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Scheduling Simulator Framework

1 Introduction

In this document we describe the Java framework that runs simulations of program scheduling. The framework may be used to develop 'discrete event simulations', where the system behaviour is modelled as a sequence of events, each occurring at discrete times. The framework defines six key types of component: a CPU, a kernel, a system timer, I/O devices, and a simulation configurator, and a profiling module.

The **CPU** simulates the processing of program instructions.

A **kernel** simulates scheduling, with processes represented by Process Control Blocks (PCB), a ready queue holding processes waiting to be executed, one or more device queues hold processes waiting for I/O to complete. The kernel moves processes between queues and onto and off the CPU.

The **system timer** records the current system time, the time spent in user space, the time spent in kernel space, and the time spent idle.

An **I/O device** simulates an I/O call: processes join a queue to access the resource and are released when the operation is completed.

The **simulation configurator** is used to instantiate and run a simulation.

The **profiling** module records the processes that are created and run during simulation. It captures the states through which a process moves from point of creation to through to termination.

(The framework also includes a **TRACE** module which may be used to assist with the development of simulation programs and kernels.)

The key concepts of a discrete event simulation are: model, event, event queue, simulation clock, and simulated time.

2 Simulation Principles

The framework supports the development of programs that simulate the execution of a set of programs under a specific scheduling strategy. A set of programs comprises a 'workload'.

2.1 Simulations

The simulator executes and schedules a set of pseudo processes. These pseudo processes are abstractions of processes and are simply a list of periods of CPU execution, followed by IO. An example follows.

```
# firefox.dat
# CPU <burst duration>
# IO <burst duration> <device id>
CPU 2
IO 2 1
CPU 3
IO 5 2
CPU 1
IO 4 1
CPU 2
```

Design based on original work by U. Ramachandran, G. Braught, and G. Nutt

Continued

- A line beginning with ‘`CPU`’ is a ‘process instruction’. It is an abstract description of a block of program code that is executed on the system CPU. It describes a **CPU burst** – a period of time during which the program only uses the CPU.
- A line beginning with ‘`IO`’ is an ‘I/O instruction’. It is an abstract description of a block of program code representing I/O activity. It describes an **IO burst** – a period of time during which the program waits for I/O.

(Further details in section 2.3.)

A simulator workload is described in a **configuration file**. An example follows.

```
# I/O Devices attached to the system.
# DEVICE <device id> <type>
DEVICE 1 DISK
DEVICE 2 CDROM
# Programs
# PROGRAM <arrival time> <priority> <program file name>
PROGRAM 8 0 firefox.dat
PROGRAM 5 0 primescalculator.dat
PROGRAM 11 0 spice.dat
```

(Further details in section 2.2.)

2.2 Workload configuration

A simulator (built with the framework) accepts as input a workload **configuration file**. The file describes I/O devices that are to be represented, and identifies programs that are to be run e.g.

```
# I/O Devices attached to the system.
# DEVICE <device id> <type>
DEVICE 1 DISK
DEVICE 2 CDROM
# Programs
# PROGRAM <arrival time> <priority> <program file name>
PROGRAM 8 0 firefox.dat
PROGRAM 5 0 primescalculator.dat
PROGRAM 11 0 spice.dat
```

- A line beginning with ‘`#`’ is a comment and is ignored by the simulator.
- A line beginning with ‘`DEVICE`’ describes a device attached to the system. A device has a unique ID number and a non-unique type.
- A line beginning with ‘PROGRAM’ describes a program that is to be run during the simulation. A program has an arrival time, a priority, and a file name. The arrival time describes the point in the simulation at which the program should be loaded. It is expressed as a number of ‘virtual’ time units.

The framework assumes Process files (‘Programs’) to be in the same folder/directory as the configuration file that references them.

2.3 Process definition

The process files used by the simulator do not contain real processes. They contain abstract descriptions of processes, as illustrated by the following excerpt:

```
# firefox.dat
```

Continued

```
# CPU <duration>
# IO <duration> <device id>
CPU 2
IO 2 1
CPU 3
IO 5 2
CPU 1
```

- A line beginning with '#' is a comment and is ignored by the simulator.
- A line beginning with '`CPU`' is a 'process instruction'. It is an abstract description of a block of program code that is executed on the system CPU. To put it another way, it describes a CPU burst – a period of time during which the process only uses the CPU.
- A line beginning with '`IO`' is an 'I/O instruction'. It is an abstract description of a block of program code representing I/O activity. To put it another way, it describes an IO burst – a period of time during which the process waits for I/O.
- The value following an '`IO`' or '`CPU`' keyword is the burst duration in virtual time units.

A program never contains two consecutive `IO` instructions or two consecutive `CPU` instructions.

The first instruction is always a `CPU` instruction.

2.4 Quick start

Jump to section 4.6 for details on a sample main simulation program and kernels that may be compiled and run.

3 Framework Design

In this section we describe the design.

3.1 Conceptual Overview

The framework defines six types of component: kernel, CPU, system timer, I/O device, simulation configurator/runner, and profiling module.

- The kernel simulates aspects of kernel behaviour relating to scheduling:
  - Processes are represented by Process Control Blocks (PCB).
  - A 'ready queue' holds processes waiting to be executed.
  - One or more device queues hold processes waiting for I/O to complete.
  - As events unfold, processes are moved between queues and onto and off the CPU.
- The CPU simulates the processing of program instructions.
- The system timer records the current system time, the time spent in user space, the time spent in kernel space, and the time spent idle.
  The timer is advanced when:
  - the CPU processes an instruction, or
  - kernel code is executed, either through system call or interrupt.
- An I/O device simulates the infrastructure needed for an I/O call: the process queues for access to the resource and is released when the operation is completed.

Kernel is defined in abstract. It is an interface declaration.

To develop a simulator you must construct:

(i) a concrete type of Kernel, and

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(ii) a driver program that can, using the simulation configurator/runner, set up and run a simulation i.e. use it to read in configuration data from a file, 'run' the programs, and write simulation data out to the screen.

(A sample simulator program and two sample kernels are provided in the framework distribution: `Simulate.java`, `FCFSKernel.java`, and `RRKernel.java`.)

3.2 Simulation Configurator/runner

The simulation configurator/runner provides facilities for simulation set up and execution.

Configuration involves reading in a workload configuration:

- For each program identified in the configuration file, create a 'load program' event and insert it in the event queue.
- For each device identified in the configuration file, perform a MAKE_DEVICE system call to the kernel.
- Then set system time to 0 in preparation for running the simulation.

Execution involves running the main simulation loop.

- Until the event queue is empty and the CPU is idle:
    - While the event queue contains an event, and the event is due to occur at or before the current system time, *st*, process the event.
    - Call the CPU to simulate execution of the currently scheduled process (if any) up to the time *tf* at which the next event is due to occur.
- Note that the processing of events may cause further events to be placed on the event queue. Similarly, simulated execution by the CPU.

3.3 Kernel

The kernel simulates process scheduling. It provides a system call interface for the loading of programs, the creation of devices, the performing of I/O, and the termination of processes; and it provides an interrupt handler interface that enables it to receive interrupts from the system timer and from I/O devices.

3.3.1 System Calls

Four types of system call are supported:

System Call Number	***Name***	***Arguments***	***Description***
1	MAKE_DEVICE	Device ID Device type	*Create a device object and I/O queue.*
2	EXECVE	Program file name	*Load the named program.*
3	IO_REQUEST	Device ID Request duration	*Simulate an IO request on the given device for the given duration.*
4	TERMINATE_PROCESS		*Terminate execution of the current process.*

When the kernel receives a MAKE_DEVICE call, it creates an object to represent the device and its corresponding queue (where processes are held when waiting for I/O requests on the device to complete.)

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When the kernel receives an EXECVE call, it creates a Process Control Block (PCB) for the program and then loads the list of instructions contained in the program file and attaches them to it. A scheduling decision is then made resulting in the process being placed on the CPU or in the 'Ready Queue'.

A process control block contains a program counter (PC) that is used to keep track of the instruction currently being executed. Initially, PC is zero.

When the kernel receives an IO_REQUEST call:

1. The currently executing process is removed from the CPU and placed on the relevant device queue.
2. A 'wakeup' interrupt is scheduled for the point at which the request is due to complete.
3. A scheduling decision is made: a process is switched from the ready queue onto the CPU.

When the kernel receives a TERMINATE_PROCESS call:

1. The currently executing process is removed from the CPU and discarded.
2. A scheduling decision is made: a process is switched from the ready queue onto the CPU.

If the kernel supports some form of time slice scheduling then IO_REQUEST and TERMINATE_PROCESS system calls will also involve cancelling and setting timer interrupts.

1. The timeout scheduled to mark the end of the current time slice is cancelled.
2. The system timer is called to set up a timeout to interrupt execution at the end of the new process time slice.

3.3.2 Interrupts

There are two types of interrupt that the kernel may be required to handle (depending on the scheduling strategy it implements).

Interrupt Number	***Name***	***Arguments***	***Description***
1	TIME_OUT	The ID of the process to be pre-empted.	*Used to signal the end of a scheduled time slice.*
2	WAKE_UP	The ID of the device issuing the interrupt. The ID of the process waiting on the device.	*Used to signal completion of the end of an I/O request.*

When the kernel receives a WAKE_UP interrupt from an I/O device:

1. The relevant device is located.
2. The relevant process is removed from its queue.
3. The process PC is incremented to step over the I/O instruction that has just been completed.
4. A scheduling decision made - the process may be placed on the ready queue or put on the CPU.

When it receives a TIME_OUT interrupt marking the end of the current slice, a scheduling decision is made.

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1. The currently executing process is either removed from the CPU and placed back on the ready queue or chosen to run for another slice.
2. If the current process is removed, a new process is switched from the ready queue onto the CPU.
3. The system timer is called to set up a new timeout to interrupt execution at the end of the new process time slice.

3.4 The CPU

The CPU component serves to hold the currently executing process and to simulate its execution. It is possible that there is no currently executing process in which case the CPU is *idle* (considered to be running a Kernel 'idle' process, though no such process is explicitly represented in the framework).

The CPU has two modes: SUPERVISOR and USER. Kernel actions strictly run in SUPERVISOR mode. Processes run in USER mode; however, a system call or interrupt requiring kernel services results in a switch to SUPERVISOR mode.

Requests to simulate execution come from the simulator's **configurator/runner**. Execution is usually bounded: the CPU is requested to simulate execution up to a system time point *tp*.

Note that a process can only be on the CPU if the current program instruction (as identified by the program counter) is a "`CPU`" instruction.

- If the current instruction can complete in the given time, then the CPU will move to the next instruction in the 'program', which (by definition) must be an I/O instruction, if it exists.
  - The CPU processes an I/O instruction by making an IO_REQUEST system call to the kernel.
  - If there is no next instruction then the CPU makes a TERMINATE_PROCESS system call to the kernel. In either case, the effect will be to switch the current process out.
- If the current instruction cannot be completed in the given time then a record of the amount remaining is made.

In either case, the CPU will update the system timer to indicate the amount of time spent processing user program instructions.

3.5 The System Timer

The system timer is essentially a set of counters that track the passage of simulated time.

The **CPU** updates **user time** when simulating **execution** and updates **kernel time** when **context switching**.

The **discrete event processing** infrastructure updates **kernel time** for **system calls** and **interrupt handling** i.e. kernel implementations do not need to do this.

A kernel may use the system timer to set up **TIME_OUT interrupts**. (The system timer handles these requests by creating 'timeout' events and placing them in the simulation event queue.)

4 Java Components

The following class diagram depicts the framework structure:

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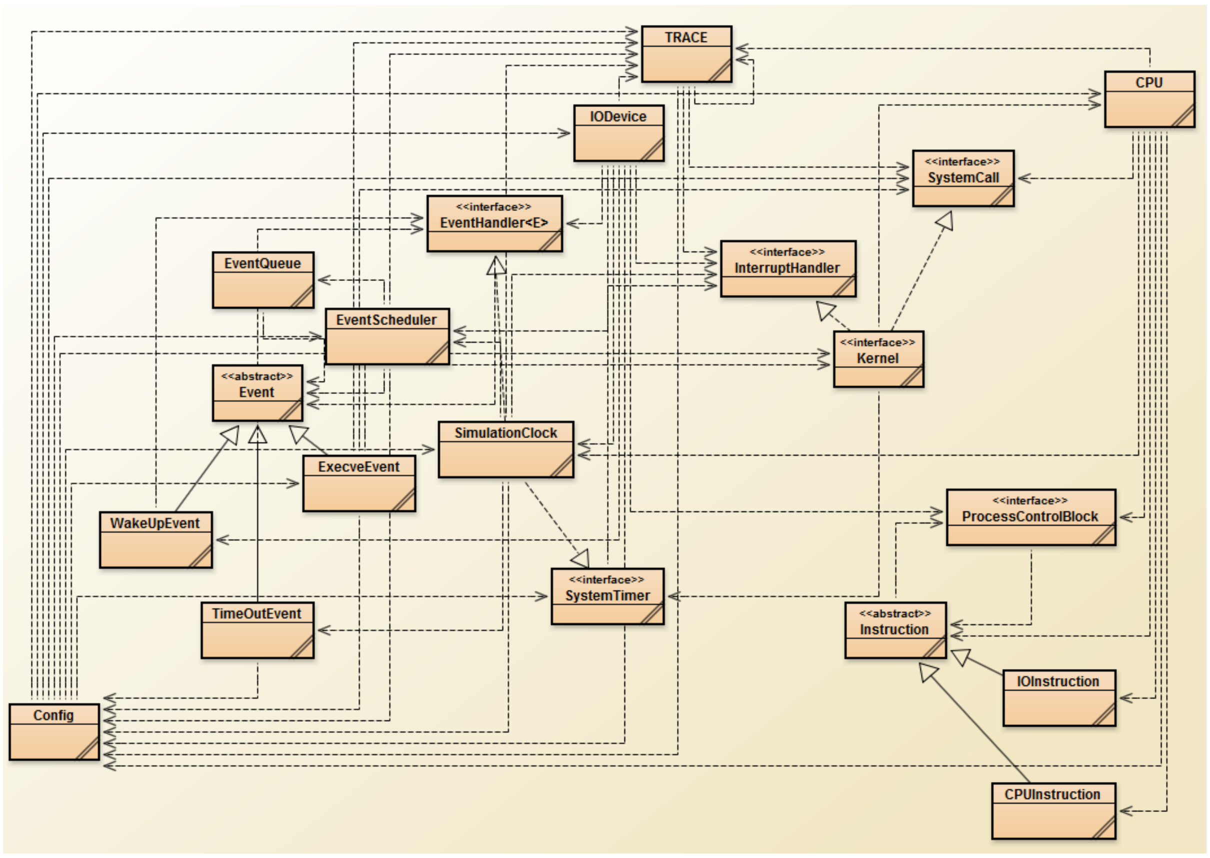

The framework is distributed in a '`.zip`' file containing a source tree structure bearing the name '`src`', a set of tests contained in a directory called '`tests`', and a '`makefile`'.

The '`src`' directory contains sub folders called '`simulator`' and '`programgenerator`'.

- The `simulator` package contains the framework.
- The `programgenerator` package contains a program for generating simulation pseudo processes. (See Section 3.2.)

Simulators (main programs and kernels) constructed using the framework must be placed in the top level of the `src` tree. A sample main program and kernels are provided: '`Simulate.java`', '`FCFSKernel.java`' and '`RRKernel.java`'. (See section 4.6.)

The `makefile` can be used to (i) compile code to a '`bin`' sub folder, and (ii) generate framework Javadocs, placing them in a '`doc`' sub folder.

The following targets are defined:

- `clean` – remove all '`.class`' files and any `doc` sub directory.
- `framework` – compile the code in the `simulator` package.
- `generator` – compile the code in the `programgenerator` package.
- `simulator` – compile the code at the top of the `src` tree.
- `doc` – generate Javadocs for the `simulator` package.

Your first step, on downloading and unpacking the materials, should be '`make docs`'. The documents are also available as a separate '`.zip`' package.

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Compiled files, i.e. '`.class`' files, are written to a '`bin`' directory. The Java class path should point to this directory when simulator code is run. For example, say we have the simulator '`src/Simulate.java`'. This class is compiled to '`bin/Simulate.class`', and is run with the following command:

```
java -ea -cp bin Simulate
```

4.1 Simulator API

The Java documentation provides you with the 'Simulator API', that is, the classes, interfaces, methods and constants that you may use when building a scheduling simulator. It hides the discrete event components that work behind the scenes.

The **Kernel** interface defines a type of object that must be implemented. The CPU, IODevice and Config classes, the SystemCall and InterruptHander interfaces, and the ProcessControlBlock.State enumerated type are required for this.

The **Config class** is the scheduler configurator/runner. **It must be used** by a simulator main program/method to load a workload and simulate its execution. It also collates the components required by a kernel implementation. A kernel uses the Config class to obtain the current configurations CPU and SystemTimer, and to store and retrieve I/O devices.

Optionally, the **Profiling** and **TRACE** classes may be used.

4.2 Kernel Interface

To emulate the 'rawness' of a real kernel system call interface, the Kernel interface uses variable argument parameters:

```
public int syscall(int number, Object... varargs);
```

```
public void interrupt(int interruptType, Object... varargs);
```

The caller provides zero or more Object parameters depending on the system call number or interrupt type number. The kernel must cast each object to the required type e.g a program filename in the case of an EXECVE call.

4.3 Simulator main program

A simulator based on the framework typically has something like the following in its main method:

```
TRACE.SET_TRACE_LEVEL(level);
final Kernel kernel = new MyKernel();
Config.init(kernel, dispatchCost, syscallCost);
Config.buildConfiguration(configFileName);
Config.run();
SystemTimer timer = Config.getSystemTimer();
System.out.println(timer);
System.out.println("Context switches:"
                  +Config.getCPU().getContextSwitches());
System.out.printf("CPU utilization: %.2f\n",
                  ((double)timer.getUserTime())/timer.getSystemTime()*100);

Profiling.writeCSV("execution_profile.csv");
```

Line-by-line:

1. Set the level of trace detail (see the final section of this document).
2. Create the kernel.

Continued

3. Initialise the simulation with the given kernel, dispatch cost and system call cost.
4. Build the workload configuration described in the given configuration file.
5. Run the simulation.
6. Get the SystemTimer object.
7. Print the SystemTimer (outputs a string describing system time, kernel time, user time, idle time).
8. Print the number of context switches recorded by the CPU.
9. Calculate and print the CPU utilisation based on the available timings.
10. Write a detailed record or process lifetimes (states and times) to a comma-separated-values (CSV) file.

4.4 Profiling

The **Profiling** module keeps an execution profile for each process created during a simulation.

A profile is a record of the series of states through which a process moves in its lifetime (READY, RUNNING in USER mode, RUNNING in SUPERVISOR mode, WAITING, TERMINATED), along with the start and end times of each.

Profiling is always on. Use of the results is optional. A single method is offered. The '`writeCSV()`' method may be used to write profiles to a comma-separated-values (CSV) file. The contents of this file may then be loaded into, EXCEL say, or passed to an 'analytics' program written by the framework user

4.5 TRACE

The **TRACE** module offers facilities for tracing execution of a simulation. A method is provided that permits the trace 'level' to be set. The level is treated as a binary number on which a bit-wise comparison is performed. Each bit represents a toggle for a particular piece of trace output.

The following table describes the effects:

Bit	***Value***	***Effect***
0	1	*Trace context switches.*
1	2	*Trace system call entry.*
2	4	*Trace system call exit.*
3	8	*Trace interrupt handler entry.*
4	16	*Trace interrupt handler exit.*
5	32	*Trace behind-the-scenes discrete events generation and process.*

By way of an example, setting the trace level to 11 causes context switch, system call entry and interrupt hander entry events to be displayed.

The TRACE module also provides a '`printf`' method that may be used to develop further trace facilities in user/application code – such as concrete kernel classes. The method is similar to the regular 'System.out.`printf()`' command except its first parameter is a trace level value, *v*. The method will only produce output if `TRACE.GET_TRACE_LEVEL()&v!=0`.

The framework currently, as indicated by the table only uses the first 6 bits of a Java `int` for trace configurations. The rest are available for use in applications.

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4.6 Sample Program and Kernels

A sample main simulation program is provided in the framework distribution along with sample FCFS and Round-Robin kernels. These are ‘`Simulate.java`’, ‘`FCFSKernel.java`’ and ‘`RRKernel.java`’ respectively.

The Simulate program should suffice for most purposes. It may be used to run a simulation on a given workload configuration, kernel, with given system call and context switch costs, and at a given level of tracing. It outputs total system time, kernel time, user time and idle time, along with number of context switches and percentage of CPU utilisation. Optionally, it will also write process execution profiles to a CSV file.

Sample I/O:

```
*** Simulator ***
Configuration file name? tests/Test2C/config.cfg
Kernel name? RRKernel
Enter kernel parameters (if any) as a comma-separated list: 1000
Cost of system call? 1
Cost of context switch: 3
Trace level (0-31)? 0
Instantiating kernel with supplied parameters...
Slice time 1000.
Building configuration...
Running simulation...
Done
System time: 5517
Kernel time: 33
User time: 3500
Idle time: 1984
Context switches: 8
CPU utilization: 63.44
Write execution profile to CSV? Enter a file name or press return:
tests/Test2C/profile.csv
```

(User input in **bold**.)

Contents of `profile.csv`:

Sample profile:

```
PID, STATE, MODE, START TIME, END TIME, PROGRAM
001, READY, N/A, 0000000001, 0000000005, tests/Test2C/programA.prg
001, RUNNING, USER, 0000000005, 0000001004, tests/Test2C/programA.prg
001, RUNNING, SUPERVISOR, 0000001004, 0000001005, tests/Test2C/programA.prg
001, READY, N/A, 0000001005, 0000001512, tests/Test2C/programA.prg
001, RUNNING, USER, 0000001512, 0000001513, tests/Test2C/programA.prg
001, RUNNING, SUPERVISOR, 0000001513, 0000001514, tests/Test2C/programA.prg
001, WAITING, N/A, 0000001514, 0000004510, tests/Test2C/programA.prg
001, READY, N/A, 0000004510, 0000004513, tests/Test2C/programA.prg
001, RUNNING, USER, 0000004513, 0000005513, tests/Test2C/programA.prg
001, RUNNING, SUPERVISOR, 0000005513, 0000005514, tests/Test2C/programA.prg
001, TERMINATED, N/A, 0000005514, -, tests/Test2C/programA.prg
002, READY, N/A, 0000000005, 0000001008, tests/Test2C/programB.prg
002, RUNNING, USER, 0000001008, 0000001508, tests/Test2C/programB.prg
```

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```
002, RUNNING, SUPERVISOR, 0000001508, 0000001509, tests/Test2C/programB.prg
002, WAITING, N/A, 0000001509, 0000002510, tests/Test2C/programB.prg
002, READY, N/A, 0000002510, 0000002513, tests/Test2C/programB.prg
002, RUNNING, USER, 0000002513, 0000003513, tests/Test2C/programB.prg
002, RUNNING, SUPERVISOR, 0000003513, 0000003514, tests/Test2C/programB.prg
002, TERMINATED, N/A, 0000003514, , tests/Test2C/programB.prg
```

End