System Calls

CPSC 457: Principles of Operating Systems
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Topics

- thread cancellation
- race conditions
- critical sections

Thread Cancellation

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Thread/work cancellation

- imagine writing a program that detects whether a given word occurs anywhere in a set of files
  - i.e. as soon as the program detects the word in any file, it can stop the search

- we want to make the search faster, by using threads
  - we create multiple threads, each searching for the word in different files
  - as soon as one thread finds a file that contains the word,
    that thread should notify the other threads, so that they can stop searching

- two general approaches:
  - asynchronous cancellation
  - deferred cancellation (aka. synchronous cancellation)

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Asynchronous thread/work cancellation

- one thread manually terminates the target thread, by calling `pthread_kill(tid, SIGUSR1)`
- target thread (`tid`) is killed nearly instantly
- what happens to data currently being updated by the target thread?
  - target thread has no chance to "clean up"
  - this can (likely) lead to leaving data in undefined state
  - for example, if the target thread is in the middle of allocating memory, the memory allocator could become corrupted and crash the entire program
- in many/most cases asynchronous cancellation is an unacceptable solution
- much better solution is to use synchronous thread cancellation

Deferred (Synchronous) thread/work cancellation

- the controlling thread somehow *indicates* it wishes to cancel a target thread (or the work in the thread)
  - e.g. by setting some shared global flag variable
  - or using `pthread_cancel()` and related mechanisms (`man pthread_cancel` for details)

- target thread periodically checks whether it should terminate
  - checking done only at *cancellation points*, where the thread can cancel itself safely
  - these are carefully chosen points, selected by the programmer

- some issues:
  - less performance – checking for cancellation flag requires at least 1 instruction…
  - target thread might not react immediately
    - it could run for a while before noticing the cancellation requested
    - e.g. continue to report results

- more flexible than asynchronous cancellation, but requires more effort to use (correctly)

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Deferred cancellation example

```
void * thread_print(void * tid) {
  while(1) {
    printf("thread %ld running\n", tid);
    sleep(1);
    /* here we need to check if cancellation was requested */
  }
}
int main() {
  pthread_t threads[N_THREADS];
  for (long i = 0; i < N_THREADS; i++) {
    if( 0 != pthread_create(& threads[i], NULL, thread_print, (void *) i)) {
      printf("Oops, pthread_create failed.\n"); exit(-1);
    }
  }
  sleep(5); // pretend to do something
  /* here we request cancellation */
  for (long i = 0; i < N_THREADS; i++)
    pthread_join(threads[i], NULL);
  printf("All threads done.\n");
}
```

keeps printing message forever

note: without thread cancellation, this program will run forever

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Deferred cancellation example (non-portable)

```
volatile int cancel_flag = 0;
void * thread_print(void * tid) {
  while(1) {
    printf("thread %ld running\n", tid);
    sleep(1);
    if(cancel_flag) return NULL;
  }
}
int main() {
  pthread_t threads[N_THREADS];
  for (long i = 0; i < N_THREADS; i++) {
    if( 0 != pthread_create(& threads[i], NULL, thread_print, (void *) i)) {
      printf("Oops, pthread_create failed.\n"); exit(-1);
    }
  }
  sleep(5); // pretend to do something
  cancel_flag = 1;
  for (long i = 0; i < N_THREADS; i++)
    pthread_join(threads[i], NULL);
  printf("All threads done.\n");
}
```

global flag

cancellation point: periodically checks global flag when it's safe

request cancellation by setting global flag

!!! non-portable code !!!

works on x86, but for portability we should use atomic operation e.g. `std::atomic<bool>`

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Deferred cancellation example (C++, portable)

```
std::atomic_bool cancel_flag { false };

void thread_print(int tid) {
  while(1) {
    std::cout << "thread " << tid << " running\n";
    sleep(1);
    if(cancel_flag.load()) return;
  }
}

int main() {
  std::vector<std::thread> threads;
  for (long i = 0; i < N_THREADS; i++)
    threads.push_back( std::thread(thread_print,i));
  sleep(5); // pretend to do something
  cancel_flag.store(true);
  for( auto & t : threads )
    t.join();
  return 0;
}
```

global flag

`std::atomic<bool>` is portable, and will work on all architectures

cancellation point: periodically checks global flag when it's safe

request cancellation by setting global flag

https://repl.it/@pfederl/c-threads-with-cancellation

Race Conditions

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Race conditions

- **race condition** is a behavior where the output is dependent on the sequence or timing of other uncontrollable events (eg. context switching, scheduling on multiple CPUs)
- race condition is a bug
- often a result of multiple processes/threads operating on a shared state/resource, eg.:
  - modifying shared memory
  - reading/writing to files
  - reading/writing to databases
- but not specific to multi-threaded applications
  - race conditions can exist among processes on the same computer; or even
  - among different computers using shared filesystems, databases, etc.

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Race conditions

```
// global variable counter
int counter;

void incr() {
  // local variable x
  int x = counter;
  x = x + 1;
  counter = x;
}

int main() {
  counter = 0;
  incr();
  incr();

  printf( "%d\n", counter);
}
```

Output:

2

… every time

Race conditions

```
// global variable "counter" is shared
int counter;

void incr() {
  // local variable "x" is not shared
  int x = counter;
  x = x + 1;
  counter = x;
}

int main() {
  counter = 0;
  pthread_create(..., incr);
  pthread_create(..., incr);
  pthread_join ...
  printf( "counter = %d\n", counter);
}
```

Thread 1:

```
void incr() {
  int x = counter;
  x = x + 1;
  counter = x;
}
```

Thread 2:

```
void incr() {
  int x = counter;
  x = x + 1;
  counter = x;
}
```

What is the value in **counter** after both threads finish executing `incr()`?

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Race conditions

```
// global variable "counter" is shared
int counter;

void incr() {
  // local variable "x" is not shared
  int x = counter;
  x = x + 1;
  counter = x;
}

int main() {
  counter = 0;
  pthread_create(..., incr);
  pthread_create(..., incr);
  pthread_join ...
  printf( "counter = %d\n", counter);
}
```

Thread 1	Thread 2	counter
		0
x = counter;		0
x = x + 1;		0
counter = x;		1
	x = counter;	1
	x = x + 1;	1
	counter = x;	2

one possible **execution sequence** resulting in

counter = 2

Race conditions

```
// global variable "counter" is shared
int counter;

void incr() {
  // local variable "x" is not shared
  int x = counter;
  x = x + 1;
  counter = x;
}

int main() {
  counter = 0;
  pthread_create(..., incr);
  pthread_create(..., incr);
  pthread_join ...
  printf( "counter = %d\n", counter);
}
```

Thread 1	Thread 2	counter
		0
x = counter;		0
	x = counter;	0
	x = x + 1;	0
	counter = x;	1
x = x + 1;		1
counter = x;		1

another possible **execution sequence** resulting in

counter = 1 !!!

This program has a race condition.

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Race conditions

```
// global variable counter
int counter;

    void incr() {
      int x = counter;
      x = x + 1;
      counter = x;
    }
```

```
void incr() {
  counter ++;
}
```

Would this get rid of the race condition?

Can a single line of code be 'interrupted' by another thread?

```
int main() {
  counter = 0;
  pthread_create(..., incr);
  pthread_create(..., incr);
  pthread_join ...
  printf( "%d\n", counter);
}
```


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Race conditions

```
int counter;

int incr1() {
    int x = counter;
    x = x + 1;
    counter = x;
}
```

```
mov eax, DWORD PTR counter[rip]
mov DWORD PTR [rbp-4], eax
add DWORD PTR [rbp-4], 1
mov eax, DWORD PTR [rbp-4]
mov DWORD PTR counter[rip], eax
```

```
int incr2() {
    counter ++;
}
```

```
mov eax, DWORD PTR counter[rip]
add eax, 1
mov DWORD PTR counter[rip], eax
```

To see how GCC compiles your code into assembly, you can try:

```
$ gcc -S -fverbose-asm test.c
```

Or use an online tool, eg: https://godbolt.org/z/WTPzC2 (full)

Race conditions

```
// global variable counter
int counter;

    void incr() {
      int x = counter;
      x = x + 1;
      counter = x;
    }
```

```
void incr() {
  counter ++;
}
```

```
int main() {
  counter = 0;
  pthread_create(..., incr);
  pthread_create(..., incr);
  pthread_join ...
  printf( "%d\n", counter);
}
```

Q: Would this get rid of the race condition?

A: No, because compiler might translate this into multiple instructions...

Q: But what if we compiled with **-O2** and compiler reduced this to a single instruction?

A: Race condition could still happen... multicore systems

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Race conditions

- debugging race conditions is not fun
  - many test runs may produce the same output, often correct
  - then, in a rare situation the output might be different, e.g. when system was less/more busy
  - C example: https://repl.it/@pfederl/counter-race-condition
  - C++ example: https://repl.it/@pfederl/c-threads-with-race-condition

- we want to avoid race conditions
  - but how?

Concurrent programming

Avoiding race conditions

- we need to prevent more than one process/thread from accessing a shared resource at any given time
- approach:
  - identify **critical sections** in code where this could happen
  - enforce **mutual exclusion** to make sure it does not happen

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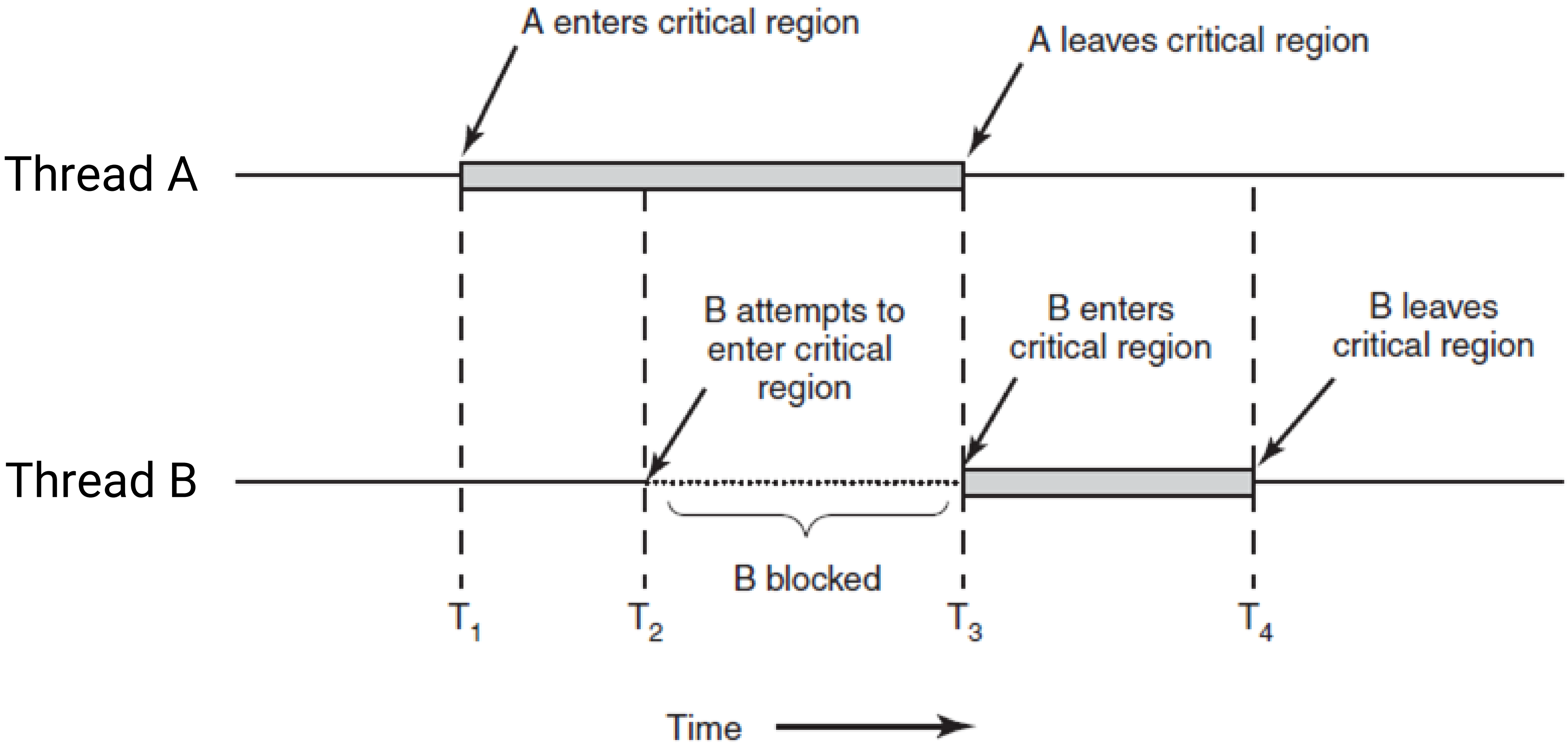
Critical sections and mutual exclusion

- **critical section** / **critical region**: part of the program that accesses the shared resource in a way that could lead to races or other undefined/unpredictable/unwanted behaviour

```
int counter;                      ← shared resource
void incr() {
  int x = counter;  ┐
  x = x + 1;        ├             ← critical section
  counter = x;      ┘
}
```

- if we can arrange tasks such that no two processes or threads will ever be in their critical sections at the same time, we could avoid the race condition (achieving **mutual exclusion**)

Critical sections and mutual exclusion



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Requirements for good race-free solution

```
General structure:

while (1) {
  CS entry code
  critical section
  CS exit code
  non-critical section
}
```

1. **Mutual exclusion**: No two processes/threads may be simultaneously inside their critical sections (CS).
2. **Progress**: No process/threads running outside its CS may block other processes/threads.
3. **Bounded waiting**: No process/thread should have to wait forever to enter its CS.
4. **Speed**: No assumptions may be made about the speed or the number of CPUs.

Review

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Summary

- thread cancellation
- race conditions
- critical sections

Threads and fork()

- is it ok to call fork() in a program with multiple threads?
  - what should happen?
  - what does happen?
- what actually happens:
  - only the calling thread survives, other threads are not duplicated
  - this creates a problem if synchronization mechanisms were used
  - it's possible to register a callback in case fork() is called using pthread_atfork()
- general advice: avoid using fork() in programs with multiple threads
- some usages are safe, eg.:
  - fork() is immediately followed by execve() to execute external program, or
  - fork() is executed before creating any threads

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Onward to … locks, mutexes, dining philosophers

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