Sun microsystems

Real-Time Java

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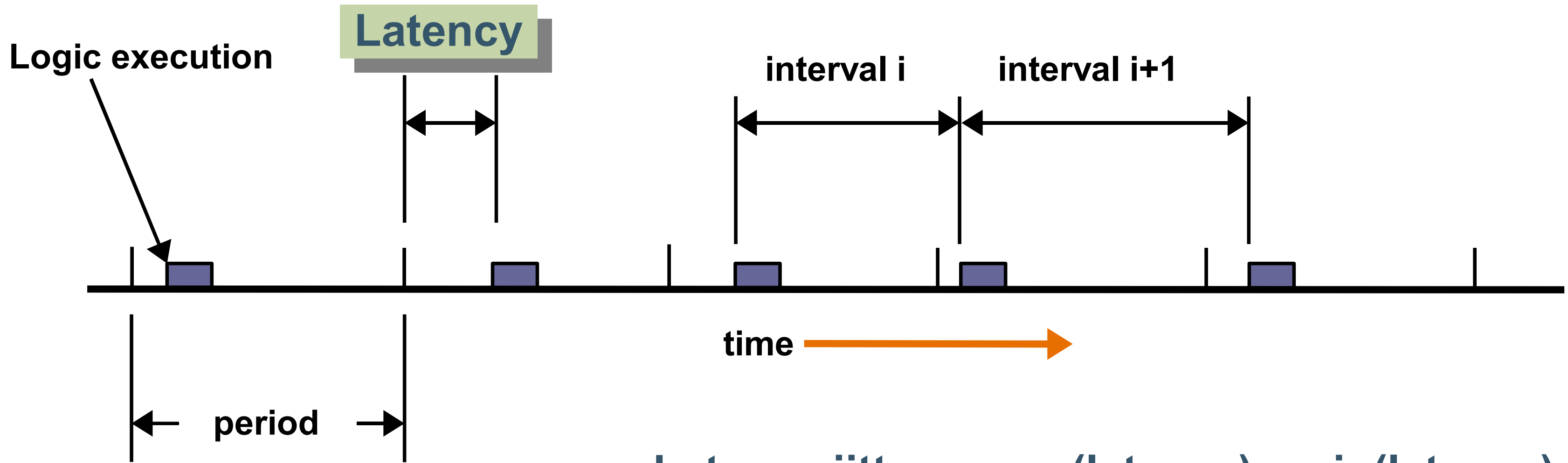
What is Real-Time?

- Simple definition: The addition of *temporal constraints* to the correctness conditions of a program
  - "When" is as important as "what"
  - "A late answer is a wrong answer"
- "real-time" <u>does not mean</u> "real-fast"
  - Going faster helps but ...
- Predictability is the key
- Non-real-time systems have many sources of unpredictable behaviour
  - Performance is based on the average-case

Example Temporal Constraints

- *Deadline*: started task must complete by a given time
  - Once a request for a trade is received, it must execute within 5ms
- *Latency*: difference between when an event happens and when it is seen to have happened
  - Stop button handler must respond within 500us of a press
- *Jitter*: Variance in the time interval between events
  - The input sensor must be sampled every 1ms +/- 100us

Latency and Jitter



Latency jitter = max(latency) - min(latency)

Interval jitter = (max(interval) - min(interval))/2

Latency is the measure of how long it takes the system to respond to an event.

Jitter is the variability of a measured value.

For both: lower is better.

Why Real-Time Java?

- Same reasons as for using Java – but applied to real-time application domains
  - Traditional C/C++/assembler implementations difficult to write, debug, maintain
- Real-time software loads are evolving
  - Increase both in size and complexity
  - Traditional, low-level programming no longer provides the required level of abstraction
- Single solution for real-time and non-real-time code
  - Re-use of people, tools, knowledge

Real-Time Specification for Java (RTSJ) JSR-001

- Started in 1998. Experts from many communities
  - Real-time systems, embedded systems, Ada, Java, academia and industry
- The standard that defines how real-time behavior must occur within Java technology
  - Therefore, the only real-time Java technology!
- APIs and semantic enhancements which allow Java code developers to correctly reason about and control the temporal behavior of applications
  - Better, high-level, portable abstractions
  - 100% Java technology

JSR-1 Evolution

1998

Real-Time Specification for Java (JSR-001) proposal submitted

Many companies represented: IBM, Sun, Ajile, Apogee, Motorola, Nortel, QNX, Thales, TimeSys, WindRiver

2002

JSR-001 approved by the Java Community Process

TimeSys Reference Implementation

2005

RTSJ update proposal submitted (JSR-282)

Several JSR-1 compliant products (Apogee, IBM, Sun)

RTGC Available in IBM's JVM

2007

RTGC added to Sun's JSR1-compliant JVM

JSR-1 APIs added to RTGC enhanced JVMs

2008

New Sun/IBM JSR

Uses of RTSJ

Inverted pendulum control problem

- Industrial automation
- Aeronautic/Aerospace

Boeing Scan-Eagle UAV

- Telecommunications
- Banking/Financial
- ...

Sun's Java Real-Time System

- Sun's implementation of the RTSJ
  - 100% compliant with Java technology and RTSJ 1.0.2
- Java RTS 2.0 highlights
  - Based on Java Platform, Standard Edition 5
  - Runs on Solaris 10 OS,
    - SPARC® technology, and x86/x64 platforms
    - Relies on Solaris platform built-in real-time capabilities
- Java RTS 2.1 Early Access
  - Runs on real-time Linux on x86
    - SUSE Linux Enterprise Real Time 10
    - Red Hat Enterprise MRG 1.0 (beta)

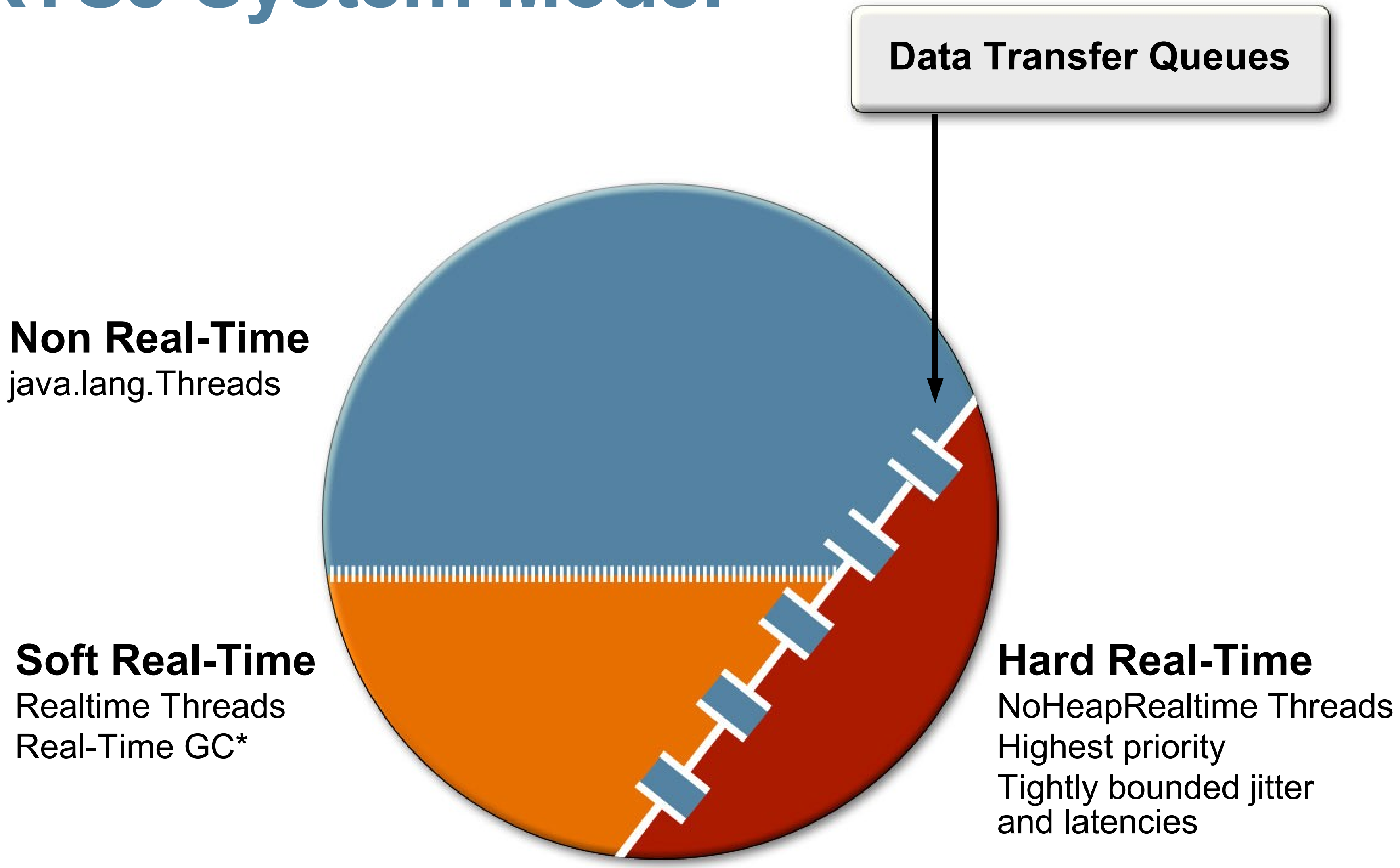
Java RTS 2.x Platforms

- From embedded single-board computers
- To carrier-grade blade servers
- To enterprise servers

Java RTS Latency and Jitter Numbers

- Example of Java RTS 2.0 on Solaris 10 / SPARC
  - Maximum Jitter: < 5 microseconds
  - Maximum Latency: < 10 microseconds
- As good as the best commercial RTOS
  - And often better, particularly on faster processors with more memory
- But No Silver Bullet!
  - Enhanced predictability comes at expense of throughput
    - How much depends on platform, hardware, #CPUs, amount of memory, JVM configuration and the application itself

RTSJ System Model

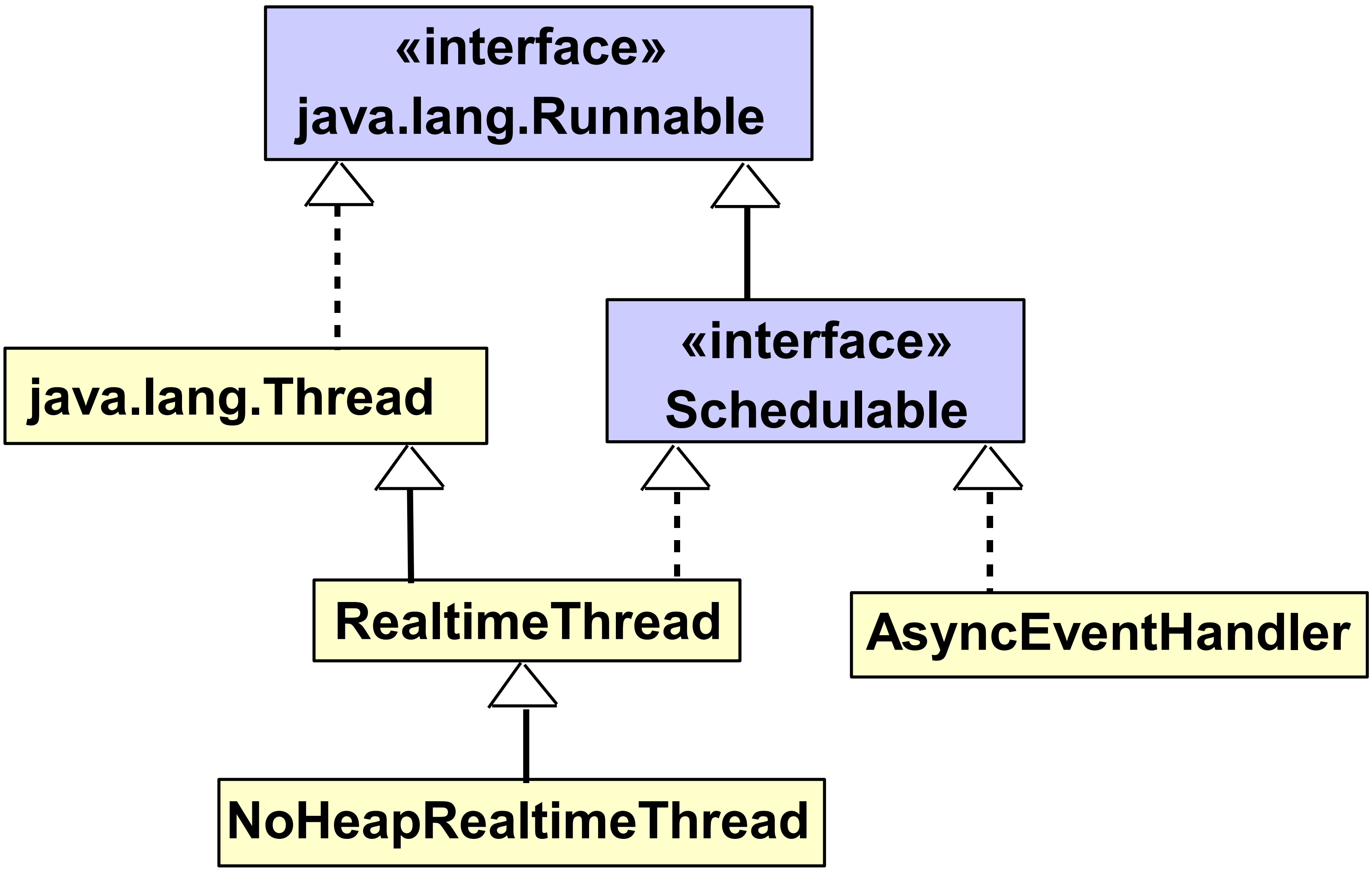


* RTGC not specified by RTSJ

Key RTSJ Features

- Scheduling and Dispatching
  - Managing schedulable objects removes unpredictable scheduling
- Synchronization
  - Priority inversion avoidance removes unpredictable delays
- Memory Management
  - Alternatives to the heap to removes unpredictable GC
- Asynchronous events and handlers
  - Event driven programming model
- Time, Clocks and Timers

Threads and Schedulable Objects



RTSJ Scheduling

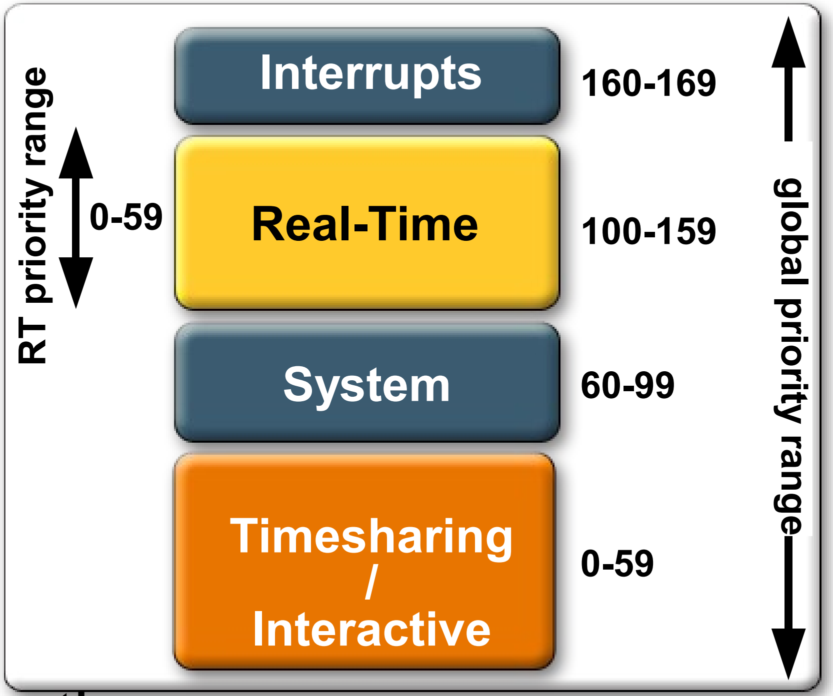
- Schedulable Object managed by a `Scheduler`
- One defined scheduler: `PriorityScheduler`
  - Singleton: `PriorityScheduler.instance()`
  - Execution eligibility based on an integer priority value
    - **Higher the value the higher the priority**
  - Minimum of 28 unique, consecutive priority levels
    - **Distinct from (and >) the 10** `java.lang.Thread` **priorities**
    - `getMinPriority()`, `getMaxPriority()`, `getNormPriority()`

Fixed Priority Preemptive Scheduling

- Highest priority schedulable object always runs
  - Higher priority SO preempts lower priority one
- Schedulable object runs until it blocks
  - No time-slicing! No “fairness”
  - Caution: “greedy” real-time threads can “hang” your system!
- `PriorityScheduler` doesn’t change priority except for priority inversion avoidance
  - Contrast with dynamic scheduler: Earliest Deadline First
- All internal system queues maintained in priority order;
  - Run queue, monitor entry queue, monitor wait-set
- Necessary for predictability, but not sufficient ...

Java RTS Predictability on Solaris OS

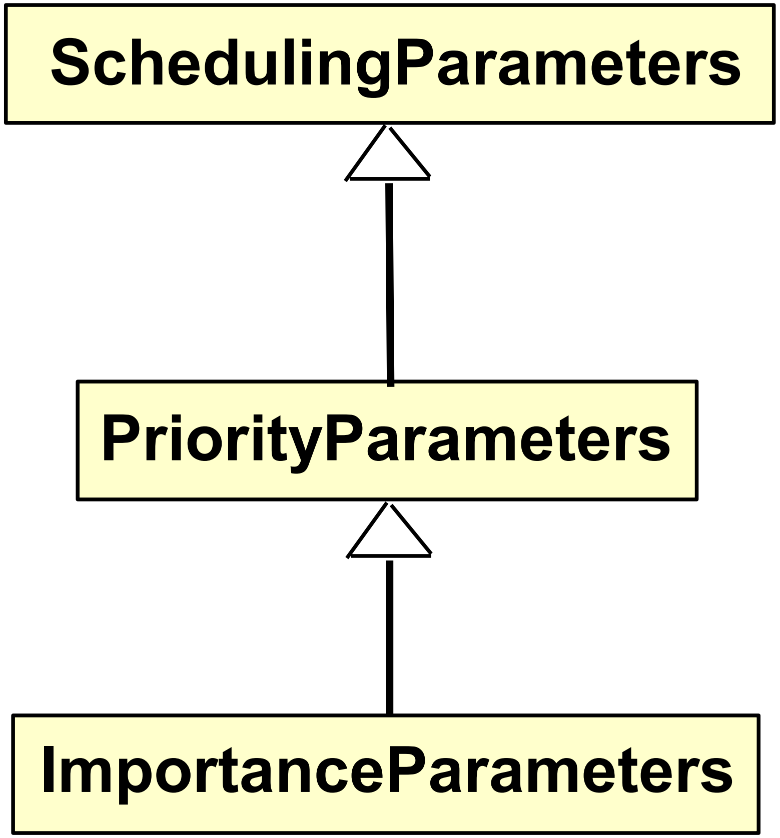
- Uses Solaris Real-Time (RT) scheduling class
  - 60 priority levels
  - Highest range of thread priorities in the system
- JVM locked into memory
  - No page swap in/swap out
- Processor set bindings
  - RTTs and NHRTs
- Class pre-loading and initialization
- Initialization Time Compilation (ITC)
  - No runtime execution variance



Characterizing Schedulable Objects

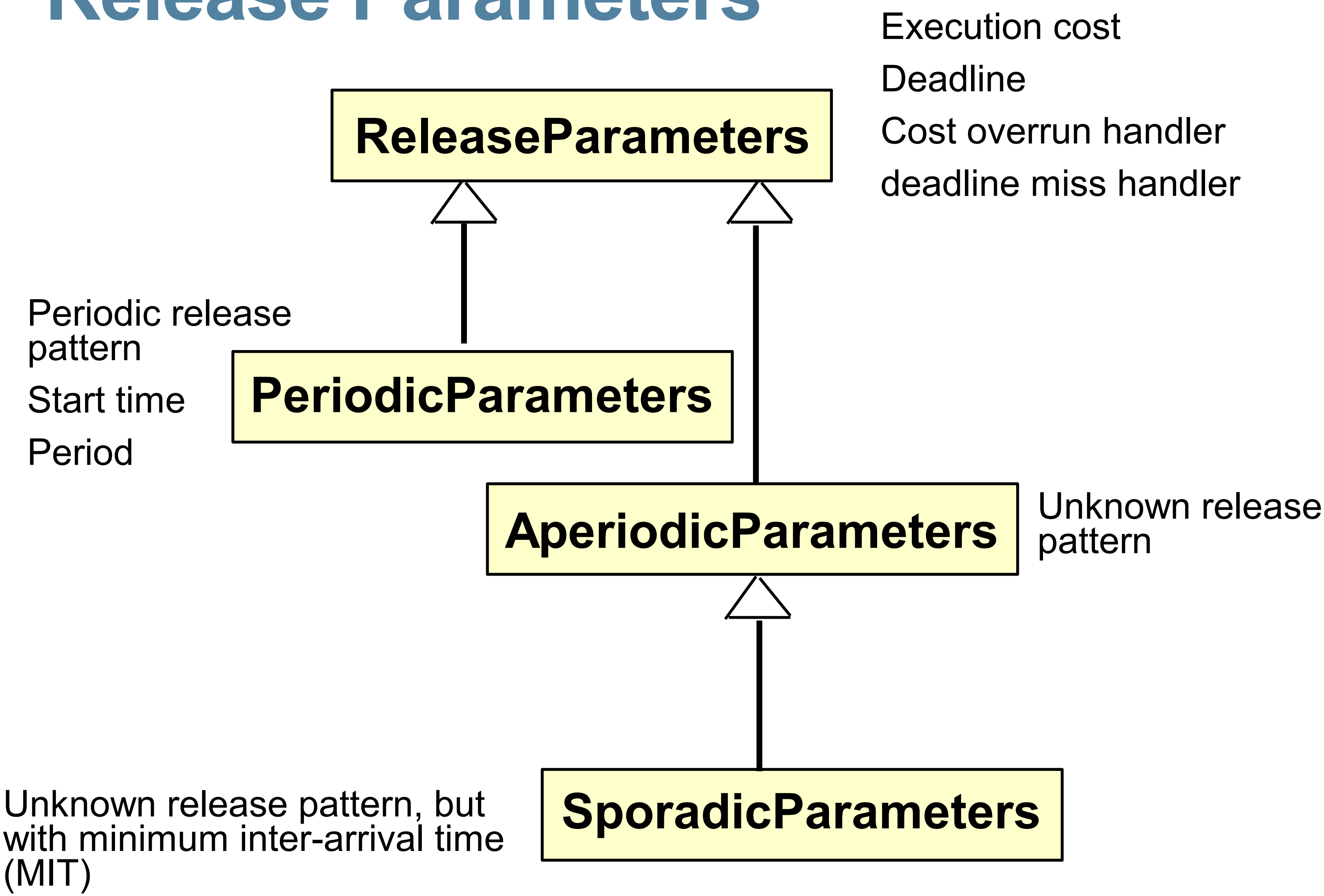
- Schedulable objects have execution characteristics
  - Scheduling behaviour, release pattern, memory constraints
- Characteristics represented by “parameter” objects:
  - `SchedulingParameters`, `ReleaseParameters`
- Parameter objects “tag” the SO and contain data
  - Priority, deadline, deadline-miss handler, cost
- An SO can link to one parameter object of a given kind
  - Initially set at SO construction, can be modified later
- A parameter object can be associated with many SO’s
  - Any change to the parameter object affects all the SO’s

Scheduling Parameters



Not used by
PriorityScheduler

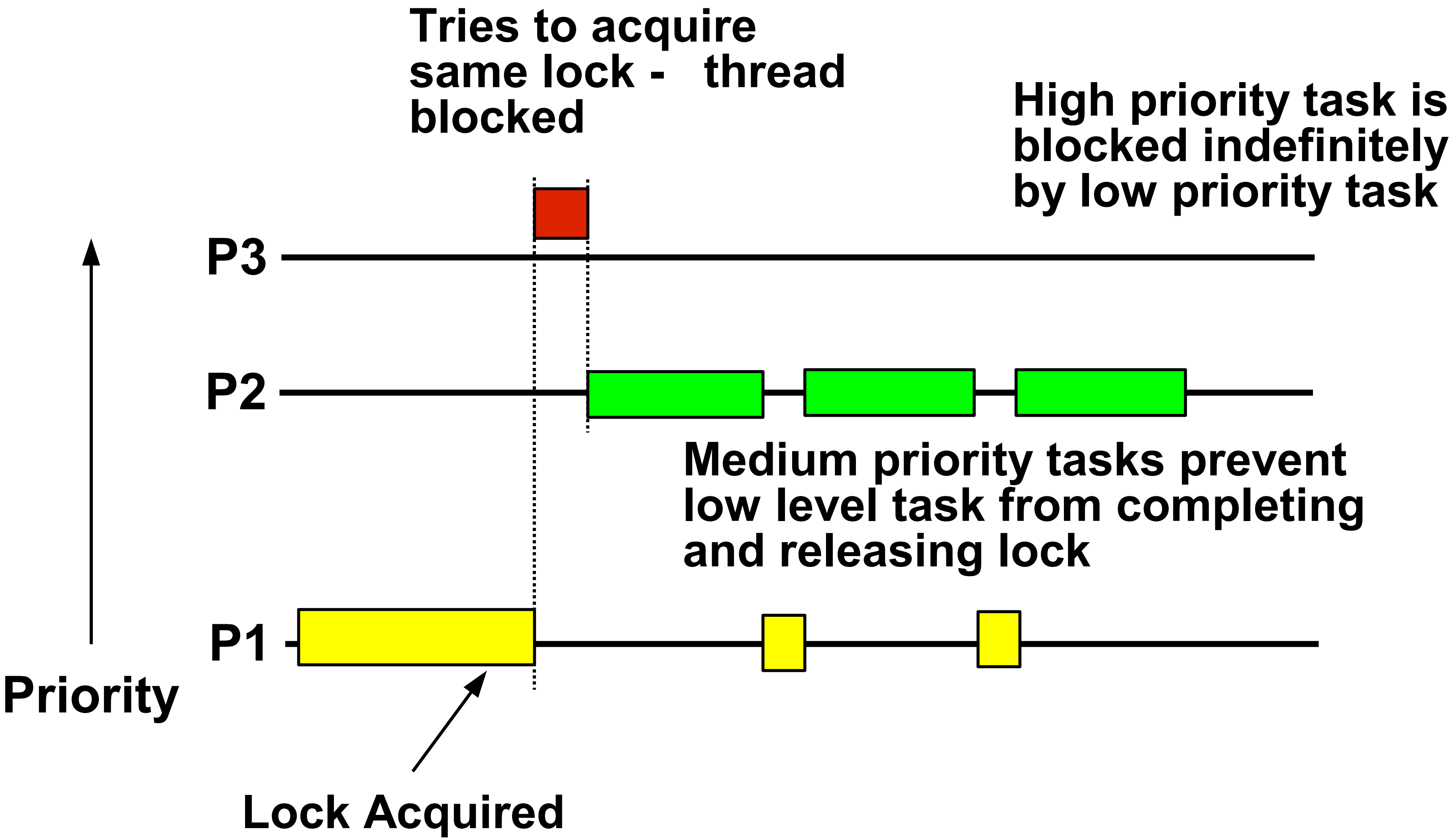
Release Parameters



Example: Periodic Real-time Thread

```
RelativeTime period = new RelativeTime(5,0); // 5ms period

AbsoluteTime start =
  Clock.getRealtimeClock().getTime().add(50,0); // now+50ms

PeriodicParameters pp = new PeriodicParameters(start, period);

int prio = PriorityScheduler.instance().getNormPriority();

PriorityParameters priop = new PriorityParameters(prio);

RealtimeThread rtt = new RealtimeThread(priop, pp) {
  public void run() {
    while (workToDo) {
      // do work
      if (!RealtimeThread.waitForNextPeriod())
        throw new Error("Deadline missed");
    }
  }
  ...
};

rtt.start();
```

Synchronization: Priority Inversion



Priority Inversion
A Real World Example: Mars Pathfinder

- Spacecraft had two high priority periodic tasks
  - Data distribution, bus scheduling
  - Data distribution must complete before bus scheduling starts
- Low priority data gathering task acquired internal lock via call to IPC mechanism
- Distribution task got blocked trying to acquire same lock
- Other medium priority tasks prevented data gathering task from completing and releasing lock
- Bus scheduler task detects distribution task has not completed in required time and takes action
  - Reboots spacecraft!

Priority Inversion Avoidance in RTSJ

- Priority Inheritance Protocol (Required)
  - Thread holding lock gets priority boosted to that of blocking thread until lock is released
  - No application code changes required
- Priority Ceiling Emulation Protocol (Optional)
  - Each object lock is assigned a “ceiling” priority
    - Highest active priority of any thread that will acquire it
  - Thread sets its priority to the ceiling value when it acquires the lock, and drops it when lock released
- Applies to Java object monitors only
  - `synchronized` methods / blocks

Wait-Free Data Transfer Queues

- Allows non-blocking data exchange between no-heap SO's and heap-using SO's
  - If NHRTT synchronizes with RTT then GC can preempt it
- `WaitFreeReadQueue`
  - Single reader can perform non-blocking read
  - Multiple writers can perform synchronized/blocking writes
- `WaitFreeWriteQueue`
  - Single writer can perform non-blocking write
  - Multiple readers can perform synchronized/blocking reads
- `WaitFreeDequeue`
  - Combined WFRQ and WFWQ

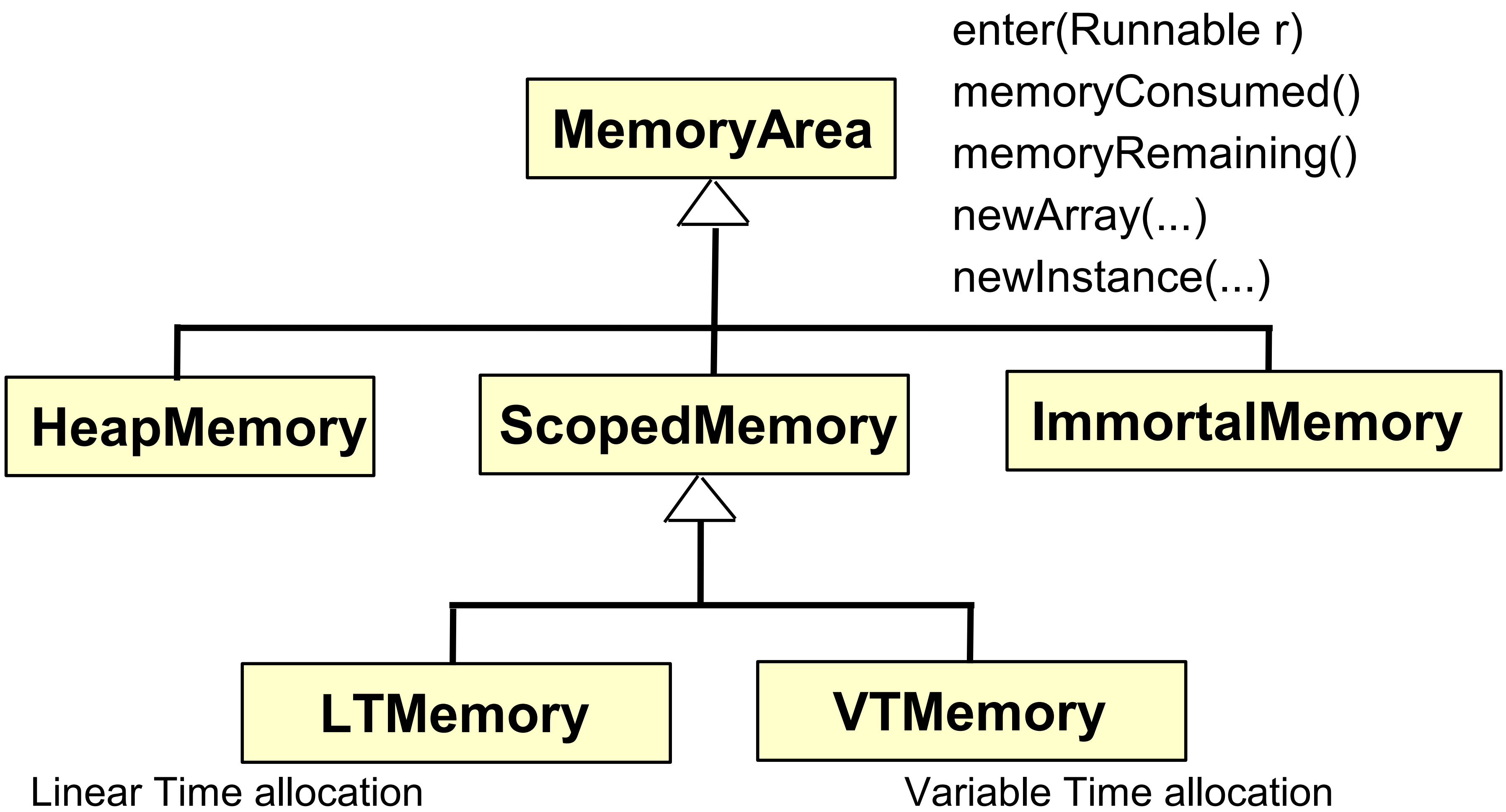
Memory Management

- C/C++ memory management is completely under program control
  - **`malloc()`**, **`free()`**
  - Obvious disadvantages for memory leaks, invalid pointers
- Java uses automatic memory management
  - Eliminates problems of **`free()`**
  - Introduces non-deterministic behavior to application as normal GC cannot be controlled directly

RTSJ Memory Management

- Goal: “to not interfere with the ability of real-time code to exhibit deterministic behavior”
- Issues with normal heap-management in Java
  - Allocation times can vary dramatically
  - GC is unpredictable in its frequency and execution
- Real-time GC was not an option in 2000!
- RTSJ introduces the notion of allocation context
  - The memory area used when code executes **`new`**
- Each area has different access and GC properties
- Access to physical memory

RTSJ Memory Areas



Immortal Memory

- Shared amongst all threads
- Objects allocated here are never garbage collected
  - Live until end of application
  - Objects referred to can also not be garbage collected!
- Three mechanisms for allocating immortal memory
  - Implicit
    - Static initialization, interned strings, string literals, Class objects
  - Direct request
    - **`newInstance()`**, **`newArray()`**
  - Execute code with immortal as current allocation context
    - **`enter()`**, **`executeInArea()`**

Scoped Memory

- Lifetime of an object is determined by the scope
  - Objects exist as long as scope is “in use”
  - When scope no longer “in use” it can be cleared and so is “empty” the next time it becomes “in use”
- Scope usage is governed by complex rules
  - Single parent rule: all entry to a scope must be from the same parent scope (or else heap or immortal)
  - Assignment rules: an object in one memory area can not hold references to objects in a shorter-lived area
    - Scopes can't hold references to objects in a child scope
    - Heap/Immortal can never hold references to objects in scope
  - Run-time checks enforce the rules

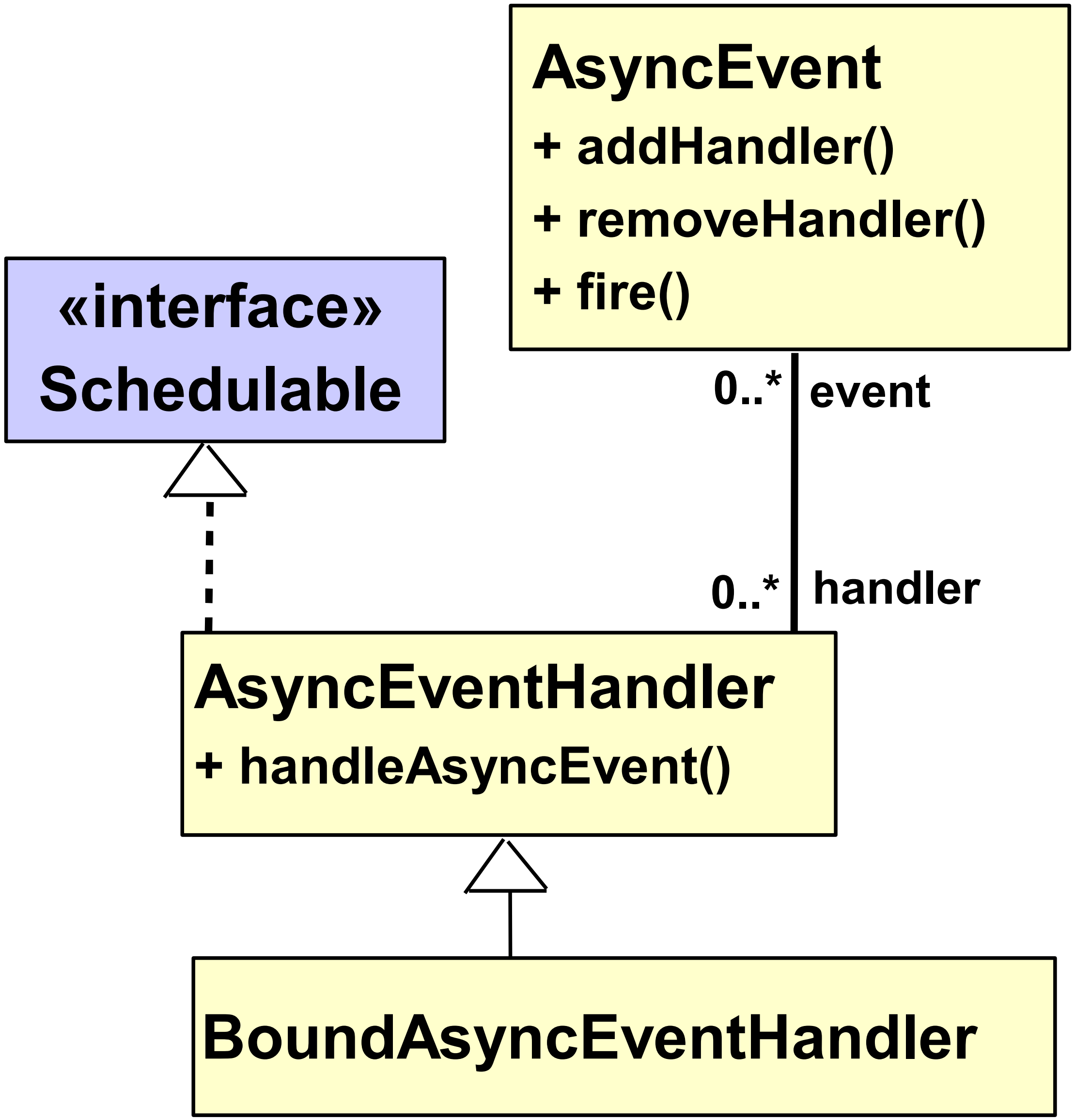
Physical Memory

- Physical memory can be mapped to particular HW
  - `PhysicalMemoryManager`
  - `ImmortalPhysicalMemory`
  - Scoped physical memory
    - `VTPhysicalMemory`, `LTPhysicalMemory`
- Raw memory access allows read/write of any address
  - Primitive types only
  - `RawMemoryAccess`
  - `RawMemoryFloatAccess`

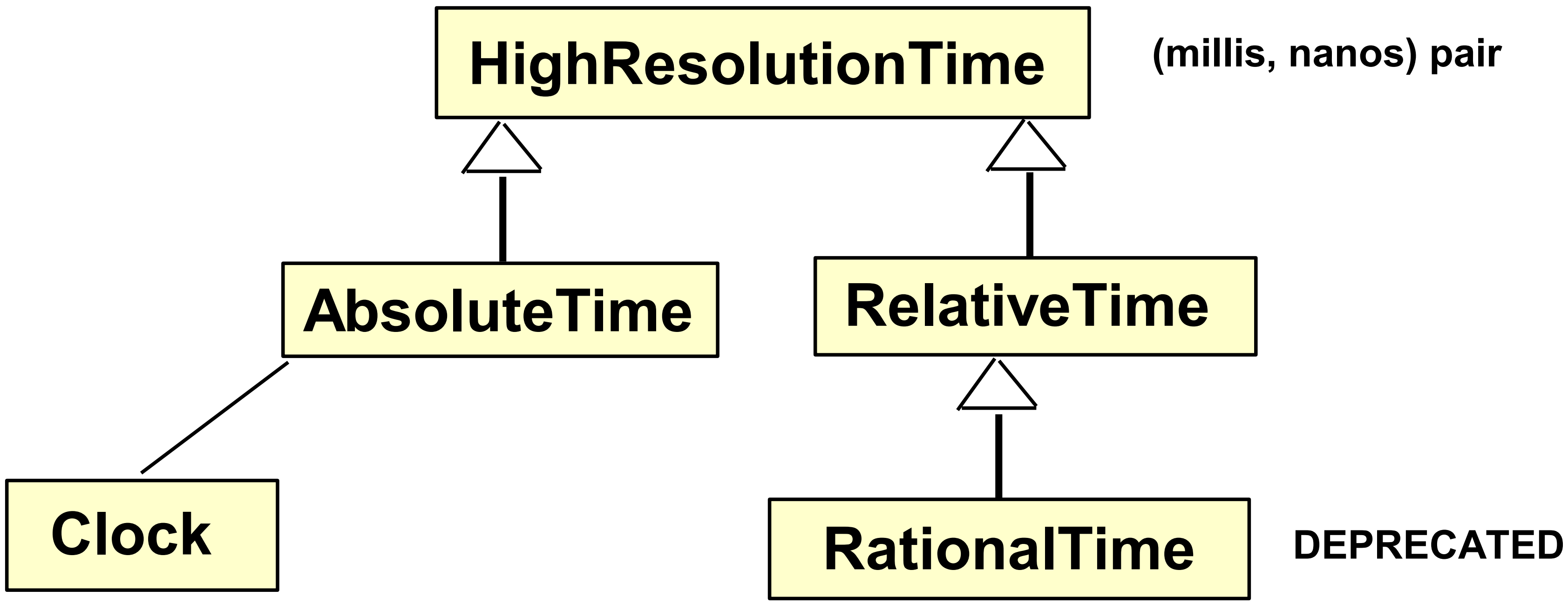
Java RTS Memory Management: Real-time Garbage Collection

- RTGC allows latency guarantees to be extended to RealtimeThreads (not just NHRTTs)
  - Under certain conditions
- Critical RTT can preempt the GC
  - And allocate from a reserved buffer
  - And avoid GC induced latencies
- Cost of RTGC is paid for by non-critical threads
  - No silver bullet!
- Very sophisticated, very configurable, very flexible

Event Based Programming



Times and Clocks

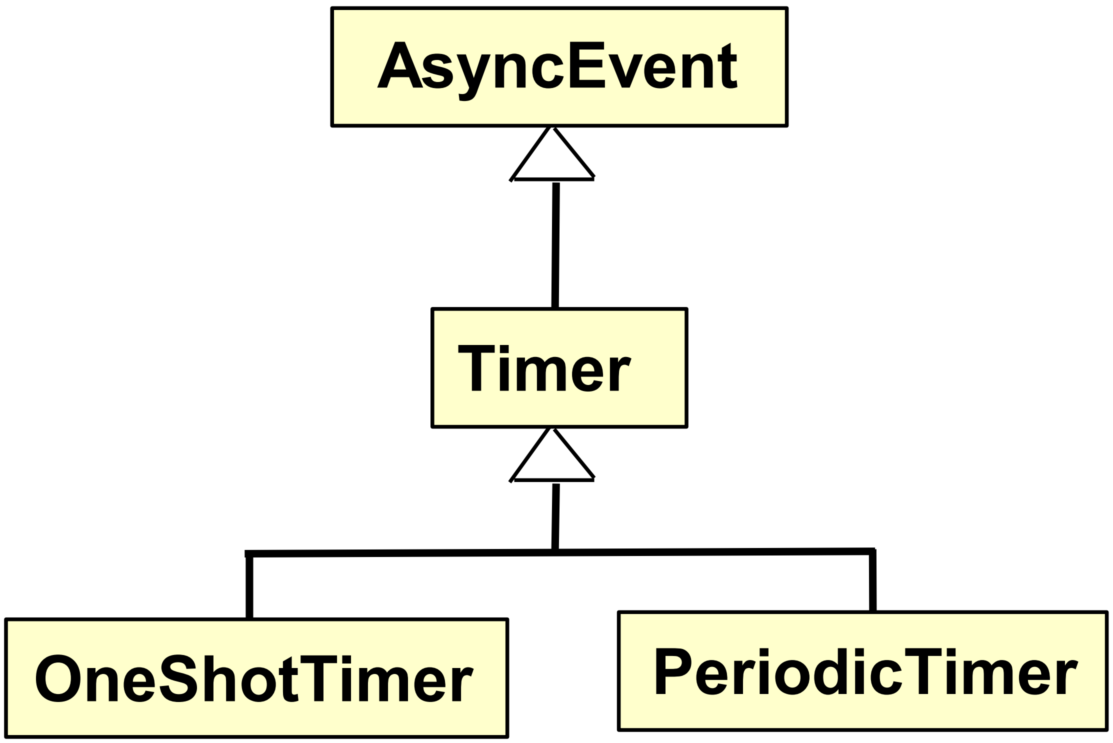


Clock.getRealtimeClock()

- **High resolution**
- **Monotonic**
- **Time zero == UNIX epoch**

Timers

Time based release of async event handlers

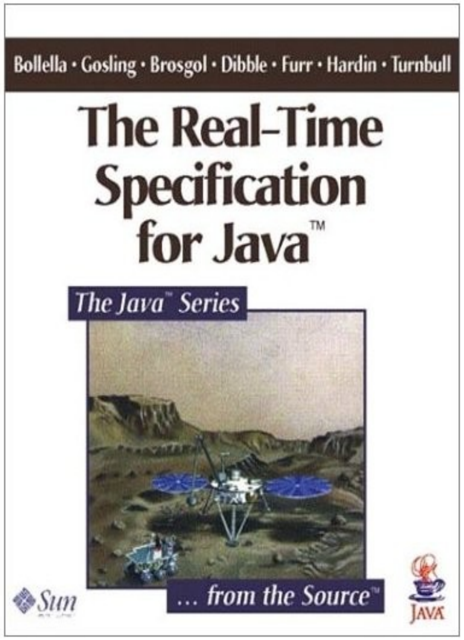


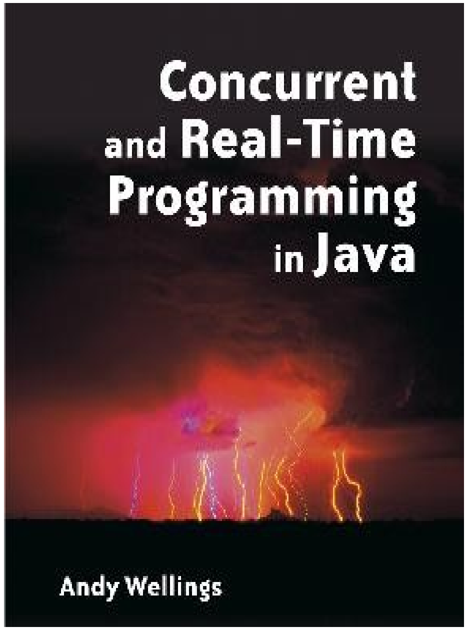
Resources

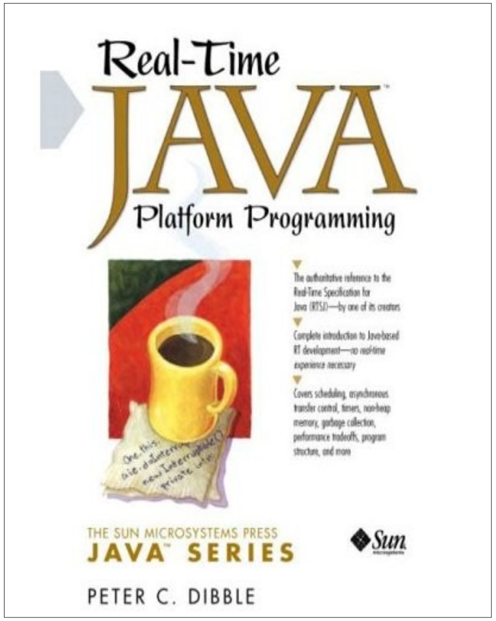
http://java.sun.com/javase/technologies/realtime/index.jsp

http://www.jcp.org (JSR-001, JSR-282)

http://www.rtsj.org







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