The Java Language

Developed by James Gosling et al.
at Sun Microsystems in the early 1990s
Originally called “Oak”
First intended application was as
an OS for TV set top boxes
Main goals were portability and safety
Originally for embedded consumer software

Aside: The JVM

```java
int gcd(int a, int b) { 
    while (a != b) { 
        if (a > b) 
            a -= b; 
        else 
            b -= a; 
    } 
    return a;
}
```

A stack-based machine language. Mostly low-level operations (e.g., add top two stack elements), but also virtual method dispatch.

The Java Language

Where does Java succeed?

Corporate programming
  - E.g., dynamic web page generation from large corporate databases in banks
  - Environment demands simpler language
  - Unskilled programmers, unreleased software
  - Speed, Space not critical
  - Tends to be run on very large servers
  - Main objective is reduced development time

The Java Language

Where does Java succeed?

Education
  - Well-designed general-purpose programming language
  - Spares programmer from many common pitfalls:
    - Uninitialized pointers
    - Memory management
  - Widely known and used, not just a teaching language

Embedded Systems?
  - Jury is still out

The Java Language

Concurrency in Java

Language supports threads
Multiple contexts/program counters running within the same memory space
All objects shared among threads by default
Fundamentally nondeterministic
Language provide synchronization facilities (monitors) to help avoid nondeterminism
Still a difficult paradigm in which to program
Sun’s libraries reputed to still not be thread-safe

Aside: The JVM

Advantages:
  - Trivial translation of expressions
  - Trivial interpreters
  - No problems with exhausting registers
  - Often compact

Disadvantages:
  - Semantic gap between stack operations and modern register machines
  - Hard to see what communicates with what
  - Difficult representation for optimization

JVM: The Lesson

If you’re going to interpret something, its level of abstraction must be sufficiently higher than assembly to offset the cost of interpretation.

Java bytecode is stack-based and therefore fairly close to assembly. Usual interpreters run at 1/10th the speed of equivalent C.

Just-in-time compilers, which translate Java bytecode to native assembly and cache the results, are the current solution.

Set-top boxes: nobody cared at the time
Next big application: “applets,” little programs dynamically added to web browsers
A partial failure despite aggressive Sun marketing.
  - Incompatible Java implementations
  - Few users had enough bandwidth
  - Fantastically slow Java interpreters

Javascript, a high-level scripting language that has nothing to do with the Java language, but leverages Sun’s marketing, has taken over this role.
Thread Basics

A thread is a separate program counter
... and stack, local variables, etc.
Not an object or a collection of things
Classes, objects, methods, etc. do not belong to a thread
But a thread may hold a lock on an object
Any method may be executed by one or more threads,
even simultaneously

The Sleep Method

class Sleeper extends Thread {
    public void run() {
        for (;;) {
            try {
                sleep(1000);  // Pause for at least a second
            } catch (InterruptedException e) {
                return;  // caused by thread.interrupt()
            }
            System.out.println("tick");
        }
    }
}

Does this print "tick" once a second?
No: the sleep() delay is merely a lower bound, and it's not clear how much time the rest of the loop takes.

Motivation for Synchronization

Something you might want to implement:

class ScoreKeeper {
    int _score = 0;
    void score(int v) {
        int tmp = _score;
        tmp += v;
        _score = tmp;
    }
}

What could the final score be if two threads simultaneously call score(1) and score(2)?

A Clock?

class PrintingClock implements Runnable {
    public void run() {
        for (;;) {
            java.util.Date now = new java.util.Date();
            System.out.println(now.toString());
            try {
                Thread.currentThread().sleep(1000);
                return;  // caused by thread.interrupt()
            } catch (InterruptedException e) {}
        }
    }
}

public class Clock {
    public static void main(String args[]) {
        Thread t = new Thread(new PrintingClock());
        t.start();
    }
}

Synchronization

Thread Basics

How to create a thread:

class MyThread extends Thread {
    public void run() {  // A thread's "main" method
        /* thread body */
    }
}

MyThread mt = new MyThread;  /* Create thread */
mt.start();  /* Start thread at run() */
// Returns immediately

implements Runnable vs. extends Thread

An alternative:

class MyRunnable implements Runnable {
    public void run() {  /* thread body */
    }
}

Thread t = new Thread(new MyRunnable());
/* Starts thread at run() */
// Returns immediately

Advantage: class implementing Runnable can be derived from some other class (i.e., not just from Thread).
Disadvantage: "this" is not a Thread so, e.g., sleep() must be called with Thread.currentThread().sleep().

What does the clock print?

$ java Clock
Sat Sep 14 13:04:27 EDT 2002
Sat Sep 14 13:04:29 EDT 2002
Sat Sep 14 13:04:30 EDT 2002
Sat Sep 14 13:04:31 EDT 2002

What happened to 13:04:28?

Non-atomic Operations

Java guarantees 32-bit reads and writes to be atomic
64-bit operations may not be
Therefore,

i = 10;
d = 10.0;

Thread 1
i = 20;
d = 20.0;

Thread 2
i will contain 10 or 20.
d may contain 10, 20, or garbage.
Per-Object Locks

Each Java object has a lock that may be owned by at least one thread
A thread waits if it attempts to obtain an already-obtained lock
The lock is a counter: one thread may lock an object more than once

Deadlock

synchronized(Foo) { synchronized(Bar) { synchronized(Foo) { // Asking for trouble } } } // Asking for trouble

Rule: always acquire locks in the same order.

The Synchronized Statement

A synchronized statement gets an object’s lock before running its body

```
Counter mycount = new Counter;
synchronized(mycount) {
    mycount.count();
}
```

Releases the lock when the body terminates.
Choice of object to lock is by convention.

Synchronized Methods

```
class AtomicCounter {
    private int _count;
    public synchronized void count() {
        _count++;
    }
}
```
synchronized attribute equivalent to enclosing body with synchronized (this) statement.
Most common way to achieve object-level atomic operations.
Implementation guarantees at most one thread can run a synchronized method on a particular object at once

Wait() and Notify() in Real Life

I often have books delivered to the CS department office.
This operation consists of the following steps:
1. Place the order
2. Retrieve the book from the CS department office
3. Place book on bookshelf
Obviously, there’s a delay between steps 1 and 2.

Synchronization

Say you want a thread to wait for a condition before proceeding.
An infinite loop may deadlock the system (e.g., if it’s using cooperative multitasking).
```
while (!condition) {}
```
Calling yield avoids deadlock, but is inefficient:
```
while (!condition) yield();
```
Scheduler may choose to run this thread often, even though condition has not changed.

The Implementation in the CS Office

This “order, retrieve, file” thread is running in me, and it needs to wait for the book to arrive.
I could check the department office every minute, hour, day, etc. to see if the book has come in, but this would be waste of time (but possibly good exercise).
Better approach would be to have the “receiving” process alert me when the book actually arrives.
This is what happens: Alice in the front office sends me email saying I have a book.

Java’s Solution: wait() and notify()

```
wait() like yield(), but requires other thread to reawaken it
while (!condition) wait();
```
Thread that changes the condition calls notify() to resume the thread.
Programmer responsible for ensuring each wait() has a matching notify().

A Flawed Implementation

```
class Mailbox {}
public class BookOrder {
    static Mailbox m = new Mailbox();
    public static void main(String args[]) {
        System.out.println("Ordering book");
        Thread t = new Delivery(m);
        t.start();
        synchronized (m) {
            try {
                m.wait(); // Must own lock on m to wait
            } catch (InterruptedException e) {
            }
        }
        System.out.println("Book Arrived");
    }
}
```

A Flawed Implementation

```java
class Delivery extends Thread {
    Mailbox m;
    Delivery(Mailbox mm) { m = mm; }
    public void run() {
        try {
            sleep(1000); // one-second delivery
        } catch (InterruptedException e) {} 
        synchronized (m) {
            m.notify(); // Must own lock on m to notify it
        }
    }
}
```

What is wrong with this?

A Flawed Implementation

What happens if the book is delivered before the main thread starts waiting?

Answer: the “notify” instruction does not wake up any threads. Later, the main thread starts to wait and will never be awakened.

As if Alice came to my office to tell me when I was not there.

The multi-book problem

```java
class Mailbox {
    int book;
    Mailbox() { book = -1; } 
    void receive_book(int b) { book = b; }
    int which_book() { return book; }
}
```

This is not thread-safe: we’ll need to synchronize all access to it.

The multi-book problem

Finally, the main routine kicks off two ordering threads.

```java
public class MultiOrder {
    static Mailbox m = new Mailbox();
    public static void main(String args[]) {
        BookOrder t1 = new BookOrder(m, 1);
        BookOrder t2 = new BookOrder(m, 2);
        t1.start();
        t2.start();
    }
}
```

$ java MultiOrder  
Ordering book 1  
Ordering book 2  
Book 1 Arrived  
Book 2 Arrived

A Better Solution

Last solution relied on threads to synchronize their own access to the Mailbox. Mailbox should be doing this itself:

```java
class Mailbox {
    int book;
    Mailbox() { book = -1; }
    synchronized void deliver(int b) {
        book = b;
        notifyAll();
    }
    synchronized void wait_for_book(int b) {
        while (book != b) {
            try { wait(); }
            catch (InterruptedException e) {}
        }
    }
}
```

Harder Problem

Sometimes I have a number of books on order, but Alice only tells me a book has arrived. How do I handle waiting for a number of books?

**Last solution assumed a single source of notify(); not true in general.**

Two rules:

1. Use `notifyAll()` when more than one thread may be waiting
2. Wait in a `while` if you could be notified early, e.g.,
   ```java
   while (!condition) {
       wait();
   }
   ```

The multi-book problem

```java
class BookOrder extends Thread {
    int book;
    BookOrder(Mailbox mm, int b) {
        m = mm; book = b;
    }
    public void run() {
        System.out.println("Ordering book " + Integer.toString(book) );
        Thread t = new Delivery(m, book);
        t.start();
        synchronized (m) {
            while (m.which_book() != book) {
                try {m.wait();}
            }
        }
        System.out.println("Book" + Integer.toString(book) + " Arrived");
    }
}
```

A Better Solution

```java
class Delivery extends Thread {
    Mailbox m;
    int book;
    Delivery(Mailbox mm, int b) {
        m = mm; book = b;
    }
    public void run() {
        try { sleep(1000); } 
        catch (InterruptedException e) {} 
        m.deliver(book);
    }
}
```
A Better Solution

class BookOrder extends Thread {
    int book;
    Mailbox m;
    BookOrder(Mailbox mm, int b) {
        m = mm; book = b;
    }
    public void run() {
        System.out.println("Ordering book " +
                            Integer.toString(book) +":");
        Thread t = new Delivery(m, book);
        t.start();
        m.wait_for_book(book);
        System.out.println("Book " +
                            Integer.toString(book) + " Arrived");
    }
}

public static void main(String args[]) {
    BookOrder t1 = new BookOrder(m, 1);
    BookOrder t2 = new BookOrder(m, 2);
    t1.start();
    t2.start();
}

$java MultiOrder2
Ordering book 1
Ordering book 2
Book 1 Arrived
Book 2 Arrived

Building a Blocking Buffer

Problem: Build a single-place buffer for Objects that will block on write if the buffer is not empty and on read if the buffer is not full.

interface OnePlace {
    public void write(Object o);
    public Object read();
}

class MyOnePlace implements OnePlaceBuf {
    Object o;
    public synchronized // ensure atomic updates
    void write(Object oo) {
        try {
            while (o != null)
                wait(); // Block while buffer is full
            o = oo;
            notifyAll(); // Awaken any waiting processes
        }
    }
    public synchronized // ensure atomic updates
    Object read() {
        try {
            while (o == null)
                wait(); // Block while buffer is empty
            o = null;
            notifyAll(); // Emptty the buffer
            return oo;
        } catch (InterruptedException e) {} // Will block
    }
}

public class OnePlace {
    static MyOnePlace b = new MyOnePlace();
    public static void main(String args[]) {
    }
    public void run() {
        Reader r = new Reader(b);
        Writer w = new Writer(b);
        r.start();
        w.start();
    }
}

Thread Priorities

Each thread has a priority from 1 to 10 (5 typical)
Scheduler's job is to keep highest-priority threads running

thread.setPriority(5)
What the Language Spec. Says

Every thread has a priority. When there is competition for processing resources, threads with higher priority are generally executed in preference to threads with lower priority. Such preference is not, however, a guarantee that the highest priority thread will always be running, and thread priorities cannot be used to reliably implement mutual exclusion.

Vague enough for you?

Multiple threads at same priority?

Language definition gives implementer freedom
Calling yield() suspends current thread to allow other at same priority to run ... maybe
Solaris implementation runs threads until they stop themselves with wait(), yield(), etc.
Solaris uses co-operative, application-level threads
Windows implementation timeslices because it uses native threads

Starvation

Java does not demand a fair scheduler
Higher-priority threads can consume all resources, prevent lower-priority threads from running
This is called starvation
Timing dependent: function of program, hardware, and Java implementation
How do you know if your program suffers from starvation?

Processes and Threads

Many operating systems now distinguish between processes and threads:

Process A thread of control running with its own address space, stack, etc. Uses inter-process communication (e.g., Pipes) with other processes.

Thread A thread of control sharing an address space with another thread, but with its own stack, registers, etc. Communicates through shared memory.

Implementing Java Threads

Many-to-one: Java VM in a single process/OS thread
Scheduler implemented directly in the JVM
+ Cheaper context switches (no need to involve the OS)
+ Does not rely on particular OS API
− Must carefully wrap all OS calls to avoid them blocking the process
− Can’t call other libraries since they may make blocking OS calls
− Often difficult to support per-thread system objects, e.g., multiple network connections

One-to-one: Each Java thread mapped gets its own OS thread
+ Can exploit multiprocessors (OS can schedule different threads on different processors
+ No need to wrap OS calls or other libraries
− More expensive context switching and thread control. Everything is a system call.
− Less portable

Java Thread Implementations

Solaris Supports Light-Weight Processes (OS threads) and Application Threads (in-process threads).
• Java VM uses Application-level threads by default,
• Application thread scheduler can move threads to other LWPs
• Has 2^{31} priority levels.
• Java thread implementation is non-preemptive
Java Thread Implementations

Windows 95 etc.  Supports OS threads only
- Java VM uses native threads only
- Has only 7 priority levels for threads
- Java thread implementation is preemptive

Linux  Supports kernel-level POSIX threads
- Java VM uses native threads

 Disturbing Conclusion

Since it is very easy to write a threaded Java program whose behavior differs depending on the scheduling policy, Java programs are not the exemplars of portability as touted by Sun.

For example, consider

```java
bool waiting = true;
while (waiting) {} // wait for waiting=false
```

This deadlocks under a (non-preemptive) green threads implementation, but it might work fine with (preemptive) native threads.

Thread Miscellany

Thread-Related Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object.wait()</td>
<td>Wait indefinitely to be notified</td>
</tr>
<tr>
<td>Object.wait(long t)</td>
<td>Wait at most t milliseconds</td>
</tr>
<tr>
<td>Object.wait(long t, int n)</td>
<td>Wait t plus n nanoseconds</td>
</tr>
<tr>
<td>Object.notify()</td>
<td>Release one waiting thread</td>
</tr>
<tr>
<td>Object.notifyAll()</td>
<td>Release all waiting threads</td>
</tr>
<tr>
<td>Thread.interrupt()</td>
<td>Break from wait, sleep, etc.</td>
</tr>
<tr>
<td>Thread.sleep(long t)</td>
<td>Sleep for t milliseconds</td>
</tr>
<tr>
<td>Thread.sleep(long t, int n)</td>
<td>Sleep t plus n milliseconds</td>
</tr>
<tr>
<td>Thread.yield()</td>
<td>Pass control to another runnable thread</td>
</tr>
<tr>
<td>Thread.join()</td>
<td>Wait for given thread to terminate</td>
</tr>
<tr>
<td>Thread.join(long t)</td>
<td>Wait for termination or timeout</td>
</tr>
<tr>
<td>Thread.setPriority()</td>
<td>Set thread’s scheduling priority</td>
</tr>
<tr>
<td>Thread.getPriority()</td>
<td>Get thread’s priority</td>
</tr>
</tbody>
</table>

Java Thread States

- **born**
- **start()**
- **ready**
- **yield()**
- **sleeping**
- **sleep()**
- **timeout**
- **terminating**
- **terminate**
- **I/O completed**
- **I/O**
- **waiting**
- **I/O completed**
- **waiting**
- **notify()**
- **notifyAll()**
- **InterruptedException**
- **IllegalMonitorStateException**
- **synchronized**

Common Mistakes

- Forgetting to catch the `InterruptedException` potentially thrown by `wait()`, `sleep()`, and other blocking thread operations.
- Forgetting the `notify()` for a corresponding `wait()` (The “Charlie Brown at the Mailbox” error.)
- Waiting on an object without having its lock (i.e., without having `synchronized` on the object).
  - Throws an `IllegalMonitorStateException`.

Deprecated Thread methods

Before JDK 1.2, Thread had three other methods:
- Thread.stop()  Terminate a thread and release locks
- Thread.suspend()  Suspend thread without releasing locks
- Thread.resume()  Resume a suspended thread

These were terribly unsafe and a recipe for disaster:
- `stop()` would release locks, but could easily leave objects in an inconsistent state. Catching the exception it threw would be possible, but insanely messy.
- `suspend()` did not release locks, so it could cause a deadlock if the thread meant to `resume()` it needed locks before it could proceed.

Real-Time Operating Systems

RTOSes

What is an Operating System?

Provides environment for executing programs:
- Process abstraction for multitasking/concurrency:
- Scheduling
- Hardware abstraction layer (device drivers)
- Filesystems
- Communication

*We will focus on concurrency and real-time issues*
Do I Need One?
Not always
Simplest approach: cyclic executive

```c
for (;;) {
    do part of task 1
    do part of task 2
    do part of task 3
}
```

Cyclic Executive

**Advantages**
- Simple implementation
- Low overhead
- Very predictable

**Disadvantages**
- Can't handle sporadic events
- Everything must operate in lockstep
- Code must be scheduled manually

Handling an Interrupt
1. Program runs normally
2. Interrupt occurs
3. Processor state saved
4. Interrupt routine runs
5. “Return from Interrupt” instruction runs
6. Processor state restored
7. Normal program execution resumes

Interrupt Service Routines
Most interrupt routines do as little as possible
- Copy peripheral data into a buffer
- Indicate to other code that data has arrived
- Acknowledge the interrupt (tell hardware)
Additional processing usually deferred to outside
E.g., Interrupt causes a process to start or resume running
Objective: let the OS handle scheduling, not the interrupting peripherals

Drawbacks of CE + Interrupts
- Main loop still runs in lockstep
- Programmer responsible for scheduling
- Scheduling static
- Sporadic events handled slowly

Cooperative Multitasking
- A cheap alternative
- Non-preemptive
- Processes responsible for relinquishing control
- Examples: Original Windows, Macintosh
A process had to periodically call `get_next_event()` to let other processes proceed

Drawbacks:
- Programmer had to ensure this was called frequently
- An errant program would lock up the whole system
- Alternative: preemptive multitasking

Concurrency Provided by OS
- Basic philosophy:
  - Let the operating system handle scheduling, and let the programmer handle function
- Scheduling and function usually orthogonal
- Changing the algorithm would require a change in scheduling
- First, a little history

Interrupts
Some events can’t wait for next loop iteration:
- Communication channels
- Transient events
Interrupt: environmental event that demands attention
- Example: “byte arrived” interrupt on serial channel
Interrupt routine code executed in response to an interrupt
A solution: Cyclic executive plus interrupt routines

Cyclic Executive Plus Interrupts
Works fine for many signal processing applications
56001 has direct hardware support for this style
Insanely cheap, predictable interrupt handler:
- When interrupt occurs, execute a single user-specified instruction
This typically copies peripheral data into a circular buffer
- No context switch, no environment save, no delay
**Batch Operating Systems**

Original computers ran in batch mode:
- Submit job & its input
- Job runs to completion
- Collect output
- Submit next job

Processor cycles very expensive at the time
Jobs involved reading, writing data to/from tapes
Costly cycles were being spent waiting for the tape!

**Timesharing Operating Systems**

Way to spend time while waiting for I/O: Let another process run
- Store multiple batch jobs in memory at once
- When one is waiting for the tape, run the other one

Basic idea of timesharing systems
- Fairness primary goal of timesharing schedulers
  - Let no one process consume all the resources
  - Make sure every process gets equal running time

**Real-Time Concurrency**

- Submit job & its input
- Job runs to completion
- Collect output
- Submit next job

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**Timesharing Operating Systems**

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**Real-Time Is Not Fair**

Main goal of an RTOS scheduler: meeting deadlines
- If you have five homework assignments and only one is due in an hour, you work on that one
- Fairness does not help you meet deadlines

**Aside: Modern Computer Architectures**

Memory latency now becoming an I/O-like time-waster.
CPU speeds now greatly outstrip memory systems.
All big processes use elaborate multi-level caches.

An Alternative:
- Certain high-end chips (e.g., Intel’s Xeon) now contain two or three contexts. Can switch among them “instantly.”
- Idea: while one process blocks on memory, run another.

**Priority-based Scheduling**

Typical RTOS has on fixed-priority preemptive scheduler
- Assign each process a priority
- At any time, scheduler runs highest priority process ready to run (processes can be blocked waiting for resources).
- Process runs to completion unless preempted

**Priority-based Preemptive Scheduling**

Always run the highest-priority runnable process

<table>
<thead>
<tr>
<th>A</th>
<th>A</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
</tbody>
</table>

**Example: Fly-by-wire Avionics**

Hard real-time system with multirate behavior

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stick</td>
<td>Joystick (500 Hz)</td>
<td>Elevator (1 kHz)</td>
</tr>
<tr>
<td>Sensor</td>
<td>Air data (1 kHz)</td>
<td>Throttle ctrl. (250 Hz)</td>
</tr>
<tr>
<td>Sensor</td>
<td>GPS (20 Hz)</td>
<td>Lateral ctrl. (250 Hz)</td>
</tr>
<tr>
<td>Sensor</td>
<td>Gyros/accel</td>
<td>Pitch ctrl. (500 Hz)</td>
</tr>
</tbody>
</table>

**Typical RTOS Task Model**

Each task a triplet: (execution time, period, deadline)
- Usually, deadline = period
- Can be initiated any time during the period

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>p = (2, 8, 8)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Solutions to equal priorities

- Simply prohibit: Each process has unique priority
- Time-slice processes at the same priority
  - Extra context-switch overhead
  - No starvation dangers at that level
- Processes at the same priority never preempt
  - More efficient
  - Still meets deadlines if possible

Rate-Monotonic Scheduling

Key RMS Result

Rate-monotonic scheduling is optimal:
If there is a fixed-priority schedule that meets all deadlines, then RMS will produce a feasible schedule.
Task sets do not always have a schedule.
Simple example: P1 = (10, 20, 20) P2 = (5, 9, 9)
Requires more than 100% processor utilization.

When Is There an RMS Schedule?

<table>
<thead>
<tr>
<th>n</th>
<th>Bound for U</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>83%</td>
</tr>
<tr>
<td>3</td>
<td>78%</td>
</tr>
<tr>
<td>4</td>
<td>76%</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>∞</td>
<td>69% Asymptotic bound</td>
</tr>
</tbody>
</table>

When Is There an RMS Schedule?

Asymptotic result:
If the required processor utilization is under 69%, RMS will give a valid schedule.
Converse is not true. Instead:
If the required processor utilization is over 69%, RMS might still give a valid schedule, but there is no guarantee.

Rate-Monotonic Scheduling

Common way to assign priorities
Result from Liu & Layland, 1973 (JACM)
Simple to understand and implement:
Processes with shorter period given higher priority
E.g.,

<table>
<thead>
<tr>
<th>Period</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1 (high)</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>20</td>
<td>4 (low)</td>
</tr>
</tbody>
</table>

When Is There an RMS Schedule?

Key metric is processor utilization: sum of compute time divided by period for each process:

\[ U = \sum \frac{c_i}{p_i} \]

No schedule can possibly exist if \( U > 1 \) No processor can be running 110% of the time.
Fundamental result: RMS schedule exists if \( U < n(2^{1/n} - 1) \)
Proof based on case analysis (P1 finishes before P2)

EDF Scheduling

RMS assumes fixed priorities.
Can you do better with dynamically-chosen priorities?
Earliest deadline first:

Processes with soonest deadline given highest priority.
**EDF Meeting a Deadline**

\[ p_1 = (2, 4, 4), \; p_2 = (3, 6, 6), \; 100\% \text{ utilization} \]

\[ 1 \quad 2 \quad 1 \quad 1 \]

\[ 1 \quad 2 \quad 2 \quad 2 \]

\[ 1 \quad 2 \quad 1 \quad 2 \]

\( p_2 \) takes priority with its earlier deadline

**Priority Inversion**

RMS and EDF assume no process interaction, often a gross oversimplification

1. Process 2 blocks Process 1 indefinitely
2. Process 2 delays Process 3
3. Process 1 preempts Process 2
4. Process 2 preempts Process 3
5. Process 3 acquires lock on resource
6. Process 3 begins running

**Key EDF Result**

Earliest deadline first scheduling is optimal:

- If a dynamic priority schedule exists, EDF will produce a feasible schedule

Earliest deadline first scheduling is efficient:

- A dynamic priority schedule exists if and only if utilization is no greater than 100%

**Static Scheduling More Prevalent**

RMA only guarantees feasibility at 69% utilization, EDF guarantees it at 100%

EDF is complicated enough to have unacceptable overhead

More complicated than RMA: harder to analyze

Less predictable: can’t guarantee which process runs when

**Priority Inversion**

Nastier Example

Process 2 blocks Process 1 indefinitely

1. Process 2 delays Process 3
2. Process 1 preempts Process 2
3. Process 2 preempts Process 3
4. Process 3 acquires lock on resource
5. Process 3 begins running

**Priority Inheritance**

Solution to priority inversion

- Increase process’s priority while it possesses a lock
- Level to increase: highest priority of any process that might want to acquire same lock
- I.e., high enough to prevent it from being preempted
- Danger: Low-priority process acquires lock, gets high priority and hogs the processor
- So much for RMS

**Priority Inheritance**

Basic rule: low-priority processes should acquire high-priority locks only briefly

An example of why concurrent systems are so hard to analyze

RMS gives a strong result

No equivalent result when locks and priority inheritance is used

**Priority Inversion**

Lower-priority process effectively blocks a higher-priority one

Lower-priority process’s ownership of lock prevents higher-priority process from running

Nasty: makes high-priority process runtime unpredictable
Summary

Cyclic executive—A way to avoid an RTOS
Adding interrupts helps somewhat
Interrupt handlers gather data, acknowledge interrupt as quickly as possible
Cooperative multitasking, but programs don’t like to cooperate

Summary

Preemptive Priority-Based Multitasking—Deadlines, not fairness, the goal of RTOSes
Rate-monotonic analysis
  - Shorter periods get higher priorities
  - Guaranteed at 69% utilization, may work higher
Earliest deadline first scheduling
  - Dynamic priority scheme
  - Optimal, guaranteed when utilization 100% or less

Summary

Priority Inversion
  - Low-priority process acquires lock, blocks higher-priority process
  - Priority inheritance temporarily raises process priority
  - Difficult to analyze