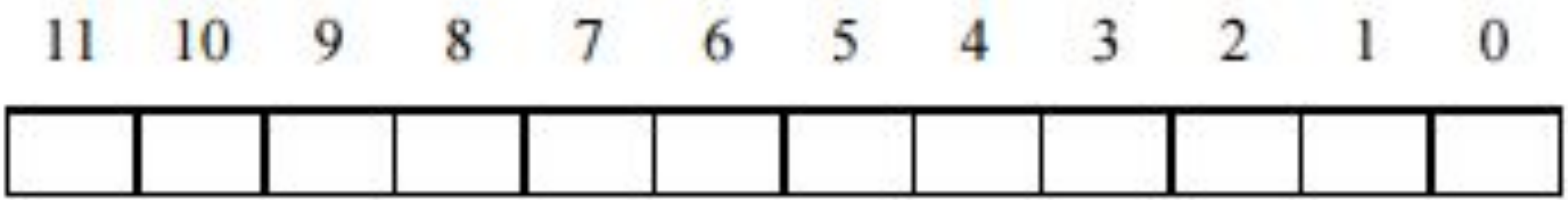
(A) *PPO:* Physical Page Offset
(B) *PPN:* Physical Page Number
(C) *CO:* Cache Offset
(D) *CI:* Cache Index
(E) *CT:* Cache Tag



# Virtual Memory

Label the following:

(A) *PPO:* Physical Page Offset



# Virtual Memory

Label the following:

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

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | A | A | A | A | A | A | A | A | A |

# Virtual Memory

Label the following:

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

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

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | B | B | A | A | A | A | A | A | A | A | A |

# 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

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | B | B | A | A | A | A | A | A | A | A | A |

# 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

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | B | B | A | A | A | A | A | A | A | A | A |

CO

# 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

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | B | B | A | A | A | A | A | A | A | A | A |

CO

# 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

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **B** | **B** | **B** | **A** | **A** | **A** | **A** | **A** | **A** | **A** | **A** | **A** |
| | | | | | | | | CI | | CO | |

# 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

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | B | B | A | A | A | A | A | A | A | A | A |

Cache Tag CI CO

# Virtual Memory

Now to the actual question!

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

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

# 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

| 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: 0x?? TLBI: 0x?? TLBT: 0x??

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

| 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: 0x?? TLBT: 0x??

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

| 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: 0x??

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

| 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/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??

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | | | | | | | | | |

# 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

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |

# Virtual Memory

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

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

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |

# 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??

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |

# 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??

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |

# 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 |

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |

# 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 |

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |

# Virtual Memory

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

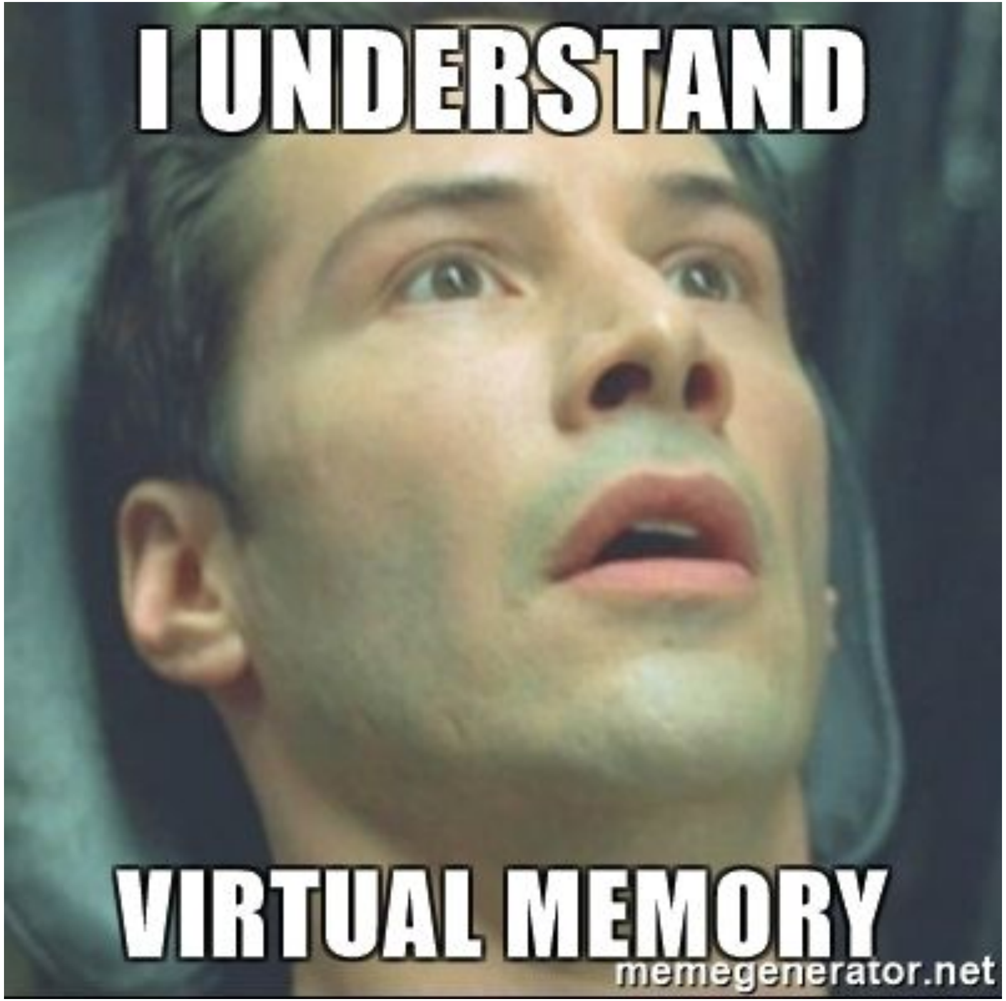
1. Extract more information
2. Go to Cache Table

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 |

| 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |

# Virtual Memory



# Good luck!

# 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
- coalesced
- 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
- 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) | | | | | | |
| 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) | | | | | | |

# 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) | | | | | | |
| 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) | 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

- 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) | | | | | | |
| f = malloc(48) | | | | | | |
| free(b) | | | | | | |

# 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) | | | | | | |

# 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) | | | | | | |

# 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 | 54a | | |
| 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 | 54a | | |
| free(b) | 48f [1] | 32f [0] | 32a | 54a | | |

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 | 54a | | |
| free(b) | 48f [1] | 32f [0] | 32a | 54a | | |

# Malloc - Best fit

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

- fragmentation?
  - internal
  - (32-16) + (54-48) = 24
  - 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 | 54a | | |
| free(b) | 48f [1] | 32f [0] | 32a | 54a | | |

# Malloc - Best fit

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

- fragmentation?
  - internal
  - (32-16) + (54-48) = 24
  - external
  - 48+32 = 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 | 54a | | |
| free(b) | 48f [1] | 32f [0] | 32a | 54a | | |

# Good luck!