Dining Philosophers: A Synchronization Problem

CS347 Operating Systems

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When you go to sleep make sure there is someone to wake you up.
(Prof. Mythili Vutukuru)

Outline

Problem Formulation

The Setup

[1] Downey Allen B. The Little Book of Semaphores

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- N philosophers denoted by P_i, $i \in [N] \triangleq \{0, ..., N-1\}$ around a circular table.

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  - a huge bowl of spaghetti in the centre of table.

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  - a huge bowl of spaghetti in the centre of table.
- P_i has p_i in their front and $f_i, f_{(i+1)\%N}$ to their right and left respectively.

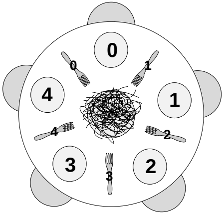

Figure: Example[1] when $N = 5$

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- A philosopher can start eating only after picking up the forks on their left and right.
- Till they start eating, they will be ‘thinking’.
- Generic Behaviour of a philosopher:

```
while (True){
    think()
    pick_up_forks()
    eat()
    put_down_forks()
}
```

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- A complicated problem as a thread can possibly context switch anytime during its execution

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right_p(i) = (i-1)\%N
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- A philosopher P_0 successfully completes/finishes when it goes back to thinking.

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- We may refer to philosophers as threads
- A philosopher P_0 successfully completes/finishes when it goes back to thinking.
- A scheduled thread is active when it has run at least once.

Semaphores

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  - When a thread calls `down(s)`, the counter is decremented and the thread is blocked if the counter value becomes negative.

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- The counter value can't be accessed once it is initialised with a suitable value.
- For a semaphore variable `s`,
  - When a thread calls `down(s)`, the counter is decremented and the thread is blocked if the counter value becomes negative.
  - When a thread calls `up(s)`, the counter is incremented and any one of blocked threads is woken up ('ready to run' again).

Semaphores – Focusing on Forks

Incorrect Solution

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- Pseudocode:

```
function pick_up_forks(philosopher i){
    down(s_{right_f(i)})
    down(s_{left_f(i)})
}
```

```
function put_down_forks(philosopher i){
    up(s_{left_f(i)})
    up(s_{right_f(i)})
}
```

Semaphores – Incorrect Solution

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- Say for $N = 3$ case, the schedule is P_0, P_1, P_2 (another example would be P_0, P_2, P_1.)
- P_0 will get the right fork f_0 by calling `down(s_{right_f(0)}) = down(s_0)` which will make $s_0 = 0$. Now, suppose P_0 gets context switched then P_1 begins.

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- P_2 will get the right fork f_2 by calling `down(s_{right_f(2)}) = down(s_2)` which will make $s_2 = 0$. Now, every P_i will have a single fork f_i.

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- P_2 will get the right fork f_2 by calling `down(s_{right_f(2)}) = down(s_2)` which will make $s_2 = 0$. Now, every P_i will have a single fork f_i.
- Now, if any thread P_i executes `down(s_{left_f(i)})`, then for $f_{\text{left}(i)}$, $s_{\text{left}(i)} = -1$. Hence, that thread will be sent to sleep.

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- Now, if any thread P_i executes `down(s_{left_f(i)})`, then for $f_{\text{left}(i)}$, $s_{\text{left}(i)} = -1$. Hence, that thread will be sent to sleep.
- Each thread will try to access their 'left fork' and will be sent to eternal sleep. A *deadlock*!

Semaphores

Incorrect Solution – Why Deadlock?

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- Intuitively, suppose each philosopher simultaneously picks up the fork to their right, then all forks are occupied. There are no 'available forks' to any philosopher's left.

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- Intuitively, suppose each philosopher simultaneously picks up the fork to their right, then all forks are occupied. There are no 'available forks' to any philosopher's left.
- Formally, if each thread gets context switched just after executing `down(s_{right_f(i)})`, then this will result in $s_i = 0, i \in [N]$.

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- Formally, if each thread gets context switched just after executing `down(s_{right_f(i)})`, then this will result in $s_i = 0, i \in [N]$.
- Now, if any thread P_i gets scheduled and executes `down(s_{left_f(i)})`, then for that fork's semaphore $s_{\text{left}(i)} = -1$. Hence, that thread will be sent to sleep.

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- Formally, if each thread gets context switched just after executing `down(s_{right_f(i)})`, then this will result in $s_i = 0, i \in [N]$.
- Now, if any thread P_i gets scheduled and executes `down(s_{left_f(i)})`, then for that fork's semaphore $s_{\text{left}(i)} = -1$. Hence, that thread will be sent to sleep.
- Similarly, each thread will try to access their 'left fork' and will be sent to sleep.

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- Similarly, each thread will try to access their 'left fork' and will be sent to sleep.
- To awake them, some thread must give signal which is not possible as all threads are sleeping. A deadlock!

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- Now, if any thread P_i gets scheduled and executes `down(s_{left_f(i)})`, then for that fork's semaphore $s_{\text{left}(i)} = -1$. Hence, that thread will be sent to sleep.
- Similarly, each thread will try to access their 'left fork' and will be sent to sleep.
- To awake them, some thread must give signal which is not possible as all threads are sleeping. A deadlock!
- Note that the above case is possible for any scheduling of threads as we haven't made any assumption on scheduling in the proof.

□

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- create another semaphore variable called $max = N - 1$, denoting the maximum number of philosophers allowed to eat at any instant.

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- In addition to the N semaphore variables, one for each fork $s_i = 1, i \in [N]$,
- create another semaphore variable called $max = N - 1$, denoting the maximum number of philosophers allowed to eat at any instant.
- Revised pseudocode:

```
function pick_up_forks(philosopher i){
    down(max)
    down(s_{right_f(i)})
    down(s_{left_f(i)})
}
```

```
function put_down_forks(philosopher i){
    up(s_{left_f(i)})
    up(s_{right_f(i)})
    up(max)
}
```

Semaphores – Correct Solution

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- Let's assume that no context switches can occur during the execution of `pick_up_forks` and `put_down_forks` (unless it sleeps due to semaphore).

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- Say for $N = 3$ case, the schedule is P_0, P_1, P_2
- Let's assume that no context switches can occur during the execution of `pick_up_forks` and `put_down_forks` (unless it sleeps due to semaphore).
- P_0 will get both it's 'right and left fork' (f_0 and f_1) and P_0 will start eating.

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- Let's assume that no context switches can occur during the execution of `pick_up_forks` and `put_down_forks` (unless it sleeps due to semaphore).
- P_0 will get both it's 'right and left fork' (f_0 and f_1) and P_0 will start eating.
- Now, one of the two things can happen:
  - P_0 successfully completes everything
  - P_0 gets context switched out before it can put down its both forks.

Semaphores – Correct Solution

Example 1

Example (continued)

Semaphores – Correct Solution

Example 1

Example (continued)

- In the first case, P_1 will get both it's 'right and left fork' and it will start eating using f_1 and f_2, whereas in the second case P_1 will only be able to get one fork (f_2) and will go to sleep.

Semaphores – Correct Solution

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- P_0 will complete eating and thus its job at sometime due to assumption that eat has to terminate. So, forks f_0 and f_1 will be available later for other threads.

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- P_0 will complete eating and thus its job at sometime due to assumption that eat has to terminate. So, forks f_0 and f_1 will be available later for other threads.
- Even in the 2^{nd} case after completion of P_0, P_1 will wake up and start eating using f_1 and f_2.

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- P_0 will complete eating and thus its job at sometime due to assumption that eat has to terminate. So, forks f_0 and f_1 will be available later for other threads.
- Even in the 2^{nd} case after completion of P_0, P_1 will wake up and start eating using f_1 and f_2.
- Hence, P_2 will get a fork f_0 and will go to sleep waiting for P_1 to complete.

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- Even in the 2^{nd} case after completion of P_0, P_1 will wake up and start eating using f_1 and f_2.
- Hence, P_2 will get a fork f_0 and will go to sleep waiting for P_1 to complete.
- Once P_1 completes eventually, P_2 will be woken up and it will also get completed.

Semaphores – Correct Solution

Example 2

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Semaphores – Correct Solution

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- Say for $N = 3$ case, the schedule is P_0, P_1, P_2
- If any thread is able to pick up both forks, it will eventually finish and the analysis will be similar to Example 1.

Semaphores – Correct Solution

Example 2

Example (continued)

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Example (continued)

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Semaphores – Correct Solution

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- So let's try the worst case, when each thread gets context switched just after picking up right fork, now the *max* semaphore comes into picture.
- P_0 and P_1 will get their right fork f_0, f_1 respectively.

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- So let's try the worst case, when each thread gets context switched just after picking up right fork, now the *max* semaphore comes into picture.
- P_0 and P_1 will get their right fork f_0, f_1 respectively.
- Only two of three threads can be active at a time. As both P_0 and P_1 are yet not completed, When P_2 tries to pick up forks, it is sent to sleep as *max* becomes -1.

Semaphores – Correct Solution

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- So, P_0 and P_1, will be able to pick up atleast one fork i.e. the uncommon forks.

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- So, P_0 and P_1, will be able to pick up atleast one fork i.e. the uncommon forks.
- Also, one of them will surely pick up the common fork between them f_1. So that thread will start eating.

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- So, P_0 and P_1, will be able to pick up atleast one fork i.e. the uncommon forks.
- Also, one of them will surely pick up the common fork between them f_1. So that thread will start eating.
- Eventually, it will finish and now the other thread will pick up f_1 and start eating .

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- So let's try the worst case, when each thread gets context switched just after picking up right fork, now the *max* semaphore comes into picture.
- P_0 and P_1 will get their right fork f_0, f_1 respectively.
- Only two of three threads can be active at a time. As both P_0 and P_1 are yet not completed, When P_2 tries to pick up forks, it is sent to sleep as *max* becomes -1.
- So, P_0 and P_1, will be able to pick up atleast one fork i.e. the uncommon forks.
- Also, one of them will surely pick up the common fork between them f_1. So that thread will start eating.
- Eventually, it will finish and now the other thread will pick up f_1 and start eating .
- Now, P_2 will be woken up and once the older thread finishes, P_2 will start eating.

Semaphores – Correct Solution

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- Due to *max*, at most $N-1$ threads have begun but there are N forks. So, by pigeonhole principle one thread (say P_i) will get two forks which will be done by `pick_up_forks`.

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- Due to *max*, at most $N - 1$ threads have begun but there are N forks. So, by pigeonhole principle one thread (say P_i) will get two forks which will be done by `pick_up_forks`.
- Semaphore variables, ensure that multiple threads can't access same fork at a time.

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Proof (continued).

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- So eventually P_i will start eating and finish eating.
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- So eventually P_i will finish and we will be left with one less thread.
- If one thread was able to finish when a total of k threads were active, then one thread can definitely finish when a total of $k - 1$ threads were active as we can always add a thread which does nothing.

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- So eventually P_i will start eating and finish eating.
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- If one thread was able to finish when a total of k threads were active, then one thread can definitely finish when a total of $k-1$ threads were active as we can always add a thread which does nothing.
- So, we have recursively shown that all threads will finish.

□

Condition Variables

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- For a condition variable `cv`,
  - When a thread calls `wait(cv)`, it is added to a list of waiting threads for `cv` and is blocked. This list is maintained for every condition variable.
  - When a thread calls `signal(cv)`, any one of blocked threads is woken up ('ready to run' again). There is no immediate context switch, it will be scheduled later.

Condition Variables – Focusing on Philosophers

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- Create N condition variables, one for each philosopher denoted by $c_i, i \in [N]$.
- Create N state variables, one for each philosopher denoted by $x_i = T$, where $i \in [N]$ and $x_i \in \{E, T\}$ denoting whether the philosopher is *E*ating or *T*hinking.
- Pseudocode:

```
function pick_up_forks(philosopher i){
    while (s_{right_p(i)} = E OR s_{left_p(i)} = E)
        wait(c_i)
    s_i = E
}
```

```
function put_down_forks(philosopher i){
    s_i = T
    if (s_{right_p(right_p(i)} = T)
        signal(c_{right_p(i)}
    if (s_{left_p(left_p(i)} = T)
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- Suppose, P_1 is context switched just before it can go to sleep. Also, same happens with P_2.
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- Now when P_0 completes eating it will execute `put_down_forks`, which changes its state back to thinking and sends the signal to wake up P_1 and P_2 using c_1 and c_2 respectively.
- Now, when P_1 and P_2 will come back they will execute the wait statement ignorant of the fact that P_0 is already completed
- So both P_1 and P_2, will go to eternal sleep, called a *missed wakeup* problem and a deadlock!

Condition Variables – Incorrect Solution

Example 2 – Race Condition

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- Now even if P_2 is scheduled next, it will remain in while loop and go to sleep as P_1 is eating. So P_0 comes back and changes its state to eating.
- The above will imply two neighbouring philosophers are eating simultaneously by using a common fork which should not happen, a *race condition*!

Condition Variables

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- Pseudocode:

```
function pick_up_forks(philosopher i){
    lock(mutex)
    while (s_{right_p(i)} = E OR s_{left_p(i)} = E)
        wait(c_i, mutex)
    s_i = E
    unlock(mutex)
}
```

```
function put_down_forks(philosopher i){
    lock(mutex)
    s_i = T
    if (s_{right_p(right_p(i)} = T)
        signal(c_{right_p(i)}
    if (s_{left_p(left_p(i)} = T)
        signal(c_{left_p(i)}
    unlock(mutex)
}
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- Suppose, P_1 is context switched just before it can go to sleep. Then as P_1 has not yet released the lock, P_0, P_2 will keep waiting for `put_down_forks` and `pick_up_forks` respectively.

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- If P_2 is scheduled earlier than P_0, then it will go to sleep eventually (directly or like in P_1).

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- When P_0 completes eating it will execute `put_down_forks` and acquire the lock then change its state back to thinking and signal P_1 and P_2 using c_1 and c_2 respectively.

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- When P_0 completes eating it will execute `put_down_forks` and acquire the lock then change its state back to thinking and signal P_1 and P_2 using c_1 and c_2 respectively.
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- Even if there are more random context switches P_1 will start eating first as P_2 will have to wait till the P_1 state changes back to thinking. So, P_1 will eventually finish.

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- Say for $N = 3$ case, the schedule is P_0, P_1, P_2
- P_0 executes `pick_up_forks` and first acquires the lock, as both its 'right and left philosopher' (P_2 and P_1) are thinking. So, P_0 exits while loop.

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- Say for $N = 3$ case, the schedule is P_0, P_1, P_2
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- Now, suppose P_0 gets context switched before P_0 changes its state to eating.

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- Now, suppose P_0 gets context switched before P_0 changes its state to eating.
- As P_0 still hasn’t released the lock, whichever thread is scheduled next (say P_1), it can’t acquire the lock in `pick_up_forks` and will be put to sleep.

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- As P_0 still hasn't released the lock, whichever thread is scheduled next (say P_1), it can't acquire the lock in `pick_up_forks` and will be put to sleep.
- If P_2 is scheduled earlier than P_0, then it will go to sleep eventually (directly or like in P_1).
- When P_0 comes back, it will change its state and release the lock and signal any one of neighbours (say P_1) to wake up. Also, P_0 can now start eating.

Condition Variables – Correct Solution

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Example (continued)

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- Now, P_1 will acquire lock but it will be put to sleep as P_0's state is eating. The lock is released only after ensuring that list of waiting processes contains P_1. Then P_1 goes to sleep.

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- When P_0 completes eating it will execute `put_down_forks` and acquire the lock then change its state back to thinking and signal P_1 and P_2 using c_1 and c_2 respectively.
- Now, whoever among P_1 and P_2 will come back first (say P_1) will reacquire lock and will release the lock only after changing its state and then it can start eating.
- Even if there are more random context switches P_1 will start eating first as P_2 will have to wait till the P_1 state changes back to thinking. So, P_1 will eventually finish.

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Example (continued)

- Now, P_1 will acquire lock but it will be put to sleep as P_0's state is eating. The lock is released only after ensuring that list of waiting processes contains P_1. Then P_1 goes to sleep.
- When P_0 completes eating it will execute `put_down_forks` and acquire the lock then change its state back to thinking and signal P_1 and P_2 using c_1 and c_2 respectively.
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- Now once P_i `pick_up_forks` starts execution, P_i will acquire a lock. So, even in the case of context switching its neighbours simply can't acquire lock in `pick_up_forks` until P_i completes `pick_up_forks`

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- Now once P_i `pick_up_forks` starts execution, P_i will acquire a lock. So, even in the case of context switching its neighbours simply can't acquire lock in `pick_up_forks` until P_i completes `pick_up_forks`
- Intuitively, we can be sure that the state changes only when both forks are available. Hence, multiple threads can't access same fork at a time.

□

Condition Variables – Correct Solution

Proof (continued).

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- So eventually P_i will start eating and finish eating.

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- So eventually P_i will start eating and finish eating.
- P_i will execute `put_down_forks` and change its state allowing its neighbours to get forks.

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- P_i will execute `put_down_forks` and change its state allowing its neighbours to get forks.
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Proof (continued).

- So eventually P_i will start eating and finish eating.
- P_i will execute `put_down_forks` and change its state allowing its neighbours to get forks.
- If one thread was able to finish when a total of k threads were active, then one thread can definitely finish when a total of $k-1$ threads were active since we can always add a thread which does nothing.
- So, we have recursively shown that all threads will finish.

□

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