TCSS 422: OPERATING SYSTEMS

Condition Variables, Producer/Consumer

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

OBJECTIVES

- Assignment 2
- Assignment 3

- **Parallel programming with P-threads cont'd**
- Chapter 32 – Concurrency Problems

- **Memory Virtualization**
- Chapter 13 – Address Spaces
- Chapter 14 – Memory API
- Chapter 15 – Address Translation
- Chapter 16 – Segmentation
- Chapter 17 – Free Space Management
- Chapter 18 – Introduction to Paging
- Chapter 19 – Translation Lookaside Buffer (TLB)

FEEDBACK FROM 2/25

- **Do producers create work assignments and consumers complete them?**
- Are atomicity violation bugs just sharing variables without (forgetting) to use locks?
  - **YES**, atomicity violation bugs result when a program is multithreaded, and a variable has ***many*** uses, but a programmer forgets to apply locks to **all** of the uses
  - Atomicity violations result from the difficulty in realizing whether each use should be atomic or not
    - Some uses may not be acted upon by multiple threads
  - Locks may be added to the program, after variables are already used/defined

FEEDBACK - 2

- Confusion on locking producers and consumers correctly
  - Bounder buffer has global variable for capacity:
  - `int BOUNDED_BUFFER_SIZE;`
  - Producer: count must be less than BOUNDED_BUFFER_SIZE
    - Otherwise – call pthread_cond_wait on FILL signal
  - Consumer: count must be greater than 0
    - Otherwise – call pthread_cond_wait on EMPTY signal
    - Tells producer(s) to produce

FEEDBACK - 3

- End of program
  - Need to coordinate that we've produced/consumed NUMBER_OF_MATRICIES total
  - For loop is insufficient if multiple producers/consumers
  - Need a counter – (good use case for synchronized counter data structure)
  - 3 producers: once p1 produces matrix 1200, need to stop p2 and p3 from producing more…

CHAPTER 32 – CONCURRENCY PROBLEMS

OBJECTIVES

- Chapter 32:
  - Non-deadlock concurrency bugs
  - Deadlock causes
  - Deadlock prevention

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**

NON-DEADLOCK BUGS

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

ATOMICITY VIOLATION - MYSQL

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

Programmer intended variable to be accessed atomically…

```
1    Thread1::
2    if(thd->proc_info){
3       …
4       fputs(thd->proc_info , …);
5       …
6    }
7
8    Thread2::
9    thd->proc_info = NULL;
```

ATOMICITY VIOLATION - SOLUTION

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

```
1   pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
2
3   Thread1::
4   pthread_mutex_lock(&lock);
5   if(thd->proc_info){
6        …
7        fputs(thd->proc_info , …);
8        …
9   }
10  pthread_mutex_unlock(&lock);
11
12  Thread2::
13  pthread_mutex_lock(&lock);
14  thd->proc_info = NULL;
15  pthread_mutex_unlock(&lock);
```


ORDER VIOLATION BUGS

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

```
1   Thread1::
2   void init(){
3        mThread = PR_CreateThread(mMain, …);
4   }
5
6   Thread2::
7   void mMain(…){
8        mState = mThread->State
9   }
```

- What if mThread is not initialized?

ORDER VIOLATION - SOLUTION

- Use condition variable to enforce order

```
1   pthread_mutex_t mtLock = PTHREAD_MUTEX_INITIALIZER;
2   pthread_cond_t mtCond = PTHREAD_COND_INITIALIZER;
3   int mtInit = 0;
4
5   Thread 1::
6   void init(){
7       …
8       mThread = PR_CreateThread(mMain,…);
9
10      // signal that the thread has been created.
11      pthread_mutex_lock(&mtLock);
12      mtInit = 1;
13      pthread_cond_signal(&mtCond);
14      pthread_mutex_unlock(&mtLock);
15      …
16  }
17
18  Thread2::
19  void mMain(…){
20      …
```


ORDER VIOLATION – SOLUTION 2

```
21      // wait for the thread to be initialized …
22      pthread_mutex_lock(&mtLock);
23      while(mtInit == 0)
24              pthread_cond_wait(&mtCond, &mtLock);
25      pthread_mutex_unlock(&mtLock);
26
27      mState = mThread->State;
28      …
29  }
```

NON-DEADLOCK BUGS - 1

- 97% of Non-Deadlock Bugs were
  - Atomicity
  - Order violations
- Consider what is involved in "spotting" these bugs in code
- Desire for automated tool support (IDE)

NON-DEADLOCK BUGS - 2

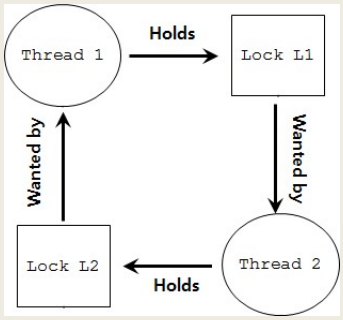
- Atomicity
  - How can we tell if a given variable is shared?
    - Can search the code for uses
  - How do we know if all instances of its use are shared?
    - Can some non-synchronized (non-atomic) uses be legal?
    - Before threads are created, after threads exit
    - Must verify the scope
- Order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

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



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:

```
1   Vector v1,v2;
2   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

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

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

```
1   int CompareAndSwap(int *address, int expected, int new){
2       if(*address == expected){
3               *address = new;
4               return 1; // success
5       }
6       return 0;
7   }
```

PREVENTION – MUTUAL EXCLUSION - 2

- Recall atomic increment

```
1   void AtomicIncrement(int *value, int amount){
2       do{
3               int old = *value;
4       }while( CompareAndSwap(value, old, old+amount)==0);
5   }
```

- 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)

MUTUAL EXCLUSION: LIST INSERTION

- Consider list insertion

```
1   void insert(int value){
2       node_t * n = malloc(sizeof(node_t));
3       assert( n != NULL );
4       n->value = value ;
5       n->next  = head;
6       head     = n;
7   }
```

MUTUAL EXCLUSION – LIST INSERTION - 2

- Lock based implementation

```
1   void insert(int value){
2       node_t * n = malloc(sizeof(node_t));
3       assert( n != NULL );
4       n->value = value ;
5       lock(listlock); // begin critical section
6       n->next  = head;
7       head     = n;
8       unlock(listlock) ;  //end critical section
9   }
```


MUTUAL EXCLUSION – LIST INSERTION - 3

- Wait free (no lock) implementation

```
1   void insert(int value) {
2       node_t *n = malloc(sizeof(node_t));
3       assert(n != NULL);
4       n->value = value;
5       do {
6               n->next = head;
7       } while (CompareAndSwap(&head, n->next, n));
8   }
```

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

CONDITIONS FOR DEADLOCK

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PREVENTION LOCK – HOLD AND WAIT

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

```
1    lock(prevention);
2    lock(L1);
3    lock(L2);
4    …
5    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…

CONDITIONS FOR DEADLOCK

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

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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

```
1   top:
2       lock(L1);
3       if( tryLock(L2) == -1 ){
4               unlock(L1);
5               goto top;
6       }
```

- Eliminates deadlocks

NO PREEMPTION – LIVELOCKS PROBLEM

- Can lead to livelock

```
1   top:
2       lock(L1);
3       if( tryLock(L2) == -1 ){
4               unlock(L1);
5               goto top;
6       }
```

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

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.
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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

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

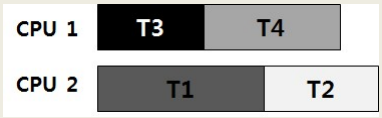
DEADLOCK AVOIDANCE VIA INTELLIGENT SCHEDULING

- 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

INTELLIGENT SCHEDULING - 2

- Scheduler produces schedule:

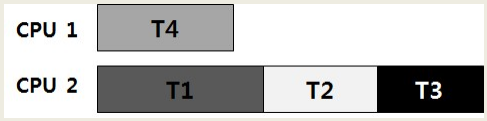


- No deadlock can occur
- Consider:

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

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

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.

CHAPTER 13: ADDRESS SPACES

OBJECTIVES – MEMORY VIRTUALIATION

- Chapter 13
  - Introduction to memory virtualization
  - The address space
  - Goals of OS memory virtualization
- Chapter 14
  - Memory API
  - Common memory errors
- Chapter 15
  - Address translation
  - Base and bounds
  - HW and OS Support
- Chapter 16
  - Memory segments, fragmentation

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

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

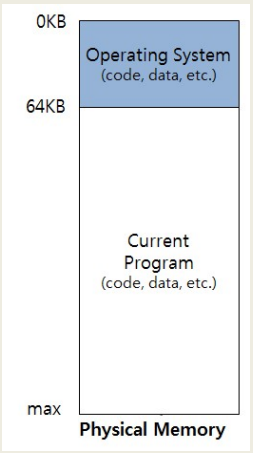
Process A **Process B** **Process C**

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)

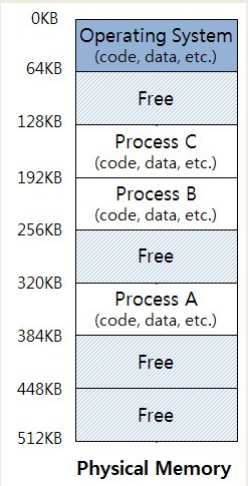
EARLY MEMORY MANAGEMENT

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



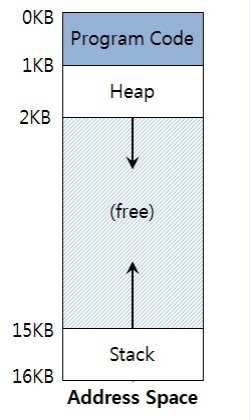
MULTIPROGRAMMING WITH SHARED MEMORY

- 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



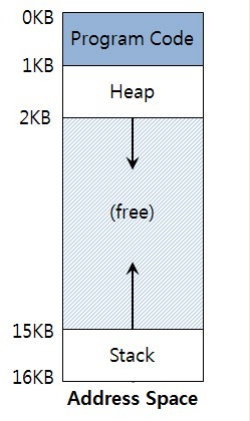
ADDRESS SPACE

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



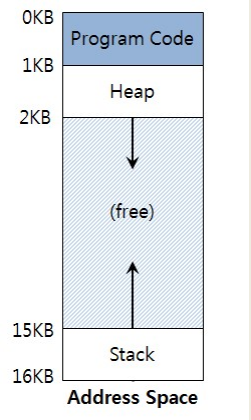
ADDRESS SPACE - 2

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



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



VIRTUAL ADDRESSING

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

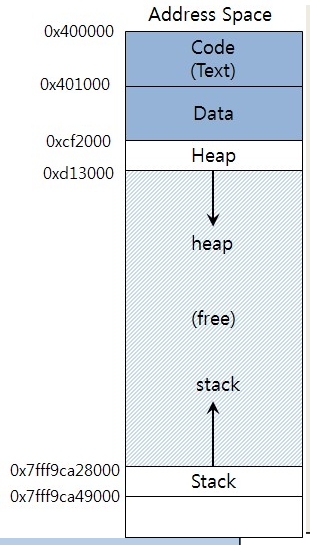
```
#include <stdio.h>
#include <stdlib.h>

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

VIRTUAL ADDRESSING - 2

- Output from 64-bit Linux:

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



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)

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*

CHAPTER 14: THE MEMORY API

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

SIZEOF()

- Not safe to assume data type sizes using different compilers, systems

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

```
4
```

- Dynamic array of 10 ints

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

- Static array of 10 ints

```
40
```

FREE()

```
#include <stdlib.h>

void free(void* ptr)
```

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

What will this code do?

```
#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;
}
```

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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).

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"

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
```

REALLOC()

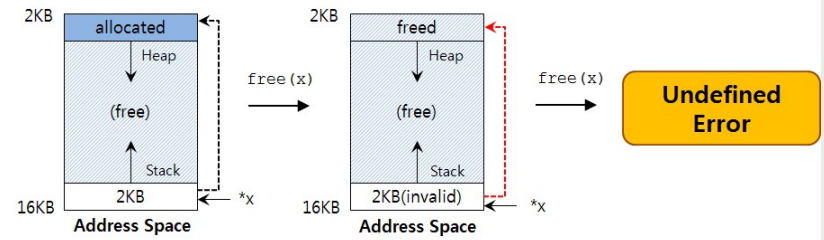
```
#include <stdlib.h>

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

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



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

QUESTIONS