Assuring Success with Scalable Real-Time Java Technologies

Kelvin Nilsen, Ph.D., Chief Technology Officer Java

Why this topic?

- A small number of companies have reported great success with the adoption of embedded/real-time Java
  - Two-fold productivity improvement during development of new functionality
  - Five- to ten-fold productivity improvement during software maintenance and reuse activities
  - Improved functionality and fewer bugs
- But some highly visible attempts to adopt embedded/real-time Java have quietly fallen off the radar screen
- And overall adoption of Java in the embedded/real-time marketplace has been relatively slow
- Understanding why some projects fail and others succeed, helps improve the likelihood of success

Sample Successes with a Soft Real-Time Java Profile

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Software modernization project implements improved user interfaces, new communication protocols, and new functionality in Java

Most common factors leading to lack of success

- Unclear, unrealistic or misguided objectives, often leading to …
  - Inadequate or misdirected risk mitigation and project planning
- Common misunderstandings regarding technology strengths and weaknesses
  - Real-time Java runs faster than normal Java
  - The risk/benefits analysis widely accepted for traditional Java is equally applicable to “real-time Java”
  - Based on experience with traditional Java, expect real-time Java developers to be 2x as productive and software maintainers to be 5-10x more productive
  - The key risk mitigation topic: determine the lower limits of scheduling latency that can be achieved with real-time Java
  - You can “easily” teach a traditional Java developer to become a real-time Java developer by introducing the “real-time Java API”
  - All real-time Java offerings are “the same”
  - By adhering to the RTSJ “standard”, we assure that real-time code is portable, interoperable, composable, and maintainable

Proactive steps to improve likelihood of success

- Address potential issues with internal “politics”
- Establish clear, measurable, and realistic objectives
- Select technologies that suit the needs of established objectives
- Obtain appropriate training
- Apply best practices at every stage of the software life cycle
- Give proper attention to architecture and design considerations
- Plan for maintenance, evolution, and reuse of software
- Establish clear separation of concerns
- Design efficient and robust interfaces between legacy components and Java software

Internal Politics

- Issues:
  - In some organizations, powerful established players may fight to “protect turf”
  - Recognize that it is appropriate for managers and senior software engineers to exercise caution with “radical” new software approaches
  - Invest in promoting Java throughout the organization
- News from the trenches:
  - Around 2000, one very large telecommunications company project chose to use Java to implement a critical new product. They hid their choice to use Java from the company’s CTO until after the product was on the market!
  - More recently, a European customer chose to use Java for implementing key parts of RADAR system software. Other parts of the system were implemented in C. When bugs surfaced, there was finger pointing and even some suspicion of sabotage between teams working in different languages.

Establish clear, measurable, realistic objectives

- "Good" reasons to pursue Java might include:
  - Improve portability of software
  - Reduce costs of development
  - Accelerate availability of new capabilities
  - Exploit off-the-shelf and open-source software capabilities
  - Reduce errors in developed software
  - Increase generality and flexibility of software
  - Enable increased future reuse of software
  - Reduce long-term software maintenance costs
  - Improve security of software systems
- Note: the choice to use Java or real-time Java does not by itself guarantee any of the above
- You must use Java in an effective way in order to achieve objectives
- If you don't plan to satisfy objectives, and don't measure results against your plan in order to "correct your course" along the way, you're likely to fail

Select technologies that suit your objectives

- Java comes in many flavors
- Java built-in libraries, and 3rd party Java software components represent many different tradeoffs
- Selecting the appropriate Java development tools also represents an important leverage point
- Do you need real-time? Do you need embedded? Do you need a "Java" logo? What tradeoffs will you accept?
  - Speed vs. footprint
  - Predictability and reliability vs. optimal throughput
  - Ease of development vs. cost of deployment
  - Cost of development vs. cost of maintenance

Real-Time Horses for Courses

start

	HotSpot Java	C	PERC Ultra	PERC Pico
Min (ns)	173	280	519	314
Max (ns)	8,089	571	1,060	633
Mean (ns)	294	360	639	392
Std deviation (ns)	228.7896	25.52465	48.66415	29.8434
Total Virtual Memory (MB)	253	2.32	24	2.5

Java

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Obtain appropriate training

- Off the street Java developers need significant training in order to cor
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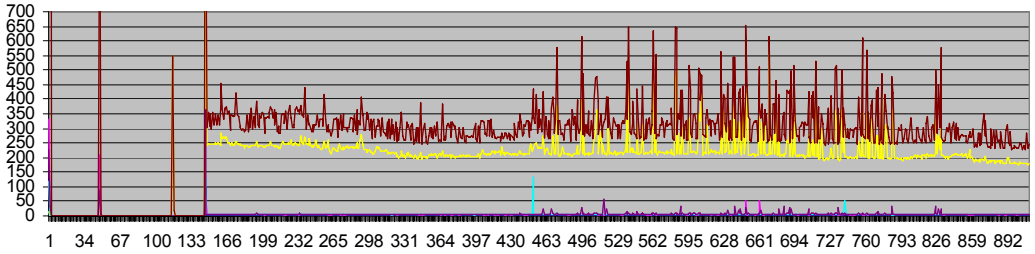
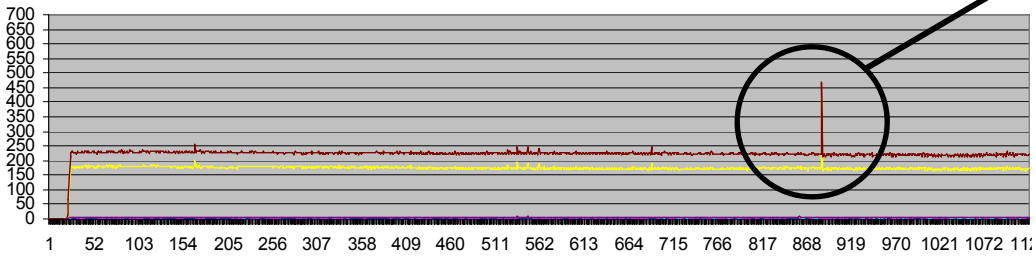
Results of moving traditional Java to real-time VM



Improvements after one week of training/consulting



Setting proper priorities is much more important with a real-time VM: “One week of on-site consulting saved six months of development time!”

Java Best Practices: Static Analysis Tools

- A static analyzer derives information about software behavior and structure by examining Java source or class files
  - Enforce compliance with particular programming style guidelines
  - Strong type checking of Java enables static checkers to perform more rigorous analysis than with C and C++
  - Popularity of Java has resulted in a variety of static analysis tools

    Each tool delivers different benefits – many organizations apply combinations of these distinct tools
    - SofCheck Inspector for Java
    - PMD (pmd.sourceforge.net)

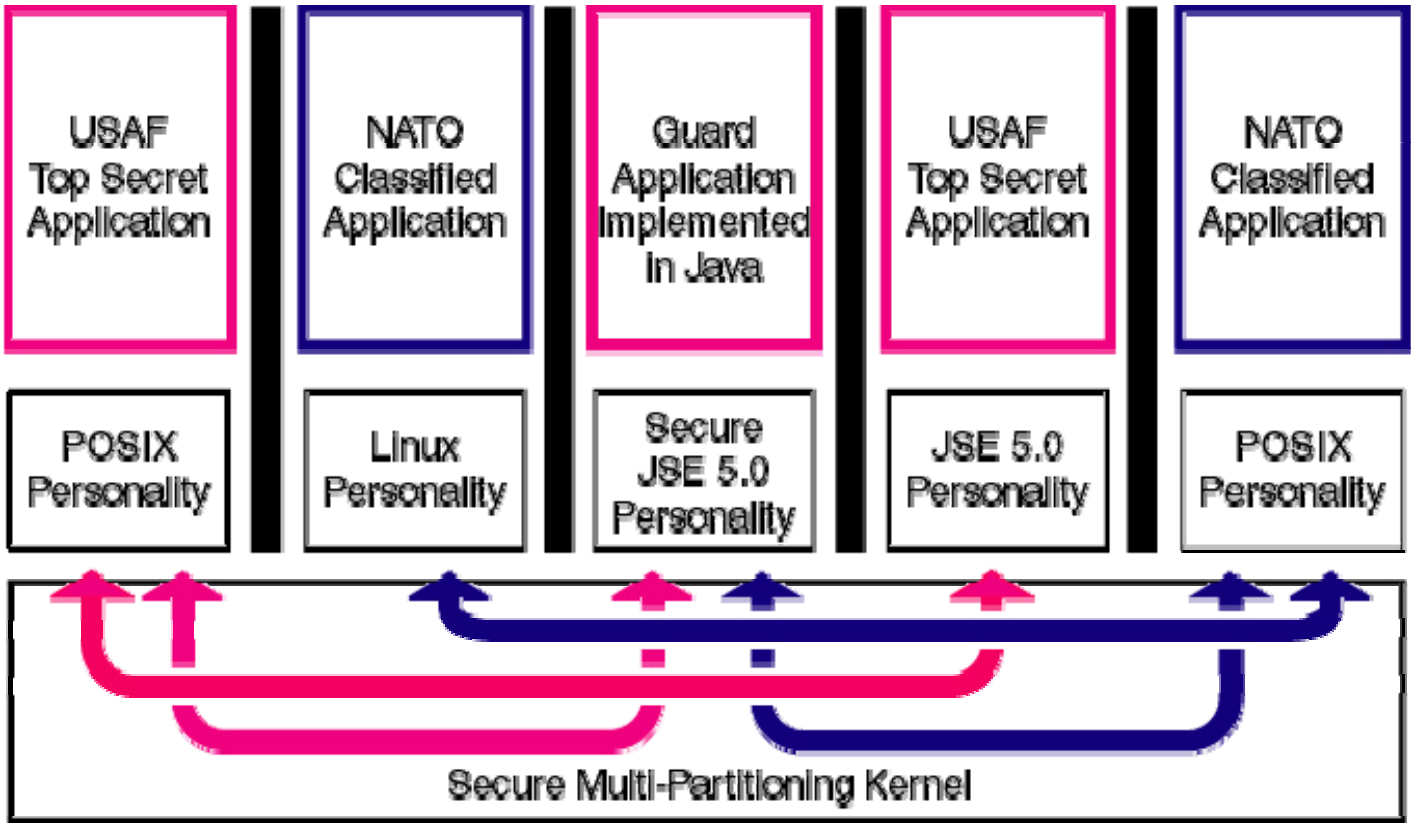
Java Best Practices: Partitioned Execution

- When mixing Java software components with different assurance (trust) levels, there are risks that less assured software will compromise higher assurance software
  - Run an infinite loop at a very high priority
  - Allocate huge amounts of memory in an infinite loop
  - Acquire and retain a mutual exclusion lock on a critical shared resource

- Separation of concerns is a common approach to managing system complexity
  - Run multiple JVM instances in virtually isolated partitions
  - Each instance of a real-time JVM can map its Java priorities to a different range of operating system priorities
  - Each instance of a real-time JVM has its own heap memory budget

Java Best Practices: Partitioning Options

- Use RTOS processes or a “secure partitioning kernels” (MILS, ARINC 653) to enforce isolation of both time and memory



Traditional Java virtual machines

- The Java platform was designed to be portable and scalable
- It was not designed to extend the benefits of portability and scalability into the realm of real-time software
  - Only ten thread priorities, and priorities are only a suggestion
  - Synchronization does necessarily implement priority inversion avoidance
  - The order of threads on an Object.wait() queue is unspecified
  - The order of threads awaiting access to a synchronized block is unspecified
  - Garbage collection happens at unpredictable times, consuming unpredictable amounts of CPU time, and does not guarantee to find all garbage, nor to defragment the available free pool
  - Common operations may have surprising effects (e.g. entering a mutual exclusion region might force allocation of memory, which might trigger garbage collection)
- The Real-Time Specification for Java (RTSJ), published in 2001, improves upon the traditional JVM specification, but still does not guarantee portability or scalability
  - Note that RTSJ is not part of the “standard edition” Java

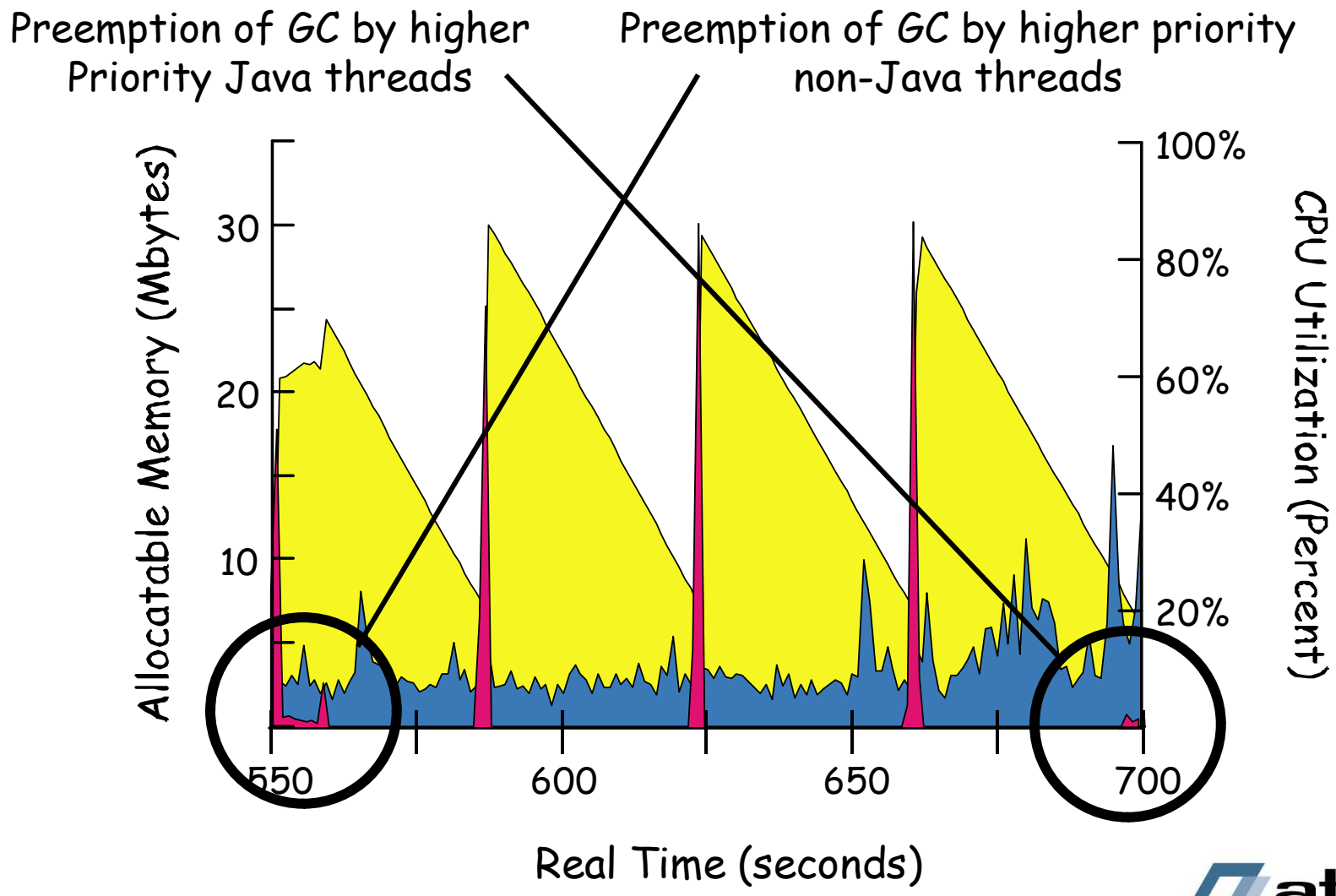
Thread Priorities

- Select an appropriate real-time virtual machine to enable enhancements to the traditional Java thread priority model. For example:
  - More than ten priorities can be supported. In case legacy software assumes only ten priorities, multiple real-time thread priorities can be mapped to a single “Java” priority (e.g. real-time priorities 11-28 all masquerade as legacy Java priority 10)
  - Strict priority dispatching is offered, rather than treating priority as only a “suggestion”
  - Java priorities can be mapped to underlying operating system priorities to enable rate monotonic analysis of mixed language real-time systems
  - CPU time accounting can be reported for each thread, and for each priority level

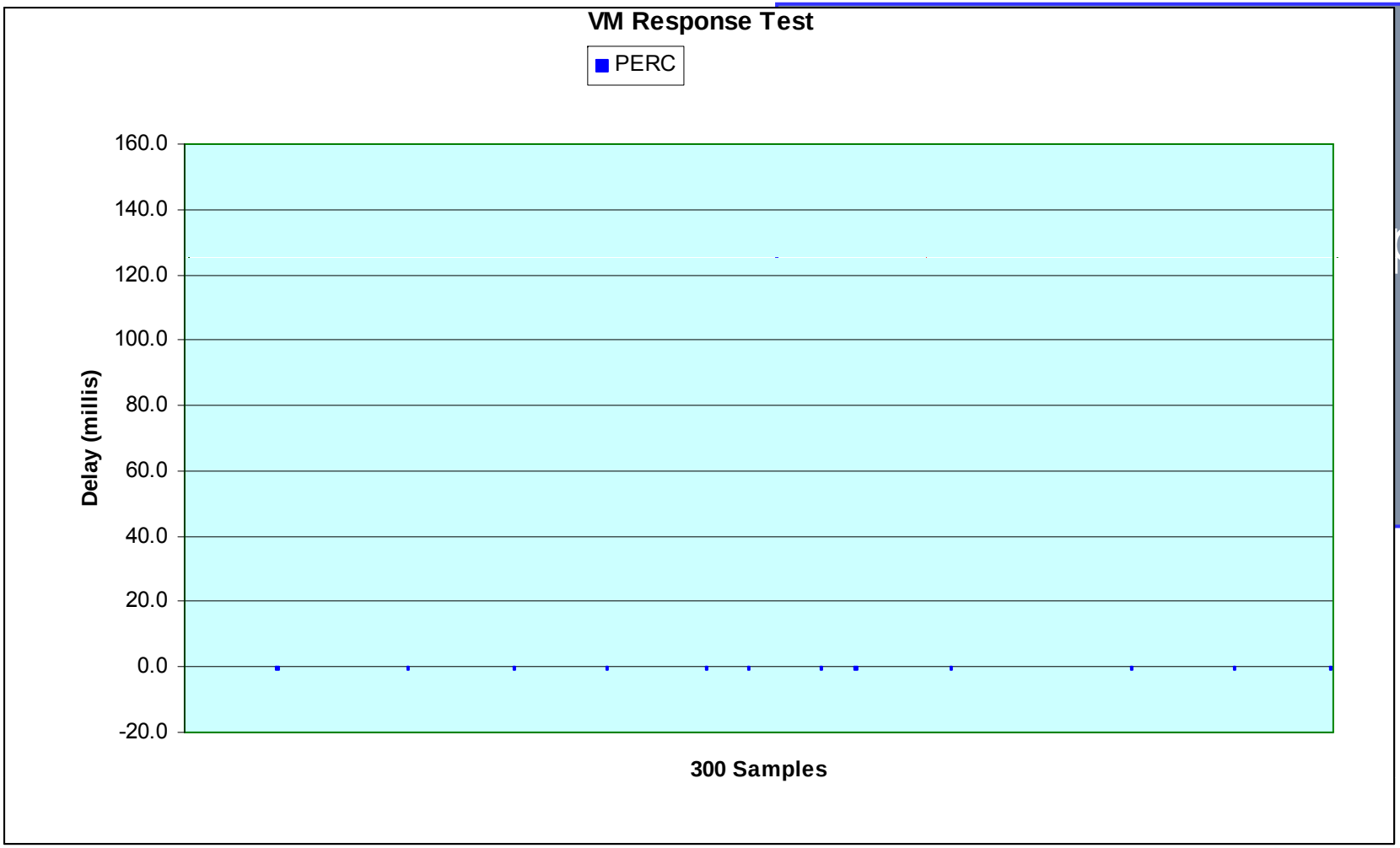
The Java Run-Time Environment

- Appropriate real-time virtual machines offer enhanced synchronization capabilities
  - Maintain all thread queues in priority FIFO order
  - Implement priority inheritance for all Java synchronization
  - Detect circular lock dependencies, which indicate deadlock
  - Priority ceiling emulation for static hard real-time code
  - On-line monitoring capabilities to identify which threads hold which locks, and which threads are blocked awaiting access to particular locks
- Real-time garbage collection can be preemptible, incremental, accurate, defragmenting, and paced

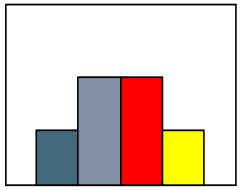
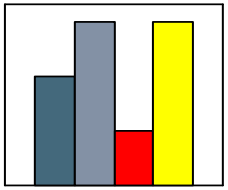
Preemption of Garbage Collection



Classic VM running VM Response Test

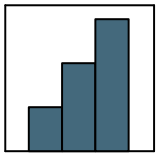


Static Linking and Ahead-of-Time Translation

	Dynamic Loading	Static Linking
Interpreted		Not "traditional Java"
JIT Compiled		Not applicable
AOT Compiled	Not "traditional Java"	Not "traditional Java"

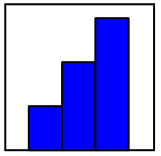
ROM Size

Large
Med
Small



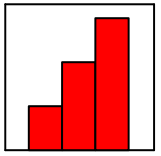
RAM Size

Large
Med
Small



Start Speed

Fast
Med
Slow



Exec Speed

Fast
Med
Slow

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Library Selection

- Though the power of standard-edition Java libraries is an important part of Java's appeal, deploying with full libraries is often undesirable:
  - Memory/cost constraints may demand library subsetting
  - Limitations of the embedded device may make certain libraries irrelevant (e.g. some devices have no file system, network connections, or GUI)
  - Stability considerations may demand that systems freeze with older library versions
  - Security and/or safety certification concerns may require exclusion of certain libraries
- Most vendors of embedded system virtual machines offer greater flexibility for library subsetting than the traditional Java license
- Some vendors provide tools to assist in analyzing interdependencies between libraries and "robustly stub out" omitted functionality

Eliminating Garbage Collection

- In systems that have severe memory or performance constraints, or that must be certified to the highest levels of safety rigor, garbage collection may be eliminated entirely
  - As an object-oriented programming language, it is difficult (and unnatural) to write programs that do not allocate any memory at all
  - In the absence of tracing garbage collection, temporary objects can be "safely" allocated on the run-time stack
    - The RTSJ introduces an explicit mechanism known as "scopes"
    - A simpler and safer specialization of RTSJ scopes is described in the draft JSR-302 (safety-critical Java) specification
    - Certain vendors provide tools to prove that scope allocations do not introduce dangling pointers and to automate the calculation of scope sizes

Interrupt Handlers and Device Drivers in Java

- Most modern device drivers are interrupt driven
- Interrupt handlers are dispatched by hardware rather than software, but traditional Java cannot run as first-level interrupt handlers
- Code written in a style of “hard real-time Java”, avoiding all dependencies on garbage collection, can be dispatched by the interrupt handling hardware
- Real-time virtual machines provide mechanisms to access hardware devices (e.g. DirectMemory API, java.nio.MappedByteBuffer)

Architecture and Design Considerations

- Note that Java is most relevant to larger, more complex systems that are beyond the “comprehension” of a single developer
- Abstraction allows teams of developers to divide and conquer
- But everyone must “see” the same abstractions
- Don’t start development until you have a general architecture and design
- Study available libraries, frameworks, and 3rd party offerings in order to determine relevance
- Establish rules for interaction and separation of concerns between independently developed components

Plan for maintenance, evolution, reuse

- The system architects and designers have greatest responsibility for organizing software so that it can evolve
- Object-oriented notations allow designers to specify component interfaces in ways that facilitate software reuse and evolution
- Establish practices that encourage communication, enable feedback from developers to designers, and allow refinements from designers to developers
- Spiral development and extreme programming offer many benefits

Establish Clear Separation of Concerns

- Expose internal details on a need-to-know basis
- Give proper attention to use of package, private, final restrictions during design
- Many real-time considerations violate traditional objectives of abstraction, for example:
  - How much memory is required to incorporate this component?
  - How much CPU time is required to invoke this service?
  - What demands does this component impose on the real-time garbage collector?
- Suggestions:
  - Architects and designers need to address real-time considerations as they specify the APIs, documentation, and other artifacts associated with specific real-time components
  - To aid maintenance and composition of components, consider wrapping components within a framework that assesses and represents resource needs

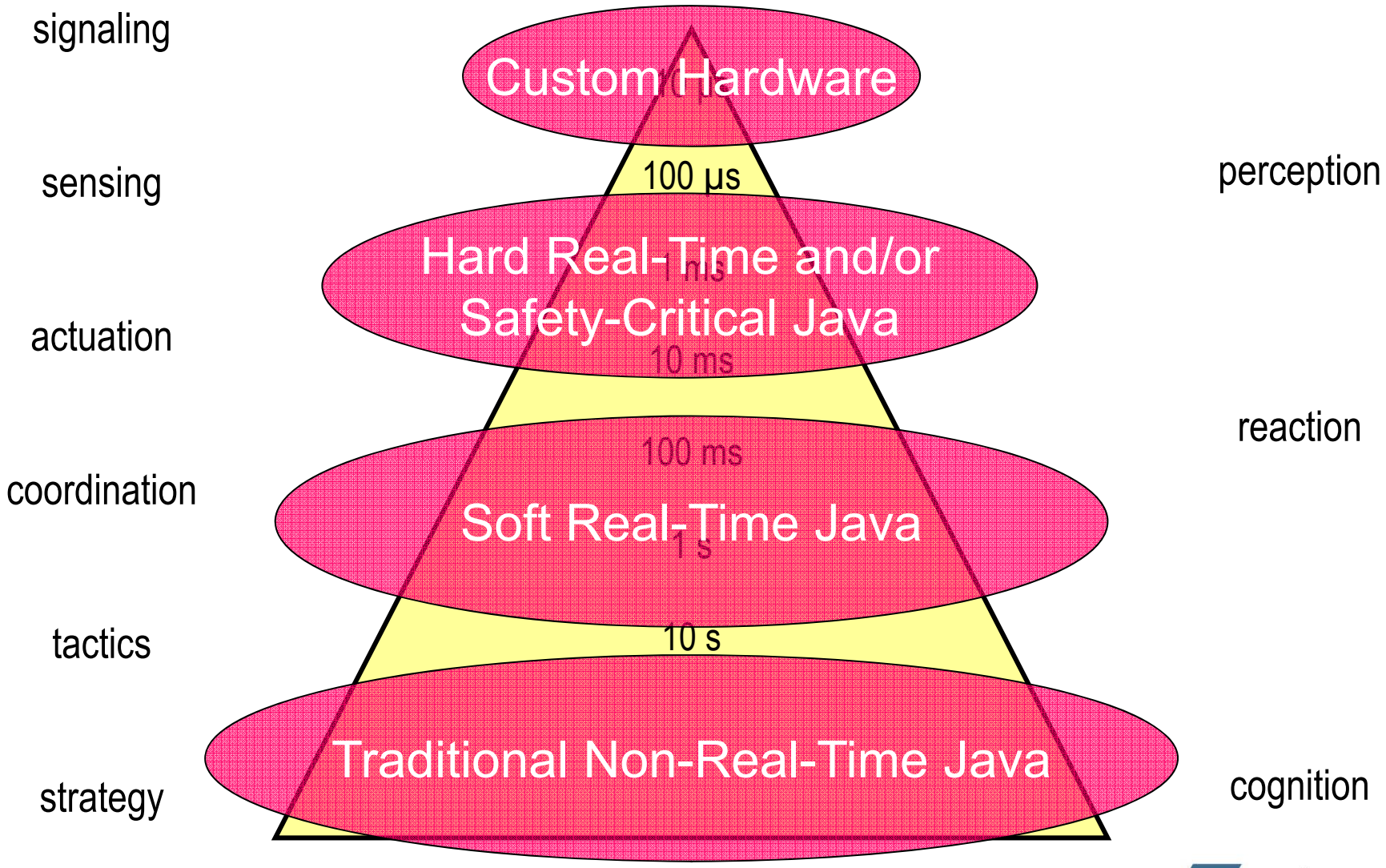
Real-time attributes of software components

- For active components, a real-time Java component framework might require individual components to identify themselves with regards to:
  - How many threads? What are their response time constraints? What is their demand for CPU time?
  - How much live memory is retained by this application?
  - What is the pace at which garbage memory is created by this application?
- For passive components, the component might report:
  - How much CPU time and memory is required to invoke each service?
- Resource requirements can be determined analytically or approximated empirically
  - To facilitate maintenance and reuse, bundle resource determination with the code
- If resource needs for certain code are not known, isolate this code (at lower priority or on distinct virtual machines)
  - Note: a low-priority thread that allocates memory can hinder progress of high-priority threads that need to allocate memory

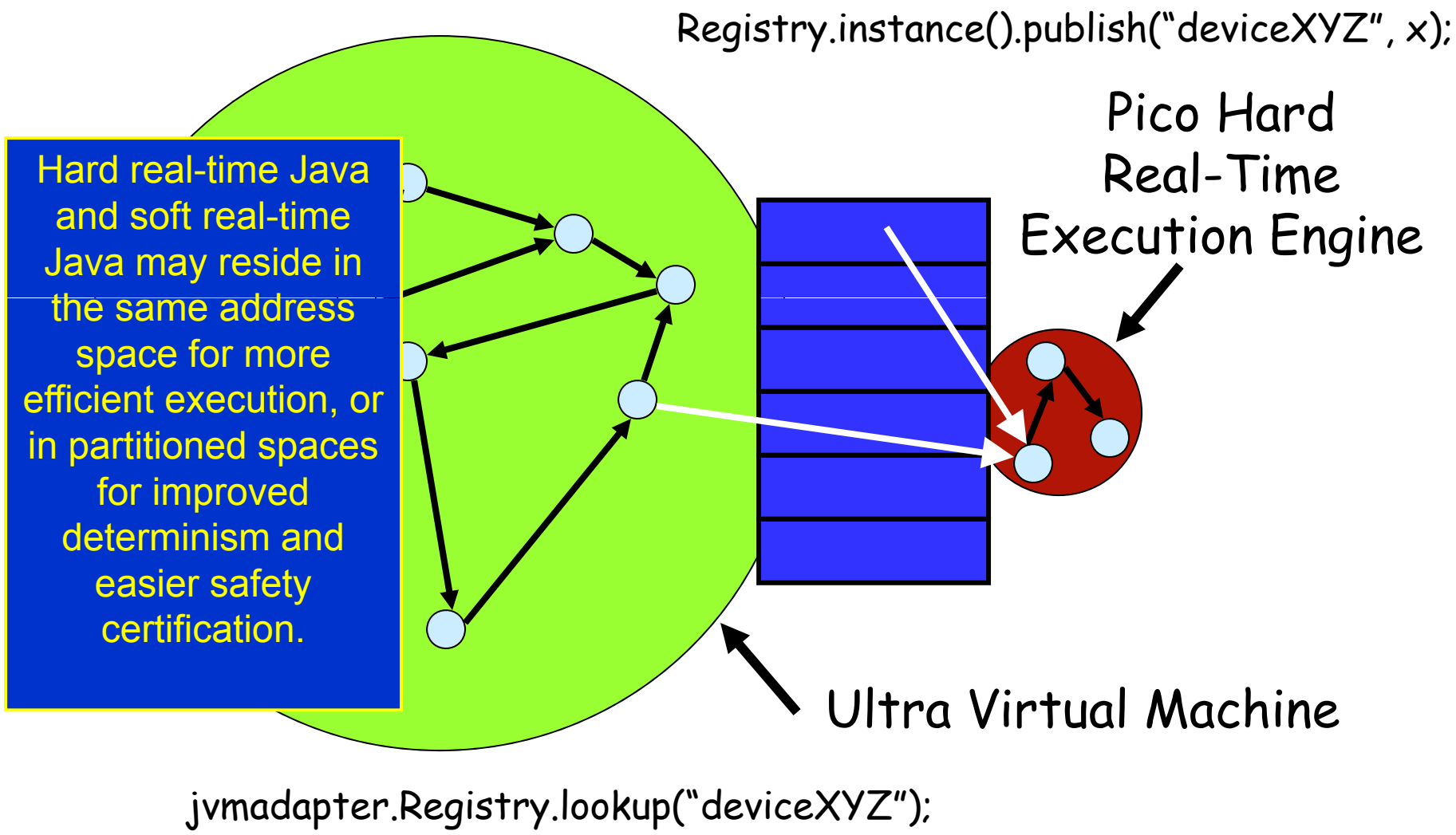
Efficient and robust integration of legacy and Java

- Most real-world systems are comprised of many different technologies, each targeting different needs and making different compromises
- Typical real-time systems address a combination of hard real-time and soft real-time constraints
- The option of using C for low-level hard real-time code and Java for higher-level soft real-time code is less desirable:
  - Performance overhead due to marshaling of data
  - Reliability and maintenance challenges because C code compromises integrity of Java security system

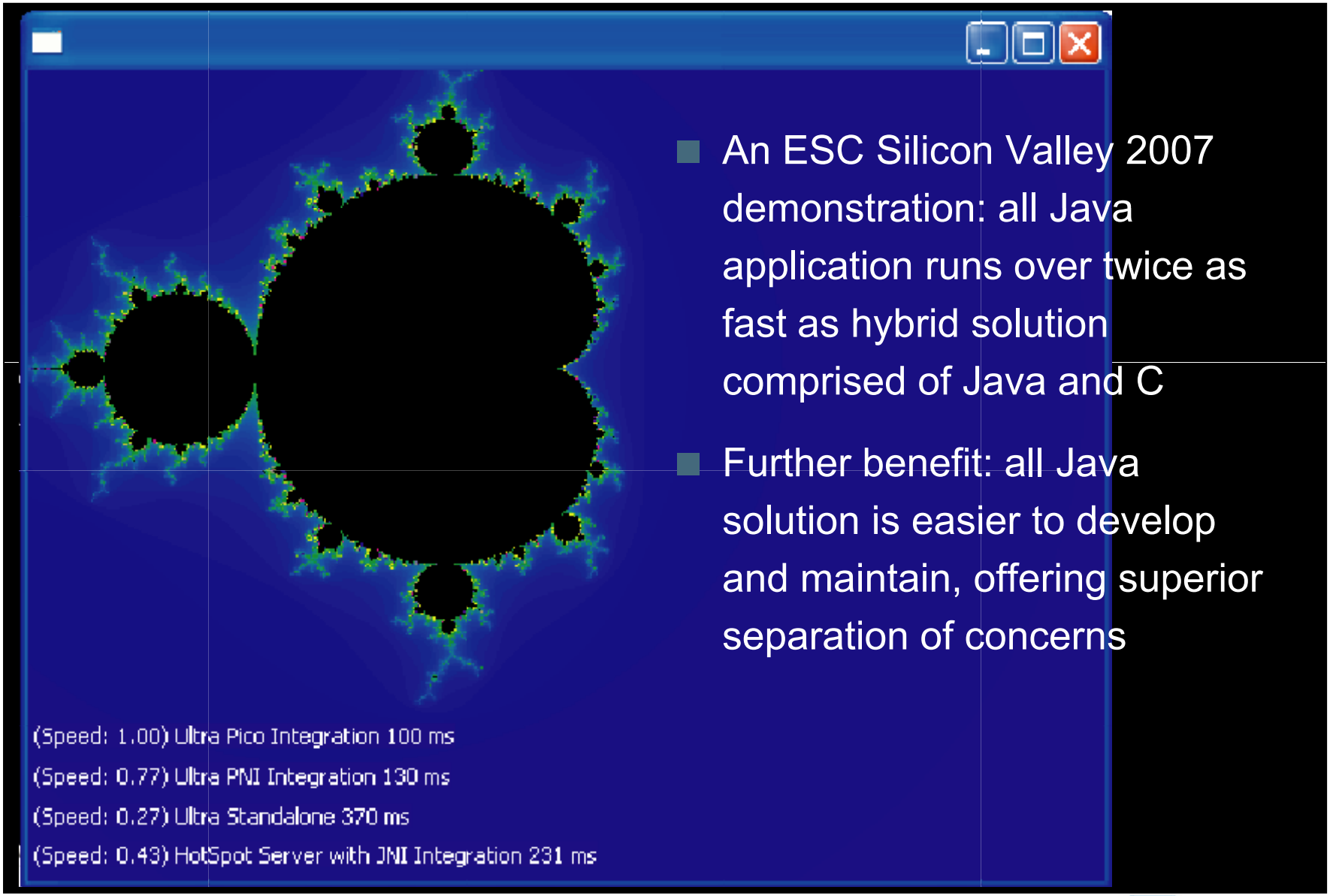
Real-Time Pyramid (Hierarchies and Layers)



Cooperating HRT Components



All Java Solution Twice as Fast as C/Java!



- An ESC Silicon Valley 2007 demonstration: all Java application runs over twice as fast as hybrid solution comprised of Java and C
- Further benefit: all Java solution is easier to develop and maintain, offering superior separation of concerns

Summary

- Real-time Java has been successfully deployed in various commercial and defense applications
- In successful projects, the choice to use Java has reduced certain risks and demonstrated concrete benefits
- However, the mere act of choosing to use Java does not guarantee successful deployment, risk elimination, or software engineering benefits
- Effective use of real-time Java requires effective management in order to address relevant success factors

Acronyms

- BAE: British Aerospace Engineering
- COTS: Commercial off-the-shelf
- DSL: Digital Subscriber Line
- ESC: Embedded Systems Conference
- FELIN: Fantassin à Equipements et Liaisons Intégrées (French)
- FIFO: First in, first out
- FTTP: Fiber to the Premises
- GPON: Gigabit Passive Optical Network
- J2SE: Java 2 Standard Edition
- JSR: Java Specification Request
- J-UCAS: Joint Unmanned Combat Air Systems
- MDS: Mission Data System
- NASA: National Aeronautics and Space Administration
- RTSJ: Real-Time Specification for Java
- SONET: Synchronous Optical Network
- UAV: Unmanned Aerial Vehicle
- UK MoD: United Kingdom Ministry of Defence