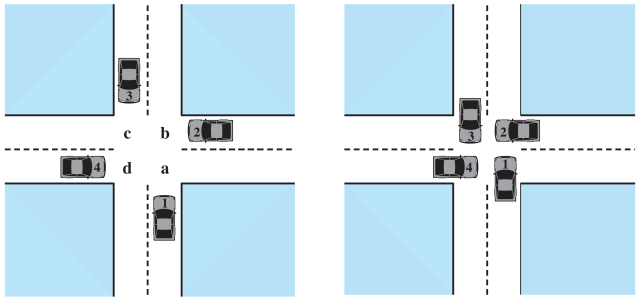
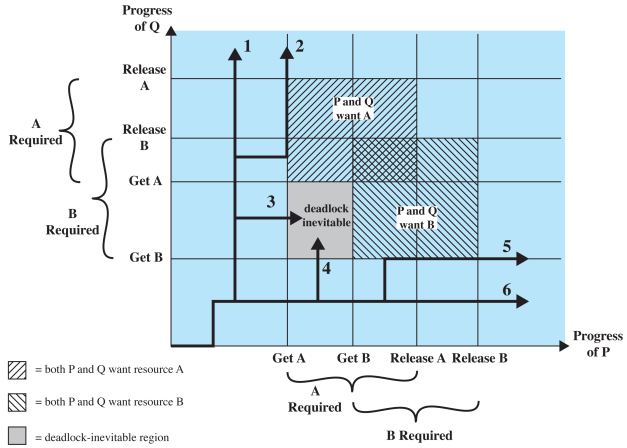
DEADLOCK

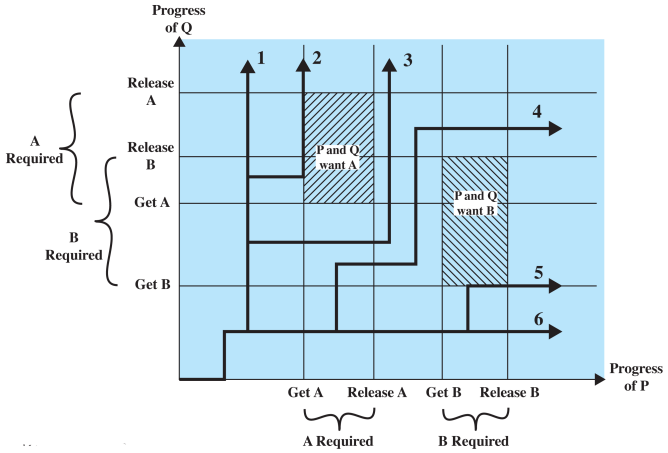
- The permanent blocking of a set of processes that either compete for resources or communicate with each other
- A set of processes is deadlocked when each process in the set is blocked awaiting an event that can only be triggered by another blocked process in the set
- Permanent; no efficient solution



JOINT PROGRESS WITH DEADLOCK



JOINT PROGRESS WITHOUT DEADLOCK



RESOURCE CATEGORIES AND DEADLOCK

- Reusable = safely used by only one process at a time but not depleted by that use
  - Processors, I/O channels, memory, devices, files, databases, semaphores
  - Sample deadlocks:

```
P1:                P2:
lock(&l2);         lock(&l1);
...                ...
lock(&l1);         lock(&l2);
...                ...
unlock(&l2);       unlock(&l2);
unlock(&l1);       unlock(&l1);
```

```
(200 KB memory available overall)

P1:                P2:
Request 80 KB      Request 70 KB
...                ...
Request 60 KB      Request 80 KB
...                ...
```

- Consumable = can be created (produced) and destroyed (consumed)
  - interrupts, signals, messages, information, data in I/O buffers
  - Sample deadlock (receive blocking):

```
P1:                P2:
Receive(P2)        Receive(P1)
...                ...
Send(P2,M1)        Send(P1,M2)
...                ...
```

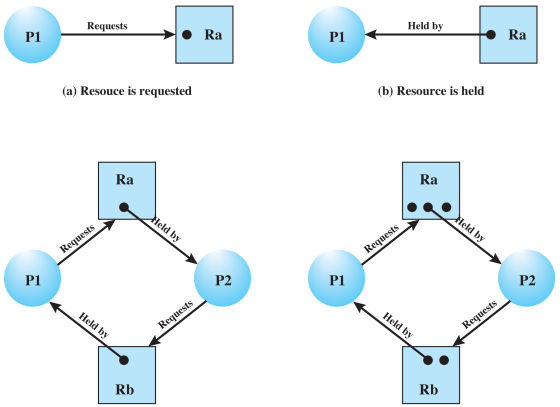
Conditions for Deadlock

- Mutual exclusion
- Hold-and-wait (a process may hold allocated resources while awaiting assignment of others)
- No preemption (no resource can be forcibly removed from a process holding it)
- Circular wait (a closed chain of processes exists, such that each process holds at least one resource needed by the next process in the chain)
- Dealing with deadlock conditions:
  - Prevent deadlock (adopt a policy that eliminates one of the conditions)
  - Avoid deadlock (make the appropriate dynamic choices based on the current state of resource allocation)
  - Detect deadlock (attempt to detect the presence of deadlock and take action to recover)

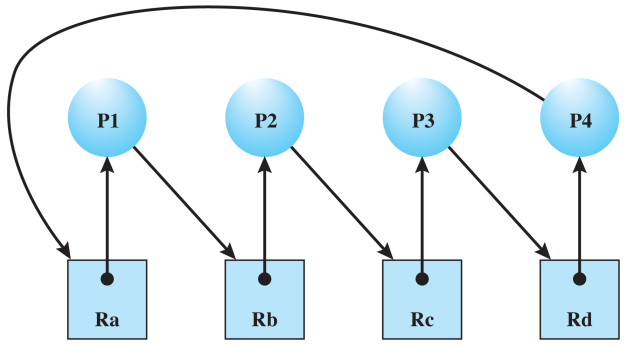
Approaches to Deadlock Detection, Prevention, and Avoidance

- Prevention: conservative, undercommits resources
  - Requesting all resources at once
    Advantages: best for processes that perform a single burst of activity; no preemption necessary
    Disadvantages: inefficient; delays process initiation; requirements must be known in advance
  - Preemption
    Advantages: convenient for resources whose state can be saved and restored easily
    Disadvantages: preempts more often than necessary
  - Resource ordering
    Advantages: enforceable via compile-time checks, so needs no run-time computation
    Disadvantages: disallows incremental resource requests
- Avoidance: finds at least one safe path; midway between detection and prevention
  Advantages: no preemption necessary
  Disadvantages: future resource requirements must be known; processes blocked for long periods
- Detection: requested resources are granted where possible (very liberal); must be invoked periodically to test for deadlock
  Advantages: never delays process initiation; facilitates online handling
  Disadvantages: inherent preemption losses

Resource Allocation Graphs



Resource Allocation Graphs (cont'd)



Deadlock Prevention

- Design a system in such a way that the possibility of deadlock is excluded
- Two main methods:
  - Indirect – prevent the occurrence of one of the three necessary conditions
    - Mutual exclusion: not required for sharable resources (but must hold for non-sharable resources)
    - Hold and wait: require that a process request all of its required resources at one time and block the process until all requests can be granted simultaneously
    - No preemption: if a process holding certain resources is denied a further request, that process must release its original resources and request them again
    - Circular wait: define a linear ordering on resource types
  - Direct – prevent the occurrence of a circular wait

Deadlock Avoidance

- A decision is made dynamically whether the current resource allocation request will, if granted, potentially lead to a deadlock
- Requires knowledge of future process requests
- Approaches:
  - Resource Allocation Denial: do not grant an incremental resource request to a process if this allocation might lead to deadlock
  - Process Initiation Denial: do not start a process if its demands might lead to deadlock
- Algorithms:
  - Single instance of a resource type: use the resource-allocation graph
    - The resource is granted iff granting it does not create a cycle
  - Multiple instances of a resource type: use the banker's algorithm

Resource Allocation Denial: The Banker's Algorithm

- State of the system reflects the current allocation of resources to processes
- Safe state is one in which there is at least one sequence of resource allocations to processes that does not result in a deadlock; the opposite is an unsafe state

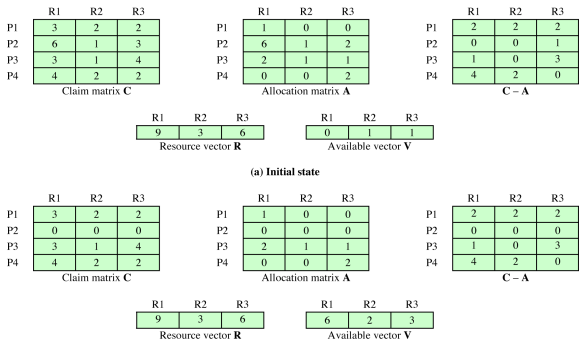
```
struct state{ int recource[m]; int available[m];
              int claim[n][m]; int alloc[n][m];

if (alloc[i, *] + request[*] > claim[i, *]) < error >;  // tot. request > claim
else if (request[*] > available[*]) < suspend process >;
else {                                                  // simulate alloc
    < define newstate as:
      alloc[i,*] = alloc[i,*] + request[*];
      available[*] = available[*] - request[*]; >;
}
if (safe(newstate)) < carry out the allocation >;
else {
    < restore original state >;
    < suspend process >;
}
```

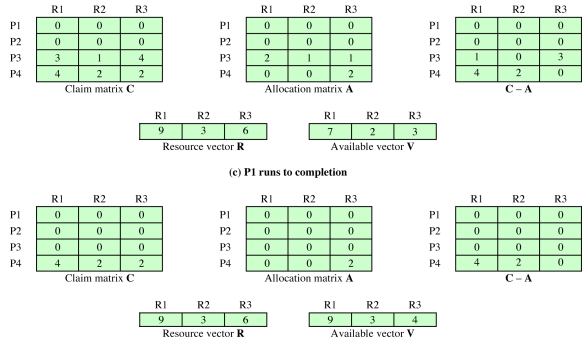

Banker's Algorithm (cont'd)

```
boolean safe (state S) {
   int currentavail[m];
   process rest[<number of processes>];
   currentavail = available;
   rest = {all processes};
   possible = true;
   while (possible) {
       <find a process Pk in rest such that
          claim [k,*] - alloc [k,*] <= currentavail;>
       if (found) {              /* simulate execution of Pk */
          currentavail = currentavail + alloc [k,*];
          rest = rest - {Pk};
       }
       else possible = false;
   }
   return (rest == null);
}
```

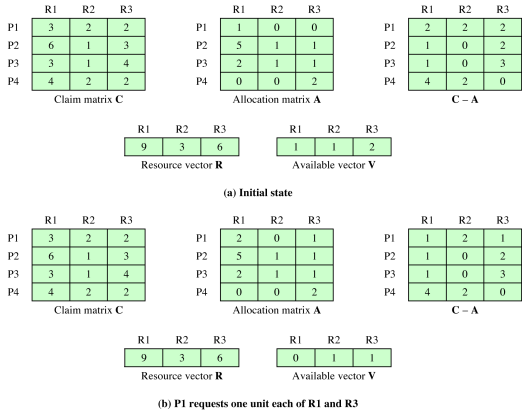
SAFE STATES



SAFE STATES (CONT'D)



UNSAFE STATES



DEADLOCK AVOIDANCE (CONT'D)

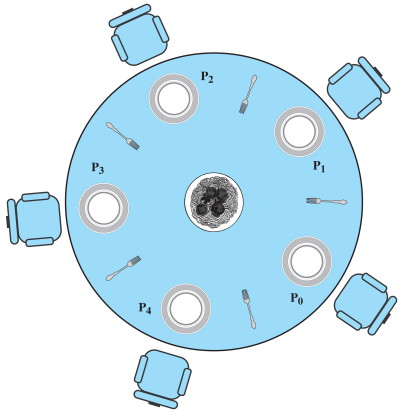
- Advantages
  - It is not necessary to preempt and rollback processes, as in deadlock detection
  - It is less restrictive than deadlock prevention
- Restrictions
  - Maximum resource requirement for each process must be stated in advance
  - Processes under consideration must be independent and with no synchronization requirements
  - There must be a fixed number of resources to allocate
  - No process may exit while holding resources

Deadlock Detection Algorithms

- Deadlock prevention is conservative (limits access by restricting processes)
- By contrast deadlock detection strategies do the opposite: resource requests are granted whenever possible
  - Check for deadlock can be made as frequently as needed
- Advantages:
  - Early detection
  - Relatively simple algorithms
- Disadvantage:
  - Frequent checks consume considerable processor time
- Recovery strategies necessary
  - Abort all deadlocked processes
  - Back up deadlocked processes to some checkpoint and restart all processes
  - Successively abort deadlocked processes until deadlock no longer exists
  - Successively preempt resources until deadlock no longer exists

The Dining Philosophers Problem

- Mutual exclusion: no two philosophers can use the same fork at the same time
- Avoid deadlock and starvation: no philosopher must starve to death



Dining Philosophers with Semaphores

```
semaphore fork [5] = {1, 1, 1, 1, 1};

void philosopher (int i) {
     while (true) {
          think();
          wait (fork[i]);
          wait (fork [(i+1) mod 5]);
          eat();
          signal(fork [(i+1) mod 5]);
          signal(fork[i]);
     }
}

void main() {
     for int i = 0 to 5 run in parallel philosopher(i);
}
```


Better Dining Philosophers

```
semaphore fork[5] = {1, 1, 1, 1, 1};
semaphore room = 4;

void philosopher (int i) {
    while (true) {
      think();
      wait (room);
      wait (fork[i]);
      wait (fork [(i+1) mod 5]);
      eat();
      signal (fork [(i+1) mod 5]);
      signal (fork[i]);
      signal (room);
    }
}

void main() {
     for int i = 0 to 5 run in parallel philosopher(i);
}
```

Dining Philosophers with a Semaphore

```
monitor dining_controller;
cond ForkReady[5];          /* condition variable for synchronization */
boolean fork[5] = {true, ...};   /* availability status of each fork */
void get_forks(int pid) {
   int left = pid;   int right = (++pid) % 5;
   if (!fork(left))                    /*grant the left fork*/
      cwait(ForkReady[left]);          /* queue on condition variable */
   fork(left) = false;
   if (!fork(right))                   /*grant the right fork*/
      cwait(ForkReady(right));         /* queue on condition variable */
   fork(right) = false:
}
void release_forks(int pid) {
   int left = pid;   int right = (++pid) % 5;
   if (empty(ForkReady[left]))     /*no one is waiting for this fork */
      fork(left) = true;           /*release the left fork*/
   else                       /* awaken a process waiting on this fork */
      csignal(ForkReady[left]);
   if (empty(ForkReady[right]))     /*no one is waiting for this fork */
      fork(right) = true;          /*release the right fork*/
   else                       /* awaken a process waiting on this fork */
      csignal(ForkReady[right]);
}
```


Dining Philosophers with a Semaphore (cont'd)

```
void philosopher[k=0 to 4] /* the five philosopher clients */
{
   while (true) {
      <think>;
      get_forks(k);        /* client requests two forks via monitor */
      <eat spaghetti>;
      release_forks(k);    /* client releases forks via the monitor */
   }
}
```


Most Common OS Approach to Deadlock

Most Common OS Approach to Deadlock

Ignore the problem and pretend that deadlocks never occur in the system!

UNIX CONCURRENCY MECHANISMS

- Pipes: FIFO queues, implement the producer/consumer model
- Messages: `msgsnd` and `msgrcv` system calls with one message queue for each process
- Signals: primitive messages, used for signaling special conditions
- Shared memory:
  - Creation: `id = shmget(IPC_PRIVATE, size, S_IRUSR|S_IWUSR);`
  - Attach: `shared_memory = (char *) shmat(id, NULL, 0);`
  - Use: like a normal buffer (array)
  - Detach shared memory from own address space: `shmdt(shared_memory);`
  - Mutual exclusion constraints are not part of the shared-memory facility but must be provided by the processes using the shared memory
- Semaphores: for mutual exclusion (as usual)

LINUX KERNEL CONCURRENCY MECHANISMS

- Atomic Operations: simplest approach to synchronization
  - Two types: integer operations (typical use: counters) and bitmap operations
- Spinlocks: most common technique for protecting a critical section in Linux
  - Integer location checked by each thread before it enters its critical section
  - Can only be acquired by one thread at a time; the others will keep trying (spinning) until they can acquire the lock
  - Effective whenever the wait time for acquiring a lock is expected to be very short
  - Disadvantage: busy-waiting
- Semaphores: binary, counting, readers/writers
- Barriers: enforce the order in which instructions are executed
  - `rmb()` - prevents loads from being reordered across the barrier
  - `wmb()` - prevents stores from being reordered across the barrier
  - `mb()` - prevents both from being reordered across the barrier
  - etc.

LINUX ATOMIC OPERATIONS

Atomic integer operations

`ATOMIC_INIT (int i)`	At declaration: initialize an `atomic_t` to `i`
`int atomic_read(atomic_t *v)`	Read integer value of v
`void atomic_set(atomic_t *v, int i)`	Set the value of `v` to integer `i`
`void atomic_add(int i, atomic_t *v)`	Add `i` to `v`
`void atomic_sub(int i, atomic_t *v)`	Subtract `i` from `v`
`void atomic_inc(atomic_t *v)`	Add 1 to `v`
`void atomic_dec(atomic_t *v)`	Subtract 1 from `v`
`int atomic_sub_and_test(int i, atomic_t *v)`	Subtract `i` from `v`; return 1 if the result is zero; return 0 otherwise
`int atomic_add_negative(int i, atomic_t *v)`	Add `i` to `v`; return 1 if the result is negative; return 0 otherwise (used for semaphores)
`int atomic_dec_and_test(atomic_t *v)`	Subtract 1 from `v`; return 1 if the result is zero; return 0 otherwise
`int atomic_inc_and_test(atomic_t *v)`	Add 1 to v; return 1 if the result is zero; return 0 otherwise

Atomic bitmap operations

`void set_bit(int nr, void *addr)`	Set bit `nr` in the bitmap `addr`
`void clear_bit(int nr, void *addr)`	Clear bit `nr` in the bitmap `addr`
`void change_bit(int nr, void *addr)`	Invert bit `nr`
`int test_and_set_bit(int nr, void *addr)`	Set bit `nr` and return the old bit value
`int test_and_clear_bit(int nr, void *addr)`	Clear bit `nr` and return the old bit value
`int test_and_change_bit(int nr, void *addr)`	Invert bit `nr` and return the old bit value
`int test_bit(int nr, void *addr)`	Return the value of bit `nr`

LINUX SPINLOCKS

- `void spin_lock(spinlock_t *lock)`: acquires the specified lock, spinning if needed until it is available
- `void spin_lock_irq(spinlock_t *lock)`: also disables interrupts on the local processor
- `void spin_lock_irqsave(spinlock_t *lock, unsigned long flags)`: also saves the current interrupt state in flags
- `void spin_unlock(spinlock_t *lock)`: releases given lock
- `void spin_unlock_irq(spinlock_t *lock)`: releases given lock and enables local interrupts
- `void spin_unlock_irqrestore(spinlock_t *lock, unsigned long flags)`: releases given lock and restores local interrupts to given previous state
- `void spin_lock_init(spinlock_t *lock)`: initializes given spinlock
- `int spin_trylock(spinlock_t *lock)`: tries to acquire specified lock; returns nonzero if lock is currently held and zero otherwise
- `int spin_is_locked(spinlock_t *lock)`: returns nonzero if lock is currently held and zero otherwise

LINUX SEMAPHORES

- Traditional semaphores:
  - `void sema_init(struct semaphore *sem, int count)`
  - `void init_MUTEX(struct semaphore *sem)` (initially unlocked)
  - `void init_MUTEX_LOCKED(struct semaphore *sem)` (initially locked)
  - `void down(struct semaphore *sem)` (and enters uninterruptible sleep if semaphore is unavailable)
  - `int down_interruptible(struct semaphore *sem)` (interruptible)
  - `int down_trylock(struct semaphore *sem)`
  - `void up(struct semaphore *sem)` (release semaphore)
- Reader-writer semaphores:
  - `void init_rwsem(struct rw_semaphore, *rwsem)`
  - `void down_read(struct rw_semaphore, *rwsem)`
  - `void up_read(struct rw_semaphore, *rwsem)`
  - `void down_write(struct rw_semaphore, *rwsem)`
  - `void up_write(struct rw_semaphore, *rwsem)`