MULTITHREADING AND SYNCHRONIZATION

CS124 – Operating Systems

Spring 2024, Lecture 9

Critical Sections

- Race conditions can be avoided by preventing multiple control paths from accessing shared state concurrently
  - Threads, processes, etc.
- A **critical section** is a piece of code that must not be executed concurrently by multiple control paths
- **Mutual exclusion**: carefully control entry into the critical section to allow only one thread of execution at a time
- Many different tools to enforce mutual exclusion in critical sections (semaphores, mutexes, read-write locks, etc.)
  - Generally, these locks block threads (passive waiting) until they can enter the critical section
- OS kernels frequently require additional tools that are compatible with use in interrupt context (i.e. nonblocking!)

Software Solutions

- A number of software solutions devised to implement mutual exclusion
- Example: Peterson's Algorithm:
  - Two processes P_0 and P_1, repeatedly entering a critical section
  - Implementation:

```
while (true) {      // i = 0 for P0, i = 1 for P1; j = 1 - i
    flag[i] = true;  // State intention to enter critical section.
    turn = j;        // Let other process go first, if they want!
    while (flag[j] && turn == j);      // Wait to enter critical section.
    …                // Critical section!
    flag[i] = false; // Leaving critical section.
    …                // Non-critical section.
}
```

Software Solutions (2)

- Peterson's Algorithm:
  - Two processes P_0 and P_1, repeatedly entering a critical section
  - Implementation:

```
while (true) {      // i = 0 for P0, i = 1 for P1; j = 1 - i
    flag[i] = true;  // State intention to enter critical section.
    turn = j;        // Let other process go first, if they want!
    while (flag[j] && turn == j);    // Wait to enter critical section.
    …                // Critical section!
    flag[i] = false; // Leaving critical section.
    …                // Non-critical section.
}
```

  - A process P_i can only exit the while-loop if one of these is true:
    - flag[j] is false (P$_j$ is outside the critical section)
    - turn == i (it's P$_i$'s turn to enter the critical section)

Software Solutions (3)

- Several other software solutions to mutual exclusion:
  - Dekker’s algorithm (first known correct solution)
  - Lamport’s bakery algorithm
  - Syzmanski’s algorithm
- All solutions are basically the same in how they work
  - Peterson’s algorithm is very representative
- Problem 1: processes must busy-wait in these solutions
  - This can be changed to passive waiting without much difficulty
- Problem 2: software solutions fail in the context of **out-of-order execution**
  - Compilers and advanced processors frequently reorder the execution of instructions to maximize pipelining/etc.

Hardware Solutions

- Modern systems provide a wide range of hardware solutions to mutual exclusion problem

- Plus, even if we want to just use the software solutions, still required to rely on specific hardware capabilities!
- Example: **barriers**
  - Previous software solutions don't work in context of out-of-order execution…
  - So, prevent out-of-order execution when it matters!
  - (Note: These are not the same as barriers in multithreading)

Optimization Barriers

- **Optimization barriers** prevent instructions before the barrier from being mixed with instructions after the barrier
  - Affects the compiler's output, not what the processor does
- Example: Linux/Pintos **`barrier()`** macro

```
#define barrier() asm volatile ("" : : : "memory")
```

  - Tells the compiler that the operation changes all memory locations
  - Compiler cannot rely on memory values that were cached in registers before the optimization barrier
- Can be used to ensure that one operation is actually completed before the next operation is started
  - e.g. acquiring a lock to access shared state must be completed before we can even begin interacting with the shared state
- Problem: optimization barriers do not prevent the CPU from reordering instructions at execution time…

Memory Barriers

- **Memory barriers** prevent instruction-reordering at the CPU level
  - All instructions before the memory barrier must be completed, before any instructions after the memory barrier are started
  - Usually, macros to impose memory barriers also impose optimization barriers; otherwise the memory barrier is useless
- Several kinds of memory barriers, depending on the need
  - **Read memory barriers** only operate on memory-read instructions
  - **Write memory barriers** only operate on memory-write instructions
  - If unspecified, barrier affects both read and write instructions
- Also, some cases only require barriers in multiprocessor systems, not on uniprocessor systems
  - e.g. Linux has **`smp_mb()`** / **`smp_rmb()`** / **`smp_wmb()`** memory-barrier macros, which are no-ops on single-processor systems

Memory Barriers (2)

- Processors often provide multiple ways to impose memory barriers
- Example: IA32 memory-fence instructions
  - **`lfence`** ("load-fence") imposes a read memory-barrier
  - **`sfence`** ("store-fence") imposes a write memory-barrier
  - **`mfence`** ("memory-fence") imposes a general memory-barrier
- Several other IA32 instructions also implicitly act as fences, e.g. **`iret`**, instructions prefixed with **`lock`**, etc.
- IA32 ensures that all operations before the fence are globally visible, even in multiprocessor systems
  - i.e. the system maintains cache coherency when fences are used
  - Not all architectures guarantee this…

Disabling Hardware Interrupts

- Another simple solution to preventing concurrent access is **disabling hardware interrupts**
- Frequently used to prevent interrupt handlers from manipulating shared state
  - Interrupt handlers cannot passively block, so they generally can't acquire semaphores, mutexes, etc.
  - To prevent access by an interrupt handler, just turn interrupts off
- On IA32, local interrupts are enabled and disabled via **`sti`** / **`cli`** instructions (Set/Clear Interrupt Flag)
- <u>Note</u>: on multiprocessor systems, this only affects the processor that executes the instruction
  - Other processors will continue to receive and handle interrupts

Spin Locks

- It is possible to disable interrupt handling on <u>all</u> processors…
  - <u>Not</u> recommended: greatly reduces system concurrency
- A much better approach is to use **spin locks**
- Locking procedure:
  - If the lock is immediately available, it is acquired
  - If the lock is not immediately available, it is actively polled in a tight loop (called "spinning" on the lock) until it becomes available
- Spin locks only make sense on multiprocessor systems
  - On single-core systems they just waste CPU time, or wait forever…
- Two scenarios prompt spin-lock use:
  - <u>Cannot</u> context-switch away from control path (interrupt context), or
  - Lock is expected to be held for a short time, and want to avoid overhead of a context-switch

Spin Locks and Interrupt Handlers

- Interrupt handlers can use spin locks on multiprocessor systems to guard shared state from concurrent access
  - Acquire the spin lock, access shared state, release the spin lock
- Example: a timer interrupt being triggered on each CPU
  - Each CPU executes the timer interrupt handler separately…
  - Handler needs to access shared state (e.g. process ready-queue, waiting queues, etc.)
  - Need to enforce a critical section on manipulation of shared state
- Timer interrupt handler can guard shared state with a spin lock
  - Interrupts are supposed to complete quickly…
  - Even if multiple CPUs have timer interrupts occur at same time, a given handler invocation won't wait long for handlers on other CPUs to finish

Spin Locks and Interrupt Handlers (2)

- Must be extremely careful using spin locks when control paths can be nested!
  - Scenario: multiprocessor system, nested kernel control paths
- Example: using a spin-lock to guard state that's shared between a trap handler and an interrupt handler
  - Trap handler acquires the spin lock
  - Trap handler begins accessing shared state
  - Interrupt fires! Handler attempts to acquire the same spin lock
- The system becomes deadlocked:
  - Trap handler holds a lock that the interrupt handler needs to proceed
  - Interrupt handler holds CPU, which the trap handler needs to proceed
  - Nobody makes any progress ☹
- For these situations, must also disable local interrupts before acquiring the spin lock, to avoid deadlocks

Spin Lock Guidelines

- Spin locks are only useful on multiprocessor systems
  - On single-processor systems, simply disable interrupt processing
- Spin locks should be held only for a short time
- If a critical section will only be entered by control paths running on different CPUs, simple spin locks will suffice
  - e.g. shared state is only accessed from one interrupt handler, and the handler runs on all CPUs in the system
- If more than one control path on the same CPU can enter a critical section, must disable interrupts before locking
  - e.g. shared state accessed from trap handlers + interrupt handlers
- Linux spinlock primitives:
  - spin_lock_irq() and spin_unlock_irq() disable/reenable interrupts
  - spin_lock() and spin_unlock() simply acquire/release the lock

Locks and Deadlocks

- Locking mechanisms for synchronization introduce the possibility of multiple processes entering into deadlock
  - A set of processes is **deadlocked** if each process in the set is waiting for an event that only another process in the set can cause.
- Requirements for deadlock:
  - **Mutual exclusion**: resources must be held in non-shareable mode
  - **Hold and wait**: a process must be holding one resource, and waiting to acquire another resource that is currently unavailable
  - **No preemption**: a resource cannot be preempted; the process must voluntarily release the resource
  - **Circular wait**: the set of processes $\{P_1, P_2, \ldots, P_n\}$ can be ordered such that P_1 is waiting for a resource held by P_2, P_2 is waiting for a resource held by P_3, …, P_{n-1} is waiting for a resource held by P_n, and P_n is waiting for a resource held by P_1

Dealing with Deadlock

- Several ways to deal with deadlock
- **Deadlock prevention**: engineer the system such that deadlock never occurs
  - Usually focuses on breaking either the "no preemption" or the "circular wait" requirement of deadlock
- No preemption: if a process cannot acquire a resource, it relinquishes its locks on all other resources
  - (rarely practical in practice)
- Circular wait: impose a total ordering over all lockable resources that all processes must follow
  - As long as resources are only locked in the total ordering, deadlock can never occur
  - If a process acquires a later resource in the ordering, then wants an earlier resource in the ordering, must release all its locks and start over
  - Usually not imposed by the OS; must be imposed by the programmer

Dealing with Deadlock (2)

- **Deadlock avoidance**: the system selectively fails resource-requests in order to prevent deadlocks
  - System detects when allowing a request to block would cause a deadlock, and reports an immediate failure on the request
- Several algorithms to do this, e.g. **Banker's algorithm**
- Also **wound/wait** and **wait/die** algorithms:
  - Given an older process P_O and a younger process P_Y
  - Wound/wait:
    - If P_O needs a resource that P_Y holds, P_Y dies
    - If P_Y needs a resource that P_O holds, P_Y waits
  - Wait/die:
    - If P_O needs a resource that P_Y holds, P_O waits
    - If P_Y needs a resource that P_O holds, P_Y dies

Dealing with Deadlock (3)

- **Deadlock detection and resolution**: simply allow deadlock!
  - When a set of processes enters into deadlock, the system identifies that deadlock occurred, and terminates a deadlocked process
  - (not used in operating systems; used heavily in database systems)

Semaphores

- **Semaphores** are a common synchronization mechanism
  - Devised by Edsger Dijkstra
- Allows two or more processes to coordinate their actions
- Typically, processes block until acquiring the semaphore
  - Can’t wait on semaphores in interrupt context
- Each semaphore has this state:
  - An integer variable **`value`** that cannot be negative
  - A list of processes/threads waiting to acquire the semaphore
- Two operations: **`wait()`** and **`signal()`**
  - Also called **`down()`** and **`up()`**
  - Dijkstra’s names:
    - P (for “prolaag,” short for “probeer te verlagen” or “try to decrease”)
    - V (for “verhogen” or “increase”)

Semaphores (2)

- Example **`wait()`** impl:

```
while sem.value == 0:
    add this thread to sem.waiting list
    passively block the thread
sem.value := sem.value – 1
```

- Example **`signal()`** impl:

```
sem.value := sem.value + 1
if sem.waiting list is not empty:
    t = pop thread from sem.waiting
    unblock t
```

- These operations <u>must</u> be enclosed in critical sections!
  - e.g. Pintos turns off interrupts inside these operations
- Blocked threads can be managed in various ways
  - e.g. always put blocked threads at end of waiting, unblock from front
  - e.g. choose a random thread to unblock
  - (Often, making things fair is more expensive)

Counting Semaphores

- Semaphore value represents how many times `wait()` can be called without blocking
  - Use it to represent e.g. how much of a given resource is available
- Called **counting semaphores** when used in this way
  - Maximum value of semaphore is greater than 1
  - *Doesn't ensure mutual exclusion!!!*
- Example: a bounded queue for communicating processes
  - From the well-known producer-consumer problem
- One semaphore to represent how much data is in the queue
  - Used by readers; passively blocks readers when no data available
  - Writers signal every time more data is added
- One semaphore to represent how much space is in the queue
  - Used by writers; passively blocks writers when no space available
  - Readers signal every time data is removed

Binary Semaphores

- Bounded-buffer example has two semaphores
  - One for readers, one for writers
  - Each semaphore uses critical sections for internal updates…
  - Semaphores and bounded-buffer contents must also be manipulated atomically…
- Use a third semaphore to enforce mutual exclusion
  - At most one process may hold this semaphore at a time
  - Processes call **`wait()`** before entering the critical section
  - Processes call **`signal()`** when leaving the critical section
- Called **binary semaphores** when used this way
  - Maximum value of semaphore is 1
  - Used to enforce mutual exclusion

Mutexes

- **Mutexes** are simplified versions of binary semaphores
  - Short for "mutual exclusion lock"
- Main difference between mutexes and binary semaphores is concept of a process "owning" a mutex when it's locked
  - e.g. one process can't lock a mutex and another process unlocks it
- As with semaphores, mutexes are frequently formulated to block processes until the mutex is acquired
  - Processes passively wait for mutex; can't be used in interrupt context
  - (Spin locks are mutexes that actively wait instead of passively waiting)
- Usually implemented with atomic test-and-set instructions
  - e.g. on IA32, **`xchg`** or **`bts`** instructions can be used to create a very efficient mutex

Other Synchronization Details

- Have only scratched the surface of synchronization
- Other thread synchronization primitives:
  - Condition variables, monitors, barriers, …
- Classic synchronization problems:
  - The producer-consumer problem (aka the bounded buffer problem)
  - The readers-writers problem (read-write locks)
  - Dining philosophers
- <u>Much</u> more detail on deadlock detection and resolution
- Other multithreading difficulties:
  - Livelock, starvation, fairness, …

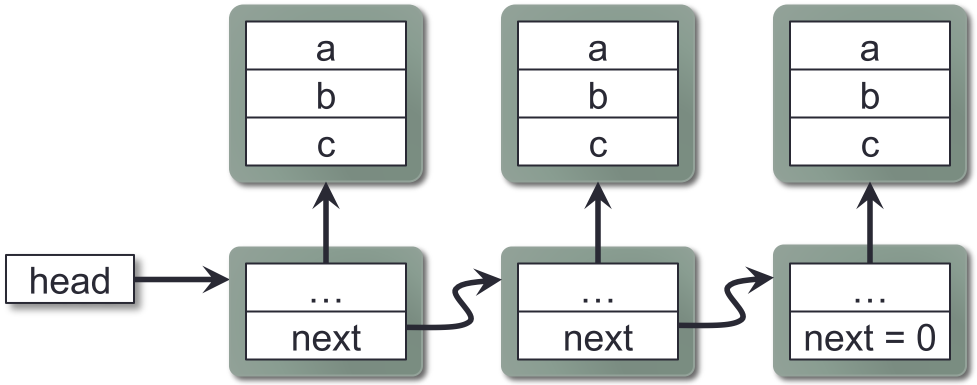
- Unfortunately, beyond scope of the class to cover it all ☹

Thinking Like a Kernel Programmer

- Kernel programming is pretty different from application programming
  - Not just because it's closer to the hardware, and harder to debug…
- Very strong focus on efficiency
  - Want to minimize both memory and computing overheads
  - Ideally without sacrificing ease of maintenance
- Typically, system code simply has fewer resources to use
  - Often, no general-purpose heap allocator in the kernel
  - Not a very large memory pool to utilize, anyway
- Also, performance issues in the kernel affect *everybody*
  - Interrupts need to complete as fast as possible
  - Process/thread scheduler needs to run quickly

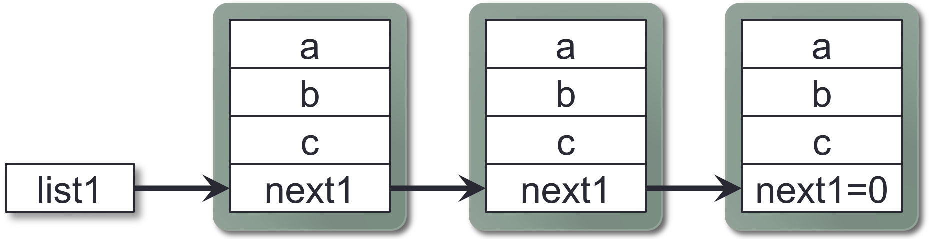
Data Structures

- Example problem: manage a linked list of items
- Typical application-programming approach:
  - Each linked-list node is separately allocated; nodes linked together
  - Often, list holds pointers to other separately-allocated structures
- In the kernel, there is often no general-purpose allocator
  - Kernels allocate a very specific and limited set of data structures
  - Can't afford to lose space required to manage heap structures, etc.



Data Structures (2)

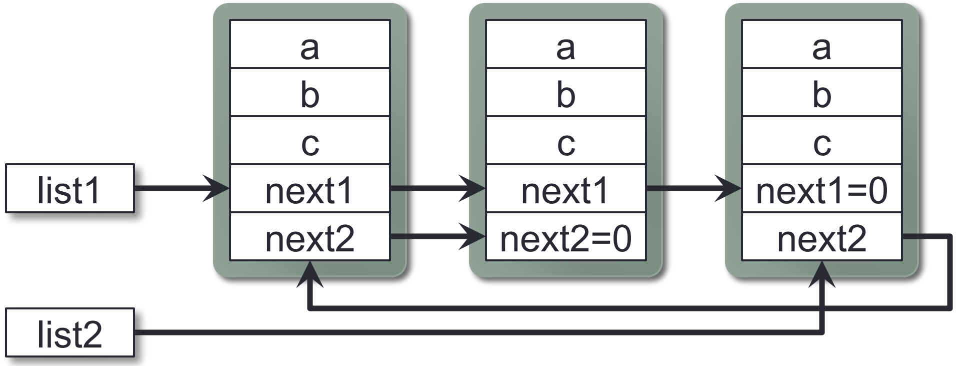
- In the kernel, collection support is often folded into the data structures being managed



- Approach is called an **intrusive linked list** implementation
- List pointers point directly to the "next1" member of the structure, not the start of the structure, in the linked list
  - Necessary for several reasons
  - e.g. many different kinds of data structures might be organized into linked lists
- Requires a simple computation to get to the start of the structure from the next1 pointer
  - e.g. (struct_t *) ((uint8_t *) ptr - offsetof(struct_t, next1))

Data Structures (3)

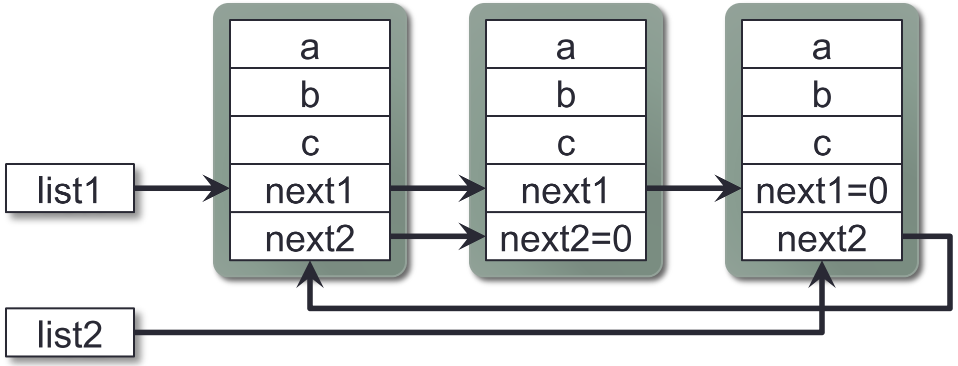
- Lists also point directly to the “next” pointer, rather than the start of the structure, to allow objects to participate in multiple lists



- Fortunately, this can be wrapped in helpful macros to simplify type declarations, list traversal, etc.

Memory Allocations

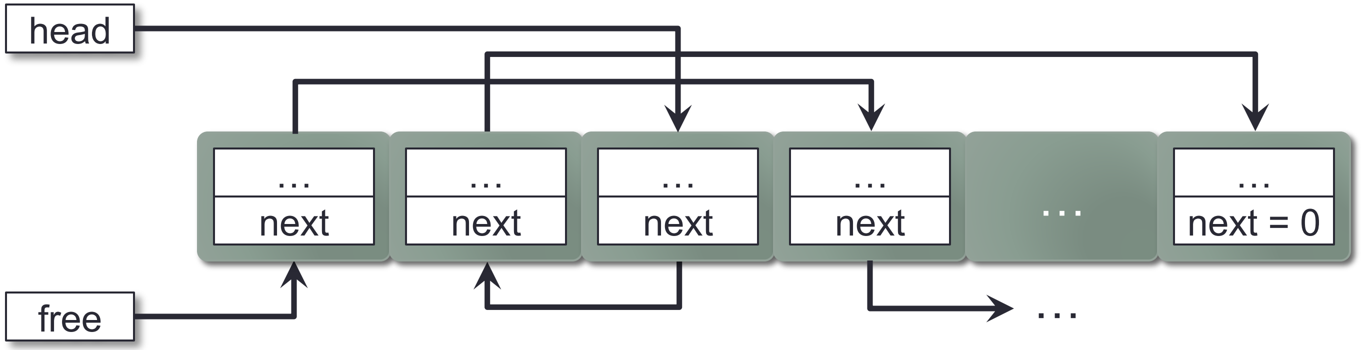
- Is it actually necessary to dynamically allocate memory?
  - Pains are taken to avoid having to do so!
- Our previous example:



- Corresponds to Pintos thread queues
  - Anchors of lists are statically-allocated global variables
  - List elements are `thread` structs, which are positioned at the lowest address of the kernel thread's stack space
- No dynamic memory allocation is required at all
  - (besides the page-allocation for the kernel thread's stack, of course)

Memory Allocations (2)

- Another example: need to manage a linked list of nodes
  - Linked list has a maximum size
  - Most of the time, linked list will either be full, or mostly full
- Instead of dynamically allocating each list node, statically allocate a whole array of nodes
  - Array size is maximum linked list size
- Avoids heap-management overhead (both space + time)
- May also require a list of nodes available for use



Interrupt Handlers

- Interrupt handlers should run as quickly as possible
  - Maintains overall system responsiveness
- Often have a choice of whether to do work in interrupt context, vs. doing the work in process context
- Generally, you want to make only one process wait, instead of making the entire system wait
- Pintos "thread sleep" functionality has good examples of this approach

Interrupt Handlers (2)

- Example: state for allowing threads to sleep
- Threads could store the “clock tick” when they went to sleep, plus the amount of time to sleep…
  - From these values, interrupt handler can compute whether it’s time for a thread to wake up or not
- Or, threads can simply store the “clock tick” when they should wake up
  - Interrupt handler doesn’t have to compute anything – it just looks to see if it’s time to wake up a given thread

- Second approach does computations in process context, not interrupt context
  - Only slows down the process that wants to sleep, not all timer interrupts
- Also requires less space in thread structs, which is good!

Interrupt Handlers (3)

- Example: storing sleeping threads
- Sleeping threads are all stored in one list
  - The queue of threads blocked on the timer
- Can store threads in no particular order…
- Or, store threads in increasing order of wake-up time
- First approach is fast for the sleeping thread
  - Just stick the thread's struct-pointer onto back of the sleep-queue
  - Interrupt handler must examine all threads in the sleep-queue
- Second approach is fast for the interrupt handler
  - Sleeping thread must insert its struct-pointer into the proper position within the sleep queue
  - Interrupt handler knows when it can stop examining threads – when it reaches the first thread that doesn't need to wake up

Interrupt Handlers (4)

- Example: storing sleeping threads
- Generally, want to choose the second approach
  - Only the sleeping thread is delayed by inserting in the proper place
  - The timer interrupt can run as fast as possible

- Aside: for priority-scheduling implementation, not such a great idea to order threads based on priority
  - Thread priorities can change at any time, based on other threads' lock/unlock operations
  - Becomes prohibitively expensive to maintain threads in priority order all the time

Exploiting System Constraints

- Finally, kernel code frequently exploits system constraints to use as little memory as possible
- Example: for scheduling purposes, threads are only ever in one queue
  - Which queue depends on their state
  - Either in the "ready" queue, or in some "blocked" queue, depending on what the thread is blocked on
- In these cases, can simply reuse fields for these various mutually-exclusive scenarios
  - e.g. only have one linked-list field for representing the thread's "current queue"

Summary: Kernel Programming

- Some of these approaches yield big savings, but most yield small savings
  - e.g. performing computations in process-context vs. interrupt handler
- Operating systems are large, complex pieces of software
  - These small savings throughout the OS accumulate in a big way
- Key kernel-programming question: *"How can I do things more efficiently?"*
  - Can I avoid dynamic memory allocation?
  - Can I move computations out of interrupt handlers and into process context?
  - Are there constraints on system behavior that I can exploit?
  - Can I reuse fields or data structures for multiple purposes?
- Often there are elegant solutions that also result in significantly improved system performance

Next Time

- A novel approach to the synchronization problem…