Lecture 9: Deadlock

601.418/618 Operating Systems

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Agenda

- Deadlocks
- Dining philosopher's problem
- Resource allocation graphs
- Preventing or mitigating deadlocks

Acknowledgments: These slides are shamelessly adapted from Prof. Ryan Huang's Fall 2022 slides, which in turn are based on Prof. David Mazières's OS lecture notes.

Deadlock

Synchronization is a live gun

- We can easily shoot ourselves in the foot
- Incorrect use of synchronization can block all processes
- You have likely been intuitively avoiding this situation already

If one process tries to access a resource that a second process holds, and vice-versa, they can never make progress

We call this situation *deadlock*, and we'll look at:

- Definition and conditions necessary for deadlock
- Representation of deadlock conditions
- Approaches to dealing with deadlock

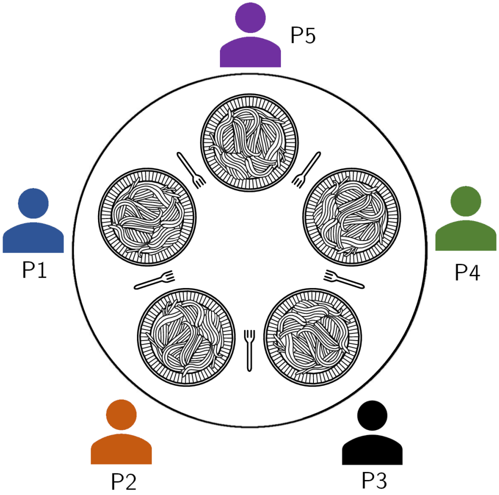
Dining Philosophers Problem

Philosophers spend their lives alternating thinking and eating

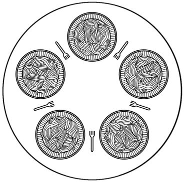
Don't interact with neighbors, occasionally eat

- Need 2 forks to eat
- Release both when done

Can only pick up 1 fork at a time



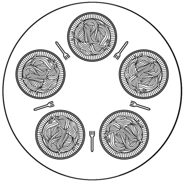
Philosophers in Code (1)



```
#define N 5 /* number of philosophers */

void philosopher(int i)     /* i: philosopher id, 0 to 4 */
{
  while (true) {
    think();                /* philosopher is thinking */
    take_fork(i);           /* take left fork */
    take_fork((i + 1) % N); /* take right fork */
    eat();                  /* yum-yum, spaghetti */
    put_fork(i);            /* put left fork back on the table */
    put_fork((i + 1) % N);  /* put right fork back on the table */
  }
}
```

Philosophers in Code (2)



```
semaphore forks[N]; /* semaphores for each fork,
                       each initialized to 1 (omitted) */
void take_fork(int i)
{
  forks[i].P(); /* wait for ith fork's semaphore */
}

void put_fork(int i)
{
  forks[i].V(); /* signal ith fork's semaphore */
}
```

What is a problem with this algorithm?

How to Avoid Deadlock Here?

Multiple solutions exist

Simple one: allow at most 4 philosophers to sit simultaneously at the table

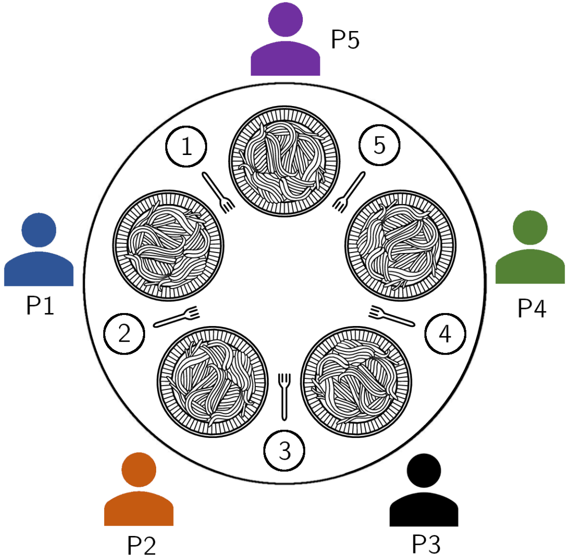
- With 5 forks for 4 philosophers, at all times one philosopher is guaranteed to be able to pick up both forks

Another solution: define a partial order for resources (forks)

- Number the forks
- Philosopher must always pick up lower-numbered fork first and then higher-numbered fork
- **What happens if the four lowest-numbered philosophers all pick up their lower-numbered fork?**
- Disadvantage
  - Not always practical, when the complete list of all resources is not known in advance

Third solution: all or none each time

Resource Ordering



2nd Attempt at Dining Philosopher Problem

```
#define N 5                                 /* number of philosophers */
#define LEFT (i+N-1) % N                    /* i's left neighbor */
#define RIGHT (i+1) % N                     /* i's right neighbor */
enum State {THINKING, HUNGRY, EATING}; /* a philosopher's status */
enum State states[N];   /* keep track of each philosopher's status */
semaphore mutex = 1;    /* mutual exclusion for critical section */
semaphore phis[N];      /* semaphore for each philosopher, init to 0 */

void philosopher(int i) /* i: philosopher id, 0 to N-1 */
{
  while (true) {
    think();            /* philosopher is thinking */
    take_forks(i);      /* take both forks */
    eat();              /* yum-yum, spaghetti */
    put_forks(i);       /* put both forks */
  }
}
```

2nd Attempt at Dining Philosopher Problem

```
void take_forks(int i) /* i: philosopher id, 0 to N-1 */
{
  mutex.P();       /* enter critical section */
  states[i] = HUNGRY; /* indicate philosopher is hungry */
  test(i);         /* try to acquire two forks */
  mutex.V();       /* exit critical section */
  phis[i].P();     /* block if forks not acquired */
}
void put_forks(int i) /* i: philosopher id, 0 to N-1 */
{
  mutex.P();       /* enter critical section */
  states[i] = THINKING; /* indicate i finished eating */
  test(LEFT);      /* see if left neighbor can eat now */
  test(RIGHT);     /* see if right neighbor can eat now */
  mutex.V();       /* exit critical section */
}
```

```
/* i: philosopher id, 0 to N-1 */
void test(int i)
{
  if (states[i] == HUNGRY &&
      states[LEFT] != EATING &&
      states[RIGHT] != EATING) {
    /* philosopher i can eat now */
    states[i] = EATING;
    /* signal i to proceed */
    phis[i].V();
  }
}
```

Notes for the 2nd Attempt Solution

What is the purpose of the `states` array?

- . . . given that already have the semaphore array?
- A semaphore doesn't have operations for checking its value!

What if we don't use the `mutex` semaphore?

Why is the semaphore array for each philosopher?

- Our first attempt uses semaphore array for each *fork*

What if we put `phis[i].P();` inside the critical section?

What if we don't call `test()` twice in `put_forks()`?

Deadlock Definition

Deadlock is a problem that can arise:

- When processes compete for access to limited resources
- When processes are incorrectly synchronized

Definition:

- Deadlock exists among a set of processes if every process is waiting for an event that can be caused only by another process in the set.

Deadlock Example

```c
mutex_t m1, m2;

void p1(void *ignored) {
  lock(m1);
  lock(m2);
  /* critical section */
  unlock(m2);
  unlock(m1);
}

void p2(void *ignored) {
  lock(m2);
  lock(m1);
  /* critical section */
  unlock(m1);
  unlock(m2);
}
```

Deadlock Example

```
mutex_t m1, m2;

void p1(void *ignored) {
  lock(m1);
  lock(m2);  /* <----- here */
  /* critical section */
  unlock(m2);
  unlock(m1);
}

void p2(void *ignored) {
  lock(m2);
  lock(m1);  /* <----- here */
  /* critical section */
  unlock(m1);
  unlock(m2);
}
```

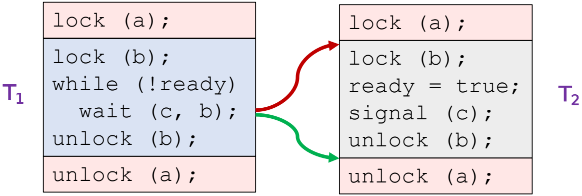
Deadlock Example

Can you have deadlock w/o mutexes?

Same problem with condition variables

- Suppose resource 1 managed by c_1, resource 2 by c_2
- A has 1, waits on c_2, B has 2, waits on c_1

Or w/ combined mutex/condition variable (tricky)



T_1

```
lock (a);
lock (b);
while (!ready)
  wait (c, b);
unlock (b);
unlock (a);
```

T_2

```
lock (a);
lock (b);
ready = true;
signal (c);
unlock (b);
unlock (a);
```

Deadlock Example

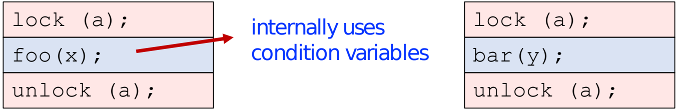
Can you have deadlock w/o mutexes?

Same problem with condition variables

- Suppose resource 1 managed by c_1, resource 2 by c_2
- A has 1, waits on c_2, B has 2, waits on c_1

Or w/ combined mutex/condition variable (tricky)

Lesson: dangerous to hold locks when crossing boundaries!

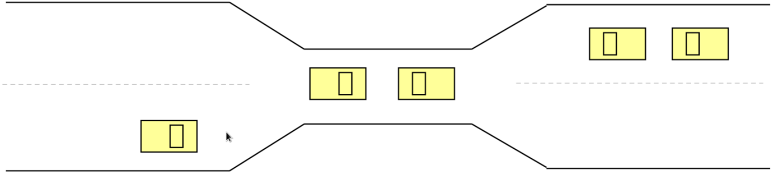


```
lock (a);
foo(x);
unlock (a);
```

internally uses condition variables

```
lock (a);
bar(y);
unlock (a);
```

Deadlocks Without Computers



Real issue is resources and how required

E.g., bridge only allows traffic in one direction

- Each section of a bridge can be viewed as a resource
- If a deadlock occurs, it can be resolved if one car backs up (preempt resources and rollback)
- Several cars may have to be backed up if a deadlock occurs
- Starvation is possible

Conditions for Deadlock

1. *Mutual exclusion*: At least one resource must be held in a non-sharable mode
2. *Hold and wait*: There must be one process holding one resource and waiting for another resource
3. *No preemption*: Resources cannot be preempted (critical sections cannot be aborted externally)
4. *Circular wait*: There must exist a set of processes $\{P_1, P_2, P_3, \ldots, P_n\}$ such that P_1 is waiting for P_2, P_2 for P_3, etc.

All of 1–4 necessary for deadlock to occur

Two approaches to dealing with deadlock:

- Pro-active: prevention
- Reactive: detection + corrective action

Prevent by Eliminating One Condition

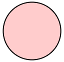
1. Mutual exclusion
    - Buy more resources, split into pieces, or virtualize to make "infinite" copies
    - Threads: threads have copy of registers = no lock
2. Hold and wait
    - Wait on all resources at once (must know in advance)
3. No preemption
    - Physical memory: virtualized with VM, can take physical page away and give to another process!
4. **Circular wait**
    - Single lock for entire system: (problems?)
    - Partial ordering of resources (next)

Resource Allocation Graph

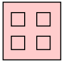
View system as graph

- Processes and Resources are nodes
- Resource Requests and Assignments are edges

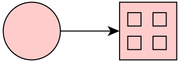
Process:



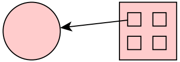
Resource with 4 instances:



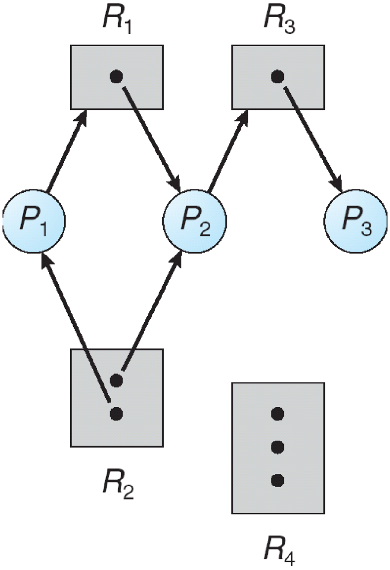
P_i requesting R_j:



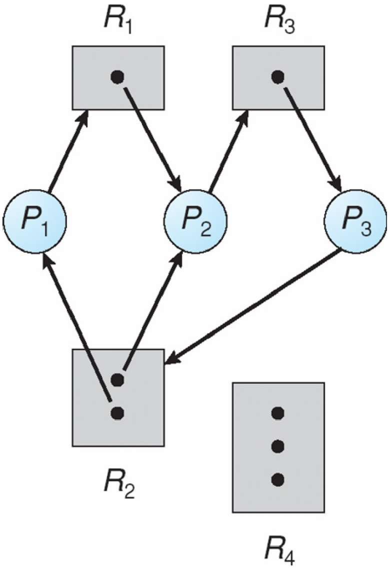
P_i holding instance of R_j:



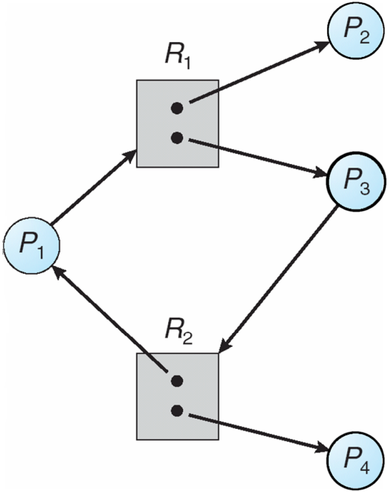
Example Resource Allocation Graph



Resource Allocation Graph with Deadlock

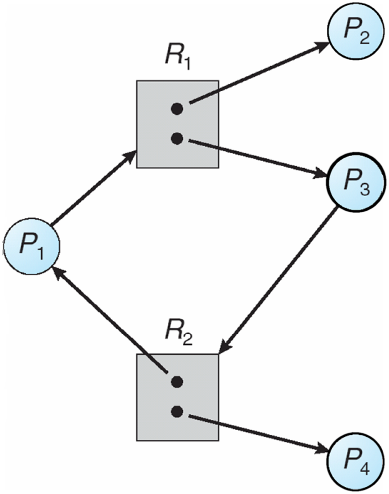


Is This Deadlock?

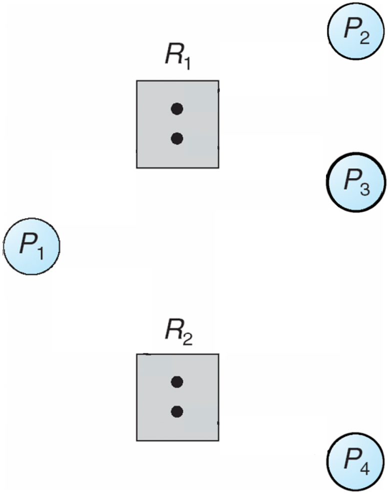


Is This Deadlock?

Before:



After:



Cycles and Deadlock

If graph has no cycles $\implies$ no deadlock

If graph contains a cycle

- Definitely deadlock if only one instance per resource
    - "waits-for graph" (WFG)
- Otherwise, *maybe* deadlock, maybe not

Prevent deadlock with partial order on resources

- E.g., always acquire mutex m_1 before m_2
- Usually design locking discipline for application this way

Dealing With Deadlock

There are four approaches for dealing with deadlock:

- *Ignore it* – how lucky do you feel?
- *Prevention* – make it impossible for deadlock to happen
- *Avoidance* – control allocation of resources
- *Detection and Recovery* – look for a cycle in dependencies

Deadlock Avoidance

Avoidance

- Provide information in advance about what resources will be needed by processes to guarantee that deadlock will not happen
- System only grants resource requests if it knows that the process can obtain all resources it needs in future requests
- Avoids circularities (wait dependencies)

Tough

- Hard to determine all resources needed in advance
- Good theoretical problem, not as practical to use

Banker's Algorithm

The Banker's Algorithm is the classic approach to deadlock avoidance for resources with multiple units

1. Assign a *credit limit* to each customer (process)
    - Maximum credit claim must be stated in advance
2. Reject any request that leads to a *dangerous state*
    - A dangerous state is one where a sudden request by any customer for the full credit limit could lead to deadlock
    - A recursive reduction procedure recognizes dangerous states
3. In practice, the system must keep resource usage well below capacity to maintain a *resource surplus*
    - Rarely used in practice due to low resource utilization

Detection and Recovery

Detection and recovery

- If we don't have deadlock prevention or avoidance, then deadlock may occur
- In this case, we need to detect deadlock and recover from it

To do this, we need two algorithms

- One to determine whether a deadlock has occurred
- Another to recover from the deadlock

Possible, but expensive (time consuming)

- Implemented in VMS
- Run detection algorithm when resource request times out

VAX 11/780

Deadlock Detection

Detection

- Traverse the resource graph looking for cycles
- If a cycle is found, preempt resource (force a process to release)

Expensive

- Many processes and resources to traverse

Only invoke detection algorithm depending on

- How often or likely deadlock is
- How many processes are likely to be affected when it occurs

Deadlock Recovery

Once a deadlock is detected, we have two options...

1. Abort processes
    - Abort all deadlocked processes
        - Processes need to start over again
    - Abort one process at a time until cycle is eliminated
        - System needs to rerun detection after each abort
2. Preempt resources (force their release)
    - Need to select process and resource to preempt
    - Need to rollback process to previous state
    - Need to prevent starvation

Deadlock Summary

Deadlock occurs when processes are waiting on each other and cannot make progress

- Cycles in Resource Allocation Graph (RAG)

Deadlock requires four conditions

- Mutual exclusion, hold and wait, no resource preemption, circular wait

Four approaches to dealing with deadlock:

- *Ignore it* – Living life on the edge
- *Prevention* – Make one of the four conditions impossible
- *Avoidance* – Banker's Algorithm (control allocation)
- *Detection and Recovery* – Look for a cycle, preempt or abort