NCS Lecture 3: Embedded Systems Programming

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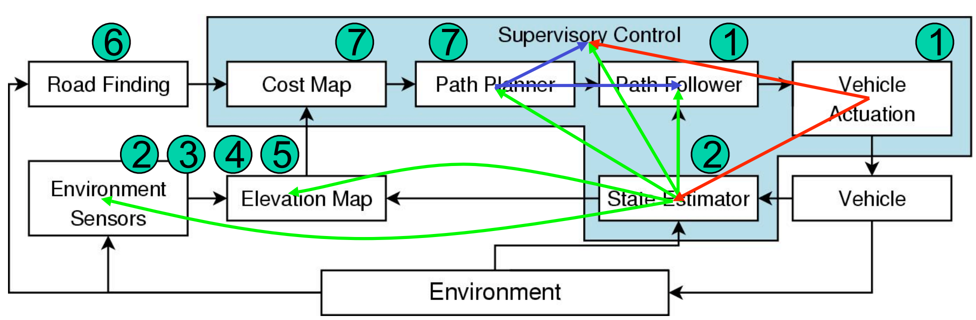
Goals:

- Describe how event ordering works in distributed systems
- Discuss choices in NCS message delivery
- Introduce Spread, a group communications toolkit
- Describe multi-threaded execution in the context of control systems
- Introduce Pthreads, a standard library for multi-threaded programming

Reading:

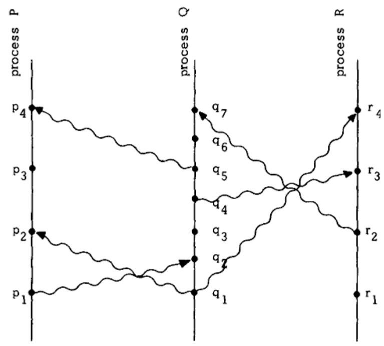
- "Time, Clocks, and the Ordering of Events in a Distributed System", L. Lamport. Comm. ACM, 1978
- "A User's Guide to Spread", Jonathan R. Stanton, 2002.
- "POSIX Threads Programming", Lawrence Livermore National Laboratory. 2006 (online tutorial)
- "Monitors: An Operating System Structuring Concept", C. A. R. Hoare. Communications of the ACM, 17(10):549--557, 1974.

Communication Management: Spread



Message type	Bytes/Freq	Recv	Comments
Vehicle State	~250 B @ 40 Hz	15	Pos, vel, acc; highest update rate
Actuator State	~220 B @ 30 Hz	3?	Actuators + OBD II information
Elevation Map	4 MB @ 10 Hz	0	Not transmitted
Cost Map	4 MB @ 10 Hz	3	Deltas transmitted
Trajectory	??? @ 5 Hz	2	Variable size (I think)
Cameras	640x480 @ 30 Hz	5	Firewire (~20 MB/s per camera)

Causality in Distributed Communications (Lamport, '78)



Partial ordering: $a \rightarrow b$

- If *a* and *b* are events in the same process, then $a \rightarrow b$
- If *a* is the sending of a message by one process and *b* is the receipt of the same message by another process, then $a \rightarrow b$
- If $a \rightarrow b$ and $b \rightarrow c$ then $a \rightarrow c$
- $a \rightarrow b$ means "*a* can causally effect *b*"

Logical Clocks

- Let $C_i\langle a \rangle$ be a clock for process P_i that assigns a number to an event
- Define $C\langle b \rangle = C_j\langle b \rangle$ if b is an event in process P_j
- *Clock condition*: for any two events *a*, *b*: if $a \rightarrow b$ then $C\langle a \rangle < C\langle b \rangle$

Remarks

- Events are *partially* ordered: can compare some events but not all events
- Example: $p_1 \rightarrow q_3$ but p_3 and q_3 are no related
- Clocks are not unique (can choose any set of integers with appropriate relations)

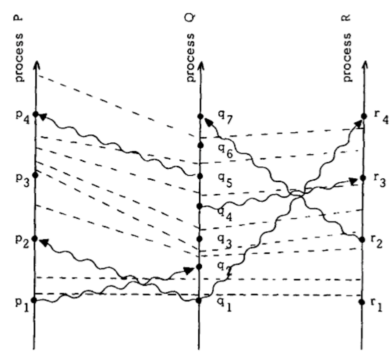
Implementing a Clock

Conditions for a clock

- C1: If *a, b* are events in process P_i and *a* comes before *b*, then $C_i\langle a \rangle < C_i\langle b \rangle$
- C2: If event *a* is the sending of a message by process P_i and event *b* is the receipt of that message by process P_j, then $C_i\langle a \rangle < C_i\langle b \rangle$

Space-Time Diagram

- Add ticks for every count in each process
- Draw "tick lines" between equally numbered ticks
- C1 ⇒ tick line between two events
- C2 ⇒ every msg must cross tick line



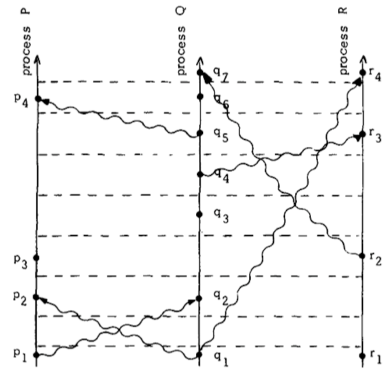
Remarks

- Events can shift around between tick lines without changing logical clocks ⇒ logical time is different than physical time

Constructing Clocks

Implementation rule

- IR1: Each process P_i increments C_i between any two successive events
- IR2:
  - (a) If event *a* is the sending a message *m* by process P_i, then the message *m* contains a timestamp $T_m = C_i\langle a\rangle$
  - (b) Upon receiving a message *m*, process P_j sets C_j greater than or equal to its present value and greater than T_m



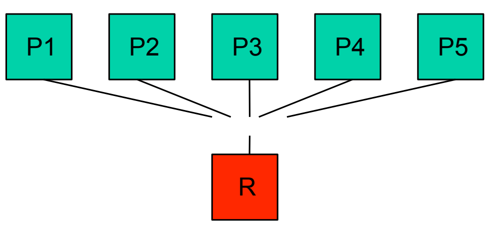
Remarks:

- Gives an easy algorithm for constructing a clock
- Note that $C\langle a\rangle < C\langle b\rangle$ does *not* imply $a \rightarrow b$. Still only a partial order (can only compare certain elements)

Total order

- Order events according to logical clocks
- Break ties using process number
- Allows any two events to be compared
- Total ordering is not unique (depends on choice of clocks)

Example: Resource allocation



Problem description

- Fixed processes P_i sharing resource R
- Once a process grabs a resource, it must release it before it is use again
- Requests granted in order they were requested
- Every request is eventually granted
- Solve in *distributed* way; processes agree on who goes next
- Problem is non-trivial, even with central scheduling (see Lamport paper)

Algorithm

1. P_i sends message T_m:P_i *request* to every other process and puts message on its queue
2. P_j queues all requests and sends timestamped acknowledgement to sender
3. Process P_i uses resource when
   1. T_m:P_i *request* is ordered before any other request in queue (according to total order)
   2. P_i has been received ack from everyone with timestamp > T_m
3. P_i removes T_m:P_i *request* message from queue and sends T_m:P_i *release* message to everyone

- When P_j receives a T_m:P_i *release* message, it removes message from its queue

Group Messaging Systems

Group

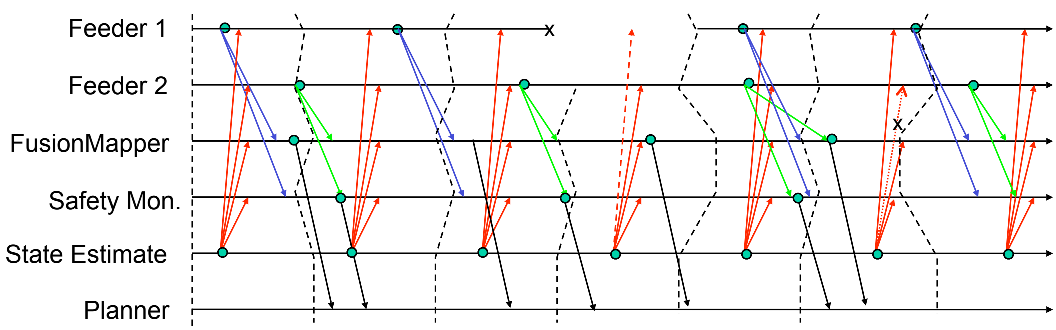
- Collections of processes that can send messages back and forth to everyone
- Messaging system has to keep track of people joining and leaving groups
- Goal: deliver packets reliably and *causally*

Ex: Alice NCS group message types

- Modules receive certain message types

Issues

- Need to track membership over time
- Need to provide different levels of reliability (at the group level)
- Need to provide different levels of ordering (or causality)
- Also need to keep track of the fact that time may be different on different computers (no global clock)



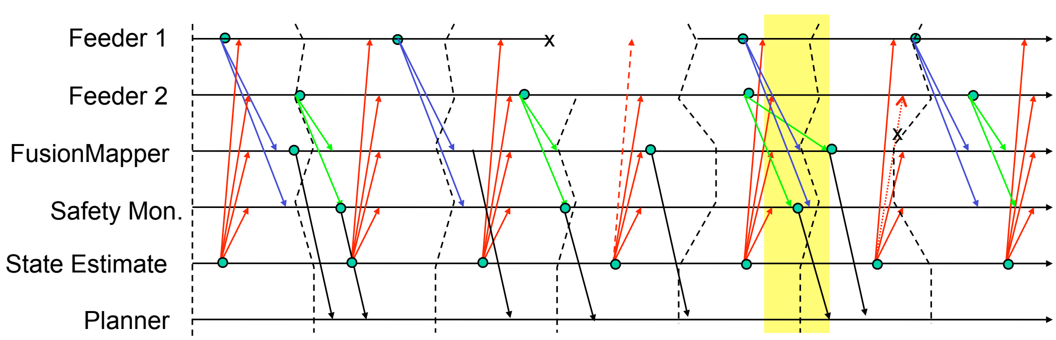
Message Ordering ("Virtual Synchrony")

Ordering

- *None* - No ordering guarantee.
- *Fifo by Sender*- All messages sent by this sender are delivered in FIFO order.
- *Causal* - All messages sent by all senders are delivered in Lamport causal order.
- *Total Order* - All messages sent by all senders are delivered in the exact same order to all recipients

Remarks

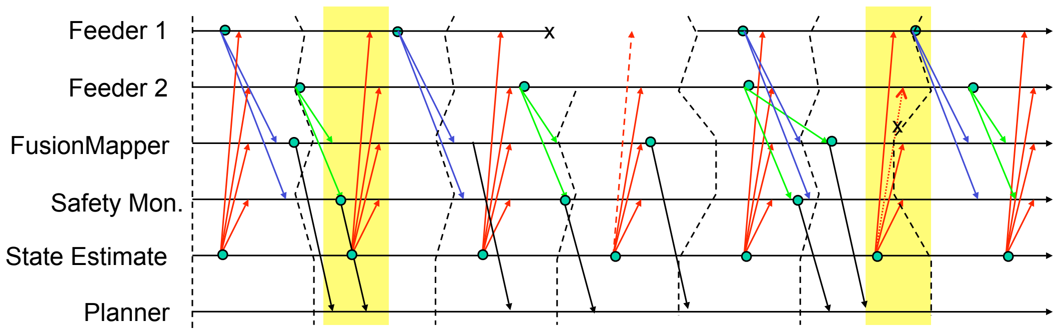
- Imposing causality increases message overhead; need to make sure that everyone has the message
- Things get interesting with multiple groups - everyone in same collection of groups should receive all messages in same order
- HW: figure out an example where causal and total order are different



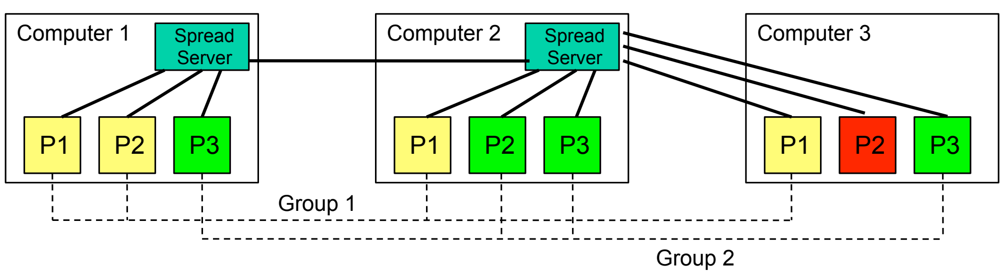
Message Reliability ("Extended Virtual Synchrony")

Reliability
- *Unreliable* - Message may be dropped or lost and will not be recovered.
- *Reliable* - Message will be reliably delivered to all recipients who are in group to which message was sent.
- *Safe* - The message will ONLY be delivered to a recipient if everyone currently in the group definitely has the message

Remarks
- Key issue is keeping track of reliability in *groups*. Reliable messages should be received by everyone (eventually).
- Requires agreement algorithm across computers (who has what)
- HW: find an example where reliable messages are not safe.



Spread Toolkit (Stanton '02)

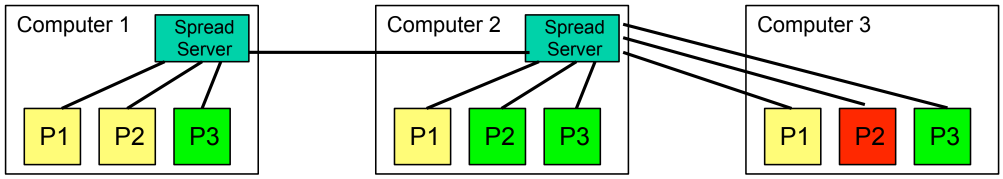


Spread Functions
- SP_connect: establish a connection with the spread daemon
- SP_disconnect: terminate connection
- SP_join(mbox. group): join a group
- SP_leave(mbox. group): leave a group
- SP_multicast(…, group, message, type): send a message to everyone in group of given type
- SP_receive: receive a message

Message types
- Unreliable - no order, unreliable
- Reliable - no order, reliable
- FIFO - FIFO by sender, reliable
- Causal - Causal (Lamport), reliable
- Agreed - Totally ordered, reliable
- Safe - Totally ordered, safe

- Note: each message has a type; these can be mixed within groups

Features of Spread



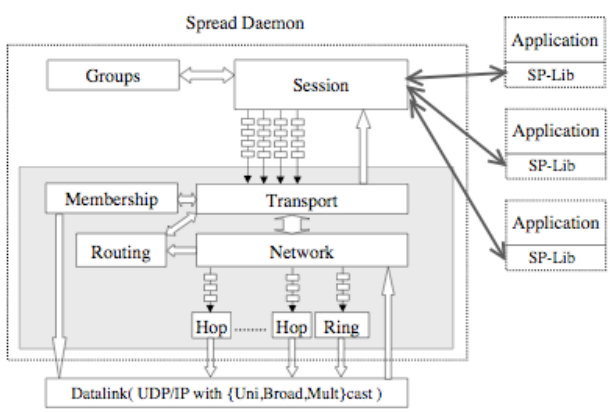
Features of Spread

- Number and location of servers are configurable
- Retransmits are optimized in multi-hop environments
- Guarantees are provided at servers; assumes that inter-process comms on single computer is reliable
- Data is combined in packets when possible to increase efficiency
  - Gives a correlated channel model when data is lost
- No hardwired addresses (exc servers)

Project ideas

- How can we model a spread-based communications network from the point of view of estimation and control
- Is it better to have one server or multiple servers? What are the latency tradeoffs?
  - Alice originally used one server per computer
  - Eventually moved to a single server (not sure why)

How Spread Works (Amir and Stanton, '98)



Spread daemon

- Implements group communications protocols
- Uses UDP to talk between spread hosts
- Two protocols: hop and ring

Applications

- Think client library
- Uses TCP to talk to server

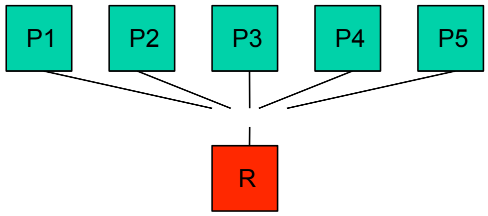
Hop protocol

- UDP-based protocol between *sites*
  - Sites connected by slower links
- Provide low latency communcations
- Packet loss handled on hop-by-hop basis (instead of end to end)

Ring Protocol

- Used for communications between multiple servers at same *site*
  - Assumes dedicated (switched) links
- Token ring based protocol: pass control from one server to the next

Example: Resource allocation



Problem description

- Fixed processes P_i sharing resource R
- Once a process grabs a resource, it must release it before it is use again
- Requests granted in order they were requested
- Every request is eventually granted

- Solve in *distributed* way; processes agree on who goes next
- Problem is non-trivial, even with central scheduling (see Lamport paper)

Solution using Spread

- Assume totally ordered, reliable messages ("agreed" message type)
- All processes and resource in single spread group

Algorithm

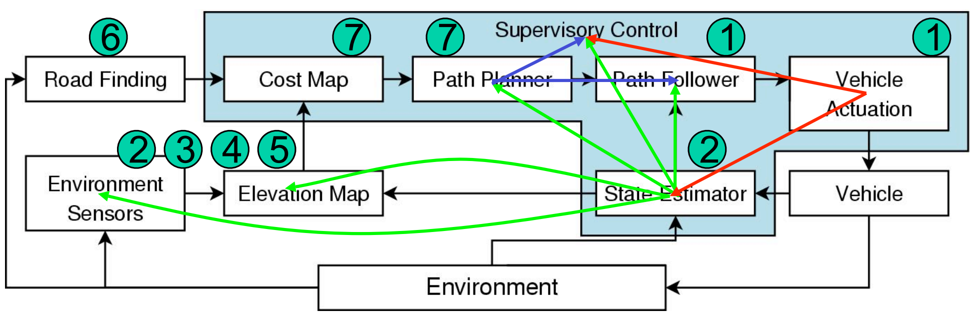
1. P_i sends multcast message to group requesting resource
2. P_j queues all requests and sends ack
3. Process P_i uses resource when
   - P_i request is at top of queue
   - Ack has been received from everyone

- P_i sends release message when done

1. P_j dequeues release when message received

2. Note: spread provides single order

Process Management: Pthreads



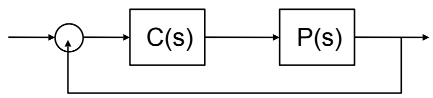
Example: vehicle actuation (adrive)

- Interface to 7 different actuation systems (steer, gas, brake, etc)
- Each actuator involves different rates, delays, comms blocking
- Asynchronous receipt of commands and state + xmit actuator state
- Hard to synchronize individual actuators with main control loop

Approach: multi-threaded programming

- Break program up into independent execution threads
- Operating system can switch threads on blocking => always executing
- Challenges: asynchronous operation, simultaneous access to variables

Traditional Control Systems Implementation (Sparrow)



$$C(s) \xrightarrow{\text{Tustin}} C(z)$$

Simplest case: interrupt driven loop
- Use HW/SW interrupts to run control routine at an accurate and fixed rate
- "Servo loop" overrides normal program operation
- Need to be careful about interaction of variables in servo loop with main pgm

Variations:
- Time-triggered protocols - scheduling of events to allow multiple "servos"

Sample program
- Discrete time implementation

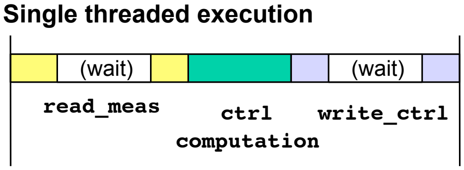
$$z_{k+1} = A_c z_k + B_c e$$
$$y_k = C_c z_k + D_c e$$

- Uses quasi-sparrow implementation

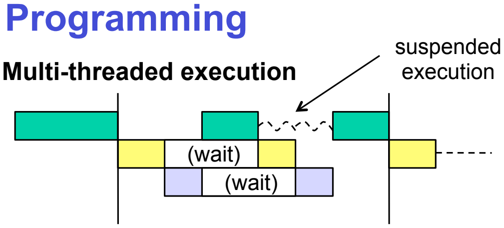
```
load_controller(file)
servo_setup(loop, rate, flags);
servo_enable();

loop()
{
  y = read_measurement();
  r = read_reference();
  xnew = Ac * x + Bc * (r - y);
  u = Cc * x + Dc * (r - y);
  write_control(u);

  x = xnew;
}
```


Multi-Threaded Programming

Single threaded execution



Multi-threaded execution



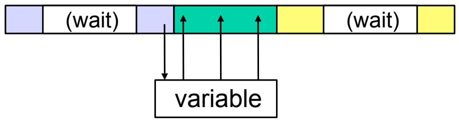
Basic Idea
- Separate code into independent segments ("threads")
- Switch between threads, allowing each to run "simultaneously"
- Threads share memory and devices; allows rapid sharing of information

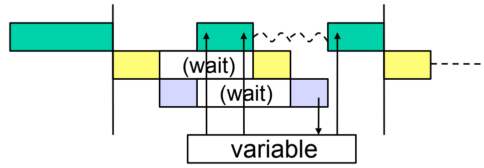
Threads vs Processes
- Processes have separate memory space and device handles
- Requires interprocess communication to share data

Advantages
- Avoid manual coding to eliminate pauses due to hardware response
- Multiple control loops become separate threads; OS insures execution
- Allows messages (or signals) to be received in middle of long computation

Issues
- Race conditions
- Dead locks ("deadly embrace")
- Asynchronous operations

Issue #1: Race Conditions





Definition

- "A *race condition* is a flaw in a system or process where the output exhibits unexpected critical dependence on the relative timing of events." (wikipedia)

Application to threads

- Execution of threads is controlled by the operating system (OS)
- It is possible for threads to be pre-empted and another thread to run ⇒ can't assume anything about order
- While easy to understand, race conditions can be hard to locate and debug

Example

- Thread 1: compute sqrt of number
- Thread 2: update number on condition

Code:

```
thread1() {
  if (x < 0)
    y = 0;
  else
    y = sqrt(x);
}

thread2() {
  if (event) x = x - 1;
}
```

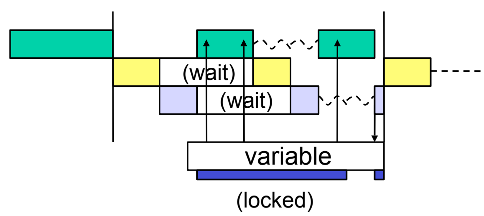

Mutual Exclusion (mutex)

Solution: exclude overlapping access

- Semaphores introduced by Djikstra in 1960s to handle this problem
- Key idea: protect "critical sections" of code by setting a "mutex"
- Mutex_lock: wait for mutex to be unblocked (if it isn't already), then set
  - While a mutex_lock is being blocked, the OS can execute code
- Mutex_unlock: unset the mutex

Atomicity

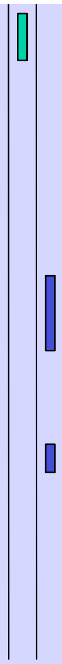
- Operating systems need to insure that mutexes are "atomic" operations - no instructions executed while checking and setting the flag
- If this doesn't happen, you can get a race condition in setting the flag (which is what we are trying to avoid…)




```
thread1() {
  mutex_lock(xmtx);
  if (x < 0)
    y = 0;                 } Critical Section
  else
    y = sqrt(x);
  mutex_unlock(xmtx);
}

thread2() {
  mutex_lock(xmtx);
  if (event) x = x - 1;    } Critical Section
  mutex_unlock(xmtx);
}
```

Issue #2: Deadlocks

```
1  thread1() {
2    mutex_lock(xmtx);
3    if (x < 0) x = 0;
4    mutex_lock(ymtx);
5    y = sqrt(-x);
6    mutex_lock(ymtx)
7    mutex_unlock(xmtx);
8  }
9
10 thread2() {
11   mutex_lock(ymtx);
12   if (y == 0) compute();
13   mutex_unlock(ymtx);
14 }
15
16 compute() {
17   mutex_lock(xmtx);
18   if (event) x = x - 1;
19   mutex_unlock(xmtx);
20 }
```



Possible execution

- Thread 1 executes up to line 3
  - Locks xmtx mutex
- Switch to thread 2
- Thread 2 executes through line 12
  - Locks ymtx mutex
- Compute() blocks on xmtx mutex
- Switch to thread 1
- Thread 1 blocks on ymtx mutex
- (no further execution)

Remarks

- Easy to fix, but sometimes hard to *spot* (especially when using subroutines)

Solution: lots of debugging

- Formal tools exist, but generally can't operate at programming code level

Thread Usage

When to use threads

- Main usage is when the program has to wait on a process or resource
- Eliminate threads if they aren't needed (eg, tight interlocking with no waits)

Avoiding deadlocks

- Never put a mutex around a call that might itself block (I/O call, mutex, etc)
- If you have to use nested mutex's, make sure they are in the same order whenever they are invoked

Performance improvements

- Try to keep critical sections as small as possible (avoids excessive waiting)
- Combine accesses to same variables in nearby sections
- Use buffers to minimize lock times

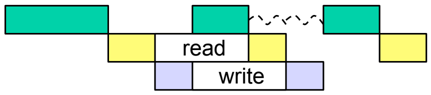
Conditional variables

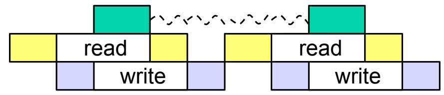
- Allows a thread to sleep until a certain condition is met
- Used in conjunction with a mutex

```
thread1() {
  mutex_lock(xmtx);
  while (!condition)
    cond_wait(&cond, xmtx);
  do_something();
  mutex_unlock(xmtx);
}

thread2() {
  mutex_lock(xmtx);
  // make condition TRUE
  if (cond)
    cond_signal(&cond);
  mutex_unlock(xmtx);
}
```

unlocks mutex on entry and relocks on return

Issue #3: Asynchronous Execution





Executation is non-deterministic
- Operating system determines when to execute individual threads
- Different operating systems will give different sequences of operations
- Avoid tuning scheduling rules to let OS optimize (eg, multi-processor core)

Use mutexes and conditions if needed
- Can insure partial synchronization by using mutexes and conditions, *but*
- Avoid overly constraining threads; can get worse performance than just doing things sequentially

Reasoning about concurrent code
- It is still possible to prove things about multi-threaded execution
- Example: Lyapunov like functions
  - Let V be a positive function whose minimum corresponds to desired state
  - Show that each portion of code does not increase V's value
  - Show that some portions of code decrease value of V
  - Conclude that V will approach minimum value
- Formal methods: temporal logic, unity

POSIX Threads (Pthreads)

Thread creation

• pthread_create	call a function as a new thread of execution
• pthread_exit	terminate the current thread
• pthread_join	wait for a specific thread to exit

Mutexes

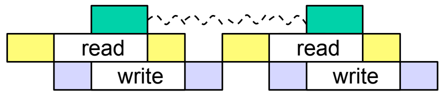
• pthread_mutex_init	initialize a mutex
• pthread_mutex_lock	lock a mutex (blocks until mutex is available)
• pthread_mutex_unlock	unlock a mutex (and unblock first blocked threads)
• pthread_mutex_destroy	free up resources associated with a mutex

Conditional variables

• pthread_cond_init	initialize a condition
• pthread_cond_wait	wait until condition is satisfied (paired with a mutex)
• pthread_cond_signal	signal that a condition is now satisfied
• pthread_cond_destroy	free up resources associate with a mutex

Read/write locks
- Variation on mutexes that allow multiple unblocking reads

Example: Threaded Control Loop




```
pthread_create(…, sensor, …);
pthread_create(…, actuator, …);
pthread_create(…, control, …);
display();

sensor() {
  // initialization
  while (1) {
    pthread_mutex_lock(smtx);
    y = read_measurement();
    r = read_reference();
    pthread_mutex_unlock(smtx);
    usleep(S_WAIT_USEC);
  }
}
```

```
control() {
 // initialization
  while (1) {
    pthread_mutex_lock(smtx);
    err = r - y;
    pthread_mutex_unlock(smtx);

    xnew = Ac * x + Bc * err;

    pthread_mutex_lock(amtx);
    u = Cc * x + Dc * err;
    pthread_mutex_unlock(amtx);

    usleep(C_WAIT_USEC)
  }
}
```

Notes

- Process inputs/outputs asynchronously
- HW: is this OK? Optimal?

Thread Scheduling

Thread scheduling policies

- *FIFO* - threads are called in first in, first out order within each priority level
  - Thread continues to run until a higher priority thread is runnable
  - Threads at same priority must block in order for other threads to run
- *Round-robin* - each thread is called in sequence, within priority level
  - Thread runs for fixed period of time before it is pre-empted
- *Other* - implementation specific
  - Operating system defines how threads are scheduled
  - This is the default (and undefined!)

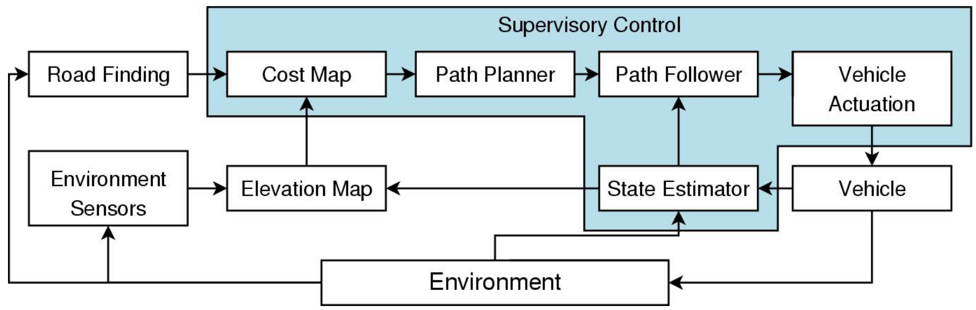
Homework

- Write a simple multi-threaded program using pthreads that reads numbers from an input stream (terminal), averages all numbers that have been read, and prints out the average once a second [use three threads]

Project Ideas

- Expand sparrow to allow multi-threaded servo and channel (I/O) execution
- Analyze how to best use mutex's for minimizing control latency when reading inputs via the network and writing outputs via (slow) serial ports
- Convert a controller from continuous to discrete for a multi-threaded control system using FIFO or round-robin scheduling

Thread Usage in Alice



Module	Threads
adrive (actuation)	19
trajFollower	10
astate (state estimator)	10
plannerModule	4
fusionMapper	16

Module	Threads
ladarFeeder (5)	8
stereoFeeder (2)	7
road (road follower)	5
superCon	3
DBS	3

* doesn't count heartbeat and logging threads

Example: State Client

- Asynchronously reads actuator state from adrive via thread
- Passes data back to calling module (eg, trajFollower)

```
void CStateClient::getActuatorStateThread() {
  int actuatorstatesocket =
    m_skynet.listen(SNactuatorstate, ALLMODULES);

  while(m_bRunThreads) {
    if(m_skynet.get_msg(actuatorstatesocket,
      &m_rcvdActuatorstate, sizeof(m_rcvdActuatorstate), 0,
      &pActuatorstateMutex) != sizeof(m_rcvdActuatorstate))
        skynet_error();
    DGCSetConditionTrue(condNewActuatorState);
  }
}

void CStateClient::UpdateActuatorState()
{
  DGClockMutex(&m_actuatorstateMutex);
  memcpy(&m_actuatorState, &m_rcvdActuatorstate, sizeof(…));
  DGCunlockMutex(&m_actuatorstateMutex);
}

void CStateClient::WaitForNewActuatorState() {
  DGCWaitForConditionTrue(condNewActuatorState);
  UpdateActuatorState();
  condNewActuatorState.bCond = false;
}
```

- Thread to read msgs
- Infinite loop
- Read msg (blocks until available)
- Unblock anyone waiting
- Copy state into buffer
- Use mutex to insure completeness
- Block until new state msg arrives

Verifying Multi-Threaded Programs

SPIN (Holzmann)

- Model system using PROMELA (Process Meta Language)
  - Asynchronous processes
  - Buffered and unbuffered message channels
  - Synchronizing statements
  - Structured data
- Simulation: Perform random or iterative simulations of the modeled system's execution
- Verification: Generate a C program that performs a fast exhaustive verification of the system state space
- Check for deadlocks, livelocks, unspecified receptions, and unexecutable code, correctness of system invariants, non-progress execution cycles
- Also support the verification of linear time temporal constraints

TLA/TLC (Lamport et al)

- Temporal Logic of Actions (TLA): Leslie Lamport, 1980's
- Behavior (a sequence of states) is described by an initial predicate and an action

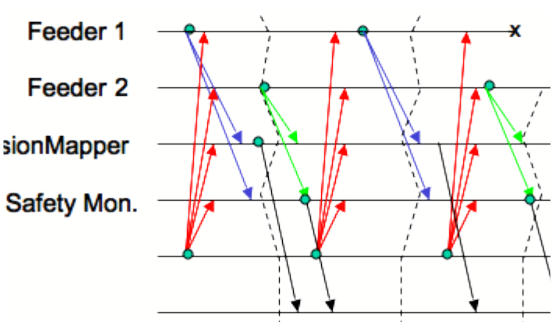
  Spec ≡ Init $\wedge$ □Action
- Specify a system by specifying a set of possible behaviors
- Theorem: A temporal formula satisfied by every behavior

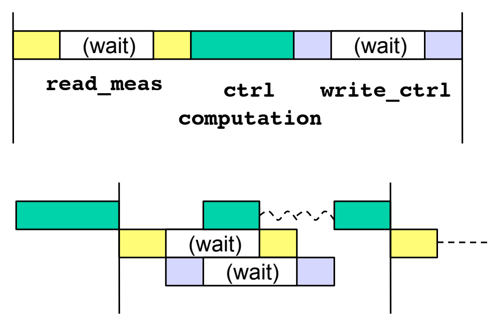
  Theorem ≡ Spec ⇒ □Properties

TLA+

- Can be used to write a precise, formal description of almost any sort of discrete system
- Especially well suited to describing asynchronous systems
- Tools: Syntactic Analyzer, TLC model checker

Summary: Embedded Systems Programming





Advantages

- Increased modularity
- Simplified programming*

Cautions

- Asynchronous execution
- Race conditions
- Deadlocking
- Debugging

Open Issues for Control Theory

- How do we best implement controllers in this setting?
- How do we verify that programs satisfy the specifications and design intent
- How do we implement multi-rate controllers using threaded process and distributed computing?