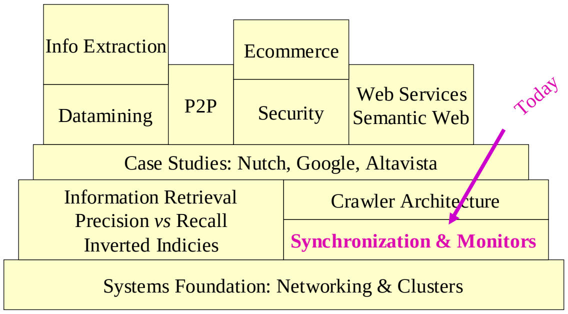
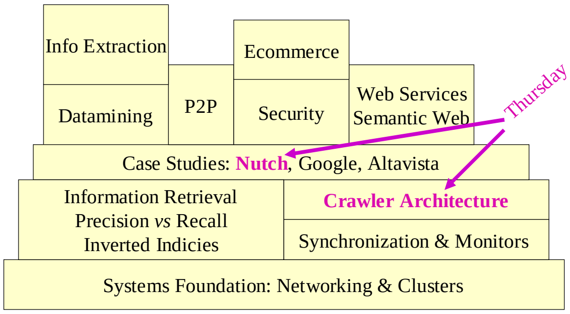
# CSE 454

## Synchronization, Monitors, Deadlocks

# Course Overview



# Course Overview



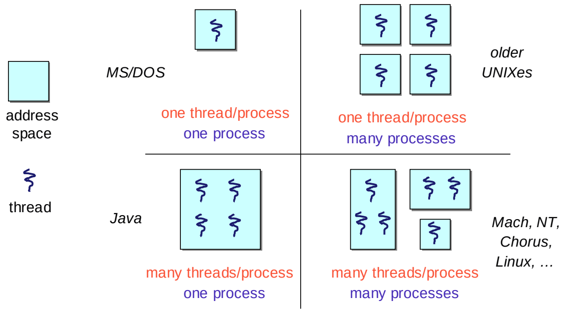
# Reading

- ***Focused Crawling: A New Approach To Topic-Specific Web Resource Discovery,***
- ***Efficient Crawling Through URL Ordering,***
  - *Ideas may well help your crawler find webcams*
  - *Read to the extent that they are helpful*
- ***The Anatomy Of A Large-Scale Hypertextual Web Search Engine***
  - "Must" reading for everyone

# Threads and processes

- **Most modern OS's support two entities:**
  - the process defines the address space and general process attributes (such as open files, etc.)
  - the thread defines a sequential execution stream within a process
- **A thread is bound to a single process**
  - processes can have multiple threads executing within them
  - sharing data between threads is cheap: all see same address space
- **Threads become the unit of scheduling**
  - processes are just containers in which threads execute

# Thread Design Space



## Synchronization

- **Threads cooperate in multithreaded programs**
  - to share resources, access shared data structures
    - e.g., threads accessing a memory cache in a web server
  - also, to coordinate their execution
    - e.g., a disk reader thread hands off a block to a network writer
- **For correctness, we have to control this cooperation**
  - must assume threads interleave executions arbitrarily and at different rates
    - scheduling is not under application writers' control
  - we control cooperation using synchronization
    - enables us to restrict the interleaving of executions
- **Note: this also applies to processes, not just threads**
  - and it also applies across machines in a distributed system

## Shared Resources

- **Focus on coordinating access to shared resources**
  - basic problem:
    - two concurrent threads are accessing a shared variable
    - if the variable is read/modified/written by both threads, then access to the variable must be controlled
    - otherwise, unexpected results may occur
- **Overview:**
  - mechanisms to control access to shared resources
    - low level mechanisms like locks
    - higher level mechanisms like monitors and condition variables
  - patterns for coordinating access to shared resources
    - bounded buffer, producer-consumer, …

## The classic example

- **Suppose we have to implement a function to withdraw money from a bank account:**

```
int withdraw(account, amount) {
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

- **Now suppose that you and your S.O. share a bank account with a balance of $100.00**
  - what happens if you both go to separate ATM machines, and simultaneously withdraw $90.00 from the account?

## Example continued

- **Represent the situation by creating a separate thread for each person to do the withdrawals**
  - have both threads run on the same bank mainframe:

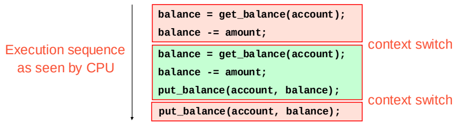
```
int withdraw(account, amount) {
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

```
int withdraw(account, amount) {
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

- **What's the problem with this?**
  - what are the possible balance values after this runs?

## Interleaved Schedules

- **The problem is that the execution of the two threads can be interleaved, assuming preemptive scheduling:**



```
balance = get_balance(account);
balance -= amount;
```

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
```

```
put_balance(account, balance);
```

- **What's the account balance after this sequence?**
  - who's happy, the bank or you? ;)

## The crux of the matter

- **The problem: two concurrent threads access a shared resource (account) without any synchronization**
  - creates a race condition
  - output is non-deterministic, depends on timing
- **We need mechanisms for *controlling access* to shared resources in the face of concurrency**
  - so we can reason about the operation of programs
  - essentially, re-introducing determinism
- **Synchronization is necessary for any shared data structure**
  - buffers, queues, lists, hash tables, …

## When are Resources Shared?

- **Local variables are not shared**
  - – refer to data on the stack, each thread has its own stack
  - – never pass/share/store a pointer to a local variable on another thread's stack
- **Global variables are shared**
  - – stored in the static data segment, accessible by any thread
- **Dynamic objects are shared**
  - – stored in the heap, shared if you can name it
    - in C, can conjure up the pointer
      - – e.g. void *x = (void *) 0xDEADBEEF
    - in Java, strong typing prevents this
      - – must pass references explicitly

## Mutual Exclusion

- **We want to use mutual exclusion to synchronize access to shared resources**
- **Code that uses mutual exclusion to synchronize its execution is called a critical section**
  - – only one thread at a time can execute in the critical section
  - – all other threads are forced to wait on entry
  - – when a thread leaves a critical section, another can enter

## Critical Section Requirements

- Mutual exclusion
  - – at most one thread is in the critical section
- Progress
  - – if thread T is outside the critical section, then T cannot prevent thread S from entering the critical section
- Bounded waiting (no starvation)
  - – if thread T is waiting on the critical section, then T will eventually enter the critical section
    - assumes threads eventually leave critical sections
- **Performance**
  - – the overhead of entering and exiting the critical section is small with respect to the work being done within it

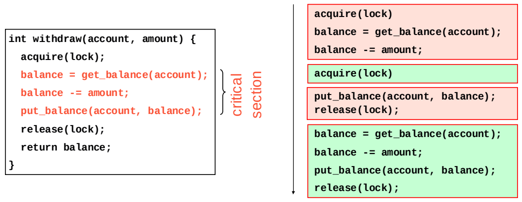
## Mechanisms for Building Critical Sections

- **Locks**
  - – very primitive, minimal semantics; used to build others
- **Semaphores**
  - – basic, easy to get the hang of, hard to program with
- **Monitors**
  - – high level, requires language support, implicit operations
  - – easy to program with;
  - – E.g., Java **"`synchronized()`"**
- **Messages**
  - – simple model of communication and synchronization based on (atomic) transfer of data across a channel
  - – direct application to distributed systems

## Locks

- **A lock is a object (in memory) that provides the following two operations:**
  - – acquire( ): a thread calls this before entering a critical section
  - – release( ): a thread calls this after leaving a critical section
- **Threads pair up calls to acquire( ) and release( )**
  - – between acquire( ) and release( ), the thread holds the lock
  - – acquire( ) does not return until the caller holds the lock
    - at most one thread can hold a lock at a time (usually)
  - – so: what can happen if the calls aren't paired?
- **Implementation requires hardware support**
  - – atomic `test-and-set` instruction
  - – disable interrupts

## Using Locks



```
int withdraw(account, amount) {
  acquire(lock);
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  release(lock);
  return balance;
}
```

```
acquire(lock)
balance = get_balance(account);
balance -= amount;
```

```
acquire(lock)
```

```
put_balance(account, balance);
release(lock);
```

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
release(lock);
```

- **What happens when green tries to acquire the lock?**
- **Why is the "return" outside the critical section?**
  - – is this ok?

# Deadlock

- **When two threads are waiting on a lock held by the other**

Dan: “Please get your clothes on Galen”

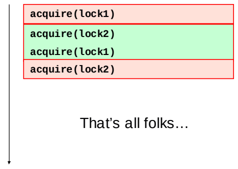
Galen: “Give me another math problem, Dad.”

Dan: “I’ll do that after you start getting your clothes on.”

Galen: “I won’t get my clothes on until you give me a problem.”

```
int dan() {
  acquire(lock1);
  acquire(lock2);
  critical
  section
  code
  release(lock2);
  release(lock1);
  return;
}
```

```
int galen() {
  acquire(lock2);
  acquire(lock1);
  critical
  section
  code
  release(lock1);
  release(lock2);
  return;
}
```



```
acquire(lock1)
acquire(lock2)
acquire(lock1)
acquire(lock2)
```

That’s all folks…

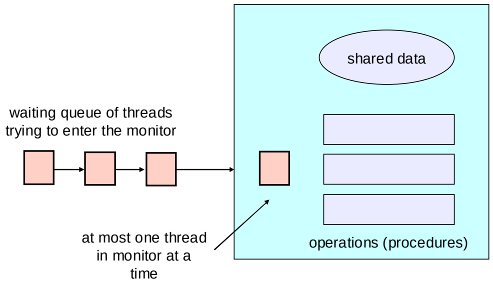
# Avoiding Deadlock

- **Simplest method**
- **Focus on lock order**
- **Every procedure should get locks in same order**
  - What if use overlapping sets of locks?

# Monitors

- **A programming language construct that supports controlled access to shared data**
  - synchronization code added by compiler, enforced at runtime
  - why does this help?
- **Monitor is a software module that encapsulates:**
  - shared data structures
  - procedures that operate on the shared data
  - synchronization between concurrent threads invoking those procedures
- **Monitor protects the data from unstructured access**
  - guarantees one may only access data through procedures
  - hence in legitimate ways

# A monitor



# Monitor facilities

- **Mutual exclusion**
  - only one process can be executing inside at any time
    - thus, synchronization implicitly associated with monitor
  - if a second process tries to enter a monitor procedure, it blocks until the first has left the monitor
    - more restrictive than locks, semaphores!
    - but easier to use most of the time
- **Once inside, a process may discover it can’t continue, and may wish to sleep**
  - or, allow some other waiting process to continue
  - condition variables provided within monitor
    - processes can wait or signal others to continue
    - condition variable can only be accessed from inside monitor

## Condition Variables

- **A place to wait; sometimes called a rendezvous point**
- **Three operations on condition variables**
  - wait(c)
    - wait for somebody else to signal condition
    - thus, condition variables have wait queues
  - signal(c)
    - release monitor lock, so somebody else can get in
    - wake up at most one waiting process/thread
    - if no waiting processes, signal is lost
  - broadcast(c)
    - release monitor lock
    - wake up all waiting processes/threads

## Bounded Buffer using Monitors

```
Monitor bounded_buffer {
    buffer resources[N];
    condition not_full, not_empty;

    procedure add_entry(resource x) {
        while(array "resources" is full)
            wait(not_full);
        add "x" to array "resources"
        signal(not_empty);
    }
    procedure get_entry(resource *x) {
        while (array "resources" is empty)
            wait(not_empty);
        *x = get resource from array "resources"
        signal(not_full);
    }
}
```

## Two Kinds of Monitors

- **Hoare monitors: signal(c) means**
  - run waiter immediately
  - signaler blocks immediately
    - condition guaranteed to hold when waiter runs
    - but, signaler must restore monitor invariants before signaling!
- **Mesa monitors: signal(c) means**
  - waiter is made ready, but the signaler continues
    - waiter runs when signaler leaves monitor (or waits)
    - condition is not necessarily true when waiter runs again
  - signaler need not restore invariant until it leaves the monitor
  - being woken up is only a hint that something has changed
    - must recheck conditional case

## Examples

- **Hoare monitors**
  - if (notReady)
    - wait(c)
- **Mesa monitors**
  - while(notReady)
    - wait(c)
- **Mesa monitors easier to use**
  - more efficient
  - fewer switches
  - directly supports broadcast

## Synchronization in the 454 Project

- **Multiple crawler threads**
  - More efficient than requesting, waiting for single page to download while doing nothing else (interleave I/O with computation)
- **What are the shared resources?**
  - Page Repository?
  - Queues?
    - Only one thread may take pages *off* a queue, but
    - What about adding to a thread's queue
  - Everything?
    - Consistent view during checkpointing