15-213

"The course that gives CMU its Zip!"

Synchronization
November 19, 2008

Topics

- Synchronizing with semaphores
- Races and deadlocks
- Thread safety and reentrancy

lecture-24.ppt

badcnt.c: An Improperly Synchronized Threaded Program

```
/* shared */
volatile unsigned int cnt = 0;
#define NITERS 100000000

int main() {
    pthread_t tid1, tid2;
    Pthread_create(&tid1, NULL,
                   count, NULL);
    Pthread_create(&tid2, NULL,
                   count, NULL);

    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    if (cnt != (unsigned)NITERS*2)
        printf("BOOM! cnt=%d\n",
               cnt);
    else
        printf("OK cnt=%d\n",
               cnt);
}
```

```
/* thread routine */
void *count(void *arg) {
    int i;
    for (i=0; i<NITERS; i++)
        cnt++;
    return NULL;
}
```

```
linux> ./badcnt
BOOM! cnt=198841183

linux> ./badcnt
BOOM! cnt=198261801

linux> ./badcnt
BOOM! cnt=198269672
```

`cnt` should be equal to 200,000,000. What went wrong?!

Assembly Code for Counter Loop

C code for counter loop

```
for (i=0; i<NITERS; i++)
    cnt++;
```

Corresponding asm code

Head (H_i)

```
.L9:
        movl -4(%ebp),%eax
        cmpl $99999999,%eax
        jle .L12
        jmp .L10
```

Load cnt (L_i)
Update cnt (U_i)
Store cnt (S_i)

```
.L12:
        movl cnt,%eax       # Load
        leal 1(%eax),%edx   # Update
        movl %edx,cnt       # Store
```

Tail (T_i)

```
.L11:
        movl -4(%ebp),%eax
        leal 1(%eax),%edx
        movl %edx,-4(%ebp)
        jmp .L9
.L10:
```


Concurrent Execution

Key idea: In general, any sequentially consistent interleaving is possible, but some are incorrect!

- I_i denotes that thread i executes instruction I
- $\%eax_i$ is the contents of %eax in thread i's context

i (thread)	$instr_i$	$\%eax_1$	$\%eax_2$	cnt
1	H_1	-	-	0
1	L_1	0	-	0
1	U_1	1	-	0
1	S_1	1	-	1
2	H_2	-	-	1
2	L_2	-	1	1
2	U_2	-	2	1
2	S_2	-	2	2
2	T_2	-	2	2
1	T_1	1	-	2

OK

Concurrent Execution (cont)

Incorrect ordering: two threads increment the counter, but the result is 1 instead of 2.

i (thread)	$instr_i$	$\%eax_1$	$\%eax_2$	cnt
1	H_1	-	-	0
1	L_1	0	-	0
1	U_1	1	-	0
2	H_2	-	-	0
2	L_2	-	0	0
1	S_1	1	-	1
1	T_1	1	-	1
2	U_2	-	1	1
2	S_2	-	1	1
2	T_2	-	1	1

Oops!

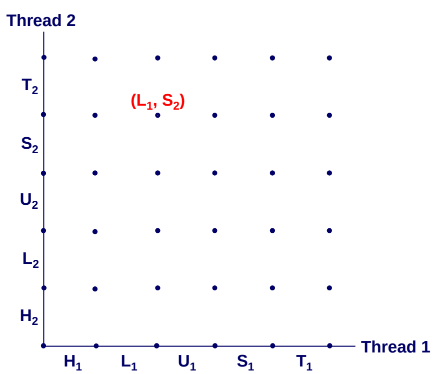
Concurrent Execution (cont)

How about this ordering?

i (thread)	$instr_i$	$\%eax_1$	$\%eax_2$	cnt
1	H_1			
1	L_1			
2	H_2			
2	L_2			
2	U_2			
2	S_2			
1	U_1			
1	S_1			
1	T_1			
2	T_2			

We can clarify our understanding of concurrent execution with the help of the *progress graph*

Progress Graphs



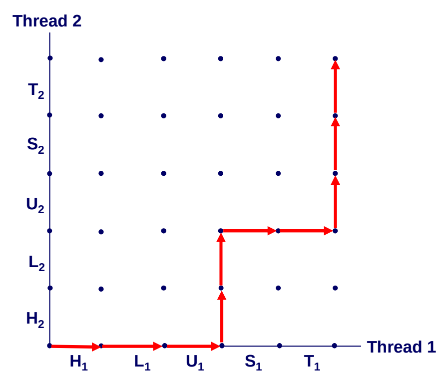
A ***progress graph*** depicts the discrete ***execution state space*** of concurrent threads.

Each axis corresponds to the sequential order of instructions in a thread.

Each point corresponds to a possible ***execution state*** $(Inst_1, Inst_2)$.

E.g., (L_1, S_2) denotes state where thread 1 has completed L_1 and thread 2 has completed S_2.

Trajectories in Progress Graphs

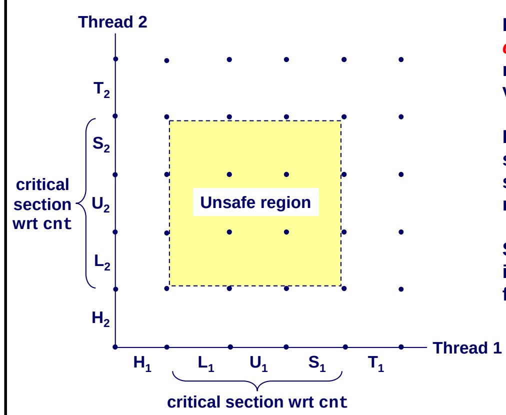


A ***trajectory*** is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

H1, L1, U1, H2, L2, S1, T1, U2, S2, T2

Critical Sections and Unsafe Regions

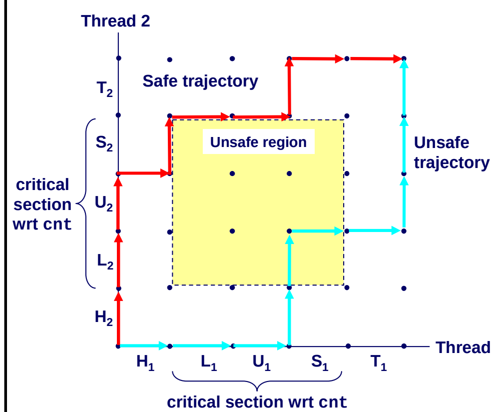


L, U, and S form a *critical section* with respect to the shared variable `cnt`.

Instructions in critical sections (wrt to some shared variable) should not be interleaved.

Sets of states where such interleaving occurs form *unsafe regions*.

Safe and Unsafe Trajectories



Def: A trajectory is *safe* iff it doesn't touch any part of an unsafe region.

Claim: A trajectory is correct (wrt `cnt`) iff it is safe.

Semaphores

Question: How can we guarantee a safe trajectory?

- We must *synchronize* the threads so that they never enter an unsafe state.

Classic solution: Dijkstra's P and V operations on *semaphores.*

- *semaphore:* non-negative integer synchronization variable
  - P(s): [`while (s == 0) wait(); s--;`]
    - » Dutch for "Proberen" (test)
  - V(s): [`s++;`]
    - » Dutch for "Verhogen" (increment)
- OS guarantees that operations between brackets [ ] are executed indivisibly
  - Only one P or V operation at a time can modify s
  - When `while` loop in P terminates, only that P can decrement s

Semaphore invariant: *(s >= 0)*

Locking with Semaphores

Here is one way we could use P and V operations to synchronize the threads that update `cnt`

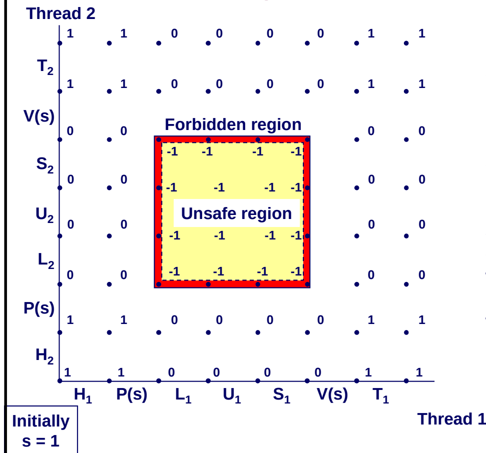
- Semaphore used like this referred to as a "lock"

```
/* Semaphore s is initially 1 */

/* Thread routine */
void *count(void *arg)
{
    int i;

    for (i=0; i<NITERS; i++) {
        P(s);
        cnt++;
        V(s);
    }
    return NULL;
}
```

Safe Sharing With Locks



Provide mutually exclusive access to shared variable by surrounding critical section with P and V operations on semaphore s (initially set to 1).

Semaphore invariant creates a *forbidden region* that encloses unsafe region and is never touched by any trajectory.

Wrappers on POSIX Semaphores

```
/* Initialize semaphore sem to value */
/* pshared=0 if thread, pshared=1 if process */
void Sem_init(sem_t *sem, int pshared, unsigned int value) {
  if (sem_init(sem, pshared, value) < 0)
    unix_error("Sem_init");
}

/* P operation on semaphore sem */
void P(sem_t *sem) {
  if (sem_wait(sem))
    unix_error("P");
}

/* V operation on semaphore sem */
void V(sem_t *sem) {
  if (sem_post(sem))
    unix_error("V");
}
```


Sharing With POSIX Semaphores

```
/* properly sync'd counter program */
#include "csapp.h"
#define NITERS 10000000

volatile unsigned int cnt;
sem_t sem;        /* semaphore */

int main() {
    pthread_t tid1, tid2;

    Sem_init(&sem, 0, 1); /* sem=1 */

    /* create 2 threads and wait */
    ...

   if (cnt != (unsigned)NITERS*2)
        printf("BOOM! cnt=%d\n", cnt);
    else
        printf("OK cnt=%d\n", cnt);
    exit(0);
}
```

```
/* thread routine */
void *count(void *arg)
{
    int i;

    for (i=0; i<NITERS; i++) {
        P(&sem);
        cnt++;
        V(&sem);
    }
    return NULL;
}
```

Warning:

It's really slow!

One worry: races

A *race* occurs when the correctness of the program depends on one thread reaching point x before another thread reaches point y

```
/* a threaded program with a race */
int main() {
    pthread_t tid[N];
    int i;
    for (i = 0; i < N; i++)
        Pthread_create(&tid[i], NULL, thread, &i);
    for (i = 0; i < N; i++)
        Pthread_join(tid[i], NULL);
    exit(0);
}

/* thread routine */
void *thread(void *vargp) {
    int myid = *((int *)vargp);
    printf("Hello from thread %d\n", myid);
    return NULL;
}
```

Race Elimination

Make sure don't have unintended sharing of state

```
/* a threaded program with a race */
int main() {
    pthread_t tid[N];
    int i;
    for (i = 0; i < N; i++) {
        int *valp = malloc(sizeof(int));
        *valp = i;
        Pthread_create(&tid[i], NULL, thread, valp);
    for (i = 0; i < N; i++)
        Pthread_join(tid[i], NULL);
    exit(0);
}

/* thread routine */
void *thread(void *vargp) {
    int myid = *((int *)vargp);
    free(vargp);
    printf("Hello from thread %d\n", myid);
    return NULL;
}
```


Another worry: Deadlock

- Processes wait for condition that will never be true

Typical Scenario

- Processes 1 and 2 needs two resources (A and B) to proceed
- Process 1 acquires A, waits for B
- Process 2 acquires B, waits for A
- Both will wait forever!

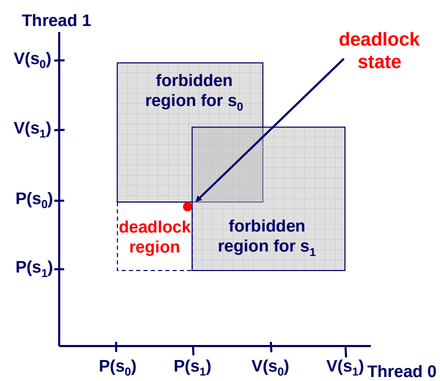
Deadlocking With POSIX Semaphores

```
int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], NULL);
    printf("cnt=%d\n", cnt);
    exit(0);
}
```

```
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
        P(&mutex[id]); P(&mutex[1-id]);
        cnt++;
        V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}
```

Tid[0]:	Tid[1]:
$P(s_0)$;	$P(s_1)$;
$P(s_1)$;	$P(s_0)$;
cnt++;	cnt++;
$V(s_0)$;	$V(s_1)$;
$V(s_1)$;	$V(s_0)$;

Deadlock



Initially, $s_0=s_1=1$

Locking introduces the potential for ***deadlock:*** waiting for a condition that will never be true.

Any trajectory that enters the ***deadlock region*** will eventually reach the ***deadlock state***, waiting for either s_0 or s_1 to become nonzero.

Other trajectories luck out and skirt the deadlock region.

Unfortunate fact: deadlock is often non-deterministic.

Avoiding Deadlock

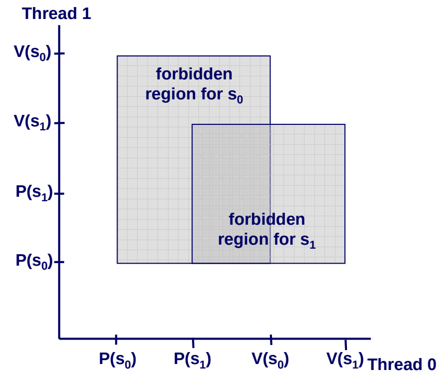
Acquire shared resources in same order

```
int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], NULL);
    printf("cnt=%d\n", cnt);
    exit(0);
}
```

```
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
        P(&mutex[0]); P(&mutex[1]);
       cnt++;
       V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}
```

Tid[0]:	Tid[1]:
$P(s_0)$;	$P(s_0)$;
$P(s_1)$;	$P(s_1)$;
cnt++;	cnt++;
$V(s_0)$;	$V(s_1)$;
$V(s_1)$;	$V(s_0)$;

Removed Deadlock



Initially, $s_0=s_1=1$

No way for trajectory to get stuck

Processes acquire locks in same order

Order in which locks released immaterial

Crucial concept: Thread Safety

Functions called from a thread (without external synchronization) must be *thread-safe*

- i.e., it must be safe for multiple threads to be calling it concurrently

Some examples of thread-unsafe functions:

- Failing to protect shared variables
- Relying on persistent state across invocations
- Returning a pointer to a static variable
- Calling thread-unsafe functions

Thread-Unsafe Functions (1)

Failing to protect shared variables

- Fix: Use P and V semaphore operations
- Example: `goodcnt.c`
- Issue: Synchronization operations will slow down code
  - e.g., `badcnt` requires 0.5s, `goodcnt` requires 7.9s

Thread-Unsafe Functions (2)

Relying on persistent state across multiple function invocations

- Example: Random number generator that relies on static state

```
/* rand - return pseudo-random integer on 0..32767 */
static unsigned int next = 1;
int rand(void)
{
    next = next*1103515245 + 12345;
    return (unsigned int)(next/65536) % 32768;
}

/* srand - set seed for rand() */
void srand(unsigned int seed)
{
    next = seed;
}
```


Making Thread-Safe RNG

Pass state as part of argument

- and, thereby, eliminate static state

```
/* rand - return pseudo-random integer on 0..32767 */

int rand_r(int *nextp)
{
    *nextp = *nextp*1103515245 + 12345;
    return (unsigned int)(*nextp/65536) % 32768;
}
```

- Consequence: programmer using rand must maintain seed

Thread-Unsafe Functions (cont)

Returning a ptr to a `static` variable

```
struct hostent
*gethostbyname(char name)
{
  static struct hostent h;
  <contact DNS and fill in h>
  return &h;
}
```

Fixes:

- 1. Rewrite code so caller passes pointer to `struct`
  - » Issue: Requires changes in caller and callee

```
hostp = Malloc(...));
gethostbyname_r(name, hostp);
```

- 2. *Lock-and-copy*
  - » Issue: Requires only simple changes in caller (and none in callee)
  - » However, caller must free memory

```
struct hostent
*gethostbyname_ts(char *name)
{
  struct hostent *q = Malloc(...);
  struct hostent *p;
  P(&mutex); /* lock */
  p = gethostbyname(name);
  *q = *p;   /* copy */
  V(&mutex);
  return q;
}
```


Thread-Unsafe Functions

Calling thread-unsafe functions

- Calling one thread-unsafe function makes the entire function that calls it thread-unsafe
- Fix: Modify the function so it calls only thread-safe functions ☺

Thread-Safe Library Functions

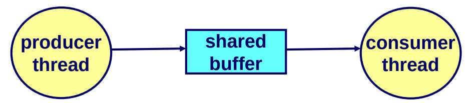
All functions in the Standard C Library (at the back of your K&R text) are thread-safe

- Examples: `malloc`, `free`, `printf`, `scanf`

Most Unix system calls are thread-safe, with a few exceptions:

Thread-unsafe function	Class	Reentrant version
asctime	3	asctime_r
ctime	3	ctime_r
gethostbyaddr	3	gethostbyaddr_r
gethostbyname	3	gethostbyname_r
inet_ntoa	3	(none)
localtime	3	localtime_r
rand	2	rand_r

Notifying With Semaphores



Common synchronization pattern:

- Producer waits for slot, inserts item in buffer, and notifies consumer
- Consumer waits for item, removes it from buffer, and notifies producer

Examples

- Multimedia processing:
  - Producer creates MPEG video frames, consumer renders them
- Event-driven graphical user interfaces
  - Producer detects mouse clicks, mouse movements, and keyboard hits and inserts corresponding events in buffer
  - Consumer retrieves events from buffer and paints the display

Producer-Consumer on a Buffer That Holds One Item

```
/* buf1.c - producer-consumer
on 1-element buffer */
#include “csapp.h”

#define NITERS 5

void *producer(void *arg);
void *consumer(void *arg);

struct {
  int buf; /* shared var */
  sem_t full; /* sems */
  sem_t empty;
} shared;
```

```
int main() {
  pthread_t tid_producer;
  pthread_t tid_consumer;

  /* initialize the semaphores */
  Sem_init(&shared.empty, 0, 1);
  Sem_init(&shared.full,  0, 0);

  /* create threads and wait */
  Pthread_create(&tid_producer, NULL,
                 producer, NULL);
  Pthread_create(&tid_consumer, NULL,
                 consumer, NULL);
  Pthread_join(tid_producer, NULL);
  Pthread_join(tid_consumer, NULL);

  exit(0);
}
```


Producer-Consumer (cont)

Initially: empty = 1, full = 0.

```
/* producer thread */
void *producer(void *arg) {
  int i, item;

  for (i=0; i<NITERS; i++) {
    /* produce item */
    item = i;
    printf("produced %d\n",
           item);

    /* write item to buf */
    P(&shared.empty);
    shared.buf = item;
    V(&shared.full);
  }
  return NULL;
}
```

```
/* consumer thread */
void *consumer(void *arg) {
  int i, item;

  for (i=0; i<NITERS; i++) {
    /* read item from buf */
    P(&shared.full);
    item = shared.buf;
    V(&shared.empty);

    /* consume item */
    printf("consumed %d\n",
           item);
  }
  return NULL;
}
```

Counting with Semaphores

Remember, it's a non-negative integer

- So, values greater than 1 are legal

Lets repeat thing_5() 5 times for every 3 of thing_3()

```
/* thing_5 and thing_3 */
#include "csapp.h"

sem_t five;
sem_t three;

void *five_times(void *arg);
void *three_times(void *arg);
```

```
int main() {
  pthread_t tid_five, tid_three;

  /* initialize the semaphores */
  Sem_init(&five, 0, 5);
  Sem_init(&three,  0, 3);

  /* create threads and wait */
  Pthread_create(&tid_five, NULL,
                 five_times, NULL);
  Pthread_create(&tid_three, NULL,
                 three_times, NULL);
  .
  .
  .
}
```


Counting with semaphores (cont)

Initially: five = 5, three = 3

```
/* thing_5() thread */
void *five_times(void *arg) {
  int i;

  while (1) {
    for (i=0; i<5; i++) {
      /* wait & thing_5() */
      P(&five);
      thing_5();
    }
    V(&three);
    V(&three);
    V(&three);
  }
  return NULL;
}
```

```
/* thing_3() thread */
void *three_times(void *arg) {
  int i;

  while (1) {
    for (i=0; i<3; i++) {
      /* wait & thing_3() */
      P(&three);
      thing_3();
    }
    V(&five);
    V(&five);
    V(&five);
    V(&five);
    V(&five);
  }
  return NULL;
}
```


Threads Summary

Threads provide another mechanism for writing concurrent programs

Threads are growing in popularity

- Somewhat cheaper than processes
- Easy to share data between threads

However, the ease of sharing has a cost:

- Easy to introduce subtle synchronization errors
- Tread carefully with threads!

For more info:

- D. Butenhof, "Programming with Posix Threads", Addison-Wesley, 1997.

Beware of Optimizing Compilers!

Code From Book

```
#define NITERS 100000000

/* shared counter variable */
unsigned int cnt = 0;

/* thread routine */
void *count(void *arg)
{
    int i;
    for (i = 0; i < NITERS; i++)
       cnt++;
    return NULL;
}
```

- Global variable cnt shared between threads
- Multiple threads could be trying to update within their iterations

Generated Code

```
movl     cnt, %ecx
movl     $99999999, %eax
.L6:
   leal  1(%ecx), %edx
   decl  %eax
   movl  %edx, %ecx
   jns   .L6
   movl  %edx, cnt
```

- Compiler moved access to cnt out of loop
- Only shared accesses to cnt occur before loop (read) or after (write)
- What are possible program outcomes?