Locks, Mutexes, and Dining Philosophers

CPSC 457: Principles of Operating Systems
Winter 2024

Contains slides from Pavol Federl, Mea Wang, Andrew Tanenbaum and Herbert Bos, Silberschatz, Galvin and Gagne

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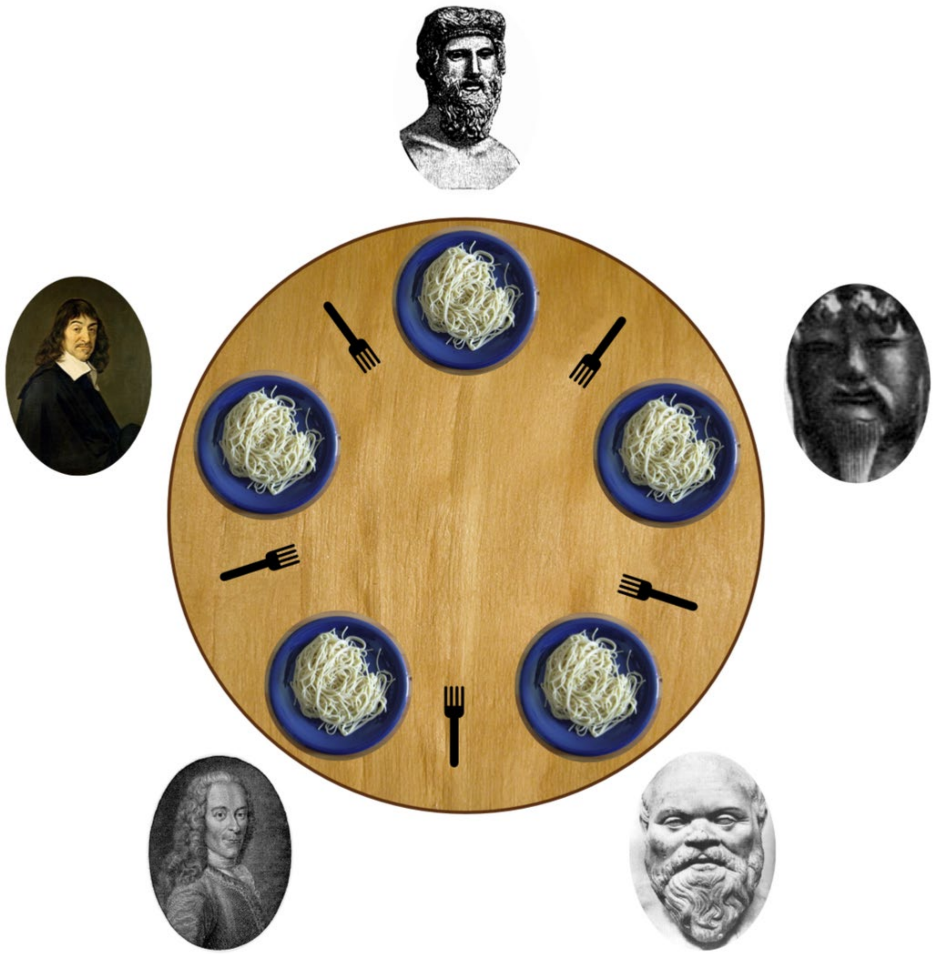
Topics

- dining philosophers
- locks
- mutexes

Dining Philosophers

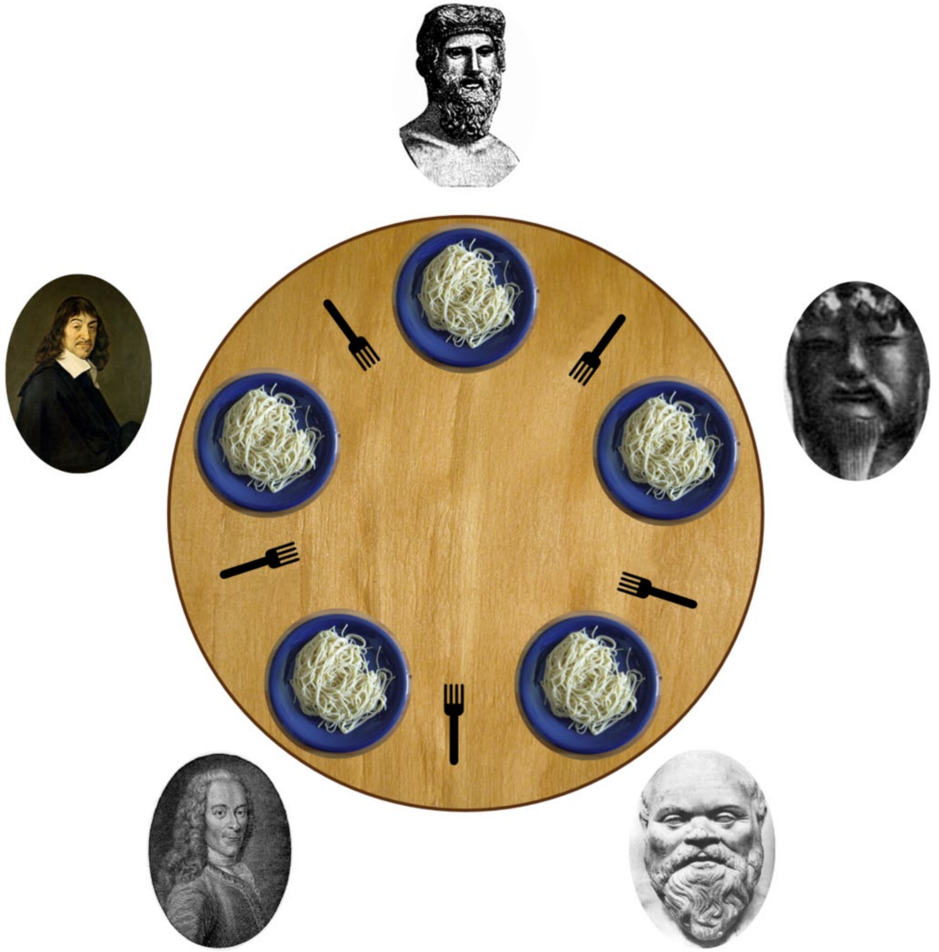
Dining philosophers problem

- 5 philosophers sitting around a table
- 5 bowls of food, one for each philosopher
- 5 forks placed between bowls
- philosophers alternate between eating and thinking
- philosophers don't mind sharing forks



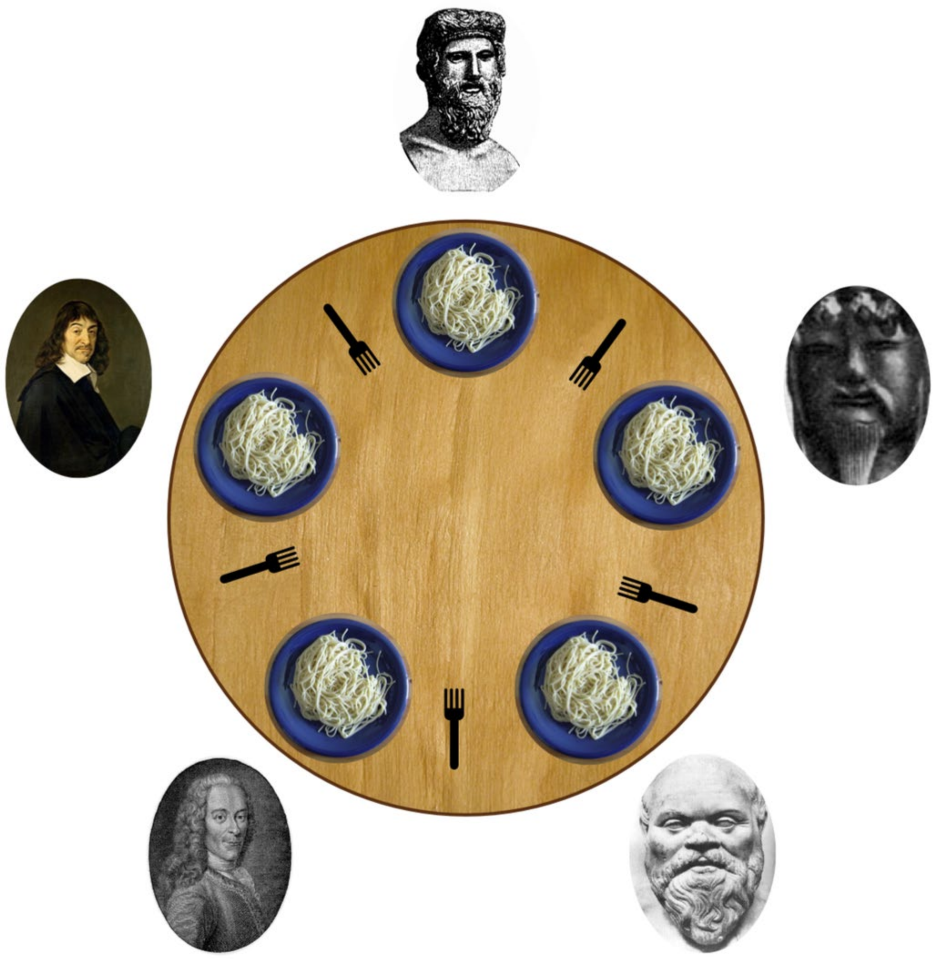
Dining philosophers problem

- before eating, a philosopher must first grab both forks, immediately to the left & right
- philosopher then eats for a short time
- when done eating, the philosopher puts down the forks in their original positions
- philosopher then thinks for a short time



Dining philosophers problem

- software scenario:
  5 processes/threads, each needs frequent exclusive access to two resources (e.g. each needs to update 2 files)
- how to allocate resources so that all process/threads get to execute?
- what is the "best" algorithm for threads/processes to follow?
  - how do we define *'best'*?
  - depends on the the objective...
  - what are we trying to optimize?



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Dining philosophers problem

- assuming each philosopher eats & thinks for the same amount of time
- optimal schedule:

  repeat:

  philosophers 1 & 3 eat

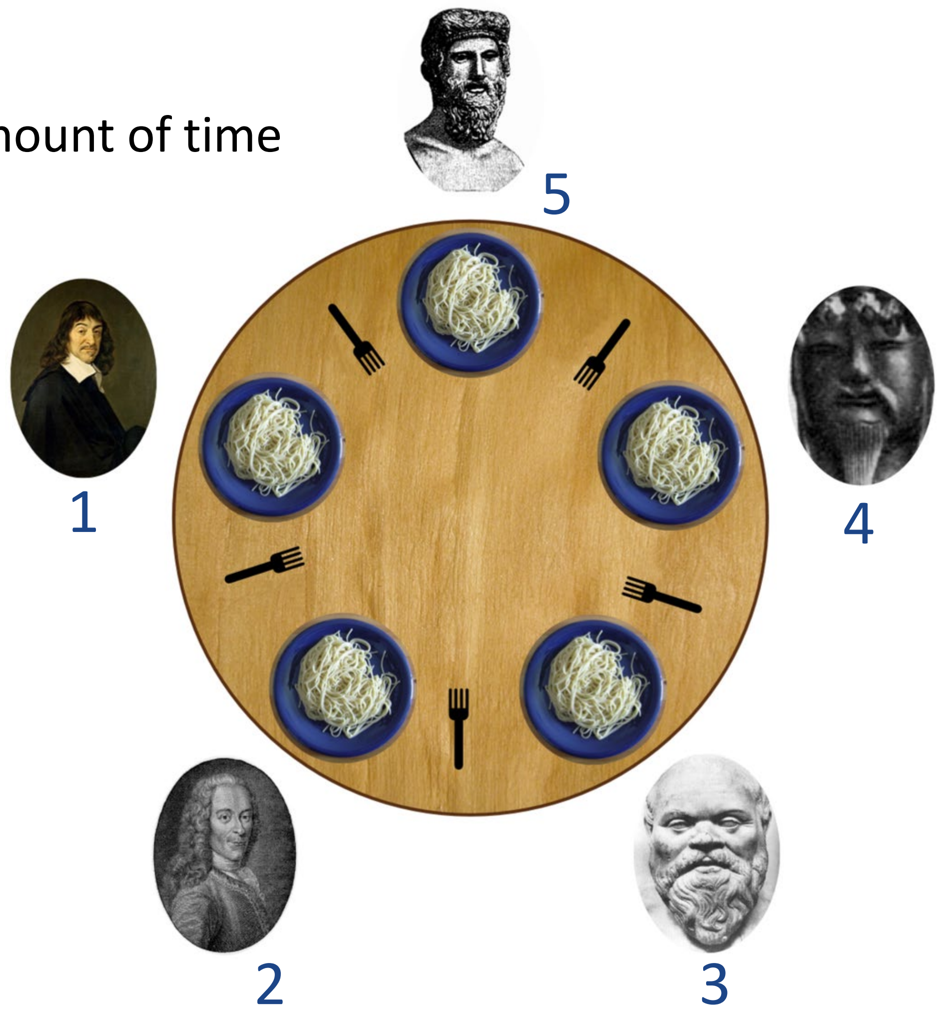
  philosophers 2 & 4 eat

  philosophers 3 & 5 eat

  philosophers 4 & 1 eat

  philosophers 5 & 2 eat

- is there a simple way to code this?
  remember that each philosopher represents an independent thread or process
- not optimal if some philosophers think/eat more than others



Dining Philosophers Attempt to do Something

Attempt 1

- each philosopher follows these steps (algorithm):

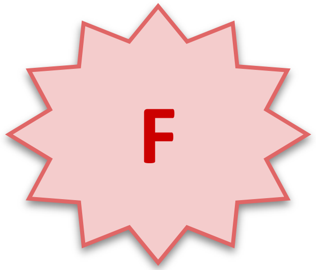
```
repeat forever:
       grab left fork
       grab right fork
       eat
       put forks back
       think
```

- would this work?

Attempt 1

- each philosopher follows these steps (algorithm):

```
repeat forever:
       grab left fork
       grab right fork
       eat
       put forks back
       think
```



- would this work?
- no, this could lead to a **deadlock**:
  - assuming all philosophers are reasonably synchronized
  - each philosopher could end up grabbing the left fork
  - then each philosopher will be 'stuck' trying grab the right fork
  - nobody gets to eat at all

Attempt 2

- each philosopher follows these steps (algorithm):

```
repeat forever:
     repeat:
            try to grab left fork
            try to grab right fork
            if both forks grabbed then break
            else put any grabbed forks back and take a short nap
       eat
       put forks back
       think
```

- would this work?

Attempt 2

- each philosopher follows these steps (algorithm):

```
repeat forever:
     repeat:
          try to grab left fork
          try to grab right fork
          if both forks grabbed then break
          else put any grabbed forks back and take a short nap
     eat
     put forks back
     think
```

F+

- would this work?
- philosophers could reach a **livelock**
  - every philosopher grabs left fork, but fails to grab right fork
  - all philosophers would indefinitely switch between napping and attempting to eat
  - nobody will eat — form of **starvation**

Attempt 3

- same as before, but there is one pink hat

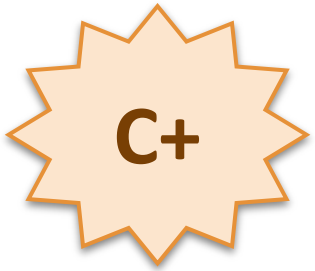
```
repeat forever:
    wait for a hat
    grab forks, eat, put forks back
    give hat to "someone" else
    think
```

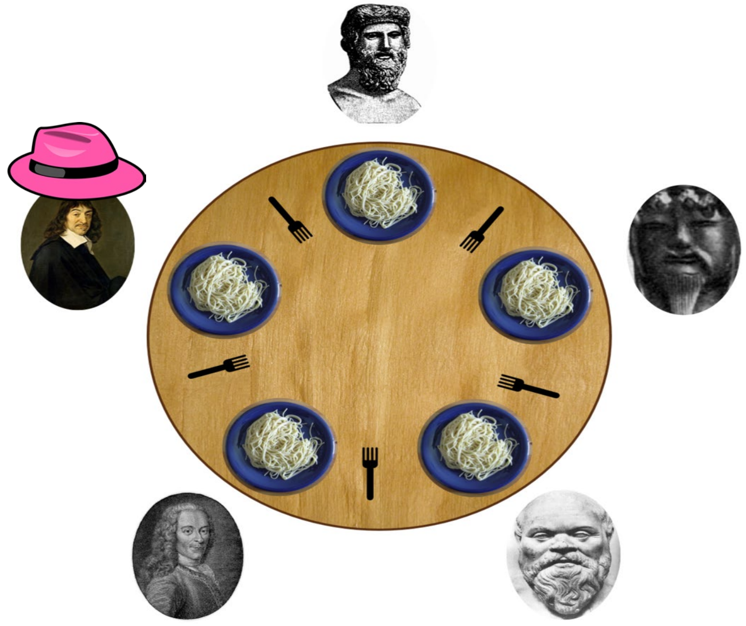
- would this work?

Attempt 3

- same as before, but there is one pink hat

```
repeat forever:
    wait for a hat
    grab forks, eat, put forks back
    give hat to "someone" else
    think
```





- would this work? yes it would, but…
  - only one philosopher is eating at any given time, but with 5 forks, 2 philosophers **could** be eating at the same time
  - non-optimal use of resources, resulting in reduced parallelism

Attempt 4

```
repeat forever:
     repeat:
           try to grab left fork
           try to grab right fork
           if both forks grabbed then break out of loop
           else put any grabbed forks back and take a short RANDOM nap
       eat
       put forks back
       think
```

- would this work?

Attempt 4

A-

```
repeat forever:
    repeat:
        try to grab left fork
        try to grab right fork
        if both forks grabbed then break out of loop
        else put any grabbed forks back and take a short RANDOM nap
    eat
    put forks back
    think
```

- the random nap will desynchronize the philosophers and is likely to work over long time
- sometimes used in real world, e.g. in networking (Exponential backoff)
- but…
  - if nap time is the same for neighbors, they do not get to eat (temporary starvation)
  - some philosophers might sleep longer than others, and eat less often (fairness problem)

Attempt 5

B+

- label the forks with numbers: 1, 2, 3, 4, 5
- each philosopher:
  - picks up the fork with the smallest number first, then the larger number second

- called a **resource hierarchy** solution – by establishing a partial order on resources

- starvation is still possible, although very unlikely
- reduced parallelism in general cases
  - e.g. already have lock on 2, 3, but now need 1, must first release 2, 3, then re-acquire 1, 2, 3

- it is not always practical for large and/or dynamic number of resources

further attempts left as a homework:
two hats, even/odd philosophers,
pick left/right forks randomly,
hungry vs more hungry queues, ...

Algorithms

Naive algorithm implementation

- let's try a naive implementation of a philospher
- consider algorithm #1 for philosopher 'i':

```
// global variable representing fork state
// false = unavailable, true = available
bool forks[5];

while (true) {
    sleep (s);                              // think for s seconds
    while (!forks[i] || !forks[i+1]) {;} // i+1 modulo 5 arithmetic
    forks[i] = false;
    forks[i+1] = false;
    sleep (m);                              // eat for m seconds
    forks[i] = true;
    forks[i+1] = true;
}
```

Critical Sections

Naive algorithm implementation

```
while (true)
{
  sleep (s); // think
  while
(!forks[i]||!forks[i+1]){;}

  forks[i] = false;
  forks[i+1] = false;
  sleep (m); // eat
  forks[i] = true;
  forks[i+1] = true;
}
```

```
while (true)
{
  sleep (s); // think
  while
(!forks[i]||!forks[i+1]){;}

  forks[i] = false;
  forks[i+1] = false;
  sleep (m); // eat
  forks[i] = true;
  forks[i+1] = true;
}
```

- depending on the execution order (eg. multi-core machines, or timing of context switches)
  - two neighboring philosophers could start eating at the same time
  - i.e. both threads could enter the critical region

Algorithm with critical sections

- the shared resource is the global variable `forks[]`
- let's identify critical sections (parts of code that use the shared resource):

```
while (true)
{
  sleep (s);
  while (!forks[i] || !forks[i+1]);
  forks[i] = false;
  forks[i+1] = false;
  sleep (m);
  forks[i] = true;
  forks[i+1] = true;
}
```

critical section 1: `while (!forks[i] || !forks[i+1]);` `forks[i] = false;` `forks[i+1] = false;`

critical section 2: `forks[i] = true;` `forks[i+1] = true;`

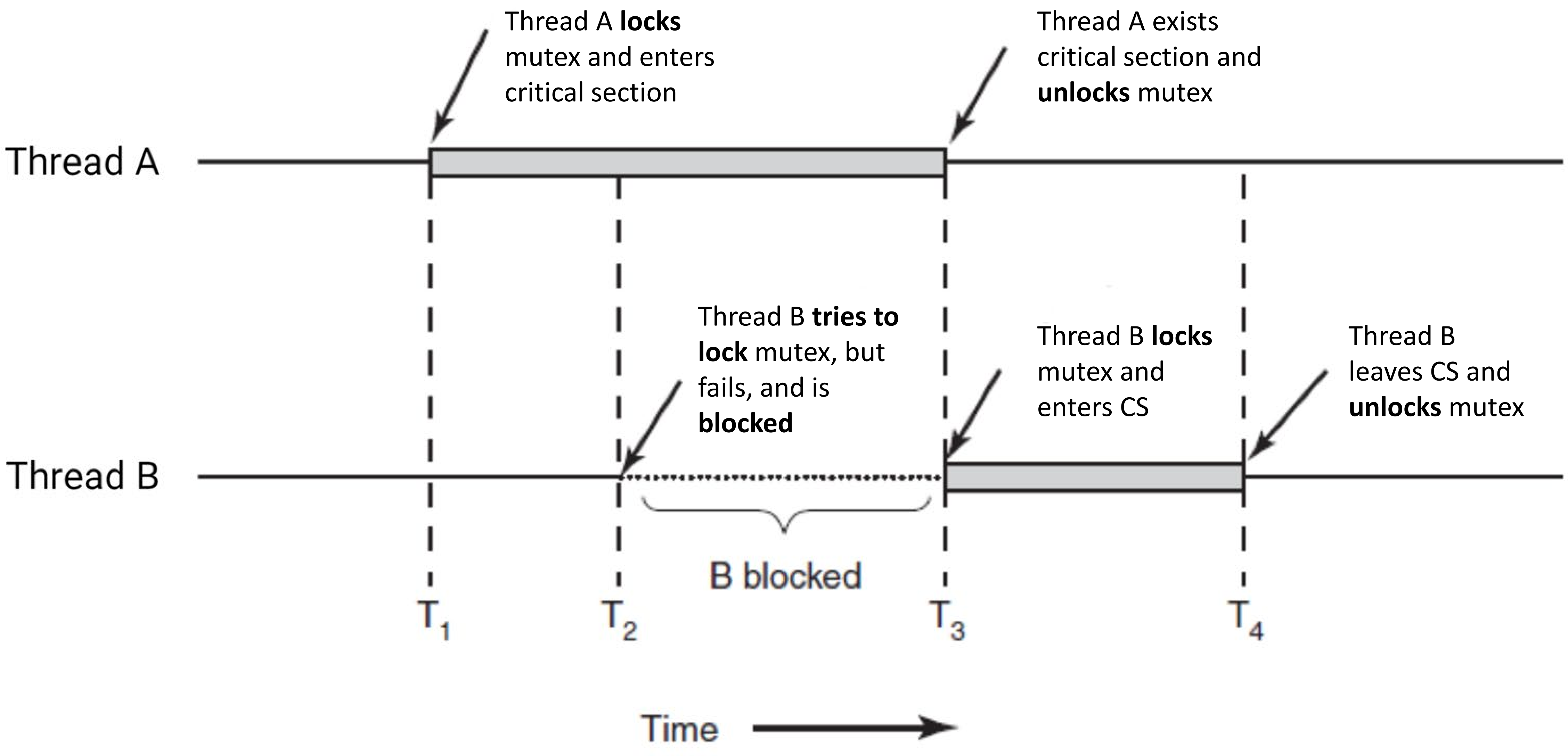
- now we need a mechanism to protect these sections via mutual exclusion

Mutexes

Mutex (aka Lock)

- **mutex** is a synchronization primitive, usually used for ensuring **exclusive access** to a resource in concurrent programs
- mutex has two possible states: **locked** and **unlocked**, and two atomic operations: `lock()` and `unlock()`
- if multiple threads call `lock()` simultaneously, only one will proceed, the rest will block
  - only the thread that locks the mutex can unlock it
  - a waiting queue is used to keep track of all threads waiting on the mutex to be unlocked
- once the mutex is unlocked, one of the waiting threads will be unlocked
  note: which one thread gets unlocked is usually not predictable
- can be implemented in software via busy waiting, but usually supported by hardware + OS
- portable libraries will try to use H/W mutex, but are able to fall back to software

Using mutexes to protect critical sections



Mutex (aka Lock)

pseudocode

```
// initialize mutex and share across all threads,
// e.g. via global variable
mutex m;

// in each thread
void run()
{
     non-critical_section_code
     // before entering critical section, lock the mutex
     lock(m);
     // now it's safe to access a shared resource
     critical_section_code
     // to exit CS, we unlock the mutex
     unlock(m);
     non-critical_section_code
}
```

Pthreads mutex

API	Description
`pthread_mutex_init()`	initialize a new mutex (unlocked state)
`pthread_mutex_destroy()`	destroy a mutex
`pthread_mutex_lock()`	try to lock a mutex, block if already locked
`pthread_mutex_unlock()`	unlock a mutex
`pthread_mutex_trylock()`	try to lock a mutex, or fail (non-blocking version of lock)

Counter with Mutex

Counter with mutex (pthreads)

```
#include <pthread.h>

pthread_mutex_t count_mutex; // must be initialized with pthread_mutex_init(),
e.g. in main()
int counter;                 // initialized with counter = 0, e.g. in main()

void incr() {
  pthread_mutex_lock(&count_mutex); // acquire the lock
    int x = counter;
    x = x + 1;
    counter = x;
  pthread_mutex_unlock(&count_mutex); // release the lock
}
```

all 3 lines must be in the same critical section !

notice the performance difference

Counter with mutex (C++ mutex)

```
#include <mutex>

std::mutex m;                    // no need to further initialize
int counter = 0;

void incr() {
  m.lock();                      // acquire the lock
    counter ++;
  m.unlock();                    // release the lock
}
```

notice the performance difference

Dining Philosopher with Mutexes

Dining philosopher with mutex

Would this work?

```
pthread_mutex_t mutex;

while (true) {
    sleep (s);  // think
    pthread_mutex_lock(&mutex);
     while (!forks[i] || !forks[i+1])
{;}
     forks[i] = false;
     forks[i+1] = false;
    pthread_mutex_unlock(&mutex);
    sleep (m);   // eat

    pthread_mutex_lock(&mutex);
     forks[i] = true;
     forks[i+1] = true;
    pthread_mutex_unlock(&mutex);
}
```

Dining philosopher with mutex

```
pthread_mutex_t mutex;

while (true) {
    sleep (s);  // think
    pthread_mutex_lock(&mutex);
     while (!forks[i] || !forks[i+1])
{;}
     forks[i] = false;
     forks[i+1] = false;
    pthread_mutex_unlock(&mutex);
    sleep (m);   // eat

    pthread_mutex_lock(&mutex);
     forks[i] = true;
     forks[i+1] = true;
    pthread_mutex_unlock(&mutex);
}
```

1 thread 1 claims forks and starts to eat

2 thread 2 attempts to claim forks, but gets stuck in while loop

3 thread 1 finishes eating and attempts to return forks, but gets stuck unable to lock mutex

Deadlock !!!

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Review

Summary

- **critical section** - part of the program where a shared resource is accessed & may cause trouble
- **mutual exclusion** - ensuring only one process accesses a resource at a time, eg. only one process can enter critical section at any given time
- **mutex/lock** - mechanism to achieve mutual exclusion, two states + queue
- **deadlock** - a state wheare each process/thread is waiting on another to release a lock → no progress is made
- **livelock** - states of the processes change, but none are progressing
- **starvation** - one process does not get to run at all
- **unfairness** - not all processes get equal opportunity to progress

- concurrent programming is hard

Review

- Name/explain two general approaches for cancelling a thread.
- Are signals handled per thread or per process?
- Define:
  - race condition, critical region, mutual exclusion
  - deadlock, livelock, starvation
- Race condition is not a problem among processes, only among threads.
  True or False?
- A mutex has only two states: locked and unlocked.
  True or False?

- more tutorials on dining philosophers:
  http://cs.mtu.edu/~shene/NSF-3/e-Book/MUTEX/TM-example-philos-1.html
  http://web.eecs.utk.edu/~mbeck/classes/cs560/560/notes/Dphil/lecture.html

Onward to … condition variables and semaphores

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