

The CLDC HotSpot™ Implementation Virtual Machine

Java™ 2 Platform, Micro Edition (J2ME™)

May 2003



Table of Contents

Table of Contents	0
Executive Summary	1
Java Technology in Small Devices	3
History of the Java Stack for Mobile Phones	4
CLDC 1.0/KVM	4
Mobile Information Device Profile (MIDP)	4
The HotSpot™ Virtual Machine	5
Wireless Deployments of Java Technology	5
Demand for Performance	6
Processor and Memory Requirements	7
Key Requirements	7
Other Small Consumer Devices	7
Design Considerations	8
Value Proposition	10
Performance Advantage	10
Robustness and Short Time to Market	11
Scalability and Small Footprint	11
CLDC HotSpot™ Implementation versus the KVM	11
Faster execution consumes less power	12
The increasing demands of next generation networks	12
CLDC Hotspot™ Implementation Architecture	13
Dynamic, Adaptive Compiler	14
Compact Object Layout	14
Unified Resource Management	14
The CLDC HotSpot™ Implementation Garbage Collector	15
Accuracy	15
Generational Mark-Sweep-Compact Collector	15
Fast Allocation	16
Fast Thread Synchronization	16
Lightweight Threads	16
Conclusion	17

Chapter 1

Executive Summary

The deployment of Java™-enabled mobile phones reached 68 million units in 2002.¹ This trend is expected to continue at a nearly exponential pace in the next few years. The ARC Group expects the number of handsets with Java capabilities to rise dramatically to 608 million in 2005, and to represent almost 100% of handsets by 2007.² Another forecast predicts over 1.2 billion Java enabled handsets in the marketplace by 2007, representing almost 70% of all wireless connections.³

Connected Limited Device Configuration HotSpot™ Implementation (CLDC HotSpot™ Implementation) is Sun's high-performance Java virtual machine for wireless phones and communicator-type devices. The first generation of Java™-enabled wireless devices were based on the KVM (K virtual machine), delivered as part of Sun Microsystems' CLDC Reference Implementation. The main objectives of this reference design were to demonstrate how the CLDC Specification could be implemented, and to validate the accompanying TCK. It provided a common base which allowed device manufacturers to port to different platforms, as well as a working environment against which developers could test their CLDC-based applications.

Sun introduced the CLDC HotSpot Implementation in mid-2002 as an optimized implementation that focuses on performance and footprint. Not only does it comply with the CLDC specification, but it also includes a number of patented features that propel faster application execution as well as more efficient resource management. It is also supported on a number of targeted platforms, which allows manufacturers to significantly reduce time-to-market.

1. John Jackson, Yankee Group, February 2003

2. "Future Mobile Handsets," The ARC Group, April 2002

3. OVUM, Ovum Forecast Global Wireless Internet Consumer Markets, December 2002

CLDC HotSpot™ Implementation delivers nearly an order of magnitude better performance than the KVM, while running in the same small memory footprint required by mobile phones, wireless e-mail clients, and personal organizers. CLDC HotSpot™ Implementation is the recommended virtual machine technology for new product deployments.

These trends are driving the features of next-generation handsets:

- More sophisticated users demanding applications such as gaming, information services, messaging, location services, and so forth.
- Larger screen sizes with higher resolution and more colors, enabling more complex graphics such as 2D, 3D, animations, and so forth.
- Faster networks, which allow larger, more complex applications to be downloaded to handsets.
- Enterprises deploying mobile workforce applications, which require enhanced security and stability in the underlying platform.

The drive for better performance in embedded Java runtime environments drove Sun Microsystems to develop the CLDC HotSpot™ Implementation Java virtual machine technology, to achieve:

- Faster performance,
- More robust platform, and
- Faster time-to-market.

CLDC HotSpot™ Implementation applies advanced tuning and performance techniques utilized in J2SE™ and J2EE™, and further reduces footprint to fit in small devices. In addition, it incorporates several innovations in design that allow the virtual machine to run in resource-constrained devices. This enables CLDC HotSpot™ Implementation to:

- deliver cutting edge performance,
- deliver fast application startup time,
- require minimal footprint,
- reduce porting efforts, and
- preserve battery life.

The version of CLDC HotSpot™ Implementation now being offered by Sun Microsystems supports either CLDC 1.0 or CLDC 1.1. (It can be compiled to support one of these.) CLDC HotSpot™ Implementation conforms to the corresponding version of the CLDC Specification and the Technology Compatibility Kit (TCK). To complete the Java technology stack, Sun is planning to release optimized implementations of the *MIDP2.0 Specification* and other commonly-used standard extensions such as MMAPI 1.1 and WMA 1.1 in late 2003.

Chapter 2

Java Technology in Small Devices

A complete Java technology stack exists today to support embedded devices such as mobile phones. The stack is based on the Java 2 Platform, Micro Edition (J2ME™), and includes layers from the Java virtual machine to GUI support. These devices are characterized as small, battery-powered devices with limited, wireless connection to the Internet.

J2ME defines configurations and profiles, which, in combination with a Java virtual machine, make up the Java technology stack. A configuration of J2ME includes a Java virtual machine, as well as the Java programming language libraries that are required as the lowest common denominator of a range of embedded devices. A *profile* is a layer on top of the configuration that provides additional APIs for a specific class of devices. A particular combination of configuration and profile is appropriate only for specific Java virtual machines.

J2ME fits in with the other editions of Java, J2SE and J2EE, as illustrated in Figure 2-1. Small, battery-powered devices such as wireless phones and communicator-type devices are the domain of CLDC and the Mobile Information Device Profile (MIDP), also shown in this figure.

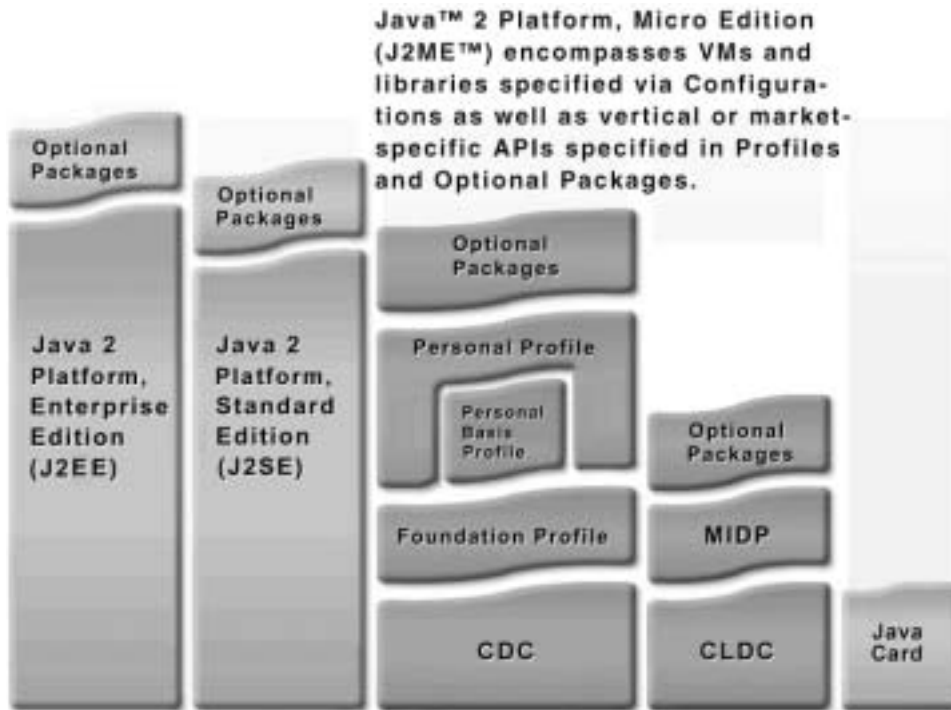


Figure 2-1: 2ME, CLDC and MIDP

CLDC HotSpot™ Implementation is now poised to take the place of the KVM as the high-performance Java virtual machine for the next generation of embedded devices.

History of the Java Stack for Mobile Phones

This history really began in 2000, with the release of two reference implementations of Java technology by Sun Microsystems, Inc. The first was the reference implementations of J2ME CLDC (Connected, Limited Device Configuration). A key component of CLDC was the KVM, the first “complete” virtual machine for small, embedded devices such as mobile phones. Also in the same year, Sun released the first reference implementation of MIDP. For the first time, it was possible to write useful applications in the Java programming language that could be run on small, embedded devices such as mobile phones. Thus, a revolution was born that, today, sees the deployment of more than 100 million Java technology-enabled mobile phones around the world.

CLDC 1.0/KVM

Working through the Java Community Process (JCP), the CLDC configuration was created to provide core Java library support to provide a basic application framework around the KVM. JSR-30 was approved in August 1999, and the final public release of the CLDC Specification 1.0 occurred in May 2000. A number of major mobile phone and PDA manufacturers participated the JCP expert group that developed CLDC 1.0.

Mobile Information Device Profile (MIDP)

In addition to a configuration, J2ME technology requires that a profile be defined to provide a complete Java application framework for a particular market segment. See Chapter 2 of J2ME

Building Blocks for Mobile Devices, White Paper on KVM and the Connected, Limited Device Configuration (CLDC), (Sun Microsystems, Inc., 2000). The MID profile (Mobile Information Device Profile, MIDP) was created through the Java Community Process to address the limited screen size and battery power of this class of device. JSR-37 was approved in September 1999, and the final public release of the MIDP Specification 1.0 occurred in September 2000.

The HotSpot™ Virtual Machine

At about the same time that the first Specification of J2ME CLDC was released, J2SE and J2EE versions of a revolutionary Java virtual machine technology called HotSpot began product deployment. The HotSpot™ performance engine was developed to address the perception that Java virtual machine performance was insufficient for many mainstream applications, especially on big servers. By implementing a host of performance enhancing techniques that went beyond innovations like just-in-time (JIT) compilers, the performance of the Java virtual machine increased by an order of magnitude. HotSpot technology was rolled out in April 1999. (See the Java HotSpot Virtual Machine Technical White Paper, Sun Microsystems, 2001.)

In 2001, these two technology trends converged to inspire the creation of the CLDC HotSpot™ Implementation virtual machine. In contrast to the reference implementation of CLDC and KVM, CLDC HotSpot™ Implementation is an *optimized implementation*. Creating Java technology-enabled consumer devices with KVM and CLDC was impressive, but the perception formed in the marketplace that here, as in conventional Java technology, there was a need for faster performance (while working within the restricted resources of the target devices). CLDC HotSpot™ Implementation applies optimization techniques similar to those used in HotSpot (but using considerably less memory and consuming less power) to realize nearly an order of magnitude improvement in CLDC-based devices.

Wireless Deployments of Java Technology

In 2001, major manufacturers of mobile phones, such as Motorola, Nokia, and Siemens, and mobile operators such as NTT DoCoMo, J-Phone and Nextel, began high volume shipments of Java technology enabled phones. Other manufacturers have now entered this space, and combined shipments have accelerated nearly exponentially. It is estimated that the number of units in the field based on J2ME reached 68 million by the end of 2002,⁴ and will reach 1.2 billion Java-enabled handsets by 2007.⁵ Part of this acceleration is due to the adoption of advanced Java technologies such as CLDC HotSpot™ Implementation.

4. Yankee Group

5. OVUM

Chapter 3

Demand for Performance

Many current generation of Java technology-enabled mobile phones have processor and memory requirements that are typical of the original design parameters of the KVM and CLDC. But increasingly, there are models being introduced with somewhat more computing power available. The typical processor is a 16 or 32-bit processor with a clock speed as little as 12-32 MHz, but more typically 60 MHz. The minimum memory requirement for a target device are 300 KB of RAM and about 1 MB of flash and ROM. More typical devices increase these sizes to 600 KB of RAM and about 1.5 MB of flash and ROM.

Although the KVM easily met the footprint requirements of this generation of target devices, the relatively slow processor and the conventional implementation of a bytecode interpreter resulted in performance that was adequate but not impressive. With CLDC HotSpot™ Implementation, Sun Microsystems accelerated performance in the current generation of devices, while looking ahead to emerging mobile phone designs.

In addition to performance demands, device manufacturers also demand robustness and rapid time-to-market.

Before finalizing the features of CLDC HotSpot™ Implementation, the development team surveyed key manufacturers to get an accurate picture of the capabilities of current generation and next generation mobile phone designs.

Processor and Memory Requirements

The following table summarizes minimum and typical requirements for processor and memory which Java virtual machine technology must work within for next generation mobile phones.⁶

Table 3-1: Next generation mobile phone minimum requirements

Item	Minimum	Typical
CPU type	mostly ARM	mostly ARM
CPU speed	12 MHz	60 MHz
RAM	300 KB (including MIDP)	600 KB (including MIDP)
ROM / Flash	1MB	1.5 MB

The ARM processor represents the majority of handset market share.

The design challenge for the development team was to make CLDC HotSpot™ Implementation run within the same limits and restrictions as the KVM. It is to be anticipated that tuning and optimization would be required for CLDC HotSpot™ Implementation to run at the minimum configurations. The typical configurations in the table would make hosting CLDC HotSpot™ Implementation easier, and allow abundant room for Java applications.

Key Requirements

Our survey revealed that the following key points are important to manufacturers of current generation and next generation mobile phones:

- Most of the available memory in a current generation or next generation handset is needed for system software and media capabilities. Thus, the memory footprint of the virtual machine and CLDC libraries must be minimized.
- Moore's Law does not apply to battery life: so far, no exponential expansion of battery capacity with the passage of years has been observed. Every effort must be made to minimize battery consumption for the foreseeable future.
- The key to executing Java programs at high speeds without draining the battery is keeping the working set of the Java virtual machine inside the on-processor cache.
- Tunability is key: Implementers must be portable to a wide range of devices with varying capabilities.

Other Small Consumer Devices

Besides mobile phones, the CLDC HotSpot™ Implementation development team also considered the processor and memory requirements of other devices that potentially belong in the CLDC and MIDP category, such as communicator type devices.

Communicator type devices typically have much more memory available than inexpensive mass market handsets, but they are also manufactured in much smaller volume. Although footprint constraints are much less stringent in this class of device, the next generation of Java virtual machine technology for embedded devices must be appropriate for smaller, high-volume handsets as well.

6. Sun Microsystems customer survey, 2001

Chapter 4

Design Considerations

Certain fundamental challenges need to be addressed in the design of any virtual machine technology in small, embedded devices. These challenges are also addressed in the CLDC HotSpot™ Implementation design:

- The trade-off between fast execution and small footprint
- Good cache behavior
- Enhancing battery efficiency
- The need for tunable parameters

Speed Versus Footprint. There is a seeming trade-off between speed of execution and memory (footprint) requirements. How can one build a fast dynamic compiler without blowing the memory budget? To simply port the HotSpot technology would result in a memory footprint far too large for mass market, battery-powered devices.

Good Memory Efficiency. How can an implementation avoid memory fragmentation as stacks and heaps shrink and expand? An efficient garbage collector is a must.

Good Cache Behavior. The importance of cache behavior might not be obvious at first. Abundant memory adds to manufacturing cost, although Moore's law tempts designers to waste memory. But additional memory — especially RAM — also puts a great load on battery capacity. It was a prime design objective of CLDC HotSpot™ Implementation to obtain good cache behavior so that the working set for Java stack could fit within the on-processor or in the secondary (on-board) cache. In this way, substantial battery conservation is achieved by avoiding reads and writes to the main memory array.

The design objective of good cache behavior implied a number of software strategies:

- Designing the virtual machine with mostly small objects
- Use of a generational garbage collector, which often touches memory only locally
- Keeping compiled code in the object heap, where it is fully relocatable or flushable

Enhancing Battery Efficiency. It bears repeating that the leap in execution speed provided by CLDC HotSpot™ Implementation directly enhances battery life. Quite simply, faster execution consumes less power

Leveraging the Advantage of Java Programming. The implementation must execute Java language programs so efficiently as to minimize the traditional advantages of native or low-level programming. More software, including system software, may now be written in the Java programming language.

Portability. The implementation must be relatively easy to port to a different operating system.

Chapter 5

Value Proposition

There was a perception early in the history of the Java programming language that the performance of the applications written in the Java programming language was inadequate. With the advent of the HotSpot performance engine, the competitive landscape was revolutionized for Java virtual machines on servers and on the desktop. In much the same way, CLDC HotSpot™ Implementation has revolutionized the deployment of Java technology in battery-powered, handheld devices.

Performance Advantage

The performance of the CLDC HotSpot™ Implementation virtual machine approaches that of Java virtual machines running on desktop systems. It does so using techniques such as:

- Dynamic, Adaptive compilation
- Lightweight Threading System
- Generational garbage collection
- Fast synchronization
- Unified resource management

To apply these techniques in the context of handheld devices, some very clever innovations were necessary. (Refer to “CLDC Hotspot™ Implementation Architecture” on page 13.)

Robustness and Short Time to Market

The CLDC HotSpot™ Implementation virtual machine answers the customer requests listed earlier:

Increased Robustness: The CLDC HotSpot™ Implementation virtual machine can be built to comply with either *CLDC Specification*, version 1.0 or *CLDC Specification*, version 1.1. Around 10,000 TCK tests ensure compliance with these specifications. Several thousand additional tests, including virtual machine stress tests, are run on CLDC HotSpot™ Implementation by Sun Microsystem's Quality Engineering team.

Faster Time to Market: The architecture of CLDC HotSpot™ Implementation is designed for easy portability to different target operating systems. In most cases, a successful port can be accomplished within a few weeks. It is also designed to be easily integrated with a J2ME profile, such as MIDP 2.0, to implement a complete Java runtime environment.

Scalability and Small Footprint

CLDC HotSpot™ Implementation places no restrictions on the number of loaded classes or on the size of the object heap.

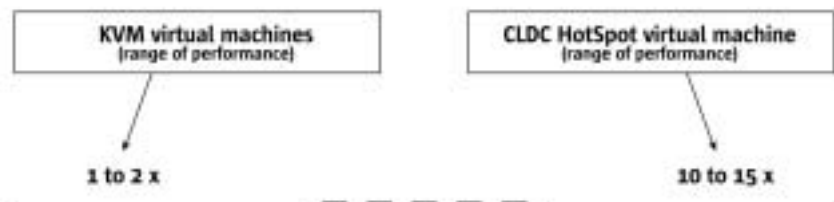
Despite its high performance, CLDC HotSpot™ Implementation is compact enough to meet the footprint constraints of next generation and many current generation mobile phones. The minimum total flash and ROM memory requirement for the virtual machine and software is on the order of 1 Mb. This includes the CLDC HotSpot™ Implementation virtual machine, the CLDC class libraries, the MIDP class libraries, and Java applications.

The manufacturers who have successfully developed and deployed Java technology-enabled handsets might feel little competitive pressure to change their offerings. However, there is a substantial value to upgrading their offerings to incorporate CLDC HotSpot™ Implementation technology.

CLDC HotSpot™ Implementation versus the KVM

In the KVM design, a heavy emphasis was placed on portability and platform-independence of the virtual machine. Consequently, the KVM is a conventional virtual machine that executes Java applications exclusively by means of a bytecode interpreter written in ANSI C. However, measurements reveal that, on average, interpreted virtual machine performance is approximately one order of magnitude slower than compiled virtual machine performance.

Figure 5-1: Performance of KVM compared with CLDC HotSpot™ Implementation



To improve the performance of a virtual machine beyond pure interpreter performance, some kind of a static or dynamic compilation strategy is needed. To approach an order-of-magnitude improvement in performance, while maintaining device-independent bytecode as the standard for applications, the CLDC HotSpot™ Implementation virtual machine has an innovative adaptive compiler. This compiler dynamically compiles the most frequently used, time-critical pieces of the applications into native code for significantly faster execution. The execution speed of optimized

native code can be up to 50 times faster than the speed of a conventional interpreter. When run in mixed mode (using the adaptive compiler to optimize the frequently used operations and using the optimized bytecode interpreter for infrequently used code), the CLDC HotSpot™ Implementation system can achieve a performance advantage of approximately 10 to 15 times when compared to traditional bytecode interpreters.

Additional performance enhancement compared to straightforward virtual machines is achieved with a HotSpot-style garbage collector and a fast synchronization mechanism.

Faster execution consumes less power

The dramatic improvement in performance of CLDC HotSpot™ Implementation “turbocharges” application startup time and execution time, resulting in a positive subjective experience. Just as importantly, it consumes battery power at a proportionally lower rate.

The increasing demands of next generation networks

With the emergence of next generation networks, the performance demands are dramatically increasing for on-phone applications and data communications.

Next generation mobile networks will support data bandwidth rates up to 2 Mbits per second, opening up new possibilities for applications in the areas of:

- Enterprise mobility applications
- Games and gambling applications
- Multimedia applications
- Location based services
- E-commerce applications
- System software
- Banking applications

The virtual machine must provide sufficient performance for these new types of applications while minimizing battery drain. Paradoxically, battery power can be optimized even though a faster processor consumes battery power at a proportionally faster rate. A very fast virtual machine such as CLDC HotSpot™ Implementation makes possible an overall savings in power even while servicing this new generation of software, because it finishes all tasks much sooner than a slower virtual machine.

Chapter 6

CLDC Hotspot™ Implementation Architecture

The CLDC HotSpot™ Implementation design team met the demands for performance and design challenges detailed in the earlier sections of this white paper. The resulting design strikes a strong balance between performance and footprint constraints.

The architecture of the CLDC HotSpot™ Implementation virtual machine includes the following features:

- Dynamic, adaptive compiler, which compiles the most-used Java methods at runtime
- Optimized interpreter (written in assembly language)
- Support for lightweight threads, which greatly simplifies porting
- Compact object layout
- Unified resource management
- Accurate generational garbage collection
- Fast synchronization
- No restriction on number of loaded classes
- ROMizer, which stores system classes in a compact format that allows faster execution
- Supports either CLDC 1.0 or CLDC 1.1 with full TCK compliance
- Support for hardware acceleration technology, with battery savings and fast startup
- Supports 32 bit addressing, useful for large-memory, next-generation phones
- Can be built as a main program or as a subroutine in an event loop

Dynamic, Adaptive Compiler

In general, Java virtual machines with a compiler are an order of magnitude faster than those with only an interpreter. For that reason, CLDC HotSpot™ Implementation includes a dynamic compiler to provide fast bytecode execution. A well-known problem with compiling bytecodes into native instructions is that the generated code takes up four to eight times as much space as the original bytecodes. Adaptive compilation alleviates this problem by only compiling methods that are recognized as “hotspots”, i.e., the most frequently used parts of the application. The CLDC HotSpot™ Implementation dynamic compiler finds the hotspot by running a statistical profiler.

To minimize the amount of compiled code, CLDC HotSpot™ Implementation virtual machine includes an optimized interpreter used for infrequently executed methods.

The CLDC HotSpot™ Implementation compiler is a simple one-pass compiler that utilizes the following basic optimizations: constant folding, constant propagation, loop peeling. It is an adaptive compiler, because it reacts to data gathered at runtime to decide which methods to compile. Only the methods that execute most frequently are compiled. Once compiled, a method is subject to deoptimization if it no longer is invoked for a period of time.

The components of the CLDC HotSpot™ Implementation virtual machine are shown in Figure 6-1.

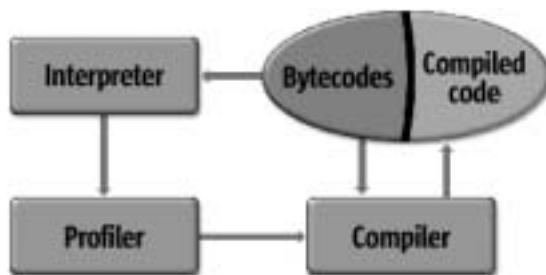


Figure 6-1: CLDC HotSpot™ Implementation Architecture

Compact Object Layout

CLDC HotSpot™ Implementation supports a compact object layout to reduce general memory consumption. A Java object has two parts. The first part is the object header, which provides reflective information and contains hash code and locking status. The second part is the object body, containing the object fields.

Most other virtual machines use at least two words for the object header. However, since the average object size is small, object headers take up a big fraction of the total object space.

CLDC HotSpot™ Implementation optimizes the usage of stack space. Only one word is needed for the object header. In addition to reducing memory usage, object allocation becomes faster.

Unified Resource Management

A major benefit of CLDC HotSpot™ Implementation is *unified resource management*. This means that all allocated data resides inside the object heap. Allocated data includes:

- Java level objects,
- Reflective objects, such as methods and classes,
- Compiler generated code
- Virtual machine internal data structures, and
- Java execution stacks.

An important advantage of this unification is that the same garbage collector takes care of cleaning up all allocated resources, even compiled code. Almost all other virtual machines have designated areas for user objects, reflective data, temporary data and generated code. Such a scheme results in memory fragmentation, multiple cleanup strategies and other complexities. CLDC HotSpot™ Implementation solves these issues by using the mark-sweep-compact garbage collector for everything.

Another benefit of unified resource management is that compiled code can be removed dynamically to free up space for user-level objects.

The CLDC HotSpot™ Implementation Garbage Collector

A garbage collector automatically reclaims unused object memory and makes the freed memory available for new allocations. CLDC HotSpot™ Implementation uses an accurate generational mark-sweep-compact garbage collector, which results in:

- Fast object allocation
- Small garbage collection pauses
- No memory fragmentation

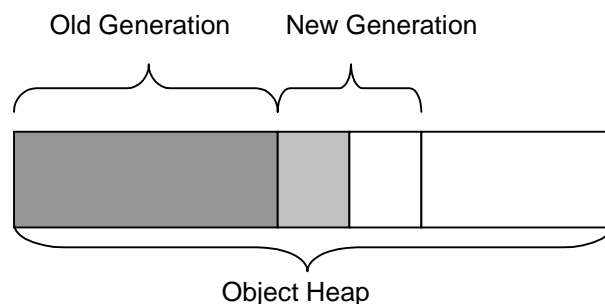
Accuracy

An accurate garbage collector knows where all pointers are when garbage collection takes place. This has two major benefits. First, all inaccessible object memory can be reclaimed reliably. Second, all objects can be relocated, allowing object memory compaction and eliminating fragmentation. Using a conservative garbage collection approach would be highly undesirable on a memory-constrained system, since it causes object fragmentation and unpredictable memory leaks.

Generational Mark-Sweep-Compact Collector

The CLDC HotSpot™ Implementation virtual machine employs a two generational garbage collector, as illustrated in Figure 6-2.

Figure 6-2: Two-generational Garbage Collection



The object heap is segmented into old generation, new generation and as-yet-unused portions of memory. The old generation segment contains objects that were previously garbage collected and compacted. New objects are allocated in the new generation segment, which is generally much smaller. When the new generation segment is full, the garbage collector runs briefly and reclaims the unused memory for that generation. When all memory in the object heap is consumed, the garbage collector runs across the entire heap and compacts objects into a “new” old generation. Only during this large garbage collection is there a noticeable pause, but it occurs infrequently.

This scheme takes advantage of the fact that the vast majority of objects are short-lived. Since most objects are short-lived, only a small portion of allocated objects are promoted to the old generation. Most garbage collection operations focus only on the new generation, resulting in only small pauses.

Fast Allocation

A side benefit of a compacting garbage collecting is that new objects are allocated contiguously in stack-like fashion in the first generation. Object allocation is then simply a matter of increasing a pointer.

Fast Thread Synchronization

The Java programming language provides language-level thread synchronization, which makes it easy to express multi threaded programs with fine-grained locking. CLDC HotSpot™ Implementation uses a variant of the block structured locking mechanism developed for the HotSpot virtual machine. As a result, synchronization performance becomes so fast that it is no longer a performance bottleneck for Java programs.

Lightweight Threads

CLDC HotSpot™ Implementation provides a lightweight threading system, which greatly reduces complexity compared to native threading mechanisms. Porting of CLDC HotSpot™ Implementation is simplified. There is also a dramatic improvement in memory usage: there is no longer a need to allocate native stack space, which must typically be of fixed size. All threads can be maintained with stacks that can be allocated in the same heap as all other objects (another example of unified resource management).

Chapter 7

Conclusion

Sun Microsystems, Inc. continues to keep pace with the demands for performance of the emerging generation of mobile phones and other small wireless devices. CLDC HotSpot™ Implementation continues to evolve, adding even more performance while reducing footprint compared to earlier versions. This optimized implementation of CLDC is available to device manufacturers under license from Sun Microsystems.



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