CSE 220: Systems Programming

Races and Synchronization

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Races

Races, or race conditions, are situations where:

- Two or more events are dependent upon each other
- Some of the events may happen in more than one order, or even simultaneously
- There exists some ordering of the events that is incorrect

For example:

- Some state will be updated multiple times
- Output will be produced based on the state

If some order of updates results in invalid output, this is a race.

Synchronization

Synchronization, in the context of a computer program, is the deliberate ordering of events via some mechanism.

There are many synchronization mechanisms, working in different ways.

Synchronization mechanisms may:

- Directly order events
- Simply ensure that events do not happen simultaneously
- Ensure that two events begin at the same time
- …

Synchronization is how we avoid races.

Race Conditions

CS:APP [1] defines a race as:

> *[...] when the correctness of a program depends on one thread reaching point* x *in its control flow before another thread reaches point* y.

Note that there may be many points *x* and *y*!

The relationship between *x* and *y* may change over time, as well.

For example, "once thread T_1 has reached point *p*, it must reach point *x* before any other thread reaches point *y*."

Data Races

While data races, or races involving modification of data, are not the only kind of race, they are very common.

A data race occurs when:

- Two or more concurrent flows access shared state
- One or more of these flows modifies the state
- The order of the accesses/modifications is important
- The synchronization in use is insufficient to preserve the necessary order

Races among any number of concurrent flows for the same data may be reduced to a set of pairwise races.

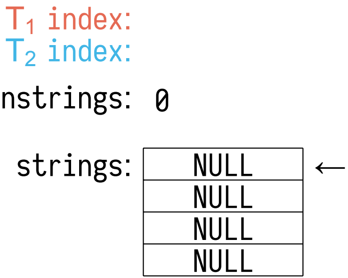
At least one access in each pair must be a modifying operation.

Example Race

Consider two threads running the following code:

```
char *strings[4];
int nstrings;

void setstring(char *str) {
  int index = nstrings;
  strings[index] = str;
  nstrings++;
}
```



T_1 index:

T_2 index:

nstrings: 0

strings:

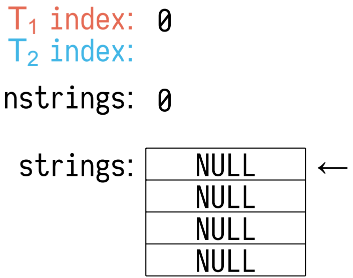
NULL ←
NULL
NULL
NULL

Example Race

Consider two threads running the following code:

```
     char *strings[4];
     int nstrings;

     void setstring(char *str) {
T1 →   int index = nstrings;
       strings[index] = str;
       nstrings++;
     }
```



T_1 index: 0

T_2 index:

nstrings: 0

strings:

NULL ←
NULL
NULL
NULL

Example Race

Consider two threads running the following code:

```
     char *strings[4];
     int nstrings;

     void setstring(char *str) {
T1 →   int index = nstrings;      ← T2
       strings[index] = str;
       nstrings++;
     }
```

T_1 index: 0
T_2 index: 0

nstrings: 0

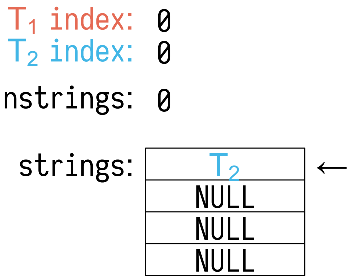
```
strings: | NULL | ←
         | NULL |
         | NULL |
         | NULL |
```

Example Race

Consider two threads running the following code:

```
       char *strings[4];
       int nstrings;

       void setstring(char *str) {
T1 →     int index = nstrings;
         strings[index] = str;        ← T2
         nstrings++;
       }
```



T_1 index: 0

T_2 index: 0

nstrings: 0

strings:

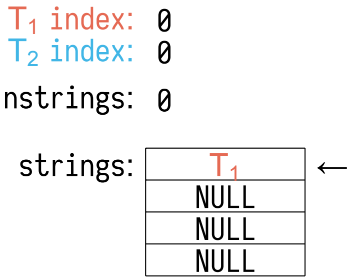
T_2 ←
NULL
NULL
NULL

Example Race

Consider two threads running the following code:

```
    char *strings[4];
    int nstrings;

    void setstring(char *str) {
      int index = nstrings;
T1 →  strings[index] = str;      ← T2
      nstrings++;
    }
```



T_1 index: 0

T_2 index: 0

nstrings: 0

strings: T_1 NULL NULL NULL ←

Example Race

Consider two threads running the following code:

```
char *strings[4];
int nstrings;

void setstring(char *str) {
  int index = nstrings;
  strings[index] = str;      ← T2
T1 → nstrings++;
}
```

T_1 index: 0

T_2 index: 0

nstrings: 1

strings:

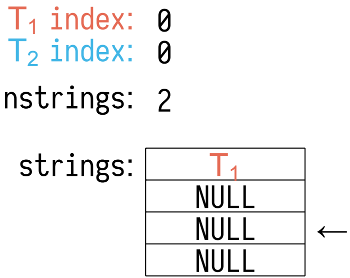
T_1
NULL ←
NULL
NULL

Example Race

Consider two threads running the following code:

```
    char *strings[4];
    int nstrings;

    void setstring(char *str) {
      int index = nstrings;
      strings[index] = str;
T1 →  nstrings++;                  ← T2
    }
```



T$_1$ index: 0

T$_2$ index: 0

nstrings: 2

strings:

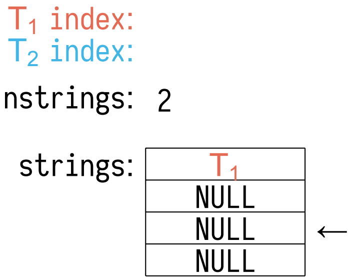
T$_1$
NULL
NULL ←
NULL

Example Race

Consider two threads running the following code:

```
char *strings[4];
int nstrings;

void setstring(char *str) {
  int index = nstrings;
  strings[index] = str;
  nstrings++;
}
```



T_1 index:

T_2 index:

nstrings: 2

strings:

T_1
NULL
NULL ←
NULL

This is probably not what was intended!

Critical Sections

```
1 void setstring(char *str) {
2   int index = nstrings;
3   strings[index] = str;
4   nstrings++;
5 }
```

Lines 2-4 of `setstring()` form a critical section.

A critical section is a region of code that must be accessed by at most one control flow at a time.

Critical Sections

Critical sections often contain code that accesses shared state.

In most cases, any write to shared state is a critical section.[1]

Reads from shared state may not be critical sections, particularly if the state is immutable or changes infrequently.

It is important to define critical sections carefully and completely.

[1] There exist protocols that allow concurrent writes, however.

Progress Graphs

Your text presents progress graphs as a tool for modeling concurrent flows and critical sections.

A progress graph is an n-dimensional space.

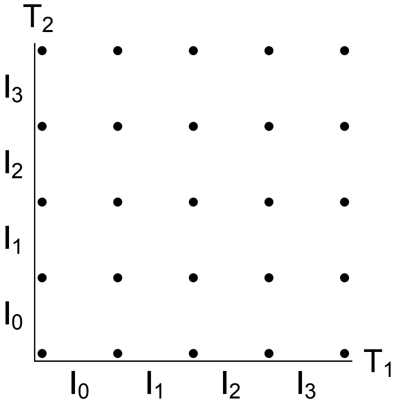
Each dimension in the graph represents a concurrent flow.

As flows make progress they move in their dimension.

Critical sections are represented as n-dimensional regions in the progress graph.

Progress Graph Example

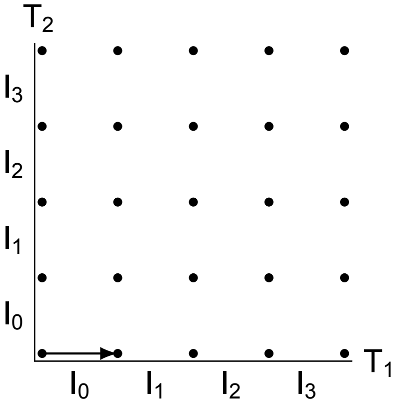
Each point marks the completion of an instruction in one thread.



Progress Graph Example

Each point marks the completion of an instruction in one thread.

Progress in T_1 moves to the right.

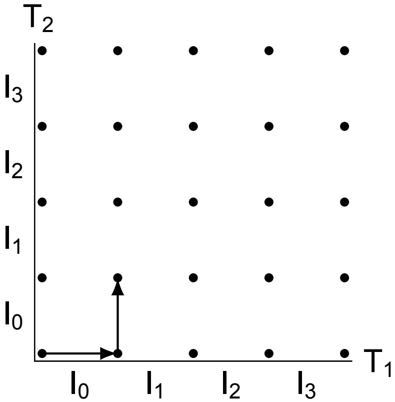


Progress Graph Example

Each point marks the completion of an instruction in one thread.

Progress in T_1 moves to the right.

Progress in T_2 moves up.



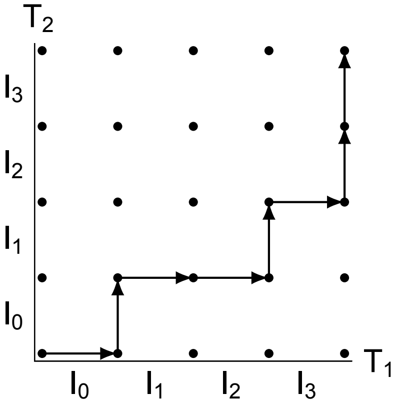
Progress Graph Example

Each point marks the completion of an instruction in one thread.

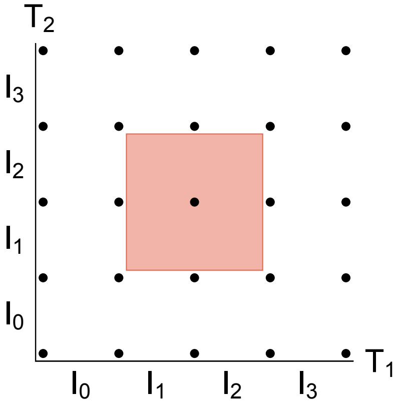
Progress in T_1 moves to the right.

Progress in T_2 moves up.

Program execution follows some path.



Progress Graph Critical Sections



A critical section can be marked on a progress graph.

Any point inside the marked region is an incorrect execution.

Atomic Operations

Atomic operations are the simplest synchronization mechanism.

An atomic operation:

- Cannot be interrupted
- Appears as if no other operations run concurrently
- Always either fully succeeds or fails with no effects

Every atomic operation requires hardware support.

Not all machine instructions are atomic!
(In fact, often very few are.)

Atomic Operations in C

C provides no guaranteed atomic operations.[2]

Atomic operations for synchronization from C require one of:

- Inline assembly code
- Library functions
- Knowledge of the compiler implementation
- Kernel assistance

[2] There is `sig_atomic_t`, which is atomic *with respect to signals*.

Mutual Exclusion

Mutual exclusion is a tool for ensuring that only one logical control flow accesses some resource.

It is one of the most basic synchronization methods.

Mutual exclusion maps almost directly to critical sections:

- The code of the critical section is the resource

The Mutex

A software tool for providing mutual exclusion is the mutex.

It provides two operations:

- Lock
- Unlock

Operation	*Mutex State*	*Action*
Lock	Unlocked	Lock mutex immediately[3]
Lock	Locked	Block until unlocked, then lock
Unlock	Locked	Unlock mutex immediately
Unlock	Unlocked	Implementation dependent

[3] If a flow locks a mutex it has already locked, behavior is implementation-dependent.

Synchronization with Mutexes

Mutexes can be used to provided synchronization.

They can:

- Ensure that two actions do not happen simultaneously
- Ensure that one action follows another

They can be used to create mechanisms to:

- Directly order events
- Ensure that two events begin at the same time
- …

Many other synchronization “primitives” use mutexes.

Using Mutexes around Critical Sections

The typical use of a mutex is to protect a critical section.

Every concurrent flow will:

1. Lock a mutex
2. Execute the critical section
3. Unlock the mutex

Since only one flow can lock the mutex at a time, this ensures mutual exclusion in the critical section.

Semaphores

Semaphores are a generalization of the mutex.

A semaphore is associated with a number.

There are two operations on a semaphore, variously named:

- P and V
- down and up
- wait and post
- …

The first term in each pair is analogue to mutex lock.
The second is analogue to mutex unlock.

We will use P and V (after the original Dijkstra paper).

Semaphore Operations

P (for *proberen* in Dutch, or “to test”)
V (for *verhogen*, “to increment”)

A semaphore *s* is initialized with a nonnegative integer.

P(s) attempts to decrement the integer:

- If it can be decremented and remain nonnegative (*i.e.*, it is ≥ 1), P returns immediately
- If decrementing it would make it negative (*i.e.*, it is 0), P blocks until it is > 0

V(s) increments the integer

- If the incremented value is 1, it releases one flow blocked on P, if such a flow exists

Semaphores as Mutexes

A semaphore initialized with the value 1 behaves like a mutex.

- P(s) succeeds immediately for the first logical control flow to attempt it
- Any further flows block on P(s) because s is now zero
- V(s) releases one flow blocked on s because s is now one

Semaphore value	*Equivalent mutex state*
1	Unlocked
0	Locked

Condition Variables

Condition variables allow a logical control flow to block until some condition is met.

They work with mutexes to provide efficient blocking.

The holder of a mutex that is locked can block for a certain condition by:

- Waiting on a condition variable in a loop
- Testing the condition when awakened
- Breaking the loop if the condition is met

A concurrent flow that may have satisfied the condition can:

- Broadcast to all waiting flows
- Signal one waiting flow

Mutex Interactions

The waiting flow must hold a mutex to wait.

The mutex must protect data used in the condition check.

Upon waiting, the mutex will be unlocked.

Upon awaking, the waiting flow will re-lock the mutex.

This means that the waiting flow cannot assume the protected data remained unchanged while it waited.

This complicated mutex interaction allows the signaling flow to modify the protected data.

Wake and Check

The wake and check procedure allows:

- A thread to safely signal the condition even if it is not sure it has been met
- A condition to be signaled in the presence of newcomers that may falsify it before the waiting thread is scheduled
- Threads to be spuriously woken for other reasons (*e.g.*, asynchronous notifications)

Example Condition Control Flow

```
Mutex m
ConditionVariable cv
Data d

waiter() {
    lock m
    while condition on d {
        wait on cv
    }
    take action
    unlock m
}
```

```
signaler() {
    lock m
    modify d
    signal cv
    unlock m
}
```

Deadlock

Deadlock is a condition in concurrent programming where two or more concurrent flows are waiting for each other and thus can never make progress.

Consider:

```
flow A:                          flow B:
    lock mutex m0                    lock mutex m1
    lock mutex m1                    lock mutex m0
    do something                     do something
```

If flow A is interrupted by flow B after locking m0 and before locking m1, deadlock occurs.

Neither flow can proceed, and neither can release the other.

Necessary Conditions

For deadlock to occur, all of the following must be true [2]:

- At least one resource is mutually exclusive.
- Flows hold locks while waiting for other locks to become available
- Locks cannot be preempted: once a flow holds a lock, it holds it until it voluntarily releases it.
- A circular chain of flows exists, such that each flow holds some lock required by the next flow

Avoiding Deadlock

Deadlock is caused by synchronization.

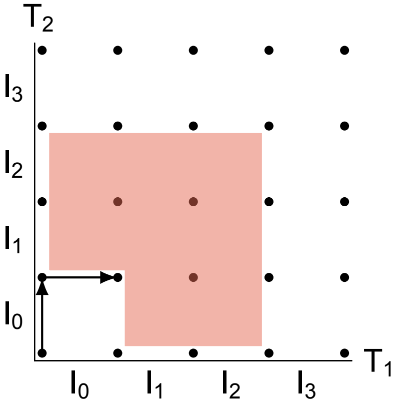
There are various techniques to avoid deadlock.

For deadlock caused by mutual exclusion on multiple locks, there is a simple solution:

- All mutexes in a system are ordered (perhaps artificially)
- All flows lock mutexes in order
- All flows unlock mutexes in reverse order

Deadlock and Progress Graphs

Deadlock on a progress graph appears as a concave region:



Summary

- A race is a situation where program correctness depends on the order of operations in concurrent flows.
- Data races are races involving modification of data.
- Synchronization is the deliberate ordering of events in a program.
- A critical section is a region of code that must be accessed by at most one concurrent flow at a time.
- Progress graphs visualize concurrent flows.
- Synchronization primitives:
    - Atomic operations
    - Mutexes
    - Semaphores
    - Condition variables
- Deadlock is a program error caused by synchronization.

Next Time …

- POSIX threads
- POSIX mutexes
- POSIX semaphores
- POSIX condition variables
- Basically POSIX

References I

Required Readings

[1] Randal E. Bryant and David R. O'Hallaron. *Computer Science: A Programmer's Perspective*. Third Edition. Chapter 12: 12.4-12.7. Pearson, 2016.

Optional Readings

[2] E. G. Coffman Jr., M. J. Elphick, and A. Shoshani. "System Deadlocks". In: *Computing Surveys* 3.2 (June 1971).

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