CS 3214

Deadlock:

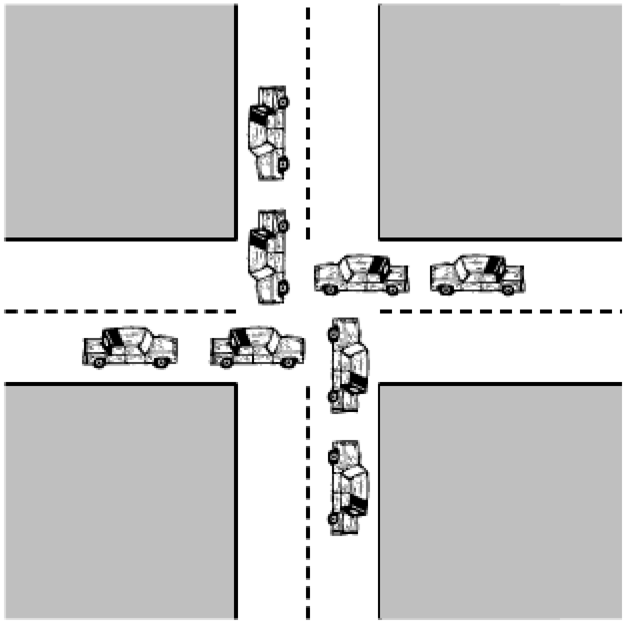
Definition, Detection, Prevention and Avoidance

Notes

- Slide set is from core OS class
  - Provided as background
  - This level of depth is not necessarily expected in this class
- But must be familiar with (have heard of) basic principles such as Coffman's conditions, and need to have a general understanding of deadlock

Deadlock (Definition)

- A situation in which two or more threads or processes are blocked and cannot proceed
- "blocked" either on a resource request that can't be granted, or waiting for an event that won't occur
  - Possible causes: resource-related or communication-related
- Cannot easily back out

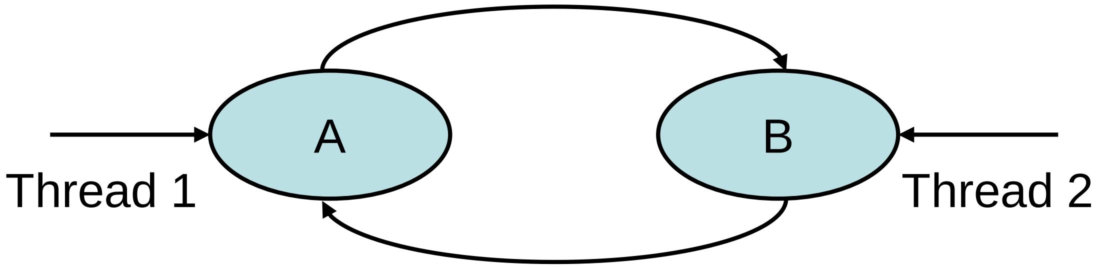


(b) Deadlock

Deadlock Canonical Example (1)

```
pthread_mutex_t A;
pthread_mutex_t B;
…
pthread_mutex_lock(&A);
pthread_mutex_lock(&B);
…
pthread_mutex_unlock(&B);
pthread_mutex_unlock(&A);
```

```
pthread_mutex_lock(&B);
pthread_mutex_lock(&A);
…
pthread_mutex_unlock(&A);
pthread_mutex_unlock(&B);
```



Canonical Example (2)

```
account acc1(10000, "acc1");
account acc2(10000, "acc2");

// Thread 1:
 for (int i = 0; i < 100000; i++)
      acc2.transferTo(&acc1, 20);
// Thread 2:
 for (int i = 0; i < 100000; i++)
      acc1.transferTo(&acc2, 20);
```

```
class account {
  pthread_mutex_t lock; // protects balance
  int balance;  const char *name;
public:
  account(int balance, const char *name) :
   balance(balance), name(name)  { pthread_mutex_init(&this->lock, NULL); }
  void transferTo(account *that, int amount) {
    pthread_mutex_lock(&this->lock);
    pthread_mutex_lock(&that->lock);
    cout << "Transferring $" << amount << " from "
         << this->name << " to " << that->name << endl;
    this->balance -= amount;
    that->balance += amount;
    pthread_mutex_unlock(&that->lock);
    pthread_mutex_unlock(&this->lock);
  }
};
```

Q.: How to fix?

Canonical Example (2, cont'd)

- Answer: acquire locks in same order

```
void transferTo(account *that, int amount) {
  if (this < that) {
        pthread_mutex_lock(&this->lock);
        pthread_mutex_lock(&that->lock);
  } else {
        pthread_mutex_lock(&that->lock);
        pthread_mutex_lock(&this->lock);
  }
  /* rest of function */
}
```

Reusable vs. Consumable Resources

- Distinguish two types of resources when discussing deadlock
- A resource:
  - “anything a process needs to make progress”
  - But must be something that can be counted in units
- (Serially) Reusable resources (*static, concrete, finite*)
  - CPU, memory, locks
  - Can be a single unit (CPU on uniprocessor, lock), or multiple units (e.g. memory, semaphore initialized with N)
- Consumable resources (*dynamic, abstract, infinite*)
  - Can be created & consumed: messages, signals
- Deadlock may involve reusable resources or consumable resources

Consumable Resources & Deadlock

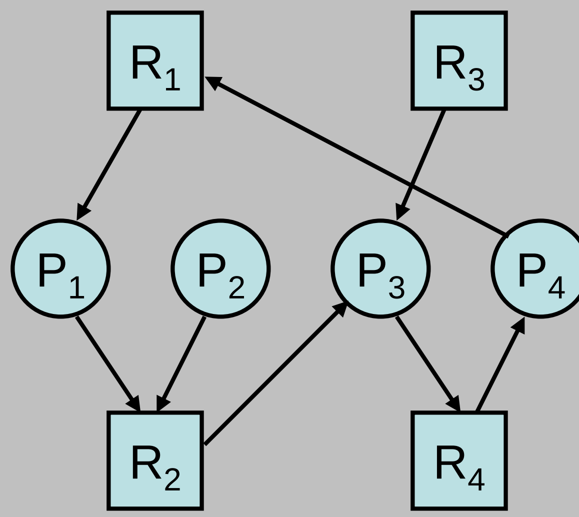
```
void client() {
    for (i = 0; i < 10; i++)
      send(request[i]);
    for (i = 0; i < 10; i++) {
      receive (reply[i]);
      send(ack);
    }
}
```

```
void server() {
    while (true) {
      receive(request);
      process(request);
      send(reply);
      receive(ack);
    }
}
```

- Assume client & server communicate using 2 bounded buffers (one for each direction)
  - Real-life example: flow-controlled TCP
- Q.: Under what circumstances does this code deadlock?

Deadlocks, more formally

- 4 necessary conditions
  1) Exclusive Access
  2) Hold and Wait
  3) No Preemption
  4) Circular Wait
- Aka Coffman conditions
  - Note that cond 1-3 represen normally desirable or requir
- Will look at strategies to
  - Detect & break deadlocks
  - Prevent
  - Avoid

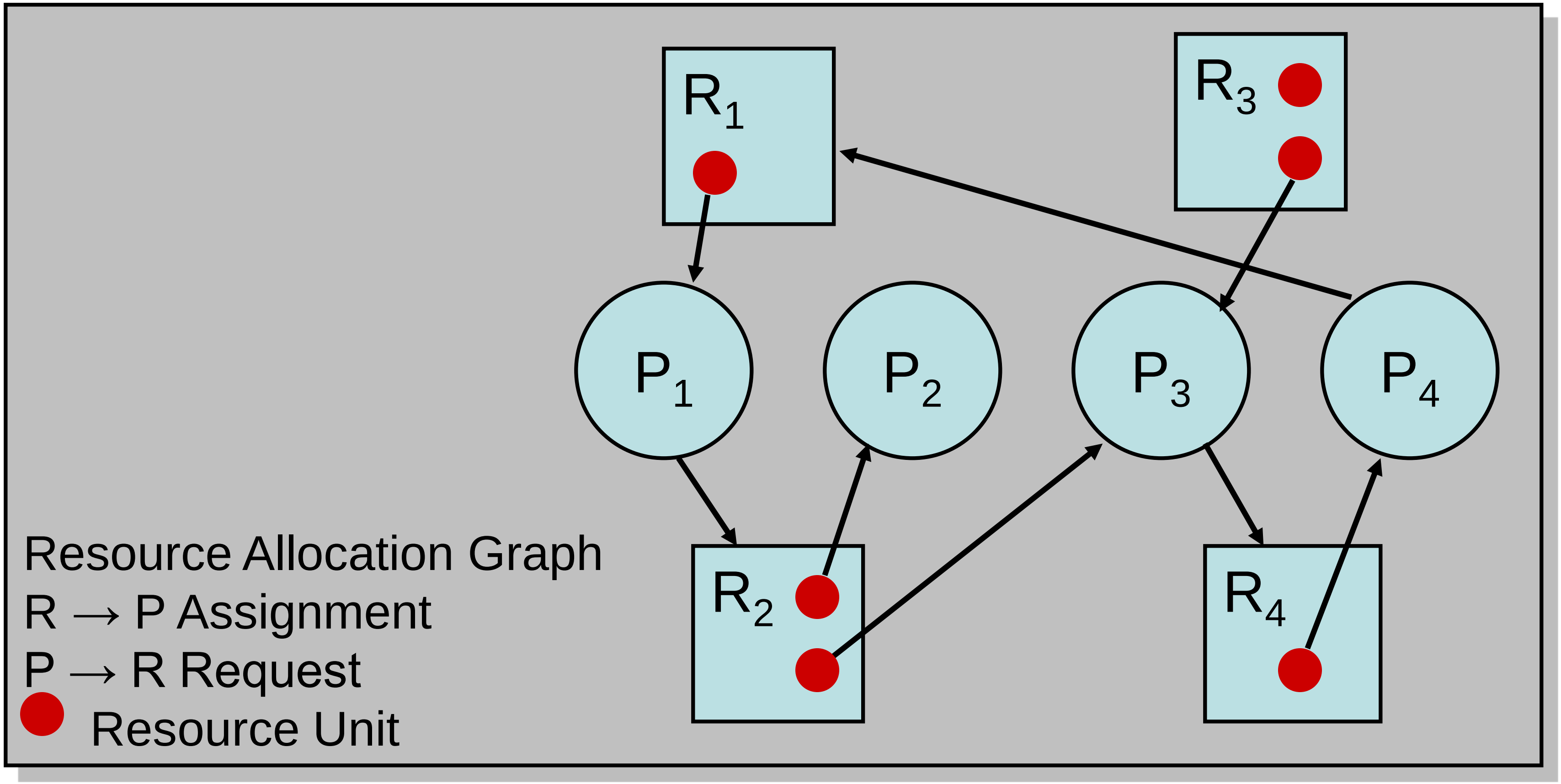


Resource Allocation Graph
R $\rightarrow$ P Assignment
P $\rightarrow$ R Request

Deadlock Detection

- Idea: Look for circularity in resource allocation graph
  - Q.: How do you find out if a directed graph has a cycle?
- Can be done eagerly
  - on every resource acquisition/release, resource allocation graph is updated & tested
- or lazily
  - when all threads are blocked & deadlock is suspected, build graph & test
- Windows provides this for its mutexes as an option
- Note: all processes in BLOCKED state is not sufficient to conclude existence of deadlock. (Why?)
- Note: circularity test is only sufficient criteria if there's only a single instance of each resource – see next slide for multi-unit resources

Multi-Unit Resources



- Note: Cycle, but no deadlock!

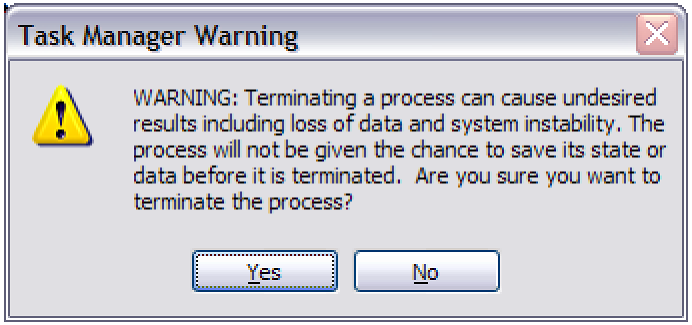
Deadlock Detection

- For reusable resources
  - If each resource has exactly one unit, deadlock iff cycle
  - If each resource has multiple units, existence of cycle may or may not mean deadlock
    - Must use reduction algorithm to determine if deadlock exists (Intuition: remove processes that don't have request edges, return their resource units and remove assignment edges, assign resources to remove request edges, repeat until out of processes without request edges. – If entire graph reduces to empty graph, no deadlock.)
- For consumable resources
  - analog algorithm possible
- Q.: What to do once deadlock is detected?

Deadlock Recovery

Increasing Severity

- Preempt resources (if possible)
- Back processes up to a checkpoint
  - Requires checkpointing or transactions (typically expensive)
- Kill processes involved until deadlock is resolved
- Kill all processes involved
- Reboot



Killing Threads or Processes

- Can be difficult issue:
  - When is it safe to kill a thread/process?
- Consider:

```
thread_func()
{
  while (!done) {
    lock_acquire(&lock);
    // access shared state
    lock_release(&lock);
  }
}
```

What if thread is killed here?

```
thread_func()
{
  while (!done) {
    lock_acquire(&lock);
    p = queue1.get();
    queue2.put(p);
    lock_release(&lock);
  }
}
```

- Must guarantee
  - full resource reclamation (e.g., locks held must be unlocked)
  - consistency of all surviving system data structures (e.g., no packets dropped)

Safe Termination

- System code must make sure that no shared data structures are left in an inconsistent state when thread is terminated
  - Same assurance must hold even if thread terminates itself (as in Pintos project 2)
- General strategy:
  - Allow termination of user processes at any point in time
    - Note: this does not protect user's data structures
  - Restrict kernel code to certain termination points (where process checks if termination request is pending):
    - E.g., after schedule(); before returning from syscall
    - Protects kernel's data structures

Deadlock Prevention (1)

- Idea: remove one of the necessary conditions!
- (C1) (Don’t require) Exclusive Access
  - Duplicate resource or make it shareable (where possible)
- (C2) (Avoid) Hold and Wait
  - a) Request all resources at once
    - hard to know in modular system
  - b) Drop all resources if additional request cannot be immediately granted – retry later
    - requires “try_lock” facility
    - can be inefficient if lots of retries

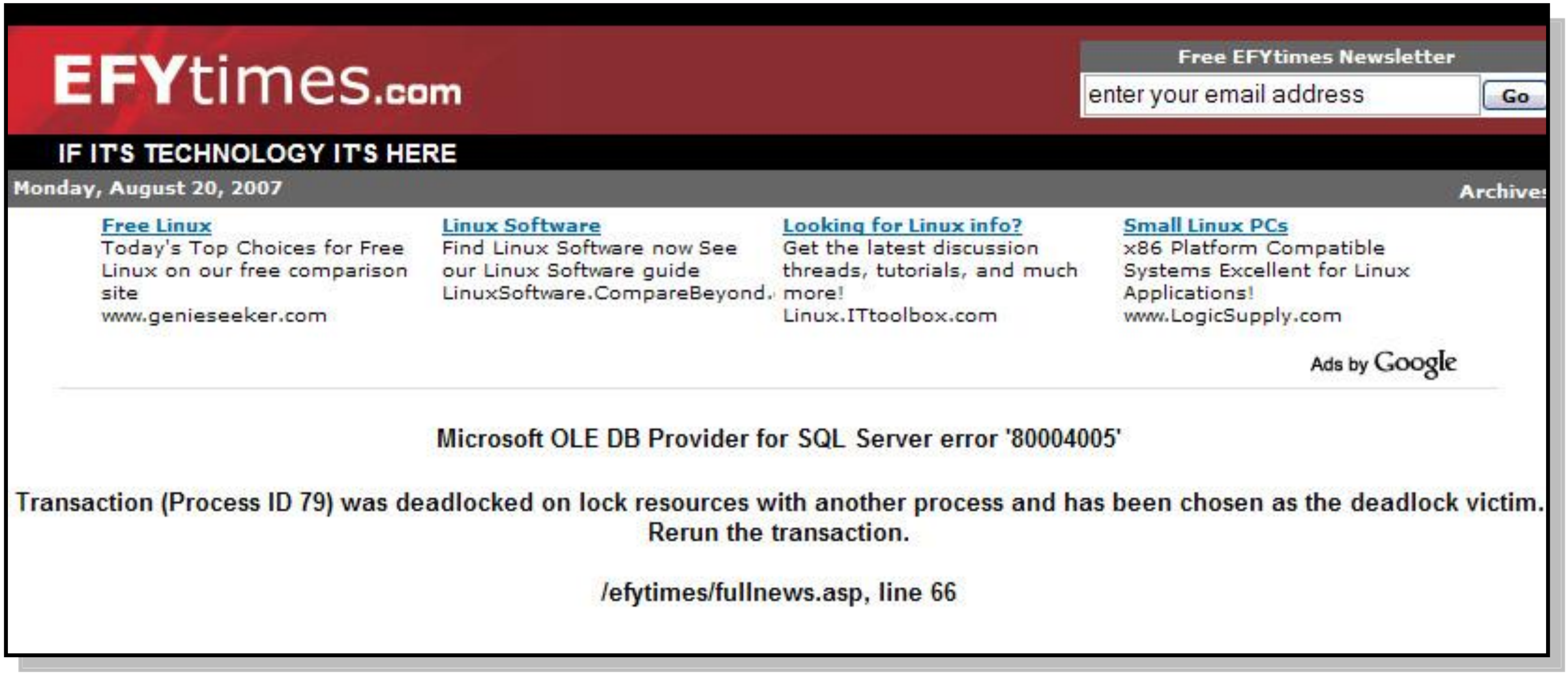
Deadlock Prevention (2)

- (C3) (Allow) Preemption
  - Take resource away from process
    - Difficult: how should process react?
  - Virtualize resource so it can be taken away
    - Requires saving & restoring resource’s state
- (C4) (Avoid) Circular Wait
  - Use partial ordering
    - Requires mapping to domain that provides an ordering function (addresses often work!)

Deadlock Avoidance

- Don’t grant resource request if deadlock could occur in future
  - Or don’t admit process at all
- Banker’s Algorithm (Dijkstra 1965, see book)
  - Avoids “unsafe” states that might lead to deadlock
  - Need to know what future resource demands are (“credit lines” of all customers)
  - Need to capture all dependencies (no additional synchronization requirements – “loans” can be called back if needed)
- Mainly theoretical
  - Impractical assumptions
  - Tends to be overly conservative – inefficient use of resources

Deadlock In The Real World



Deadlock in the Real World

- Most common strategy of handling deadlock
  - Test: fix all deadlocks detected during testing
  - Deploy: if deadlock happens, kill and rerun (easy!)
    - If it happens too often, or reproducibly, add deadlock detection code
- Weigh cost of preventing vs cost of (re-) occurring
- Static analysis tools detects some kinds of deadlocks before they occur
  - Example: Microsoft Driver Verifier
  - Idea: monitor order in which locks are taken, flag if not consistent lock order

Deadlock vs. Starvation

- Deadlock:
  - No matter which policy the scheduler chooses, there is no possible way for processes to make forward progress
- Starvation:
  - There is a possible way in which threads can make possible forward progress, but the scheduler doesn't choose it
    - Example: strict priority scheduler will never scheduler lower priority threads as long as higher-priority thread is READY
    - Example: naïve reader/writer lock: starvation may occur by "bad luck"

Informal uses of term `deadlock’

- 4 Coffman conditions apply specifically to deadlock with definable resources
- Term deadlock is sometimes informally used to also describe situations in which not all 4 criteria apply
  - See interesting discussion in Levine 2003, Defining Deadlock
  - Consider: *When two trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone.*
  - Does it meet the 4 conditions?
- However, even under informal/extended view, not all “lack of visible progress” situations can reasonably be called deadlocked
  - e.g., an idle system is not usually considered deadlocked

Summary

- Deadlock:
  - 4 necessary conditions: mutual exclusion, hold-and-wait, no preemption, circular wait
- Strategies to deal with:
  - Detect & recover
  - Prevention: remove one of 4 necessary conditions
  - Avoidance: if you can't do that, avoid deadlock by being conservative