CS 153
Design of Operating Systems

Fall 20

Lecture 14: Deadlock

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Deadlock — the deadly embrace!

- Synchronization – 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
- Consider: threads that use multiple critical sections/need different resources
  - If one thread tries to access a resource that a second thread 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

Deadlock Definition

- Deadlock is a problem that can arise:
  - When threads/processes compete for access to limited resources
  - When threads/processes are incorrectly synchronized
- Definition:
  - Deadlock exists among a set of threads if every thread is waiting for an event that can be caused only by another thread in the set

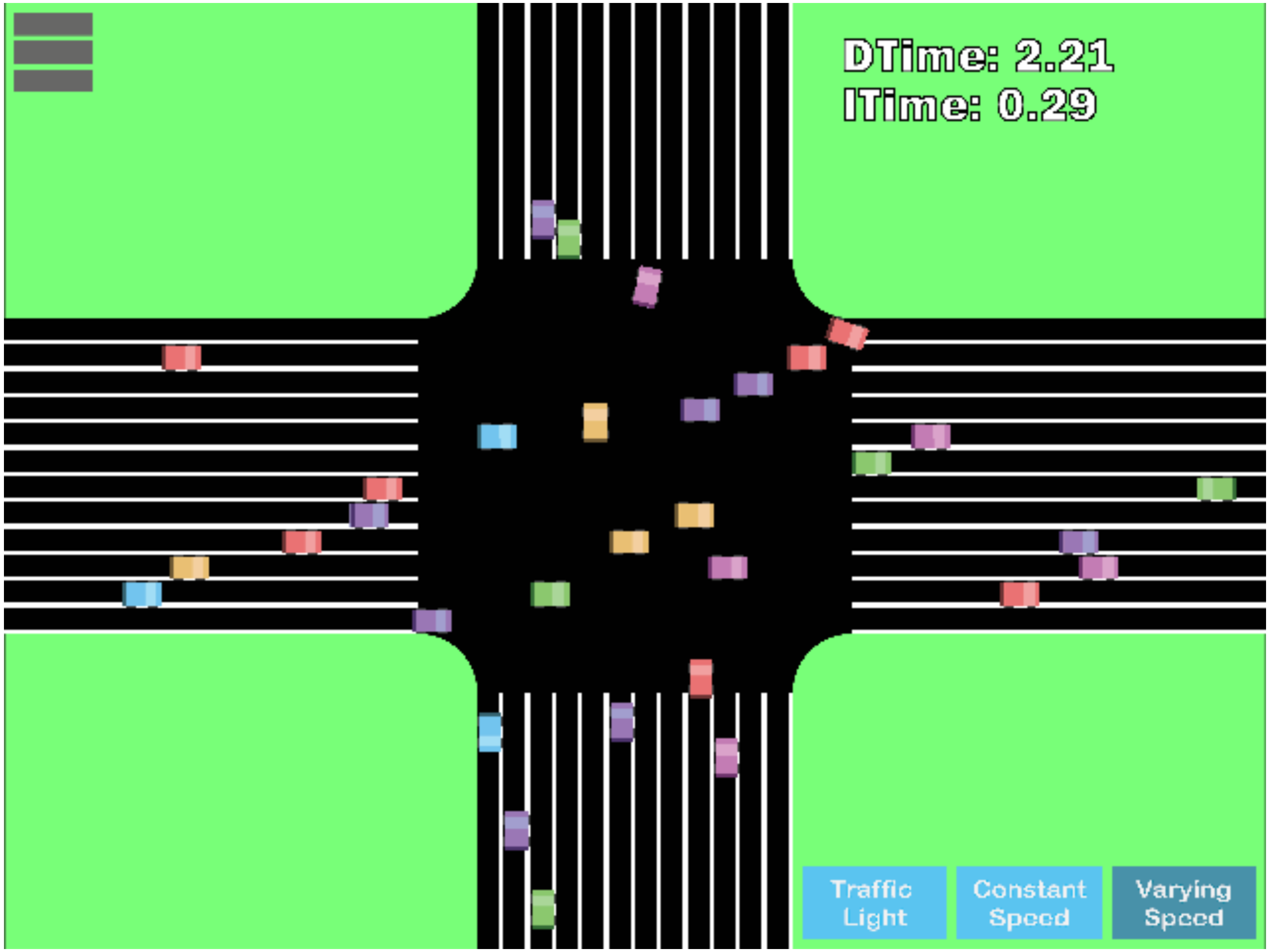
Thread 1

```
lockA->Acquire();
…
lockB->Acquire();
```

Thread 2

```
lockB->Acquire();
…
lockA->Acquire();
```

Real example!

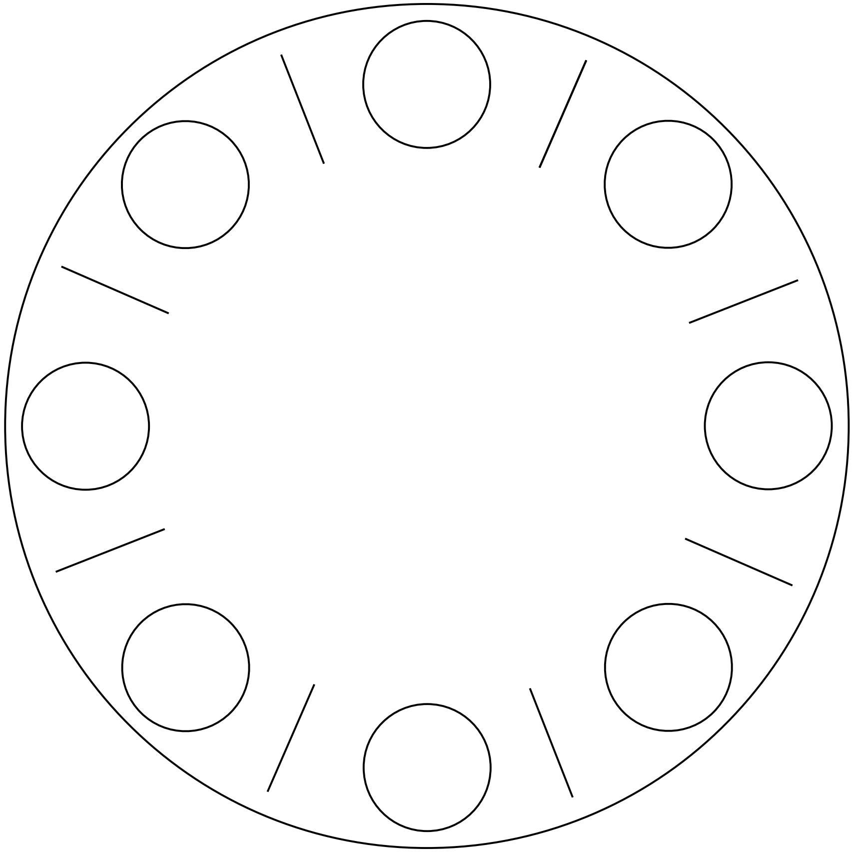


Real example!

Conditions for Deadlock

- Deadlock can exist if and only if the following four conditions hold **simultaneously**:
  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 threads [T_1, T_2, T_3,…,T_n] such that T_1 is waiting for T_2, T_2 for T_3, etc.

Dining Lawyers

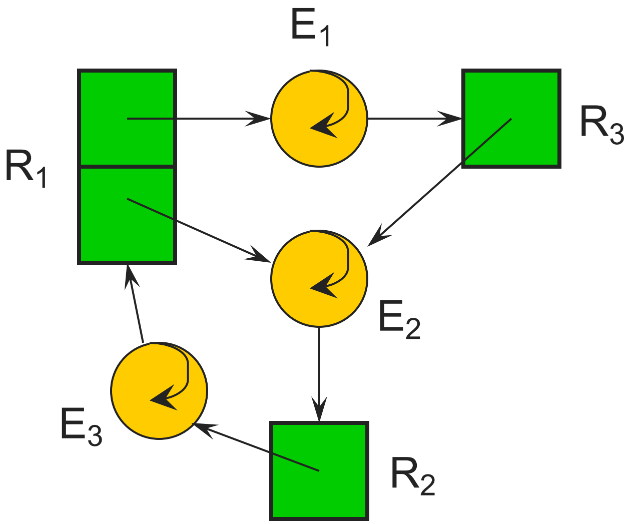


Each lawyer needs two chopsticks to eat.
Each grabs chopstick on the right first.

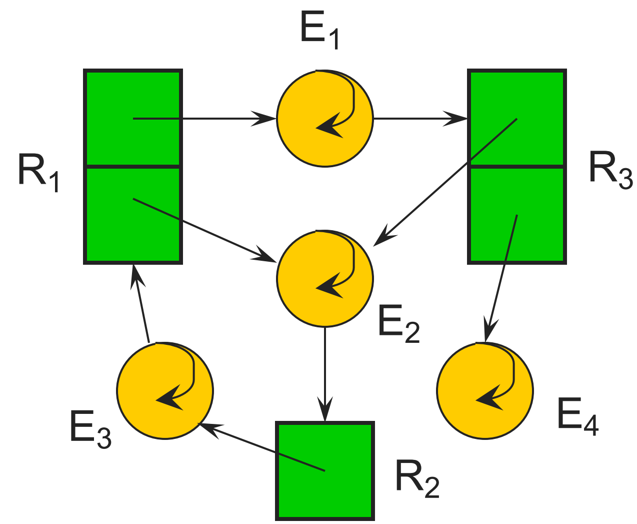
Let's get formal for a minute

- Deadlock can be described using a resource allocation graph (RAG)
- The RAG consists of a set of vertices $E=\{E_1, E_2, \ldots, E_n\}$ of entities and $R=\{R_1, R_2, \ldots, R_m\}$ of resources
  - A directed edge from a entity to a resource, $E_i \rightarrow R_i$, means that E_i has requested R_j
  - A directed edge from a resource to a entity, $R_i \rightarrow E_i$, means that R_j has been allocated to E_i
  - Each resource has a fixed number of units
- If the graph has no cycles, deadlock cannot exist
- If the graph has a cycle, deadlock may exist

RAG Example



A cycle…and deadlock!



Same cycle…but no deadlock. Why?

A Simpler Way

- If all resources are single unit and all processes make single requests, then we can represent the resource state with a simpler waits-for graph (WFG)
- The WFG consists of a set of vertices $E=\{E_1, E_2, \ldots, E_n\}$ of entities
  - A directed edge $E_i \rightarrow E_j$ means that E_i has requested a resource that E_j currently holds
- If the graph has no cycles, deadlock cannot exist
- If the graph has a cycle, deadlock exists

In Practice

- Resources are usually synchronization primitives
  - Locks, semaphores, …
- Entities are usually threads, but could also be processes

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 Prevention

- Prevention – Ensure that at least one of the necessary conditions cannot happen
  - Mutual exclusion
    - Make resources sharable (not generally practical)
  - Hold and wait
    - Process/thread cannot hold one resource when requesting another
  - Preemption
    - OS can preempt resource (costly)
  - Circular wait
    - Impose an ordering (numbering) on the resources and request them in order (popular implementation technique)

Deadlock Prevention

- One shot allocation: ask for all your resources in one shot; no more resources can be requested
  - What ingredient does this prevent?
  - Comments?
- Preemption
  - Nice: Give up a resource if what you want is not available
  - Aggressive: steal a resource if what you want is not available
- Hierarchical allocation:
  - Assign resources to classes
  - Can only ask for resources from a higher number class than what you hold now

Deadlock Avoidance

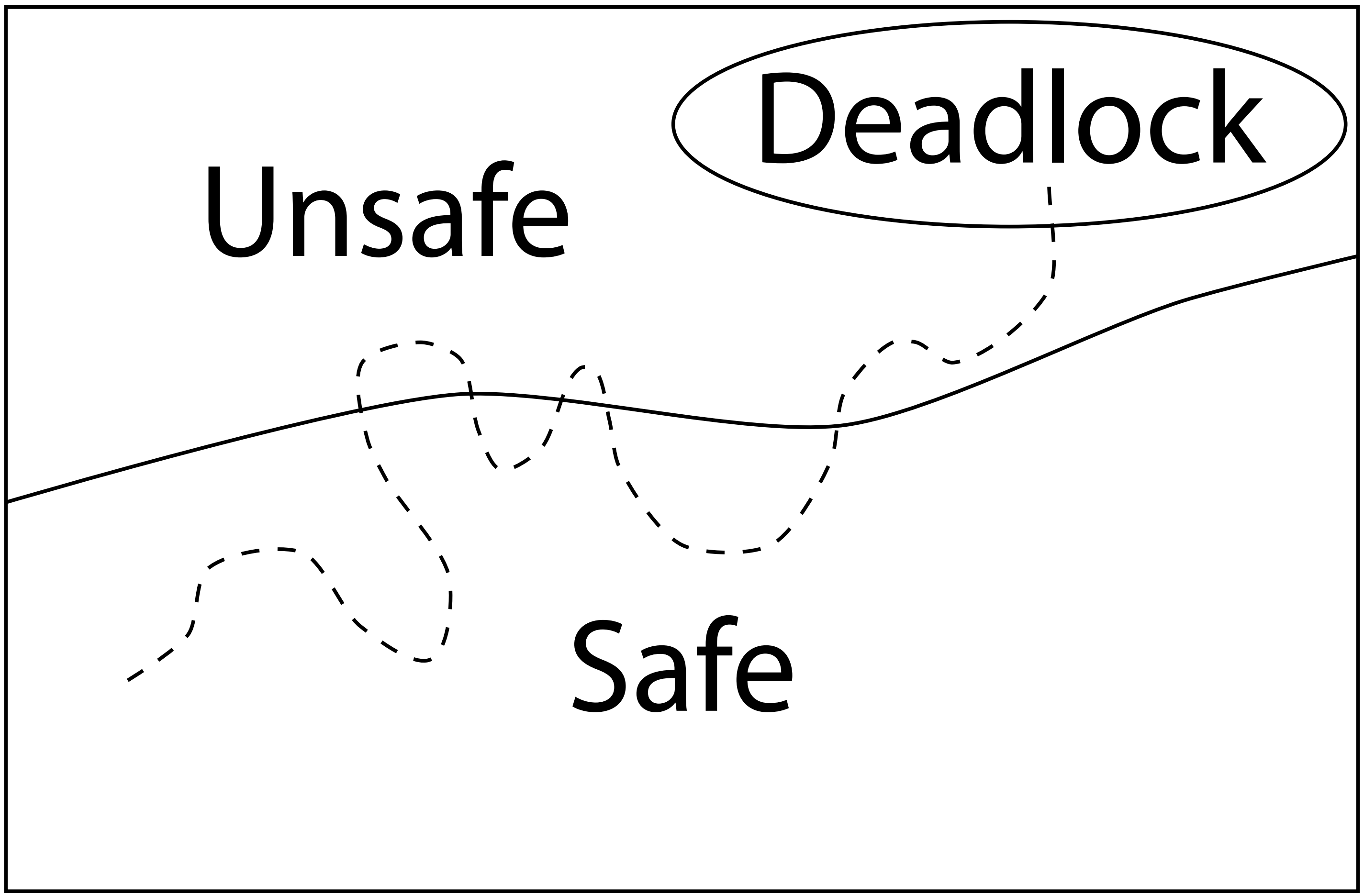
- Prevention can be too conservative – can we do better?
- Avoidance
  - Provide information in advance about what resources will be needed by processes
  - System only grants resource requests if it knows that deadlock cannot happen
  - Avoids circular dependencies
- Tough
  - Hard to determine all resources needed in advance
  - Good theoretical problem, not as practical to use

Banker's Algorithm

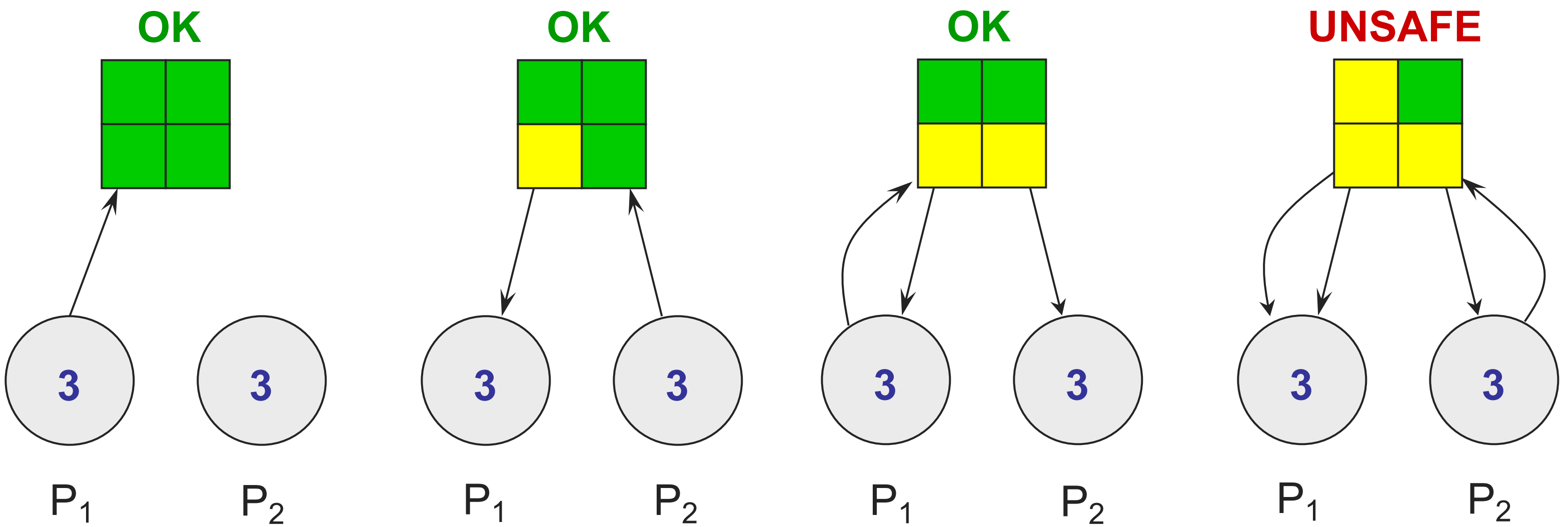
- The Banker's Algorithm is the classic approach to deadlock avoidance for resources with multiple units

  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

Possible System States



Banker's Algorithm Simplified



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

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 threads/processes are waiting on each other and cannot make progress
  - Cycles in Wait For Graph (WFG)
- 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