JAVA FOR

SAFETY CRITICAL EMBEDDED HARD-REAL-TIME SYSTEMS

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A typical safety critical embedded hard-real-time program

Cruise control:

```
Loop every X microseconds
    Read the sensors;
    Compute speed;
    if speed too high
        Compute pressure for brake pedal;
    if speed too low
        Compute pressure for accelerator;
    Transmit the outputs to actuators;
    wait for next period;
```

How hard can it be to program such systems?

Aparently hard enough

- Toyota's Accelerator Problem Probably Caused by Embedded Software Bugs

- Software Bug Causes Toyota Recall of Almost Half a Million New Hybrid Cars

- BMW recall: The company will replace defective high-pressure fuel pump and update software in 150,000 vehicles.

Some examples

- The Ariane 5 satellite launcher malfunction
  – caused by a faulty software exception routine resulting from a bad 64-bit floating point to 16-bit integer conversion
- LA Air Traffic control system shutdown (2004)
  – Caused by count down timer reaching zero
- Airbus A330 nose-diving twice while at cruising altitude (2001)
  – 39 injured, 12 seriously. Problem never found

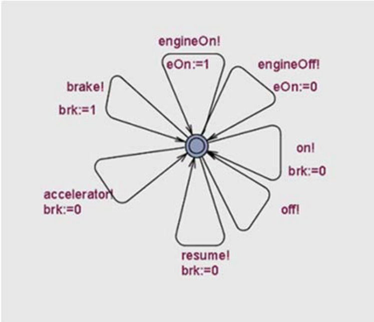
A hard real-time problem

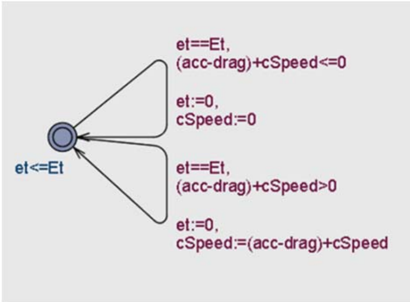
Embedded Systems

- Over 90% of all microprocessors are used for real-time and embedded systems
  - Market growing 10% year on year
- Usually programmed in C or Assembler
  - Hard, error prone, work
  - But preferred choice
    - Close to hardware
    - No real alternatives   Well … ADA – 10th on the list of most wanted skills
  - Difficult to find new skilled programmers
    - Jackson Structured Development (1975) still widely used
    - EE Times calling for re-introducing C programming at US Uni

Model Driven Development

- Develop Model of System
- Verify desirable properties
- Generate Code from Model





- But ..
  - Many finds developing models harder than programming
  - Often some parts have to be programmed anyhow
  - Model and code have tendency to drift apart

We need to look for other languages

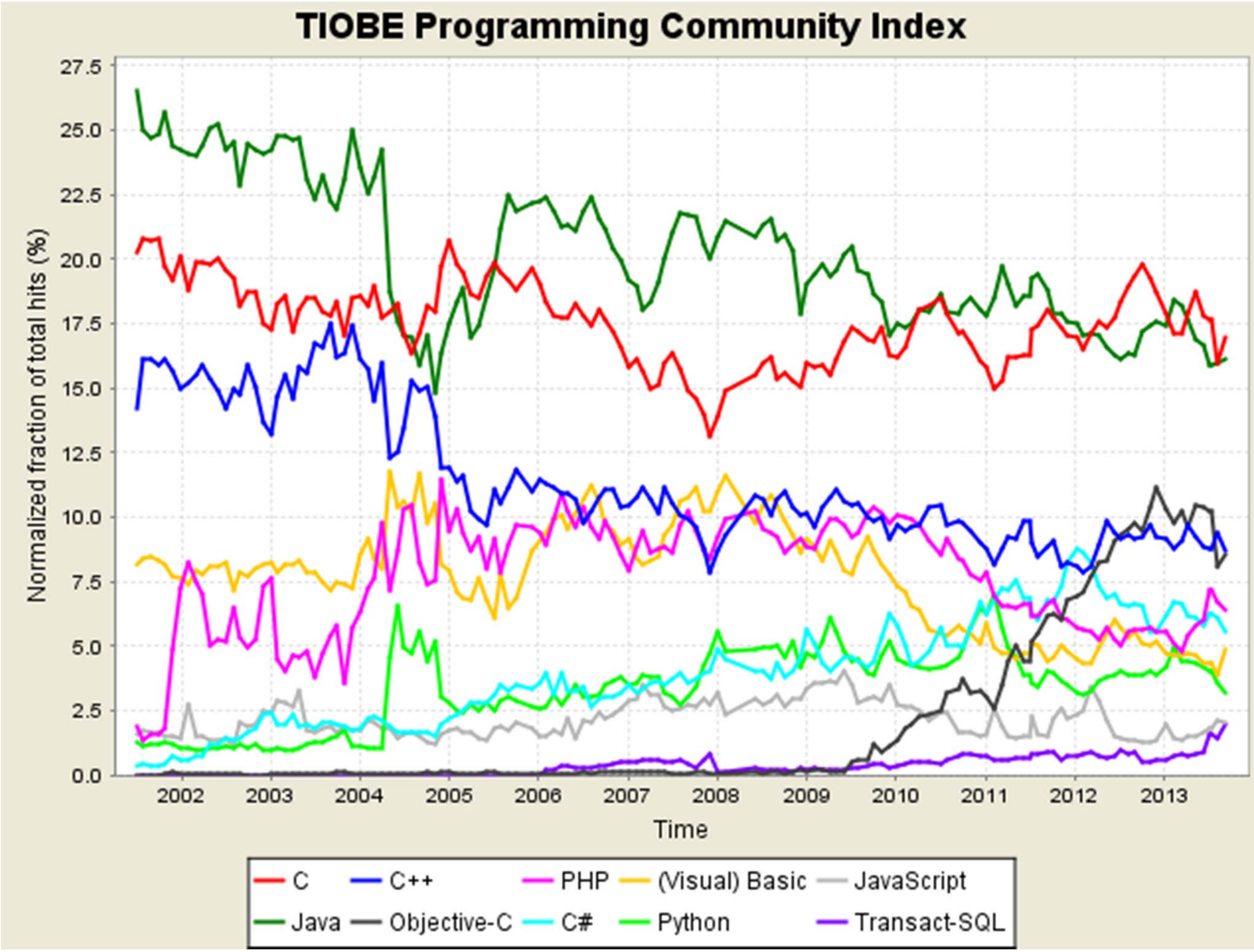
- The number of embedded systems is growing
- More functionality in each system is required
- More reliable systems are needed
- Time to market is getting shorter
- Increase productivity
  - Software engineering practices (OOA&D) – 10%
  - Tools (IDEs, analyzers and verifiers) – 10%
  - New Languages -700%
    - 200%-300% in embedded systems programming (Atego)

Java

- Most popular programming language ever !
  - In 2005 Sun estimated 4.5 million Java programmers
  - In 2010 Oracle estimated 9 million Java programmers

  - 61% of all programmers are Java programmers
- Originally designed for setop-boxes
- But propelled to popularity by the internet

http://jaxenter.com/how-many-java-developers-are-there-10462.html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2005
2006
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2008
2009
2010
2011
2012
2013
Time
C
C++
PHP
(Visual) Basic
JavaScript
Java
Objective-C
C#
Python
Transact-SQL

Advantage of Java over C and C++

- Clean syntax and (relative) clean semantics
- No preprocessor
- Wide range of tool support
- Single dispatch style OOP
- Strong, extendible type system
- Better support for separating subtyping and reuse via interfaces and single inheritance
- No explicit pointer manipulation
- Pointer safe deallocation
- Built-in Concurrency model
- Portability via JVM (write once, run anywhere)

Embedded hard real-time safety-critical systems

- Nuclear Power plants, car-control systems, aeroplanes etc.

- Embedded Systems
  - Limited Processor power
  - Limited memory
  - Resources matter!
- Hard real-time systems
  - Timeliness
- Safety-critical systems
  - Functional correctness

- Grundfos pumps and SKOV pig farm air conditions
- Aalborg Industries (ship boilers) and Therma (aero, defence)
- GomSpace and NASA

What is the problem with Java?

- Unpredictable performance
  - Memory
    - Garbage collected heap
  - Control and data flow
    - Dynamic class loading
    - Recursion
    - Unbounded loops
    - Dynamic dispatch
  - Scheduling
  - Lack high resolution time
- JVM
  - Good for portability – bad for predicatbility

Observation

There is essentially only one way to get a more predictable language:

- namely to select a set of features which makes it controllable.
- Which implies that a set of features can be deselected as well

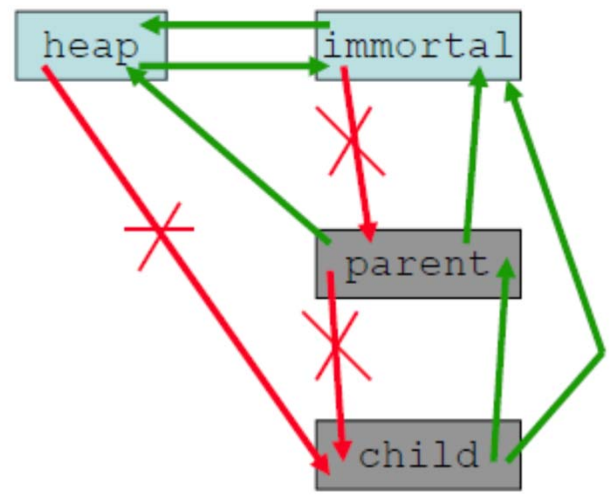
Real-Time Java Profiles

- RTSJ (JSR 001)
  - The Real-Time Specification for Java
  - An attempt to cover everything
  - too complex and dynamic
  - Not suitable for high integrity systems
- Safety-Critical Java (draft) (JSR 302)
  - Subset of RTSJ
  - Focus on simplicity, analysability, and certification
  - No garbage collection: Scoped memory
  - Missions and Handlers (and some threads)
  - Implementation: sub-classes of RTSJ
- Predictable Java
  - Super classes for RTSJ
  - Simple structure
  - Inspiration for SCJ

Real-Time Specification for Java (RTSJ)

- Java Community Standard (JSR 1, JSR 282)
  - Started in 1998
    - January 2002 – RTSJ 1.0 Accepted by JSP
    - Spring 2005 – RTSJ 1.0.1 released
    - Summer 2006 – RTSJ 1.0.2 initiated
    - March 2009 Early draft of RTSJ version 1.1 now called JSR 282.
- Most common for real-time Java applications
  - Especially on Wall Street
- New Thread model: NoHeapRealtimeThread
  - Never interrupted by Garbage Collector
  - Threads may not access Heap Objects
  - Extends Java’s 10 priority levels to 28

RTSJ Overview



- Clear definition of scheduler
- Priority inheritance protocol
- NoHeapRealtimeThread
- BoundAsyncEventHandler
- Scoped memory to avoid GC
- Low-level access through raw memory
- High resolution time and timer
- Originally targeted at larger systems
  - implementation from Sun requires a dual UltraSparc III or higher with 512 MB memory and the Solaris 10 operating system

RTSJ Guiding Principles

- Backward compatibility to standard Java
- No Syntactic extension
- Write Once, Run Anywhere
- Reflected current real-time practice anno 1998
- Allow implementation flexibility

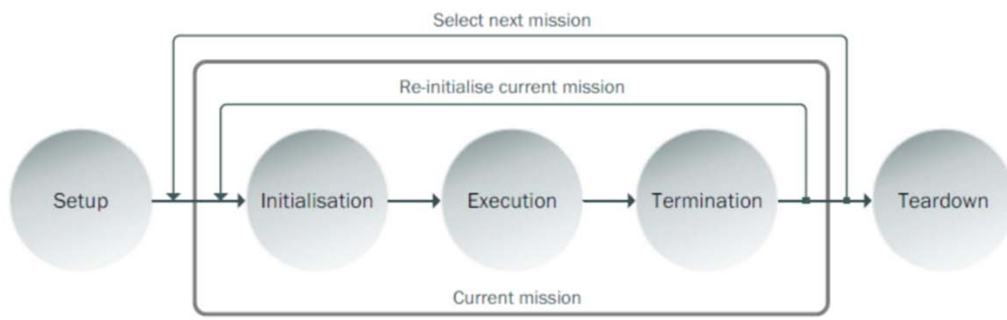
- Does not address certification of Safety Critical applications

Safety-Critical Java (SCJ)

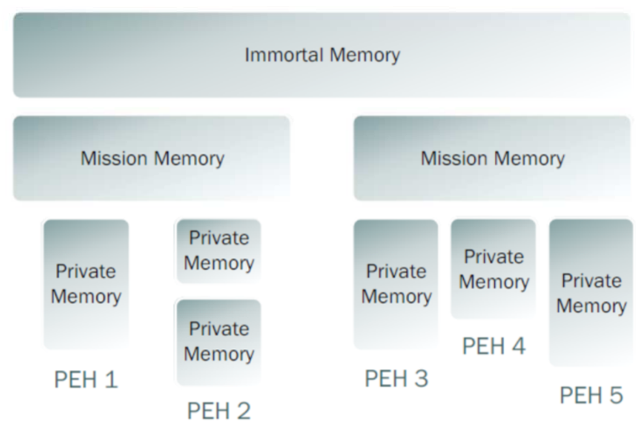
- Java Specification Request 302
- Aims for DO178B, Level A
- Three Compliance Points (Levels 0, 1, 2)
  - Level 0 provides a cyclic executive (single thread), no wait/notify
  - Level 1 provides a single mission with multiple schedulable objects,
  - Level 2 provides nested missions with (limited) nested scopes
- More worst case analysis friendly
- Restricted subset of RTSJ

SCJ

- Only RealtimeThreads are allowed
- Notions of missions and handlers



- No heap objects/ no GC
- Restricted use of scopes

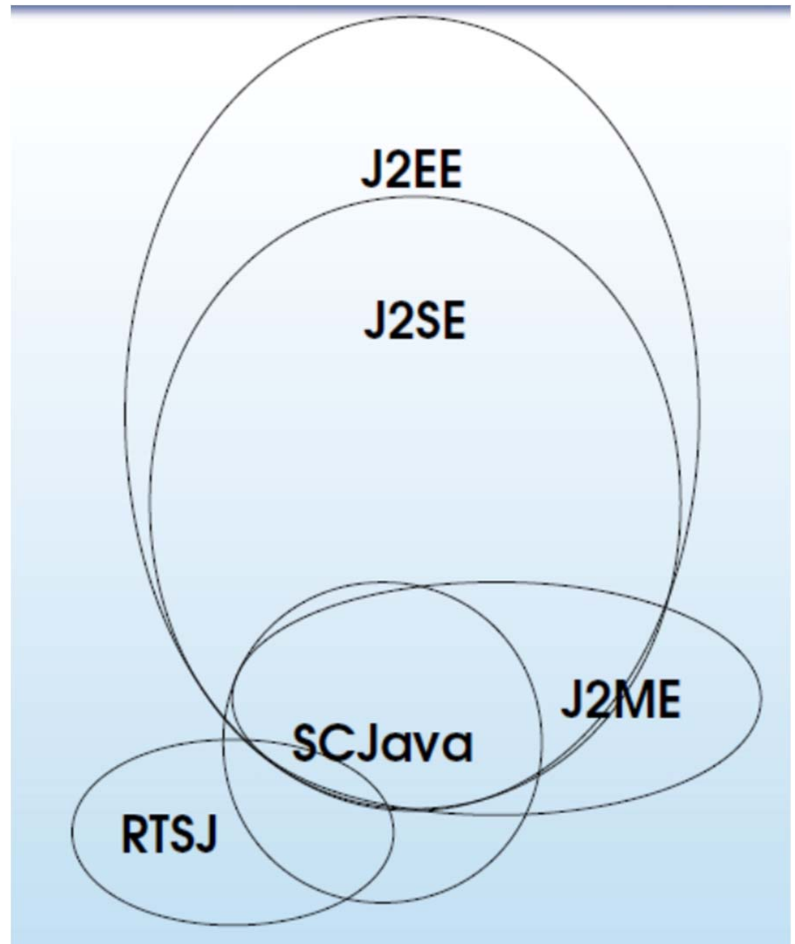


Predictable Java (PJ)

- Predictable Java intended as guidance/ideas for SCJ
- JSR-302 uses inheritance for limitation
  - Lots of @SCJAllowed annotations everywhere
- RTSJ would be a specialisation of a smaller profile
- PJ suggests to use inheritance for specialisation
  - Generalisation of RTSJ
- Missions are first-class handlers
  - Scoped memory belonging to the mission
    - No need for immortal memory known from RTSJ and SCJ.
    - Simplifies memory hierarchy
    - Programs are more Java like

Many variants of Java

- J2EE
  - J2SE & enterprise extensions
- J2SE
  - Standard Java
- J2ME
  - Subset of J2SE & additional classes
- RTSJ
  - Add on to J2EE, J2SE, or J2ME for realtime
- SCJava
  - Subset of RTSJ, subset of J2SE, & additional classes



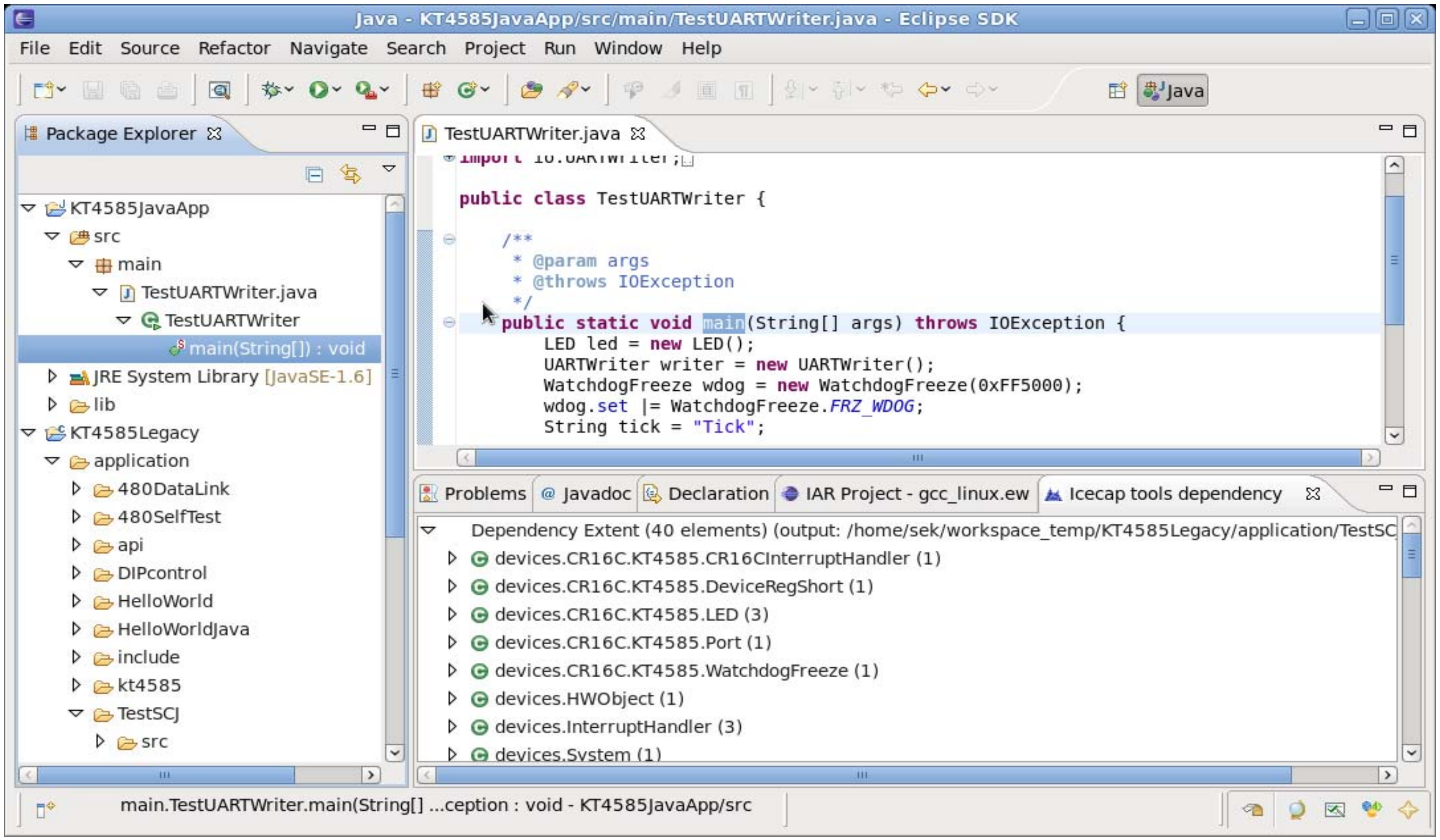
Predicatble JVM

- JOP
  - Java Optimized Processor
  - JVM in Hardware (FPGA)

- HVM
  - targeted at devices with 256 kB flash and 8kB of RAM
  - Interpreted or AOT compilering
  - 1st level interupt handlers in Java
  - Runs on ATmega2560, CR16C, ARM7, ARM9 and x86
- JamaicaVM
  - Industrial strength real-time JVM from Aicas
  - Enroute for Certification for use in Airplanes and Cars

The HVM

Java-to-C compiler with an embedded interpreter



Java look-and-feel for low-end embedded devices

Support incremental move from C to Java

Features

- Execution on the bare metal
- First level interrupt handling & Hardware Objects
- Hybrid execution style (interpretation + AOT)
- Program specialization
  * Classes & methods
  * Interpreter
- Native variable support
- Portability
  * No external dependencies
  * Strict ANSI-C
- Process switching & scoped memory

The Predictable Real-time HVM

- Time predictable implementations of Interpreter loop and each bytecode

```
static int32 methodInterpreter(const MethodInfo* method, int32* fp) {
  unsigned char *method_code;
  int32* sp;
  const MethodInfo* methodInfo;

  start: method_code = (unsigned char *) pgm_read_pointer(&method->code, unsigned char**);
  sp = &fp[pgm_read_word(&method->maxLocals)+2];

  loop: while (1) {
    unsigned char code = pgm_read_byte(method_code);
    switch (code) {
    case ICONST_0_OPCODE:
    //ICONST_X Java Bytecodes
    case ICONST_5_OPCODE:
      *sp++ = code - ICONST_0_OPCODE;
      method_code++;
      continue;
    case FCONST_0_OPCODE:
    //Remaining Java Bytecode impl...
    }
  }
}
```

What about Time Analysis?

Utilisation-Based Analysis

- A simple sufficient but not necessary schedulability test exists

$$U \equiv \sum_{i=1}^{N} \frac{C_i}{T_i} \leq N(2^{1/N} - 1)$$

$$U \leq 0.69 \text{ as } N \rightarrow \infty$$

Where C is WCET and T is period

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Response Time Equation

$$R_i = C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

Where $hp(i)$ is the set of tasks with priority higher than task i

Solve by forming a recurrence relationship:

$$w_i^{n+1} = C_i + \sum_{j \in hp(i)} \left\lceil \frac{w_i^n}{T_j} \right\rceil C_j$$

The set of values $w_i^0, w_i^1, w_i^2, \ldots, w_i^n, \ldots$ is monotonically non decreasing
When $w_i^n = w_i^{n+1}$ the solution to the equation has been found, w_i^0 must not be greater that R_i (e.g. 0 or C_i)

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- Traditional approaches to analysis of RT systems are hard and conservative

- Very difficult to use with Java because of JVM (and Object Orientedness)

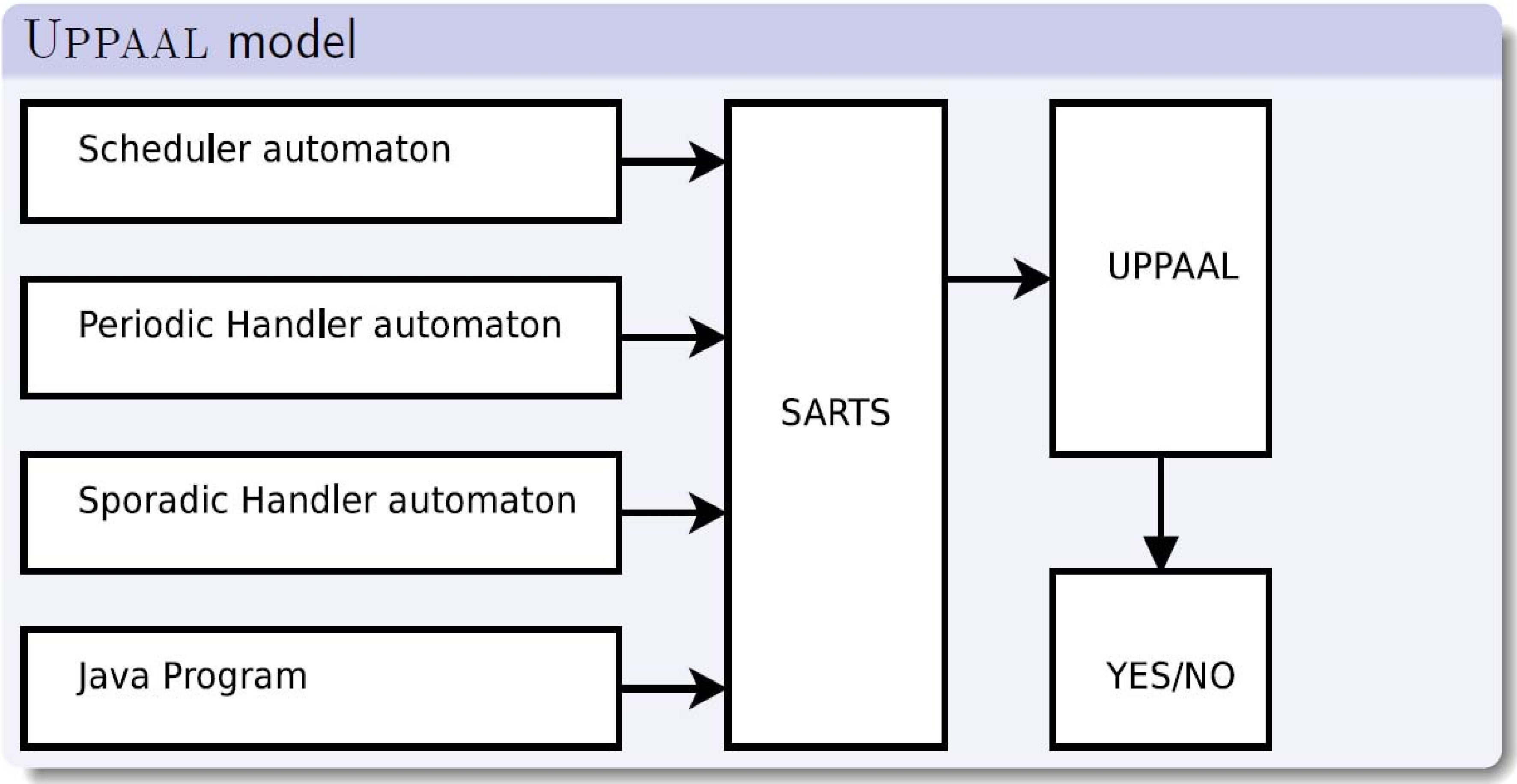
Model based Analysis

- TIMES
  - Model based schedulability tool based on UPPAAL
- WCA
  - WCET analysis for JOP
- SARTS
  - Schedulability on JOP
- TetaJ
  - WCET analysis for SW JVM on Commodity HW
- TetaSARTS
  - Schedulability analysis for SW JVM on Commodity HW and JOP

SARTS

- Schedulability analyzer for real-time Java systems
  - Assumes program in SCJ profile
  - Assumes correct Loop bounds annotations
  - Assumes code to be executed on JOP
- Generates Timed Automata
  - Control flow graph with timing information
  - Uppaal Model-checker checks for deadlock
  - Based on ideas from TIMES tool

SARTS Overview



SARTS Overview

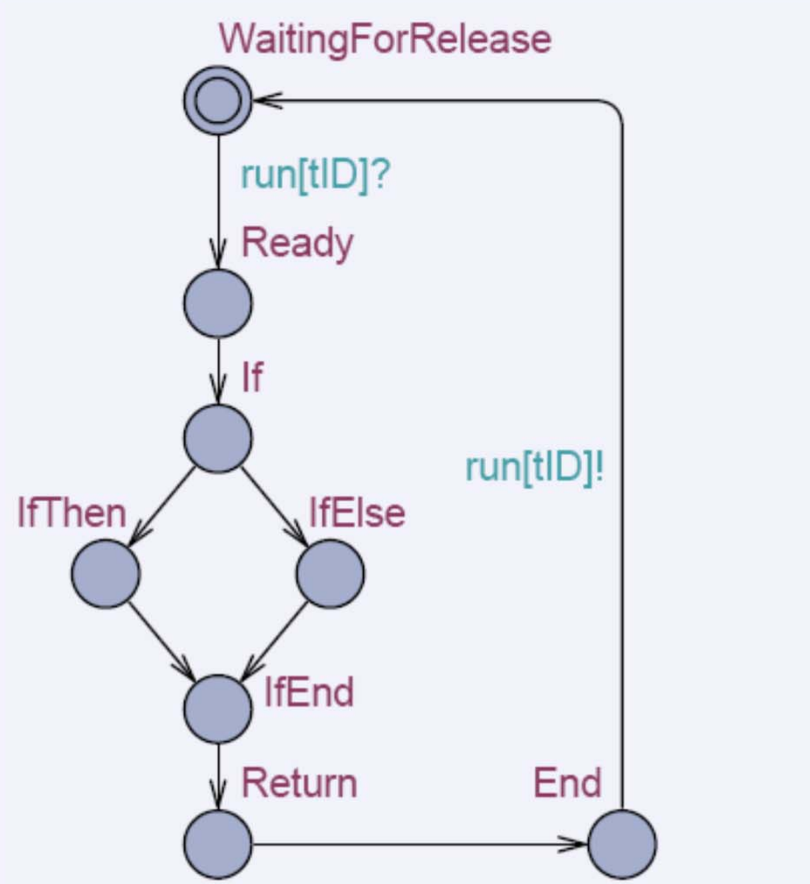
- A scheduler automaton models FPS
- A controller automaton, periodic/sporadic, is created for each handler
- Each Java method results in a parametrised automaton
  - One clock per task/thread
  - Pre-emption is modelled using stopwatches
  - Control-transfer is modelled using synchronization

Java to UPPAAL

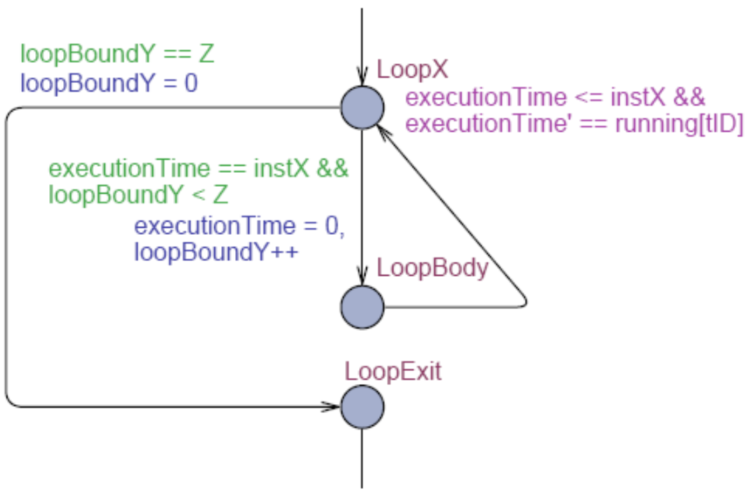
Java code

```java
protected boolean run() {
  if (condition){
    //then statements
  } else {
    //else statements
  }
  return true;
}
```

UPPAAL model

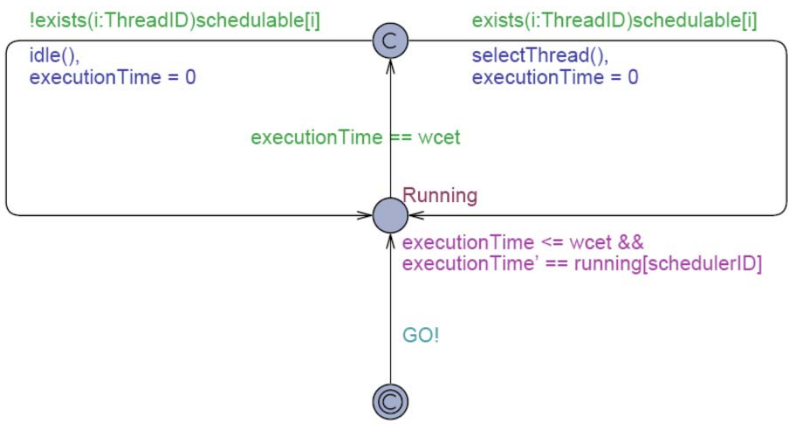


Timed Automata templates



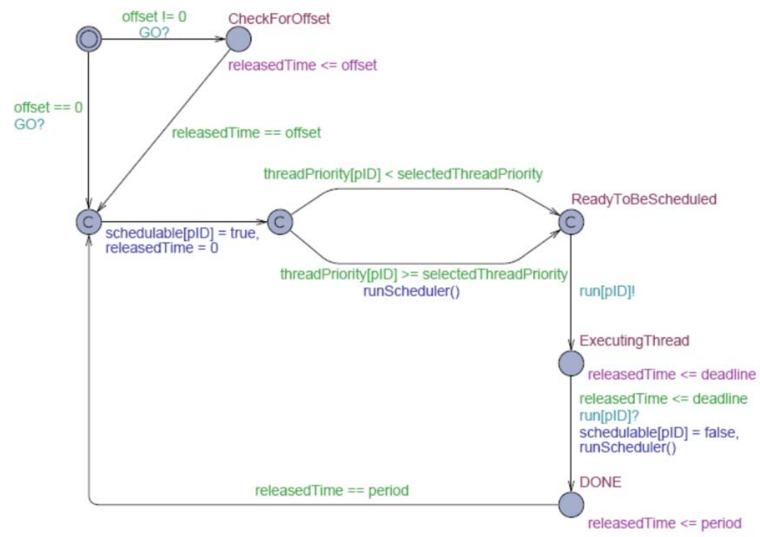
- Translation of Basic Blocks into states and transitions
- Patterns for:
  - Loops
  - Monitor statements
  - If statements
  - Method invoke
  - Sporadic task release

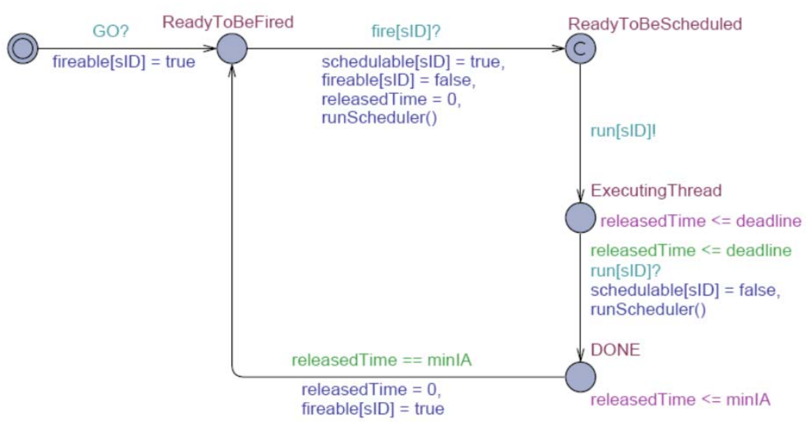
Simple models of RM scheduler



- Predefined models
  - Scheduler
  - Periodic Task
  - Sporadic Task

Periodic Task/Sporadic Task





SARTS sales pitch

- The schedulability question is “translated" to a deadlock question
  - no deadlock means schedulable
- Compared to traditional schedulability analysis
  - Control flow sensitive
  - Fine grained interleaving
  - Less pessimism
  - Fully automatic

SARTS can do better than utilisation test

- Example
- One periodic task
- Two sporadic tasks
  - Mutually exclusive

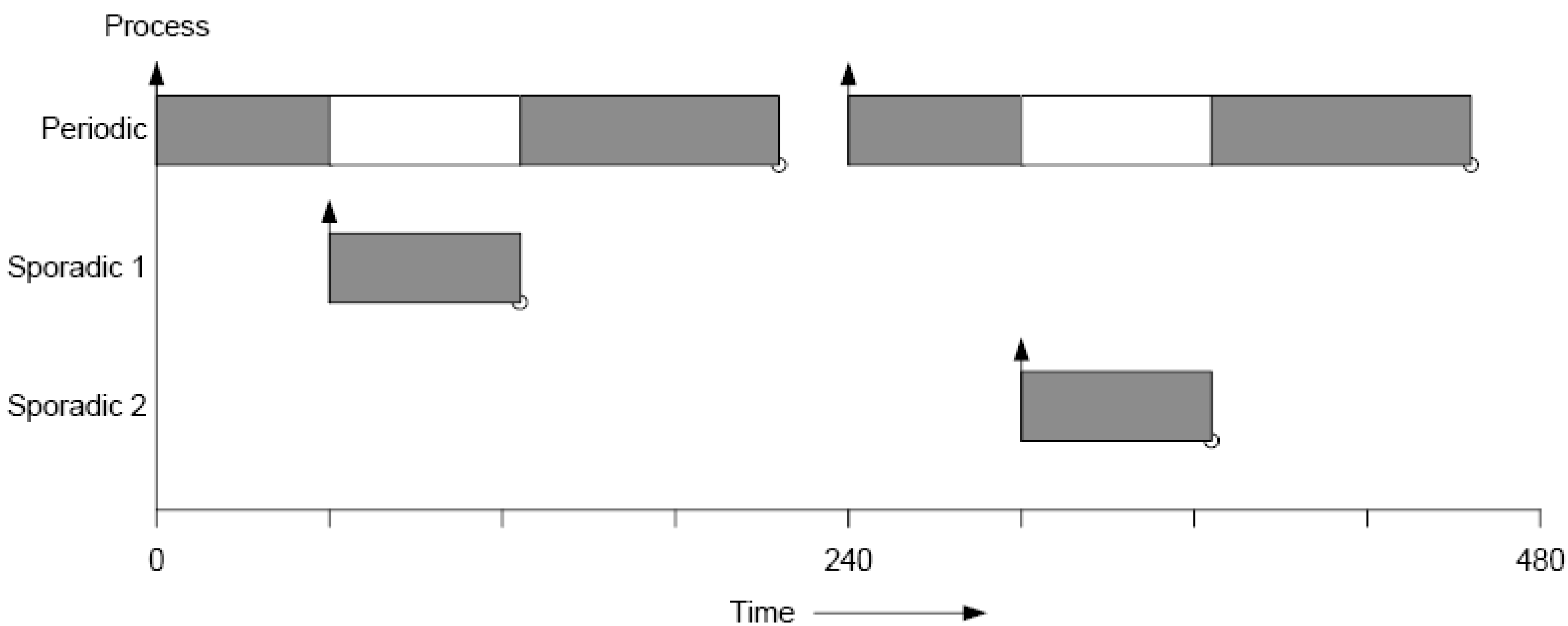
```
public class Experiment2 extends PeriodicThread {
  public boolean run() {
    if (b) {
      RealtimeSystem.fire(1);
    } else {
      RealtimeSystem.fire(2);
    }
    return true;
  }
}
```

SARTS can do better than utilisation test

- Period: 240
- Minimum inter-arrival time: 240
- Periodic cost: 161
- Sporadic cost: 64
- Utilisation test fails:

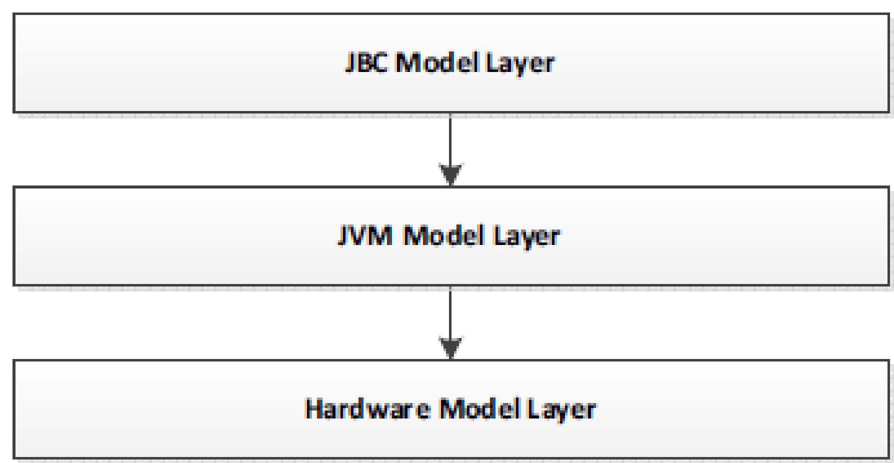
$$\left(\frac{161}{240}\right) + \left(\frac{64}{240}\right) + \left(\frac{64}{240}\right) = 1.20$$

Time Line



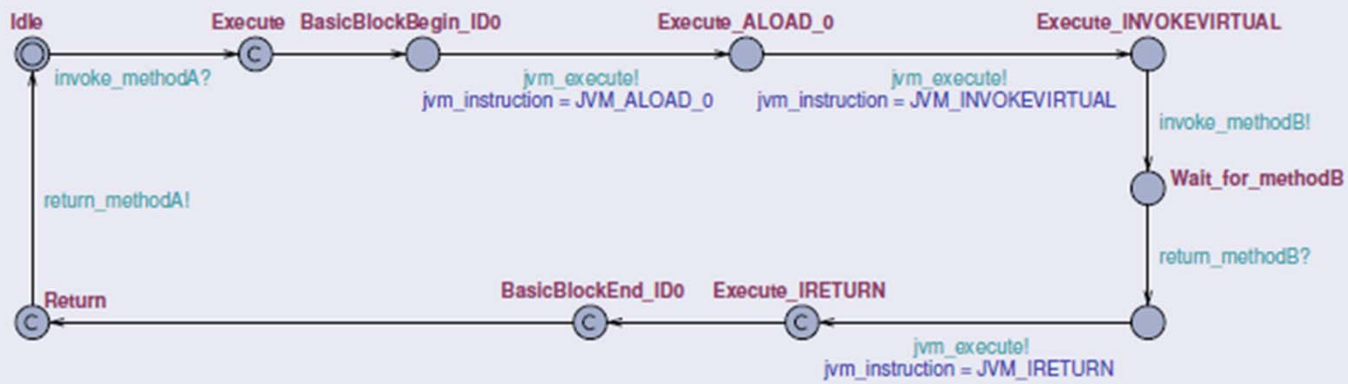
TetaJ

- WCET analysis tool
  - taking Java portability into account
- Analysis at method level
- Can be used interactively
- Takes VM into account
- Takes HW into account

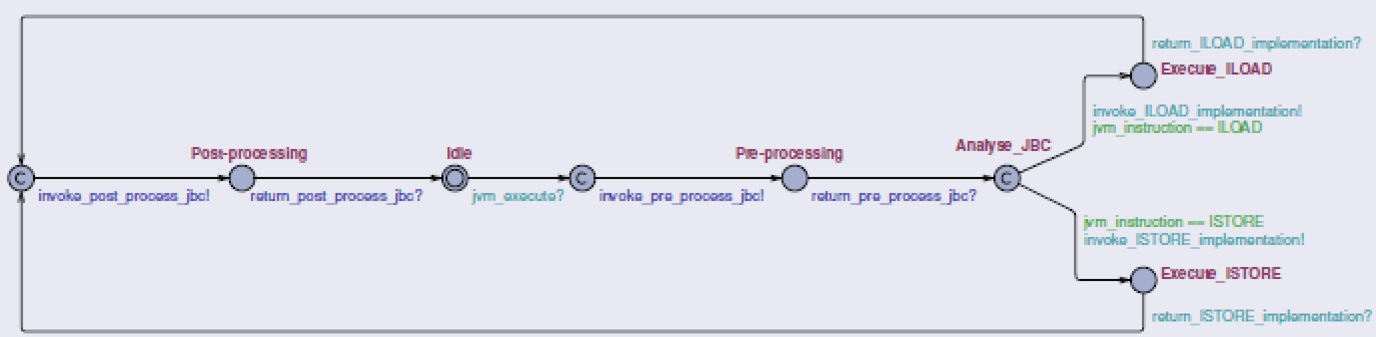


Initialisation Model

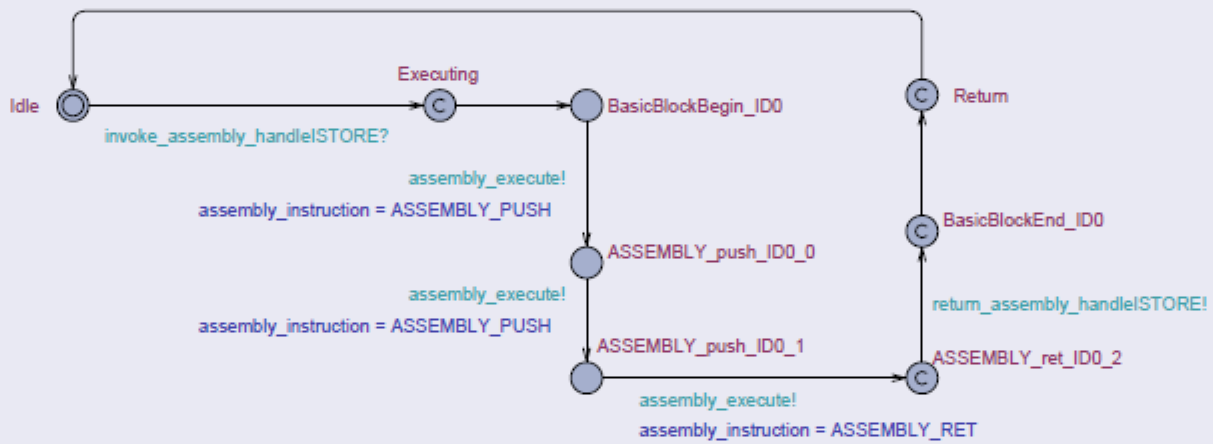
Program Model



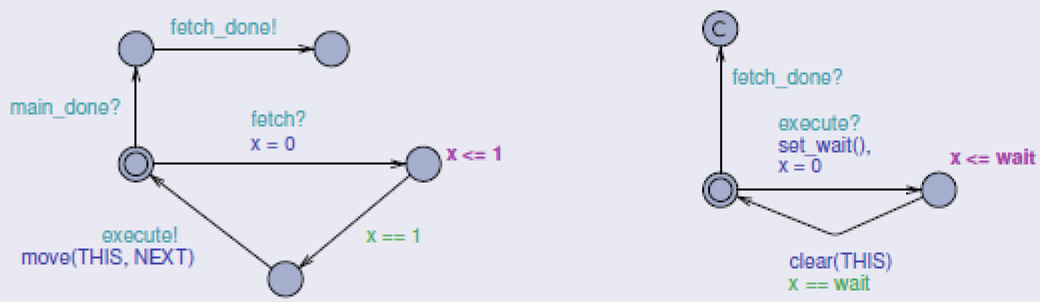
JVM Model (excerpt)



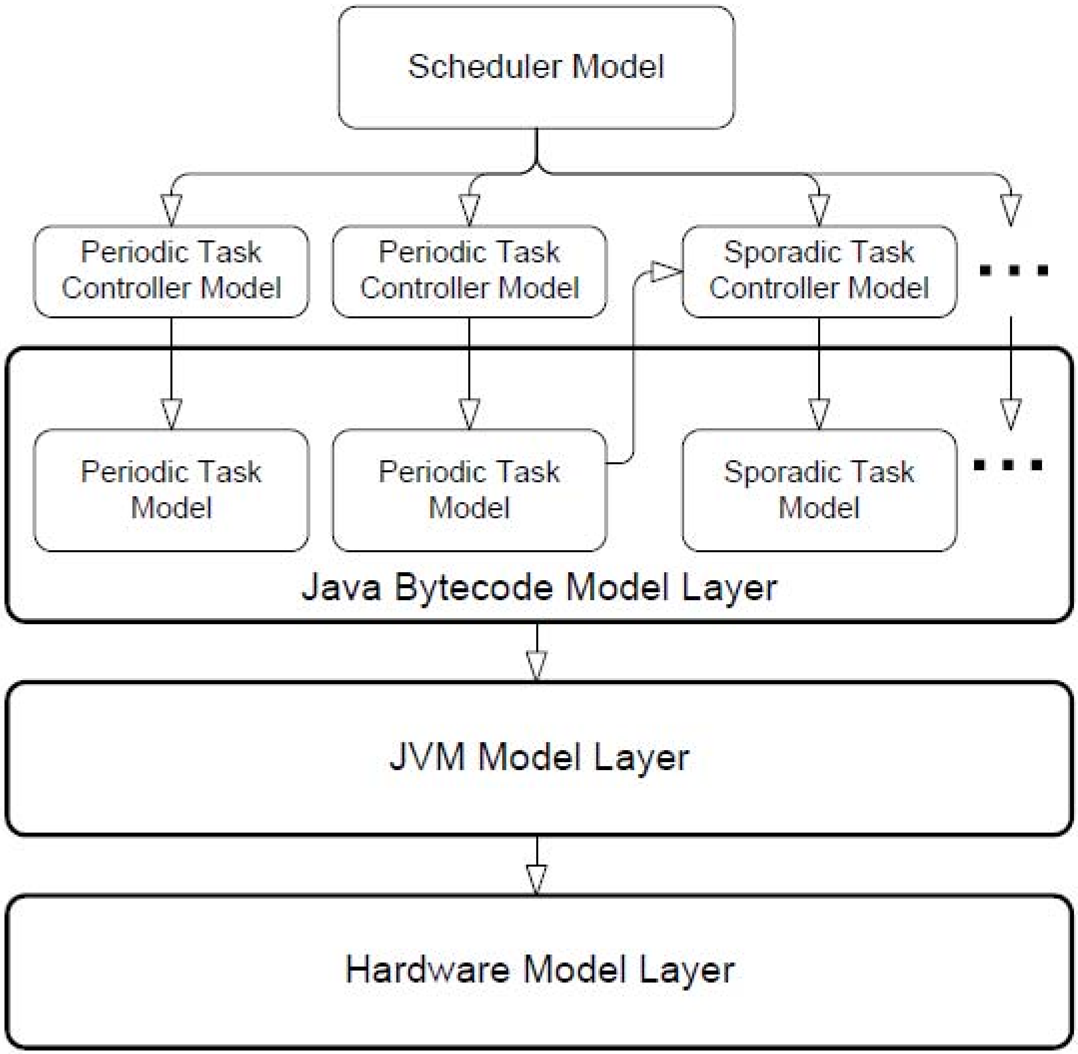
Java Bytecode Implementation



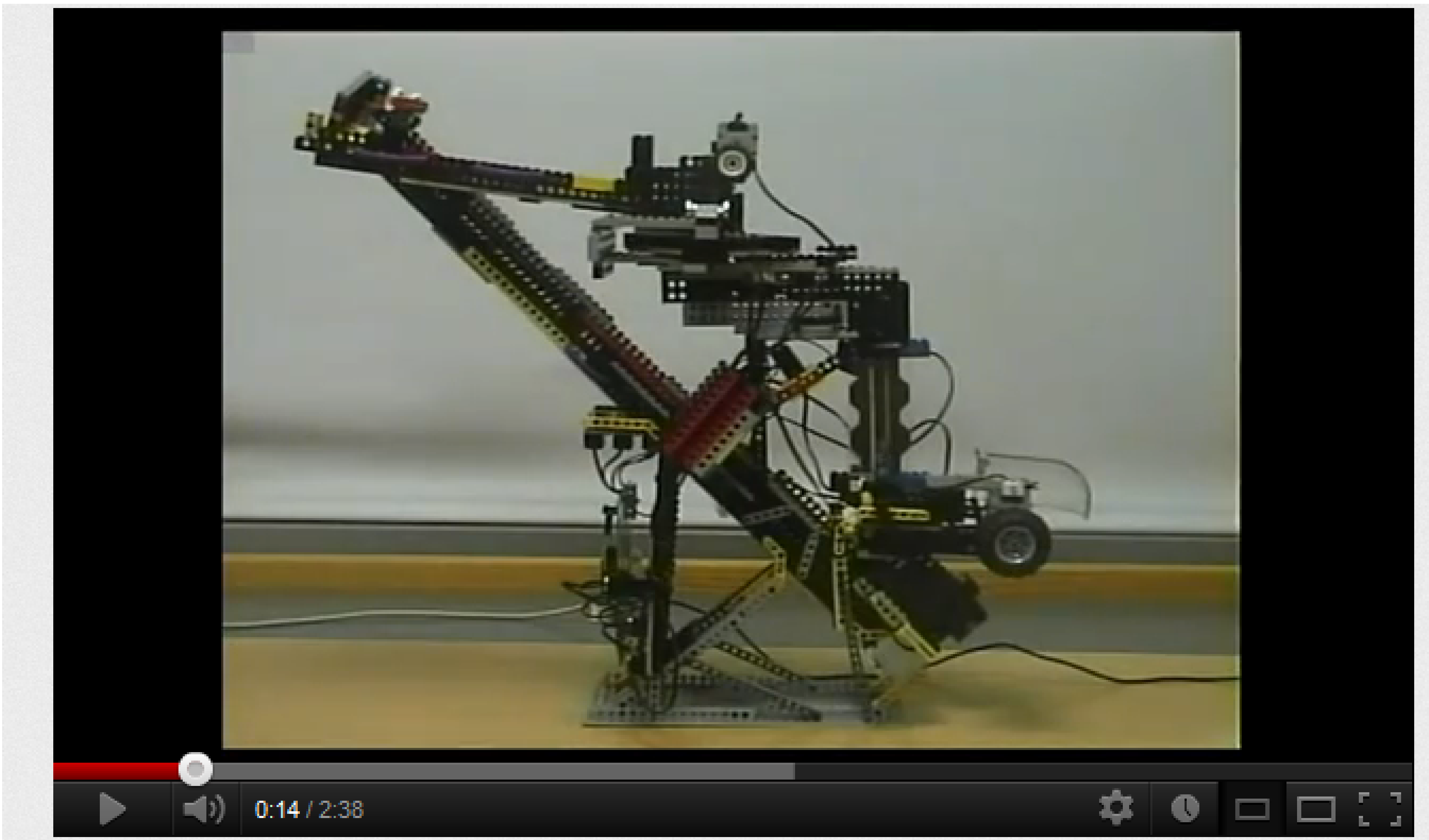
Hardware Models (From METAMOC)



TetaSARTS


Scheduler Model
Periodic Task Controller Model
Periodic Task Controller Model
Sporadic Task Controller Model
...
Periodic Task Model
Periodic Task Model
Sporadic Task Model
...
Java Bytecode Model Layer
JVM Model Layer
Hardware Model Layer

Minepump example



Minepump example
Write once – run whereever possible

Execution Environment	Water Deadline	Methane Deadline	Schedulable
HVM + AVR @ 10 MHz	12 ms	12 ms	✓
HVM + AVR @ 5 MHz	12 ms	12 ms	×
HVM + AVR @ 10 MHz	6 ms	6 ms	×
JOP @ 100 MHz	6 ms	6 ms	✓
JOP @ 100 MHz	12 μs	12 μs	✓

Table 2. Using TetaSARTS with various execution environments.

Experiment	Exec. Env.	Optimised	Analysis Time	Mem. Usage
Minepump	HVM + AVR	✓	15h 25m 16s	17933 MB
Minepump	JOP	✓	7s	27 MB
Minepump	JOP	×	6m 18s	62 MB
SARTS Minepump	JOP	N/A	21s	42 MB
Simple System	HVM + AVR	✓	49s	168 MB
Simple System	HVM + AVR	×	22m 58s	238 MB
Simple System	JOP	✓	0.05s	7 MB
Simple System	JOP	×	0.5s	20 MB

Table 1. Results obtained using TetaSARTS and SARTS.

Energy Optimize Applications

Execution Environment	Clock Freq.	Schedulable
HVM + AVR	10 MHz	✓
HVM + AVR	5 MHz	×
JOP	2 MHz	✓
JOP	1 MHz	×

System	Clock Freq.	Proc. Util.	Proc. Idle
RTSM	100 MHz	48.5 μs	4.0 ms
RTSM	60 MHz	80.8 μs	4.0 ms
Minepump	100 MHz	25.9 μs	2.0 ms
Minepump	10 MHz	259 μs	11.8 ms

Compositional Verification

- TetaSARTS generates model for whole program
- Library routines analysed again and again
- Models based on control flow can be complicated

- Idea: Annotate interfaces with abstract description of behaviour
  - Time and Resource Specification Language (TRSL)
  - Could have been any of a range of spec. lang.
    - UML/Marte, ACSR, TADL

```
class Task2 extends PeriodicEventHandler{
  Buffer buf;                // shared buffer
  //@ TRSL = [5]
  private int calculate(){..}
  //@ TRSL = [2]
  private void prepare(..){..}
   //@ TRSL = [1]
  private void register(..){..}
  //@ TRSL = [1 ; 7? ; using(r)[2] ; 1 ]
  public void handleEvent(){
    if(!ready){              // wcet: 1
      value = calculate();   // wcet: 5
      prepare(value);        // wcet: 2
    }
    input = buf.remove();    // wcet: 2
    register(input);         // wcet: 1
  }
}
```

Note – could have used [1..8 ; using(r)[2] ; 1] since
[1 ; 7? ; using(r)[2] ; 1] ≤ [1 ..8 ; using(r)[2] ; 1]

TetaSARTS+

- Schedulability analysis now in three steps
  - Verify that implementation is simulated by specification
    - Check L(Implementation) ≤ L(specification)
    - Possible since TRSL TAs are simple instances of the Event-Clock Automata
  - Generate TAs from Specs
  - Use TetaSARTS

Further Analysis and tools

- Scope compliance analysis for SCJ
- SCJ compliance analyzer
- Eclipse plug-in
- Lot’s of work on (analyzable) Real-time GC

Future Work

- Experiment with deductive verification
  - Functional requirements
  - JML and Key
  - Especially loop bounds
- Symbolic model checking
  - JavaPathFinder
- Termination Analysis
  - Recursion bounds
- Analyse non-SCJ programs
  - Java, Groovy, Scala
- Multi-core HVM

Learn more

- Model-based schedulability analysis of safety critical hard real-time java programs
  – T. Bøgholm, H. Kragh-Hansen, P. Olsen, B. Thomsen, and K. G. Larsen
  – JTRES 2008
- Schedulability Analysis Abstractions for Safety Critical Java
  – Thomas Bøgholm, Bent Thomsen, Kim G. Larsen, Alan Mycroft
  – ISORC 2012
- Wcet analysis of java bytecode featuring common execution environments
  – C. Frost, C. S. Jensen, K. S. Luckow, and B. Thomsen
  – JTRES 2011
- TetaSARTS: A Tool for Modular Timing Analysis of Safety Critical Java Systems
  – Kasper Luckow, Thomas Bøgholm, Bent Thomsen, and Kim Larsen
  – To appear JTRES 2013

Join InfinIT network on High Level Languages in Embedded Systems

- http://www.infinit.dk/dk/interessegrupper/hoejniveau_sprog_til_indlejrede_systemer/hoejniveau_sprog_til_indlejrede_systemer.htm

Try it out?

- TetaSARTS
  - http://people.cs.aau.dk/~luckow/tetasarts/
- Hardware Near Virtual Machine
  - http://icelab.dk/
- oSCJ (open Safety-Critical Java Implementation)
  - http://sss.cs.purdue.edu/projects/oscj/
- Java Optimized Processor
  - http://www.jopdesign.com/
- JamaicaVM
  - http://www.aicas.com/jamaica.html

Joint work with:

- Allan Mycroft
  - Cambridge University
- Hans Søndergaard, Stephan Korsholm
  - Via University College
- Thomas Bøgholm, Kasper Søe Luckow, Anders P. Ravn, Kim G. Larsen, Rene R. Hansen and Lone Leth Thomsen
  - CISS/Department of Computer Science, Aalborg University