Discrete Event Simulation

- Why DES?
- Overview
- Approaches
- Details of Event Scheduling Systems
Why Discrete Event Simulation

- Most CS is concerned with computing answers at some time in the future (hopefully soon)
- Discrete event simulation models time as well as processes
- DES techniques turn out to be very relevant to real-time, interactive music systems.

Overview of Discrete Event Simulation

- Model behavior …
- … consisting of discrete state changes
- State: all information describing system at a given point in time
- Event: a trigger that initiates an action that changes the state
- Process: a sequence of events, usually associated with some simulated entity
Simulation Structure

- Executive: manages events and runs actions, keeps track of time
- Utilities: random number generation, statistics, etc.
- Model (program): code that models the specific behavior of the simulated system.
  - Note the design strategy: separate system-specific code from generic, reusable code.

Time in Simulation

- Usually, simulation time is not real time.
- Results of simulation available faster than real time (e.g. weather, climate simulation)
- Simulation time
- Run time
- Event time
Time in Simulation

- Usually, simulation time is not real time.
- Results of simulation available faster than real time (e.g. weather, climate simulation)
- Simulation time: the time in the model
  - Also logical time or virtual time
- Run time: the real (cpu) time of the simulation
- Event time: the simulation time at which an event should happen

Scheduling Events

- (1) Synchronous simulation
  - What it does:
    - Advance virtual time by small fixed interval
    - Run all events in that interval
  - Timing not precise
  - Wastes computation when no events enabled
  - Similar to frame-by-frame animation engine
- (2) Event-scanning simulation:
  - Advance time to next event time
  - Run the event
(1) Synchronous Simulation

Discrete times ➔

Call every object at every time step

Objects being simulated

Question:

- What are some examples where synchronous simulation makes sense?
  - Computer animation – everything changes frame-by-frame; maybe drawing dominates cost (so testing for behavior is insignificant)
  - Physical simulation, difference equations, everything changes each time step
  - Continuous music control, e.g. objects generate envelopes, vibrato, etc. and change “continuously” (i.e. at each time step)
(2) Event-Scanning Executive

- Event: data structure containing...
  - Event time: when to dispatch the event
  - Function: reference to a method or procedure
  - Parameters: for the function
- Future event list: data structure
  - Priority Queue: insert/remove events

Question:

- What are some examples where event-scanning makes sense?
  - Music with discrete events, e.g. notes, sequencers, MIDI
  - Operating systems: processes call sleep()
Simulation Organization

- Activity Scanning
- Event Scanning/Scheduling
- Process Interaction

Activity Scanning

- Organized around the activity
- Activities start when conditions are met
- Executive scans for an activity that is enabled

- Makes sense when enabling conditions are complex, e.g. particle systems, crowds, physics with collision detection
- Amounts to synchronous simulation with polling to decide when to perform events
Event Scheduling

- Organized around the event
- Activities change the state, figure out time of next event and schedule events accordingly
- Appropriate when
  - Interactions are limited
  - Precise timing is important
  - Timed state changes

Process Interaction

- Organized around the Process
- Modeled entities represented by processes
- Processes can wait to simulate passing of time
- Processes can use synchronization, e.g. semaphores or condition variables to represent interdependencies.
Example

- Manufacturing

Four ways to approach this (at least):
  - Activity scanning model
  - Event scheduling model
  - Process interaction model
    - Process could be a manufactured article
    - Process could be a manufacturing station
  - (discuss each of these four approaches)

Event Model in More Detail

- Why focus on event model? Because we’re going to be using the event model for music generation.

- State:
The number of objects at each position

- Event: Begin or end a step
Events

```python
def start_step(i):
    if s[i] > 0:
        s[i] = s[i] - 1
        schedule(now + dur(i), 'event_done', i)

def event_done(i):
    s[i+1] = s[i+1] + 1  # increment output tray
    start_step(i)  # begin work on next input
```

**Bugs:**
- Need range check on i, there's no step 3, 4, 5, ...
- If step is inactive and item is added to input tray, need to start the step. How do we implement this?

Events and Time

- Virtual time does not advance while events are “running” – being computed.
- Virtual time only advances when the next event is in the future.
- If there are multiple events at the same virtual time, time does not advance until all are computed: Arbitrary amounts of computation in zero logical time.
- Event “duration” is zero, but we can model process begin, middle, end as multiple events
Processes/Threads

- A “natural” way to model behaviors
- But processes can be “heavy”
  - Stacks
  - Context switch must swap all registers
- Processes must coordinate updates to the state. Consider this in parallel:
  - \[ s[i] = s[i] + 1 \]
  - \[ s[i] = s[i] - 1 \]

Processes and Time

- How can we model time with Processes?
- *Virtual time should only advance when processes block or sleep.*
- Blocking and sleeping are typical OS primitives, but not designed for simulation
- Coordinating multiple CPUs to order computation with respect to virtual time is tricky and beyond our (current) discussion
- Processes are not recommended for DES
Coroutines

- Similar to processes, but
- “synchronous” in that threads must explicitly yield:
  - sleep() – run other threads for some amount of virtual time
  - semaphores and condition variables – block until ready to run, run other threads in the meantime
  - yield() – just pick another thread and run
- Consider:
  - \( s[i] = s[i] + 1 \)
  - \( s[i] = s[i] - 1 \)

Each of these is an atomic operation: it runs to completion with no possibility of another thread seeing intermediate results.

Coroutines and Logical Time

- How can we model time with coroutines?
- Sleep(): inserts an event in a priority queue
  - Advance virtual time to next event in queue (virtual time does not necessarily change)
  - Event wakes up the sleeping coroutine
- Yield(): checks and switch to ready-to-run coroutines.
- Assessment:
  - Similar to Event Model
  - Ability to suspend (sleep) within a procedure
Coroutines, Threads, Serpent

- Until last year, this discussion of coroutines was mainly for completeness, since few languages support them.
- Serpent has a new feature: non-preemptive threads!
- Note: Python can implement coroutines by building on generators; semantics are different
- Coroutines in Serpent are called “threads” (sorry, but “non-preemptive threads” was too verbose)
- Serpent scheduler works with threads

Simulating a Sequence with Serpent Threads

```python
def myseq():
    if fork(): return
    # computation in STEP1
    sched_wait(DUR1)
    # computation in STEP2
    sched_wait(DUR2)
    # computation in STEP3
    sched_wait(DUR3)
    ...
```
Simulating a Sequence with Events

```python
def myseq():
    if state == START:
        state = STEP1
        // computation in STEP1
        schedule(now + DUR1, 'myseq')
    elif state == STEP1:
        state = STEP2
        // computation in STEP2
        schedule(now + DUR2, 'myseq')
    elif state == STEP2:
        state = STEP3
        // computation in STEP3
    ...  
What if we want multiple instances of myseq?
```

Events and Instances

```python
def myseq(state):
    if state == START:
        state = STEP1
        schedule(now + DUR1, 'myseq', state)
    elif state == STEP1:
        state = STEP2
        schedule(now + DUR2, 'myseq', state)
    elif state == STEP2:
        state = STEP3
    ... 
Now we can launch many instances of myseq(START)
But, what if we need local state for each instance?
```
Events and Instances (2)

```python
def myseq(state, per_inst):
    if state == START:
        state = STEP1
        schedule(now + DUR1, 'myseq',
                 state, per_inst)
    elif state == STEP1:
        state = STEP2
        schedule(now + DUR2, 'myseq',
                 state, per_inst)
    elif state == STEP2:
        state = STEP3
        ...
```

Now we can launch many instances of `myseq(START, x)` where each instance has its own local state (x).

Simulating a Sequence with Events – A Variation

```python
def myseq_step1():
    schedule(now + DUR1, 'myseq_step2')

def myseq_step2():
    schedule(now + DUR2, 'myseq_step3')

def myseq_step3():
    schedule(now + DUR3, 'myseq_step4')
```

...
Object Oriented Simulation

- In previous slide, what if we wanted more state?
  - Events solution requires us to pass state or at least a reference to state through parameters.
  - Let’s look at Object Oriented simulation as another way to deal with instances and state.

Object Oriented Approach

- Scheduling an event effectively calls a procedure in the future
  - Procedures are not the best model for entities in the real world (that have state)
  - A previous example shows how we can pass state through parameters
- What if we extend events to activate objects?
  - Object can hold state – no need to encode into parameters
  - Objects can model entities in the real world
Object Oriented Approach

```python
class My_thing (Event):
    var state // an instance variable
    def init():
        state = START
    def run():
        switch (state):
            START:
                state = STEP1
                schedule(now + DUR1) // inherited method
            STEP1:
                state = STEP2
                schedule(now + DUR2)
            STEP2:
                state = STEP3
            ...
```

Object Oriented Approach (2)

- Notes on the previous slide:
  - Everything can be statically type checked
    - schedule() takes an object of type Event rather than a procedure reference
    - no dynamically typed parameters to pass to an event
  - State is encapsulated in objects
  - Slightly clumsy that every schedule results in a call to run()
    - Some languages allow you to pass pointers to methods, similar to passing function pointers in the Event Model
    - OO languages allow you to pass objects that could then invoke the desired method, but this could be clumsy too
Summary

- Discrete Event Simulation computes (virtual) time as well as state changes
- Event Scheduling can compute timing with high precision (no rounding to discrete intervals or system clock)
- Various approaches:
  - Processes – heavy and hard to manage time
  - Coroutines – stacks, context switch, relatively easy to incorporate virtual time
  - Objects – lighter weight, popular for models
  - Events – very lightweight, simple
Review

- Discrete – at points in time
- Event – state changing action
- Simulation – a model
- Big ideas:
  - All behavior modeled as instantaneous events
  - Compute precise times of events
  - Future events in a priority queue (sort by time)
  - Perform events in time order
  - Always keep track of virtual (simulated) time
Representing Events in Serpent

- Want to separate “simulation executive” from details of model.
- Need “event” representation: how do we represent a function call to take place in the future?
- “event” should support these operations:
  - Dispatch – allows the executive to execute events without knowing the details
  - Compare – allows executive to see which event comes first

The event Representation

- Just an array:
  - [time, // the event time
  - target, // object
  - message_name, // method to invoke
  - parms] // parameters to pass
- Or
  - [time, // the event time
  - nil, // nil→call a function
  - function_name, // function to call
  - parms] // parameters to pass
Dispatching an event

```python
def general_apply(target, message, parms):
    if target:
        sendapply(target, message, parms)
    else:
        apply(message, parms)

// note: parms is an array, e.g.
//
// general_apply(synth, 'play', [60, 100])
// is same as: synth.play(60, 100)
//
// general_apply(nil, 'foo', [10, "hi"])
// is same as: foo(10, "hi")
```

Implementing a scheduler (a "simulation executive")

- Need two operations:
  - Schedule ("cause") an event: the event is remembered and dispatched at the specified event time
  - Poll:
    - advance virtual time to the earliest event time,
    - if real time >= virtual time
    - dispatch the earliest event
- Design choice:
  - Simulation executive can be a process that polls
  - It can be our responsibility to call poll() frequently
Implementation 1: linked list

- To schedule, insert event at the head of a list

\[
\text{while } \text{len(list)} > 0: \quad // \text{run until done} \\
\text{for each } r \text{ in list} \\
\quad \text{if } r[0] < \text{now} \\
\quad \quad \text{list.remove}(r) \\
\quad \quad \text{dispatch}(r) \\
\quad \text{now} += \text{interval}
\]

- Example of Event Scanning
- Problems:
  - Could run events out of order
  - Searches entire list very often
  - Bug: changing list while iterating over list is not allowed

Implementation 2: priority queue

- Like before, but linked list is sorted:

\[
\text{Increasing timestamps}
\]

\[
\text{while } \text{len(list)} > 0: \quad // \text{run until done} \\
\quad \text{var } r = \text{list}[0] \\
\quad \text{list.remove}(r) \\
\quad \text{now} = r[0] \quad // \text{get the event time} \\
\quad \text{dispatch}(r)
\]

- Problems:
  - Scheduling (insertion) is linear in size of list
  - In Serpent, list.remove(r) is linear as well
Implementation 3: heapsort

- Trick: embed complete binary tree in array.

- Parent(n) = floor(n/2)
- left_subtree(n) = 2 * n
- right_subtree(n) = 2 * n + 1

- Heap invariant:
  No parent is greater than its children
  It follows that the root is the minimal element

Heapsort (2)

- After removing least element (array[1]), move last array element to first. Then, “bubble” down the tree by swapping new element with least of two children (iteratively) until no child is smaller.
- To add an element, insert at end of array. Then “bubble” up the tree by swapping new element with parent until parent is smaller.
- Log(n) insert and delete.
Heapsort (3): Remove

Heapsort (3): Remove
Heapsort (3): Remove

```
   29
  /  \
20   6
 /    /
35   29
```

Heapsort (3): Remove

```
   6
  /  \
20   29
 /    /
35   29
```
Heapsort (3): Insert

Heapsort (3): Insert
From DES to Real-Time Systems

- DES computes and simulates precise timing
- We want precise timing in music systems too
- Example:
  - Thread1():
    - loop:
      - play bass_drum
      - sleep(1.0)
  - Thread2():
    - loop:
      - play snare
      - sleep(1.0)
  - main():
    - new Thread1()
    - sleep(0.5)
    - new Thread2()
How Much Precision Do We Need?

- Suppose we compute things to nearest frame of a video game:
  - Frame rate = 60fps
  - Frame period = 1/60 = 17ms
  - Quantization error is perceptible
- What if system always responds within 1ms?
  - 100 beats per minute * 0.5ms error = 50ms error per minute (!)
- Recommendation: compute time with doubles

What can we hear?

- 0.1s jitter
- 20ms jitter
- 5ms jitter
- 1ms jitter
- 10ms is typical Just-Noticeable Difference (JND) for (almost) equally spaced taps
- 10ms jitter in a drum roll is clearly audible though, so 1ms is a much better goal
**DES-like Real-Time Scheduling**

- In music, usually very small timing errors (~1ms) are OK, but cumulative errors are bad:
  - Otherwise, two musical lines might drift apart
  - Otherwise, MIDI synchronized to audio or video might drift
- By the way, what are synchronization requirements for audio/video?
  - EBU R37: recommends audio at most 40ms early, at most 60ms late

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**DES-like Real-Time Scheduling (2)**

- Key ideas:
  - DES techniques to compute when things should happen – a specification
  - Use clock reference to make things happen as close to specification as possible
- Algorithm:
  periodically do this:
  ```
  if time of first event in queue < get_time()
    remove event from queue
    now = event.time
    event.run()
  ```
Where do we get “real time”? 

- system clock – every computer has a built-in crystal clock
- audio sample count – to sync to audio
- video frame count or SMPTE – sync to video

How to implement “periodically”

- Simplest scheme (for command line – e.g. serpent64 – or embedded programs)
  - while true
    - do periodic computation
      - sleep(0.002) // sleep 2ms to reduce CPU load
- GUI toolkits/libraries usually have a timer callback function, e.g. in Swing:
  - new Timer(2, periodicComputation).start();
  - Where periodicComputation implements Action interface
Scheduler in Serpent

```python
require "sched"
def sched_poll():
    nil
sched_init()
// put something on the scheduler
def demo(n):
    print "I'm alive!", n
    sched_cause(1, nil, 'demo', n + 1)
sched_select(rtsched)
sched_cause(1, nil, 'demo', 0)
sched_run()
```

Scheduler in wxSerpent

```python
require "sched"
sched_init()
def demo(n):
    print "I'm alive!", n
    sched_cause(1, nil, 'demo', n + 1)
sched_select(rtsched)
sched_cause(1, nil, 'demo', 0)
// do not call sched_run()
```
Review

- Now you know how to build an accurate scheduler for music that:
  - Can handle hundreds or thousands of concurrent streams of events (notes, chords, beats, etc.)
  - Is efficient with computer time
  - Does not drift with respect to reference clock
  - Does not introduce critical sections, locks, multiple threads, or the overhead of traditional concurrent programs
- Let’s look at some more scheduling algorithms…

Implementation 4: no polling

- Implementations 2 and 3 use priority queues
- Time of the next event is easily determined
- Why wake up periodically?
- Instead, sleep until the next event time.

- Observations:
  - +Saves time when there nothing to do
  - -Overhead of polling every ms or so is small
  - -Often, you need to poll for other things (audio processing, sensor input, …)
Implementation 5: timing wheel or calendar queue

To Schedule: insert in table[int(ticks) mod n]
To Dispatch: every tick, search in table[tick mod n]

Assuming event times are random, and table size \( n \) is comparable to number of events, this can have \( O(1) \) scheduling and dispatching time.

Implementation 6

- What happens if events are not randomly distributed but separated by \( n \)?
  - E.g. table size = 1024 and each slot represents 1ms. Many events are scheduled at times 50+1024\(n\) ms. Slot 50 gets all events!

- Suppose we use table only for events in the near future?

- Note: reading makes this assumption already in Implementation 5.

- What do we do with events too far in future?
Implementation 6 (2)

- The answer:
  - Keep far-future events in a heap-based priority queue and deal with them later.
  - But a heap-based priority queue has $O(\log n)$ insert time, so...
  - Schedule far-future events by inserting into a list; process the events later.

![Diagram of Pending List, Priority Queue, and Table]

Implementation 6 (3)

```
Incoming Events
  ▼ this period
    ▼ next period
       ▼ “far future”
```

![Diagram of Pending List 1, Pending List 2, Priority Queue, Table 1, and Table 2]
Implementation 6 – Analysis

- Schedule time is $O(1)$: based on time, just insert into Table 1, Table 2, or Pending List.
- Dispatch time is $O(1)$ per event and $O(1)$ per clock tick: dispatch everything in corresponding slot in Table 1.
- Additional background processing time is $O(\log n)$ per far-future event.
- Background processing must be completed each period.

Implementation 6 – Discussion

- How do you schedule background processing? What if it doesn’t finish in time?
- Yann Orlarey has a related scheme using an incremental radix sort instead of the heap – implemented and used in MidiShare system.
- I currently use Serpent’s (linear) resort() method to make priority cues. In C, I use Implementation 5 (timing wheel):
  - Simple to implement.
  - Works with floating point timestamps.
  - Worst-case performance not bad in practice.
  - Determining when to do background processing and coordinating that with foreground processing really needs OS support so it’s hard to do right.
Summary

- Events and Priority Queue
- Adaptable to almost any programming language
  - Function pointers
  - Subclass events
- Accurate timing
- Deterministic execution even in the face of some timing jitter
- Scheduling can be both fast and simple
- Implementation 5 is common, but tricky to implement due to rounding issues