CSE 332:
Locks and Deadlocks

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Announcements

Recall Bank Account Problem

```
class BankAccount {
  private int balance = 0;
  synchronized int getBalance()
    { return balance; }
  synchronized void setBalance(int x)
    { balance = x; }
  synchronized void withdraw(int amount) {
        int b = getBalance();
     if(amount > b)
       throw …
     setBalance(b – amount);
  }
  // deposit would also use synchronized
}
```

Call to setBalance in withdraw

- tries to lock **this**

Re-Entrant Lock

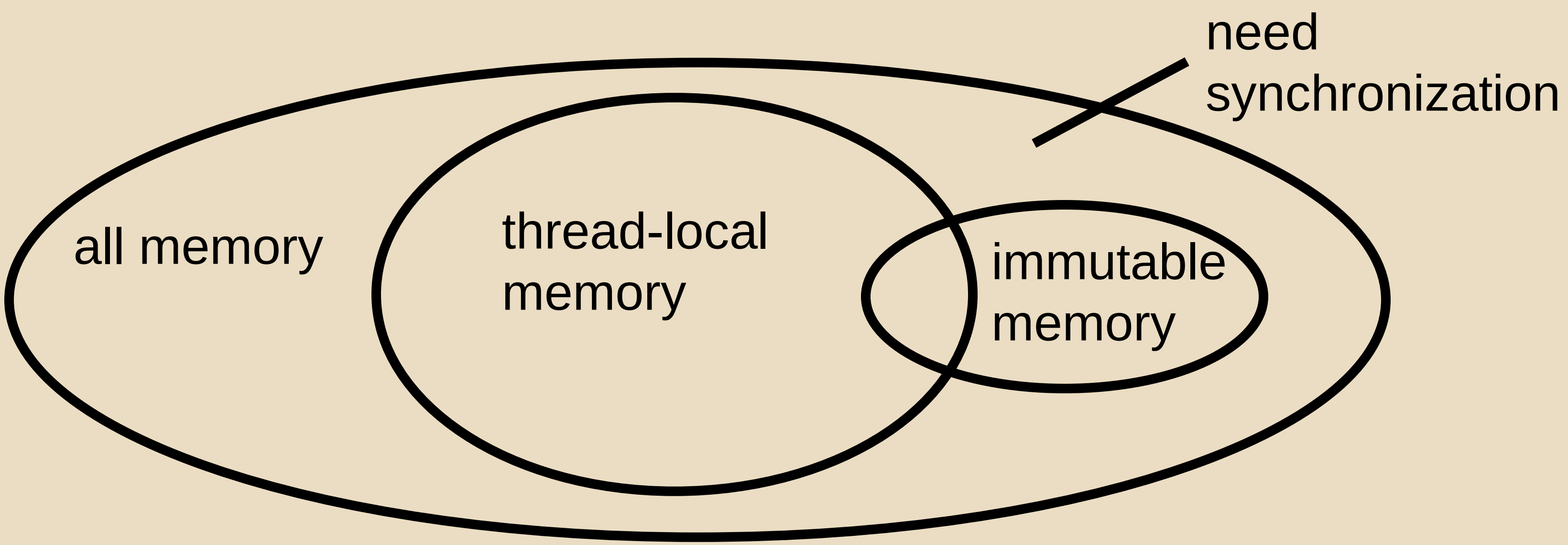
- A re-entrant lock (a.k.a. recursive lock)
  - If a thread holds a lock, subsequent attempts to acquire the **same lock** in the **same thread** won't block
  - **`withdraw`** can acquire the lock and **`setBalance`** can also acquire it
  - implemented by maintaining a count of how many times each lock is acquired in each thread, and decrementing the count on each release.

- Java **`synchronize`** locks are re-entrant

Lock everything? No.

For every memory location (e.g., object field), obey at least one of the following:

1. **Thread-local**: only one thread sees it
2. **Immutable**: read-only
3. **Shared-and-mutable**: control access via a lock



Thread local

Whenever possible, do ***not*** share resources

- easier to give each thread its own local copy
- only works if threads don't need to communicate via resource

In typical concurrent programs, the vast majority of objects should be thread local: shared memory should be rare—minimize it

Immutable

If location is read-only, no synchronizatin is necessary

Whenever possible, do ***not*** update objects

- make new objects instead!
- one of the key tenets of *functional programming* (CSE 341)

In practice, programmers usually over-use mutation – minimize it

The rest: keep it synchronized

Other Forms of Locking in Java

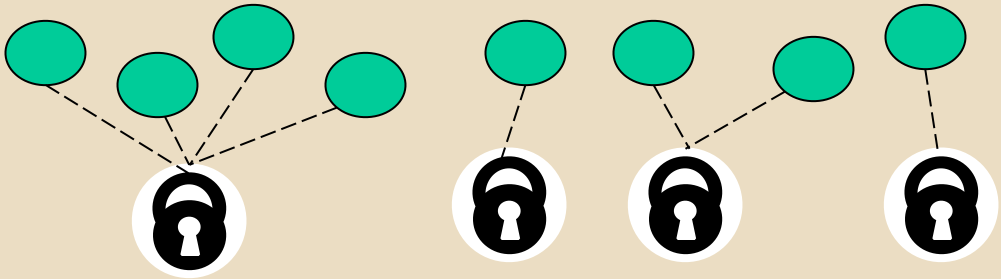
- Java provides many other features and details. See, for example:
  - Chapter 14 of CoreJava, Volume 1 by Horstmann/Cornell
  - Java Concurrency in Practice by Goetz et al

Locking Guidelines

- Correctness
- Consistency: make it well-defined
- Granularity: coarse to fine
- Critical Sections: make them small, atomic
- Leverage libraries

Consistent Locking

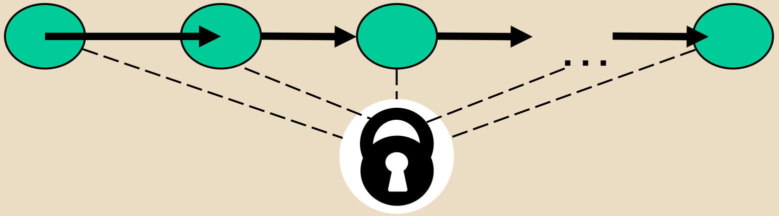
- Clear mapping of locks to resources
  - followed by all methods
  - clearly documented
  - same lock can guard multiple resources



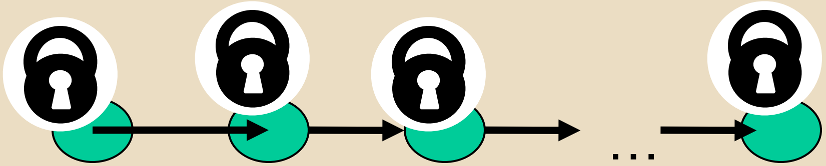
  - what's a resource? Conceptual:
    - object
    - field
    - data structure (e.g., linked list, hash table)

Lock Granularity

- Coarse grained: fewer locks, more objects per lock
  - e.g., one lock for entire data structure (e.g., linked list)



  - advantage:
  - disadvantage:
- Fine grained: more locks, fewer objects per lock
  - e.g., one lock for each item in the linked list



Lock Granularity

Example: hashtable with separate chaining

- coarse grained: one lock for whole table
- fine grained: one lock for each bucket

Which supports more concurrency for **`insert`** and **`lookup`**?

Which makes implementing **`resize`** easier?

Suppose hashtable maintains a **`numElements`** field. Which locking approach is better?

Critical Sections

- Critical sections:
  - how much code executes while you hold the lock?
  - want critical sections to be short
  - make them “atomic”: think about smallest sequence of operations that have to occur at once (without data races, interleavings)

Critical Sections

- Suppose we want to change a value in a hash table
  - assume one lock for the entire table
  - computing the new value takes a long time (“expensive”)

```
synchronized(lock) {
  v1 = table.lookup(k);
  v2 = expensive(v1);
  table.remove(k);
  table.insert(k,v2);
}
```

Critical Sections

- Suppose we want to change a value in the hash table
  - assume one lock for the entire table
  - computing the new value takes a long time (“expensive”)
  - will this work?

```
synchronized(lock) {
  v1 = table.lookup(k);
}
v2 = expensive(v1);
synchronized(lock) {
  table.remove(k);
  table.insert(k,v2);
}
```

Critical Sections

- Suppose we want to change a value in the hash table
  - assume one lock for the entire table
  - computing the new value takes a long time ("expensive")
  - convoluted fix:

```
done = false;
while(!done) {
  synchronized(lock) {
    v1 = table.lookup(k);
  }
  v2 = expensive(v1);
  synchronized(lock) {
    if(table.lookup(k)==v1) {
      done = true; // I can exit the loop!
      table.remove(k);
      table.insert(k,v2);
}}}
```

Leverage Libraries

- Use built-in libraries whenever possible
- In “real life”, it is unusual to have to write your own data structure from scratch
  - Implementations provided in standard libraries
  - Point of CSE332 is to understand the key trade-offs, abstractions, and analysis of such implementations

- Especially true for concurrent data structures
  - Very difficult to provide fine-grained synchronization without race conditions
  - Standard thread-safe libraries like **`ConcurrentHashMap`** written by world experts

Another Bank Operation

Consider transferring money:

```
class BankAccount {
  …
  synchronized void withdraw(int amt) {…}
  synchronized void deposit(int amt) {…}
  synchronized void transferTo(int amt,
                               BankAccount a) {
    this.withdraw(amt);
    a.deposit(amt);
  }
}
```

What can go wrong?

Deadlock

`x` and **`y`** are two different accounts

Time

```
acquire lock for x
withdraw from x



block on lock for y
```

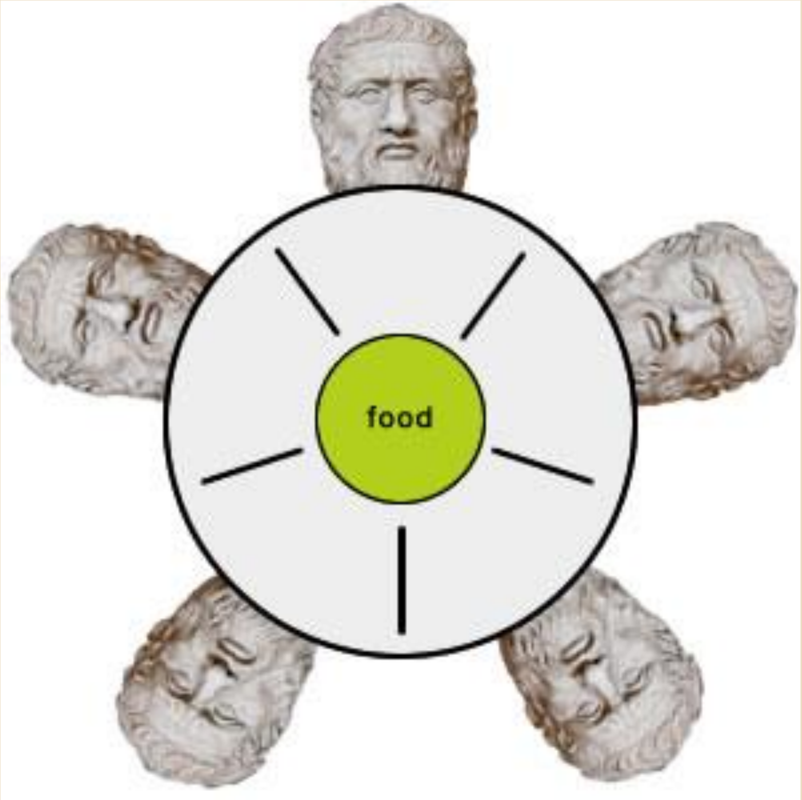
```


acquire lock for y
withdraw from y

block on lock for x
```

Thread 1: **`x.transferTo(1,y)`**

Thread 2: **`y.transferTo(1,x)`**

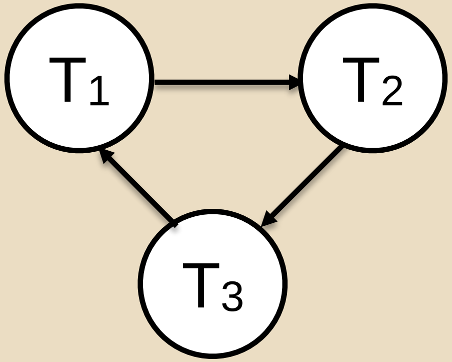
Dining Philosopher's Problem

- 5 Philosopher's eating rice around a table
- one chopstick to the left and right of each
- first grab the one on your left, then on your right…



Deadlock = Cycles

- Multiple threads depending on each other in a cycle



  - T2 has lock that T1 needs
  - T3 has lock that T2 needs
  - T1 has lock that T3 needs

- Solution?

How to Fix Deadlock?

In Banking example

```
class BankAccount {
  …
  synchronized void withdraw(int amt) {…}
  synchronized void deposit(int amt) {…}
  synchronized void transferTo(int amt,
                               BankAccount a) {
    this.withdraw(amt);
    a.deposit(amt);
  }
}
```

How to Fix Deadlock?

Separate withdraw from deposit

```
class BankAccount {
  …
  synchronized void withdraw(int amt) {…}
  synchronized void deposit(int amt) {…}
  synchronized void transferTo(int amt,
                                BankAccount a) {
    this.withdraw(amt);
    a.deposit(amt);
  }
}
```

Problems?

Possible Solutions

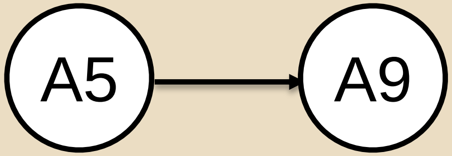
1. **`transferTo`** not synchronized
   – exposes intermediate state after **`withdraw`** before **`deposit`**
   – may be okay here, but exposes wrong total amount in bank

2. Coarsen lock granularity: one lock for each pair of accounts allowing transfers between them
   – works, but sacrifices concurrent deposits/withdrawals

3. Give every bank-account a unique ID and always acquire locks in the same ID order
   – *Entire program* should obey this order to avoid cycles

Ordering Accounts

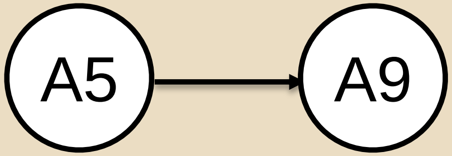
Transfer from bank account 5 to account 9



1. lock A5
2. lock A9
3. withdraw from A5
4. deposit to A9

Ordering Accounts

Transfer from bank account 5 to account 9



1. lock A5
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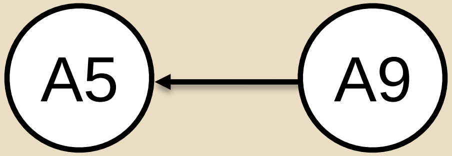
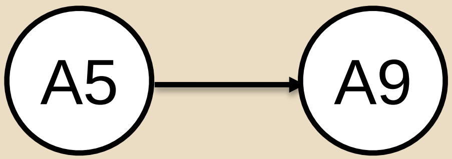
Transfer from bank account 9 to account 5



1. lock
2. lock
3. withdraw from
4. deposit to

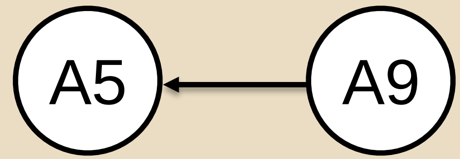
Ordering Accounts

Transfer from bank account 5 to account 9



1. lock A5
2. lock A9
3. withdraw from A5
4. deposit to A9

Transfer from bank account 9 to account 5



1. lock
2. lock
3. withdraw from
4. deposit to

No interleavings will produce deadlock!

– T1 cannot block on A9 until it has A5
– T2 cannot acquire A9 until it has A5

Banking Without Deadlocks

```
class BankAccount {
  …
  private int acctNumber; // must be unique
  void transferTo(int amt, BankAccount a) {
    if(this.acctNumber < a.acctNumber)
       synchronized(this) {
       synchronized(a) {
          this.withdraw(amt);
          a.deposit(amt);
       }}
    else
       synchronized(a) {
       synchronized(this) {
          this.withdraw(amt);
          a.deposit(amt);
       }}
  }
}
```

Lock Ordering

- Useful in many situations
  - e.g., when moving an item from work queue A to B, need to acquire locks in a particular order
- Doesn't always work
  - not all objects can be naturally ordered
  - Java StringBuffer append is subject to deadlocks
    - thread 1: append string A onto string B
    - thread 2: append string B onto string A

Locking a Hashtable

- Consider a hashtable with
  - many simultaneous **`lookup`** operations
  - rare **`insert`** operations

- What's the right locking strategy?

Read vs. Write Locks

- Recall race conditions
  - two simultaneous write to same location
  - one write, one simultaneous read
- But two simultaneous reads OK
- Synchronize is too strict
  - blocks simultaneous reads

Readers/Writer Locks

A new synchronization ADT: The readers/writer lock

- A lock's states fall into three categories:
  - "not held"
  - "held for writing" by one thread
  - "held for reading" by *one or more* threads

$0 \leq$ writers ≤ 1
$0 \leq$ readers
writers*readers==0

- **`new:`** make a new lock, initially "not held"
- **`acquire_write:`** block if currently "held for reading" or "held for writing", else make "held for writing"
- **`release_write:`** make "not held"
- **`acquire_read:`** block if currently "held for writing", else make/keep "held for reading" and increment *readers count*
- **`release_read:`** decrement readers count, if 0, make "not held"

In Java

Java's **synchronized** statement does not support readers/writer

Instead, library

java.util.concurrent.locks.ReentrantReadWriteLock

- Different interface: methods **readLock** and **writeLock** return objects that themselves have **lock** and **unlock** methods

Concurrency Summary

- Parallelism is powerful, but introduces new concurrency issues:
  - Data races
  - Interleaving
  - Deadlocks
- Requires synchronization
  - Locks for mutual exclusion
- Guidelines for correct use help avoid common pitfalls