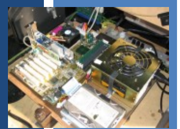
TCSS 422: OPERATING SYSTEMS



Condition Variables II, Concurrency Problems

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma

May 9, 2024 TCSS422: Operating Systems [Spring 2024] School of Engineering and Technology, University of Washington - Tacoma

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OFFICE HOURS – THURSDAY

- **SPECIAL TIME THURSDAY MAY 9**
- **Thursday Office Hours**
  - 6:00pm to 7:00 pm – CP 229 and Zoom

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OBJECTIVES – 5/9

- **Questions from 5/9**
- Pthread Tutorial-May 24 / Assignment 2 posted next week
- Quiz 3 – Synchronized Array (class activity-next week)
- Chapter 30: Condition Variables
  - Covering Conditions
- Chapter 32: Concurrency Problems
  - Non-deadlock concurrency bugs
  - Deadlock causes
  - Deadlock prevention
- Chapter 13: Address Spaces
- Chapter 14: The Memory API

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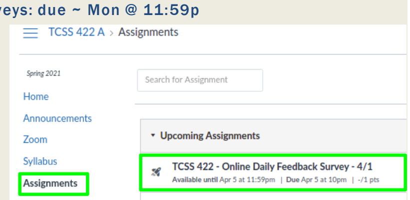
ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by ~ Wed @ 11:59p
- Thursday surveys: due ~ Mon @ 11:59p



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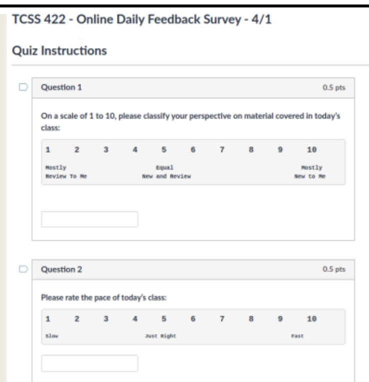

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (26 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.58 (↑ - previous 6.56)**
- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.31 (no change - previous 5.31)**

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FEEDBACK FROM 5/7

- ***Why does the (bounded) buffer consist of only 1 element?***
  - In the textbook example, the initial bounded buffer example is a single integer
  - Think of this as an integer array of 1 element
  - This is initially done for simplicity it teaching the bounded buffer concepts
  - By not having an array, it is not necessary to track the index for where elements are added (***fill index***), and where elements are removed (***use index***) from the bounded buffer
- ***Why isn't the buffer an array of multiple pointers that stores data in a FIFO order?***
  - This can be done. For example, we could have an array of matrices, where each matrix is a 2-D array of integers on the heap

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FEEDBACK - 2

- ***Is the buffer in the stack or in the heap?***
  - In signal.c (chapter 30), the bounded buffer is a matrix pointer which is defined as a global variable in the program's data segment

```
int ** bigmatrix;
```

  - Globals are not on the stack or heap, but in the data segment
- ***How are the memory addresses of each element in a matrix assigned (in signal.c)?***
  - In GenMatrix(), the 2-D matrix is represented as an array of integer arrays
  - Int *mm is made to point at a row: matrix[i]

```
int * mm = matrix[i];
```

  - Then, we access the j^th element of the row to assign the column value

```
mm[j] = rand() % ELEMENT_SIZE;
```

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OBJECTIVES – 5/9

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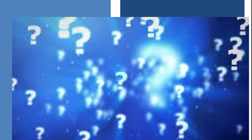

CHAPTER 30 – CONDITION VARIABLES

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OBJECTIVES – 5/9

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- Chapter 30: Condition Variables
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COVERING CONDITIONS

- A condition that covers ***all*** cases (conditions):
- Excellent use case for **pthread_cond_broadcast**
- Consider memory allocation:
  - When a program deals with huge memory allocation/deallocation on the heap
  - Access to the heap must be managed when memory is scarce

    PREVENT: Out of memory:
    - queue requests until memory is free
  - Which thread should be woken up?

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COVERING CONDITIONS - 2

```c
// how many bytes of the heap are free?
int bytesLeft = MAX_HEAP_SIZE;

// need lock and condition too
cond_t c;
mutex_t m;

void *
allocate(int size) {
    Pthread_mutex_lock(&m);
    while (bytesLeft < size)
        Pthread_cond_wait(&c, &m);
    void *ptr = ...;                // get mem from heap
    bytesLeft -= size;
    Pthread_mutex_unlock(&m);
    return ptr;
}

void free(void *ptr, int size) {
    Pthread_mutex_lock(&m);
    bytesLeft += size;
    Pthread_cond_signal(&c);        //
    Pthread_mutex_unlock(&m);
}
```

Check available memory

Broadcast

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COVER CONDITIONS - 3

- Broadcast awakens all blocked threads requesting memory
- Each thread evaluates if there's enough memory: (bytesLeft < size)
  - Reject: requests that cannot be fulfilled- go back to sleep
    - *Insufficient memory*
  - Run: requests which **can** be fulfilled
    - with newly available memory!
- **Another use case**: coordinate a group of busy threads to gracefully end, to EXIT the program
- **Overhead**
  - Many threads may be awoken which can't execute

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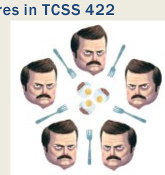
CHAPTER 31: SEMAPHORES

- Offers a combined C language construct that can assume the role of a lock or a condition variable depending on usage
  - Allows fewer concurrency related variables in your code
  - Potentially makes code more ambiguous
  - For this reason, with limited time in a 10-week quarter, we do not cover semaphores in TCSS 422
- **Ch. 31.6 – Dining Philosophers Problem**
  - Classic computer science problem about sharing eating utensils
  - Each philosopher tries to obtain two forks in order to eat
  - Mimics deadlock as there are not enough forks
  - Solution is to have one left-handed philosopher that grabs forks in opposite order



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OBJECTIVES – 5/9

- Questions from 5/9
- Pthread Tutorial-May 24 / Assignment 2 posted next week
- Quiz 3 – Synchronized Array (class activity-next week)
- Chapter 30: Condition Variables
  - Producer/Consumer
  - Covering Conditions
- **Chapter 32: Concurrency Problems**
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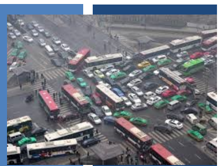

CHAPTER 32 – CONCURRENCY PROBLEMS

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CONCURRENCY BUGS IN OPEN SOURCE SOFTWARE

- "Learning from Mistakes – A Comprehensive Study on Real World Concurrency Bug Characteristics"
  - Shan Lu et al.
  - Architectural Support For Programming Languages and Operating Systems (ASPLOS 2008), Seattle WA

Application	What it does	Non-Deadlock	Deadlock
MySQL	Database Server	14	9
Apache	Web Server	13	4
Mozilla	Web Browser	41	16
Open Office	Office Suite	6	2
Total		**74**	**31**

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OBJECTIVES – 5/9

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NON-DEADLOCK BUGS

- Majority of concurrency bugs
- Most common:
  - Atomicity violation: forget to use locks
  - Order violation: failure to initialize lock/condition before use

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ATOMICITY VIOLATION - MYSQL

- Two threads access the `proc_info` field in `struct thd`
- `NULL` is 0 in C
- Mutually exclusive access to shared memory among separate threads is not enforced (e.g. non-atomic)
- Simple example: ***proc_info deleted***

Programmer intended variable to be accessed atomically…

```
Thread1::
if(thd->proc_info){
    …
    fputs(thd->proc_info , …);
    …
}

Thread2::
thd->proc_info = NULL;
```


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ATOMICITY VIOLATION - SOLUTION

- Add locks for all uses of: `thd->proc_info`

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;

Thread1::
pthread_mutex_lock(&lock);
if(thd->proc_info){
    …
    fputs(thd->proc_info , …);
    …
}
pthread_mutex_unlock(&lock);

Thread2::
pthread_mutex_lock(&lock);
thd->proc_info = NULL;
pthread_mutex_unlock(&lock);
```


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ORDER VIOLATION BUGS

- Desired order between memory accesses is flipped
- E.g. something is checked before it is set
- Example:

```
Thread1::
void init(){
    mThread = PR_CreateThread(mMain, …);
}

Thread2::
void mMain(…){
    mState = mThread->State
}
```

- What if mThread is not initialized?

ORDER VIOLATION - SOLUTION

- Use condition & signal to enforce order

```
pthread_mutex_t mtLock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t mtCond = PTHREAD_COND_INITIALIZER;
int mtInit = 0;

Thread 1::
void init(){
    …
    mThread = PR_CreateThread(mMain,…);

    // signal that the thread has been created.
    pthread_mutex_lock(&mtLock);
    mtInit = 1;
    pthread_cond_signal(&mtCond);
    pthread_mutex_unlock(&mtLock);
    …
}

Thread2::
void mMain(…){
    …
```


ORDER VIOLATION – SOLUTION - 2

- Use condition & signal to enforce order

```
    // wait for the thread to be initialized …
    pthread_mutex_lock(&mtLock);
    while(mtInit == 0)
            pthread_cond_wait(&mtCond, &mtLock);
    pthread_mutex_unlock(&mtLock);

    mState = mThread->State;
    …
}
```


NON-DEADLOCK BUGS - 1

- 97% of Non-Deadlock Bugs were
  - Atomicity
  - Order violations
- Consider what is involved in "spotting" these bugs in code
  - *>> no use of locking constructs to search for*
- Desire for automated tool support (IDE)

NON-DEADLOCK BUGS - 2

- Atomicity
  - How can we tell if a given variable is shared?
    - Can search the code for uses
  - How do we know if all instances of its use are shared?
    - Can some non-synchronized, non-atomic uses be legal?
      - Legal uses: before threads are created, after threads exit
    - Must verify the scope
- Order violation
  - Must consider all variable accesses
  - Must know desired order

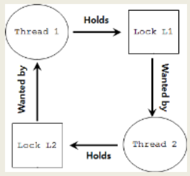
WE WILL RETURN AT 4:50PM

DEADLOCK BUGS

- Presence of a cycle in code
- Thread 1 acquires lock L1, waits for lock L2
- Thread 2 acquires lock L2, waits for lock L1

```
Thread 1:        Thread 2:
lock(L1);        lock(L2);
lock(L2);        lock(L1);
```

- Both threads can block, unless one manages to acquire both locks



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OBJECTIVES – 5/9

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REASONS FOR DEADLOCKS

- Complex code
  - Must avoid circular dependencies – can be hard to find...
- Encapsulation hides potential locking conflicts
  - Easy-to-use APIs embed locks inside
  - Programmer doesn't know they are there
  - Consider the Java Vector class:

```
Vector v1,v2;
v1.AddAll(v2);
```

  - Vector is thread safe (synchronized) by design
  - If there is a v2.AddAll(v1); call at nearly the same time deadlock could result

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CONDITIONS FOR DEADLOCK

- **Four conditions** are required for dead lock to occur

Condition	Description
Mutual Exclusion	Threads claim exclusive control of resources that they require.
Hold-and-wait	Threads hold resources allocated to them while waiting for additional resources
No preemption	Resources cannot be forcibly removed from threads that are holding them.
Circular wait	There exists a circular chain of threads such that each thread holds one more resources that are being requested by the next thread in the chain

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PREVENTION – MUTUAL EXCLUSION

- Build wait-free data structures
  - Eliminate locks altogether
  - Build structures using CompareAndSwap atomic CPU (HW) instruction
- C pseudo code for CompareAndSwap
- Hardware executes this code atomically

```
int CompareAndSwap(int *address, int expected, int new){
    if(*address == expected){
        *address = new;
        return 1; // success
    }
    return 0;
}
```


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PREVENTION – MUTUAL EXCLUSION - 2

- Recall atomic increment

```
void AtomicIncrement(int *value, int amount){
    do{
            int old = *value;
    }while( CompareAndSwap(value, old, old+amount)==0);
}
```

- Compare and Swap tries over and over until successful
- CompareAndSwap is guaranteed to be atomic
- When it runs it is **ALWAYS** atomic (at HW level)

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MUTUAL EXCLUSION: LIST INSERTION

- Consider list insertion

```
void insert(int value){
    node_t * n = malloc(sizeof(node_t));
    assert( n != NULL );
    n->value = value ;
    n->next  = head;
    head     = n;
}
```


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MUTUAL EXCLUSION – LIST INSERTION - 2

- Lock based implementation

```
void insert(int value){
    node_t * n = malloc(sizeof(node_t));
    assert( n != NULL );
    n->value = value ;
    lock(listlock); // begin critical section
    n->next  = head;
    head     = n;
    unlock(listlock) ;  //end critical section
}
```


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MUTUAL EXCLUSION – LIST INSERTION - 3

- Wait free (no lock) implementation

```
void insert(int value) {
    node_t *n = malloc(sizeof(node_t));
    assert(n != NULL);
    n->value = value;
    do {
            n->next = head;
    } while (CompareAndSwap(&head, n->next, n));
}
```

- Assign &head to n (new node ptr)
- Only when head = n->next

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PREVENTION LOCK – HOLD AND WAIT

- Problem: acquire all locks atomically
- Solution: use a "lock" "lock"… (*like a* ***guard lock***)

```
lock(prevention);
lock(L1);
lock(L2);
…
unlock(prevention);
```

- Effective solution – guarantees no race conditions while acquiring L1, L2, etc.
- Order doesn't matter for L1, L2
- Prevention (GLOBAL) lock decreases concurrency of code
  - Acts Lowers lock granularity
- Encapsulation: consider the Java Vector class…

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PREVENTION – NO PREEMPTION

- When acquiring locks, don't BLOCK forever if unavailable…
- pthread_mutex_trylock() - try once
- pthread_mutex_timedlock() - try and wait awhile

```
top:
    lock(L1);
    if( tryLock(L2) == -1 ){
        unlock(L1);
        goto top;
    }
```

- Eliminates deadlocks

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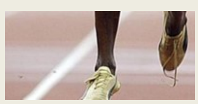
NO PREEMPTION – LIVELOCKS PROBLEM

- Can lead to livelock

```
top:
    lock(L1);
    if( tryLock(L2) == -1 ){
        unlock(L1);
        goto top;
    }
```

- Two threads execute code in parallel → always fail to obtain both locks
- Fix: add random delay
  - Allows one thread to win the livelock race!



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CONDITIONS FOR DEADLOCK

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PREVENTION – CIRCULAR WAIT

- Provide **total ordering** of lock acquisition throughout code
  - Always acquire locks in same order
  - L1, L2, L3, …
  - Never mix: L2, L1, L3; L2, L3, L1; L3, L1, L2….
- Must carry out same ordering through entire program

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CONDITIONS FOR DEADLOCK

- **If any of the following conditions DOES NOT EXSIST, describe why deadlock can not occur?**

Condition	Description
Mutual Exclusion	Threads claim exclusive control of resources that they require.
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No preemption	Resources cannot be forcibly removed from threads that are holding them.
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The dining philosophers problem where 5 philosophers compete for 5 forks, and where a philosopher must hold two forks to eat involves which deadlock condition(s)?

- Mutual Exclusion
- Hold-and-wait
- No preemption
- Circular wait
- All of the above

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DEADLOCK AVOIDANCE VIA INTELLIGENT SCHEDULING

- Consider a smart scheduler
  - Scheduler knows which locks threads use
- Consider this scenario:
  - 4 Threads (T1, T2, T3, T4)
  - 2 Locks (L1, L2)
- Lock requirements of threads:

	T1	T2	T3	T4
L1	yes	yes	no	no
L2	yes	yes	yes	no

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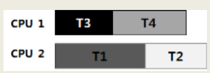
INTELLIGENT SCHEDULING - 2

- Scheduler produces schedule:



- No deadlock can occur
- Consider:

	T1	T2	T3	T4
L1	yes	yes	yes	no
L2	yes	yes	yes	no

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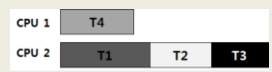
INTELLIGENT SCHEDULING - 3

- Scheduler produces schedule



- Scheduler must be conservative and not take risks
- Slows down execution – many threads
- There has been limited use of these approaches given the difficulty having intimate lock knowledge about every thread

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DETECT AND RECOVER

- Allow deadlock to occasionally occur and then take some action.
  - Example: When OS freezes, reboot…
- How often is this acceptable?
  - Once per year
  - Once per month
  - Once per day
  - *Consider the effort tradeoff of finding every deadlock bug*
- Many database systems employ deadlock detection and recovery techniques.

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CHAPTER 13: ADDRESS SPACES

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OBJECTIVES – 5/9

- Chapter 13: Introduction to memory virtualization
  - The address space
  - Goals of OS memory virtualization
- Chapter 14: Memory API
  - Common memory errors

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MEMORY VIRTUALIZATION

- What is memory virtualization?
- This is not "virtual" memory,
  - Classic use of disk space as additional RAM
  - When available RAM was low
  - Less common recently

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MEMORY VIRTUALIZATION - 2

- Presentation of system memory to each process
- Appears as if each process can access the entire machine's address space
- Each process's view of memory is isolated from others
- Everyone has their own sandbox

Process A

Process B

Process C

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MOTIVATION FOR MEMORY VIRTUALIZATION

- Easier to program
  - Programs don't need to understand special memory models
- Abstraction enables sophisticated approaches to manage and share memory among processes
- Isolation
  - From other processes: easier to code
- Protection
  - From other processes
  - From programmer error (segmentation fault)

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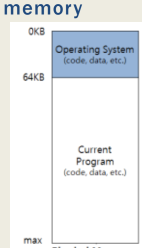
EARLY MEMORY MANAGEMENT

- Load one process at a time into memory
- Poor memory utilization
- Little abstraction



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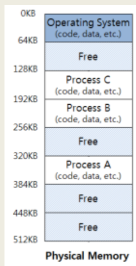
MULTIPROGRAMMING WITH SHARED MEMORY

- Later machines supported running multiple processes
- Swap out processes during I/O waits to increase system utilization and efficiency
- Swap entire memory of a process to disk for context switch
- Too slow, especially for large processes
- Solution→
  - Leave processes in memory
- Need to protect from errant memory accesses in a multiprocessing environment



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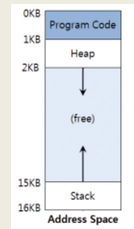
ADDRESS SPACE

- Easy-to-use abstraction of physical memory for a process
- Main elements:
  - Program code
  - Stack
  - Heap
- Example: 16KB address space



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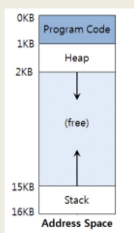
ADDRESS SPACE - 2

- Code
  - Program code
- Stack
  - Program counter (PC)
  - Local variables
  - Parameter variables
  - Return values (for functions)
- Heap
  - Dynamic storage
  - Malloc() new()



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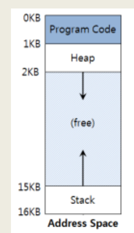
ADDRESS SPACE - 3

- Program code
  - Static size
- Heap and stack
  - Dynamic size
  - Grow and shrink during program execution
  - Placed at opposite ends
- Addresses are virtual
  - They must be physically mapped by the OS



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VIRTUAL ADDRESSING

- Every address is virtual
  - OS translates virtual to physical addresses

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

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

    printf("location of code  : %p\n", (void *) main);
    printf("location of heap  : %p\n", (void *) malloc(1));
    int x = 3;
    printf("location of stack : %p\n", (void *) &x);

    return x;
}
```

- EXAMPLE: virtual.c

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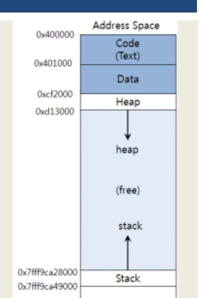
VIRTUAL ADDRESSING - 2

- Output from 64-bit Linux:

```
location of code: 0x400686
location of heap: 0x1129420
location of stack: 0x7ffe040d77e4
```



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GOALS OF OS MEMORY VIRTUALIZATION

- Transparency
  - Memory shouldn't appear virtualized to the program
  - OS multiplexes memory among different jobs behind the scenes
- Protection
  - Isolation among processes
  - OS itself must be isolated
  - One program should not be able to affect another (or the OS)

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GOALS - 2

- Efficiency
  - Time
    - Performance: virtualization must be fast
  - Space
    - Virtualization must not waste space
    - Consider data structures for organizing memory
    - Hardware support TLB: Translation Lookaside Buffer
- *Goals considered when evaluating memory virtualization schemes*

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OBJECTIVES – 5/9

- Questions from 5/9
- Pthread Tutorial-May 24 / Assignment 2 posted next week
- Quiz 3 – Synchronized Array (class activity-next week)
- Chapter 30: Condition Variables
  - Covering Conditions
- Chapter 32: Concurrency Problems
  - Non-deadlock concurrency bugs
  - Deadlock causes
  - Deadlock prevention
- Chapter 13: Address Spaces
- **Chapter 14: The Memory API**

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CHAPTER 14: THE MEMORY API

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OBJECTIVES – 5/9

- Chapter 13: Introduction to memory virtualization
  - The address space
  - Goals of OS memory virtualization
- **Chapter 14: Memory API**
  - Common memory errors

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MALLOC

```
#include <stdlib.h>

void* malloc(size_t size)
```

- Allocates memory on the heap
- size_t unsigned integer (must be +)
- size size of memory allocation in bytes
- Returns
- SUCCESS: A void * to a memory address
- FAIL: NULL
- sizeof() often used to ask the system how large a given datatype or struct is

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SIZEOF()

- Not safe to assume data type sizes using different compilers, systems
- Dynamic array of 10 ints
- Static array of 10 ints

```
int *x = malloc(10 * sizeof(int));
printf("%d\n", sizeof(x));
```

```
4
```

```
int x[10];
printf("%d\n", sizeof(x));
```

```
40
```


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FREE()

```
#include <stdlib.h>

void free(void* ptr)
```

- Free memory allocated with malloc()
- Provide: (void *) ptr to malloc'd memory
- Returns: nothing

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```
#include<stdio.h>

int * set_magic_number_a()
{
  int a =53247;
  return &a;
}

void set_magic_number_b()
{
  int b = 11111;
}

int main()
{
  int * x = NULL;
  x = set_magic_number_a();
  printf("The magic number is=%d\n",*x);
  set_magic_number_b();
  printf("The magic number is=%d\n",*x);
  return 0;
}
```

What will this code do?

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```
#include<stdio.h>

int * set_magic_number_a()
{
  int a =53247;
  return &a;
}

void set_magic_number_b()
{
  int b = 11111;
}

int main()
{
  int * x = NULL;
  x = set_magic_number_a();
  printf("The magic number is=%d\n",*x);
  set_magic_number_b();
  printf("The magic number is=%d\n",*x);
  return 0;
}
```

What will this code do?

Output:

```
$ ./pointer_error
The magic number is=53247
The magic number is=11111
```

We have not changed *x but the value has changed!!

Why?

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DANGLING POINTER (1/2)

- Dangling pointers arise when a variable referred (a) goes "out of scope", and it's memory is destroyed/overwritten (by b) without modifying the value of the pointer (*x).
- The pointer still points to the original memory location of the deallocated memory (a), which has now been reclaimed for (b).

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DANGLING POINTER (2/2)

- Fortunately in the case, a compiler warning is generated:

```
$ g++ -o pointer_error -std=c++0x pointer_error.cpp

pointer_error.cpp: In function 'int* set_magic_number_a()':
pointer_error.cpp:6:7: warning: address of local variable 'a' returned [enabled by default]
```

- This is a common mistake - - - accidentally referring to addresses that have gone "out of scope"

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CALLOC()

```
#include <stdlib.h>

void *calloc(size_t num, size_t size)
```

- Allocate "C"lear memory on the heap
- Calloc wipes memory in advance of use…
- `size_t num` : number of blocks to allocate
- `size_t size` : size of each block(in bytes)

- Calloc() prevents…

```
char *dest = malloc(20);
printf("dest string=%s\n", dest);
```

dest string=��F

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REALLOC()

```
#include <stdlib.h>

void *realloc(void *ptr, size_t size)
```

- Resize an existing memory allocation
- Returned pointer may be same address, or a new address
  - New if memory allocation must move
- `void *ptr`: Pointer to memory block allocated with malloc, calloc, or realloc
- `size_t size`: New size for the memory block(in bytes)

- EXAMPLE: realloc.c
- EXAMPLE: nom.c

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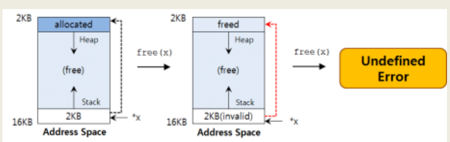
DOUBLE FREE

```
int *x = (int *)malloc(sizeof(int)); // allocated
free(x); // free memory
free(x); // free repeatedly
```

- Can't deallocate twice
- Second call core dumps



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SYSTEM CALLS

- brk(), sbrk()

- Used to change data segment size (the end of the heap)
- Don't use these

- Mmap(), munmap()

- Can be used to create an extra independent "heap" of memory for a user program

- See man page

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QUESTIONS

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