Review: Test-and-set spinlock

```
struct var {
  int lock;
  int val;
};

void atomic_inc (var *v) {
  while (test_and_set (&v->lock))
    ;
  v->val++;
  v->lock = 0;
}

void atomic_dec (var *v) {
  while (test_and_set (&v->lock))
    ;
  v->val--;
  v->lock = 0;
}
```

Relaxed consistency model

- **Suppose no sequential consistency**
  - Recall alpha `test_and_set` had `mb` instruction
- **What happens if we omit `mb`?**
  - Hardware could violate program order

```
    PROGRAM ORDER                          VIEW ON OTHER CPU
read/write: v->lock = 1;                   v->lock = 1;
      read: v->val;
     write: v->val = read_val + 1;
     write: v->lock = 0;                   v->lock = 0;
                                           /* danger */
                                           v->val = read_val + 1;
```

- **If `atomic_dec` called where `danger`, bad `val` results**
- **`mb` in `test_and_set` preserves program order**
  - All ops before `mb` in program order appear before on all CPUs
  - All ops after `mb` in program order appear after on all CPUs

Cache coherence

- **Performance requires caches**
- **Sequential consistency requires cache coherence**
- **Bus-based approaches**
  - "Snoopy" protocols, each CPU listens to memory bus
  - Use write through and invalidate when you see a write
  - Or have ownership scheme (e.g., Pentium MESI bits)
  - Bus-based schemes limit scalability
- **Cache-Only Memory Architecture (COMA)**
  - Each CPU has local RAM, treated as cache
  - Cache lines migrate around based on access
  - Data lives only in cache

cc-NUMA

- **Previous slide had "dance hall" architectures**
  - Any CPU can "dance with" any memory equally
- **An alternative: Non-Uniform Memory Access**
  - Each CPU has fast access to some "close" memory
  - Slower to access memory that is farther away
  - Use a directory to keep track of who is caching what
- **Originally for machines with many CPUs**
  - Now AMD Opterons are kind of like this
- **cc-NUMA = cache-coherent NUMA**
  - Can also have non-cache-coherent NUMA, though uncommon
  - BBN Butterfly 1 has no cache at all
  - Cray T3D has local/global memory

NUMA and spinlocks

- **Test-and-set spinlock has several advantages**
  - Simple to implement and understand
  - One memory location for arbitrarily many CPUs
- **But also has disadvantages**
  - Lots of traffic over memory bus
  - Not necessarily fair (same CPU acquires lock many times)
  - Even less fair on a NUMA machine
  - Allegedly Google had fairness problems even on Opterons
- **Idea 1: Avoid spinlocks altogether**
- **Idea 2: Reduce bus traffic of spinlocks**
  - Design lock that spins only on local memory
  - Also gives better fairness

Eliminating locks

- **One use of locks is to coordinate multiple updates of single piece of state**
- **How to remove locks here?**
  - Factor state so each variable only has a single writer (Assuming sequential consistency)
- **Producer/consumer example revisited**
  - Assume one producer, one consumer
  - Why do we need `count` written by both?
    To detect buffer full/empty
  - Have producer write `in`, consumer write `out`
  - Use `in`/`out` to detect buffer state

```c
void producer (void *ignored) {
    for (;;) {
        /* produce an item and put in nextProduced */
        while (((in + 1) % BUFFER_SIZE) == out)
            ; // do nothing
        buffer [in] = nextProduced;
        in = (in + 1) % BUFFER_SIZE;
        count++;
    }
}

void consumer (void *ignored) {
    for (;;) {
        while (in == out)
            ; // do nothing
        nextConsumed =  buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        /*  consume the item in nextConsumed */
    }
}
```

Non-blocking synchronization

- **Design algorithm to avoid critical sections**
  - Any threads can make progress if other threads are preempted
  - Which wouldn't be the case if preempted thread held a lock
- **Requires atomic instructions available on some CPUs**
- **E.g.,** `ATOMIC_COMPARE_AND_SWAP: CAS (mem, old, new)`
  - If `*mem == old`, then set `*mem = new` and return true
- **Can implement many common data structures**
  - Stacks, queues, even hash tables
- **Can implement any algorithm on right hardware**
  - Need operation such as `ATOMIC_COMPARE_AND_SWAP` (has property called consensus number $= \infty$)
  - Rarely used in practice because inefficient (lots of retries), though entire cache kernel written w/o locks using double C&S

Example: stack

```
struct item {
  /* data */
  struct item *next;
};
typedef struct item *stack_t;

void atomic_push (stack_t *stack, item *i) {
  do {
    i->next = *stack;
  } while (!CAS (stack, i->next, i));
}

item *atomic_pop (stack_t stack) {
  item *i;
  do {
    i = *stack;
  } while (!CAS (stack, i, i->next));
  return i;
}
```

Benign races

- **Can also eliminate locks with race conditions**
- **Sometimes "cheating" buys efficiency…**
- **Care more about speed than accuracy**

```
hits++;  // each time someone accesses web site
```

- **Know you can get away with race**

```
if (!initialized) {
  lock (m);
  if (!initialized) { initialize (); initialized = 1; }
  unlock (m);
}
```

Read-copy update [McKenney]

- **Some data is read way more often than written**
- **Routing tables**
  - Consulted for each packet that is forwarded
- **Data maps in system with 100+ disks**
  - Updated when disk fails, maybe every 10^{10} operations
- **Optimize for the common case or reading w/o lock**
  - E.g., global variable: `routing_table *rt;`
  - Call `lookup (rt, route);` with no locking
- **Update by making copy, swapping pointer**
  - E.g., `routing_table *nrt = copy_routing_table (rt);`
  - Update `nrt`
  - Set global `rt = nrt` when done updating
  - All `lookup` calls see consistent old or new table

Garbage collection

- **When can you free memory of old routing table?**
  - When you are guaranteed no one is using it—how to determine
- **Definitions:**
  - *temporary variable* – short-used (e.g., local) variable
  - *permanent variable* – long lived data (e.g., global `rt` pointer)
  - *quiescent state* – when all a thread's temporary variables dead
  - *quiescent period* – time during which every thread has been in quiescent state at least once
- **Free old copy of updated data after quiescent period**
  - How to determine when quiescent period has gone by?
  - E.g., keep count of syscalls/context switches on each CPU
  - Can't hold a lock across context switch or user mode

MCS lock

- **Lock designed by Melloc-Crummey and Scott**
  - Goal: reduce bus traffic on cc machines
- **Each CPU has a `qnode` structure in local memory**

```
typedef struct qnode {
  struct qnode *next;
  bool locked;
} qnode;
typedef struct qnode qnode;
```

  - Local can mean local memory in NUMA machine
  - Or just its own cache line that gets cached in exclusive mode
- **A lock is just a pointer to a `qnode`**

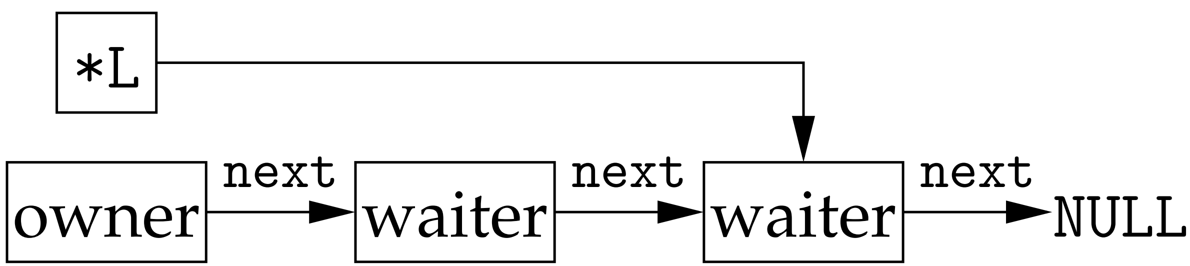
```
typedef qnode *lock;
```

- **Lock list of CPUs holding or waiting for lock**
- **While waiting, just spin on local `locked` flag**

MCS Acquire

```
acquire (lock *L, qnode *I) {
  I->next = NULL;
  qnode *predecessor = I;
  ATOMIC_SWAP (predecessor, *L);
  if (predecessor != NULL) {
    I->locked = true;
    predecessor->next = I;
    while (I->locked)
      ;
  }
}
```

- **If unlocked,** `L` **is** `NULL`
- **If locked, no waiters,** `L` **is owner's** `qnode`
- **If waiters,** `*L` **is tail of waiter list:**



MCS Release w. C&S

```
release (lock *L, qnode *I) {
  if (!I->next)
    if (ATOMIC_COMPARE_AND_SWAP (*L, I, NULL))
      return;
  while (!I->next)
    ;
  I->next->locked = false;
}
```

- **If** `I->next` **NULL and** `*L == I`
  - No one else is waiting for lock, OK to set `*L = NULL`
- **If** `I->next` **NULL and** `*L != I`
  - Another thread is in the middle of `acquire`
  - Just wait for `I->next` to be non-NULL
- **If** `I->next` **is non-NULL**
  - `I->next` oldest waiter, wake up w. `I->next->locked = false`

MCS Release w/o C&S

- **What to do if no atomic compare & swap?**
- **Be optimistic–read `*L` w. two `ATOMIC_SWAPS`:**
  1. Atomically swap NULL into `*L`
     - If old value of `*L` was `I`, no waiters and we are done
  2. Atomically swap old `*L` value back into `*L`
     - If `*L` unchanged, same effect as `ATOMIC_COMPARE_AND_SWAP`
- **Otherwise, we have to clean up the mess**
  - Some "userper" attempted to acquire lock between **1** and **2**
  - Because `*L` was `NULL`, the userper succeeded
    (May be followed by zero or more waiters)
  - Stick old list of waiters on to end of new last waiter

MCS Release w/o C&S code

```
release (lock *L, qnode *I) {
  if (I->next)
    I->next->locked = false;
  else {
    qnode *old_tail = NULL;
    ATOMIC_SWAP (*L, old_tail);
    if (old_tail == I)
      return;

    qnode *userper = old_tail;
    ATOMIC_SWAP (*L, userper);
    while (I->next == NULL)
      ;
    if (userper != NULL)
      userper->next = I->next;
    else
      I->next->locked = false;
  }
}
```

Kernel support for synchronization

- **Locks must interact with scheduler**
  - For processes or kernel threads, must go into kernel (expensive)
  - Common case is you can acquire lock—how to optimize?
- **Idea: only go into kernel if you can't get lock**

```
struct lock {
  int busy;
  thread *waiters;
};
void acquire (lock *lk) {
  while (test_and_set (&lk->busy)) {    /* 1 */
    atomic_push (&lk->waiters, self);   /* 2 */
    sleep ();
 }
}
void release (lock *lk) {
  lk->busy = 0;
  wakeup (atomic_pop (&lk->waiters));
}
```

Race condition

- **Unfortunately, previous slide not safe**
  - What happens if release called between lines 1 and 2?
  - `wakeup` called on `NULL`, so `acquire` blocks
- ***futex* abstraction solves the problem**
  - Ask kernel to sleep only if memory location hasn't changed
- `void futex (int *uaddr, FUTEX_WAIT, int val...);`
  - Go to sleep only if `*uaddr == val`
  - Extra arguments allow timeouts, etc.
- `void futex (int *uaddr, FUTEX_WAKE, int val...);`
  - Wake up at least `val` threads sleeping on `uaddr`
- `uaddr` **is translated down to offset in VM object**
  - So works on memory mapped file at different virtual addresses in different processes

Transactions

- **Another paradigm for handling concurrency**
  - Often provided by databases, but some OSes use them
  - *Vino* OS used to abort after failures
  - OS support for transactional memory now hot research topic
- **A *transaction* T is a collection of actions with**
  - *Atomicity* – all or none of actions happen
  - *Consistency* – T leaves data in valid state
  - *Isolation* – T's actions all appear to happen before or after every other transaction T'
  - *Durability** – T's effects will survive reboots
- **Transactions typically executed concurrently**
  - But *isolation* means must *appear* not to
  - Must roll-back transactions that use others' state
  - Means you have to record all changes to undo them

The deadlock problem

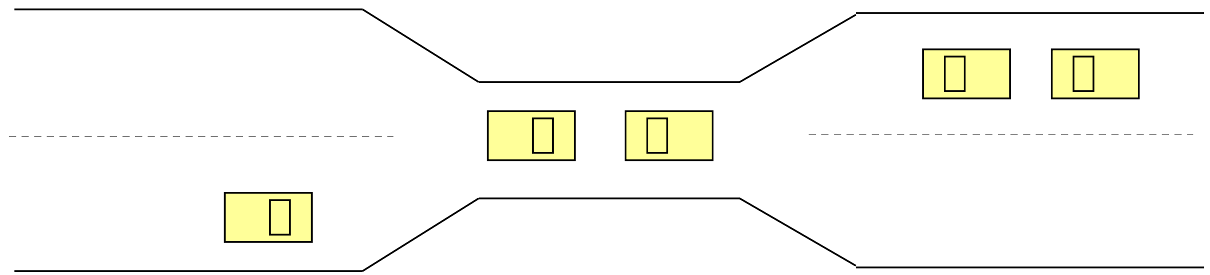
```
mutex_t m1, m2;

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);
}
```

- **This program can cease to make progress – how?**
- **Can you have deadlock w/o mutexes?**

More deadlocks

- **Same problem with condition variables**
  - Suppose resource 1 managed by c_1, resource 2 by c_2
  - A has 1, waits on c2, B has 2, waits on c1
- **Or have combined mutex/condition variable deadlock:**
  - `lock (a); lock (b); while (!ready) wait (b, c);`
    `unlock (b); unlock (a);`
  - `lock (a); lock (b); ready = true; signal (c);`
    `unlock (b); unlock (a);`
- **One lesson: Dangerous to hold locks when crossing abstraction barriers!**
  - I.e., `lock (a)` then call function that uses condition variable

Deadlocks w/o computers



- **Real issue is *resources* & 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.

Deadlock conditions

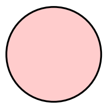
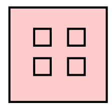
1. **Limited access (mutual exclusion):**
   - Resource can only be shared with finite users.
2. **No preemption:**
   - once resource granted, cannot be taken away.
3. **Multiple independent requests (hold and wait):**
   - don't ask all at once (wait for next resource while holding current one)
4. **Circularity in graph of requests**

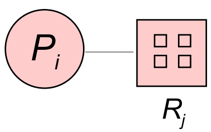
- **All of 1–4 necessary for deadlock to occur**
- **Two approaches to dealing with deadlock:**
  - pro-active: prevention
  - reactive: detection + corrective action

Prevent by eliminating one condition

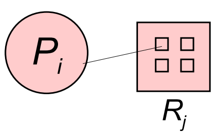
1. **Limited access (mutual exclusion):**
   - Buy more resources, split into pieces, or virtualize to make "infinite" copies
2. **No preemption:**
   - Threads: threads have copy of registers = no lock
   - Physical memory: virtualized with VM, can take physical page away and give to another process!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

Resource-allocation graph

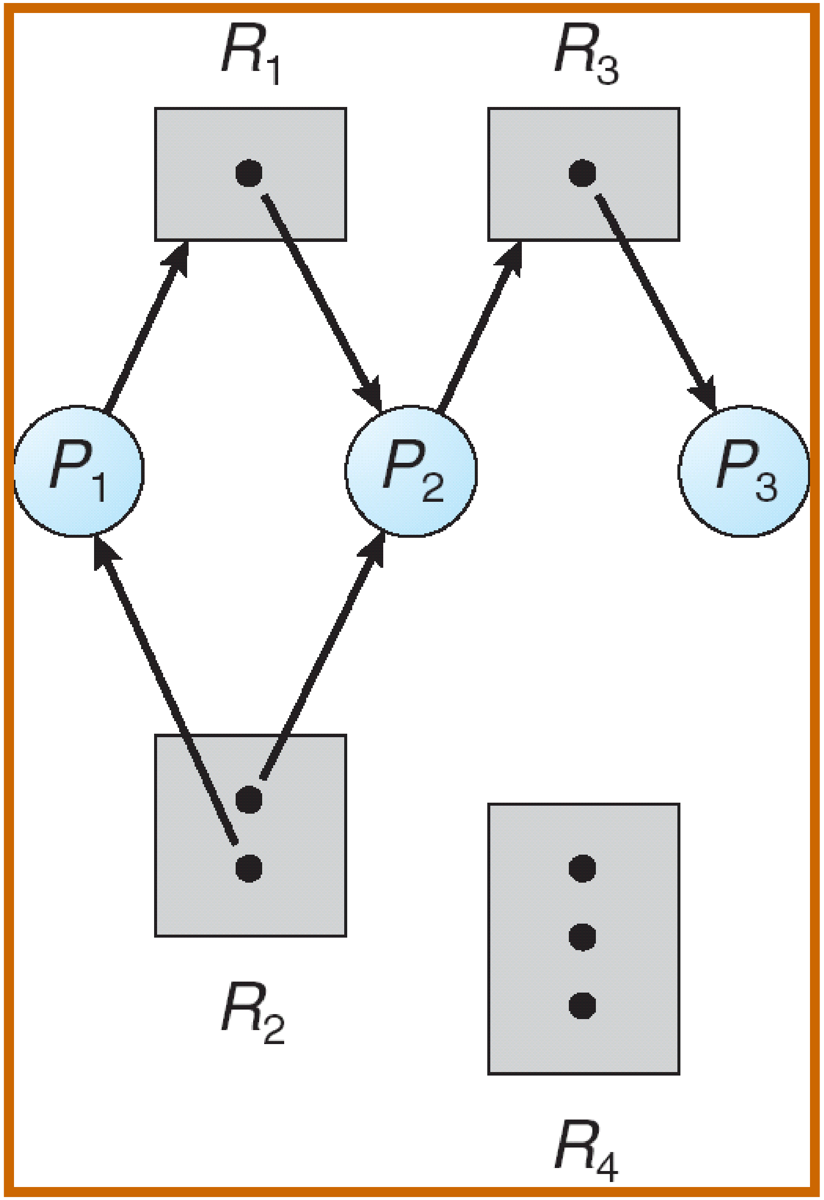
- **View system as graph**
  - Processes and Resources are nodes
  - Resource Requests and Assignments are edges
- **Process:** 
- **Resource w. 4 instances:** 
- P_i **requesting** R_j**:**



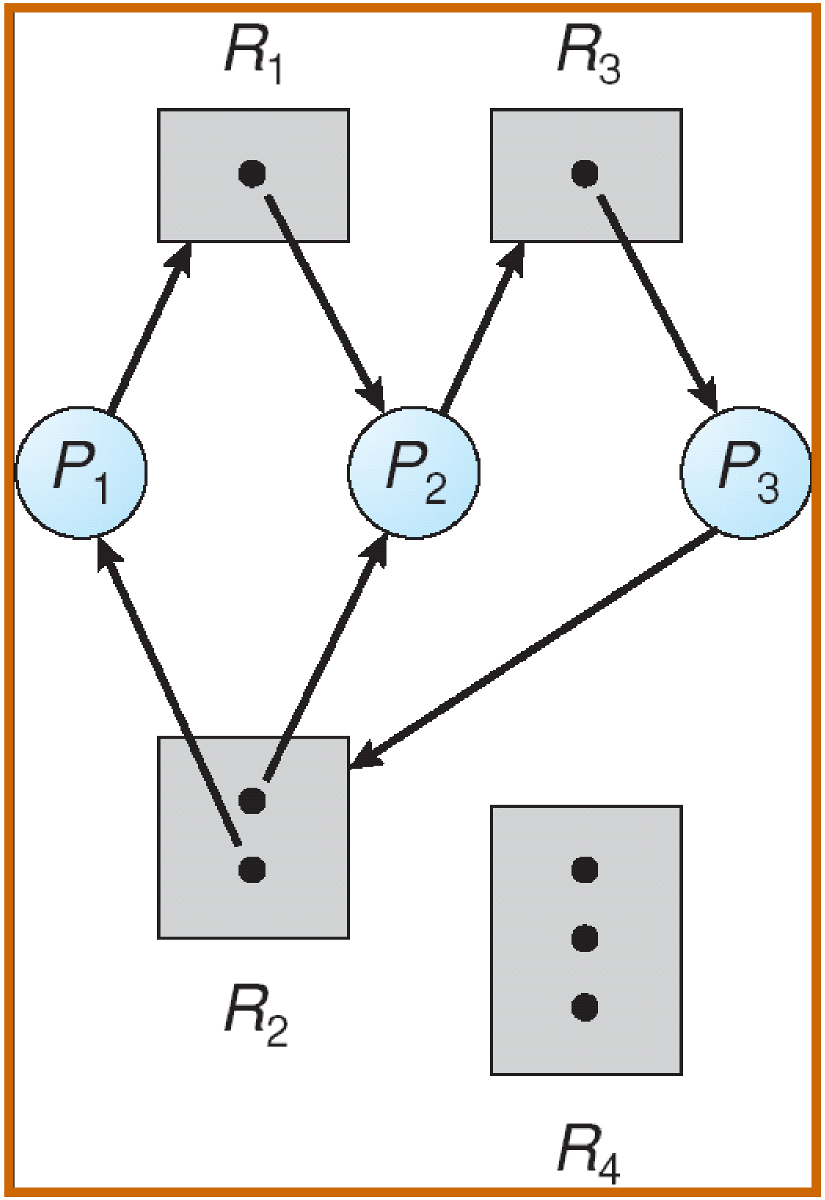
- P_i **holding instance of** R_j**:**



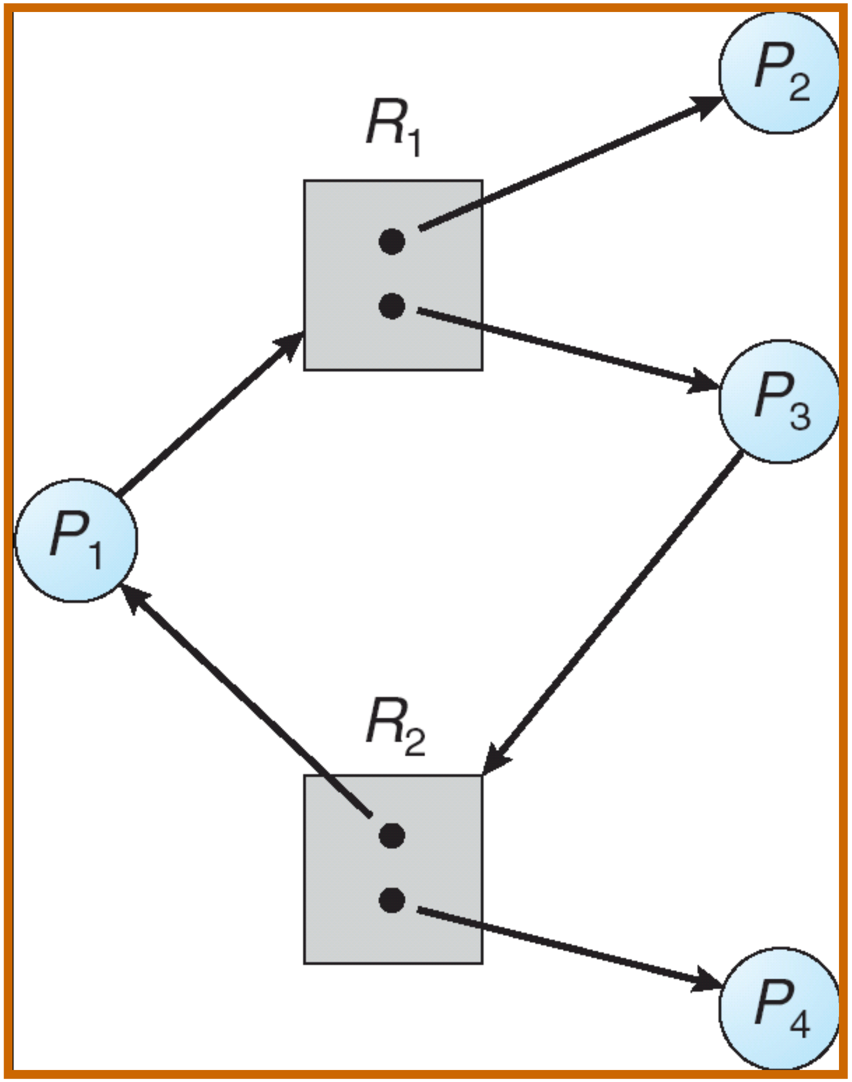
Example resource allocation graph



Graph with deadlock



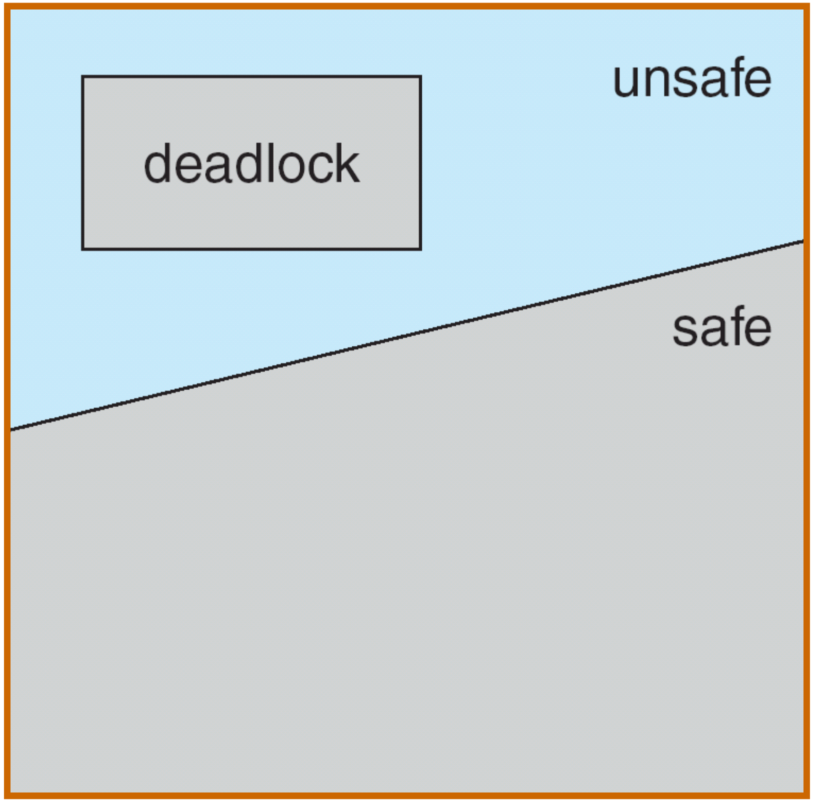
Is this deadlock?



Cycles and deadlock

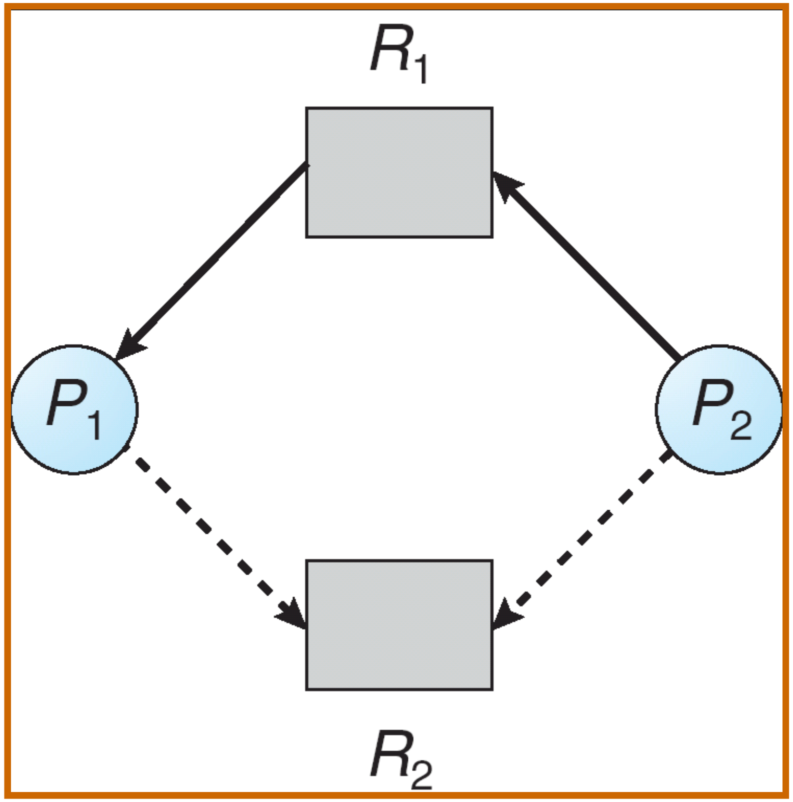
- **If graph has no cycles $\Longrightarrow$ no deadlock**
- **If graph contains a cycle**
  - Definitely deadlock if only one instance per resource
  - Otherwise, maybe deadlock, maybe not
- **Prevent deadlock w. partial order on resources**
  - E.g., always acquire mutex m_1 before m_2
  - Usually design locking discipline for application this way

Prevention



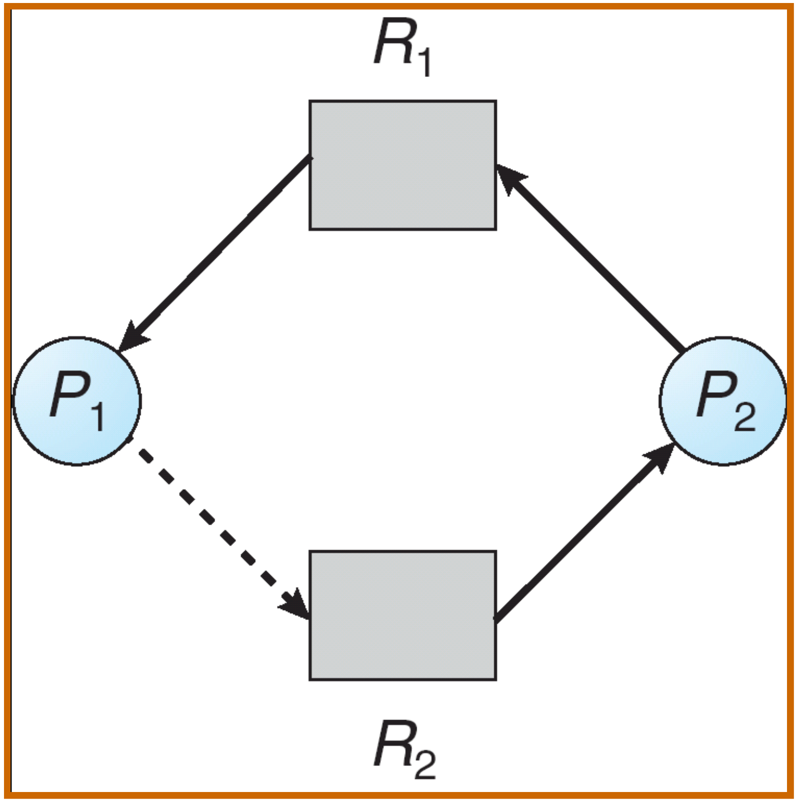
- **Determine safe states based on *possible* resource allocation**
- **Conservatively prohibits non-deadlocked states**

Claim edges



- **Dotted line is *claim edge***
  - Signifies process *may* request resource

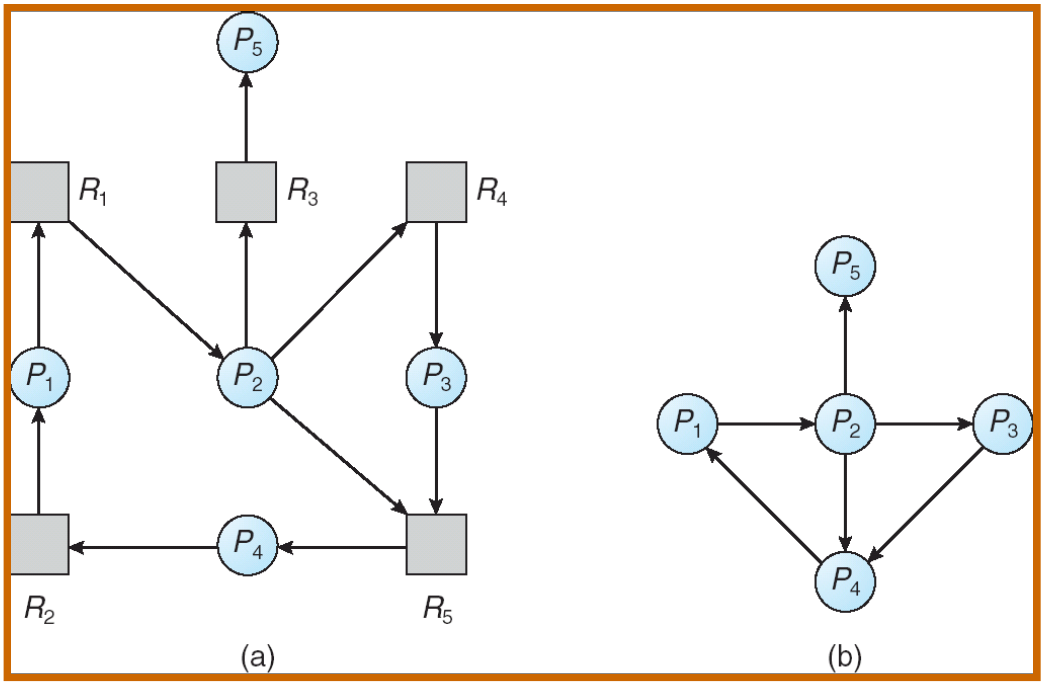
Example: unsafe state



- **Note cycle in graph**
  - P_1 might request R_2 before relinquishing R_1
  - Would cause deadlock

Detecting deadlock

- **Static approaches (hard)**
- **Program grinds to a halt**
- **Threads package can keep track of locks held:**



Resource-Allocation Graph   Corresponding wait-for graph

Fixing & debugging deadlocks

- **Reboot system (windows approach)**
- **Examine hung process with debugger**
- **Threads package can deduce partial order**
    - For each lock acquired, order with other locks held
    - If cycle occurs, abort with error
    - Detects *potential* deadlocks even if they do not occur
- **Or with transactions, can just tolerate**
    - Just abort a transaction when deadlock detected
    - Safe, though inefficient if it happens often

Detecting data races

- **Static methods (hard)**
- **Debugging painful—race might occur rarely**
- **Instrumentation—modify program to trap memory accesses**
- **Lockset algorithm (eraser) particularly effective:**
  - For each global memory location, keep a "lockset"
  - On each access, remove any locks not currently held
  - If lockset becomes empty, abort: No mutex protects data
  - Catches potential races even if they don't occur