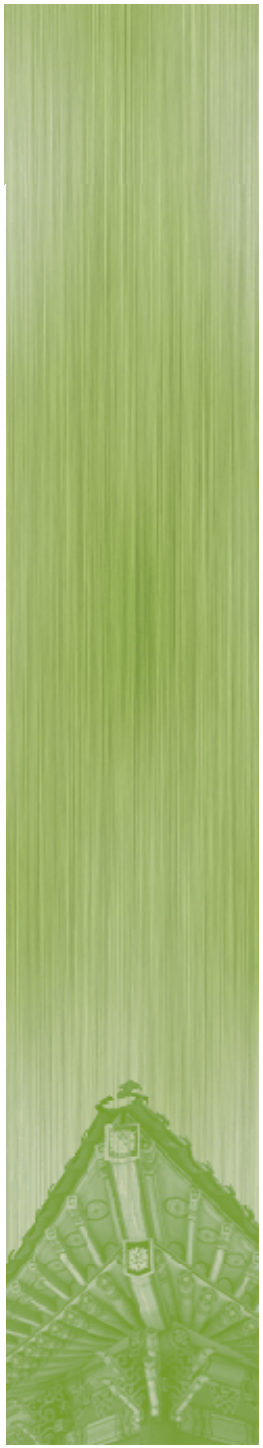
Midterm Exam

- **13:30 – 14:50, October 19 (Monday), 2009.**
- **Semiconductor building #330110**
- **Scope**
  - Chap. 1-4, Chap. 6 (Up to semaphores)
  - Pintos
- **Closed-book exam**

Grading Policy

- **Before**
  - Class attendance: 10%
  - Projects: 30%
  - Exams: 60%

- **After**
  - Class attendance: 10%
  - Projects: 45% (2% + 10% + 15% + 18%)
  - Exams: 45% (Mid 20% + Final 25%)



Synchronization I

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Today's Topics

- Synchronization problem
- Locks

Synchronization

- **Threads cooperate in multithreaded programs**
  - To share resources, access shared data structures
  - Also, to coordinate their execution

- **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 execution.
  - (Note) This also applies to processes, not just threads.
    - And it also applies across machines in a distributed system.

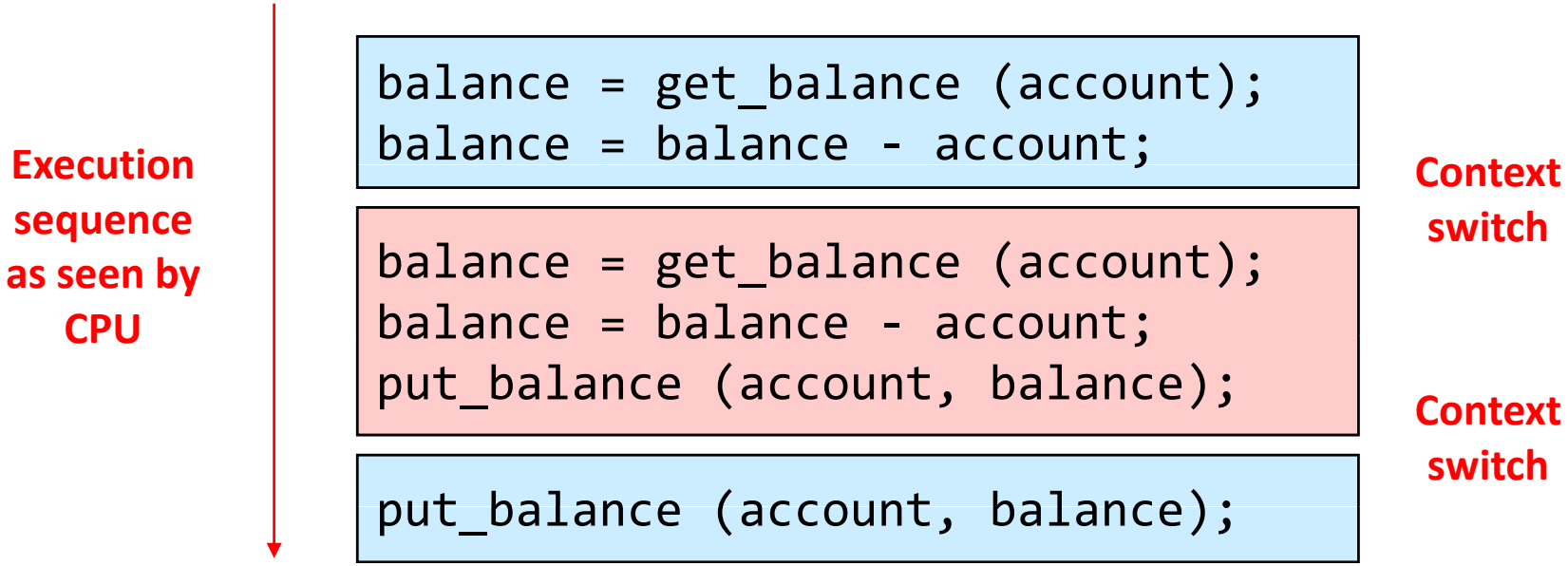
The Classic Example (1)

- **Withdraw money from a bank account**
  - Suppose you and your girl(boy) friend share a bank account with a balance of 1,000,000won.
  - What happens if both go to separate ATM machines, and simultaneously withdraw 100,000won from the account?

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

The Classic Example (2)

- **Interleaved schedules**
  - Represent the situation by creating a separate thread for each person to do the withdrawals.
  - The execution of the two threads can be interleaved, assuming preemptive scheduling:



Synchronization Problem

- **Problem**
  - Two concurrent threads (or processes) access a shared resource without any synchronization.
  - Creates a **race condition**:
    - The situation where several processes access and manipulate shared data concurrently.
    - The result is non-deterministic and depends on timing.
  - We need mechanisms for controlling access to shared resources in the face of concurrency.
    - So that we can reason about the operation of programs.
  - Synchronization is necessary for any shared data structure
    - buffers, queues, lists, etc.

Sharing Resources

- **Between threads**
  - 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 static data segment, accessible by any thread.
  - Dynamic objects are shared.
    - Stored in the heap, shared through the pointers.
- **Between processes**
  - Shared-memory objects, files, etc. are shared.

Critical Sections (1)

- **Critical sections**
  - Critical sections are parts of the program that access shared memory or shared files or other shared resources.
  - We want to use mutual exclusion to synchronize access to shared resources in critical sections.
    - 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.
  - Otherwise, critical sections can lead to race conditions.
    - The final result depends on the sequence of execution of the processes.

Critical Sections (2)

- **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.
  - **Performance**
    - The overhead of entering and exiting the critical section is small with respect to the work being done within it.

Critical Sections (3)

- **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: Java "synchronized"
  - **Messages**
    - Simple model of communication and synchronization based on (atomic) transfer of data across a channel.
    - Direct application to distributed systems.

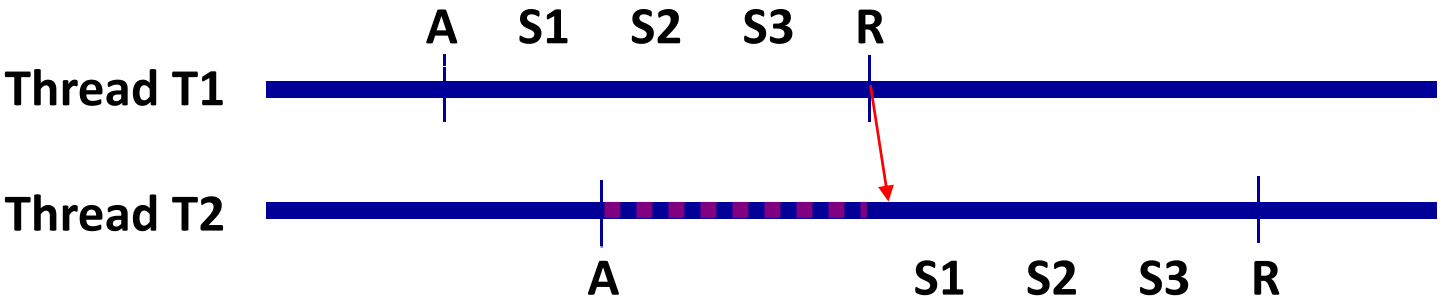
Locks

- **Locks**
  - A lock is an object (in memory) that provides the following two operations:
    - acquire(): wait until lock is free, then grab it.
    - release(): unlock, and wake up any thread waiting in acquire()
  - Using locks
    - Lock is initially free.
    - Call acquire() before entering a critical section, and release() after leaving it.
    - 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.
  - Locks can spin (a spinlock) or block (a mutex).

Using Locks

```
A    int withdraw (account, amount)
     {
     acquire (lock);
S1   balance = get_balance (account);
S2   balance = balance - amount;
S3   put_balance (account, balance);
R    release (lock);
     return balance;
     }
```

Critical section



Implementing Locks (1)

- **An initial attempt**

```
struct lock { int held = 0; }

void acquire (struct lock *l)  {
   while (l->held);
   l->held = 1;
}
void release (struct lock *l)   {
   l->held = 0;
}
```

The caller "busy-waits", or spins for locks to be released, hence spinlocks.

- Does this work?

Implementing Locks (2)

- **Problem**
  - Implementation of locks has a critical section, too!
    - The acquire/release must be atomic.
    - A recursion, huh?
  - Atomic operation
    - Executes as though it could not be interrupted.
    - Code that executes "all or nothing".

Implementing Locks (3)

- **Solutions**
  - Software-only algorithms
    - Dekker's algorithm (1962) (cf. Exercises 6.1)
    - Peterson's algorithm (1981)
    - Lamport's Bakery algorithm for more than two processes (1974)
  - Hardware atomic instructions
    - Test-and-set, compare-and-swap, etc.
  - Disable/reenable interrupts
    - To prevent context switches

Software-only Algorithms

- **Wrong algorithm**
  - Mutual exclusion?
  - Progress?

```
int interested[2];

void acquire (int process)   {
   int other = 1 - process;
   interested[process] = TRUE;
   while (interested[other]);
}

void release (int process)   {
   interested[process] = FALSE;
}
```

Peterson's Algorithm

- **Solves the critical section problem for two processes**

```
int turn;
int interested[2];

void acquire (int process)   {
   int other = 1 - process;
   interested[process] = TRUE;
   turn = other;
   while (interested[other] && turn == other);
}

void release (int process)   {
   interested[process] = FALSE;
}
```

Bakery Algorithm (1)

- **Multiple-process solution**
  - Before entering its critical section, process receives a sequence number.
  - Holder of the smallest number enters the critical section
  - If processes P_i and P_j receive the same number, if $i < j$, then P_i is served first; else P_j is served first.
  - The numbering scheme always generates numbers in increasing order of enumeration; i.e. 1,2,3,3,3,4,4,5…

Bakery Algorithm (2)

```
int number[N];
int choosing[N];

#define EARLIER(a,b)   \\
   ((number[a] < number[b]) || \\
   (number[a] == number[b] && \\
    (a) < (b)))

int Findmax ()   {
   int i;
   int max = number[0];
   for (i = 1; i < N; i++)
      if (number[i] > max)
         max = number[i];
   return max;
}
```

```
void acquire (int me)   {
   int other;
   choosing[me] = TRUE;
   number[me] = Findmax() + 1;
   choosing[me] = FALSE;
   for (other=0; other<N; other++)
   {
      while (choosing[other]);
      while (number[other] &&
                EARLIER(other, me));
   }
}

void release (int me)   {
   number[me] = 0;
}
```

Atomic Instructions (1)

- Test-and-Set

```
int TestAndSet (int *v)   {
    int rv = *v;
    *v = 1;
    return rv;
}
```

- Using Test-and-Set instruction

```
void struct lock { int value = 0; }

void acquire (struct lock *l)   {
    while (TestAndSet (&l->value));
}
void release (struct lock *l)   {
    l->value = 0;
}
```

Atomic Instructions (2)

- Swap

```
void Swap (int *v1, int *v2)   {
    int temp = *v1;
    *v1 = *v2;
    *v2 = temp;
}
```

- Using Swap instruction

```
void struct lock { int value = 0; }
void acquire (struct lock *l)   {
    int key = 1;
    while (key == 1) Swap(&l->value, &key);
}
void release (struct lock *l)   {
    l->value = 0;
}
```

Atomic Instructions (3)

- **Locks using Test-and-Set with bounded-waiting**

```
struct lock { int value = 0; }
int waiting[N];

void acquire (struct lock *l,
              int me)
{
   int key;

   waiting[me] = 1;
   key = 1;
   while (waiting[me] && key)
     key = TestAndSet (&l->value);
   waiting[me] = 0;
}
```

```
void release (struct lock *l,
              int me)
{
   int next = (me + 1) % N;

   while ((next != me) &&
          !waiting[next])
      next = (next + 1) % N;
   if (next == me)
      l->value = 0;
   else
      waiting[next] = 0;
}
```

Problems with Spinlocks

- **Spinlocks**
  - Horribly wasteful!
    - If a thread is spinning on a lock, the thread holding the lock cannot make progress.
    - The longer the critical section, the longer the spin.
    - CPU cycle is wasted.
    - Greater the chances for lock holder to be interrupted through involuntary context switch.
  - Only want to use spinlock as primitives to build higher-level synchronization constructs.

Disabling Interrupts (1)

- **Implementing locks by disabling interrupts**

```
void acquire (struct lock *l)  {
    cli();          // disable interrupts;
}
void release (struct lock *l)  {
    sti();          // enable interrupts;
}
```

- Disabling interrupts blocks notification of external events that could trigger a context switch (e.g., timer)
- There is no state associate with the lock.
- Can two threads disable interrupts simultaneously?

Disabling Interrupts (2)

- **What's wrong?**
  - Only available to kernel
    - Why not have the OS support these as system calls?
  - Insufficient on a multiprocessor
    - Back to atomic instructions
  - What if the critical section is long?
    - Can miss or delay important events.
      (e.g., timer, I/O)
  - Like spinlocks, only use to implement higher-level synchronization primitives.

Summary

- **Implementing locks**
  - Software-only algorithms
  - Hardware atomic instructions
  - Disable/reenable interrupts

- **Spinlocks and disabling interrupts are primitive synchronization mechanisms.**
  - They are used to build higher-level synchronization constructs.