SYSC 5701

Operating System Methods for Real-Time Applications

Real-Time Java

Winter 2014

Real-Time Java
http://www.rtj.org/

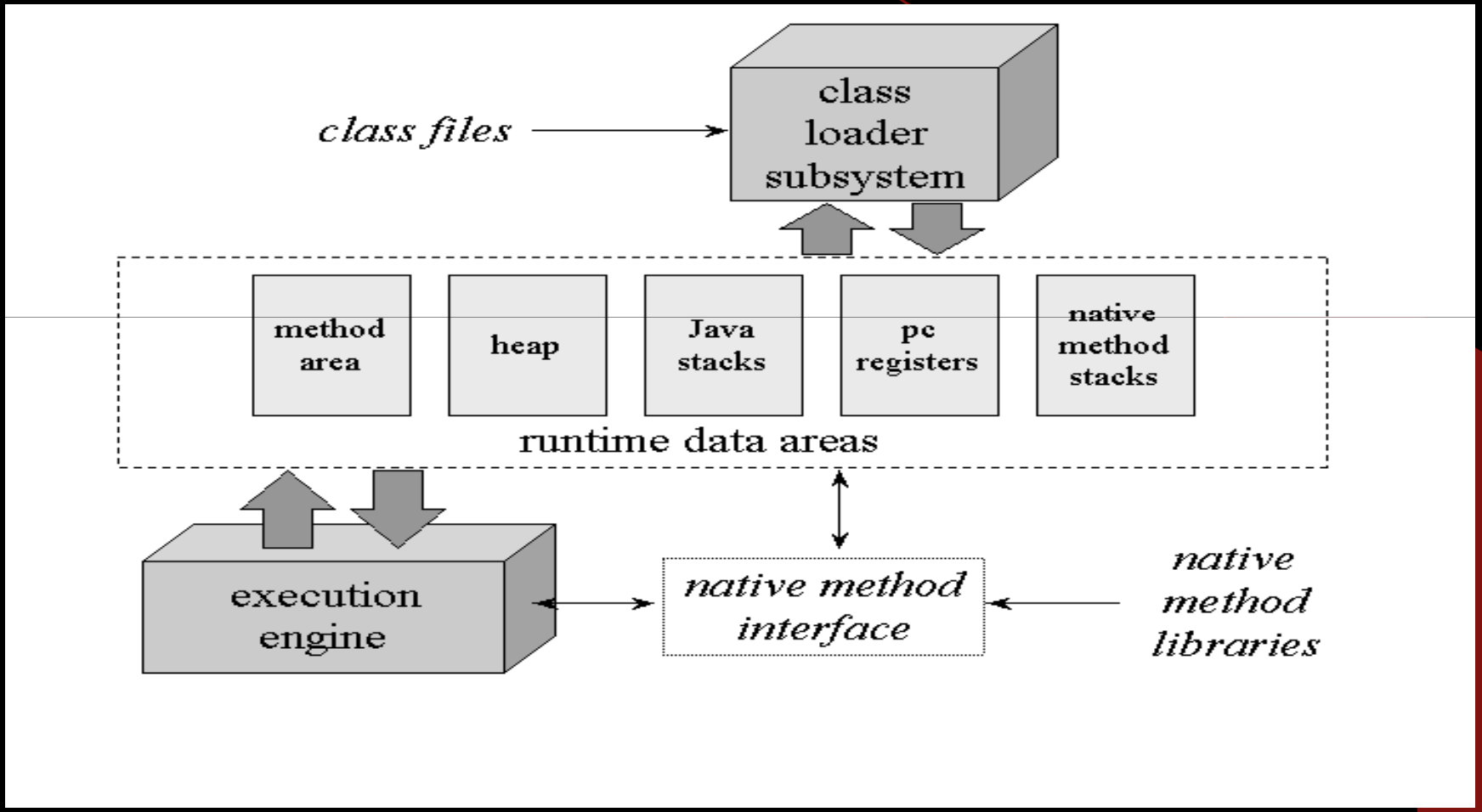
terminology in slides

- relevant parts of “traditional” Java = Java
  - threads, monitors, memory access, garbage collection
- real-time Java solution = RTJava
  - “battle” between 2 proposals
- RTJava Specification = RTJS
  - the “winner” → 2000
- industrial status? – Mars rover?

Warning!

- The following slides have Java details that were relevant at the time of the conception of RTJava (circa 2000)
- Java's concurrency support made some improvements in Java 5 (circa 2004)
  - e.g. semaphores

Java Virtual Machine



Java

- **concurrency** → threads
- **synchronization** → monitors
- Java language spec → vague in many spots
  - under-specified → allows many possible implementations
- OK for soft real-time
  - not appropriate for hard real-time

Java Threads

- priority driven scheduler
  - unknown scheduling algorithm
  - may be time sliced
- unknown number of priorities

under-specified!

- allows mapping to a wide variety of native threading models (Windows, Unix, etc.)
- in general, not safe to explicitly transfer control from one thread to another
  - killing threads, asynchronous control transfer

Thread LifeCycle

- **`new Thread`** → an **empty** **`Thread`** object
- no system resources allocated to it
- in this state, can only **start** the thread,
- **`start`**:
  - creates system resources needed to run the thread
  - schedules the thread to run
  - calls the thread's **`run`** method
- return from **`start`** → thread is Runnable

thread state

to Not Runnable

- A thread becomes **Not Runnable** when:
  - its `sleep` method is invoked
  - thread calls `wait` → wait for a specific condition to be satisifed
  - thread is blocked on I/O

monitors!

back to Runnable

- if thread is sleeping and the specified number of milliseconds elapse
- if thread is waiting for a condition and another object notifies the thread of a change in condition
  - call to **`notify`** or **`notifyAll`**

monitors!

- if thread is blocked on I/O and the I/O completes
- **stop** a thread: **`run`** method terminates

Thread Example (Sun Doc's)

```
public class SimpleThread extends Thread {
  public SimpleThread(String str) {
  super(str);
  }
  public void run( ) {
  /* … thread's execution code goes here … */
  }
}
```

constructor

super class constructor

this example:
subclasses Thread and overrides run

Creating Instances of Threads

```
public class ThreadsDemo {
  public static void main (String[] args) {
     new SimpleThread(“AThread").start();
     new SimpleThread(“BThread").start();
  }
}
```

Inheritance Problem

- how can a class **X** be extended with thread behaviour if it does not already have threads?
- Java does not support multiple class inheritance
  - e.g. inherit from X and Thread
- add runnable interface to class **X**

Runnable Example ☹

```
public class ThreadedX extends X implements Runnable {
   private Thread MyXThread = null;
   public void start( ) { if (MyXThread == null) {
   MyXThread = new Thread(this, “MyXThread");
   MyXThread.start(); }
}
public void run( ) {
   Thread myThread = Thread.currentThread( );
   while (MyXThread == myThread) {
       /* … do stuff approx every second … */
   try { Thread.sleep(1000); }
   (InterruptedException e)
       { /*stop sleep, get back to work */ }  }
}
public void stop( ) {
   // stop MyXThread
   MyXThread = null;
}
```

this example: implements runnable

what happens to “Thread” ?

“asynchronous stop” ? ☹ ?

Thread Synchronization

- **`synchronized`** → **monitor**

well … sort of

- only one thread at a time can be executing a synchronized block in an object
  - managed by runtime environment
- not really a monitor ?
  - managing other threads in monitor?

Synchronized Methods

```
public class SharedQ {
   public synchronized int get() { ... }
   public synchronized void put(int value) { ... }
}
```

- SharedQ object locked automatically during **`get`** & **`put`** calls
- prevents interference
- what about **`put`** when full (**`get`** when empty)?

Wait / Notify Conditions

- **`wait`** – allows thread to block self
- **`notify`** – signals one thread that is waiting on object
  - But choice of thread is arbitrary !?!
- **`notifyAll`** – signals all threads that are waiting on object

SharedQ Revisited

```
public class SharedQ {
   … synchronized … as before
   boolean SpaceAvailable = true;
   boolean DataAvailable = false;

   public synchronized int get() {
       while ( DataAvailable == false ) {
       try {
         // wait for data
         wait();
       } catch (InterruptedException e) { ... }
       }
   here … get value from queue and adjust state variables
   notifyAll(); // let others in!
   return value; }
}
```

release **all**? busy wait? ugly!?

why not just "**notify**" ?

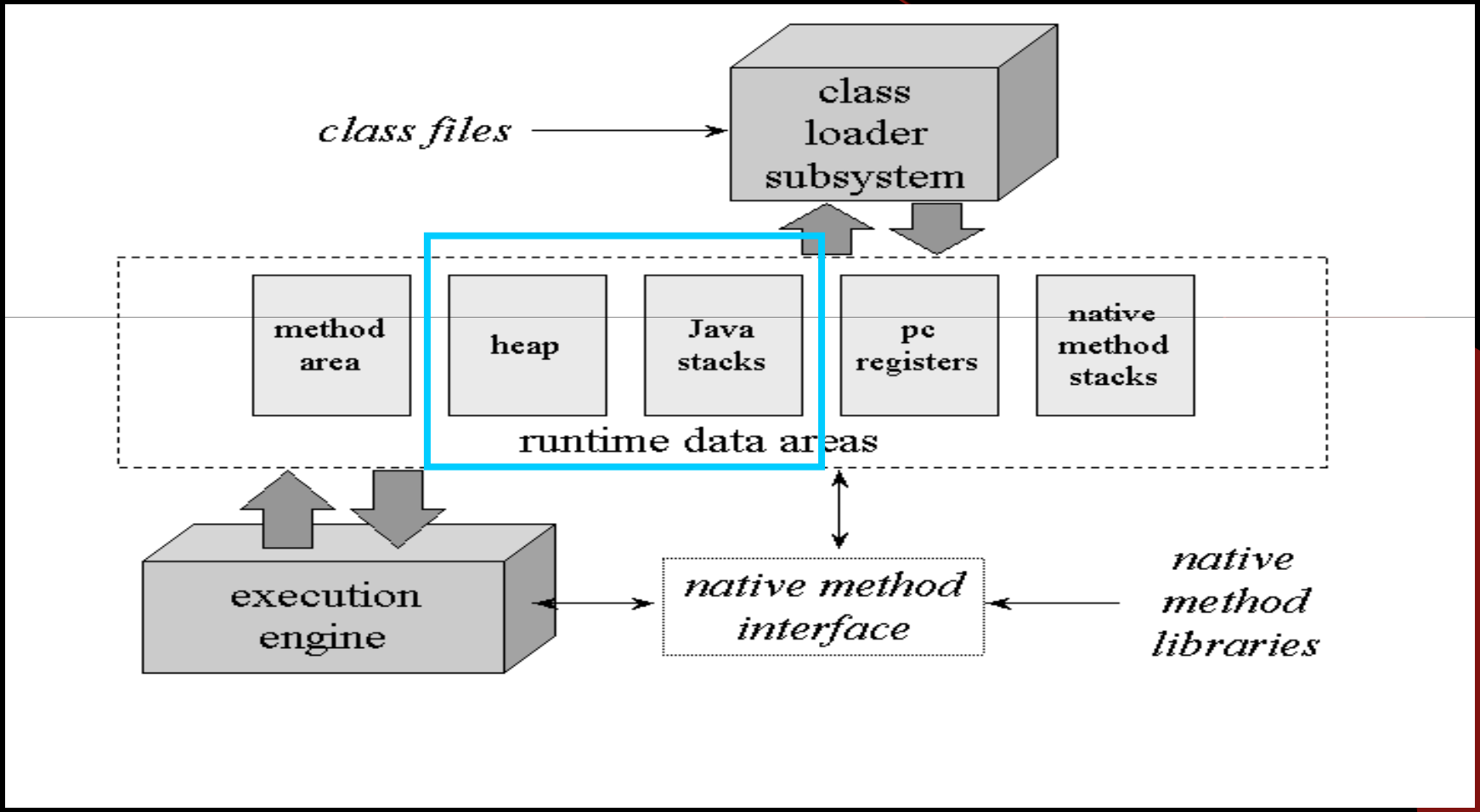
not really monitor!?

revisit on slide 44

InterruptedException

- thrown when a thread is waiting, sleeping, or "otherwise paused for a long time" (?) and another thread interrupts it using the **`interrupt`** method in class **`Thread`**
- maybe this could be used to implement thread management in "monitors" ?!
  - backdoor? using "exception" mechanism for planned "normal" operation ☹

Memory Issues



Lifetime of Variables

- Java allows variables to be:
  - Globally available for the life of the program
  - Local to functions: exist for the life of a function call
  - Local to objects: exist for the life of an object

Java Memory Access

- no “physical memory” access by address
  - no pointers !!!
- abstract references only
- **objects** created in heap
  - create objects using **new**
  - cannot explicitly delete!
    - automatic garbage collection (GC)
    - reclaim object when no longer in use

Java Stack

- each thread has its own “Java stack”
- Java stack **frames** for local data needs:
  - local variables, arguments, return values, intermediate calculations
  - unavailable to Java programmers
    - managed by virtual machine

Garbage Collection

- run by virtual machine when free heap space goes below some “low” level
- all details are managed by virtual machine
- garbage collection thread is often non-preemptible by other threads
- a significant problem for real-time deadlines!

overhead vs. program robustness

Garbage Collection Implementation

- find at least one reference to object
- if no references, object "dead" → collect object
- possible sources of references:
  - from variable in stack frame
  - from a static variable
  - from a field in a live object
  - from a virtual machine internal variable
- search for references? → no time guarantees!

Real-Time Java Battle

the armies:

1. backward compatible with Java
   - minimize expansion of language
     - extend existing Java classes
2. new language
   - target real-time systems
     - don't require backward compatibility

taste's great!

less filling!

The Winner: backward compatible

- RTJ Experts Group
- started work ~ 1998
- RTJ Specification v1.0, 2000
- November 2001, reference implementation
  - TimeSys

Guiding Approach

- general applicability
- backward compatibility with Java
- **Write Once** Carefully, **Run Anywhere** Conditionally (WOCRAC ?)
- reflect current practice
- predictable execution
- no syntactic extensions
- allow implementation variation/customization
  - documented!

WORA ?

Key Advances

- thread scheduling and dispatching
- synchronization
- memory management
- asynchronous actions
- time, clocks & timers

Priority

- stricter notion of priority
  - (original) Java threads – “low” priority
  - garbage collector – dividing line
  - higher than garbage collector – real-time!
- priority inversion control!
  - default = priority inheritance
- 28 unique priorities

Realtime Threads

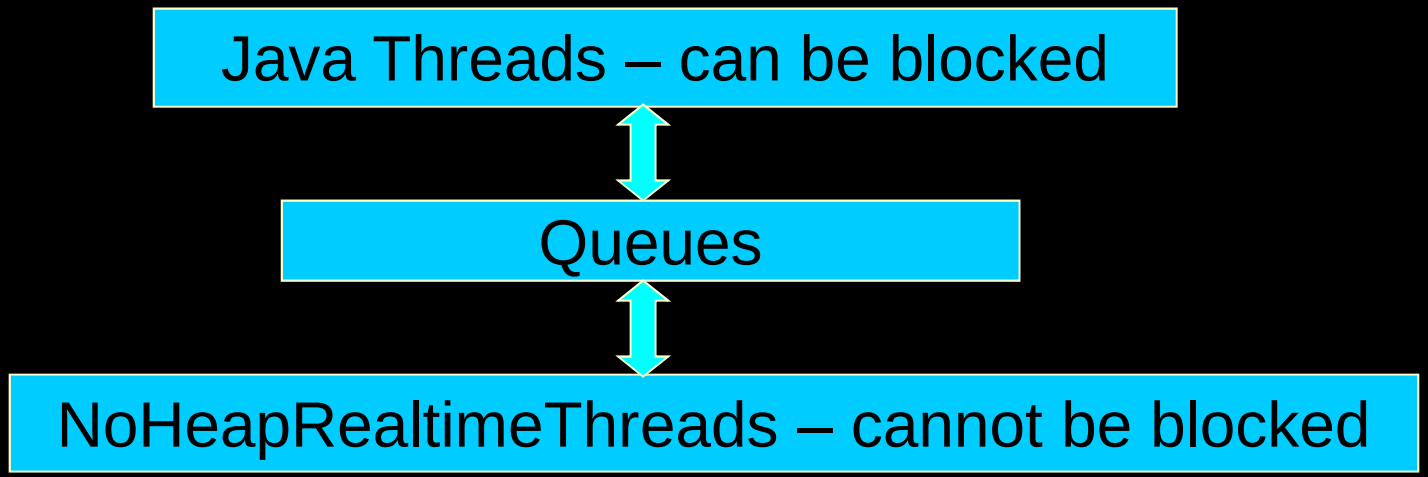
- **extend** Thread → RealtimeThread
  - priority overlaps with Java threads, garabage collector & “higher”
    - can be run higher than GC!
  - can access new memory types (later)
  - can also allocate in heap ☹
    - potential priority inversion with GC!

No Heap Realtime Threads

- **extend** RealtimeThread → NoHeapRealtimeThread
  - priority always higher than GC
  - cannot access heap or references to heap
    - never priority inversion with GC! ☺

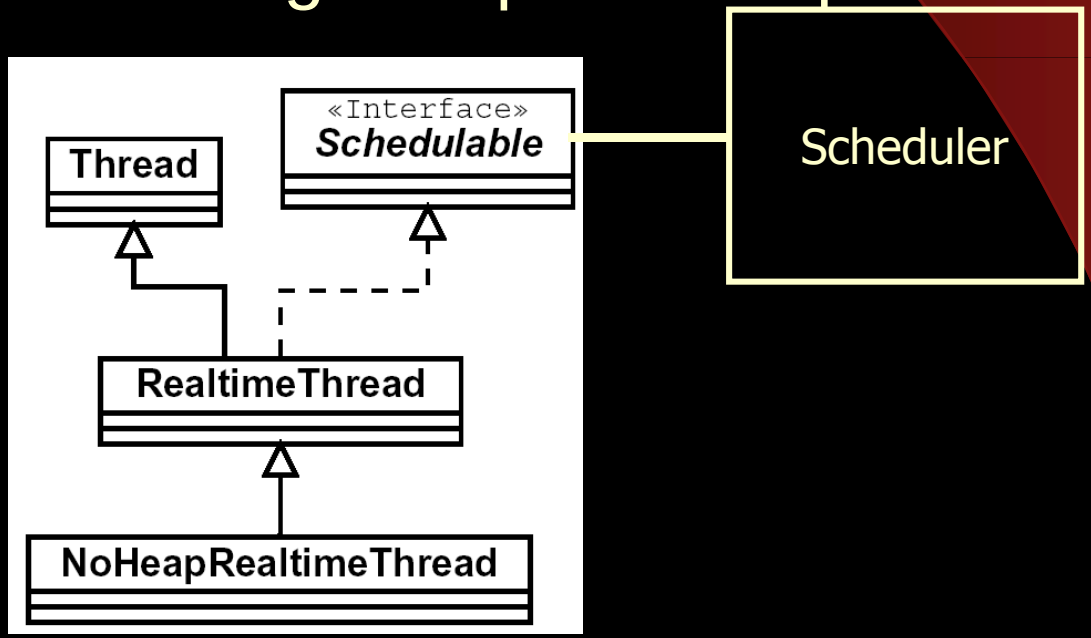
Can NoHeapRealtime Threads Interact with Java Thread?

- cannot allow Java thread to block NoHeapRealtimeThread !
  - unbounded priority inversion!
- wait-free queuing to pass messages



Scheduling

- introduce:
  - Schedulable entities: RealTimeThreads
  - Scheduler – manages Schedulable objects
  - API is scheduling discipline independent



Scheduler

- methods for:
  - feasibility analysis
  - admission control
  - dispatching
  - asynchronous event handling
- extend Scheduler → PriorityScheduler
  - customize – override methods above, e.g.:
    - RMAScheduler extends Scheduler
    - EDFScheduler extends Scheduler

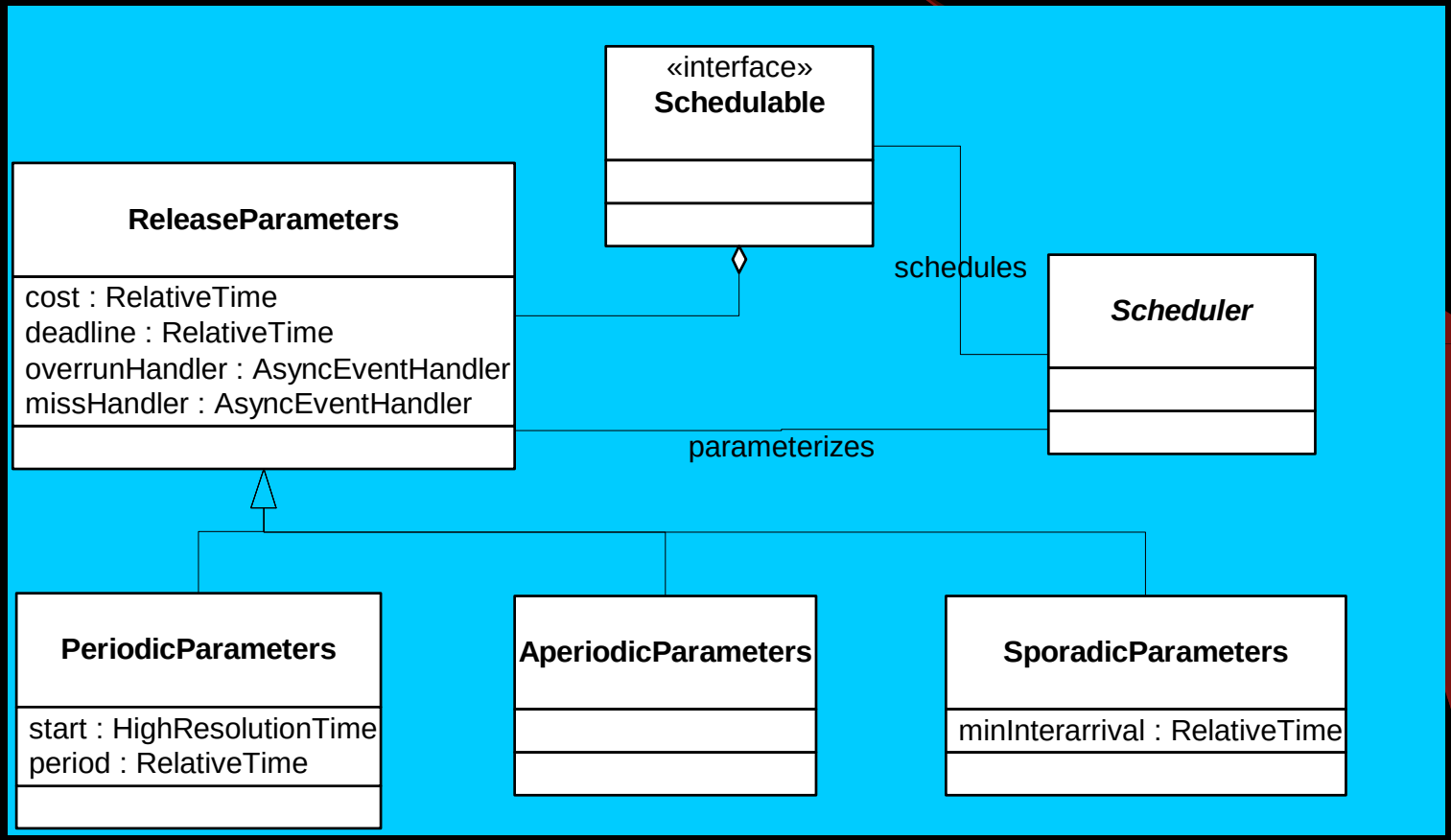
Schedulable Interface

- objects that **`implement Schedulable`** are scheduled by Scheduler
- RealTimeThreads and AsyncEventHandlers implement Schedulable
- Schedulable object includes reference to Scheduler to be used

Scheduling Parameters

- priority & importance
- periodic, aperiodic, sporadic
- memory demands

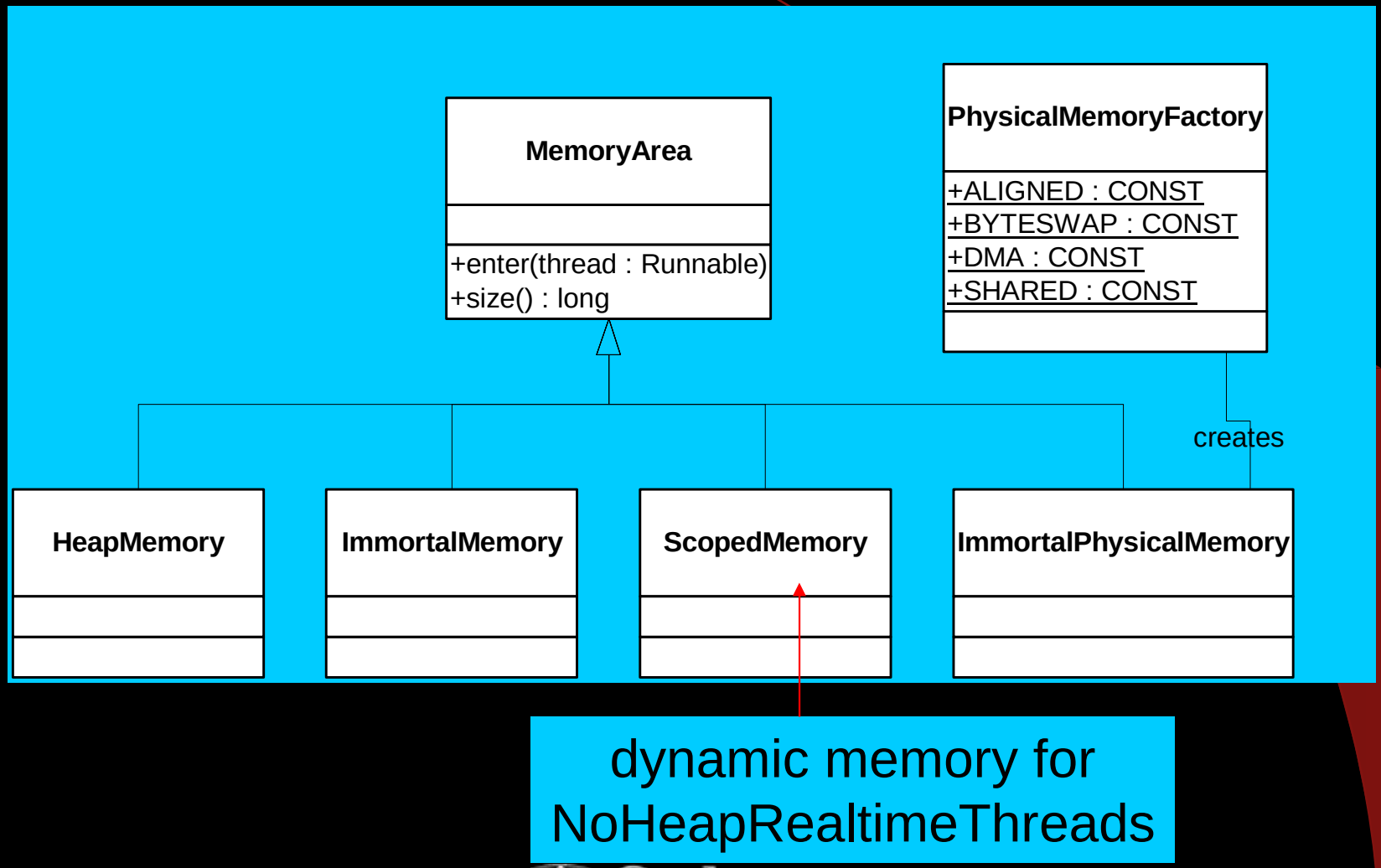
Scheduling


«interface»
Schedulable
ReleaseParameters
cost : RelativeTime
deadline : RelativeTime
overrunHandler : AsyncEventHandler
missHandler : AsyncEventHandler
schedules
Scheduler
parameterizes
PeriodicParameters
start : HighResolutionTime
period : RelativeTime
AperiodicParameters
SporadicParameters
minInterarrival : RelativeTime

Memory Management

- object lifetime control:
  - manual → under explicit program control
  - automatic → visibility (scope)
- memory areas
  - not managed by garbage collector !
  - immortal → persistent for life of application
  - scoped → life of run( )

Memory Areas



Immortal Memory Example

```
import javax.realtime.*;
/** Example of the use of "Immortal" memory in a periodic
   processing context. No heap allocation, avoids garbage
   collection overhead! */


/** Class that performs processing in Immortal memory */
  class Runner implements Runnable {
    public void run( ) {
          // Processing code goes here
     }
```

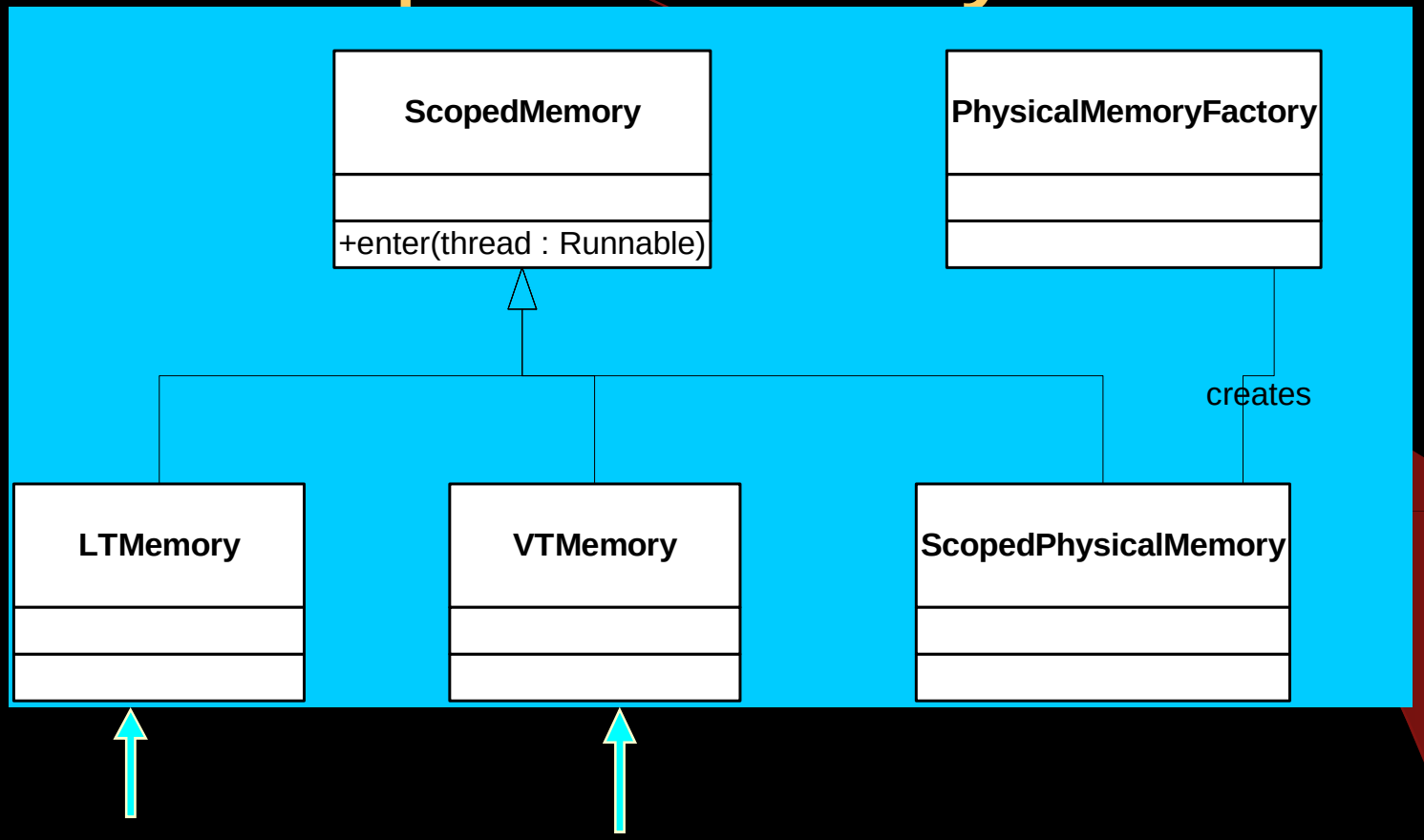
```
public static void main(String[] Args) {
  NoHeapRealtimeThread t = null;

 // Set up periodic processing
 PeriodicParameters timeParams = new PeriodicParameters();
 // 1 msec computation
 timeParams.cost = new RelativeTime(1, 0);
 // 10 msec period
 timeParams.period = new RelativeTime(10, 0);

 // Set up immortal memory; size given in RealtimeSystem
  MemoryParameters memParams = new
          MemoryParameters(ImmortalMemory.instance());
// Processing is encapsulated in a Runnable object
  Runner r = new Runner();
```

```
/* Create a NoHeapRealtimeThread with Periodic
   scheduling parameters and ImmortalMemory memory
    parameters. */
    try {
      t  =  new  NoHeapRealtimeThread( timeParams,
                                       memParams, r );
      }  catch (AdmissionControlException e) { }
      // Start processing
      t.start( );
      }
 } // end of main
```

Scoped Memory Area



Linear
allocation time

Variable
allocation time

Asynchronous Event Handling

- **`AsyncEvent`** objects
  - instance represents an event that can happen
- **`AsyncEventHandler`** implements Schedulable
  - logic to process AsyncEvent
  - execute with semantics of threads

as if it was a thread

- handlers bound to events:

```
AsyncEvent.addHandler( AsyncEventHandler a);
```

- may be bound to external events, or invoked internally:

```
AsyncEvent.fire( )
```

Asynchronous Transfer of Control

- "throws" clause including **`AsynchronouslyInterruptedException`** (*AIE*)
  - exception raised by the JVM when the **`interrupt()`** method for thread is called
- mechanism extends the current semantics of the `interrupt()` method from only certain blocking calls to straight-line code
- can be used to fudge “killing” a thread ☹

recall slide 18

AsyncEvents & Interrupts Example

```
import javax.realtime.*;
/** Example of using Asynchronous Event/Event Handling facility
   to provide an interface to hardware events, i.e. interrupts. A
   hardware interrupt conceptually fires an AsyncEvent, which
   causes the associated handler to run. */
public class HardwareEventExample extends AsyncEvent {
  private int interruptNum;

  /** Construct a new Hardware Event for a given interrupt. */
  public HardwareEventExample(int num) { interruptNum = num; }

 /** Bind a handler to the interrupt. */
  public void setHandler(AsyncEventHandler h) {
  super.setHandler(h);
  Hardware.bind(interruptNum, h);
 }
}
```

define event

Interrupt Example (con't)

```
class HardwareEventHandler extends AsyncEventHandler {
    private int interruptCount = 0;
    /** Interrupt handler method. */
    public void handleAsyncEvent() {
        interruptCount++;
        // Driver code
        }
    }
```

define handler

bind this handler to interrupt using previous **setHandler** method

Industry Status?

- TimeSys has commercial RTJS compliant compiler product – built over RTLinux
  - Mars Rover
  - Team Jefferson in DAPRA Grand Challenge 2007
- still missing many of the higher-level real-time language features Halang & Stoyenko would like to see!
- long-term ?
- Distributed RTJ movement already in progress!