DM510: Deadlocks

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Disclaimer

These slides contain (modified) content and media from the official Operating System Concepts slides: https://www.os-book.com/OS10/slide-dir/index.html

Today's lecture

- Chapter 8 of course book

The Problem

Example: dining philosophers

- 5 philosophers alternatingly think and eat
- To eat they need to pick up their left and right chopstick (one at a time)
- Chopsticks (implemented as mutexes) are shared with the neighbors

```
/* Algorithm for philosopher i */
while (true) {
        aquire(&chopstick[i]);
        aquire(&chopstick[(i+1)%5]);
        eat();
        release(&chopstick[i]);
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        think();
}
```

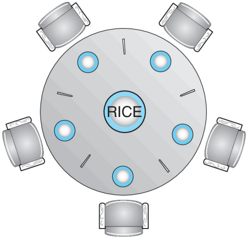

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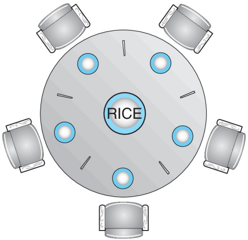


Deadlock

If each philosopher grabs the left chopstick before their neighbor grabs the right one, then they are stuck in a **deadlock**!

Formal model

- Deadlocks can occur with mutexes (last lecture), files, limited resources, etc.
- Since the problem is the same, we consider it in the following abstract model

Resources

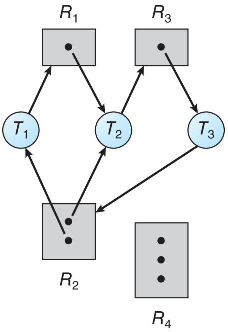
- $R_1, R_2, \ldots, R_m$: resources with one or more **instances**
- **Mutual exclusion:** only one thread can hold the same instance at a time

Threads

- $T_1, T_2, \ldots, T_n$: threads of the system

Edges

- **request edge:** from thread to resource
- **assignment edge:** from resource instance to thread

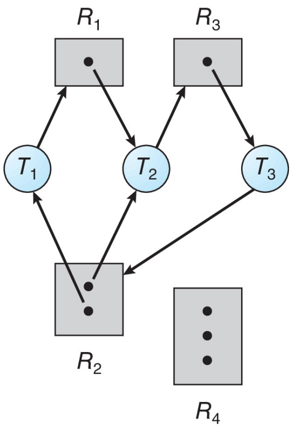


Deadlock characterization

Conditions for deadlock

- **Mutual exclusion** resource instances are held by one thread at a time
- **Hold and wait:** thread holding one resource instance waits for other resources
- **No preemption:** a resource can only be released voluntarily
- **Circular wait:** Threads $T_1, \ldots, T_n$ such that T_i waits for a resource that T_{i+1} (or T_1 if $i = 1$) holds for each $i = 1, 2, \ldots, n$.

- Conditions necessary (no cycle $\Rightarrow$ no deadlock)



Cycle with deadlock

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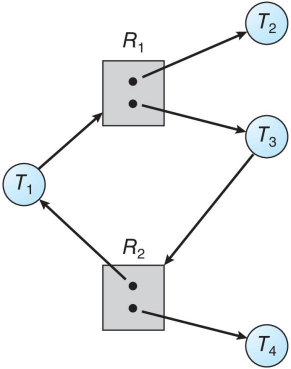

Cycle without deadlock

- Conditions necessary (no cycle $\Rightarrow$ no deadlock)
- But not sufficient (cycle $\Rightarrow$ maybe deadlock)

Handling deadlocks

- Ensure that system **never** enters deadlock state by **deadlock prevention** or **deadlock avoidance**
- Allow system to enter deadlock state and recover
- Ignore that there can be deadlocks

Deadlock Prevention

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It is enough to remove one of the four necessary conditions for a deadlock

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Hold and wait

- Make threads request all resources before execution
- Make threads request resources only when none are allocated
- **Disadvantages of the above:** lower resource utilization, possible starvation

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- Thread waiting for some resource releases the ones it is currently holding
- Thread is woken up once the new resource and the previously released ones are allocated to it

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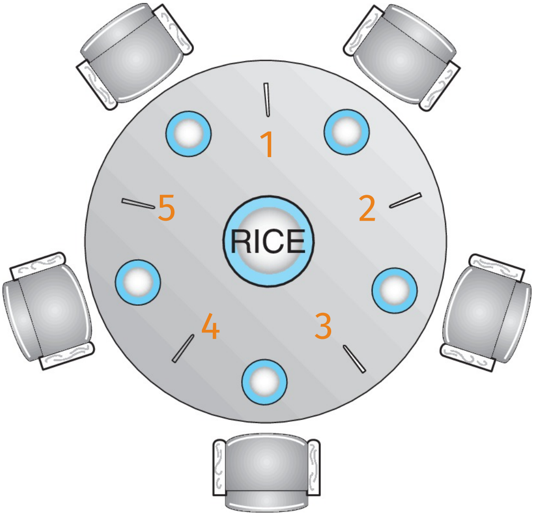
Circular wait

- Define total order on resources and require threads to request resources in that order

Example: total order



Solution for dining philosophers

```
/* philosopher i=1,2,3,4 */
while (true) {
        aquire(&chopstick[i]);
        aquire(&chopstick[i+1]);
        eat();
        release(&chopstick[i]);
        release(&chopstick[i+1]);
        think();
}
/* for philosopher 5 */
while (true) {
        aquire(&chopstick[1]);
        aquire(&chopstick[5]);
        eat();
        release(&chopstick[1]);
        release(&chopstick[5]);
        think();
}
```

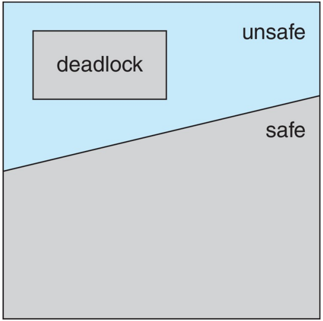
Deadlock Avoidance

Approach

- **Assumption:** we know the resources (and maximum no. instances) a thread can request and no new threads arrive
- Algorithm grants requested resources to threads in such a way that unsafe state (= potential deadlock) never reached

Safe state

- Threads can be reordered as $(T_1, T_2, \ldots, T_n)$ such that for each thread T_i the resource that $T_1, T_2, \ldots, T_{i-1}$ hold suffice to satisfy T_i's additional resource need
- No deadlock because T_1 does not wait; once T_1 is done, T_2 does not wait; once T_1, T_2 are done, T_3 does not wait; etc.



Detecting (un-)safe states

Input

- **avail** $\in \mathbb{Z}^m_{\geq 0}$: no. instances of resource not allocated
- **max** $\in \mathbb{Z}^{n \times m}_{\geq 0}$: maximum no. instances of resource a thread might request
- **alloc** $\in \mathbb{Z}^{n \times m}_{\geq 0}$: no. instances of resource allocated to thread

Safe state detection

1. initialize work $\in \mathbb{Z}^m_{\geq 0}$ with
$$\text{work}[j] = \text{avail}[j]$$
2. initialize need $\in \mathbb{Z}^{n \times m}_{\geq 0}$ with
$$\text{need}[i, j] = \max[i, j] - \text{alloc}[i, j]$$
3. initialize finish $\in \mathbb{Z}^n_{\geq 0}$ with
$$\text{finish}[i] = \text{false}$$
4. while true
   - 4.1 let $i \in \{1, 2, \ldots, n\}$ with
   $$\text{finish}[i] = \text{false} \text{ and}$$
   $$\text{need}[i, j] \leq \text{work}[j] \ \forall j$$
   - 4.2 if no such i exists: break
   - 4.3 $\text{finish}[i] \leftarrow \text{true}$
   - 4.4 for $j \in \{1, 2, \ldots, m\}$:
   $\text{work}[j] \leftarrow \text{work}[j] + \text{alloc}[i, j]$
5. **Result:** if $\text{finish}[i] = \text{false}$ for some thread T_i then state is unsafe, otherwise safe

Banker's algorithm for deadlock avoidance

- Banker's algorithm tests if request by a thread T_i can be granted
- If T_i has to wait, try again after resources have been released

Input

- **avail** $\in \mathbb{Z}^m_{\geq 0}$: no. instances of resource not allocated
- **max** $\in \mathbb{Z}^{n \times m}_{\geq 0}$: maximum no. instances of resource a thread might request
- **alloc** $\in \mathbb{Z}^{n \times m}_{\geq 0}$: no. instances of resource allocated to thread
- Thread T_i and request **req** $\in \mathbb{Z}^m_{\geq 0}$ for additional resources

Banker's algorithm

1. if $\mathrm{req}[j] > \max[i, j]$ for some j: raise runtime error
2. if $\mathrm{req}[j] > \mathrm{avail}[j]$ for some j: make T_i wait
3. store current state in S
4. for each resource R_j:
   /* *give requested resources to* T_i */

   $$\mathrm{avail}[j] \leftarrow \mathrm{avail}[j] - \mathrm{req}[j]$$

   $$\mathrm{alloc}[i, j] \leftarrow \mathrm{alloc}[i, j] + \mathrm{req}[j]$$

5. if unsafe state detected: restore state S and make T_i wait

Deadlock Recovery

Deadlock detection

Input

- **avail** $\in \mathbb{Z}^{m}_{\geq 0}$: no. instances of resource not allocated
- **alloc** $\in \mathbb{Z}^{n\times m}_{\geq 0}$: no. instances of resource allocated to a thread
- **req** $\in \mathbb{Z}^{n\times m}_{\geq 0}$: no. additional instances of resource requested by a thread

- Periodically check for deadlock
- Algorithm (right) requires $O(mn^2)$ operations

Algorithm

1. let work $\in \mathbb{Z}^{m}_{\geq 0}$ with
   $$\mathrm{work}[j] = \mathrm{avail}[j]$$
2. let finish $\in \mathbb{Z}^{n}_{\geq 0}$ with
   $$\mathrm{finish}[i] = \begin{cases} \mathrm{true} & \text{if } \mathrm{alloc}[i,j] = 0\ \forall j \\ \mathrm{false} & \text{otherwise.} \end{cases}$$
3. while true
   - 3.1 let $i \in \{1, 2, \ldots, n\}$ with
     $$\mathrm{finish}[i] = \mathrm{false} \text{ and}$$
     $$\mathrm{req}[i,j] \leq \mathrm{work}[j]\ \forall j$$
   - 3.2 if no such i exists: break
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   - 3.4 for $j \in \{1, 2, \ldots, m\}$:
     $\mathrm{work}[j] \leftarrow \mathrm{work}[j] + \mathrm{alloc}[i,j]$
4. **Result:** every thread i with $\mathrm{finish}[i] = \mathrm{false}$ is in deadlock

Recovering: process termination

Terminate threads (processes) to remove deadlock. Variants:

- Abort all threads (processes) in a deadlock
- Abort one thread (process) at a time until deadlock is removed. In which order? Examples:
  - By priority
  - By how long the thread has been computing or how much longer it needs
  - By resource usage
  - By resource requirements to complete
  - By number of threads that need to be terminated

Recovering: resource preemption

- pick a victim thread
- roll back thread to safe state and restart from there
- can lead to **starvation** if same thread is picked over and over again, to avoid: include number of times picked in victim selection