Week 10 – Concurrency

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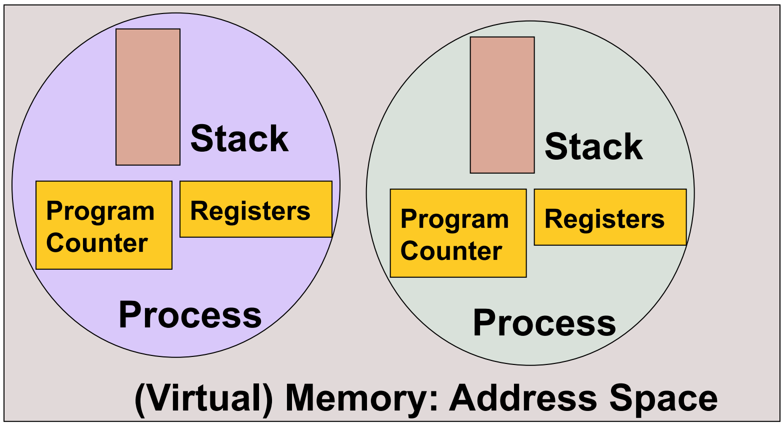
Introduction

- Why concurrency?
- Concurrency problems
- Synchronization
- More Problems
- Lock-free synchronization
- Aura Example

What Is Concurrency?



Concurrent Execution

- With a single CPU,
  - each process runs for awhile
  - processes switch at distinct time points
  - …but…
  - switch can happen at any time
  - on any instruction boundary
- We must assume any ordering of instructions is possible
- With multiple CPUs,
  - Atomic memory operations (read & write)
  - ...but...
  - Memory reads and writes are not in instruction order

Concurrent and Parallel

- **Concurrent** means multiple processes (or threads) that either
  - Run in an interleaved fashion, or
  - Run on multiple processors (or cores)
- **Parallel** means the latter: running on multiple processors (or cores)

Non-Reasons for Concurrency

- Multiple tasks
  - … but tasks can be interleaved in a single threaded program
    - Example: our discrete event simulations
- I have to pause task 1 and let others proceed
  - … but you can break up task 1 into multiple code blocks and run them separately
  - … or you can use active objects to retain state
  - … or you can use co-routines (not quite a process because there's no preemption; aka cooperative multitasking)

More Non-Reasons for Concurrency

- I need to block on I/O devices without blocking other tasks
  - … but you can use asynchronous I/O (sometimes)

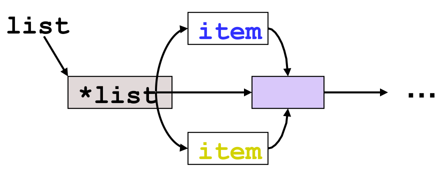
Reasons for Concurrency

- **Fault-tolerance**: isolate programs so that bugs do not bring down entire system
- **Time-sharing**:
  - prevent any program from taking control of the computer system
  - allow multiple programs to run without any designed-in cooperative behavior
- **Software Architecture**
  - make programs easier to build and understand
- **Low latency/fast response**:
  - … by preempting a slow process

Concurrency Problems

```
insert(list_node** list,
       item)
  node = new(list_node)
  node->value = item
  node->next = *list
  *list = node
```

```
node = new(list_node)
node->value = item
 node = new(list_node)
 node->value = item
node->next = *list
 node->next = *list
*list = node
 *list = node
```



Another Example

```
def withdraw(m)
  balance = balance – m
```

```
load r1, balance
load r2, m
sub r1, r2
store balance, r1
```

```
 load r1, balance=100
 load r2, m=75
 sub r1=100, r2=75
load r1, balance=100
load r2, m=60
sub r1=100, r2=60
store balance, r1=40
 store balance, r1=25
```

So balance == 25!

Yet Another Example

Parameter Update:
(lowpass filter)

```
lp_set_cutoff(hz):
  b=2.0-cos(hz*PI2/sr)
  c2=b-sqrt((b^2)-1)
  c1=1-c2
```

```
    b=2.0-cos(hz*PI2/sr)
    c2=b-sqrt((b^2)-1)
b=2.0-cos(hz*PI2/sr)
```

(maybe the filter runs here in a third thread!)

```
c2=b-sqrt((b^2)-1)
c1=1-c2
    c1=1-c2
```

This c2 is in a CPU register.

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Atomicity and Critical Sections

- We say that a set of operations is "atomic" if no other operations can be interleaved or concurrent.
- Some machine steps are always atomic, e.g.
  - Loading a memory word to a register
  - Storing a memory word from a register
- A set of operations that *must* be atomic for correctness is called a "critical section"

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Critical Sections Can Be Implemented with Locks

```
insert(list_node**list,
       item)
  LOCK(list_lock)
  node = new(list_node)
  node->value = item
  node->next = *list
  *list = node
  UNLOCK(list_lock)
```

```
LOCK(list_lock)
node = new(list_node)
node->value = item
 LOCK(list_lock)
node->next = *list
*list = node
UNLOCK(list_lock)
 node = new(list_node)
 node->value = item
 node->next = *list
 *list = node
 UNLOCK(list_lock)
```

Blocked

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Another Example

```
def withdraw(m)
  LOCK(account)
  balance = balance - m
  UNLOCK(account)
```

```
call LOCK(account)
load r1, balance
load r2, m
sub r1, r2
store balance, r1
call UNLOCK(account)
```

```
 call LOCK(account)
 load r1, balance=100
 load r2, m=75
 sub r1=100, r2=75
call LOCK(account)
 store balance, r1=25
 call UNLOCK(account)
load r1, balance=25
load r2, m=60
sub r1=25, r2=60
store balance, r1=-35
call UNLOCK(account)
```

Blocked

So balance == -35!

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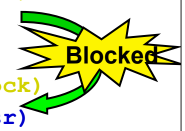
Yet Another Example

Parameter Update:
(lowpass filter)

```
lp_set_cutoff(hz):
  LOCK(filter_lock)
  b=2.0-cos(hz*PI2/sr)
  c2=b-sqrt((b^2)-1)
  c1=1-c2
  UNLOCK(filter_lock)
```

```
  LOCK(filter_lock)
  b=2.0-cos(hz*PI2/sr)
  c2=b-sqrt((b^2)-1)
LOCK(filter_lock)
  c1=1-c2
  UNLOCK(filter_lock)
b=2.0-cos(hz*PI2/sr)
```

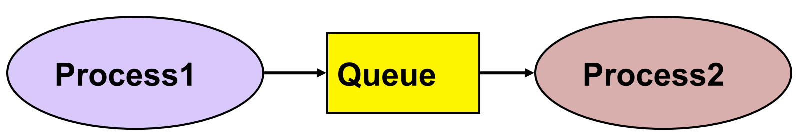


(maybe the filter *tries* to run here in a third thread!)

```
c2=b-sqrt((b^2)-1)
c1=1-c2
UNLOCK(filter_lock)
```

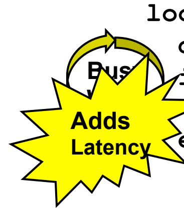

Synchronized *Communication* Is a Standard Problem

- Process1 puts tasks in a queue for Process2
- What should Process2 do when queue is empty?




```
loop
  generate data
  queue.insert(data)
```

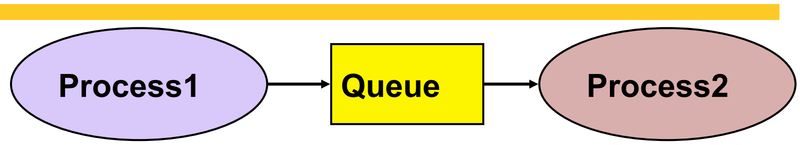
```
loop
  data=queue.remove()
  if data
    process data
  else sleep(1)
```



Events and Signals Are the Standard Alternative to Polling

- Event object
  - States: signaled, nonsignaled
  - Operations: SetEvent, WaitEvent
- SetEvent: sets state of Event to signaled
- WaitEvent:
  - block until state is signaled, then *atomically:*
  - [unblock caller and set state to nonsignaled]
  - *Only one blocked thread is released per SetEvent*

Event/Signal Example




```
loop
  generate data
  queue.insert(data)
  SetEvent(qevt)
```

```
loop
  data=queue.remove()
  if data
    process data
  else WaitEvent(qevt)
```

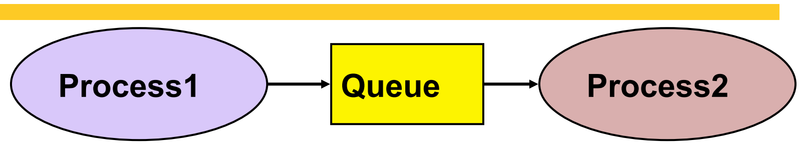
Proof by contradiction:
assume queue non-empty and waiting forever
in order to be waiting, queue was empty
after queue was empty, it became non-empty
but after an insert, Process1 calls SetEvent
so Process2 will proceed from WaitEvent.

***Note many hidden assumptions*:**
no other processes,
strict execution order,
queue access primitives atomic

Semaphores Are Another Approach to Many Synchronization Problems

- Similar to Event objects, but
- State is an integer
- Signal (V) increments integer (atomically)
- Wait (P) blocks until state > 0, then
  - [decrements integer, unblock caller] atomically
- If initialized to 1, LOCK = P(s), UNLOCK = V(s)
- Useful for queues, allowing *n* processes to share a resource, pools of *n* resources

Semaphore Example




```
Initially, qsem == 0

loop
  generate data
  queue.insert(data)
  V(qsem)
```

```
loop
  P(qsem)
  data=queue.remove()
  process data
```

Note that we still need mutual exclusion on queue access.

Readers and Writers Problem

- A classic concurrency problem:
  - Only one process can write at a time
  - Any number of processes can read concurrently
  - Why would you want this?
- We won't take time to present the solution
- See any OS textbook or the web
- You should recognize the problem when you see it

Fairness and Starvation

- If many threads wait on a lock, a process may never wake up – *starvation*
- You can wait in a FIFO queue
- You can wake up a random process
- Maybe the process waiting the longest should get the lock next – this is a *fairness* consideration.
- Fairness requirements can make analysis even more difficult

Deadlock Is Another Potential Problem in Concurrent Programs

`LOCK(a)`	`LOCK(b)`
`LOCK(b)` OOPS!	`LOCK(a)` OOPS!
`work with a and b`	*`work with a and b`*
`UNLOCK(b)`	`UNLOCK(a)`
`UNLOCK(a)`	`UNLOCK(b)`

Monitors Are an Attempt to Create More Intuitive, High-Level Abstractions for Concurrency

- Roughly speaking, an *object* that allows at most one process to execute any method is called a *Monitor*
- Nice abstraction: methods become atomic operations
- Java uses *synchronized* keyword to require object to be locked before executing the method

Monitor Example

```
class Queue {
   synchronized void enqueue(Item *item);
   synchronized Item *dequeue();
};
```

Calling q.enqueue(item) effectively does this:

```
lock(q.lock);
q.enqueue(item);
unlock(q.lock);
```

Monitors have additional features to block and wake up
(what happens in dequeue() when queue is empty?)

Nested Monitor Calls Require Great Care

- Problem:
  - Monitor A calls method in Monitor B
  - Monitor B calls a different method in Monitor A
  - DEADLOCK!

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Real-Time Issues: Priority

- Recall that within single applications, the only *essential* reason for concurrency is to reduce latency
- We want to preempt long-running tasks to meet deadlines
- Two popular methods:
  - Deadline Scheduling
  - Fixed-priority Scheduling

Deadline Scheduling Is Optimal, But Failure Mode Can Be Arbitrarily Bad

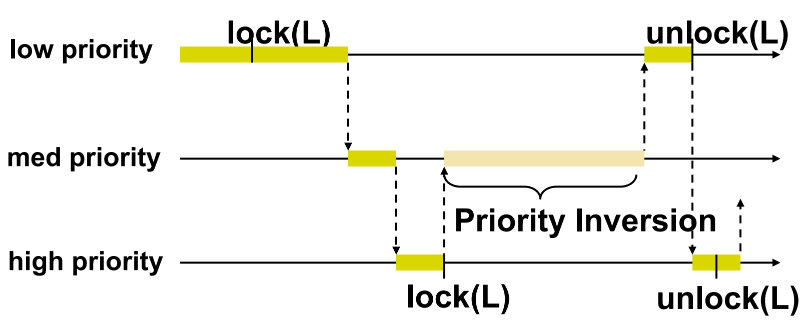
- Every task has a deadline
- Run the task with the nearest deadline first
- Optimal, *if all deadlines can be met*
- But it could force you to miss *all* deadlines
- Another problem: what's a deadline?
  - Maybe easy when controlling hardware
  - For audio computation, deadline is when the output buffer runs out of samples
  - Difficult to say when controlling music processes
- Effectively, our class project schedulers are deadline schedulers because they sort events by their ideal execution times and run them in that order.

Fixed Priority Is Commonly Available and Very Usable

- Each process has a fixed priority
- Run the highest priority process that is ready to run
- Often implemented in OS's
- Often used for periodic tasks of various periods
  - *If the tasks are schedulable*
  - In this case, called *rate-monotonic* scheduling
- Fairly easy mapping to music tasks:
  - Audio computation gets highest priority
  - (MIDI) control gets medium priority
  - Graphical user interface gets low priority

Priority Inversion Can Lead to Disasters

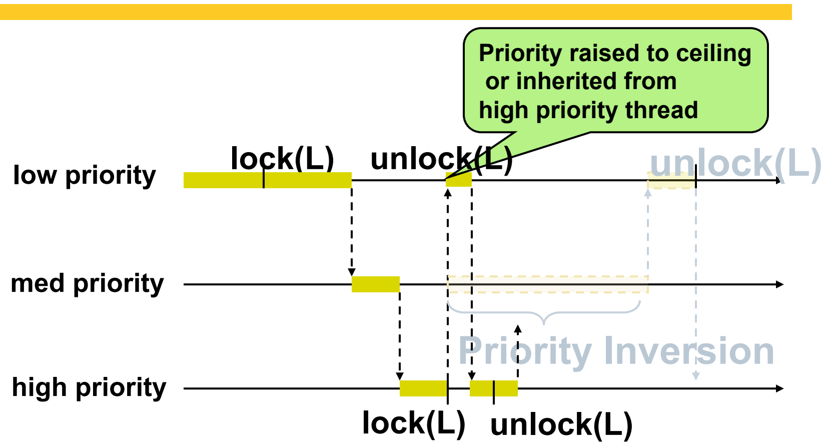
- Static priority scheduling and synchronization primitives can have catastrophic interactions



Solving the Priority Inversion Problem

- Priority Ceiling: when you acquire a lock, raise your priority to the highest priority of any other process that might acquire the lock
- Priority Inheritance: make the priority of the lock holder greater than or equal to the priority of any process waiting on the lock
- Probably cannot depend on OS solving this problem for you unless you control the OS

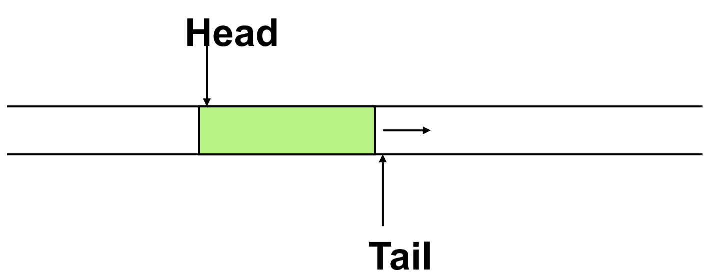
Priority Inversion Solved



Lock-Free Synchronization

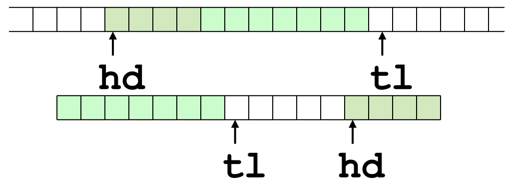
- Priority inversion problem can make available synchronization primitives *unusable for (reliable) real-time applications*
- Alternative: synchronization without locks
- Simplest example: Atomic memory writes
  - you can share a 32-bit value and assume reads/writes are atomic
  - Writer can update value asynchronously
  - Reader always gets an (almost) up-to-date value

Lock-Free Queue



Single CPU, Single-Reader, Single-Writer Queue

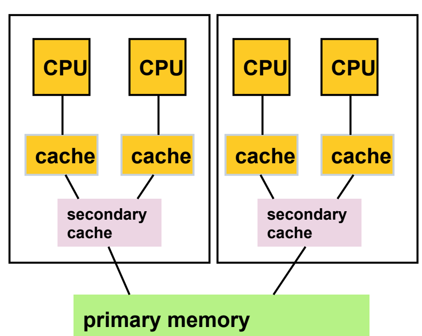
```
hd = 0
tl = 0
q = array(N)
def insert(x)
  if tl < hd + N
    q[tl%N] = x
    tl = tl + 1
def remove()
  if hd < tl
    var x = q[hd%N]
    hd = hd + 1
    return x
  else
    return EMPTY
```



- Note that the order of instructions is critical
- Must store value before incrementing tl
- Must retrieve value before incrementing hd
- Compilers may cause problems: see "volatile" attribute in C compiler
- There are versions without "%" operation, e.g. (hd & mask).
- There are versions without unbounded hd and tl (otherwise this approach would be pretty useless)

Why did we specify "Single CPU" for the Queue Example?

- Multiprocessors rely on multi-level cache
- What happens when there are multiple reads and writes to the same address?
- Modern systems increasingly allow reordering of memory reads and writes(!)



What Can Go Wrong?

```
hd = 0
tl = 0
q = array(N)
def insert(x)
  if tl < hd + N
    q[tl%N] = x
    tl = tl + 1
def remove()
  if hd < tl
    var x = q[hd%N]
    hd = hd + 1
    return x
  else
    return EMPTY
```

Out of order writes cause problem:

store
read
read (the wrong value!)
store

This used to be only :-) a problem of preventing the optimizing compiler from reordering assignments, but now write reordering happens in hardware.

A Multiple-CPU, Single Reader, Single Writer FIFO Queue

- Communication through "handshaking":

```
Process 1:                Process 2:
  while true:               while true:
    if not flag               if flag
      flag = true               flag = false
```

Processes synchronize in setting flag to true/false. Depends* only *on atomic memory reads/writes.

- Slight change: send non-zero value:

```
var buf = 0               def receive():
def send(x):                while true
  while buf != 0:             var r = buf
    nil                       if r != 0
  buf = x                         buf = 0
                                  return r
```

Light Pipe Algorithm - Alexander Dokumentov

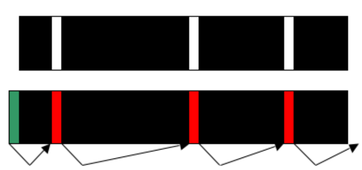
- Expand buf to be a circular buffer:

```
var buf = array(N)
initialize buf to zero
var i = 0
def send(x):
  while buf[i] != 0:
    nil
  buf[i] = x
  i = (i + 1) % N
```

```
var j = 0
def receive():
  while buf[j] == 0:
    nil
  var result = buf[j]
  Buf[j] = 0
  j = (j + 1) % N
  return result
```


Light Pipe Algorithm (2)

- What about zero values?
- Encode M words with zeros as M+1 words:



Reference: http://www.ddj.com/dept/cpp/189401457

Other Lock-Free Algorithms

- Some based on CAS (Compare-and-Swap)

```
bool cas(a, e, n) {
  atomically {
    if (*a == e) {
      *a = n;
      return true;
    }else
      return false;
  }
}
```

- Examples of Lock-Free Algs:
  - FIFO queue
  - Freelist
- "The difficulty of achieving lock-free 64-bit-clean implementations of such mundane data structures strongly suggests that improved hardware support is necessary before practical lock-free data structures will be widely available."
- Simon Doherty, Maurice Herlihy, V. Luchangco and M. Moir. Bringing practical lock-free synchronization to 64-bit applications. *Twenty-Third Annual Symposium on Principles of Distributed Computing (PODC).31-39.*

Memory Consistency and Future Processors

- Memory Barrier Instruction and WriteMB
  - The MB instruction can be used to maintain program order from any memory operations before the MB to any memory operations after the MB.
- See S. V. Adve and K. Gharachorloo, "Shared memory consistency models: A tutorial," in Technical Report WRL-TR 95/7, Digital Western Research Laboratory, September, 1995.

Blocking vs. Polling

- Lock-free synchronization does not allow processes to block
- Standard solution is polling
  - Wake up every 1ms or so,
  - Do whatever work there is to be done
  - Go to sleep (here's where blocking takes place) for 1ms or so

Periodically "Waking Up"

- Use an OS call to sleep
- Use an OS blocking call with a timeout
- Block waiting for audio input (wake up every 32 or 64 samples)
- Use a timer facility like Window MM system timer that calls a function periodically

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Is Polling Bad?

- Waste of CPU time when nothing to do.
  - But CPU load can be low: 1 to 5%
  - In dedicated systems, there's no cost (well maybe power)
- Context switches are expensive
  - But if there's work to do, you're going to context switch anyway
  - Synchronization primitives are expensive too
- Latency: code doesn't run immediately after data available
  - But if polling frequency is high enough, latency is negligible
  - Real time systems care about being *fast enough,* not being *as fast as possible.*
- Polling is *more efficient* as load increases, so polling can actually be better from a real-time perspective (real time systems care about the worst case, not the average case).

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Example: Aura Architecture

- Goal 1: General platform for interactive multimedia
- Goal 2: Open-ended, extensible for video, graphics, networking, software systems.
- Based on Real-Time Distributed Object System
- Objects have globally-unique 96-bit names
- Asynchronous messages
- Location independent

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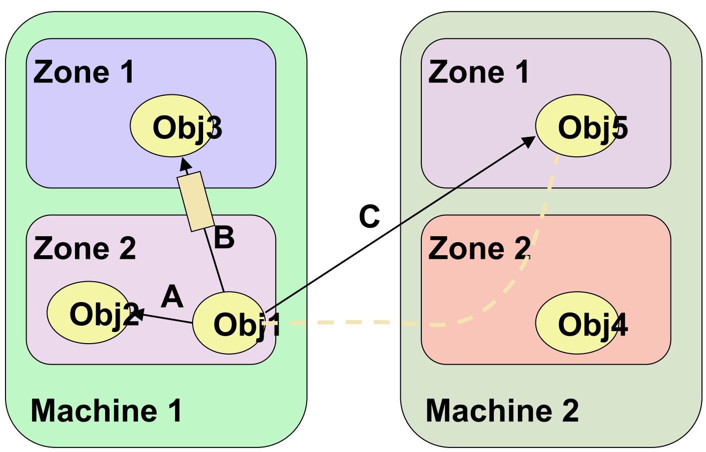
Communication with Aura

- Remote Method Invocation
  - *send_set_hz_to*(*osc,* 440.0)
  - Automatically generated macros to send messages
  - Receiver is indicated by globally unique ID
- Location Transparency
  - Object in same thread – synchronous call
  - Object in same address space – msg queue
  - Object on remote machine – TCP/IP to msg queue

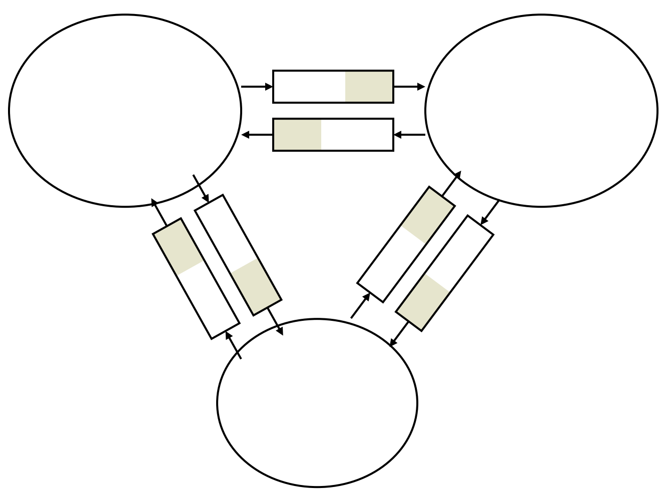
Messages and Location Transparency



Aura Details

- Each Zone (thread + memory + scheduler):
  - Memory pool and real-time allocator
  - Calendar Queue-based scheduler
  - Time (seconds) based on audio sample count
- Pre-processor generates:
  - RPC message handlers
  - Stubs to pack parameters into msgs and send
  - Macros to make them easy to call
- Structure by *latency*, not *function*

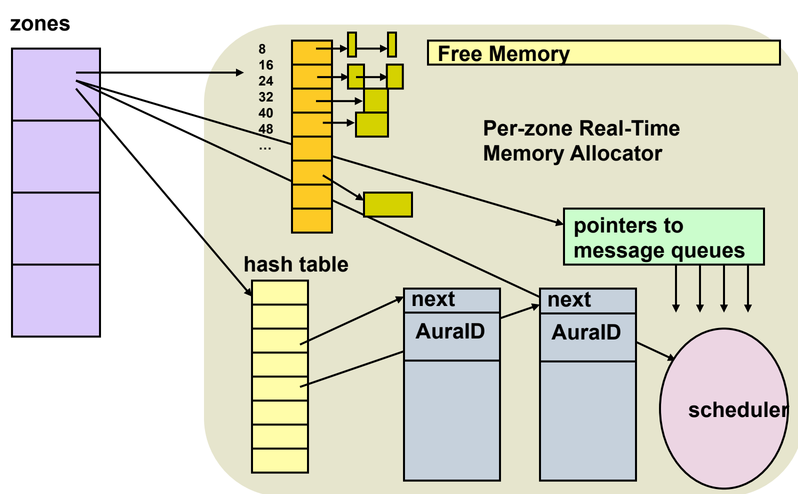
Message Passing Details



Zone Processing Loop

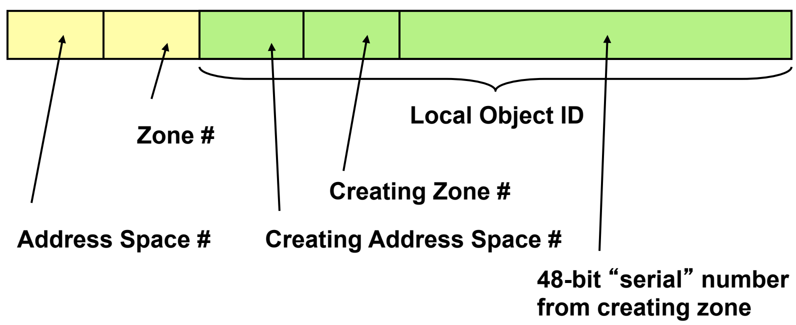
- Every zone runs periodically
- Messages are blocks of memory:
  - [bytecount, timestamp, object-ID, method, arglist]
- Poll:
  - Dispatch any scheduled messages
  - Check each incoming queue for messages
    - Either dispatch immediately (no copy), or
    - Allocate memory, copy, and schedule future msg
  - Actions can send and schedule new messages
- No blocking except:
  - Audio thread does blocking I/O (32 samples = 0.7ms)
  - Midi thread sleeps 1ms when nothing to do
  - Graphics thread run by GUI, uses periodic callback

Aura Objects



Aura ID

- 96-bit globally unique identifier (48 low-order bits of two 64-bit words)



Sending a Message

```
if space(msg.dest) == my_space_id
    if zone(msg.dest) == my_zone_id
        if msg.timestamp >= NOW
            obj = zone[my_zone_id].lookup(msg.dest)
            obj->msg_handler(msg)
        else
            zone[my_zone_id].schedule(
                                  msg.timestamp, msg)
    else
        zone[my_zone_id].queue[zone(msg.dest)].
                             enqueue(msg)
else
    space_proxy[space(msg.dest)]->send(msg)
```

Summary

- Concurrency: good reasons and bad reasons
- In real-time systems, preemption->low-latency
- Atomic actions and Critical sections
- Synchronization primitives:
  - locks, events, semaphores, monitors
- The dark side:
  - Starvation, Deadlock, Priority Inversion
- Lock-free structures
- Polling vs Blocking
- Aura