Model Checking Real Time Java --- Wrap Up Report

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Outline

- Review
  - Motivation and approach
- RTSJ implementation strategy
  - In pure Java
  - Exploiting JPF
- Examples
  - Multiprogramming operating system
  - Cars crossing intersection
- Status and *To Do* list
  - Gleams in our eyes

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What Is Real Time Java?

- A Java extension supporting real time applications
  - Defined in *Realtime Specification for Java* (RTSJ)
  - New classes, e.g. **`RealtimeThread`**
  - New semantics for existing classes, e.g., **`java.lang.Thread`**
  - No language extensions, e.g., new syntax or keywords

Key Features of RTSJ

- Threads
  - Real time threads
- User definable schedulers
  - Default: priority based (32 levels)
  - Priority inversion avoided by *priority inheritance*
- Events and event handlers
  - Events bound to clocks and timers
  - Or external *happenings*

Other Features of RTSJ

- Memory areas
  - Scoped, immortal, physical
  - **`NoHeapRealtimeThreads`** not impeded by GC
- Asynchronous transfer of control (ATC)
  - Asynchronous interrupt handling
  - Within defined scopes
    - Those throwing **`AsynchronousInterruptException`**

RTSJ Validation Challenges

- More dynamic program behavior
  - Consequence of *no language extension*
  - Means more possible exceptions
- Role of time complicates correctness
  - Will a handler complete by its deadline?
  - If not, will overrun events be generated?
- How do we model environment in which RTSJ code runs?

Model Checking RTSJ

- System under test has 2 components
  - *Embedded* code: RTSJ code itself
    - e.g., flight control software
  - *Embedding* code: modeling environment
    - e.g., the airplane sensors and actuators
  - Both can be complex and difficult to specify
  - Both must be tested and validated

RTSJ Under JPF

- *Option 1*:
  - Extend JPF JVM to support RTSJ features
    - Custom scheduling, memory areas, ATC, …
- *Option 2*:
  - Don't change JPF JVM
  - Instead, add features external to JPF
  - *Bonus:* will run under ordinary Java

RTSJ Under JPF (cont'd)

- *Example:* custom schedulers
  - *Option 1*: make JPF scheduler programmable
    - But this is integral to JPF state management
  - *Option 2*: constrain the JPF scheduler to become deterministic
    - Run real time threads as coroutines
    - Define customized scheduler logic externally

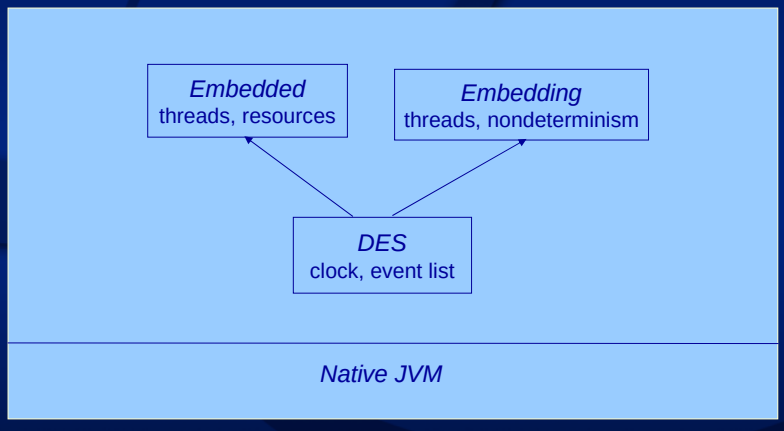
Our First Implementation Follows Option 2

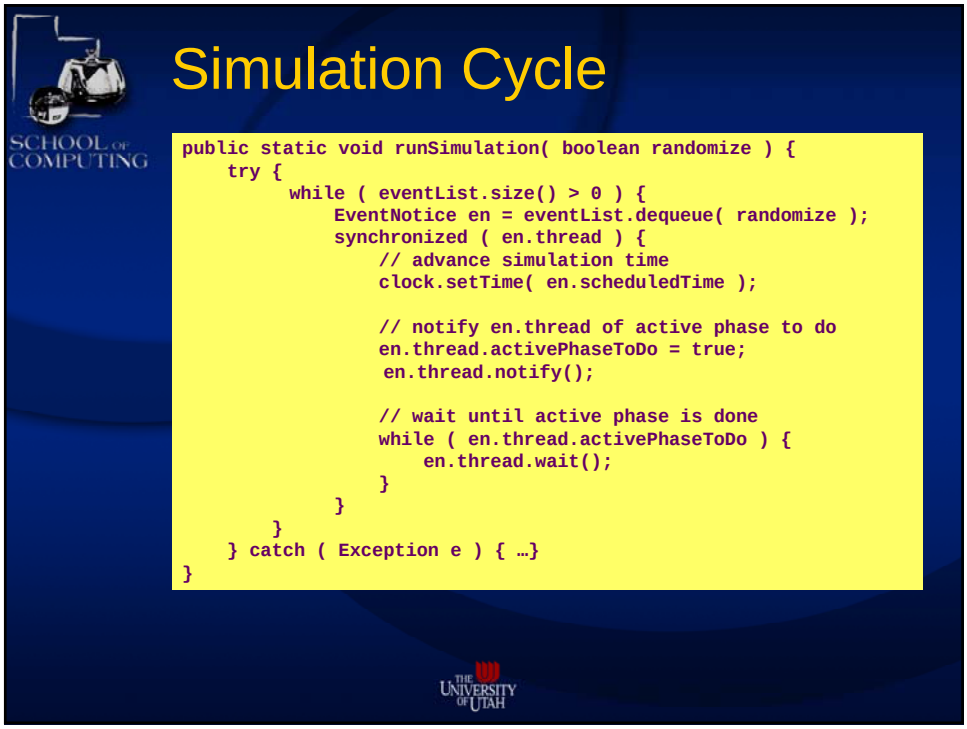
- Requirements
  - Discrete event simulation (DES) framework models time
  - 100% Java
  - Runs under native Java *or* JPF
    - *Native Java* => speed, portability
    - *JPF* => value added
      - Nondeterministic state exploration
      - Cost modeling, using JPF JVM instrumentation

Key To External Scheduler: Resource Objects

- Focus of thread interactions
- Serializes thread possession
  - **`seize()`**: wait for resource to be free
    - Wait set is priority queue
    - Priority inheritance (PI) on holder thread
  - **`release()`**: relinquish resource
    - Dynamic priority may decrease due to PI
- Most vital application:
  - The CPU, which for which threads contend
  - This is how external scheduler mimics RTSJ default scheduler

Native Java Implementation

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Simulation Cycle
public static void runSimulation(boolean randomize) {
try {
while (eventList.size() > 0) {
EventNotice en = eventList.dequeue(randomize);
synchronized (en.thread) {
// advance simulation time
clock.setTime(en.scheduledTime);
// notify en.thread of active phase to do
en.thread.activePhaseToDo = true;
en.thread.notify();
// wait until active phase is done
while (en.thread.activePhaseToDo) {
en.thread.wait();
}
}
}
} catch (Exception e) { …}
}
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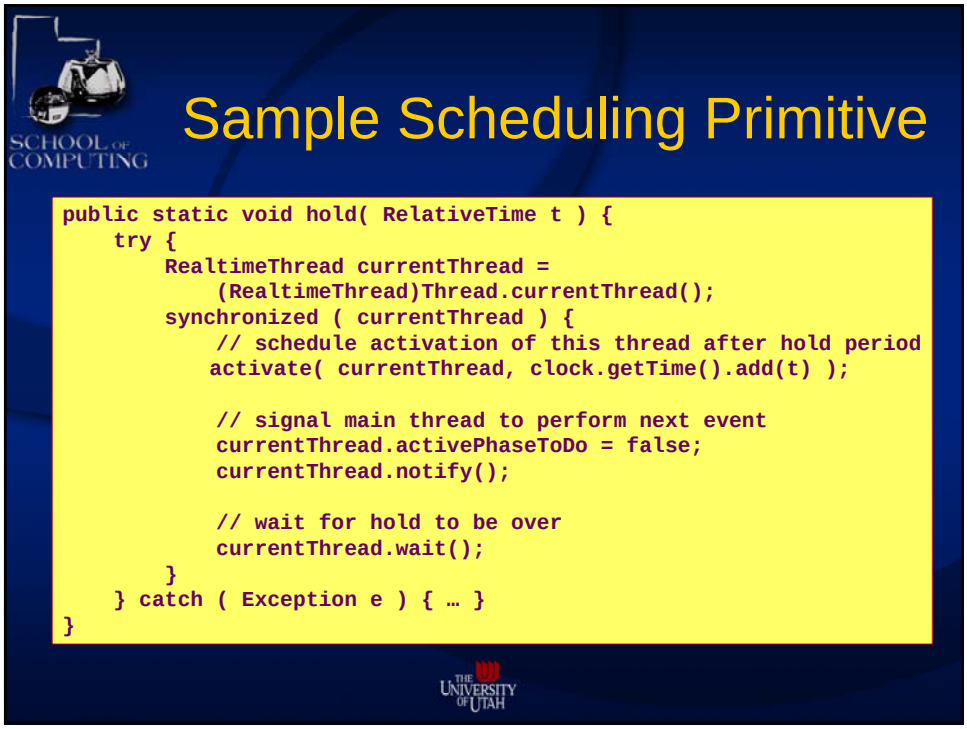
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Sample Scheduling Primitive
public static void hold(RelativeTime t) {
try {
RealtimeThread currentThread =
(RealtimeThread)Thread.currentThread();
synchronized (currentThread) {
// schedule activation of this thread after hold period
activate(currentThread, clock.getTime().add(t));
// signal main thread to perform next event
currentThread.activePhaseToDo = false;
currentThread.notify();
// wait for hold to be over
currentThread.wait();
}
} catch (Exception e) { … }
}
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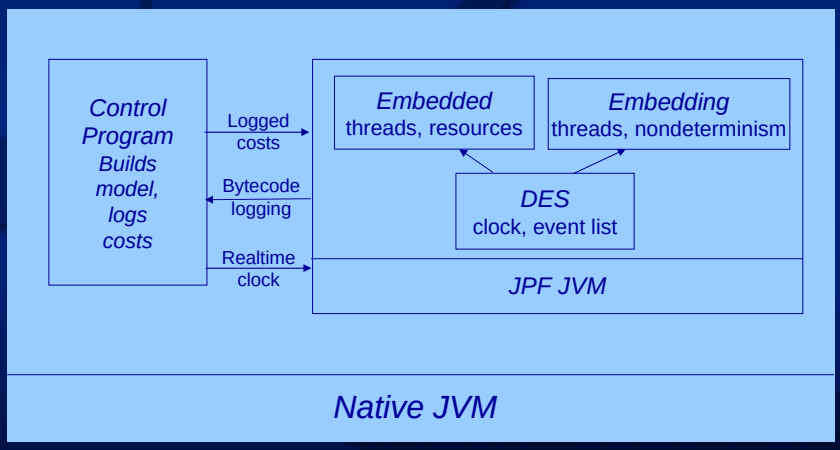
JPF Implementation

- Two layer architecture
  - *Native Java JVM layer*
    - Runs start up program and JPF model checker
    - Listeners logging execution costs
  - *JPF value-added JVM layer*
    - State exploration
    - Property checking
    - Cost instrumentation

RTSJ / JPF Architecture



Listener Utilization

```
public static void main( String args[] ) {
        …
        JPF.addVMListener(theTestClient);
        …
}

public void instructionExecuted (VM vm) {
        JVM jvm = (JVM)vm;
        Instruction instruction = jvm.getLastInstruction();
        int byteCode = instruction.getByteCode();

        // catch opcodes without costs
        assert byteCodeCosts[byteCode] > 0;

        instructionCount++;
        byteCodeCounts[byteCode]++;
        totalCost += byteCodeCosts[byteCode];
}
```

MJI Utilization

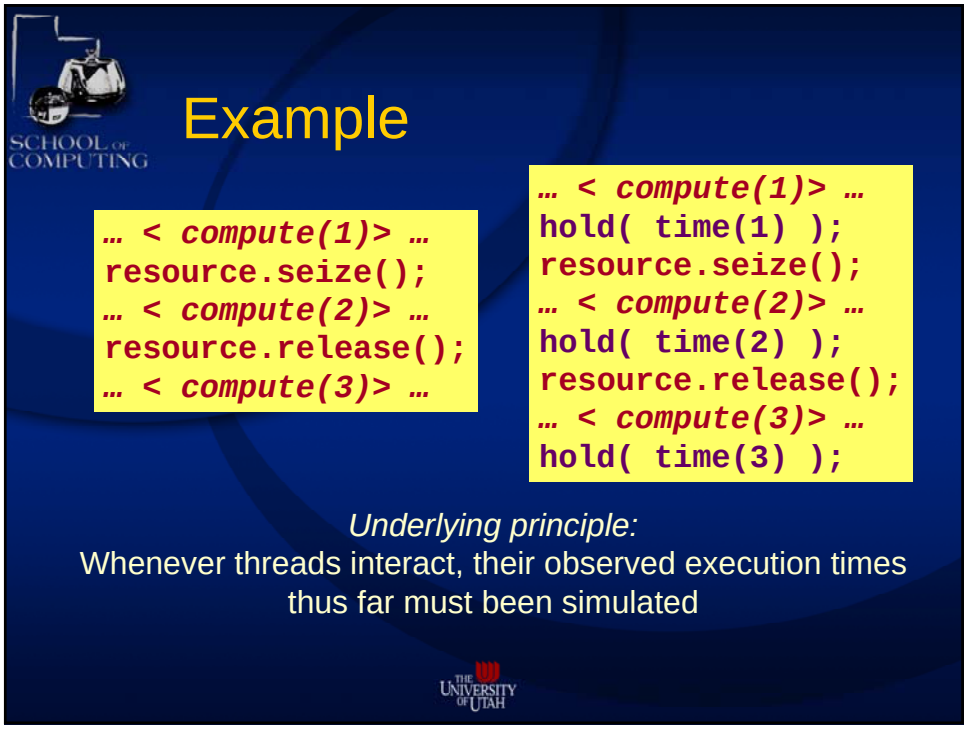
```
public class JPF_gov_nasa_jpf_rtsj_TestClient{

        public static int getCost(
                        MJIEnv env, int objRef ) {
                return gov.nasa.jpf.TestClient.getCost();
        }

        /*
         * so model can have access to true real time clock
         */
        public static long millisSinceEpoch(
                        MJIEnv env, int objRef ) {
                GregorianCalendar gc = new GregorianCalendar();
                return gc.getTimeInMillis();
        }
```

A Delicate Issue: Time

- In real systems, only time is real time
- In our system, we have 2 times:
  1. Simulated time
  2. Time (cost) of RTSJ code execution
- Under most simulations, second time is ignored
  - *Not here*, because ability to meet time deadlines is a crucial correctness issue
  - *Plus*, we have byte code logging capability

Options on Reconciling Simulated and Logged Times

1. Assume RTSJ code runs in zero time
   - Ignores important correctness issues
2. Log and simulate delays for each byte code
   - Costly, and invasive to JPF code base
3. The *Goldilocks* (just right) solution
   - Do delays for accumulated time at points where threads could interact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Example
… < compute(1)> …
resource.seize();
… < compute(2)> …
resource.release();
… < compute(3)> …
… < compute(1)> …
hold(time(1));
resource.seize();
… < compute(2)> …
hold(time(2));
resource.release();
… < compute(3)> …
hold(time(3));
Underlying principle:
Whenever threads interact, their observed execution times thus far must been simulated
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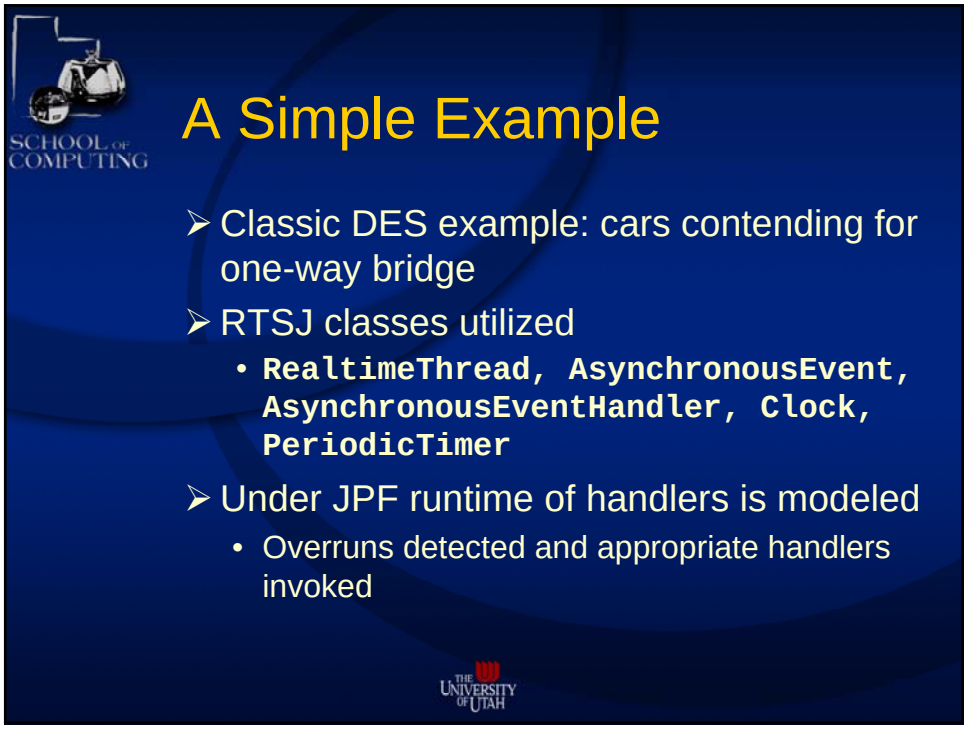
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A Simple Example
Classic DES example: cars contending for one-way bridge
RTSJ classes utilized
RealtimeThread, AsynchronousEvent, AsynchronousEventHandler, Clock, PeriodicTimer
Under JPF runtime of handlers is modeled
Overruns detected and appropriate handlers invoked
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Performance Comparison

	Native Java	*JPF*
Deterministic	.041	13.94
Nondeterministic	.020	596.758

- Times are in seconds on 786MB Pentium 2 laptop
- *Nondeterministic* means:
  - *Native Java:* pseudo random selection
  - *JPF:* all possibilities -- 175 paths explored
- Single runs – only relative magnitudes are important

Second Example: Asaf Degani's Accident Scenario

- Recall talk two weeks ago
  - Actual commercial airline accident
  - Premature spoiler deployment caused airframe damage
  - Spoilers were not armed during pre-landing checklist
  - Due to delay in landing gear door retraction
  - Manual spoiler deployment was done before landing

Simplified RTSJ Model

- Two dimensional approach
  - 1 dimension horizontal (distance)
  - 1 dimension vertical (altitude)
- Pilot performs scenario
  - Crux is whether gear doors retract before flaps 25 action
- Gear/door deployment time is a normal distribution
  - Mean 28 sec, standard deviation 5.5 sec
  - JPF nondeterministically makes 3 draws
    - random, mean +/- 2 standard deviations

Additional Features

- 5 resource types
  - *FIFO*
  - *Priority*
  - *Priority ceiling*
  - *Priority Inheritance*
  - *Preemption*
- Detailed per thread cost accounting
  - With cost overrun and deadline miss handlers
- Physical memory model
  - With segments

Features Added Since 12/9

- 4 new resource types
  - *FIFO*
  - *Priority*
  - *Priority ceiling*
  - *Preemption*
  - (Had *Priority Inheritance* in 12/9)
- Detailed per thread cost accounting
  - With cost overrun and deadline miss handlers
- Physical memory model
  - With segments

Other Accomplishments

- Port to Open JPF
- JavaDoc
- Configuration control
  - Native Java vs. JPF
  - Choice mode
    - Deterministic
    - Pseudo random
    - Non deterministic (only JPF)

Multiprogramming OS Example

- Jobs contend for CPU resource
  - CPU types FIFO, priority, priority inheritance, priority ceiling, preemption
- Most interesting case is preemption
  - Requires notion of resource interrupt
  - **`hold(t,r)`** requires loop until full time **`t`** has elapsed while holding resource **`r`**
    -- time while **`r`** is stolen does not count

Comparative Results

	Job1(5)	*Job2(6)*	*Job3(4)*	*Job4(3)*	*CPU Busy*
FIFO	80ms/27%	101/40	101/37	101/38	95%
Priority	68/17	72/27	101/35	101/41	88%
PC(6)	68/16	73/26	100/30	101/45	88%
PI	69/16	73/26	101/30	101/41	88%
Preempt	65/19	54/0	101/39	101/62	85%

Notes:

- Job % is resource wait time
- Priority, PC and PI are essentially the same
- FIFO evens run time, but improves CPU usage
- Preempt speeds align with priorities

More Comprehensive Example

- Cars at uncontrolled intersection
  - Can go straight, turn left, or turn right
  - Admissible combinations are familiar
    - Straight through if:
      - Opposite car is not turning left
      - Car on left is not going straight or turning left
      - Car on right is not going straight or turning left or right
    - Similar rules for Left and Right turns

Modeling The Intersection: Four Sector Resources

Northbound shown
-- symmetric for other three directions

Experiment 1: Deadlocks

- How can we let cars in opposite directions both make left turns?
  - But not a car in a cross direction?
- For northbound (others analogous):
  - *Seize SE and NE*
  - *Release SE*
  - *Seize NW*
  - *Release NE and NW*
- What if we seized all three at once?
  - *Deadlock* – found easily by JPF

Experiment 2: Resource Types

- Each car is a real time thread
- Sectors have nominal transit time t
- Cars have priorities p in {1, …, 10}
  - Sector transit time = 10 * t / p
- Various sector resource types:
  - *FIFO, priority, priority inheritance, priority ceiling*
  - *Preempt* is physically impossible!

Sample Results

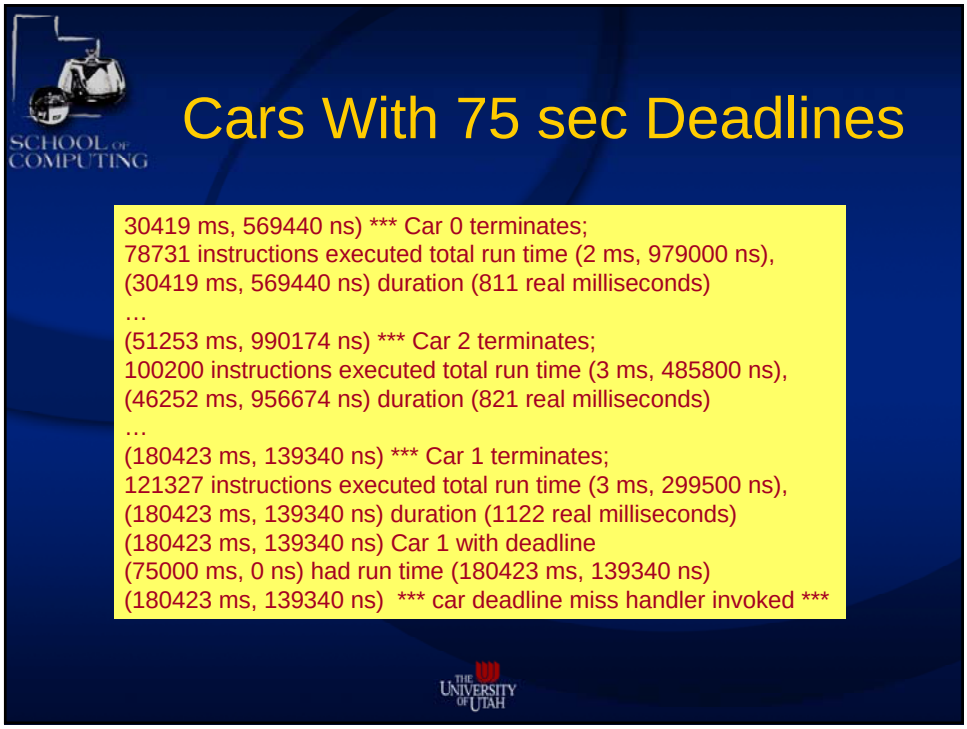
	Car 0 (5/N/S)	*Car 1 (2/S/L)*	*Car 2 (8/E/L delay 5s)*
FIFO	33s/0%	183/18	49/21
Priority	33/0	183/18	49/21
PC(8)	25/0	63/40	45/15
PI	30/0	180/16	46/17

Notes:

- Nominal sector time 10 sec.
- FIFO, Priority are essentially the same
- Cars 0 and 1 benefit from car speed increase under PC
- Car 1 gets small speed up under PI

Experiment 3: Deadlines

- Real time threads can be given miss handlers
  - Invoked when deadline is not met on thread completion
- This makes sense in Native Java, as well as JPF
  - Later we will deal with cost overruns, which require JPF listeners on JVM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Cars With 75 sec Deadlines
30419 ms, 569440 ns) *** Car 0 terminates;
78731 instructions executed total run time (2 ms, 979000 ns),
(30419 ms, 569440 ns) duration (811 real milliseconds)
…
(51253 ms, 990174 ns) *** Car 2 terminates;
100200 instructions executed total run time (3 ms, 485800 ns),
(46252 ms, 956674 ns) duration (821 real milliseconds)
…
(180423 ms, 139340 ns) *** Car 1 terminates;
121327 instructions executed total run time (3 ms, 299500 ns),
(180423 ms, 139340 ns) duration (1122 real milliseconds)
(180423 ms, 139340 ns) Car 1 with deadline
(75000 ms, 0 ns) had run time (180423 ms, 139340 ns)
(180423 ms, 139340 ns) *** car deadline miss handler invoked ***
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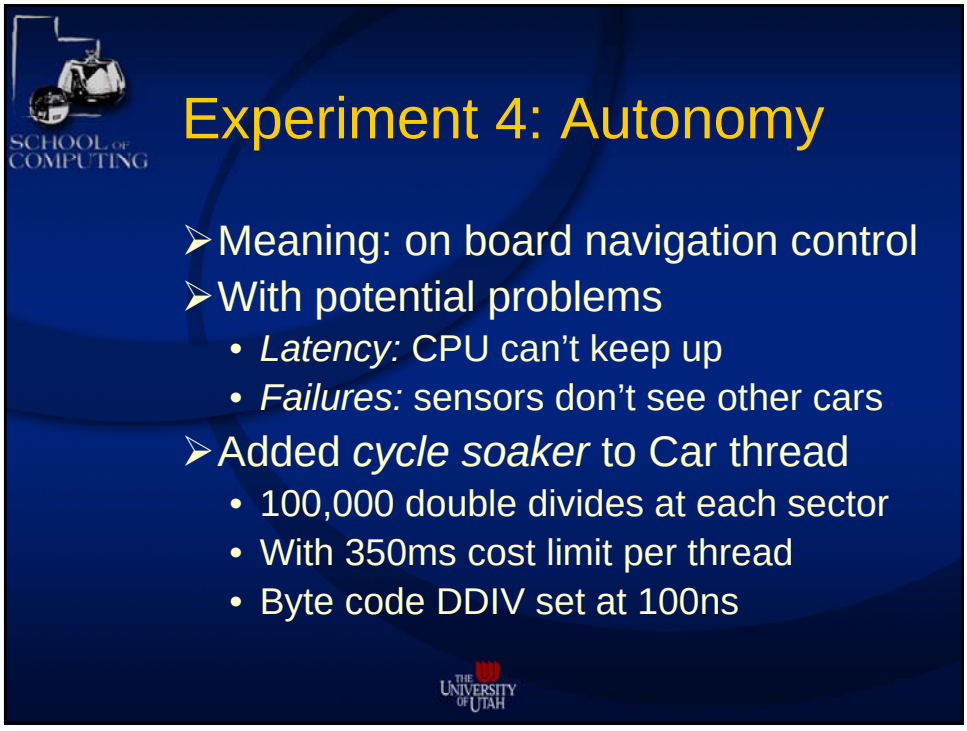
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Experiment 4: Autonomy
Meaning: on board navigation control
With potential problems
Latency: CPU can't keep up
Failures: sensors don't see other cars
Added cycle soaker to Car thread
100,000 double divides at each sector
With 350ms cost limit per thread
Byte code DDIV set at 100ns
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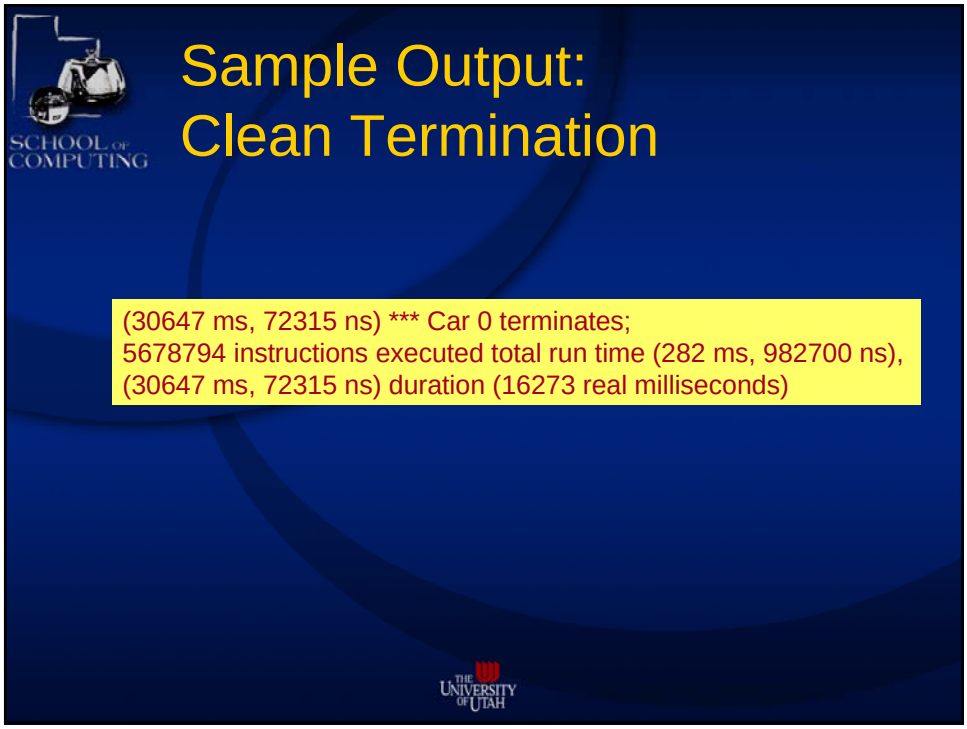
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Sample Output:
Clean Termination
(30647 ms, 72315 ns) *** Car 0 terminates;
5678794 instructions executed total run time (282 ms, 982700 ns),
(30647 ms, 72315 ns) duration (16273 real milliseconds)
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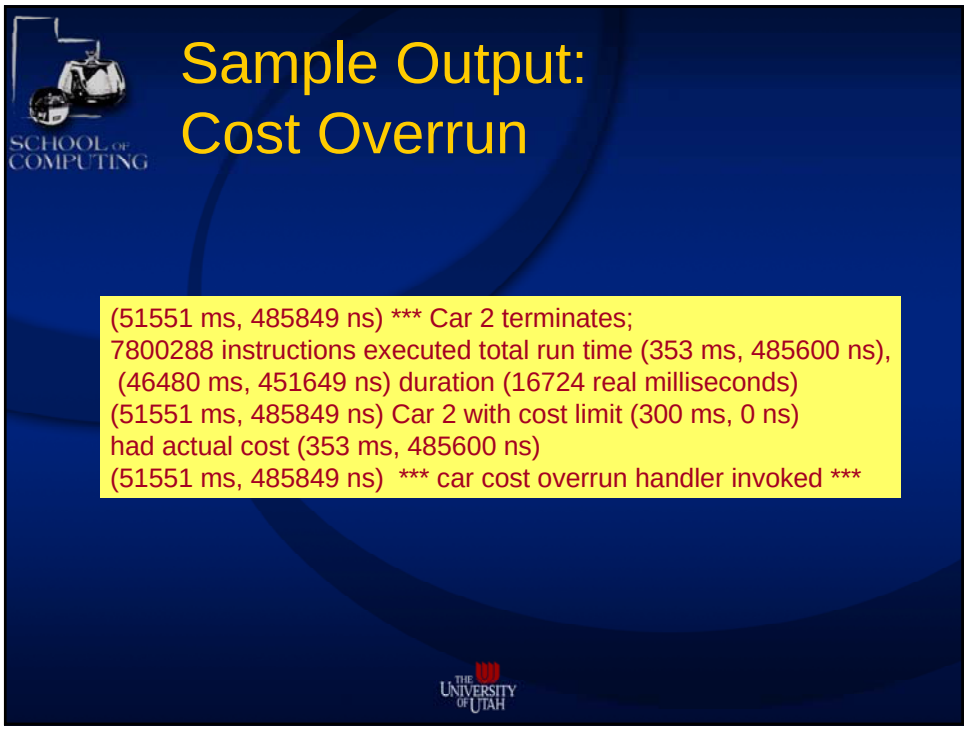
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Sample Output:
Cost Overrun
(51551 ms, 485849 ns) *** Car 2 terminates;
7800288 instructions executed total run time (353 ms, 485600 ns),
(46480 ms, 451649 ns) duration (16724 real milliseconds)
(51551 ms, 485849 ns) Car 2 with cost limit (300 ms, 0 ns)
had actual cost (353 ms, 485600 ns)
(51551 ms, 485849 ns) *** car cost overrun handler invoked ***
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Sample Output: Both Cost and Deadline Overruns

```
(180930 ms, 717415 ns) *** Car 1 terminates;
9922129 instructions executed
   total run time (353 ms, 299200 ns),
(180930 ms, 717415 ns) duration (23153 real milliseconds)
(180930 ms, 717415 ns) Car 1 with cost limit (300 ms, 0 ns)
had actual cost (353 ms, 299200 ns)
(180930 ms, 717415 ns)  *** car cost overrun handler invoked ***
(180930 ms, 717415 ns) Car 1 with deadline (75000 ms, 0 ns)
had run time (180930 ms, 717415 ns)
(180930 ms, 717415 ns)  *** car deadline miss handler invoked ***
```

Sample Output Sections

```
[313674:0] altitude 1800, runway 28691 ft.,
    gear change requested from up to down
[330674:0] altitude 1800, runway 24203 ft.,
    gear change from up to down completed
[330674:0] altitude 1800, runway 24203 ft.,
    spoilers armed
…
[470180:0] altitude 0, runway 1 ft., on ground
[470180:0] altitude 0, runway 1 ft., >>> spoilers deploy automatically <<<
```

```
[313674:0] altitude 1800, runway 28691 ft.,
    gear change requested from up to down
[352674:0] altitude 1800, runway 18395 ft.,
    gear change from up to down completed
[352674:0] altitude 1800, runway 18395 ft.,
    doors not retracted -- arm spoilers manually!
…
[452400:0] altitude 0, runway 1 ft., on ground
[452400:0] altitude 0, runway 1 ft., >>> deploy spoilers manually! <<<
```

Gleams In Our Eyes

- Customized state abstractions
  - e.g., focused on event list structure and history
- Symbolic, constraint based analysis
  - Exploit event causality relationships
- Other applications
  - Generation of test scripts
  - Generation of procedures (scripts)

For More Information

- Consult project web site
  - http://www.cs.utah.edu/~gary/RTSJ/
  - Includes:
    - ATVA '05 paper
    - RTSJ API Javadoc
    - Examples
    - These slides