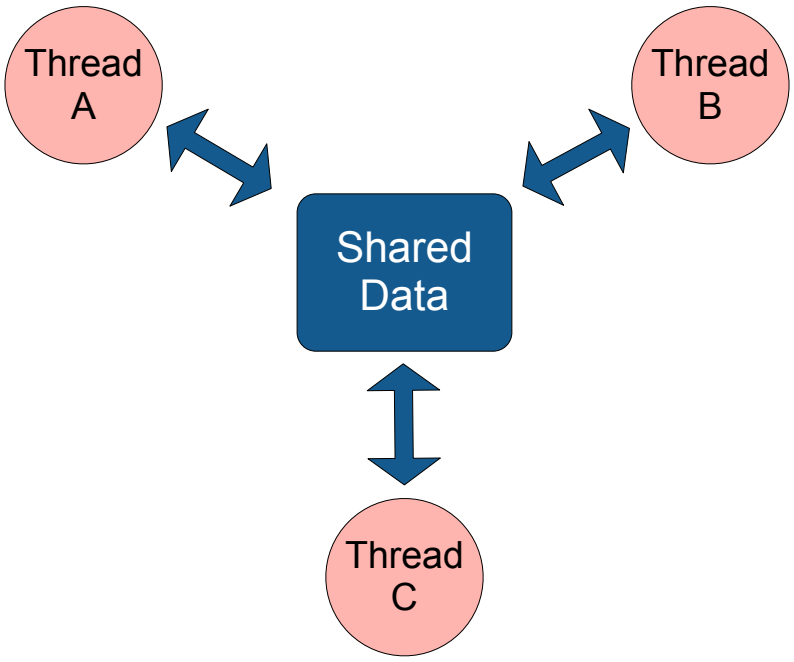
Synchronization



ATM Program

```
// get funds in account
int total = get_account_total();

// get amount to withdraw
int withdraw = get_withdraw_amount();

// check for sufficient funds
if (total >= withdraw) {

   // withdraw funds from account
   update_account_total(total - withdraw);
   dispense_money(withdraw);

}
```

Too Much Milk

```
if (noMilk) {
  buy milk;
}
```

```
if (noMilk) {
  buy milk;
}
```

Time	You	Your Roommate
3:00	Arrive home	
3:05	Look in fridge, no milk	
3:10	Leave for grocery store	
3:15		Arrive home
3:20	Arrive at grocery store	Look in fridge, no milk
3:25	Buy milk	Leave for grocery store
3:30	Arrive home, put milk in fridge	
3:35		Arrive at grocery store
3:40		Buy milk
3:45		Arrive home – **too much milk!**

Too Much Milk: Solution 1?

Thread A

```
if (noMilk & noNote) {
    leave note;
    buy milk;
    remove note;
}
```

Thread B

```
if (noMilk & noNote) {
    leave note;
    buy milk;
    remove note;
}
```

Too Much Milk: Solution 2?

Thread A

```
leave note A;
if (noNote B) {
   if (noMilk) {
      buy milk;
   }
}
remove note A;
```

Thread B

```
leave note B;
if (noNote A) {
   if (noMilk) {
      buy milk;
   }
}
remove note B;
```


Too Much Milk: Solution 3?

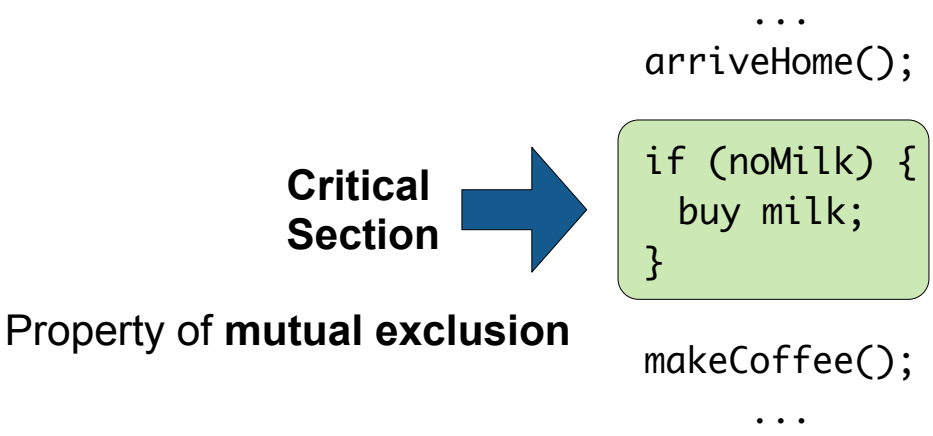
Thread A

```
leave note A;
while (note B) {
   do nothing;
}
if (noMilk) {
   buy milk;
}
remove note A;
```

Thread B

```
leave note B;
if (noNote A) {
   if (noMilk) {
      buy milk;
   }
}
remove note B;
```

Critical Sections



Property of **mutual exclusion**

Mutex Locks

Too Much Milk with Locks

Thread A

```
lock.acquire();
if (noMilk) {
   buy milk;
}
lock.release();
```

Thread B

```
lock.acquire();
if (noMilk) {
   buy milk;
}
lock.release();
```


Implementing Locks: Interrupts (version 1)

```
class Lock {
  public:
    void acquire();
    void release();
}
```

```
Lock::acquire() {
  disable interrupts;
}
```

```
Lock::release() {
  enable interrupts;
}
```

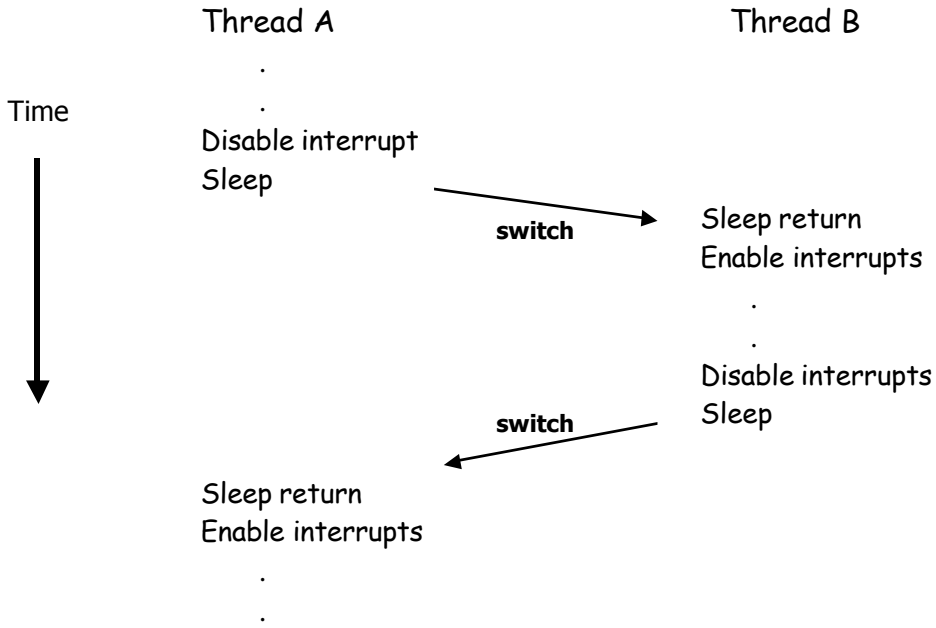
Implementing Locks: Interrupts (version 2)

```
class Lock {
  public:
    void acquire();
    void release();
  private:
    int value = FREE;
    Queue Q = empty;
}
```

```
Lock::acquire() {
  disable interrupts;
  if (value == FREE) {
     value = BUSY;
  } else {
     add curThread to Q;
     put curThread to sleep;
  }
  enable interrupts;
}
```

```
Lock::release() {
  disable interrupts;
  if queue not empty {
     take thread T off Q;
     put T on ready queue;
  } else {
     value = FREE;
  }
  enable interrupts;
}
```


Interrupt Disable/Enable Pattern



Implementing Locks: Atomic Test&Set

```
class Lock {
  public:
    void acquire();
    void release();
  private:
    int value = FREE;
}
```

```
Lock::acquire() {
  while (test&set(value) == BUSY) {
    // do nothing
  }
}
```

```
Lock::release() {
  value = FREE;
}
```


Minimizing Busy-Waiting

```
class Lock {
  public:
    void acquire();
    void release();
  private:
    int value = FREE;
    int guard = 0;
    Queue Q = empty;
}
```

```
Lock::acquire() {
  while (test&set(guard) == 1) {
    // do nothing
  }
  if (value == FREE) {
    value = BUSY;
    guard = 0;
  } else {
    put curThread on Q;
    guard = 0 & put curThread to sleep;
  }
}
```

```
Lock::release() {
  while (test&set(guard) == 1) {
    // do nothing
  }
  if Q is not empty {
    take T off Q;
    put T on ready queue;
  } else {
    value = FREE;
  }
  guard = 0;
}
```

Producer/Consumer

```
class ProducerConsumer {

  private Queue<Item> queue;
  private Lock lock;

  public void add(Item item) {
    lock.acquire();
    queue.add(item);
    lock.release();
  }

  public Item remove() {
    lock.acquire();
    Item item = queue.remove();
    lock.release();
    return item;
  }

}
```

What if full?

What if empty?

Condition Variables

```
private Queue<Item> queue;
private Lock lock;
private ConditionVariable cv;
```

```
public void add(Item item) {
  lock.acquire();

  queue.add(item);
  cv.signal(lock);

  lock.release();
}
```

```
public Item remove() {
  lock.acquire();

  while (queue.isEmpty()) {
    // release lock & sleep
    cv.wait(lock);
  }
  Item item = queue.remove();

  lock.release();
  return item;
}
```

Mesa semantics

Condition Variables (2)

```
private Queue<Item> queue;
private Lock lock;
private ConditionVariable cv1, cv2;
```

```
public void add(Item item) {
  lock.acquire();

  while (queue.isFull()) {
    cv2.wait(lock);
  }
  queue.add(item);
  cv1.signal(lock);

  lock.release();
}
```

```
public Item remove() {
  lock.acquire();

  while (queue.isEmpty()) {
    cv1.wait(lock);
  }
  Item item = queue.remove();
  cv2.signal(lock);

  lock.release();
  return item;
}
```

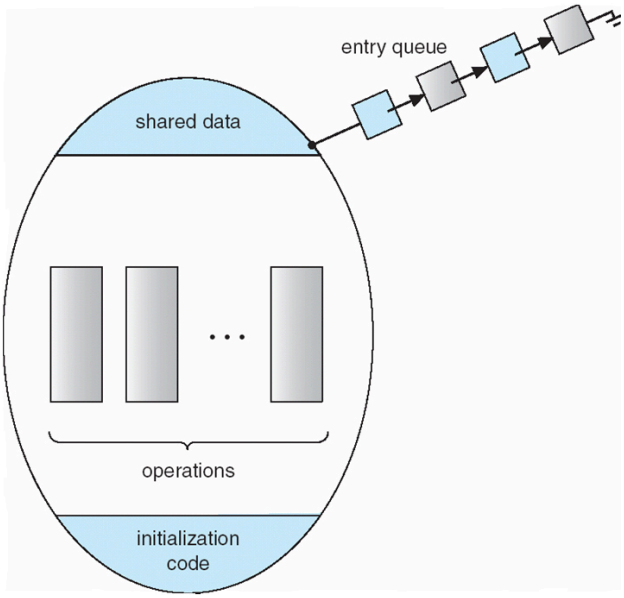

Implementing Condition Variables

```
class ConditionVariable {
  public:
    void wait(Lock cvLock);
    void signal();
  private:
    Queue Q = empty;
    Lock Qlock = FREE;
}
```

```
ConditionVariable::wait(Lock cvLock) {
  Qlock.acquire();
  put curThread on Q;
  Qlock.release();
  cvLock.release() & put curThread to sleep;
  cvLock.acquire();
}
```

```
ConditionVariable::signal() {
  Qlock.acquire();
  if Q is not empty {
    take T off Q;
    put T on ready queue;
  }
  Qlock.release();
}
```

Monitors



Producer/Consumer (redux)

```
class ProducerConsumer {

  private Queue<Item> queue;
  private Lock lock;

  public void add(Item item) {
    lock.acquire();
    queue.add(item);
    lock.release();
  }

  public Item remove() {
    lock.acquire();
    Item item = queue.remove();
    lock.release();
    return item;
  }

}
```

Producer/Consumer with Java Monitors

```
class ProducerConsumer {

  private Queue<Item> queue;

  public synchronized void add(Item item) {
    queue.add(item);
  }

  public synchronized Item remove() {
    return queue.remove();
  }

}
```


Java Condition Variables

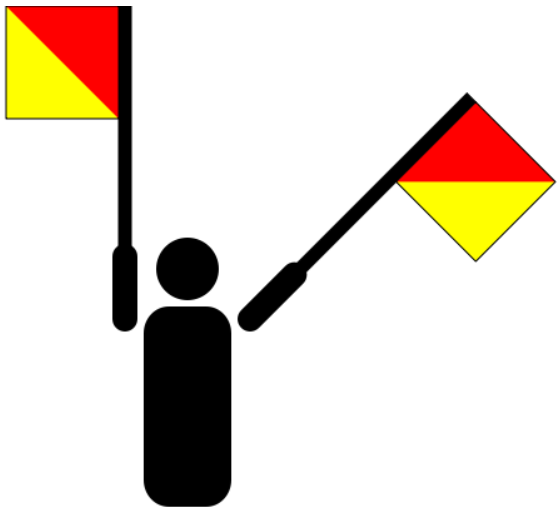
```
class ProducerConsumer {

  private Queue<Item> queue;

  public synchronized void add(Item item) {
    queue.add(item);
    this.notify(); // signal
  }

  public synchronized Item remove() {
    while (queue.isEmpty()) {
      this.wait(); // release lock and sleep
    }
    return queue.remove();
  }

}
```

Too Few Chairs

Threads A, B, C, ...

```
if (chairs > 0) {
    chairs--;
    doSomeWork();
    chairs++;
}
```


Semaphores



Counting Semaphore

```
sem = new Semaphore(NUM_CHAIRS);
```

Threads A, B, C, ...

```
sem.wait();
doSomeWork();
sem.signal();
```


Binary Semaphore

```
sem = new Semaphore(1);
```

Threads A, B, C, ...

```
sem.wait();
if (noMilk) {
   buy milk;
}
sem.signal();
```

Semaphore for Ordering

```
sem = new Semaphore(0);
```

Thread A

```
attend_os_class();
write_notes();
sem.signal();
```

Thread B

```
sem.wait();
read_notes();
do_os_project();
```


Condition Variables (redux)

```
private Queue<Item> queue;
private Lock lock;
private ConditionVariable cv1, cv2;
```

```
public void add(Item item) {
  lock.acquire();

  while (queue.isFull()) {
    cv2.wait(lock);
  }
  queue.add(item);
  cv1.signal(lock);

  lock.release();
}
```

```
public Item remove() {
  lock.acquire();

  while (queue.isEmpty()) {
    cv1.wait(lock);
  }
  Item item = queue.remove();
  cv2.signal(lock);

  lock.release();
  return item;
}
```

Producer/Consumer with Semaphores

```
private Queue<Item> queue(N); // capacity N
private Semaphore mutex = 1;  // binary (lock)
private Semaphore empty = N;  // # free slots
private Semaphore full = 0;   // # occupied slots
```

```
public void add(Item item) {

  // one fewer slot, or wait
  empty.wait();

  mutex.wait();
  queue.add(item);
  mutex.signal();

  // one more used slot
  full.signal();
}
```

```
public Item remove() {

  // wait until nonempty
  full.wait();

  mutex.wait();
  Item item = queue.remove();
  mutex.signal();

  // one more free slot
  empty.signal();

  return item;
}
```


Implementing Semaphores

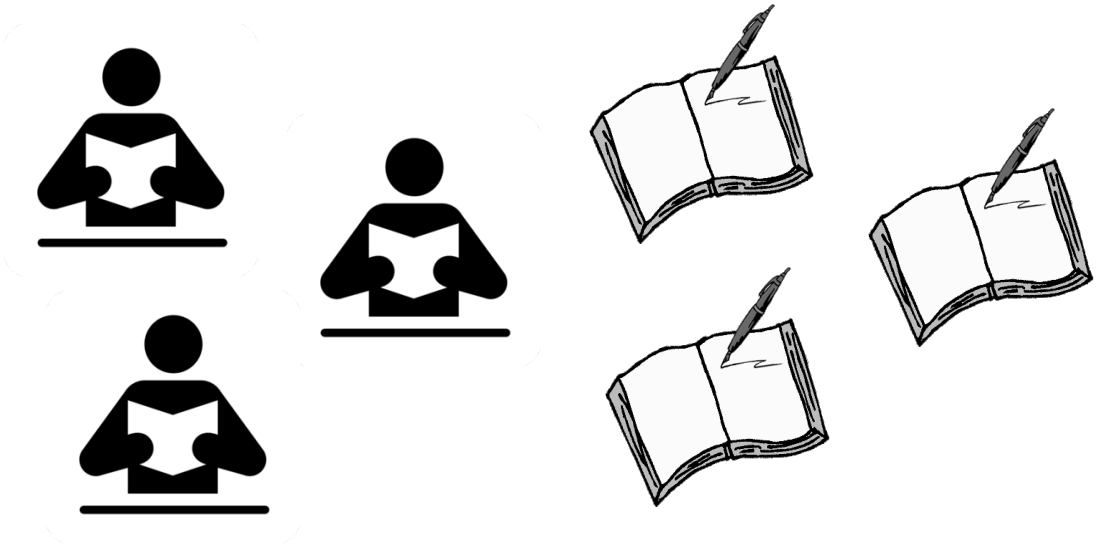
```
class Semaphore {
  public:
    Semaphore(int N); // starting value
    void wait();
    void signal();
  private:
    int value = N;
    Queue Q = empty;
}
```

```
Semaphore::wait() {
   value--;
   if (value < 0) {
      put curThread on Q;
      put curThread to sleep;
   }
}
```

```
Semaphore::signal() {
   value++;
   if (value <= 0) {
      take T off Q;
      put T on ready queue;
   }
}
```

(+ atomicity via interrupts or Test&Set)

Readers/Writers Problem



Readers/Writers with Semaphores

```
class ReadWrite {
   public:
      void read();
      void write();
   private:
      Semaphore wrt = 1;
      Semaphore mutex = 1;
      int readers = 0;
}

ReadWrite::write() {
   wrt.wait();
   <perform write>
   wrt.signal();
}
```

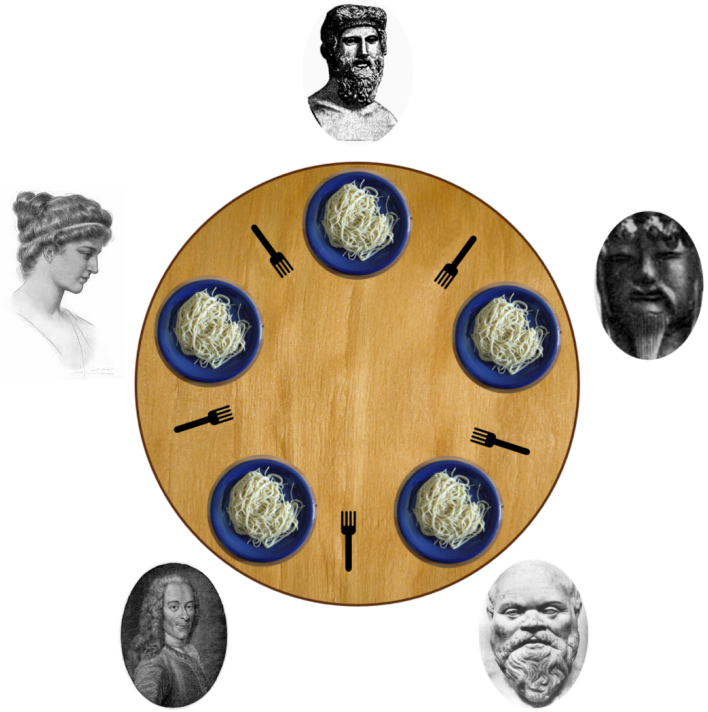
```
ReadWrite::read() {
   mutex.wait();
   readers++;
   if (readers == 1)
      wrt.wait();
   mutex.signal();
   <perform read>
   mutex.wait();
   readers--;
   if (readers == 0)
      wrt.signal();
   mutex.signal();
}
```

Readers/Writers with Monitors

```
private int numReaders = 0;
private int numWriters = 0;

private synchronized void prepareRead() {
  while (numWriters > 0) wait();
  numReaders++;
}

private synchronized void doneRead() {
  numReaders--;
  if (numReaders == 0) notify();
}

public void read() {
  // reads NOT synchronized
  prepareRead();
  <perform read>
  doneRead();
}
```

```
private void prepareWrite() {
    numWriters++;
    while (numReaders > 0) wait();
}

private void doneWrite() {
    numWriters--;
    notify();
}

public synchronized void write() {
    // writes synchronized
    prepareWrite();
    <perform write>
    doneWrite();
}
```


The Dining Philosophers



Dining Philosophers with Locks

Deadlock!

```
Lock chopsticks[5];

void philosopher(int i) {
  while (true) {

    think();

    chopsticks[i].acquire(); // left chopstick
    chopsticks[(i+1)%5].acquire(); // right chopstick

    eat();

    chopsticks[i].release();
    chopsticks[(i+1)%5].release();
  }
}
```


Dining Philosophers with Monitors

```
monitor DiningPhilosophers  {
   enum {EAT, THINK, HUNGRY}
      state[5];
   condition self[5];
}

void synchronized pickup(int i) {
   state[i] = HUNGRY;
   tryEat(i);
   if (state[i] != EAT)
     self[i].wait();
}

void synchronized putdown(int i) {
   state[i] = THINK;
   // test left and right neighbors
   tryEat((i+4)%5);
   tryEat((i+1)%5);
}
```

```
void philosopher(int i) {
  state[i] = THINK;
  while (true) {
    think();
    pickup(i); // pickup both
    eat();
    putdown(i);
  }
}


void tryEat(int n) {
  // check left and right of n
  if (state[n] == HUNGRY &&
      state[(n+4)%5] != EAT &&
      state[(n+1)%5] != EAT) {
    state[n] = EAT;
    self[n].signal();
  }
}
```

Deadlock

Thread A:

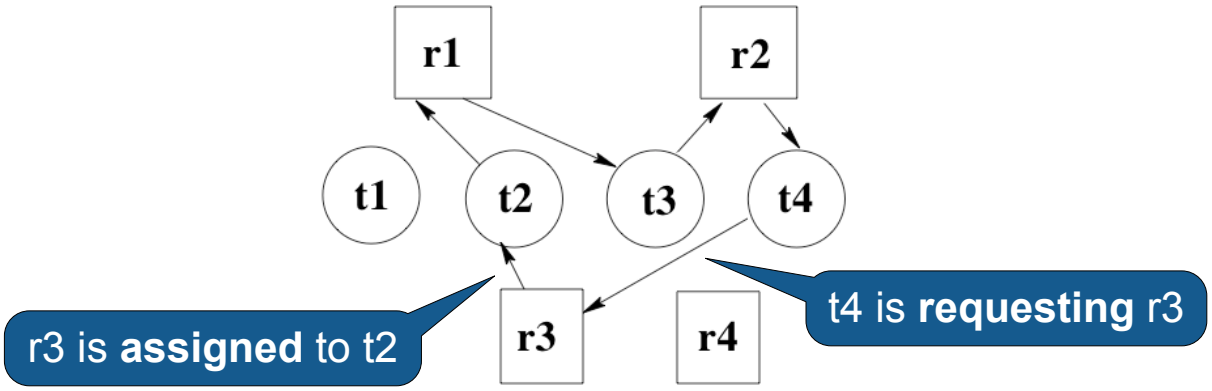
```
lock1.acquire();
lock2.acquire();

// do something

lock1.release();
lock2.release();
```

Thread B:

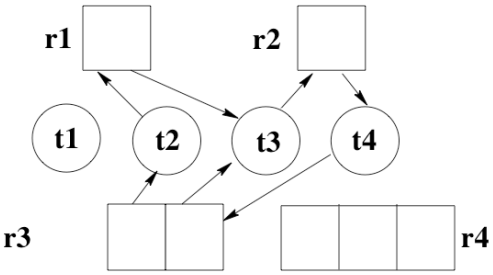
```
lock2.acquire();
lock1.acquire();

// do something

lock1.release();
lock2.release();
```

Thread group waiting on events from same group

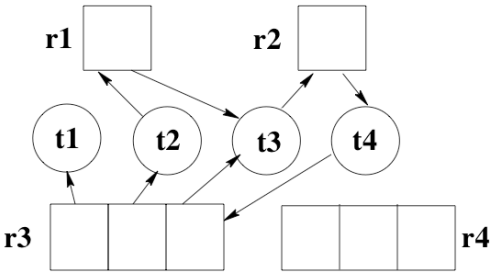
Resource Allocation Graph



Multiple Copies of Resources



Deadlock!



No deadlock!

Allocation Example

3 threads, 12 interchangeable resources (11 used)

	maximum	current	could request
t_1	4	3	1
t_2	8	4	4
t_3	12	4	8

Safe state!

Allocation Example

t_3 requests last resource (now all 12 used)

	maximum	current	could request
t_1	4	3	1
t_2	8	4	4
t_3	12	5	7

Unsafe state!

Deadlock Avoidance with RAG