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Building Memory Efficient Java Programs

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PREFACE

Over the past ten years, we have worked with developers, testers, and performance analysts to help fix memory-related problems in large Java applications. During the many years we have spent studying the performance of Java applications, it has become clear to us that the problems related to memory is a topic worthy of a book. In spite of the fact that computers are now equipped with gigabytes of memory, Java developers face an uphill battle getting their applications to fit in memory. Ten years ago, a 500MB heap was considered big. Now it is not unusual to see applications that are having trouble fitting into 2 to 3 gigabyte heaps, and developers are turning to 64-bit architectures to be able to run with even larger heaps.

Java heaps are not just big, but are often bloated, with as much as 80% of memory devoted to overhead rather than "'real data"'. This much bloat is an indication that a lot of memory is being used to accomplish little. We have seen applications where a simple transaction needs 500K for the session state for one user, or 1 Gigabyte of memory to support only a few hundred users.

By the time we are called in to help with a performance problem, the situation is often critical. The application is either in the final stages of testing or about to be deployed. Fixing problems this late in the cycle is very expensive, and can sometimes require major code refactoring. It would certainly be better if it were possible to deal with memory issues earlier on, during development or even design.

Why ...? Java developers face some unique challenges when it comes to memory. First, much is hidden from view. A Java developer who assembles a system out of reusable libraries and frameworks is truly faced with an "'iceberg"', where a single call or constructor may invoke many layers of hidden framework code. We have seen over and over again how easy it is for space costs to pile across the layers. trying to predict their usage, and design for every possible case, often an impossible task, usually leading to waste for some case that matters to you! While there is much good advice on how to code flexible and maintainable systems, there is little information available on space. The space costs of basic Java features and higher-level frameworks can be difficult to ascertain. In part this is by design - the Java programmer has been encouraged not to think about physical storage, and instead

to let the runtime worry about it. The lack of awareness of space costs, even among many experienced developers, was a key motivation for writing this book. By raising awareness of the costs of common programming idioms, we aim to help developers make informed tradeoffs, and to make them earlier.

The design of the Java language and standard libraries can also make it more difficult for programmers to use space efficiently. Java's data modeling features and managed runtime give developers fewer options than a language like C++, that allows more direct control over storage. Taking these features out of the hands of developers has been a huge plus for ease of learning and for safety of the language. However, it leaves the developer who wants to engineer frugally with fewer options. developers make informed decisions between competing options was another aim for the book.

This book is a comprehensive, practical guide to memory-conscious programming in Java. It addresses two different and equally important aspects of using memory well. Much of the book covers how to represent your data efficiently. It takes you through common modeling patterns, and highlights their costs and discusses tradeoffs that can be made. The book also devotes substantial space to managing the lifetime of objects, from very short-lived temporaries to longer-lived structures such as caches. Lifetime management issues are a common source of bugs, such as memory leaks, and inefficiency (mostly performance). Throughout the book we use examples to illustrate common idioms. Most of the examples are distilled from more complex examples we have seen in real-world applications. Throughout the book are also guides to Java mechanisms that are relevant to a given topic. These include features in the language proper, as well as the garbage collector and the standard libraries.

While the book is a collection of advice on practical topics, it is also organized so as to give a systematic approach to memory issues. When read as a whole it can be helpful in seeing the range of topics that need to be considered, especially early in design. That does not mean that one must read the whole book in order, or do a comprehensive analysis of every data structure in your design, in order to get the benefit. The chapters are written to stand on their own where possible, so that if a particular pattern comes up in your code you can quickly get some ideas on costs and alternatives. At the same time, familiarizing yourself with a few concepts in the Introduction will make the reading much easier.

The book is appropriate for Java developers (experienced and novice alike), especially framework and applications developers, who are faced with decisions every day that will have impact down the line in system test and production. It is also aimed at technical managers and testers, who need to make sure that Java software meets its performance requirements. This material should be of interest to students and teachers of software engineering, who would like to gain a better understanding of memory usage patterns in real-world Java applications. Basic knowledge of Java is assumed.

Much of the content relies on knowing or measuring the size of objects at runtime. Sizes vary depending which JRE you are using. Our reference JRE is Sun Java 6 Update 14. Unless otherwise stated, all sizes are for this reference JRE. The book is self-contained in that it teaches how to calculate object sizes from scratch. We realize, of course, that this can be a tedious endevour, and so the appendix provides a list of tools and resources that can help with memory analysis. Nevertheless, we belief that performing detailed calculations are pedagogically important.

The book is divided into four parts:

Part 1 introduces an important theme that runs through the book: the health of a data design is the fraction of memory devoted to actual data vs. various kinds of infrastructure. In addition to size, memory health can be helpful for gauging the appropriateness of a design choice, and for comparing alternatives. It can also be a powerful tool for recognizing scaling problems early.

Part 2 covers the choices developers face when creating their physical data models, such as whether to delegate data to separate classes, whether to introduce subclasses, and how to represent sparse data and relationships. These choices are looked at from a memory cost perspective. This section also covers how the JVM manages objects and its cost implications for different designs.

Part 3 is devoted to collections. Collection choices are at the heart of the ability of large data structures to scale. This section covers, through examples, various design choices that can be made based on data usage patterns (e.g. load vs. access), properties of the data (e.g. sparseness, degree of fan-out), context (e.g. nested structures) and constraints (e.g. uniqueness). We look closely at the Java collection classes, their cost in different situations, and some of their undocumented assumptions. We also look at some alternatives to the Java collection classes.

Part 4 covers the topic of lifetime management, a common source of inefficiency, as well as bugs. This section examines the costs of both short-lived temporaries and long-lived structures, such as caches and pools. We explain the Java mechanisms available for managing object lifetime, such as ThreadLocal storage, weak and soft references, and the basic workings of the garbage collector. Finally, we present techniques for avoiding common errors such as memory leaks and drag.

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Chapter 1

INTRODUCTION

Managing your Java program's memory couldn't be easier, or so it would seem. Java provides you with automatic garbage collection, and a compiler that runs as your program is running and responds to its operation. There are many standard, open source, and proprietary libraries available that provide powerful functionality, and are written by experts. All you have to do is piece together the parts and let the Java runtime system do the rest for you.

The reality, unfortunately, is very different. If you just assemble the parts, take the defaults, and follow all the good advice to make your program flexible and maintainable, you will likely find that your memory needs are *much* higher than imagined. You may also find that precious memory resources are wasted holding on to data that is no longer needed, or, even worse, that your system suffers from memory leaks. Java is filled with costly memory traps that are easy to fall into. All too often, these problems won't show up until late in the cycle, when the whole system comes together. You may discover, for example, when your product is about to ship, that your design is far from fitting into memory, or that it does not support nearly the number of users it needs to support. Fixing these problems can take a major effort, requiring extensive refactoring or rethinking architectural decisions, such as the choice of frameworks you use.

This book is a guide to using memory wisely in Java. Memory usage, like any other aspect of software, needs to be carefully engineered. Predicting your system's memory needs early in the cycle, and engineering with those needs in mind, can make the difference between success and failure of your project. Engineering means making informed tradeoffs, and, unfortunately, the information to do so isn't always available. While there has been much written on how to build systems that are bug-free, easy to maintain, and secure, there is little guidance available on how to use Java memory efficiently or even correctly. (Too often memory issues are left to chance, or at least put off until there is a crisis.) This book gives you the tools to make informed choices early on. It gives you an approach to looking at your system's uses of memory, and a practical guide to making informed tradeoffs in every part of your design and implementation. (Common patterns that make up your design - helps you understand costs and alternatives. Also relevant Java mechanisms). Three kinds of info: patterns, mechanisms, and an organization/approach to thinking

about memory.

(If you are like most Java developers, you probably don't have a good picture of of how much memory your designs use.)

Achieving efficient memory usage takes some effort in any language. There are things about Java that make it especially easy to end up with bloated or even incorrect data designs. One reason is that Java is so easy to program, so it gives you a false sense of security that everything is being handled for you. (Languages like C give you a lot of control over storage, and so it is clear what the consequences of your choices are.) Also, as we shall see, the basic costs of building blocks such as Strings, can be surprisingly expensive, when compared with languages like C++. So much is done for you in Java, from management of the heap, to all the functionality hidden behind framework APIs, that it can be difficult to find out how much memory your data structures need, or how long they are staying around, until you have a fully running system. Compared to many languages, Java also gives you fewer options for designing your data structures and managing their storage. This means that if you find you have problems, you have fewer ways of fixing them without rethinking larger aspects of your design. All of this makes it important to understand what memory costs and alternatives are, as early as possible.

Beyond the technical realities of using memory well in Java there are some commonly held misconceptions that often make things worse. So before getting into how to engineer memory in Java, it is worth dispelling some of these myths, and getting a better understanding of why memory problems can be so common in Java.

1.1 Facts and Fictions

In addition to the technical reasons why managing memory can be a challenge, there are other reasons why memory footprint problems are so common. In particular, the software culture and popular beliefs can lead you to ignore memory costs. Some of these beliefs are really myths — they might have once been true, but no longer. Here are several.

1.2 Memory-conscious Engineering

At a high level, the approach we present in this book is simple. For each part of your data design: - understand the space needs of the various implementation alternatives - determine how long that data should remain alive, and then choose an appropriate implementation to achieve that

The bulk of this book takes you through the most common patterns that come up in practice for each topic. We show you how to recognize these patterns in your designs, and give you relevant information about costs and other pitfalls.

discuss looking at each data structures separately

1.2.1 Estimating Space Costs

discuss estimating (Edith text on counting bytes, etc is great) (including scalability discussion) (and focusing on important stuff)

discuss health very briefly

discuss entities and collections

Entity-Collection Diagrams

Much of this book is about how to implement your data designs to make the most efficient use of space. In this section we introduce a diagram, called the *entity-collection(E-C) diagram*, that helps with that process. It highlights the major elements of the data model implementation, so that the costs and scaling consequences of the design are easily visible. We use these diagrams throughout the book to illustrate various implementation options and their costs.

A data model implementation begins with a conceptual understanding of the entities and relationships in the model. This may be an informal understanding, or it may be formalized in a diagram such as an E-R diagram or a UML class diagram. At some point that conceptual model is turned into Java classes that represent the entities, attributes, and assocations of the model, as well as any auxiliary structures, such as indexes, needed to access the data. The example below shows a simple conceptual model, using a UML class diagram. A Java implementation of that model is also shown, using rectangles for classes and arrows for references.

In these models we make a distinction between the implementations of entities and the implementation of collections. We do this for a number of reasons. First, the kinds of choices you make to improve the storage of your entities are often different from those Collections are also depicted as nodes, using an octagonal shape. This is different from UML class diagrams, where associations are shown as edges. E-C diagrams show

1.2.2 Managing lifetime

discuss overview of approach to lifetime management

1.2.3 Defining Terms

Terms like object can have different meanings in the literature. The following are the conventions used throughout this book.

Since the word *object* can have different meanings, we precisely define the terminology used:

- A *class* is a Java class. A class name, for example `String`, always appears in type-writer font.

- A *data model* is a set of classes that represents one or more logical concepts.

- Finally, an *object* is an instance of a class, that exists at runtime occupying a contiguous section of memory.

Part I

Using Space

Chapter 2

MEMORY HEALTH

A data structure may be big, but how do you know if it is too big? This chapter introduces the concept of memory health, a way to gauge how efficiently a data structure uses memory. Java developers often have to piece together many smaller objects to build a single data structure. Memory health is a way to understand the overhead introduced in each object, the impact of connecting these objects into larger data structures, and, finally, how a data structure scales as the amount of data it holds grows. Understanding memory health can provide valuable insight into each step of the data modeling process.

Later chapters show how to estimate both the size and health of data structure designs. Both of these are important. Memory health is independent of size: a small structure can be unhealthy, and a large structure can be healthy. A healthy data structure will generally scale well, while unhealthy data structures are often the root causes of memory footprint problems.

2.1 Distinguishing Data from Overhead

The size of a data structure is the number of bytes it occupies. The *health* of a data structure tells you what these bytes are accomplishing. Is the memory being spent on something important? A very useful way to classify bytes is as either data or overhead. Bytes classified as data represent the real data intrinsic to your program. All other bytes are overhead of the particular representation you have chosen for that data. A healthy data structure, from a space standpoint, is one with a low overhead. Sometimes there are tradeoffs; a larger design may be necessary for performance. Sometimes, though, choosing a design with lower memory overhead actually improves performance.

In Java, it is all too easy to design a data structure that is bloated by a factor of more than 50%; this means that over half of the data structure is devoted to things unrelated to the data that the application cares about. To understand why there is so much overhead, it is useful to dig deeper into its different sources:

- *JVM overhead.* Each object has a header imposed by the JVM to facilitate various administrative tasks, such as garbage collection. In addition, the JVM may impose additional object alignment overhead.

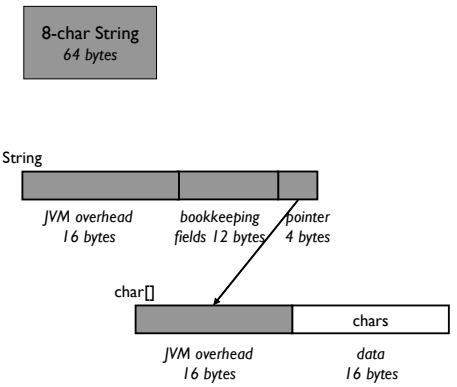


Figure 2.1. An eight character string in Java 6.

- *Pointers.* Pointers glue objects together into data structures. Pointers can be null or non-null.
- *Bookkeeping fields.* Not all primitive fields store real application data. Some are bookkeeping fields needed by the representation.

The Memory Bloat Factor

An important metric for evaluating the health of a data model design is the fraction of overhead in the objects of that data model. The *memory bloat factor*, or simply *bloat factor*, is the ratio of overhead to total size.

Example: An 8-Character String You learned in the quiz in Chapter 2 that an 8-character string occupies 64 bytes, which seems surprisingly high. The actual character data takes up 16 bytes, since Java supports the international character set, which uses 2-bytes per character. So it costs 16 bytes to represent the eight characters themselves. The other 48 bytes are pure overhead. This structure has a *bloat factor* of 75%. The actual data occupies only 25%. These numbers vary from one JVM to another, but the overhead is always very high. (Unless otherwise noted, all measurements in this book are from the 32-bit IBM Java 6 JVM.)

Figure 2.1 shows why the bloat factor is so high. Strings have all three kinds of overhead – JVM overhead, pointers, and bookkeeping fields. Every Java string is

really two objects: a `String` that serves as a wrapper, and a `char` array with the actual characters. Two objects means two object headers, plus the pointer glueing the two objects together. The `String` object is entirely overhead, containing no real data. Part of its cost is three bookkeeping fields: a length and an offset, which have meaning only when this string is the result of a substring operation, and a saved hashcode. Adding all of this together, the overhead is 48 bytes. If you were to design a string from scratch, 20% overhead might seem a reasonable target. For such a common data type, it is important to obtain a low overhead. Unfortunately, for a string to have only 20% overhead with its current implementation, it would need to be 96 characters long. As bad as this seems, this string representation does at least have the benefit that it amortizes away its overhead. The overhead cost is always 48 bytes, so overhead of a string approaches 0% for larger and larger strings. For some data structures it is not possible to amortize away overhead costs, as discussed in Section 2.4.

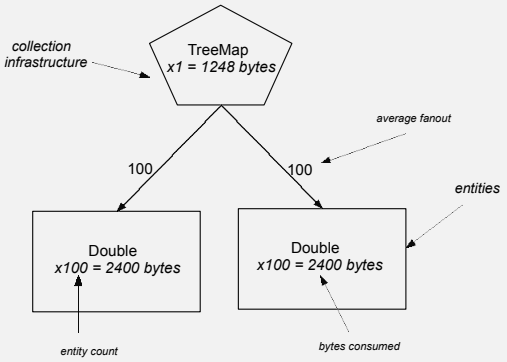
Strings, in particular short strings, are pervasive. It is important to be aware of the overhead of strings when incorporating them into your data design. Given the overhead of Java strings, the choices you make in Java need to be different than in a language like C, where the string overhead is minimal. Making informed choices is critical for the overall memory health of an application. There will be more on strings in later chapters.

2.2 Entities and Collections

A string is an example of a very simple data structure. When modeling a more complex data structure, you design classes to represent application entities, and choose collections in which to store them. Seemingly small choices you make in both cases can have a big impact in memory bloat. For example, the choice of the initial capacity of a collection can make or break the scalability of your design.

To help understand the health of more complex data structures, it is useful to have a diagram notation that spells out the impacts of various choices. An Entity-Collection (EC) diagram is a cousin of an Entity-Relation (ER) diagram, that exposes just the right level of implementation detail to help calculate the memory bloat factor of a complex data structure. As its name implies, an EC diagram shows the entities and collections of a design. It is important to remember that the entities and collections in the diagram are abstracted from the actual data structure objects. A diagram box may be hiding other objects that help implement the entity or collection. For example, a diagram box for a `String` entity represents both the `String` object and its underlying character array.

The Entity-Collection (EC) Diagram



In an EC diagram, there are two types of boxes, pentagons and rectangles. Each box summarizes the implementation details of a portion of a data structure. Pentagons represent collection infrastructure, and rectangles represent the entities of your application.

An EC diagram represents the *containment* structure of your data model. So, an edge from a collection to a rectangular entity indicates membership of the entity in the collection. This also means that, if a certain type of collection or entity is used in multiple ways in the same data structure, then this type will appear in multiple locations — one in each location in the data structure in which that type is used.

The notation $xN = M$ inside each node means there are N objects of that type in that location in the data structure, and in total these objects occupy M bytes of memory. Each edge in a content schematic is labeled with the average fanout from the source entity to the target entity.

Where an ER or UML diagram would show the attributes of each entity, but ignore the implementation costs, an EC diagram summarizes the total cost in the single sizing number shown in each node. Where these other diagrams would show relations or roles as edges, an EC diagram shows a node summarizing the collections implementing this relation.

Example: A Monitoring System A monitoring program collects samples from a distributed system. Each sample it collects consists of a unique timestamp and a value, each represented as a double. The samples arrive out of order. The task

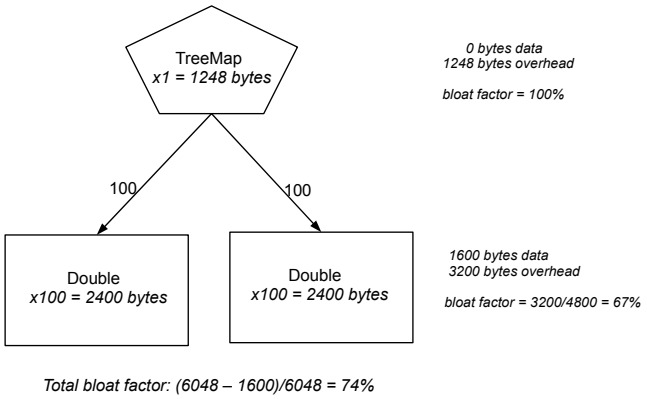


Figure 2.2. EC Diagram for 100 samples stored in a `TreeMap`

is to display samples in chronological order, after all of the data has been collected. The solution requires a data structure to store the samples.

A map is a convenient way to store these timestamp-value pairs. A regular `HashMap` only solves part of the monitoring system problem. To be able to display the samples in chronological order, the entries have to be sorted by timestamp. The first idea that leaps forward is to use a `TreeMap`. A `TreeMap` is a map that maintains its entries in sorted order, so this appears to be a perfect choice. The only problem is the memory cost.

An EC diagram of a `TreeMap` storing 100 samples is shown in Figure 2.2. This diagram gives a schematic view of the `TreeMap` and the entities it contains, along with their costs. The total cost, obtained by adding up the entity and collection costs, is 6,048 bytes. The real data consumes only 1,600 bytes of this, since a double occupies 8 bytes and there are 200 of them. Therefore, the bloat factor is 74%.

Looking at the individual parts of the EC diagram can provide some insight into the source of this overhead. First, the sample timestamps and values are stored as `Double` objects. This is because the standard Java collection APIs take only `Objects` as parameters, not scalars, forcing you to box your scalars before putting them in a collection. Even with Java's autoboxing, the compiler still generates a boxed scalar in order to store a value in a standard collection. A single instance of a `Double` is 24 bytes, so 200 `Doubles` occupy 4,800 bytes. Since the data is only 1,600 bytes, 33% of the `Double` objects is actual data, and 67% is overhead. This is a high price for a basic data type.

The `TreeMap` infrastructure occupies an additional 1,248 bytes of memory. All of this is overhead. What is taking up so much space? `TreeMap`, like every other collection in Java, has a wrapper object, the `TreeMap` object itself, along with other internal objects that implement the collection functionality. Each type of collection in the standard library has a different kind of infrastructure, some are built from arrays, some from separate entry objects linked together, and some use a combination of both. Internally, `TreeMap` is a self-balancing search tree. The tree nodes maintain pointers to parents and siblings. In newer releases of Java 6, each node in the tree can store up to 64 key-value pairs in two arrays. This example uses this newer implementation, which is more memory-efficient for this case, but still expensive.

Using a `TreeMap` is not *a priori* a bad design. It depends on whether the overhead is buying something useful. `TreeMap` has a high memory cost because it maintains its entries in sorted order while they are being randomly inserted and deleted. It constantly maintains a sorted order. If you need this capability, for instance, if you have a real time monitor that is constantly being updated, and you need to look at the data in order, then `TreeMap` is a great data structure. But if you do not need this capability, there are other data structures that could provide sorted-map functionality with less memory consumption. In this example, the data needs to be sorted only after data collection is complete. There is an initial load phase followed by a use phase. The sorted order is only needed during the second phase, after all the data is loaded. This load-and-use behavior is a common pattern, and it can be exploited to choose a more memory-efficient representation.

Of course, another nice aspect of `TreeMap` is that it can be pulled off the shelf. It would be ideal if there were another collection that provides just the needed functionality. If not, maybe there is a way to easily extend another collection class by adding a thin wrapper around it. Writing your own collection class from scratch should rarely be necessary, and is not recommended.

2.3 Two Memory-Efficient Designs

This section describes two other data structure designs to store the monitoring system samples. These designs use less memory and do not maintain sorted order while the data is being loaded. This is not a problem, since the data can be sorted after loading.

The first design stores the samples in an `ArrayList`, where each entry is a `Sample` object containing a timestamp and value. Both values are stored in primitive `double` fields of `Sample`. There is a bit more code that has to be written, but it is not excessive. Fortunately, the standard Java `Collections` class has some useful static methods so that new sort and search algorithms do not have to be implemented. The `sort` and `binarySearch` methods from `Collections` each can take an `ArrayList` and a `Comparable` object as parameters. To take advantage of these methods, the

new `Sample` class has to implement the `Comparable` interface, so that two sample timestamps can be compared:

```
public class Sample implements Comparable<Sample> {

    private final double timestamp;
    private final double value;

    public Sample(double timestamp, double value) {
        this.timestamp = timestamp;
        this.value = value;
    }

    public double getTimestamp() {
        return timestamp;
    }

    public double getValue() {
        return value;
    }

    public int compareTo(Sample that) {
        return Double.compare(this.getTimestamp(), that.getTimestamp());
    }
}
```

Additionally, the `ArrayList` needs to be stored in a wrapper class that implements map operations. Here are two methods, `getValue` and `sort`, of a wrapper class `Samples`.

```
public class Samples {

   public final static double NOT_FOUND = -1d;
    private ArrayList<Sample> samples = new ArrayList<Sample>();
    ....

    public double getValue(double timestamp) {
        Sample sample = new Sample(timestamp, 0.0);
        int result = Collections.binarySearch(samples, sample);
        if (result < 0) {
         return NOT_FOUND;
```

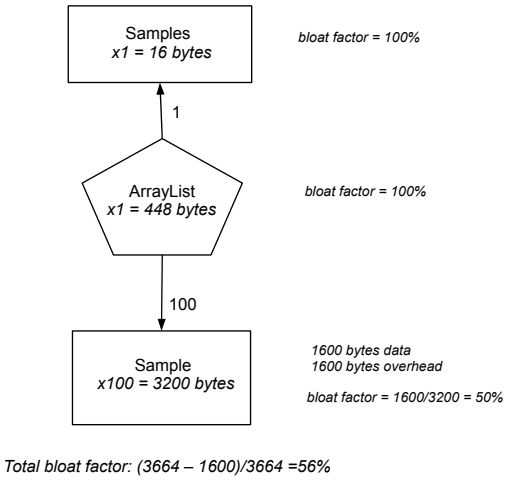


Figure 2.3. EC Diagram for 100 samples stored in an `ArrayList` of `Samples`

```
        }
        return samples.get(result).getValue();
    }

    public void sort() {
        Collections.sort(samples);
        samples.trimToSize();
    }
}
```

The EC diagram for 100 entries is shown in Figure 2.3. This design uses less memory and has better health than the `TreeMap` design. The memory cost is reduced from 6,048 to 3,664 bytes, and the overhead is reduced from 74% to 56%. There are two reasons for this improvement. First, the timestamps and values are not boxed. They are stored as primitive double fields in each `Sample`. This reduces the number of objects needed to store the actual data from 200 to 100. Fewer objects means fewer object headers and pointers, which is significant in this case. Secondly, an `ArrayList` has lower infrastructure cost than a `TreeMap`. `ArrayList` is one of the most memory-efficient Java collections. It is implemented using a wrapper object and an array of pointers. This is much more compact than the heavy-weight `TreeMap`.

While this is a big improvement, 56% overhead still seems high. Over half the memory is being wasted. How hard is it to get rid of this overhead completely?

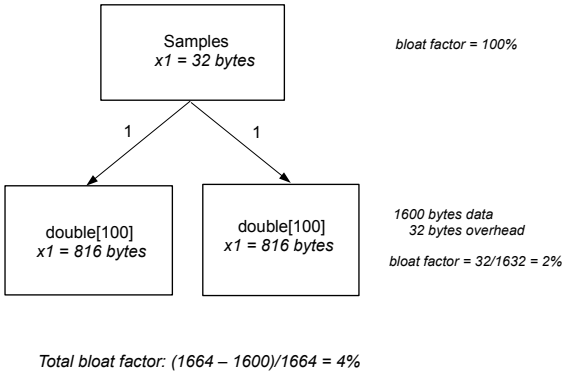


Figure 2.4. EC Diagram for 100 samples stored in two parallel arrays

Eliminating overhead means eliminating objects altogether. This is not a recommended practice, unless memory is extremely tight, and there is no other choice. It is none the less an interesting exercise to compare a best case design with the other designs. The most space-efficient design uses two parallel arrays of doubles. One array stores all of the sample timestamps, and the second stores all of the values. These arrays can be stored in a wrapper class that implements a map interface.

This design requires a bit more code, but, again, it is not excessive. Like the `Collections` class, the `Arrays` class provides static `sort` and `binarySearch` methods. However, these methods apply only to a single array. If you sort the timestamp array, you will lose the association between the timestamps and their corresponding values. You can use an extra temporary array to get around this problem. The implementation is left as an exercise. The EC diagram for this design using two double arrays is shown in Figure 2.4. The overhead is only 4%.

For the three designs presented, there is a tradeoff between ease of programming and memory efficiency. More programming is needed as the design becomes more memory efficient. However, in many cases, memory efficient designs are just as easy to implement as inefficient designs. When there are two distinct execution phases, as in this example, the data structure can be trimmed after the first phase, to eliminate empty space reserved for growth. Another option is to use one data structure in the first phase, and copy it into a second data structure for the second phase. This approach can sometimes be a good compromise between ease-of-programming and memory efficiency.

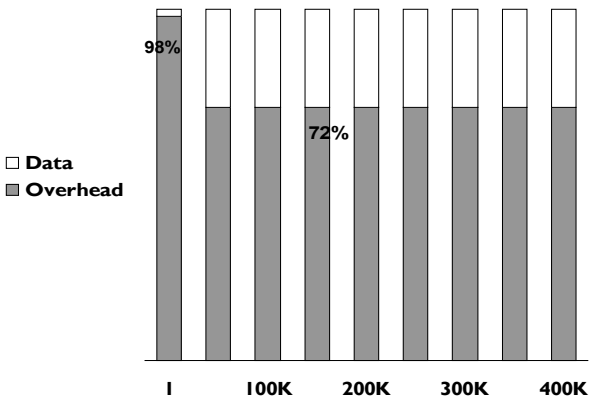


Figure 2.5. Health Measure for the `TreeMap` Design Shows Poor Scalability

2.4 Scalability

The evaluation of the three monitoring system designs was based on only 100 samples. In a real scenario, a monitoring system might have to handle hundreds of thousands, or millions, of samples. Stress testing is usually performed late in a development cycle, when it is very costly to fix a memory footprint problem. Using a memory health approach, it possible to predict how well a data structure design will scale much earlier.

The basic question for predicting scalability is what happens to the bloat factor as a data structure grows. The `TreeMap` design has 74% overhead with 100 samples. With 100,000 samples, maybe the high overhead will be amortized away. Maybe this design will scale well, even if it is inefficient for small data sizes. The bar graph in Figure 2.5 shows how the `TreeMap` design scales as the number of samples increase. Each bar is split into two parts: the percentage of overhead and the percentage of data. For a single sample, the overhead is 98%! As more samples are added, the bloat factor drops to 72%. Unfortunately, with 200,000 samples, and 300,000 samples, the bloat factor is still 72%. The `TreeMap` design is not only bloated, but it also does not scale. It is constantly bloated.

To understand why this happens, recall that the infrastructure of `TreeMap` is made up of nodes, with two 64-element arrays hanging off of each node. As samples are added, the infrastructure grows, since new nodes and arrays are being created. Also, each additional sample has its own overhead, namely the JVM overhead in each `Double` object. When the `TreeMap` becomes large enough, the *per-entry overhead* dominates and hovers around 72%. The bloat factor is larger when the `TreeMap`

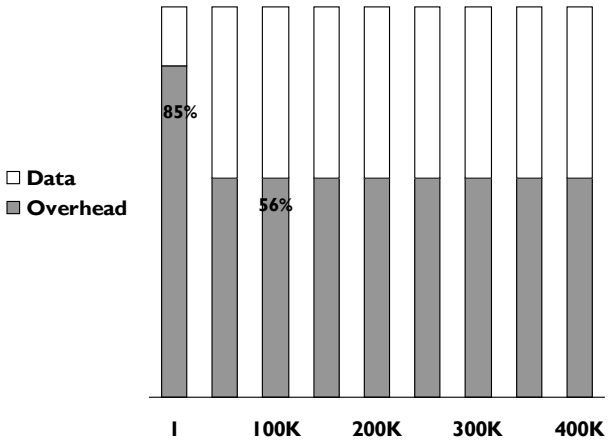


Figure 2.6. Health Measure for the `ArrayList` Design

is small. In contrast, for small `TreeMap`s, the fixed cost of the initial `TreeMap` infrastructure is relatively big. The `TreeMap` wrapper object alone is 48 bytes. This initial fixed cost is quickly amortized away as samples are added.

Fixed vs Per-Entry Overhead

The memory overhead of a collection can be classified as either *fixed* or *per-entry*. Fixed overhead stays the same, no matter how many entries are stored in the collection. Small collections with a large fixed overhead have a high memory bloat factor, but the fixed overhead is amortized away as the collection grows. Per-entry overhead depends on the number of entries stored in the collection. Collections with a large per-entry overhead do not scale well, since per-entry costs cannot be amortized away as the collection grows.

Figure 2.6 shows similar data for the `ArrayList` design. Like the `TreeMap` design, there is a fixed overhead, which is significant when the `ArrayList` is small. As the `ArrayList` grows, the fixed overhead is amortized away, but there is still a per-entry cost of 56%, that remains constant.

For the last design that uses arrays, there is only fixed overhead, namely, the `Samples` object and JVM overhead for the arrays. There is no per-entry overhead at all. Figure 2.7 shows the initial 80% fixed overhead is quickly amortized away. When more samples are added, the bloat factor becomes 0. The samples themselves are pure data.

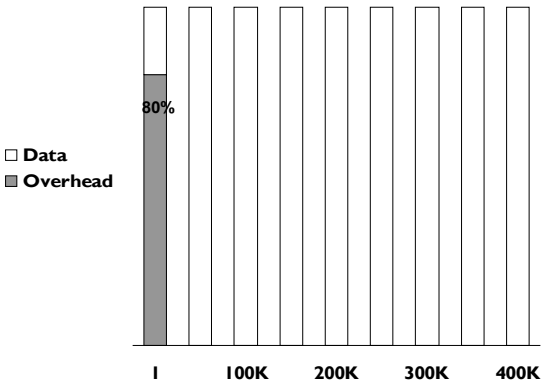


Figure 2.7. Health Measure for the Array-Based Design Shows Perfect Scalability

This analysis helps predict the memory requirements for large sample sizes. Suppose the monitoring system needs to process 10 million samples. The data alone takes up 160 million bytes (153MB). The graphs shown in this section can be used to quickly calculate how much memory you will need. For the `TreeMap` design, the overhead cost is 72%, so you will need 546MB to store the samples. For the `ArrayList` design, you will need 347MB. For the `array` design, you will need only 153MB. As these numbers show, the design choice can make a huge difference.

2.5 Summary

When you are developing a large application, closing your eyes to quantitative considerations and thinking everything is going to be fine is risky. Taking the time to measure the cost and health of your data design can pinpoint problems early on. This chapter described three conceptual tools to help evaluate the memory-efficiency of a design.

- The *memory bloat factor* measures how much of your the memory usage of your design is real data, and how much is an artifact of the way you have chosen to represent it. This metric tells you how much room there is for improvement, and if in fact you are paying a reasonable price for what you are getting.
- Complex data structures are built up from data entities and collections of these entities. The *Entity-Collection (EC) Diagram* shows the costs associated with the different parts of a complex data structure. These diagrams help you to compare the memory efficiency of different representation choices.
- By classifying the overhead of a collection as either *fixed* or *per-entry*, you can predict how much memory you will need to store very large collections. Being able to predict scalability is critical to meeting the requirements of larges applications.

These are the basic tools used in the rest of this book. To estimate the cost of an entity, you will need to know how many bytes each primitive type needs, what is the pointer size, and what the JVM overhead is. You will learn how to estimate the cost of entities in Chapter 4. To estimate scalability, you will need to know what the fixed and per-entry costs are for the collection classes you are using. These are given in Chapter 7.

Chapter 3

OBJECTS AND DELEGATION

An important design decision when modeling data is how many Java classes to use to represent a logical concept. The choices made at this design stage can impact memory costs significantly. At one extreme, a single class may store all attributes. At the other extreme, a main class may delegate many of its attributes to other classes, resulting in a fine-grained design. Delegation is a very popular pattern because of the flexibility it provides. It is also one of the few ways Java allows you to reuse existing classes. Yet, overly fine-grained data models can result in poor memory health. This chapter explains how to evaluate the granularity of a design from a memory perspective. It begins with the costs of basic objects, and moves on to examples from real applications.

3.1 The Cost of Objects

There is no Java library method that returns the size of an object. This is by design. Unlike systems languages like C, a Java programmer is not supposed to know either the size of an object or how it is laid out in memory. The JRE, not the programmer, manages storage, and the JRE has the freedom to implement its own storage policy. However, knowing the sizes of objects is necessary for understanding memory requirements and scalability. Fortunately, it is not hard to estimate the size of an object, and a good estimate of the most prevelant classes is usually sufficient for making intelligent design choices. You need to know just a few basics, starting with the number of bytes needed to store primitive data types. These sizes are defined in the Java language specification [1], and are given in Table 3.1. Fields can also be reference fields, pointing to other objects. Their size depends on the architecture of the JRE. They are 4 bytes on a 32-bit JRE.

Object-level overhead Objects are bigger than the sum of their fields, and their size depends on the specific JRE implementation. The JRE allocates a header with each object that stores information such as the object's class, an identity hashcode, a monitor used for locking, and various flags. For array objects, the header has an additional integer to store the number of array elements. Additionally, the JRE requires objects to be aligned on specific address boundaries, for example, addresses that are multiples of 8. To show how implementations differ, Table 3.2 gives object

Data type	Number of bytes
boolean, byte	1
char, short	2
int, float	4
long, double	8
reference (32-bit JRE)	4

Table 3.1. The number of bytes needed to store primitive data and reference fields.

	Sun Java 6 (u14)	IBM Java 6 (SR4)
Object header size	8 bytes	12 bytes
Array header size	12 bytes	16 bytes
Object alignment	8 byte boundary	8 byte boundary
Minimum field alignment	1 byte boundary	4 byte boundary

Table 3.2. Object overhead used by the Sun and IBM JREs for 32-bit architectures.

		Sun Java 6 (u14)			IBM Java 6 (SR4)		
Class	Data size	Header	Alignment fill	Total bytes	Header	Alignment fill	Total bytes
Boolean, Byte	1	8	7	16	12	3	16
Character, Short	2	8	6	16	12	1	16
Integer, Float	4	8	4	16	12	0	16
Long, Double	8	8	0	16	12	4	24

Table 3.3. The sizes of boxed scalar objects, in bytes, for 32-bit architectures.

header and alignment costs imposed by two JREs, Sun Java 6 (Update 14) and IBM Java 6 (Service Release 4), both for 32-bit architectures. [1]

The simplest objects are the boxed scalars, which are objects with a single primitive data type field. Since both of these JREs align objects on 8-byte boundaries and object headers are at least 8 bytes, a boxed scalar takes at least 16 bytes. Table 3.3 gives the sizes of boxed scalars.

Field-level overhead Estimating the size of an object with more than one field is a bit more complicated, since the hardware imposes additional alignment requirements on specific data types. For example, integer fields are usually aligned on 4 byte boundaries. This field alignment potentially introduces more padding.

For example, consider a class `SimpleEmployee`, which has all primitive fields. The comments show the number of bytes needed to store the primitive data.

```
class SimpleEmployee {
    int id;             // 4 bytes
```

[1] Unless otherwise noted, all of the numbers throughout the book are based on the Sun JRE for 32-bit architectures. Appendix A gives information needed to estimate sizes in various environments.

```
    int hoursPerWeek;   // 4 bytes
    boolean exempt;     // 1 byte
    double salary;      // 8 bytes
    char jobCode;       // 2 bytes
    int yearsOfService; // 4 bytes
}
```

If the fields are laid out one after the other with no fill, then the field `salary` would have to begin on a 5-byte boundary, which is not allowed for `doubles`. To avoid adding 3 more bytes of padding, the JRE could rearrange the fields to take up the smallest amount of space. In fact, the Sun JRE does a good job rearranging and packing fields, and the IBM JRE does not. This means that field sizes depend on the specific JRE also.

Using the Sun JRE, you can assume each field is the size of its primitive data type because the fields are packed. The size of a `SimpleEmployee` object is 32 bytes:

```
8 + (4+4+1+8+2+4) = 31 bytes, rounds up to 32 bytes
```

In contrast, using the IBM JRE, all fields in non-array objects are either 4 or 8 bytes. Here is the `SimpleEmployee` class with field sizes adjusted accordingly.

```
class SimpleEmployee {
    int id;               // 4 bytes
    int hoursPerWeek;     // 4 bytes
    boolean exempt;       // 4 byte
    double salary;        // 8 bytes
    char jobCode;         // 4 bytes
    int yearsOfService;   // 4 bytes
}
```

The size of a `SimpleEmployee` is 40 bytes:

```
12 + (4+4+4+8+4+4) = 40 bytes, with no object alignment
    needed
```

Arrays For arrays, the data is always packed with no spaces. For example, here is a formula that estimates the size of an array of 100 `chars`:

```
header + 100*2, round up to a multiple of the object
    alignment
```

Class	Number of objects	Size in bytes
String (8-character)	2	56
Date	1	24
BigDecimal	usually 1, up to 5	32, when 1 object
Enum	0	one shared object per enum constant

Table 3.4. Memory requirements for the most common field types that are implemented as separate objects. Sizes do not include a referring pointer.

Estimating Object Sizes

The size of an object can be estimated as follows:

1. Add together the sizes of all of the fields and the object header. Fields include those in the object's class and all of its superclasses.
2. Round up the result to the next multiple of the object alignment.

The object header size and alignment depend on the JRE. Field sizes also depend on the JRE. For example, the JRE may pack fields to obtain the minimum possible size, or align fields on word boundaries. Array data is always packed.

For objects with only a small amount of primitive data, the overhead is relatively high. But as the amount of primitive data increases, the bloat factor decreases. The overhead cost consists of a fixed object header cost and a bounded alignment cost, which are amortized when the object is big. For example, for the Sun JRE, the bloat factors for the boxed scalars range from 94% for a `Boolean` down to 50% for a `Double`. The bloat factor for a `SimpleEmployee` is 28%. The bloat factor for an array of 100 `char`s is insignificant. An exception to this rule is when objects have a lot of fields such as `boolean`s, that carry very little data. These objects will have a high bloat factor, especially if the JRE doesn't pack fields tightly. In that case, the more fields, the more overhead.

3.2 The Cost of Delegation

The `SimpleEmployee` class is not very realistic, since it has only primitive fields. Usually, a class has some fields that are objects. In Java, this kind of field is implemented using *delegation*, that is, by storing a reference to another object. Some of the most common field types are modeled this way, requiring one or more separate objects. Table 3.4 shows the space needs of a few common ones.

Here is a more realistic employee class with several reference fields. An employee now has a name, which is a `String`, instead of an integer id. It also has a start date,

which is a `Date`. The type of `salary` has been changed from `double` to `BigDecimal`. `BigDecimal` avoids potential roundoff errors.

```
class Employee {
    String name;              // 4 bytes
    int hoursPerWeek;         // 4 bytes
    BigDecimal salary;        // 4 bytes
    Date startDate;           // 4 bytes
    boolean exempt;           // 1 byte
    char jobCode;             // 2 bytes
    int yearsOfService;       // 4 bytes
}
```

On 32-bit architectures, a pointer is 4 bytes. You can calculate the size of any object as described in Section 3.1. Assuming the Sun JRE, the size of an Employee object is 32 bytes:

```
8 + (4+4+4+4+1+2+4) = 31, rounds up to 32 bytes
```

While an instance of the `Employee` class is a single 32 byte object, an entire employee, including name, salary, and start date consists of at least five objects. Two of these objects are used to store the name. (Recall from Section 2.1 that a string is represented by a wrapper `String` object and a `char` array.) `BigDecimal` usually requires 1 object but can take up to 5 depending on the usage. The memory layout for a specific employee "John Doe" is shown in Figure 3.1.

A comparion of a `Employee` object with a `SimpleEmployee` object from Section 3.1 shows that the size has increased from 32 to 144 bytes, and the bloat factor has increased from 28% to 65%. There is more information stored in the new version, so it is no surprise that it is bigger. The increase in the bloat factor is more significant. Delegation increases memory bloat. Delegation introduces additional object headers, a pointer for each delegated object, including empty pointer slots for uninitialized object fields. Delegation may also force additional alignment costs, since each new delegated object has to be aligned to an 8-byte boundary.

In the spirit of keeping things simple, Java does not allow you to nest objects inside other objects, to build a single object out of other objects. You cannot nest an array inside an object, and you cannot store objects directly in an array. You can only point to other objects. Even the basic data type `String` consists of two objects. This means that delegation is pervasive in Java programs, and it is difficult to avoid a high level of delegation overhead. Single inheritance is the only language feature that can be used instead of delegation to compose two objects, but single inheritance has limited flexibility. In contrast, C++ has many different ways to compose objects. C++ has single and multiple inheritance and union types. C++ allows you to have fields that are `classes`, `structs`, or arrays, not just references to them. Similarly, you can have arrays of `class` or `struct`.

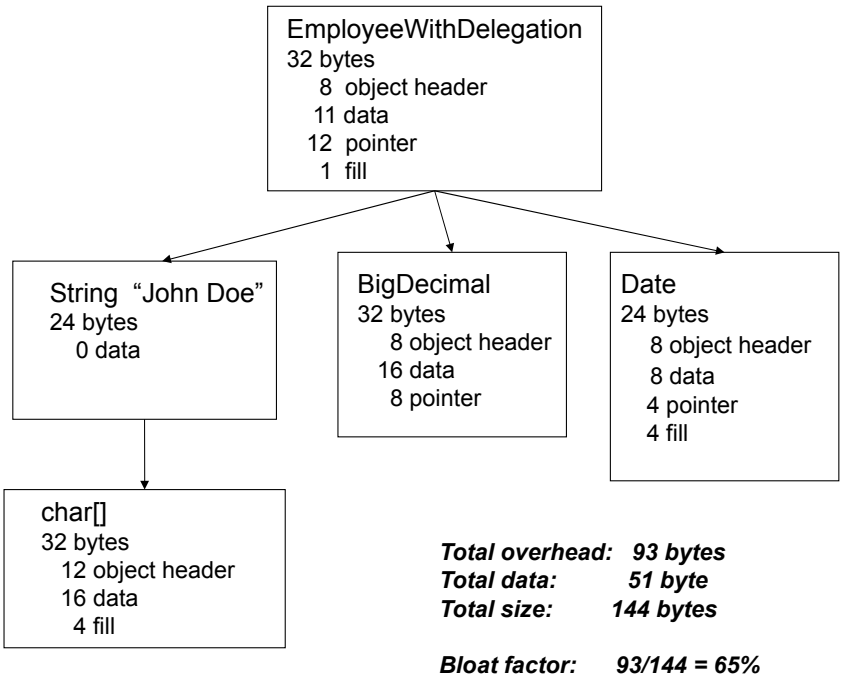


Figure 3.1. The memory layout for an employee, with some field data delegated to additional objects.

Because of the design of Java, there is a basic delegation cost that is hard to eliminate. This is the cost of object-oriented programming in Java. While it is hard to avoid this basic delegation cost, it is important not to make things a lot worse, as discussed in the next section.

3.3 Fine-Grained Data Models

The software engineering culture tends to promote delegation, and for good reasons. Delegation provides a loose coupling of objects, making refactoring and reuse easier. Replacing inheritance by delegation is often recommended, especially if the base class has extra fields and methods that the subclass does not need. In languages with single inheritance, once you have used up your inheritance slot, it becomes hard to refactor your code. Therefore, delegation can be more flexible than inheritance for implementing polymorphism. However, overly fine-grained data models can be expensive both in execution time and memory space.

There is no simple rule that can always be applied to decide when to use delegation. Each situation has to be evaluated in context, and there may be tradeoffs among different goals. To make an informed decision, it is important to know what the costs are.

Example Suppose an emergency contact is needed for each employee. An emergency contact is a person along with a preferred method to reach her. The preferred method can be email, cell phone, work phone, or home phone. All contact information for the emergency contact person must be stored, just in case the preferred method does not work in an actual emergency. Here are class definitions for an emergency contact, written in a highly delegated style that is not uncommon in real applications.

```
class EmployeeWithEmergencyContact {
    ...
    EmergencyContact contact;
}

class EmergencyContact {
    ContactPerson contact;
    ContactMethod preferredMethod;
}

class ContactPerson {
    String name;
    String relation;
    EmailAddress email;
    PhoneNumber phone;
```

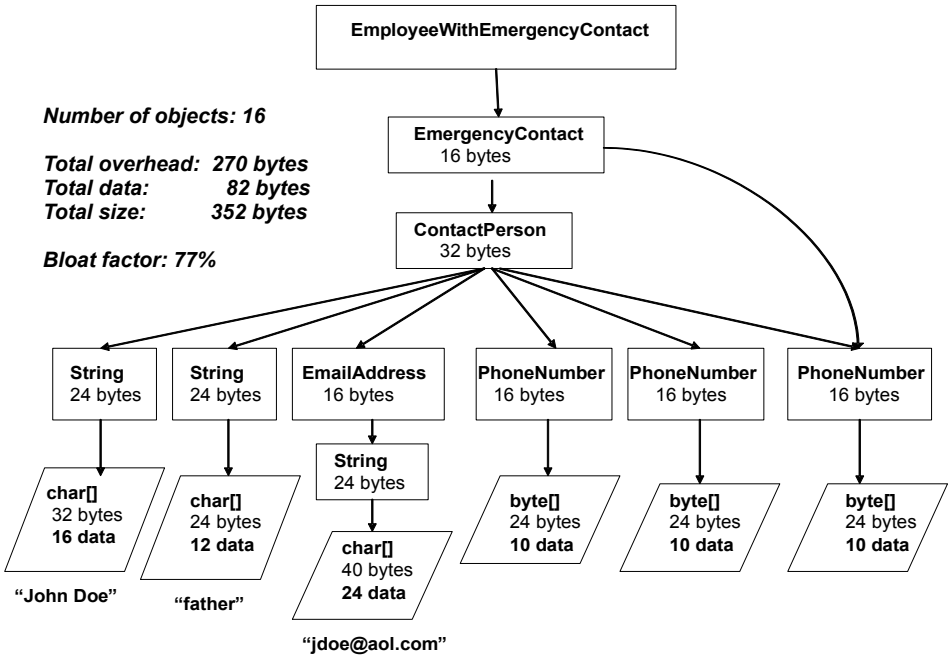


Figure 3.2. The memory layout for an employee with an emergency contact, using a fine-grained design.

```
    PhoneNumber cell;
    PhoneNumber work;
}

abstract class ContactMethod {
}

class PhoneNumber extends ContactMethod {
    byte[] phone;
}

class EmailAddress extends ContactMethod {
    String address;
}
```

The memory layout for a sample employee is shown in Figure 3.2. There are 15 objects used to store emergency contact information, with a bloat factor of 77%, which

seems excessive. The objects are all small, containing only one or two meaningful fields, which is a symptom of an overly fine-grained data model. Also, all of the data is at the bottom of object chains, 4 to 5 objects long. Refactoring can flatten this structure somewhat.

Example, optimized One object that looks superfluous is `EmergencyContact`, which encapsulates the contact person and the preferred contact method. Removing this delegation involves moving the fields of `EmergencyContact` into other classes, and eliminating the `EmergencyContact` class. Here are the refactored classes:

```
class EmployeeWithEmergencyContact {
    ...
    ContactPerson contact;
}

class ContactPerson {
    String name;
    String relation;
    EmailAddress email;
    PhoneNumber phone;
    PhoneNumber cell;
    PhoneNumber work;
    ContactMethod preferredMethod;
}
```

This change eliminates an object from Figure 3.2, but it only recovers 8 bytes, since a 16 byte object is removed and `ContactPerson` is 8 bytes bigger. You can save considerably more space by inlining the four `ContactMethod` classes into the `ContactPerson` class, which removes 64 bytes of overhead. In a system with many instances of employees stored in memory, this reduction is significant. In order to make this change, the preferred contact method must be encoded somehow in `ContactPerson`. A simple way to achieve this is to use an enumerated type field, which has the same size as a reference field, to discriminate among the different contact methods:

```
enum PreferredContactMethod {
    EMAIL, HOME_PHONE, CELL_PHONE, WORK_PHONE;
}

class ContactPerson {
    PreferredContactMethod preferredMethod;
    String name;
    String relation;
    String email;
```

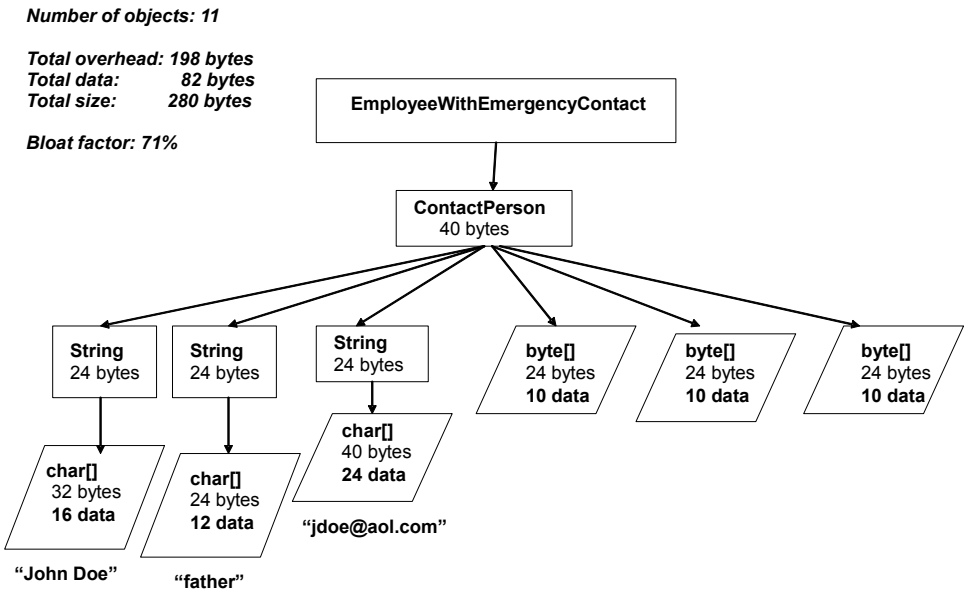


Figure 3.3. The memory layout for an emergency contact, with a more streamlined design.

```
    byte[] cellPhone;
    byte[] homePhone;
    byte[] workPhone;
}
```

Figure 3.3 shows the memory layout after these changes. Both the size and the bloat factor have been reduced.

When many objects are used to represent one logical concept, this is an indication that the data model may be using too much delegation. Delegation is good, but it is possible to overuse a good thing. A design with fewer, bigger objects has less overhead and is more scalable. Whenever you use delegation, there should be a good reason. This is especially true for the important data entities in an application, those that will determine the scalability of the program.

3.4 64-bit Architectures

If your application does not fit into memory, perhaps moving to a 64-bit architecture will save you. However, to support a 64-bit address space, more memory is required.

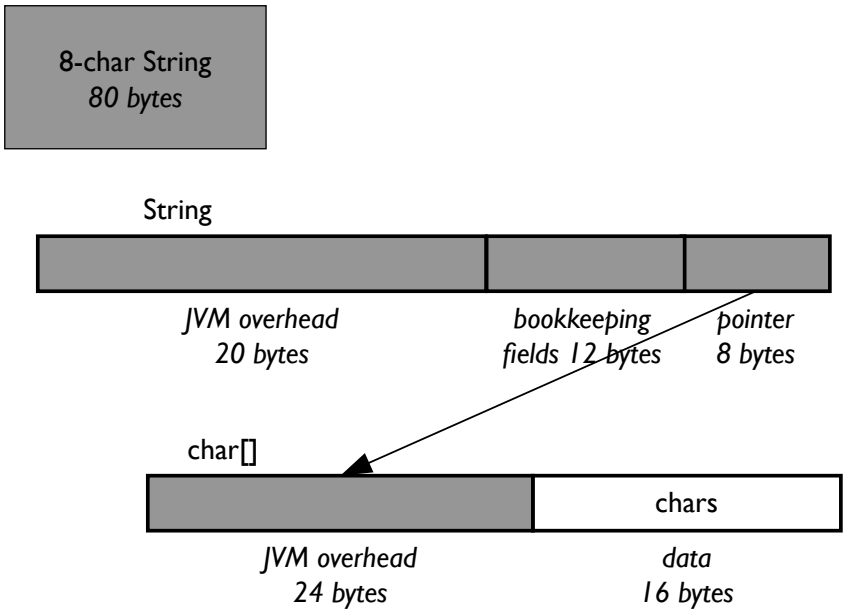


Figure 3.4. The memory layout for an 8-character string on a 64-bit JRE.

Object header sizes double, and pointers are 8 bytes instead of 4. Some studies [2] show that memory consumption can increase by 40%-50% going from a 32-bit to a 64-bit address space for the same Java program.

Consider what happens to the 8-character string from Section 2.1 in a 64-bit JRE. The memory layout is shown in Figure 3.4. The 64-bit string is 43% bigger than the 32-bit string. All of the additional cost is overhead. Fine-grained designs and those with a lot of pointers will suffer the most when moving to 64-bit architectures.

Fortunately, in practice things are not always so bad. Both the Sun and the IBM JREs have implemented a scheme for compressing addresses that avoids this blowup, provided that the heap is less than 32 gigabytes. Address compression is implemented by stealing a few unused bits from 32-bit pointers. Objects are laid out just like in a 32-bit address space. During execution, 32-bit compressed addresses are converted into 64-bit native addresses, and vice-versa. See Appendix A for the specifics of using this feature.

3.5 Summary

The decision to delegate functionality to another object sometimes involves making a tradeoff between flexibility and memory cost. You need to decide how much flexibility is really needed, and you also need to be aware of the actual memory costs. This chapter provides the basic knowledge for estimating memory costs.

- An object size depends on the object header size, field alignment, object align-

ment, and pointer size. These can vary, depending on the JRE and the hardware. The size of an object is the sum of the header and the field sizes, rounded up to an alignment boundary.

If you need the exact size of objects, there are various tools available. A list of resources is provided in the Appendix.

This chapter also describes several costly anti-patterns to avoid.

- A *highly-delegated data model* results in too many small objects and a large bloat factor. Typically, each object has only a few fields, which is excessive data granularity.
- A *highly-delegated data model with large base classes* results in too many big objects. Often, the data model is providing a fine granularity of function, which may no be needed.

Both the design of Java and software engineering best practices encourage highly delegated data models with many objects. This cost is often considered to be insignificant — delegating to another object is just a single level of indirection. But the costs of the pointers and object headers needed to implement delegation indirection add up quickly, and contribute significantly to large bloat factors in real applications.

Chapter 4

FIELD PATTERNS FOR EFFICIENT OBJECTS

[TODO: Fix word wrap in source listings]

In many applications, the heap is filled mostly with instances of just a few important classes. You can increase scalability significantly by making these objects as compact as possible. This chapter describes field usage patterns that can be easily optimized for space, for example, fields that are rarely needed, constant fields, and dependent fields. Simple refactoring of these kinds of fields can sometimes result in big wins.

4.1 Rarely Used Fields

Side Objects Chapter 3 presents examples where delegating fields to another class increases memory cost. However, sometimes delegation can actually save memory, if you don't have to allocate the delegated object all the time.

As an example, consider an on-line store with millions of products. Most of the products are supplied by the parent company, but sometimes the store sells products from another company:

```
class Product {
    String sku;
    String name;
    ..
    String alternateSupplierName;
    String alternateSupplierAddress;
    String alternateSupplierSku;
}
```

When there is no alternate supplier, the last three fields are never used. By moving these fields to a separate side class, you can save memory, provided the side object is allocated only when it is actually needed. This is called *lazy allocation*. Here are the refactored classes:

```
class Product {
    String sku;
    String name;
    ..
    Supplier alternateSupplier;
}

class Supplier {
    String supplierName;
    String supplierAddress;
    String sku;
}
```

For products with no alternate supplier, eight bytes are saved per product, since three fields are replaced by one. Of course, products with an alternate supplier pay a delegation cost: an extra pointer and object header, totaling 12 bytes. An interesting question is how much total memory is actually saved? The answer depends on the percentage of products that have an alternate supplier and need a side object, which we'll call the *fill rate*. The higher the fill rate, the less memory is saved. In fact, if the fill rate is too high, memory is wasted.

Figure 4.1 shows the memory saved for different fill rates, assuming three fields (12 bytes) are delegated. The most memory that can be saved is 8 bytes per object on average, when the fill rate is 0%. That's 67% of the size of the fields that were delegated. When the fill rate is 10%, only 50% of the delegated field bytes are saved on average. When the fill rate is over 40%, the memory saved is negative, that is, memory is wasted. The lesson here is that if you aren't sure what the fill rate is, then using delegation to save memory may end up backfiring.

In addition to the fill rate, the memory savings also depends on the number of fields delegated and their sizes. The more bytes delegated, the larger the memory savings, assuming the same fill rate. Figure 4.2 shows the memory saved or wasted for different fill rates and delegated-field sizes. Each line represents a different delegated-field size. The bottom-most line represents a delegated field size of 16 bytes, the next line represents 32 bytes, the next represents 48 bytes, and so on, up to 144 bytes. As the delegated object size increases, you can worry less about the fill rate. For example, if 32 bytes are delegated, there is almost 90% savings with a low fill rate, and some memory savings with a fill rate up to 70%. As the delegation size increases, the lines start to converge, since the delegation overhead becomes less important. At larger sizes there is less of a chance that underestimating the fill rate will cause you to waste memory, and if it does, the memory lost will be relatively small.

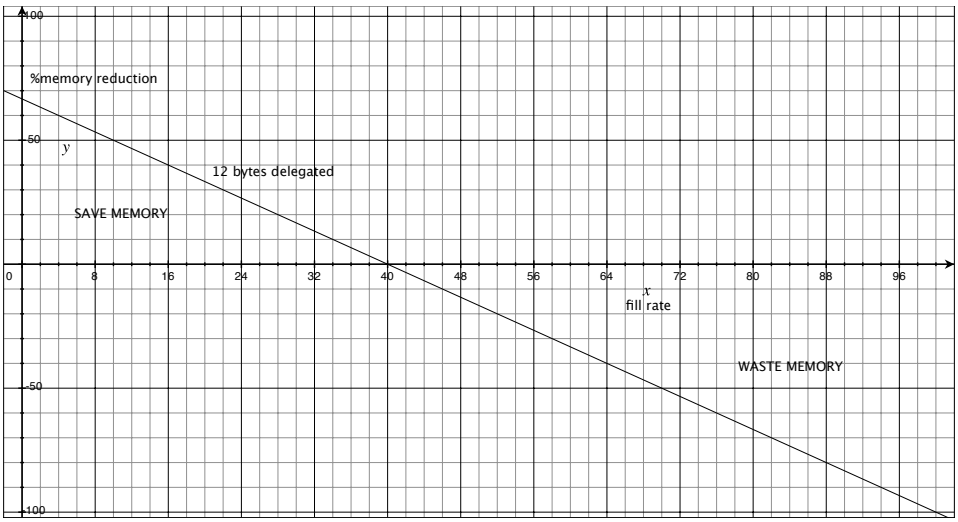


Figure 4.1. This plot shows how much memory is saved or wasted by delegating 12 bytes of memory to a side object. The x-axis is the fill rate, and the y-axis is the average memory saved as a percent of the bytes delegated.

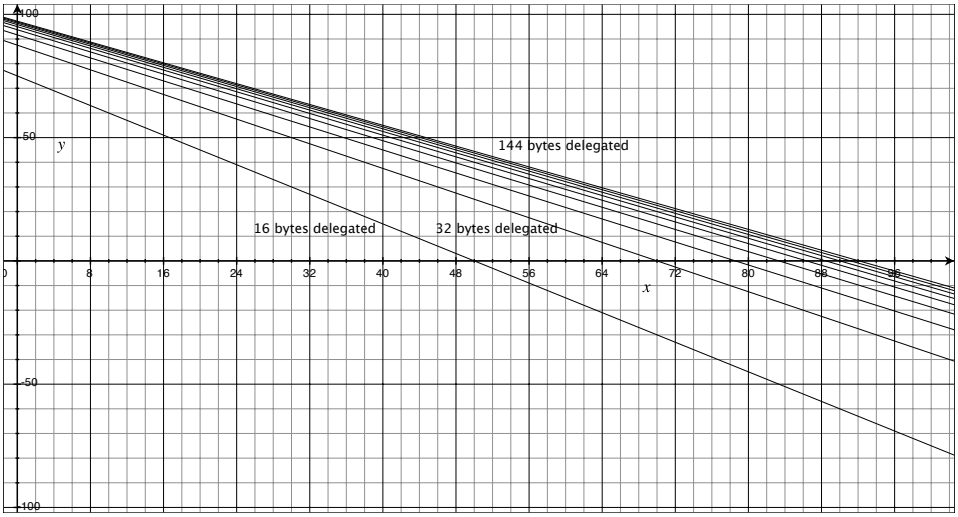


Figure 4.2. This plot shows how much memory is saved or wasted depending on how many bytes are delegated to a side object. The x-axis is the fill rate, and the y-axis is the average memory saved as a percent of the bytes delegated. Each line represents a different delegated-fields size, from 16 to 144 bytes, in increments of 16 bytes.

Delegation Savings Calculation

Assume the cost of a pointer is 4 bytes, and the cost of an object header is 8 bytes. Let:

$$B = \textit{the size in bytes of the delegated fields}$$
$$F = \textit{the fill rate, between } 0 \textit{ and } 1$$

While every object pays a 4-byte pointer cost, only F of them pay for a side object. Therefore, using a side object will result in an average savings per object of:

$$B - 4 \quad - \quad F(B + 8)$$

For the savings to be positive, the following must be true [a]:

$$F < \frac{B-4}{B+8}$$

[a] This calculation does not include alignment overhead. Delegating fields to a side object may increase alignment costs, depending on the other fields in your object. If the header size is not a multiple of the alignment (e.g. on the IBM 32-bit JRE), delegation can sometimes reduce alignment costs.

A common error is to put rarely used fields in a side class with lazy allocation, but have code paths that cause the side object to be allocated all the time, even when it's not needed. In this case, instead of saving memory, you pay the full cost of delegation as well as the cost of unused fields. Lazy allocation can also be error-prone because it may require testing whether the object exists at every use. If you need concurrent access to the data in the side object, you have to take special care to code the checks correctly to avoid race conditions. This complexity has to be weighed against potential memory savings.

Side Tables If a field is very rarely used, then it might make sense to delete it from its class altogether, and store it in a separate table that maps objects to attribute values. For example, suppose that only a few of the products have won major awards, and you want to record this information. Rather than maintaining a field `majorAward` in every product, you can define a table that maps a product `sku` to an award.

```
class Product {
    static HashMap<String, String> majorAward =
        new HashMap<String, String>();
    ..
}
```

Even though a `HashMap` has its own high overhead, this design can come out ahead if there are a small number of major awards. You can do a similar analysis as you would for side objects to decide if this approach is worth it. A hash entry typically takes more memory than a side object (see Section **??**). Therefore, a side table will start wasting memory at a lower fill rate than would a side object approach. Whenever you add a new table like this you also have to be careful not to introduce a memory leak. If products are no longer needed and are garbage collected, the corresponding entries in the table must be cleaned up. This topic is discussed at length in Section **??**.

Subclassing The least expensive way to model rarely used fields is to move them to a subclass. Unlike the optimizations we've discussed, subclassing costs no extra space. It can have some disadvantages from a software engineering standpoint, though, when compared with delegation or a side table approach. It can make your code less flexible, making it more difficult to add or rearrange functionality later on. Since Java supports only single inheritance, defining a subclass for rarely used fields will prevent you from having subclasses for other purposes. Using delegation or a side table also allows your data to be more dynamic. Rarely used fields can be added after an instance is created.

4.2 Mutually Exclusive Fields

Sometimes a class has fields that are never used at the same time, and therefore they can share the same space. Two mutually exclusive fields can be conflated into one field if they have the same type. Unfortunately, Java does not have anything like a union type to combine fields of different types. However, if it makes sense, mutually exclusive field types can be broadened to a common base type to allow this optimization.

For example, suppose that each women's clothing product has a size, and there are different kinds of sizes: xsmall-small-medium-large-xlarge, numeric sizes, petite sizes, and large women's sizes. One way to implement this is to introduce a field for each kind of size:

```
class WomensClothing extends Product {
    ..
    SMLSize     smlSize;
    NumericSize numSize;
    PetiteSize  petiteSize;
    WomensSize  womensSize;
}
```

Each type is an enum class, such as:

```
enum SMLSize {
```

```
    XSMALL, SMALL, MEDIUM, LARGE, XLARGE;
}

enum NumericSize {
    ZERO, TWO, FOUR, SIX, EIGHT, TEN, TWELVE, FOURTEEN,
       SIXTEEN;
}

enum PetiteSize {
    ZERO, TWO, FOUR, SIX, EIGHT, TEN, TWELVE, FOURTEEN,
       SIXTEEN;
}

enum WomensSize {
    ONEX, TWOX, THREEX, FOURX;
}
```

These four size fields are mutually exclusive — a clothing item cannot have both a petite size and a women's size, for example. Therefore, you can replace these fields by one field, provided that the four enum types are combined into one enum type:

```
enum ClothingSize {
    XSMALL, SMALL, MEDIUM, LARGE, XLARGE,
    ZERO, TWO, FOUR, SIX, EIGHT, TEN, TWELVE, FOURTEEN,
       SIXTEEN,
    PETITE_ZERO, PETITE_TWO, PETITE_FOUR, PETITE_SIX,
       PETITE_EIGHT, PETITE_TEN,
    PETITE_TWELVE, PETITE_FOURTEEN, PETITE_SIXTEEN,
    ONEX, TWOX, THREEX, FOURX;
}

class Clothing extends Product {
    ..
    private ClothingSize  size;
    ..
    public SMLSize getSMLSize() {..}
    public void setSMLSize(SMLSize smlSize) {..}

    public NumericSize getNumericSize() {..}
    public void setNumericSize(NumericSize numericSize) {..}

    public PetiteSize getPetiteSize() {..}
    public void setPetiteSize(PetiteSize PetiteSize) {..}
```

```
    public void setNumericSize(WomensSize womensSize) {..}
    public WomensSize getWomensSize() {..}
    ..
}
```

You can easily write access and update methods that translate to and from the original types, so that the caller is insulated from this storage trick.

If the mutually exclusive fields are of different classes, you can generalize their types by defining a common superclass, if possible. As a last resort, you can always combine these fields into a single field of type `Object`. Finally, if there are sets of fields that are mutually exclusive, then you can define a side class for each set of fields, where all side classes have a common superclass. In this case, you need to do the math to make sure that you actually save memory, given the extra cost of delegation.

Just like rarely used fields, mutually exclusive fields can also be modeled using subclassing. Again, the space savings have to be weighed against other software engineering goals.

4.3 Constant Fields

Declaring a constant field `static` is a simple way to save memory. Programmers usually remember to make constants like *pi* static. There are other situations that are a bit more subtle, for example, when a field is constant because of how it is used in the context of an application.

Returning to the product example, suppose that each product has a field `catalog` that points to a store catalog. If you know that there is always just one store catalog, then the field `catalog` can be turned into a static, saving 4 bytes per product.

As a more elaborate example, suppose that a `Product` has a field referencing a `Category` object, where a category may be books, music, clothes, toys, etc. Clearly, different products belong to different categories. However, suppose we define subclasses `Book`, `Music`, and `Clothing` of the class `Product`, and all instances of a subclass belong to the same category. Now the `category` field has the same value for products in each subclass, so it can be declared static:

```
public abstract class Product {
    public abstract Category getCategory();
    ..
}

class Book extends Product {
    static Category bookCategory; // Points to the
                                  // book category object
```

```
    public Category getCategory() {return bookCategory;}
    ..
}

class Music extends Product {
    static Category musicCategory; // Points to the
                                   // music category object
    public Category getCategory() {return musicCategory;}
    ..
}

class Clothing extends Product {
    static Category clothingCategory; // Points to the
                                      // clothing category
                                      // object
    public Category getCategory() {return clothingCategory;}
    ..
}
```

Knowing the context of how objects are created and used, and how they relate to other objects, is helpful in making these kinds of memory optimizations.

4.4 Nonstatic Member Classes

Sometimes it is useful to define a class within a larger class or method. Java lets you create four kinds of nested classes, each for a different purpose. They are *static member*, *nonstatic member*, *local*, and *anonymous* classes. Instances of the latter three are always created within the context of an instance of the enclosing class. Their methods can refer back to the enclosing instance. To accomplish this, these three kinds of nested classes maintain an extra, hidden field, the `this` pointer of the enclosing instance. In contrast, instances of a static member class do not have this extra field. They are created independently of any instances of the enclosing class.

A common error is to declare a nonstatic member class when you don't really need to maintain a link with an enclosing instance. To illustrate, let's return to the example from Section 4.1, where we moved some rarely used fields into a side class, `Supplier`. Suppose we wanted to hide this decision, so that we would have the freedom to change our minds later if the optimization didn't work out. We could make `Supplier` a member class of Product, as follows:

```
class Product {
    class Supplier {
        String supplierName;
        String supplierAddress;
```

```
        String sku;
    }

    ..
    Supplier alternateSupplier;
    ..
    public void setAlternateSupplierName(String name) {
        // Lazily allocate the alternate supplier object
        if (alternateSupplier == null) {
            alternateSupplier = new Supplier();
        }
        alternateSupplier.supplierName = name;
    }
    ..
}
```

Since we didn't declare `Supplier` to be static, every instance of `Supplier` will contain an extra pointer back to the product which created it. In cases like this, a static member class can work just as well, and save the 4-byte pointer field. The only code change is to add the keyword `static` to the declaration of `Supplier`. Notice how Java makes it easy to make this mistake, since the `new` statement that creates an instance of `Supplier` looks the same either way. In the nonstatic case, it hides the fact that it's passing in the enclosing `this` pointer.

The book Effective Java [3] gives more reasons to "favor static member classes over nonstatic" when you don't need to maintain a link to the outer instance. For example, the hidden pointer can lead to a memory leak, by inadvertently holding on to the enclosing instance longer than it's needed.

4.5 Redundant Fields

A field is redundant if it can be computed on the fly from other fields, and, in principle, can be eliminated. In the simplest case, two fields store the same information but in different forms, since the two fields are used for different purposes. For example, product IDs are more efficiently compared as `ints`, but more easily printed as `Strings`. Since it is possible to convert one representation into the other, storing both forms is not necessary, and only makes sense if there is a large performance penalty from performing the data conversion. In the more general case, a field may depend on many other values. For example, you could allocate a field to store the number of items in a shopping cart, or simply compute it by adding up all of the shopping cart items.

There is a trade-off between the performance cost of a conversion or computation and the memory cost of an extra field, which has to be weighed in context. How often is the information needed and how expensive is it to compute? What's the

total memory cost? Comparing performance cost to memory cost is a bit like apples and oranges, but often it is clear which resource is most constrained. Here are several considerations to keep in mind:

- Computed `String` fields should be used only if there's a good reason, since strings have a very high overhead in Java, as we have seen.
- Computed fields are very useful when storing partial values avoids expensive quadratic computations. For example, if you need to support finding the number of children of nodes in a graph, then caching this value for each node is a good idea.

If you do need to store a computed field, make sure that you are using the most efficient representation. For example, `StringBuffer` is useful for building a character string, but is less space-efficient than `String` for storing the final result. Chapter 5 compares different ways to represent some common datatypes. Another thing to watch for is storing many copies of the same computed value. Even something as simple as an empty `String` will add up if you have a lot of them. Chapter 6 looks at ways to share read-only data.

4.6 Large Base Classes and Fine-grained Designs

As discussed in the previous chapter, highly-delegated data models can result in too many small objects. Occasionally, you run across a highly-delegated data model where the delegated objects are large. This can happen when delegated classes inherit from a large base class. When fine grained data modeling is combined with inheriting from large base classes, memory costs multiply and can become prohibitive.

A frequent data management requirement is to track creation and update information, that is, when data is created or updated and by whom. Here is a base class, taken from a real application, that stores create and update information.

```
class UpdateInfo {
     Date creationDate;
     Party enteredBy;
     Date updateDate;
     Party updatedBy;
}
```

You can track changes by subclassing from `UpdateInfo`. Update tracking is a *cross-cutting feature*, since it can apply to any class in a data model.

Returning to the original, unoptimized version of `EmployeeWithEmergencyContact` in Section 3.3, suppose that updates to employee emergency contacts need to be tracked. You need to decide how fine the tracking should be. Should every update to every phone number and email address be tracked, or is it sufficient to track the

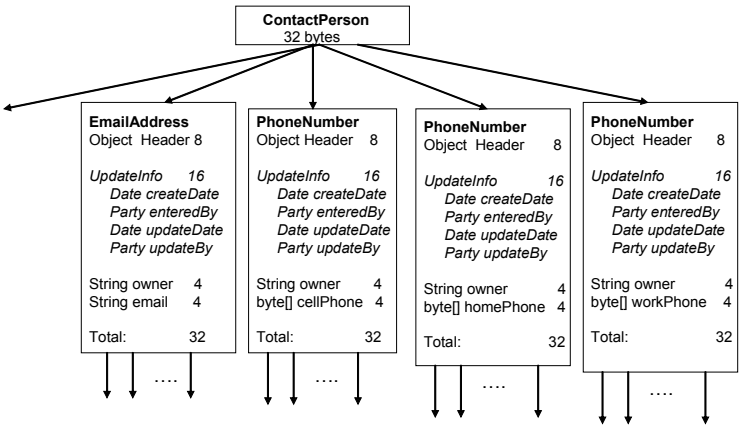


Figure 4.3. The cost of associating `UpdateInfo` with every `ContactMethod`.

fact that some contact information was changed for an emergency contact? If you decide to track changes to every contact phone number or email address, you can easily achieve this by extending the `ContactMethod` class defined in the fine-grained data model from Section 3.3:

```
abstract class ContactMethod extends UpdateInfo {
}
```

Figure 4.3 shows an instance of a contact person with update information associated with every `ContactMethod`. Not only is this a highly delegated structure with multiple `ContactMethod` objects, but each one has an additional 16 bytes. Furthermore, there are potentially four more objects of type `Date` and `Party` for each of the four `ContactMethod` objects. A far more scalable solution is to move up a level, and track changes to each `ContactPerson`. With this solution, you do not need such a fine-grained data model, and the update tracking functionality is 1/4 the cost.

The solution in Figure 4.3 provides a very fine granularity of functionality. An argument can be made in favor of this solution, since you lose functionality and flexibility if you only track updates to `ContactPerson`. However, if the program hits a scalabity problem, it may not be possible to be this casual with memory. Also, an alternate design may be available that gives the desired functionality in a more memory-efficient way. In this example, you could implement an update log instead of tracking updates in the objects themselves. Assuming updates are sparse, this is a much better solution. It is very easy define a subclass without looking closely at the memory size of its superclasses, especially if the inheritance chain is long.

4.7 Writing Efficient Framework Code

The storage optimizations described in this chapter assume that you are familiar with the entire application you are working on. You need to understand how objects are created and used, and therefore know enough to determine whether these optimizations make sense. However, if you are programming a library or framework, you have no way of knowing how your code will be used. In fact, your code may be used in a variety of different contexts with different characteristics. Premature optimization — making an assumption about how the code will be used, and optimizing for that case — is a common pitfall when programming frameworks.

For example, suppose the online store is designed as a framework that can be extended to implement different kinds of stores. For some stores, most products may have an alternate supplier. For other stores, most products may not. There is no way of knowing. If the `Product` class is designed so that the alternate supplier is allocated as a side object, then sometimes memory will be saved and sometimes wasted. One possibility is to define two versions of the `Product` class, one that delegates and one that doesn't. The framework user can then use the version that is appropriate to the specific context. However, this is generally not practical.

Frequently, decisions are made that trade space for time. There are many instances of this trade-off in the Java standard library. For example, lets look at `String`, which has three bookkeeping fields: an offset, a length, and a hashcode. These 12 bytes of overhead consume 21% of an eight character string. The offset and length fields implement an optimization for substrings. That is, when you create a substring, both the original string and substring share the same character array, as shown in Figure 4.4. The offset and length fields in the substring `String` object specify the shared portion of the character array. This scheme optimizes the time to create a substring, since there is no new character array and no copying. However, every string pays the price of the offset and length field, whether or not they are used. In practice, most Java applications have far more strings than substrings[], so a lot of memory is wasted. Even when there are many substrings, if the original strings go away, you have a different footprint problem, namely, saving character arrays which are too big.

The third bookkeeping field in `String` is a hashcode. Storing a hashcode seems like a reasonable idea, since it is expensive to compute it repeatedly. However, you have to be puzzled by the space-time trade-off, since a string only needs its hashcode when it is stored in a `HashSet` or a `HashMap`. In both of these cases, the `HashSet` or `HashMap` entry already has a field for hashcode for each element. [1]

This is a cautionary tale of premature optimization. Framework decisions can have a long-lived impact. At the same time, it is difficult to test new frameworks in realistic settings, or to even predict how they will be used. For these `String`

[1] There may be some benefit in saving the hashcode in a `String` that's used for looking up a map entry, but only when the same `String` object is used for lookup repeatedly.

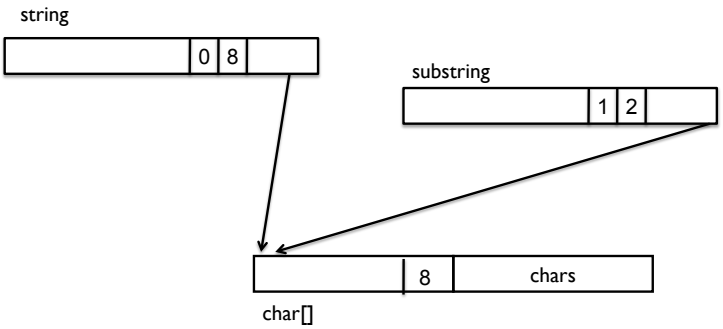


Figure 4.4. A string and a substring share the same character array. The length and offset fields are needed only in substrings. In all other strings, the offset is 0 and the length is redundant.

optimizations, it's not clear that there is any performance gain in real-world applications, as opposed to benchmarks. Meanwhile all applications must pay the price in memory footprint.

4.8 Summary

Even though Java does not let you control the layout of objects, it is still possible to make objects smaller by recognizing certain usage patterns. Optimization opportunities include:

- Rarely used fields can be delegated to a side object, or stored in a completely separate attribute table.
- Mutually exclusive fields can share the same field, provided they have the same type.
- Fields that have the same value in all instances of a class can be declared static.
- Redundant fields whose value depends on the value of other fields can be eliminated, and recomputed each time they are used.
- Inner classes which can be made static will avoid storing a hidden `this` pointer.

Every field eliminated saves around 4 bytes per object, which may seem small. However, often several optimizations can be applied to a class, and if the class has a lot of instances, then these small optimizations turn out to be significant. They are especially useful in base classes, where their effect can be multiplied.

Many of these optimizations do not come for free. They trade one kind of cost for another, and can easily make things worse, depending on the context. So it's important to look at how your data will be used, and to estimate and then measure the effect of any optimizations. It's also a good idea to design your APIs so that classes can be easily refactored later on:

- Callers use interfaces rather than concrete classes.
- Callers use factory methods rather than constructors.

Chapter 5

REPRESENTING FIELD VALUES

So far, we have been concerned with the wasteful overhead that results from data representation. But what about the data itself? Java gives you a number of different ways to represent common datatypes, such as strings, numbers, dates, and bit flags. Depending on which representation you choose, the overhead costs can vary quite a bit. These costs, hidden in the implementation, are not obvious, and can be surprisingly high. In this chapter, we look at the costs of different representations for the most commmon datatypes.

5.1 Character Strings

Strings are the most common non-trivial datatype found in Java programs. We discuss when to represent data as a Java `String`, and when not to.

External vs. Internal Datatype forms Forms TOWRITE: - It's very common to represent scalar data, such as int, boolean, or date, as strings. There are many reasons why it's preferable to represent these as scalars when you can. - give some reasons other than space (Effective Java makes a good argument for this), such as availability of operators, type checking, self-documenting. - in addition, the overhead of a string representation is usually much higher than scalar forms. Much higher than even the boxed form as well. Much higher than in languages like C, as we saw in reference-chapter-on-datatypes. Mention bloat factor from one or two examples from the little table below.

- short table with 3 most common examples, comparing cost of scalar vs. boxed form vs. String form. Examples: int (95%), boolean (using "Y" and "N"), and enum.

StringBuffer vs. String It is well-known that `StringBuffer` is more efficient than `String` for performing string concatenation. Since `String`s are immutable, concatenating `String`s involves allocating a temporary `char` array, copying the `String`s into it, and then constructing a result `String`. A `StringBuffer`, on the other hand, is mutable. If the `StringBuffer` capacity is sufficient, then `String`s can be concatenated by simply appending them to the `StringBuffer`.

However, long-lived `StringBuffer`s can waste memory. Usually a `StringBuffer`

is 40% empty space, since they double in size whenever they need to be reallocated. Typically, after a string is built up in the `StringBuffer`, it is stable, at which point it should be converted to a `String`, so that the `StringBuffer` can be garbage collected. Using `StringBuffer`s to facilitate building a `String` is fine, but they should be used only as temporaries.

5.2 Representing Bit Flags

TOWRITE: - Discuss/compare cost of three representations: a bunch of boolean fields, a byte with bit flags that you manage yourself, EnumSet.

5.3 Dates

TOWRITE: - Discuss/compare cost of three representations: Date vs. Calendar vs. time in millis. Advice on when each is appropriate.

5.4 BigInteger and BigDecimal

TOWRITE: - Discuss need for these, and costs. - Describe the number of objects in each (I don't think we need a diagram). - Compare to long/double.

Chapter 6

SHARING IMMUTABLE DATA

If you examine any Java heap, you will find that a large amount of the data is duplicated. At one extreme, there are often thousands of copies of the same boxed integers, especially 0 and 1. At the other extreme, there may be many small data structures that have the same shape and data. And, of course, duplicate strings are extremely common. This chapter describes various techniques for sharing read-only data to avoid duplication, including a few low-level mechanisms that Java provides. Section 6.1 looks at sharing literal data, known at compile time. The rest of the chapter describes techniques for sharing more dynamic data.

6.1 String Literals and `enum` Types

Duplicate strings are not only one of the most common sources of memory waste, they are also very expensive, since even small strings incur a large overhead. Fortunately, it is not hard to eliminate string duplication.

One technique is to represent strings as literals whenever possible. Duplication problems arise because dynamically created `Strings` are stored in the heap without checking whether they already exist. `String` literals, on the other hand, are stored in a *string constant pool* when classes are loaded, where they are shared. Therefore, there is a big advantage to `String` literals.

As an example, suppose an application reads in property name-value pairs from files into tables:

```
class ConfigurationProperties {
    ..
    void handleNextEntry() {
        String propertyName = getNextString();
        String propertyValue = getNextString();
        propertyMap.put(propertyName, propertyValue);
    }
}
```

The `Strings` stored in `propertyMap` are created dynamically. If there are just a few distinct property names in all of the input pairs, these property names will be

duplicated many times in the heap.

However, if you know in advance what all of the property names are, then you can define them once as `String` literals, which can be shared among the entries of `propertyMap`.

```
class PropertyNames {
    final public static String numberOfUnits = ‘‘NUM_UNITS’’
        ;
    final public static String minWidgets = ‘‘MIN_WIDGETS’’;
    ..
}

class ConfigurationWithStaticProperties {
    void handleNextEntry() {
       String propertyName = getNextPropertyName();
       String propertyValue = getNextString();
       propertyMap.put(propertyName, propertyValue);
    }
}
```

The `getNextPropertyName` method reads in a property name, and returns a pointer to a property name literal, stored in the JVM string constant pool. Alternatively, defining an enumeration type to encode property names may be a better stylistic choice. Like `String` literals, the JRE maintains just a single copy of each `enum` constant.

A common mistake is to create a new `String` from a `String` literal, which is usually completely unnecessary:

```
class PropertyNames {
    final public static String numberOfUnits =
                              new String(‘‘NUM_UNITS’’);
    final public static String minWidgets =
                              new String(‘‘MIN_WIDGETS’’);
    ..
}
```

Even though the standard library is smart enough to share character arrays in this case, this code still creates redundant `String` objects in the heap.

Using `String` literals to avoid dulication is only possible when the `String` values are known in advance. Section 6.2 introduces the notion of a sharing pool for sharing dynamic data. Section 6.3 describes the Java string interning mechanism, which uses a built-in string sharing pool to eliminate duplication.

(a) (b)

Figure 6.1. (a) Objects A and B point to duplicate data. (b) Objects A and B share the same data, stored in a sharing pool.

6.2 The Sharing Pool Concept

Suppose an application generates a lot of duplicated data and the values are unknown before execution. You can eliminate data duplication by using a *sharing pool*, also known as a *canonicalizing map*. A sharing pool will eliminate not just duplicate data, but all of its associated overhead. Since many Java data structures employ some delegation in their designs, sharing duplicate data can avoid multiple levels of identical objects.

An example is shown in Figure 6.1. The example is from a text processing system, which assigns a type to each word in a document. Each type is identified by a `String` type name. The complete set is only known at run time, so an `enum` type cannot be used. In Figure 6.1(a), objects A and B are words that have been classified as having the same type. Figure 6.1(b) shows objects A and B sharing the type structure, which is stored in a sharing pool. In this example, each use of a shared structure saves three objects.

```
public class Word {
    private Type type;
}

public class Type {
    final private String typeName;
}
```

[TODO: Redraw sharing pool figure, making it a concrete example.]

Sharing Pool

A *sharing pool* is a centralized structure that stores canonical, read-only data that would otherwise be replicated in many instances. A sharing pool itself is usually some sort of hash table, although it could be implemented in other ways.

There are several issues that you need to be aware of before using a sharing pool.

Shared objects must be immutable. Changing shared data can have unintended side effects. For example, changing the contents of the Type that A points to in Figure 6.1(b), would also change the type of B.

The result of `equals` testing should be the same, whether or not objects are shared. In particular, you should never use `==` on shared objects. In Figure 6.1, `A.type == B.type` is false in Figure 6.1(a) and true in Figure 6.1(b), which can lead to very subtle bugs. Using `equals` also allows you to safely change your design, should you later decide to share a different set of instances, or to not share data at all. [1]

Sharing pools should not be used if there is limited sharing. A sharing pool itself adds memory costs, including additional per-entry costs. If there is not much sharing, then the memory saved from eliminating duplicates isn't enough to compensate for the extra cost, and memory will be wasted instead of saved. In Section 6.6 is a sample analysis of when it's worth sharing Strings.

Sharing pools can have performance costs. Sharing pools can sometimes add a performance cost when creating new instances to be shared. First, each new instance requires a lookup and possible addition to the sharing pool. Second, in a multithreaded environment, checking and adding to the sharing pool can introduce latency if the sharing pool is synchronized. The use of shared instances, however, does not incur any extra time costs.

Sharing pools should be either stable or garbage collected. In Figure 6.1(b), the sharing pool stores an object that no other object is pointing to. Over time, the sharing pool can fill up with garbage, that is, items that were once needed but not any more. If the sharing pool is not purged of these unused items, there is a memory leak that can eventually use up all of memory. If a sharing pool, however, has only a small set of shared instances, or a set of shared instances that is unchanging for the lifetime of the pool, then garbage collection doesn't need to be a concern.

Fortunately, Java provides a few built-in mechanisms that take care of some of these concerns.

[1] An argument sometimes heard for sharing data is that it allows for speedier comparisons, using `==` rather than `equals`. In fact, most `equals` methods already perform this optimization, making the performance virtually identical.

6.3 Sharing Strings

Since `String` duplication is so common, Java provides a built-in string pool for sharing `Strings`, implemented by the JRE. To share a `String`, you simply call the method `intern` on it. If an equivalent `String` is not found, your `String` will be added to the pool. In either case, you will be returned a pointer to the new or existing `String`. Since `Strings` are immutable, sharing is safe. However, the rule about not using `==` still holds on shared `Strings`. Remember that only some `Strings` will be shared in any application, namely those specific instances that you choose to intern.

In the example from Section 6.1, `ConfigurationWithStaticProperties` eliminates property name duplication but not property value duplication. Suppose you know that there are not too many distinct values, but you don't know what they are. In this case, property values are perfect candidates for interning.

```
class ConfigurationPropertiesWithInterning {
   void handleNextEntry() {
      PropertyName propertyName = getNextPropertyName();
      String propertyValue = getNextString().intern();
      propertyMap.put(propertyName, propertyValue);
   }
}
```

The call to `intern` adds the new property value `String` to the internal string pool if it isn't there already, and return a pointer to it. Otherwise, the new `String` is a duplicate, and a previously saved `String` is returned.

Interned `Strings` are stored in a separate heap known as the *perm space*. Interning `Strings` indiscriminately will waste memory, and can exceed the size of the perm space, resulting in an exception: `java.lang.OutOfMemoryError:PermGen Space`. [2] There are JVM parameters to adjust the perm space size: `-XX:PermSize=128m` sets perm size to 128 megabytes, and `-XX:MaxPermSize=512m` sets the maximum perm size to 512 megabytes. Fortunately, the JVM performs garbage collection on the internal string pool, so there is no danger of a memory leak.

The built-in interning mechanism is synchronized, and can incur a latency cost in a multithreaded environment, when new `Strings` are interned. [3], pp. xxx-yyy, gives an example of how to build a concurrent sharing mechanism for `Strings`.

6.4 Sharing `Integers` and Other Boxed Scalars

As of Java 5, the Java library provides sharing pools for `Integers` and some of the other boxed scalars. Unlike the string pool, the `Integer` pool is initialized at

[2] This is an issue only for the Oracle JRE. The IBM JRE places no fixed limit on interned `Strings`.

class load time to store all `Integers` in a fixed range, from -128 to 127 by default. The method `Integer.valueOf(int value)` returns a pointer to an `Integer` in the pool, provided `value` is in range; otherwise it returns a new `Integer`. For example, the code in Figure 6.2 stores `Integers` from 1 to 500 in an array. `valueOf` returns an existing `Integer` for the first 127 numbers, and, for the rest of the numbers, `valueOf` returns a new `Integer` instance.

Because the `Integer` sharing pool is pre-initialized and fixed in size, it's always a good idea to call `Integer.valueOf` instead of the constructor to create a new `Integer`. The pooling aspect is very cheap, and you never have to worry about garbage collection, wasting memory, or concurrency issues. You do have to be careful, however, to avoid using `==` to compare `Integers`, since it's impossible to know with certainty which instances are actually shared. As always, using `equals` is a better practice.

```
for (int i=1; i<=500; i++)
    {
 numbers[i] = Integer.
     valueOf(i);
}
```

Figure 6.2. By using the `valueOf` method, you can leverage the standard library's integer sharing pool.

[TODO: (GSS) verify AutoBoxCacheMax - this was mentioned in the text. I think this is for a different purpose.]

There is a JVM parameter to change the upper limit of the `Integer` sharing pool. By adding `-Djava.lang.Integer.IntegerCache.high=100` to your application's command line, the pooled integers will range over the values -128 to 100.

The JRE provides a similar `valueOf` method for sharing each of the boxed scalars. In some cases, such as `float`, there is no sharing actually implemented, at least as of Java 6. For `Boolean` and `Byte`, a shared constant is returned for every possible value. In general, there is no penalty for always using `valueOf`.

6.5 Sharing Your Own Structures

Beyond strings and boxed scalars, there can be other kinds of duplicated data structures that consume large portions of the heap. There is no built-in Java mechanism to share data in general, so you have to implement a sharing pool for them from scratch. All of the sharing pool issues from Section 6.2 need to be addressed. The shared objects or structures must be immutable, they must not be compared using `==`, there must be sufficient memory savings from sharing to justify the sharing pool, and the sharing pool must not cause a memory leak.

There are two common styles of implementing your own sharing pools, depending on the complexity of the data being shared. We illustrate both in this section. For the purposes of this discussion we assume that the set of shared data is always needed throughout the run, so there is no need to worry about garbage collection. In Section 13.2.3 we revisit these two examples, and show how to implement sharing pools with garbage collection. We leave the addition of concurrent access as an

exercise.

To illustrate one common style of user-written sharing pool, consider a graph where the nodes have annotations, many of which are duplicates. Each annotation is a single object, containing a few scalar fields, recording whether a node has been visited, and the reason for the visit. Both the graph and the annotations are modified dynamically. Assume for now that the same universe of annotations is needed for the duration of the run. The main requirement is the ability to find and retrieve existing annotations quickly to share them.

Interestingly, none of the common collection classes meet this requirement out of the box. A `HashSet` can store `Annotation`s uniquely, but retrieving an existing `Annotation` is not easy. The `HashSet` can let you know whether an equivalent item already exists in the set, but can not return that item quickly. To get the preexisting item, you would need to iterate over the entire set. The most common approach is to use a `HashMap` that maps the `Annotation` to itself, as shown on the right. This design assumes that an `Annotation` can serve as its own key. In other words, that the `hashcode` and `equals` methods are defined on `Annotation` so that they ensure uniqueness. Note that, unless overridden, `equals` is implemented as `==`, so sharing data structures typically requires writing a new `equals` method.

```
HashMap<Annotation, Annotation>
    canonicalizingMap;
```

Callers must create an instance of `Annotation` in order to find out whether it's already in the shared pool. This is similar to the pattern of using `String.intern`, where you create a new `String` in order to see if a matching shared `String` exists. Therefore, this type of canonicalizing map only makes sense when sharing relatively simple data that is inexpensive to create.

Suppose now that we would like to share more complex data, such as the type information from Figure 6.1. In this example, the type is uniquely identified by a `String` type name. Each shared structure consists of three objects. Rather than asking the programmer to create a new `Type` structure only to discover that it exists in the pool, we can instead use the type name as the key, as shown on the right. That way callers of the sharing pool only have to create a `String` in order to find or retrieve the `Type`. In this example we save the creation of one object for each new instance of the structure created. For more complex structures the savings are even more.

```
HashMap<String, Type>
    canonicalizingMap;
```

6.6 Quantifying the Savings

Before implementing a sharing scheme, we can estimate the space savings, to make sure it's worth the effort, and to make there isn't a net gain in memory usage. Here

is a sample analysis of sharing `Strings`. This style of analysis can be applied to other types of shared data.

[TODO: Move just the string interning analysis from the chapter on bulk storage.]

The techniques described in this chapter for sharing immutable data can lead to substantial savings for many applications. All of these techniques are within the bounds of standard, object-oriented programming practice. Later in the book, in Chapter 17, we look at bulk storage and sharing techniques that stretch beyond the normal Java box in order to achieve even greater space savings.

6.7 Summary

Not only are Java heaps bloated from too much overhead, they are also bloated from duplicated data. If you know that your application generates many copies of the same data, then you should find a way to share the data. Java provides several built-in sharing mechanisms:

- you can use `String` literals or `enum` constants to share data that is known at compile time.
- The JRE maintains a sharing pool for `Strings`. Use `String` interning to make use of this sharing pool.
- The standard library maintains fixed-size pools for a fixed range of `Integers`, and other boxed scalars. You should use `valueOf` to create boxed scalars, instead of a constructor.

You can implement your own sharing pool using `Map` classes.
When sharing data, you should remember these four rules:

- Shared objects must be immutable.
- The result of `equals()` testing should be the same, whether or not objects are shared. Always use `equals()` rather than `==` to test equality.
- Sharing pools should not be used if there is limited sharing.
- Unless the set of shared objects is small or is stable for the lifetime of the sharing pool, shared objects must be garbage collected.

Chapter 7

COLLECTIONS: AN INTRODUCTION

Collections are the glue that bind your data together. Whether providing random or sequential access, or enabling look up by value, collections are an essential part of any design. In Java, collections are easy to use, and, just as easily, to misuse when it comes to space. Like much else in Java, they don't come with a price tag showing how much memory they need. In fact, collections often use much more memory than you might expect. In most Java applications they are the second largest consumer of memory, after Strings. It's not unusual for collection overhead to take up between x and y% of the Java heap. The way collections are employed can make or break a system's ability to scale up.

This chapter and the next three chapters are about using collections in a space-efficient way. Collections may serve a number of very different purposes in your application. You may use them to implement relationships, to organize data into tables, to enable quick lookup via indexes, or to store annotations alongside more formally modeled data. Each use has its own best practices as well as traps.

The current chapter is a short introduction to common issues that are important to understand in any use of collections. It concludes with a summary of resources that are available in the standard and some open source alternative frameworks. Each of the following three chapters then goes into depth about a specific way that collections can be used. Each of these chapters takes you through typical patterns of usage, shows what collections cost for those patterns, and gives you techniques for analyzing how local implementation decisions will play out at a larger scale. We will also look at the internal design of a few collection classes.

Chapter 8. Relationships An important use of collections is to implement relationships that let you quickly navigate from an object to related objects via references. This chapter covers the patterns and pitfalls of implementing relationships. At runtime, each relationship becomes a large number of collection instances, with many containing just a few elements. The main issues to watch for are: keeping the cost of small and empty collections to a minimum, sizing collections properly, and paying only for features you really need.

Chapter 9. Indexes and Other Large Collection Structures A collection can serve as the jumping off point for accessing a large number of objects. For example, your application might maintain a list of all the objects of one type, or have an index for looking up objects by unique key. This chapter shows how to analyze the memory costs of these structures. The main issue is understanding which costs will be amortized as the structure grows. The chapter also covers more complex cases, such as a multikey map, where there is a choice between a single collection and a multilevel design.

Chapter 10. Attribute Maps and Dynamic Records Many applications need to represent data whose shape is not known at compile time. For example, your application may read property-value pairs from a configuration file, or retrieve records from a database using a dynamic query. Since Java does not let you define new classes on the fly, collections are a natural, though inefficient way to represent these dynamic records. This chapter looks at the common cases where dynamic records are needed, and shows how to identify properties of your data that could lead to more space-efficient solutions.

7.1 The Cost of Collections

Like other building blocks in Java, the memory costs of the standard collections are high overall. The very smallest collection, an *empty* `ArrayList`, takes up 40 bytes, and that's only when it's been carefully initialized. By default it takes 80 bytes. That may not sound like a lot by itself, but when deeply nested in a design, that could easily be multiplied by a few hundred thousand instances.

Fortunately, there are some easy choices you can make that can save a lot of space. The cost of different collection classes varies greatly, even among ones that could work equally well in the same situation. For example, a 5-element `ArrayList` with room for growth takes 80 bytes. An equivalent `HashSet` costs 276 bytes, or 3.5 times as much. Like other kinds of infrastructure, collections serve a necessary function, and paying for overhead can be worthwhile. That is, as long as you are not paying for features you don't need. In the above example, a 70% space savings can be achieved if the application can do without the uniqueness checking provided by `HashSet`. In Section 2.3 we saw a similar example, achieving a large improvement when real-time maintenance of sort order wasn't needed. In the next chapters we'll see more examples of how a careful look at your system's requirements can help you reduce space.

There is also much that is not under your control in the cost of collections. Because the collection libraries are written in Java, they suffer from the same kinds of bloat we've seen in other datatypes. They have internal layers of delegation, and extra fields for features that your program may not use. The standard collections do have a few options that can help, such as specifying the excess capacity for growth. On the whole, though, they do not provide many levers for tuning to different

situations. They were mostly designed for speed rather than space. They seem to have been designed for applications with a few large and growing collections. Yet many systems have large numbers of small collections that never grow once initialized. Given all of this, it is important to be aware of what collections cost, so you can make informed choices as early as possible.

It is not enough to know the cost of a collection in the abstract, but to understand *how it will work in your design.* This is because some collections were only designed to be used at a certain scale. For example, a certain map class may work well as an index over a large table, but can be prohibitively expensive when you have many instances of it nested inside a multilevel index. Collections have fixed and variable costs, as discussed in Section 2.4. The fixed cost is the minimum space needed with or without any elements; the variable cost is the additional space needed to store each element. The way these costs add up depends on the context — whether there are many small collections, or a few large ones. High fixed costs take on more significance in smaller collections, especially when there are many instances of them. High variable costs matter when there are a lot of elements, regardless of whether the elements are spread across a lot of small collections or concentrated in a few large ones. We'll analyze the space needs of small collections a little differently from those of large collections. Table **??** in the next chapter shows the sizes of small (and empty) collection for some commonly used collection classes. In the following chapter, Table **??** gives information for computing the costs of larger collections.

It is helpful to look at collection costs together with the data they are storing. If a data structure uses expensive collections to store small amounts of data, than it will have a high bloat factor, and ultimately the application's ability to support a large amount of data will be limited. The next chapters show how to analyze collection costs in the context of your design. This analysis will help you choose the right collection for your design, or restructure your data into a more efficient design if necessary.

7.2 Collections Resources

In this book we focus mostly on the standard collections. We also include some information on classes from alternative, open source frameworks that can be helpful in keeping memory costs down.

The Standard Collections There are some lesser-known resources in the standard Java Collections framework that provide specialized functionality. Some can help you save memory if you require only those features. Others provide useful features, but can have a significant memory cost if not used carefully. Table 7.1 is a guide to the resources we discuss in this book.

Alternative Collections Frameworks In addition to the standard Java classes, there are a number of open source collections frameworks available. Some are designed specifically to improve space and time efficiency, while others are aimed at making

Resource	Description	Discussed in
`Collections` statics	Memory-efficient implementations of singleton and empty collections.	Section **??**
	Unmodifiable, checked, and synchronized behaviors are added via collection wrappers. Can be costly if used at too fine a granularity.	Section **??**
`Arrays` statics	Provides static methods if you need to create simple collection functionality from arrays	Section **??** shows one example
`IdentityHashMap`	Lower-cost map when using an object reference as key	Section **??**
`EnumMap`	Compact map when keys are `Enum`s	Section **??**
`EnumSet`	Compact representation of a set of flags	Section **??**
`WeakHashMap`	Supports one common scenario for managing object lifetime using weak references.	Section **??**
Java 1 collections	Some classes in the earlier, Java 1 libraries, like Vector and Hashtable, are a lower-cost choice in some contexts where synchronized collections are needed	Section **??**
`ConcurrentHashMap`	Hash map when contention is a concern. Avoid use at too fine a granularity.	Section **??**

Table 7.1. Some useful resources in the Java standard library

it easier to program, adding commonly needed features not found in the standard libraries. The alternative collections frameworks can be helpful in two ways when it comes to saving memory. First, some frameworks provide space-optimized collection implementations. Second, some frameworks provide classes that make it easier to manage object lifetime. Building your own object lifetime management mechanisms, for example a concurrent cache, can be error-prone (see, for example, Section **??**). Well-tested implementations will save you a lot of effort, and can lead to better overall use of space. Keep in mind that not all alternative collection classes have been optimized for space. Some of them actually take up more space than a similar design using the standard collections. As always, there is no substitute for analyzing space costs empirically.

In this book we'll look at four of the most recent and relevant open source collections frameworks. In the next few chapters we'll look at how you can use some of these classes to solve specific problems. Table 7.2 gives a summary of the capabilities that we discuss (sometimes only briefly). This is only a sampling of what's out there. We encourage you to further explore these and other frameworks on your own.

The Guava framework, which grew out of the Google Collections, is designed primarily for programmer productivity, providing many useful features missing from the standard Java collections. Although space usage has not been the main focus, it does include some specialized classes, for example the immutable collections, that are more space-efficient than their general-purpose equivalents. Guava's `MapMaker` class provides very general support for building caches and other lifetime management mechansisms, with optional support for concurrency. While most open source frameworks provide some level of compatibility with the standard collections APIs, Guava has made compatibility a priority.

The Apache Commons Collections framework has similar objectives to the Guava framework, focusing mostly on programmer productivity rather than on efficiency per se. It does however provide some capabilities for saving memory, such as maps and linked lists with customizable storage, and specialized maps that contain just a few elements. It also provides lifetime management support through its `ReferenceMap` class, in a less general manner than the Guava equivalent. As of this writing, the Commons API has not been updated to take advantage of generics.

The GNU Trove framework has time and space efficiency as its main goal. From a memory standpoint its highlights are: collections of primitives that avoid boxing and unboxing; map and set implementations that are lighter weight than the standard ones; and linked lists that can be customized to use less memory.

The fastutil framework has similar goals to Trove, primarily time and space efficiency. Like Trove, fastutil provides primitive collections, along with lighter-weight implementations of maps and sets. Some other memory-related features include array-based implementations for small maps and sets, and support for very large arrays and collections when working in a 64-bit address space.

Feature	Supported by	Discussed in
Primitive collections	fastutil, Trove	Section ??
Lighter-weight maps and sets of objects	fastutil, Trove	Section ??
Immutable collections	fastutil, Guava	Section ??
Small collections	Commons (maps only), fastutil	Section ??
Customized linked list storage	Trove	Section ??
Maps with weak/soft references	Commons, Guava	Chapters ?? and ??
Caches	Guava	Section ??

Table 7.2. A sampling of memory-related resources available in open source frameworks

Important note: there are many kinds of open source licenses. Each has different restrictions on usage. Make sure to check with your organization's open source software policies to see if you may use a specific framework in your product, service or internal system.

7.3 Summary

Using collections carefully can make the difference between a design that scales well and one that doesn't. Some items to be aware of when working with collections:

- The standard Java collections were designed more for speed than for space. They are not optimized for some common cases, such as designs with many small collections. In general the Java collections use a lot of memory.
- Collections vary widely in their memory usage. Awareness of costs is an essential first step in choosing well. Sometimes there is a less expensive choice of collection class available, either from the standard library or from open source alternatives. Initialization options can also make a difference.
- The same collection class will scale differently depending on its context. Ensuring scalability means analyzing how a collection's fixed and variable costs play out in a given situation. Watch out for: collections with high fixed costs when you have a lot of small collections, and collections with high variable costs when you have a lot of elements.

- Analyzing your application's requirements, specifically which features of a collection you really need, can suggest less expensive choices.

Chapter 8

RELATIONSHIPS

Relationships in an entity-relationship model are typically implemented in Java using the standard library collection classes: each object points to collections of other objects related to it. Since relationships are at the core of any data model, it is not uncommon for a Java application to create hundreds of thousands, even millions, of collections. Therefore, simple decisions, like which collection class to use, when to create it, and how to initialize it, can make a surprisingly big difference on memory cost. This chapter shows how to lower memory costs when implementing relationships with collections.

8.1 Choosing The Right Collection

The standard Java collection classes vary widely in terms of how much memory they use. Not surprisingly, the more functionality a collection provides, the more memory it consumes. Collections range from simple, highly efficient `ArrayLists` to very complex `ConcurrentHashMaps`, which offer sophisticated concurrent access control at an extremely high price. Using overly general collections, that provide more functionality than really needed, is a common pattern leading to excessive memory bloat. This section looks at what to consider when choosing a collection to represent a relationship target.

Using collections for relationships often results in many small or empty collections, because there are either lots of objects in the relationship or many objects are related to a only few other objects, or both. When there are lots of collections with only a few entries, you need to ask whether the functionality of the collection you choose is worth the memory cost of that functionality.

To make this discussion more concrete, let's return to the product and supplier example from section 4.1, and change it a little bit. Instead of only one alternate supplier, a product now may have multiple alternate suppliers, and each product stores a reference to a collection of alternate suppliers. An obvious choice is to store the alternate suppliers in a `HashSet`:

```
class Product {
    String sku;
    String name;
```

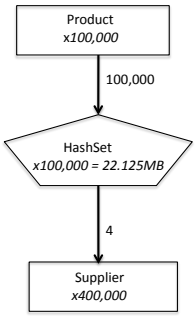


Figure 8.1. A relationship between products and alternate suppliers, stored as a `HashSets` of alternate `Suppliers` related to `Products`.

```
    ..
    HashSet<Supplier> alternateSuppliers;
}

class Supplier {
    String supplierName;
    String supplierAddress;
    String sku;
}
```

Suppose there are 100,000 products that each have four alternate suppliers on average. Figure 8.1 shows an entity-collection diagram for the relationship between products and alternate suppliers.

Using a `HashSet` for alternate suppliers turns out to be a very costly decision. The alternate suppliers are represented by 100,000 very small `HashSets`, each consuming 232 bytes, for a total cost of 22.125MB. This cost is all overhead. It's hard to think of a good reason why such a heavy-weight collection should ever be used for storing just a few entries, and yet, this pattern is very, very common. For small sets, `ArrayList` is almost always a better choice. `HashSet` maintains uniqueness and provides fast access, but enforcing uniqueness is not always needed. If uniqueness is important, it can be enforced for an `ArrayList` with little extra checking code,

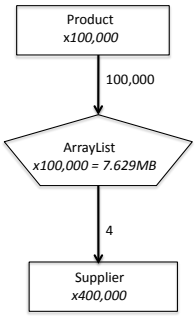


Figure 8.2. A relationship between 100,000 products and alternate suppliers, where the alternate `Suppliers` associated with each `Product` are stored in an `ArrayLists`.

and usually without significant performance loss when sets are small. Figure 8.2 shows improved memory usage with `ArrayList`. Each `ArrayList` incurs 80 bytes of overhead, approximately a third the size of a `HashSet`. This simple change saves 14.49MB.

8.2 The Cost Of Collections

Let's look inside a `HashSet` to see why it is so much bigger than an `ArrayList`. Some of its extra cost is because of additional functionality, such as entry uniqueness and constant-time access. Other extra cost because of unavoidable Java overhead, and because `HashSet` is optimized for performance: the `HashSet` implementation assumes `HashSets` will be very large, and sacrifices memory space in favor of performance. Additionally, `HashSet` reuses the `HashMap` implementation, which is expensive memory-wise. `HashSet` is implemented as a degenerate `HashMap`, that is, a `HashMap` with no values.

The internal structure of a `HashSet`, shown in Figure 8.3, consists of wrapper objects, an entry array, and linked lists of entries. Most collections have similar kinds of internal components.

Wrapper Objects. The `HashSet` object itself is just a wrapper, delegating all of its work to a `HashMap`. Therefore, there is an additional wrapper, a `HashMap` object.

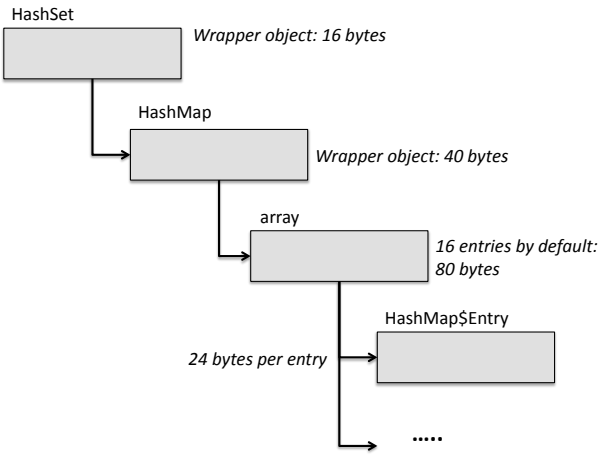


Figure 8.3. The internal structure of a `HashSet`.

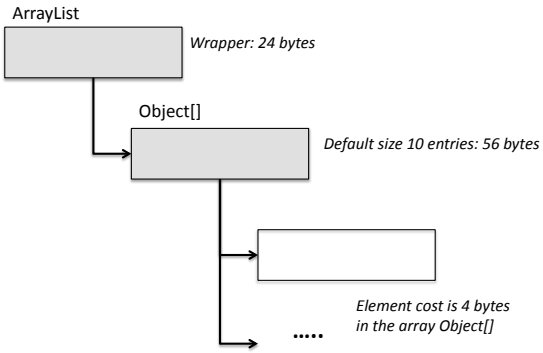


Figure 8.4. The internal structure of an `ArrayList`, which has a relatively low fixed overhead, and is scalable.

All collections have wrapper objects, but a `HashSet` has two of them.

Entry Array. Since this is a hashing structure, there is an array to store the hashed entries. The default initial size of the array is 16.

Entries. `HashMap` stores all entries in clash lists, so there is a `HashMap$Entry` object for each `HashSet` entry. The size of a `HashMap$Entry` is 24 bytes.

In contrast, `ArrayList` has a smaller fixed cost and a smaller variable cost than `HashSet`. It is really just an expandable array, consisting of a wrapper object and an array of entries, as shown in Figure 8.4. Lower fixed cost means that an `ArrayList` with just a few elements is smaller than a `HashSet` with the same elements. Fixed costs include wrapper objects and unitialized array elements. The fact that `HashSet` delegates to `HashMap` inflates its fixed cost. Lower variable cost means that `ArrayList` scales much better than `HashSet`. The variable cost of an `ArrayList` entry is an entry array pointer, which is 4 bytes. The variable cost of a `HashSet` is an entry array pointer plus a `HashMap$Entry`, which is 28 bytes. So `ArrayList` is better both for small and large sets.

Table 8.1 shows the memory costs of four basic collections, `ArrayList`, `LinkedList`, `HashMap`, and `HashSet`. This table shows the default size when the collection is just allocated without entries, and any additional entry cost. These costs have been calculated based on the Sun JVM, using the techniques described in Chapter 3.

Collection	Fixed Default Cost with No Entries	Variable Cost
ArrayList	80 bytes (capacity for 10 entries)	4 bytes
LinkedList	48 bytes	24 bytes
HashMap	120 bytes (capacity for 16 entries)	28 bytes
HashSet	136 bytes (capacity for 16 entries)	28 bytes

Table 8.1. The cost breakdown of four basic Java standard library collections with default size and no entries. The fixed cost includes an array whose size equals the default capacity. The variable cost, the memory needed for an entry, indicates scalability.

The various other Java standard library implementations in circulation have costs similar to these. You can calculate them using the same methodology.

Our guess is that the collection class developers would be surprised by the relationship usage pattern that results in hundreds of thousands of small `HashSets`. Why bother implementing expandable structures and clever hashing algorithms for only a few entries? This mismatch between collection implementation and usage is a leading cause of memory bloat. The overhead cost of a `HashSet` is remarkably high. Creating many small collections multiplies this basic infrastructure cost, which is all overhead, filling the heap.

8.3 Properly Sizing Collections

Collections such as `HashMap` and `ArrayList` store their entries in arrays. When these arrays become full, a larger array is allocated and the entries are copied into the new array. Since allocation and copying can be expensive, these entry arrays are always allocated with some extra capacity, to avoid paying these growth costs too often. This is why the initial capacity of an `ArrayList` is 10 rather than zero or one, and why its capacity increases by 50% when it is reallocated. Similarly, the capacity of a `HashMap` starts at 16, and grows by a factor of 2 when the `HashMap` becomes 75% full.

These default policies trade space for time, on the assumption that collections grow. However, collections used to represent relationships may have hundreds of thousands of small collections that don't grow. As a result, there is no performance gain, and the extra empty array slots can add up to significant bloat problem, unless you take explicit action.

Fortunately, it is possible to right-size `ArrayLists`. If you know that an `ArrayList` has a maximum size x, which is less than the default size, then it's worth passing x as a parameter to the constructor to set the initial capacity of the `ArrayList` to x. However, if you are wrong and the `ArrayList` grows bigger than x, then it will grow by 50%, which may be worse than just taking the default initial size.

Alternatively, you can call the `trimToSize` method which shrinks the entry array by eliminating the extra growth space. Trimming reallocates and copies the array,

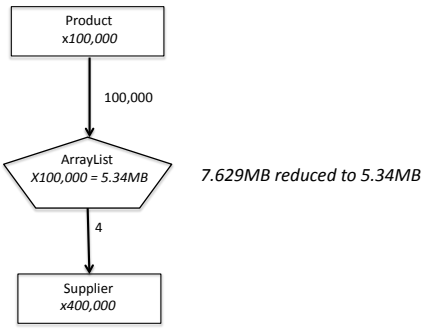


Figure 8.5. The relationship between `Products` and `Suppliers` after all of the `ArrayLists` have been trimmed by calling the `trimToSize` method.

so it is expensive to keep calling `trimToSize` while an `ArrayList` is still growing. Trimming is appropriate after it has been fully constructed and will never grow again. In fact, applications often have a build phase followed by a used phase, in which case `ArrayLists` can be trimmed between these two phases, so that the cost of reallocation and copying is paid only once.

Returning to the example of the relationship between products and alternate suppliers, the `ArrayLists` in Figure 8.2 have default capacity. If we assume that the the relationship is built in one phase, and used in another phase, then it is possible to trim the `ArrayLists` after the first phase. This should save quite a bit of space, since there are 100,000 `ArrayLists` with four entries on average. In fact, trimming these `ArrayLists` saves 2.29MB, as shown in Figure 8.5.

`HashSets` and `HashMaps` do not have `trimToSize` methods, but it is possible to pass the initial capacity and load factor as constructor parameters when creating a `HashSet` or `HashMap`. However, before changing the initial capacity, you should ask yourself whether using a `HashSet` or `HashMap` is a wise decision in the first place. If you are going to end up with many collections with fewer than 16 elements, perhaps there is a more memory-efficient solution, like `ArrayList`.

A `LinkedList` is another alternative for small collections, and are better than `ArrayLists` if the collections are changing a lot. The 24 byte per-entry cost is larger, but there is no element array, and only one extra entry, which is a sentinal.

8.4 Avoiding Empty Collections

Too many empty collections is another common problem that leads to memory bloat. A quick look inside an empty collection shows that it is not all that empty.

bytes, assuming a default initial size. Even if the default initial size is overridden and set to zero, empty collections are still large. A zero-sized `HashMap` consumes 56 bytes, and a zero-sized `ArrayList` consumes 40 bytes. Empty `HashSets` are even bigger.

Empty collection problems are generally caused by eager initialization, that is, allocating collections before they are actually needed. Exacerbating this problem, collections themselves also allocate their internal objects in an eager fashion. For example, `HashMap` allocates its entry array before any entries are inserted. You might think that eager initialization is not such a big problem, since entries will be added eventually. However, often collections are allocated just in case they are needed later, and remain empty throughout the execution.

Suppose the relationship in Figure **??** is initialized by the code:

```
ArrayList<Product> products;
int numProducts;
   ..
   public void initAlternateSupplierRelationship() {
       ..
       for (int i = 0; i < numProducts; i++) {
          Product product = products.get(i);
          product.alternateSuppliers =
                          new ArrayList<Supplier>();
       }
   }
```

Initially, each product is mapped to an empty `ArrayList` for alternate suppliers, so there are 100,000 empty `ArrayLists` before any `Suppliers` are inserted. As the alternate suppliers are populated, many of these `ArrayLists` will become non-empty, but it is likely that a good number of products have no alternate suppliers. If 25% of the products in the final graph still have no alternate suppliers, there will be 25,000 empty `ArrayLists`, which consume .95MB even after calling `trimToSize`. Figure 8.6 shows the entity-collection diagram after removing 25,000 empty alternate supplier `ArrayLists`. Note that there are now only 75,000 alternate supplier `ArrayLists` shown, and since there are no more empty `ArrayLists`, the average fanout increases to 5.33.

Delaying allocation prevents creating too many empty collections. That is, instead of initializing all of the collections that you think you may need, allocate them on-demand, just before inserting an edge. On-demand allocation requires more checking code, to avoid `NullPointerExceptions`.

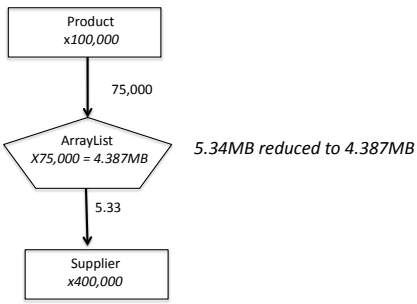


Figure 8.6. The relationship between `Products` and `Suppliers` where there are no empty `ArrayLists`.

Alternatively, you can initialize collection fields to reference static empty collections, including EMPTY_SET, EMPTY_LIST, and EMPTY_MAP. For example, calling static method `Colletions.emptyList` to initialize edge `ArrayLists` maps all nodes to a singleton immutable static `ArrayList`, so that no empty `ArrayLists` are created:

```
public void initAlternateSupplierRelationship() {
  ..
  for (int i = 0; i < numProducts; i++) {
     Product product = products.get(i);
     product.alternateSuppliers =
                         Collections.emptyList();
  }
}
```

This initialization avoids the need to check whether an `ArrayList` exists at every use. For example, the size method and iterators will just work. However, you have to be careful not to let any references to static empty collections escape their immediate context. If you give out a reference to a static empty collection, then there is no way to update this escaped empty-collection reference once an actual collection is allocated.

8.5 Fixed Size Collections

Java collections can grow to be arbitrarily big, but this functionality comes at a cost. Collections include wrapper objects, and may be sized with extra growth room. If you know that the size of a collection is fixed, having the ability to expand the collection is unnecessary, and it is better to choose a cheaper alternative. In fact, often you can use a simple Java array, and not use a collection at all.

In our example, alternate suppliers are stored in an `ArrayList`, which inside is a wrapper pointing to an array of `Suppliers`. If we assume that every product has at most four alternate suppliers, then it isn't necessary to store these in an `ArrayList` — a simple array will do. Eliminating the `ArrayList` object removes 24 bytes per product, but we have to add 4 bytes to each `Product` to store the number of alternate suppliers. The total savings is 1.43MB for 75,000 products:

```
class Product {
    String sku;
    String name;
    ..
    int numAlternateSuppliers;
    Supplier[4] alternateSuppliers;
}
```

This is an example of choosing an overly-general collection. In this situation, you don't need a collection at all. Using `ArrayList` for storing fixed- or bounded-size arrays is a common practice that can be easily avoided.

There is one final optimization that can be performed on the `Product` class. Namely, making the four alternate suppliers into fields of `Product` instead of elements of an array. This optimization a 32 byte array object for 75,000 products, while adding three additional fields to the `Product` for 100,000 objects, saving another 1.1MB in total:

```
class Product {
    String sku;
    String name;
    ..
    Supplier alternateSupplier1;
    Supplier alternateSupplier2;
    Supplier alternateSupplier3;
    Supplier alternateSupplier4;
}
```

This representation is very similiar to the original `Product` class in section 4.1 where there is one alternate suppler field, and here there are four. Taking all of the optimizations together, we have gone from the initial `HashSet` representation of 22.125MB in Section 8.1 to the in-lined field representation of 1.86MB.

8.6 Hybrid Representation

An interesting case is when the sizes of the collections used in a relationship is not uniform. That is, some collections are small and some collections are very big. It's reasonable to use an expensive collection like `HashSet` for the big collections, but then the small collections pay the price. One way to handle this problem is to use a hybrid representation. For example, you can use arrays for smaller collections, and `HashSets` for larger collections.

One catch is that usually you will not know in advance which collections in the relationship will end up being small and which will grow to be large. Therefore a conversion operation will be necessary at some point if a collection grows large enough. Each collection starts as an array, and then once it grows past a threshhold, it is converted to a `HashSet`.

In our example, suppose that the vast majority of products have four alternate suppliers on average, but a few products have over 100 alternate suppliers. We can choose a threshhold, say six entries, which triggers a conversion to a `HashSet` when the threshhold is exceeded. Here is the class `Product`:

```
public class Product {
```

```
static final int threshhold = 6;
String sku;
String name;
..
int numAlternateSuppliers;
Supplier[] alternateSuppliers;
HashSet<Supplier> bigAlternateSuppliers;

void addAlternateSupplier(Supplier supplier) {

    /* Check for duplication */
    if (hasAlternateSupplier(supplier)) {
        return;
    }

    /* Try to add the supplier to the array
       alternateSuppliers */
    if (numAlternateSuppliers == 0) {
        alternateSuppliers = new Supplier[threshhold
            ];
    }
    if (numAlternateSuppliers < threshhold) {
        alternateSuppliers[numAlternateSuppliers++] =
            supplier;
        return;
    }

    /* If threshhold is exceeded, need to use
       bigAlternateSuppliers */
    if (numAlternateSuppliers == threshhold) {
        bigAlternateSuppliers = new HashSet<Supplier
            >();
        for (int i = 0; i < threshhold; i++) {
            bigAlternateSuppliers.add(
                alternateSuppliers[i]);
        }
        alternateSuppliers = null;
    }
    bigAlternateSuppliers.add(supplier);
    numAlternateSuppliers++;
    return;
}
```

```
}
```

The method `addAlternateSupplier` adds the supplier to the array if the size is less than the thresshold, otherwise, it adds the supplier to the `HashSet`. It allocates the alternate supplier array and `HashSet` only if and when it is needed, to avoid wasting space with empty collections when there are no or only a few alternate suppliers.

Implementing hybrid representations is more complicated than just using one collection for a relationship. However, it can save significant space in some cases.

8.7 Summary

Collections used to represent relationships often result in many small collection instances, whose cost is dominated by a fixed-size overhead. This chapter describes a number of ways to mitigate high fixed memory costs for relationships implemented with collections:

- Choose the most memory-efficient collection for the job at hand. In particular when collections have at most a few elements in them, you don't need expensive functionality like hashing.
- Make sure collections are properly sized. If you know that a collection will not grow any more, then there is no reason to maintain extra room for growth.
- Avoid lots of empty collections. It is common to allocate collections ahead of time, whether or not they will eventually ever be used. If you postpone creating them until they are needed, often you will end up with fewer collections, and no empty collections.
- Use arrays instead of `ArrayLists` when you know the maximum size of the collections in advance. You can also eliminate an `ArrayList` altogether when there are always at most a few entries that can be stored in fields.
- When the usage pattern is not uniform, it is sometimes reasonable to use a hybrid representation.

Knowing which relationships and collections in your application are the most important and need to scale is key to applying these optimizations effectively.

Chapter 9

LARGE COLLECTION STRUCTURES

In a relational database system, data is neatly organized for you into tables. While you may suggest a few fields to index, the structures that allow you to access your data are taken care of for you. In object-oriented programming languages you have more freedom. You have a sea of interconnected objects, and you are responsible for designing the structures that are the entry points into various groupings of these objects. In this chapter we look at the memory considerations when designing large structures for accessing your data. We'll look briefly at large collections that just gather data in one place, such as a list of all the objects of one type. The bulk of the chapter is about indexes, also known as maps, that let you look up data by value. We'll first look at the costs of large collections, and at ways to keep them to a minimum for the task at hand. In the second half of the chapter we'll look at the cost tradeoffs when you need to design more complex access structures made of multiple levels of collections.

9.1 Large Collections

Just as with small collections, choosing the right collection for the task can make a big difference in the memory overhead of large collections. Suppose you need to maintain a collection of all the orders processed for the day. At the end of the day these orders are posted in bulk to a remote database. The orders contain their own timestamps, so we don't really care about maintaining the sequence in which they were received. Figure **??** compares an implementation using `ArrayList` with one using `HashSet`. As with small collections, if we don't need the uniqueness checking or some of the other features of `HashSet`, then we are clearly much better off with `ArrayList`.

In larger collections, the variable overhead — the cost each element incurs — determines the cost of the collection. That's because as a collection grows its fixed overhead, such as wrapper objects and array headers, becomes insignificant. For example, in an `ArrayList` with 100 elements, the fixed cost is only 9% of the total. With 1000 elements, it falls to 0.1%. The difference in size in the above example

is pretty dramatic, more than 7:1. That reflects the difference in the variable overheads of the two collection classes. Like much else in Java, variable overheads in large collections can take up a surprising amount of memory if you are not careful. As a general rule, the variable overhead of array-based collections, like `ArrayList` is much lower than that of entry-based collections where a new entry object is allocated for each element in the collection. You may have noticed that most of the collections in the standard collection library are entry-based, including `HashMap`, `HashSet`, `LinkedList`, and `TreeMap`. Table **??** shows a comparison of variable costs for the most commonly used classes from the standard collections library, along with a sampling from open source libraries.

Excess Capacity As we saw in the previous chapter, many collection classes allocate excess capacity for performance reasons, mainly to accomodate growth. One difference between small and large collections is the way excess capacity is computed. In the very smallest collections, excess capacity comes from the initial capacity being too large. In contrast, as a collection grows larger, the amount of spare capacity allocated is proportional to the number of elements. For example, whenever an `ArrayList` needs more space, it allocates an array that is 50% larger than its current size; `HashMap` doubles the number of buckets when the number of elements reaches a user-specified load factor. So for any collection that's grown beyond its initial size, you can think of spare capacity as part of the variable cost. If an `ArrayList` is 1/3 spare capacity, then every element really costs 6 bytes, rather than the 4 bytes for the array slot that holds the pointer.

Collections grow in jumps, which makes predicting the size of a collection a little tricky. For that reason, Table**??** shows a range of variable costs for each collection. You can use the minimum number if you expect no spare capacity, or in the case of hashtable-based maps and sets, no spare capacity beyond what is required for reasonable operation. The maximum number gives you a worst case, if you added just that one extra element that caused the jump. Slightly less than the midpoint of the range will give you an estimate of the variable cost if the most recently allocated spare capacity is half occupied. Again, the table only applies to collections once they have grown beyond their initial size.

Solutions for reducing excess capacity for larger collections are the same as for small collections. If you can estimate the number of elements in advance, you can try to size the collection carefully when you create it. If your data structure has a distinct load phase, and the collection has a `trimToFit()` call, you can trim the size of the collection after the load phase is complete. In hash-based collections, such as `HashMap` and `HashSet`, excess capacity is needed to reduce the likelihood of collisions, so it's important to leave headroom for this purpose. The default load factor is usually a pretty good guide.

Excess capacity isn't much of an issue for collections like `HashMap` and `HashSet`, where the bulk of the overhead is from the entry objects. For larger array-based collections, excess capacity can be a more significant part of the overhead, though

it's relative to a more efficient representation in the first place.

Array-based Hash Maps and Hash Sets There are two primary ways that hash tables are implemented. Most of the maps and sets in the standard libraries use a technique known as *chaining* (also known as open hashing). Figure **??** in the previous chapter shows a typical implementation. There is a separate entry object for element in the collection. Each entry object points to a key and a value, and may contain additional information such as a cached hash code. There is a linked list of entry objects for each hash bucket.

The other main technique is known as *open addressing* (for added confusion, it is also known as closed hashing). In this technique, keys, values, and other information are stored directly in arrays. These are usually parallel arrays, though some implementations use a single array and interleave different kinds of information in successive slots. Chains of entries that map to the same bucket are threaded through the arrays. Figure **??** shows a typical implementation. There are many variations in practice.

Generally speaking, for larger collections, open addressing hash tables use less memory — at least in Java, where the cost of an entry object is so high. fastutil and Trove are examples of open source frameworks that provide open addressing maps and sets that save space. The sets in these frameworks save even more space for a different reason: they are specialized for the task, rather than delegating their work to a more general map. So unlike in the Java standard libraries, you are paying only for a value, not a key and value, per entry.

Since open addressing hash tables usually use less memory, why do so many hash table libraries use chaining? Generally speaking, hash tables based on chaining are much simpler to implement. More importantly, there are performance differences between the two approaches, though there is no easy rule about one always being faster than the other. For your own system, if performance of your collections is critical it can be worth doing some timings first. Keep in mind that in many systems, the amount of time spent in hash table lookups is a small fraction of the total execution time to begin with.

Another thing to be aware of in open addressing implementations is that the need for excess capacity will reduce the space savings to a greater extent than in open chaining implementations. So it's important to look at the entire variable cost when making decisions on which framework to use (see Table **??**). For example, fastutil's object to object open addressing hash map maintains only 9 bytes of data for each element, compared to the standard `HashMap`'s 28. When you add in the greater cost of excess capacity that difference is reduced to approximately 1:2. ¡or example here instead, with absolute numbers¿

Sharing the Costs in Entry-based Collections Some alternative frameworks provide another approach to reducing space in entry-based collections. The idea is that your objects become the collection's entry objects, thus saving a delegation overhead. The

downside is that they transfer some of the work of maintaining the collection to your code. One example is in the Apache Commons framework, which lets you subclass its map and map entries. If you have a key with two fields, for example, you would normally have to wrap those fields into a key object. Now you could include those fields in a custom map entry instead, and save a delegation cost. ¡figure here?¿ This introduces a reliability and maintenance problem, however, since it relies on subclassing a fairly complex class. You must now make sure your code doesn't break anything in current and future versions of Commons's hash map implementation.

A simpler approach is taken by Trove's linked list. If you have a class whose objects are to be stored in a linked list, your class can implement the `TLinkable` interface. Your class would provide the chaining, and again, save the cost of a separate entry object. Some restrictions are necessary in order for this to work: no instance of your class can be a member of more than one linked list simultaneously, nor appear more than once in the same list. In addition, your class must now include pointer fields, which increase the cost of these instances when they are not stored in a list.

9.2 Identity Maps

The Java standard library does provide one hash map class that uses an open addressing implementation. The `IdentityMap` class can save you space if you have the need for a large map that fits its requirements. The idea is that it uses the identity of the key object, rather than its contents for comparisons. In other words, it uses `==` against the key your provide, rather than the `.equals()` method. This breaks the `Map` contract, but there are a number of applications where this doesn't matter.

Suppose I want to associate additional information with each product. Using a standard map, I could map the product's unique key, say SKU,

9.3 Maps with Scalar Keys or Values

9.4 Multikey Maps. Example: Evaluating Three Alternative Designs

9.5 Concurrency and Multilevel Indexes

9.6 Multivalue Maps

9.7 Summary

Chapter 10

ATTRIBUTE MAPS AND DYNAMIC RECORDS

Part II

Managing the Lifetime of Data

Chapter 11

LIFETIME REQUIREMENTS

Your application needs some objects to live forever and it needs the rest to die a timely death. Unfortunately, some of the important details governing memory management are left in your hands. Java promised, with its automatic memory management, that you could create objects without regard for the messy details of storage allocation and reclamation. In Java, you needn't explicitly free objects, which is at once the saviour from, and the source of, many problems with memory consumption. Unless you are careful, your program will suffer from bugs such as memory leaks, race conditions, lock contention, or excessive peak footprint. Furthermore, if your objects don't easily fit into the limits of a single Java process, you will need to manage, explicitly, marshalling them in and out of the Java heap.

Very often, your application uses a data structure in a way that falls into one of a handful of common *lifetime requirements*. The nature of each requirement dictates how much help you will get from the Java runtime in the desired preservation and reclamaion of objects, and where it leaves you to your own devices.

An important step in the design process of any large application is understanding the lifetime requirement for each of your data models. In this chapter, we describe the five common lifetime requirements: objects needed only transiently, objects needed for the duration of the run, objects whose lifetime ends along with a method invocation, objects whose lifetime is tied to some other object, and, most difficult of all, objects that live or die based on need. Table 11.1 summarizes these five important requirements, which are also visualized in Figure 11.1. This chapter steps through these requirements, defining them and giving examples each.

Once you have mapped out the lifetime requirements of your data models, the next step is to chose the right implementation details in order to correctly implement each requirement. The remaining chapters in this part show how to implement these requirements.

11.1 Object Lifetimes in A Web Application Server

To introduce the common requirements for object lifetime, we walk through several scenarios found in most long-running server applications. These applications provide an interesting case study for lifetime management. Managing lifetime when

Lifetime Requirement	Example
Temporary	new parser for every date
Correlated with Another Object	object annotations
Correlated with a Phase or Request	tables needed only for parsing
Correlated with External Event	session state, cleared on user logout
Permanently Resident	product catalog
Time-space Tradeoff	database connection pool

Table 11.1. Common requirements for the lifetime of objects that your application must implement properly, in order to avoid correctness or performance problems.

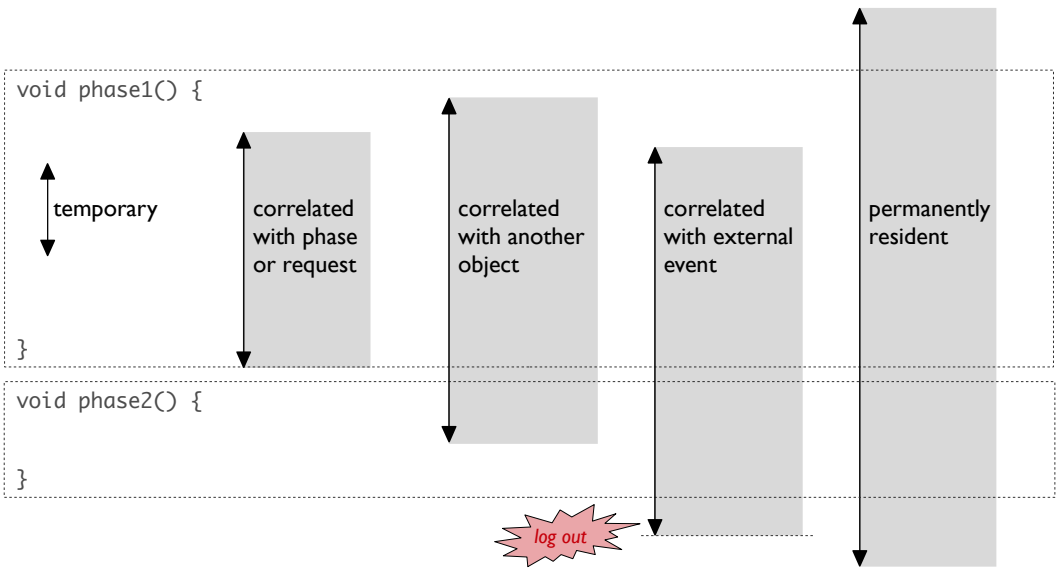


Figure 11.1. Illustration of some common lifetime requirements.

the application runs forever is an especially complex issue. This is true for more than server applications. Desktop applications such as the Eclipse integrated development environment share many of the same challenges. Improperly managing the lifetimes of objects, for short-running applications, often does not result in critical failure. Indeed, a short-running application often finishes its run before one would even notice a problem with memory consumption. Plus, you probably don't run many instances of a short-running application simultaneously; and so achieving the ultimate in scalability is not a primary concern. In contrast, if an application runs more or less forever, then mistakes pile up over time. In addition, caching plays a large role in these applications, since they often depend on data fetched from remote servers, or from disk, neither of which can support the necessary throughput and response time requirements. The possibility for mistakes to pile up, and for misconfigured or poorly implemented caches to impede performance means that special care must be taken to manage object lifetimes correctly when implementing a server application.

The heap consumption of a long-running application fluctuates over time, depending on the application phase. A timeline view of expected memory consumption, such as shown in Figure 11.2, helps to visualize these phase fluctuations. It shows memory during the lulls and peaks of activity: when the server starts up, when requests are processed, and when sessions time out. We will use timeline views as we walk through the common cases of lifetime requirements.

To help introduce the common lifetime requirements, we walk through an example of a shopping cart server application. The server, on startup, preloads catalog data into memory to allow for quick access to this commonly used data. It also maintains data for users as they interact with the system, browsing and buying products. Finally, it caches the response data that comes from a remote service provider that charges per request. The remainder of this chapter walks you through understanding the lifetime requirements of these data structures.

11.2 Temporaries

The catalog data and session state are both examples of objects that are expected to stick around for a while. In the course of preloading the cache and responding to client requests, the server application will create a number of objects that are only used for a very short period of time. They help to faciliate the main operations of the server. These temporary objects will be reclaimed by the JRE garbage collector in relatively short order. The point at which an object is reclaimed depends on when the garbage collector notices that it is reclaimable. Normally, the garbage collector will wait until the heap is full, and then inspect the heap for the objects that are still possibly in use. In this way, the area under the *temporaries* curve in Figure 11.2 has a see-saw shape. As the temporaries pile up, waiting for the next garbage collection, they contribute more and more to memory footprint. Normally,

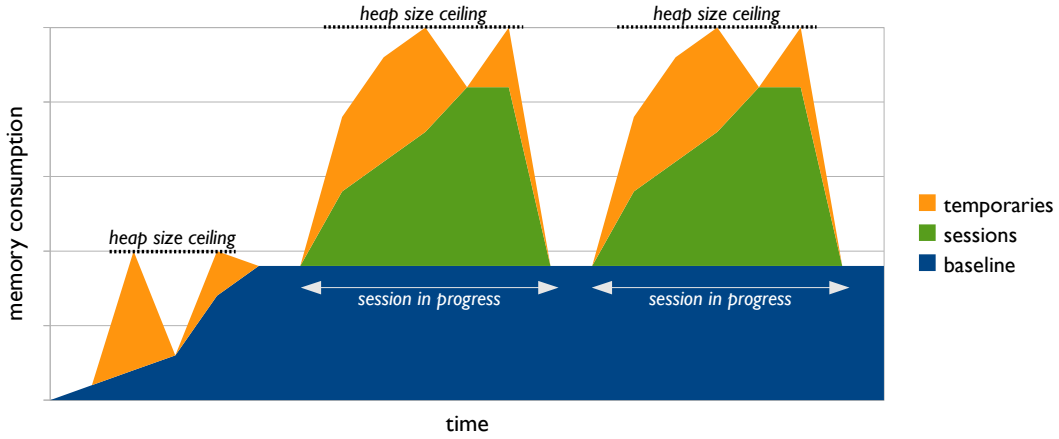


Figure 11.2. Memory consumption, over time, typical of a web application server.

once the JRE runs a garbage collection, the temporaries no longer in use will no longer be in the heap.

In this way, temporary objects *fill up the headroom* in the heap. If there is a large amount of heap space unused by the longer-lived objects, then the temporaries can be reclaimed less often. This is a good thing, because a garbage collection is an expensive proposition. When configuring your application, you may specify a maximum heap size. It should certainly be larger than the baseline and session data. How much larger than that? This choice directly affects the amount of *headroom*, that is the amount of space available for temporaries to pile up.

Temporaries in Practice If your application is like most Java applications, it creates a large number of temporary objects. They hold data that will only be used for a very short interval of time. It is often the case that the objects in these transient data structures are only ever reachable by local variables. For example, this is the case when you populate a `StringBuilder`, turn it into a `String`, and then ultimately (and only) print the string to a log file. Shortly after they are constructed, the string builder, string, and character arrays, are no longer used:

```
String makeLogString(String message, Throwable exception) {
    StringBuilder sb = new StringBuilder();
    sb.append(message);
    sb.append(exception.getLocalizedMessage());
    return sb.toString();
}
void log(String message, Throwable exception) {
    System.err.println(makeLogString(message, exception));
}
```

A temporary object serves as a transient home for your data, as it makes its way through the frameworks and libraries you depend on. Temporaries are often necessary to bridge separately developed code and enable code reuse. The above example avoids code duplication and ensures uniformity of the output data by factoring out the logic of formatting messages into the `makeLogString` method.

In many cases, the JRE will do a sufficient job in managing these temporary objects for you. Generational garbage collectors these days do a very good job digesting a large volume of temporary objects. In a generational garbage collector, the JRE places temporary objects in a separate heap, and thus need only process the newly created objects, rather than all objects, during its routine scan.

There are two potential problems that you may encounter with temporary objects. The first is the runtime cost of initializing the state of the temporary objects' fields. Even if allocating and freeing up the memory for an object is free, there remains the work done in the constructor:

```
class Temp {
    private final Date date;

    public Temp(String input) { // constructor
        this.date = DateFormat.getInstance().parse(input);
    }
}
```

Even if an instance of `Temp` lives for only a very short time, its construction has a high cost. It is often the case that this expense is hidden behind a wall of APIs. If so, then what you think of as trivial temporary (since you, after all, are in control of when the instance of `Temp` lives and dies), would in actuality be far from trivial in runtime expense. Expenses can pile up even further if temporary object constructions are nested.

There is a second potential problem with temporary objects. By creating temporary objects at a very high rate, it is possible to overwhelm either the garbage collector, or the physical limitations of your hardware. For example, at some point, the memory bandwidth necessary to initialize the temporary objects will exceed that provided by the hardware. Say your application fills up the temporary heap every second. In this case, based on the common speeds of garbage collectors, your application could easily spend over 20% of its time collecting garbage. Is it difficult to fill up the temporary heap once per second? Typical temporary heap sizes run around 128 megabytes. Say your application is a serves a peak of 1000 requests per second, and creates objects of around 50 bytes each. If it creates around 2500 temporaries per request, then this application will spend 20% of its time collecting garbage.

Example: How Easy it is to Create Lots of Temporary Objects A common example of temporaries is parsing and manipulating data coming from the

outside world. Identify the temporary objects in the following code.

```
void main(String xy) {
    doWork(xy.substring(0,10), xy.substring(10));
}
void doWork(String x, String y) {
    doRemoteProcedureCall(parse(x));
    doRemoteProcedureCall(parse(y));
}
Date parse(String string) {
    return DateFormat.getInstance().parse(string, new
        ParsePosition(0));
}
void doRemoteProcedureCall(Date date) {
    long timestamp = date.getTime();
    ...
}
```

This code starts in the `main` method by splitting the input string into two substrings. So far, the code has created four objects (one `String` and one character array per substring). Creating these substrings makes it easy to use the `doWork` method, which takes two Strings as input. However, observe that these four objects are not a necessary part of the computation. Indeed, these substrings are eventually used only as input to the `DateFormat parse` method, which has been nicely designed to allow you to avoid this very problem. By passing a `ParsePosition`, one can parse substrings of a string without having to create temporary strings (at the expense of creating temporary `ParsePosition` objects).

11.3 Correlated Lifetimes

Often objects are needed for a bounded interval of time. In some cases, this interval is bounded by the lifetime of another object. In a second important scenario, the lifetime of an object is bounded by the duration of a method call. Once that other object is not needed, or once that method returns, then these *correlated* objects are also no longer needed. These are the two important cases of objects with correlated lifetime.

Objects that Live and Die Together If you need to augment the state stored in instances of a class that you are responsible for, you could modify the source code of that class. For example, to add a secondary mailing address to a `Person` model, you add a field to that class and update the initialization and marshalling logic accordingly. This works fine for classes that you own, and when most `Person` instances have a secondary mailing address. However, sometimes you will find it necessary

to associate information with an object that is, for one reason or the other, locked down, or where the attributes are only sparsely associated with the related objects.

Example: Annotations In order to debug a performance problem, you need to associate a timestamp with another object. Unfortunately, you don't have access to the source code for that object's class. Where do you keep the new information, and how can you link the associated storage to the main objects without introducing memory leaks?

If you can't modify the class definition for that object, then you will have to store the extra information elsewhere. These *side annotations* will be objects themselves, and you need to make sure that their lifetimes are correlated with the main objects. When one dies, the other should, too.

Objects that Live and Die with Program Phases Similar to the way the lifetime of an object can be correlated with another object, lifetimes are often correlated with method invocations. When a method returns, objects correlated with it should go away. For short-running methods, you don't have to think about it, since local stack-allocated temporaries go away automatically when the method exits. For the medium-to-long running methods that implement the core functionalities of the program, this correlation is harder to get right.

For example, if your application loads a log file from disk, parses it, and then displays the results to the user, it has roughly three phases for this activity. Most of the objects allocated in one phase are scoped to that phase; they are needed to implement the logic of that phase, but not subsequent phases. The phase that loads the log file is likely to maintain maps that help to cross reference different parts of the log file. These are necessary to facilitate parsing, but, once the log file has been loaded, these maps can be discarded. In this way, these maps live and die with the first phase of this example program. If they don't, because the machinery you have set up to govern their lifetimes has bugs, then your application has a memory leak.

This lifetime scenario is also common if your application is a server that handles web requests.

Example: Memory Leaks in an Application Server A web application server handles servlet requests. How is it possible that objects allocated in one request would unintentionally survive beyond the end of the request?

In server applications, most objects created within the scope of a request should not survive the request. Most of these *request-scoped* objects are not used by the application after the request has completed. In the absence of application or framework bugs, they will be collected as soon as is convenient for the runtime. In this example, the lifetime of objects during a request are *correlated* with a method invocation: when the servlet `doGet` or `doPut` (etc.) invocations return, those correlated objects had better be garbage collectible.

There are many program bugs and configuration missteps that can lead to problems. The general problem is that a reference to an object stays around indefinitely, but becomes *forgotten*, and hence rendered unfindable by the normal application logic. If this request-scoped data structure were only reachable from stack locations, you would be fine. Therefore, a request-scoped object will leak only when there exist references from some data structure that lives forever. Here are some common ways that this happens.

- Registrars, where objects are registered as listeners to some service, but not deregistered at the end of a request.
- Doubly-indexed registrars. Here the outer map provides a key to index into the inner map. A leak occurs when the outer key is mistakenly overwritten mid-request. This can happen if the namespace of keys isn't canonical and two development groups use keys that collide. It can also happen if there is a mistaken notion, between two development groups, of who owns responsibility of populating this registrar.
- Misimplemented hashcode or equals, which foils the retrieval of an object from a hash-based collection. If developers checked the return value of the `remove` method, which for the standard collections would indicate a failure to remove, then this bug could be easily detected early; but developers tend not to do this.

The next chapter goes into greater detail on how to avoid these kinds of errors. **??** describes tooling that can help you detect and fix the bugs that make it into your finished application.

Correlated with External Event After the server is warmed up, it begins to process client requests. Imagine interacting with a commerce site with a web browser. First you browse around, looking for items that you like, and add them to your shopping cart. Eventually, you may authenticate and complete a purchase. As you browse and buy, the server maintains some state, to remember aspects of what you have done so far. For example, the server stores the incremental state of multi-step transactions, those that span multiple page views. This session state, at least the part of it stored in the Java heap, will go away soon after your browsing session is complete. In the timeline figures, this portion of memory is labeled *sessions*. It ramps up while a session is in progress, and then, in the example illustrated here, soon all of that session memory should be reclaimed.

Session state objects need to be kept around for operations that span several independent operations, and are possibly used across multiple threads. They are used beyond the scope of a phase, are not correlated with another object, but don't live forever. Like objects associated with requests, objects associated with sessions may accidentally live forever because of a bug, causing a memory leak. possible

that session state will live beyond the end of the session. In this case, over time, the amount of heap required for the application to run will increase without bound. Figure 11.3 illustrates this situation, in the extreme case when all of session state leaks. Over time, the area under the curve steps higher and higher.

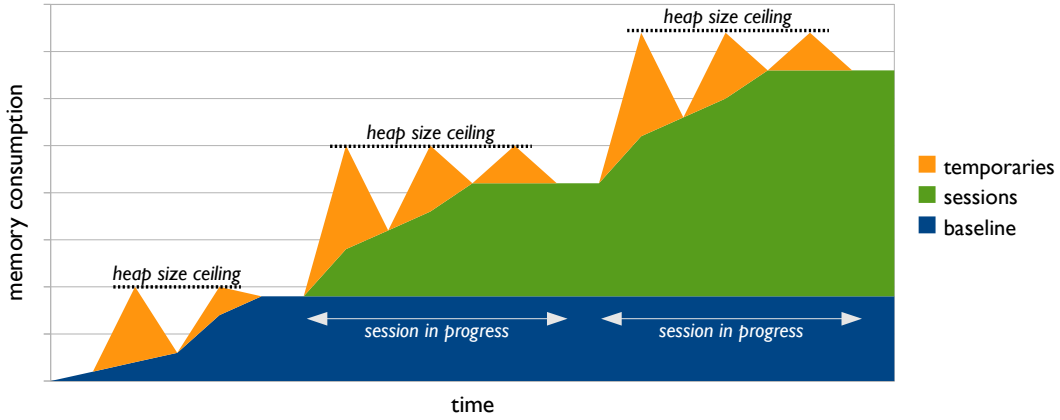


Figure 11.3. If session state is not cleaned up properly, a memory leak is the result. This means more frequent garbage collections, and ever increasing heap size.

11.4 Permanently Resident

Figure 11.2 shows the timeline of memory consumption of our example server during and shortly after its initial startup. During the startup interval, the server preloads catalog data into the Java heap. Then, the server is warmed with two test requests. The total height of the area under the curves represents the memory consumption at that point in time. The preloaded catalog data will be used for the entire duration of the server process. Therefore, the Java objects that represent this catalog are objects that are needed forever. In the timeline picture, this data is respresented by the lowest area, labeled *baseline*. Notice how it ramps up quickly, and then, after the server has reached a "warmed up" state, memory consumption of this baseline data evens out on a plateau for the remainder of the run.

Permanently Resident Objects in Practice In the above data parsing example, a `DateFormat` object was created in every loop iteration and used only once. We can improve this situation by creating and using a single formatter for the duration of the run. The Java API documentation, in writing at least, encourages this behavior, but leaves the burden of doing so on you. You must be careful to remember that it is not safe to do so in multiple threads. The next chapter will discuss remedies to this problem. The updated code for the `parse` method would be:

```
static final DateFormat fmt = new DateFormat.getInstance();
```

```
Date parse(String string) {
    return fmt.parse(string, new ParsePosition(0));
}
```

There are other cases where your application routinely accesses data structures for the duration of the program's run. For example, if your application loads in trace information from a file and visualizes it, then the data models for the trace data cannot be optimized away entirely. Sometimes it is possible, but not practical from a performance perspective, to reload this data. You could architect your program so that subsets of the trace data are re-parsed as they are needed. Unfortunately, the resulting performance, or the complexity of the code, may suffer drastically. If so, these data structures must, for practical purposes, reside permanently in the heap.

When Objects Don't Fit Sometimes, despite your best efforts at tuning these long-lived data structures, the structures still don't fit within your given Java heap constraints. Chapter 17 discusses strategies for coping with this situation.

11.5 Time-space Tradeoffs

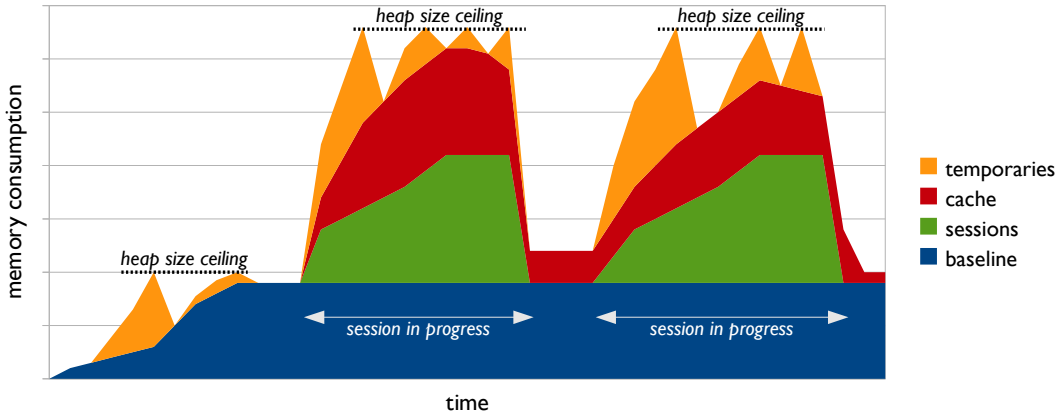


Figure 11.4. When a cache is in use, there is less headroom for temporary object allocation, often resulting in more frequent garbage collections.

It is sometimes beneficial to extend, or shorten, the lifetime of an object, depending on whether you need to optimize for time or space. For example, if every request creates an object of the same type, with the same, or very similar, fields, then you should consider caching or pooling a single instance of this object. There are four important cases of time-space tradeoffs. The first covers the situation where recomputing attributes, rather than storing them, is a better choice. The next three cover situations where spending memory to extend the lifetime of certain objects

saves sufficient time to be worthwhile: caches, sharing pools, and resource pools. Chapter 13 discusses implementation strategies for these situations.

Our example server application caches data from an expensive third-party data source. Caching external data in the Java heap complicates programming and management tasks. The cache must be configured properly so that its contents live long enough to amortize their costs of fetching, while not occupying too much of the heap. If caches are sized too large, this would leave little space for the temporaries that your application creates. Figure 11.4 shows an example where the cache has probably been configured to occupy too much heap space. Observe how, compared to the other timeline figures, there is little headroom for temporary objects. The result is more frequent garbage collections. If the cache were sized to occupy an even greater amount of heap space, it is possible that there would no longer be room to fit session data. The result in this case would be failures in client requests.

Sizing caches is important, but tricky to get right. If the data to be cached is stored on a local disk, then another strategy to caching is to use *memory mapping*. Section 18.2 describes how to utilize built-in Java functionality that lets you take advantage of the underlying operating system's demand paging functionality to take care of caching for you.

11.6 Summary

This chapter sets the stage for Part 2 of this book by defining five types of object lifetime requirements that programmers need to be aware of, especially for long-lived applications like servers. If you make the effort to identify the lifetime requirements for the objects in your application, you can avoid common mistakes that result in memory leaks. Here is a high level summarization of the different kinds of lifetime requirments.

- At one extreme are short-lived temporary objects that are managed by the JRE garbage collector. You don't have to worry too much about temporaries, except that creating too many of them can cause a performance problem.
- Some objects have a lifetime requirement that is correlated with something else, such as the lifetime of another object, an execution phase, or an external event. Often, these correlated objects must be explicitly freed based on another object going away, a phase ending, or an event notification. Managing correlated lifetimes can be tricky and error-prone. There is, or course, no way to explicitly free objects in Java, so Chapter 13 describes a variety of techniques for implicitly freeing correlated objects.
- At the other extreme, many objects are needed throughout the execution, and must be permanently resident in the heap.

The moral is that even though Java has a garbage collector, you still have to understand and implement object lifetime requirements.

Chapter 12

MEMORY MANAGEMENT BASICS

[NOTE: Section 12.1 has way too much detail. I think the whole section could be deleted, but if you want to keep some of the points, should be much shorter, maybe one page. It's certainly out of place after Chapter 11. The remaining sections are more appropriate, especially Basic Ways of Keeping an Object Alive – I like that — Edith]

The Java language has a *managed runtime*. As part of being a managed runtime, as a Java program runs, a supporting JIT compilation and other support threads are spawned. These thread work on your program's behalf and, together, compose a runtime system that manage important aspects of execution. One of these tasks is memory allocation and reclamation. The runtime automatically takes care of many important cases of memory management. You needn't, for example, be concerned with explicitly deallocating *most* of the objects you allocate, because the runtime includes automatic garbage collection of instances. The Java runtime also provides built-in support that let you manually take care of some of the more complex cases, such as implementing appropriate caching policies.

Taking advantage of these facilities requires some care, from issues as straightforward sounding as choosing a reasonable bound for memory consumption, to deciphering the cause of failures due to memory exhaustion. Surprisingly, memory leaks are possible, even common, in Java, and can easily lead to application failures without good design and testing. Furthermore, some of the runtime facilities appear in the form of low-level JVM hooks, or implicit behavior that you have to carefully govern, and so require careful coding to make correct use of them.

12.1 Heaps, Stacks, Address Space, and Other Native Resources

As your program runs, there is a good chance that quite a bit of memory will be allocated and reclaimed. Some of the memory allocations will come directly from your code, as it calls `new` to instantiate classes. Other times, memory will be allocated behind the scenes, such as by the class loading or JIT compilation mechanisms, or by native code that your code uses. Under the covers, the managed

runtime will service allocation requests from a number of memory pools. Most of these will be allocated on the *Java heap*, but there are other memory areas that you need to be aware of. Each area has its own sizing and growth policies, and its own constraints on maximum capacity.

The Heap Usually, a call to `new` results in a memory allocation on the Java heap. The heap is a region of memory that the JVM allocates on startup, sized to your specification. It contains Java objects, linked together in the way that they reference eachother. In Java, each object can contain either primitive data or references to other objects. One Java object cannot contain, inline, the fields another Java object. This is possible in languages such as C or C# through the use of `structs`.

In Java, the heap is bounded in size, and so it will never consume more than a fixed amount of memory. The maximum size of the heap, along with the initial size and a policy for growing the heap, are all under your control. If you don't make a choice for any of these, the JRE will choose some reasonable defaults. Always experiment to see whether the defaults suit your needs. The defaults vary, from one JRE to the next. Older JREs, typically those prior to Java 5, tend to have hard-coded default values, indepdendent of how much physical memory your machine actually has. Most JREs now attempt to adjust the the heap sizing criteria based on the physical memory capacity of your machine.

It often makes sense to keep a small initial Java heap size and a large maximum size. If your application requires a varying amount of memory, an amount that depends on the size of the input data, then this strategy can pay off. For example, say you run multiple copies of the application on one machine, and, most of the time, the inputs are on the small side. Then this strategy will allow you to run more copies simultaneously, while still allowing for the rare cases when an input requires more memory. You needn't worry too much about this affecting performance for the cases of larger inputs. JREs are pretty smart these days, and make a good effort to adjust the size of the heap from the initial size to the maximum size, and back down, as it finds that your application memory needs change. Still, you should always experiment! JREs don't always get this right.

Experimentation is also important, because the default choice of initial and maximum Java heap size may result in your application running more slowly than it could. Sometimes, this sub-par performance is due to having an *initial* size that is too low. It takes a while for the JRE to learn that it should increase the heap size beyond the initial size. If your application only runs for a short time, and your application commonly needs more than the default initial size, why should you burden the JRE with learning something that you have already learned by your own experimentation?

In terms of finding a good maximum heap size, you should be very careful never to set it to be more than the amount of physical memory on your machine. If your application runs as multiple processes, you have to make sure to divide physical memory between them. Also, the operating system itself, and other processes run-

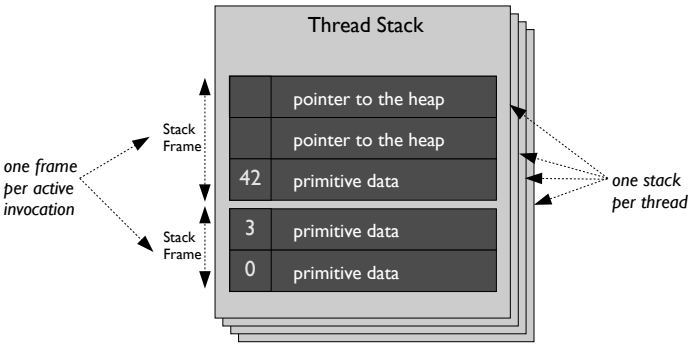


Figure 12.1. The compiler takes care managing the stack, by pushing and popping the storage (called *stack frames*) that hold your local variables and method parameters.

ning on the machine will consume physical memory, taking away from the resources available to your application. Further complicating matters, behind the scenes aspects of the managed runtime will consume resources even within your process. This practice of continual experimentation is important, given the disparity between the speed of accessing RAM versus the speed of accessing disk; these days, swapping memory to and from disk is too slow to be worth even considering. In particular, the way that the managed runtime reclaims memory, via automatic garbage collection, usually doesn't mix well at all with swapping memory to and from disk.

To specify the initial size of the Java heap, pass the `-Xms` flag on the launch command line; to specify the maximum size, pass the `-Xmx` flag. For example, by passing `-Xms100M -XmX1G`, you are telling the JRE to use an initial size of 100 megabytes, and a maximum size of 1 gigabyte. **??** goes into more detail on the tuning parameters at your disposal.

The Stack The Java heap is the main storage for your objects, including all of their fields and primitive data. When your code has a local variable that references an object, this pointer is stored on the *stack*. In the example on the right, for the duration of an invocation of the method `f`, your code needs to store references to those two instances of `X` and the primitive data value `z`. The JIT compiler sets aside space for these three local variables on the stack, as illustrated in Figure 12.1. Each method invocation, in each thread, has memory associated with it to store these local variables. This space is pushed and popped, as the thread invokes and returns from the execution of methods. The stack memory that is set aside for a method invocation is commonly called a *stack frame*.[1] As is the case with Java objects, it is also the case that the stack can only contain primitive data or references to objects.

```
void f() {
   X x = new X();
   X y = new X();
   int z = ...;
   ...
}
```

[1]Historically, it has also been referred to as an *activation frame* or *activation record*.

Like the heap, the stack also has limits to its size. Each thread in your program can have a stack no deeper than a fixed limit, in bytes. If, during the execution of a thread, these stack limits are exceeded, you may see a `java.lang.StackOverflowError` exception thrown. You can configure this property via the `-oss` command-line parameter.

A JIT Optimization: Stack Allocation Sometimes, the JIT compiler is clever enough to observe that a call to `new` can safely be allocated on the stack. This optimization is called *stack allocation* of objects. It is enabled, by default, as of Sun Java 6 Update 21 and IBM Java 6 Service Release 2. When this optimization is possible, objects created and used *only* as local variables will be stored on a stack frame; it is as if you were using C `structs`. Though the JIT compiler can optimize away a fair number of short-lived objects via stack allocation, you should not depend upon this optimization. It is a tricky thing for the JIT compiler to do correctly, and so the compiler is very conservative in its application.[2]

Java Memory vs. Native Memory In addition to the heap and stack space that are devoted to Java data, every Java program also has separate memory areas devoted to native data. The native heap stores a variety of things, including memory allocations made by native code that your application uses and the JIT compiled code of your application. The JRE imposes an upper limit on the Java heap. In contrast, the operating system sometimes imposes no limit on the total amount of memory consumed by a process. Therefore you should be careful, and observe whether your application is indeed swapping any native allocations to and from disk.

In addition, every thread in a Java program actually has two stacks, one for the Java stack frames and one to hold the stack frames of any native methods that either your Java code invokes or invokes your Java code. There is a command-line parameter that you can use to configure the size of every native stack: `-ss`.

When your application exceeds any native limits you may confusingly see the same error that you would see for exhaustion of Java memory resources: the `OutOfMemoryError`. Therefore, you should be aware of the Java and native heap limits, in order to confirm the true source of the resource exhaustion: was it due to running out of Java heap, or running out of native resources?

The Permspace Heap The JRE stores information about classes, including executable code and string constants, in memory areas that are separate from those for instances of classes. Some JREs create a distinct heap for this data, one that can be sized like the other heaps. Other JREs store this data in an undifferentiated part of the general native heap. The Sun JRE is in the former camp, while the IBM and JRockit JREs are in the latter camp. The Sun JREs call this heap the *permspace* heap. This name came about because the heap contains objects and other data that

[2] If you are curious, the best you can do is to analyze performance both with and without the underlying anlaysis. On Sun JVMs, you can disable the analysis by adding `-XX:-DoEscapeAnalysis` to your application's command line.

Platform	Pointer Size	maximum memory consumption per process
z/OS	31-bit	1.3GB
Microsoft Windows	32-bit	1.8GB
UNIX-based	32-bit	2GB
Microsoft Windows	32-bit `/3GB`	3GB
all	64-bit	$\geq$ 256TB

Table 12.1. Even with plenty of physical memory installed, every process of your application is still constrained by the limits of the address space. On some versions of Microsoft Windows, you may specify a boot parameter `/3GB` to increase this limit.

are, at least for the most part, immortal. On Sun JREs, you can size the permspace heap via the command-line parameter `-XX:MaxPermSize`.

Physical Memory versus Address Space Physical memory is one of the primary underlying constraints on how big you can size your heaps. There is another limit that is independent of how much physical memory you install on your machine. The limit depends on the number of memory locations that can be addressesed, given the size of pointers on your machine. The *address space* of a process is the set of addresses that the process can read or write via pointers. Therefore, this limit depends upon the size of pointers on your platform, and, to a lesser extent, upon the underlying operating system. Table 12.1 gives numbers for some common platforms. For example, if your application runs on a 32-bit Windows operating system, the total amount of memory that each process can access is 1.8 gigabytes.[3] A pointer that is 32 bits wide can address 4 gigabytes, of which the operating system reserves roughly half for its own use. If a process of your application attempts to allocate memory beyond this address space limit, a failure will occur. It is quite often the case that this failure will manifest itself also as a `java.lang.OutOfMemoryError`. Since both Java heap exhaustion and address space exhaustion can manifest as the same error, you will need to dig down to root out the true nature of the failure.

Some operating systems let you specify limits on the amount of address space that a process can use. This is similar to the way that you can specify `-Xmx` to limit the maximum amount of Java heap that a process should consume. On UNIX platforms, you can use the `ulimit` command. For example, on Linux, to limit the amount of address space any process launched from the current shell can access, say to 1 gigabyte, issue this command in Figure 12.2.

```
% ulimit -m 1048576
```

Figure 12.2. Limiting the addressible memory of a process to 1 gigabyte.

[3]Some versions of 32-bit Windows let you specify a `/3GB` boot option, which increases this limit from 1.8GB to 3GB.

Native Resources: File Descriptors, etc. Address space constraints exist on every operating system. Depending on your operating system, there are often other resource limits that can lead to program failures. For example, processes may be limited in the number of open files they may have at any one time. You may see failures in your application, despite having lots of memory and stack space free, because an application process has exhausted file descriptors. On Windows platforms, there are other system-imposed limits, such as the number of open font handles. You should be aware of these common resource constraints, because they may impact the scalability of your application. For example, you may have designed your application to keep many font handles open for each thread, rather than keeping a common pool of them, and sharing them across threads.

12.2 The Garbage Collector

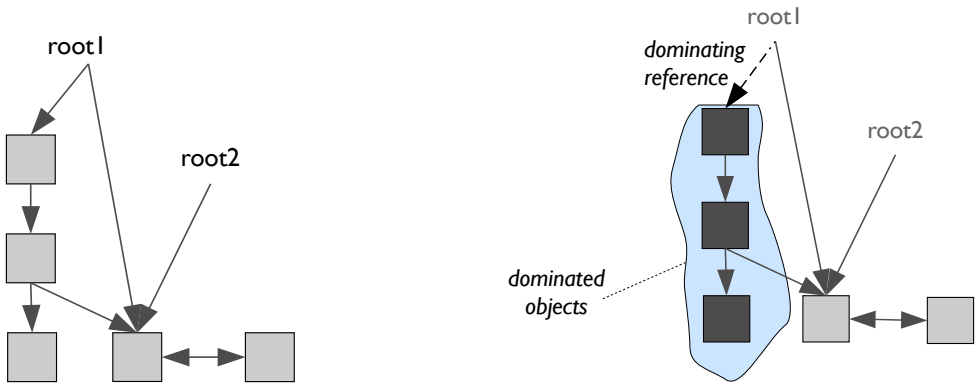
Garbage collection is the mechanism that determines when the memory allocation of an object can be reclaimed for future use. To determine whether an object is dead, the garbage collector looks at the structure of object interconnections in the heap. Any objects that future code cannot possibly access are certainly ready to be reclaimed.

Your application uses objects by traversing references to them. For example `o.f` gives access to the contents of the object referenced by field `f` of instance `o`. Your code has to start this chain of field references somewhere, of course, and the garbage collector simulates this process. It traverses references from all possible variables that your code might possibly access. Each time a garbage collection occurs, the collector scans the heap for *live* objects in this way. A live object is one that might possibly be used in the future.

When to Collect: GC Safe Points The garbage collector typically only runs when it has decided that heap memory has become highly constrained. When this happens, it quite often needs to stop the application threads, so that it can look for objects to reclaim.[4] It requests that the threads stop, and then waits until each thread has reached a *safe point* in the code. Safe points commonly include the beginning or end of method invocations, the end of each loop iteration, and points surrounding native method invocations. At this juncture, it begins to look for objects to reclaim.

What to Collect: Reachability The collector treats the heap as a graph of objects. The nodes are the objects themselves, and the edges are the non-null fields and non-null entries of arrays. Liveness is a recursive concept: an object is *live* if it is referenced either by a live object or, in the base case, by a *root*. The roots of garbage collection include: objects serving as monitors, objects on the stack of a

[4] A *concurrent* collector only performs part of the garbage collection work concurrently with the application threads. Most concurrent collectors still need to pause the threads in order to perform reclamation.



(a) A live data structure.

(b) Then, a reference is clipped.

Figure 12.3. The garbage collector uses the references between objects to determine what objects are collectable. The data structure on the left is filled entirely with live objects. The one on the right, after a link is clipped, now contains some collectable objects; all objects reachable only by traversing a *dominating reference* will be collectable, as well.

method invocation in progress, and references from native code via the Java Native Interface (JNI). Every other object is ready for collection.

This recursive aspect can also be expressed in terms of *reachability*. The live objects are those objects reachable, by following a chain of references, from some root. Figure 12.3 illustrates a simple data structure, and shows which part becomes collectable when a reference is set to null, or "clipped". When the indicated reference is clipped, there is no chain of references from a root to the shaded region of objects.

Reachability is the graph property that determines what objects are still live. This is all the garbage collector cares about, finding the objects that need to be kept around. It is also helpful for programmers to know which objects become dead as the result of a pointer being clipped. The objects within the shaded region of Figure 12.3(b) have the property that each is reachable *only* from the clipped reference. That clipped reference is the unique owner of the shaded objects. The clipped reference is said to dominate those objects that it uniquely owns.

Dominance (Unique Ownership)

One node in a graph *dominates* another if the only way to reach the latter is by traveling through zero or more nodes from the former. This property is important for determining which other objects will be garbage collectable when an object is reclaimed: those it dominates. If an object only dominates itself, but isn't a root of the graph, then you know that it has *shared ownership*. Otherwise, it is *uniquely owned* by that dominating node.

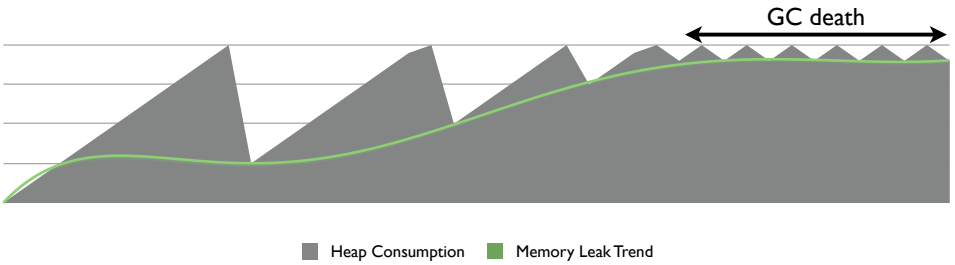


Figure 12.4. When your application suffers from a memory leak, you will likely observe a trend of heap consumption that looks something like this. As memory grows more constrained, garbage collections are run with increasing frequency. Eventually, either the application will fail, or enter a period of super-frequent collections. In this period of "GC death", your application neither fails, nor makes any forward progress.

Most of the time, the garbage collector does what you'd expect, and you needn't worry about freeing up memory. Java applications are frequently plagued by memory leaks, and cases where memory allocations *drag* out their lifetime, beyond when your code needs them. Avoiding these problems, especially in more complex cases such as those involving caching or the use of native resources, is a perennial challenge of writing in Java. For these cases, you need to be aware of the how the managed runtime treats an object in various stages of its life.

Memory Leaks, and Running Out of Java Heap If your application seems to have periods where it runs very slowly, and then either magically recovers or dies, then it may be suffering from a memory leak. Figure 12.4 shows a typical trend of heap consumption that you may observe, if it indeed does have a leak. This chart represents how much Java heap memory is free *after* each garbage collection. The characteristic aspect of a leak is an inexorable decrease in the amount of free memory after each garbage collection. Sometimes, the amount of free memory after a garbage collection sawtooth up and down, for example because caches fill up and are cleaned out as memory grows tight, or due to the natural ebb and flow of load on your application over time. Nevertheless, the upwards climb is stll there. As heap memory becomes less and less available, garbage collections become increasingly frequent.

If your application exhausts the Java heap, you will observe an `OutOfMemoryError` exception thrown. On Sun JVMs, you will sometimes see a variant of this: `GC overhead limit exceeded`. On all JVMs, it is possible that the runtime will enter a nasty state where it is spending all of its time reclaiming memory.

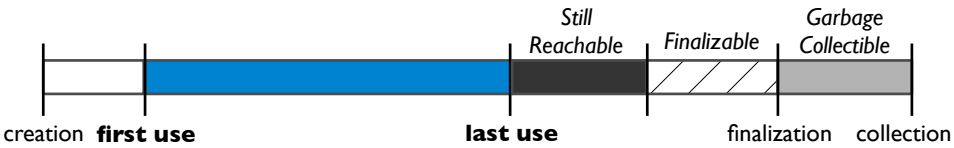


Figure 12.5. Timeline of the life of a typical object.

GC Death

Sometimes, your application will appear to grind to a halt, without any exceptions appearing on the error console. If you observe this situation, then your application may be suffering from what is nicknamed *GC death*. In this situation, the JRE is frantically, but ineffectually, trying to find free space. The situation becomes dire when the time it takes the garbage collector to perform one scan is large relative to the time before your application next runs out of space.

It is easy to know whether your application is suffering from GC death. A universal way to do this, one that works on any JVM, is to enable verbose garbage collection. This requires modifying your application's command line, and therefore restarting it, if this option is not already enabled. Each JRE provider offers good alternatives to verbose garbage collection. If you are using a Sun JDK build of the JRE, then you can use the `jstat` tool.[5] If you are using an IBM JRE, then you can request `javacores`, which contain a small historical window of garbage collection events. Neither of these require modifying your application command line, and so are very nice alternatives. In any case, by inspecting the resulting output, you will observe that the collector is active 99% or more of the time.

12.3 The Object Lifecycle

Memory in a managed runtime goes through a complex lifecycle, from allocation to eventual reclamation. In contrast, memory in the C language has a very simple lifecycle. In C, memory is allocated by calls to `malloc` and reclaimed by explicit calls to `free`. For C, that's all there is to it: from your program's perspective, a piece of memory is either in use or it isn't. In Java, objects go through many more stages.

In a well-behaved application, an object's lifetime starts with its allocation, continues with the application making use of it, and concludes with the (hopefully) short period during which the JRE takes control and reclaims the space. Figure 12.5 illustrates the lifecycle of a typical object in a well behaved application.

[5]The `jstat` tool is only available with JDK builds. It is neither available with JRE builds, nor with any builds prior Java 5.

Example: Parsing a Date Consider a loop that shows an easy way to parse a list of dates. What objects are created, and what are their lifetimes?

```
for (String string : inputList) {
  ParsePosition pos = new ParsePosition(0);
  SimpleDateFormat parser = new SimpleDateFormat();
  parser.parse(string, pos);
  ...
}
```

For each iteration of this loop, this code takes a date that is represented as a string and produces a standard Java `Date` object. In doing so, a number of objects are created. Two of these are easy to see, in the two `new` calls that create the parse position and date parser objects. The programmer who wrote this created two objects, but many more are created by the standard libraries behind the scenes. These include a calendar object, number of arrays, and the `Date` itself. None of these objects are used beyond the iteration of the loop in which they were created. Within one iteration, they are created, almost immediately used, and then enter a state of drag.

Memory Drag

At some point, an object will never be used again, but the JRE doesn't yet know that this is the case. The object hangs around, taking up space in the Java heap until the point when some action is taken, either by the JRE or by the application itself, to make the object a candidate for reclamation. The interval of time between its last use and ultimate reclamation is refered to as *drag*.

An object can either:

- **Drag forever**. This can happen when you allocate and use a data structure at application startup, but never again.
- **Drag with lexical scope**. This can happen when a data structure is allocated early on in a method invocation, but not used after some early point in the execution of that method.
- **Drag until GC**, i.e. the next time the JRE decides to scan the heap, looking for dead objects. This can be a problem if your application creates temporary objects at a low rate, or if you have configured a very large heap. In either case, the next garbage collection may be far in the future.

In the date formatting loop above, the `pos` object represents to the parser the position within the input string to begin parsing. The implementation of the `parse` method uses it early on in the process of parsing. Despite being unused for the remainder of the parsing, the JRE does not know this until the current iteration of the loop has finished. For this duration of time the object is in a kind of limbo, where it is referenced but never be used again. This limbo time also includes the entirety of the call to `System.out.println`, an operation entirely unrelated to the creation or use of the parse position object. Once the current loop iteration finishes, these two objects will become candidates for garbage collection. The object now enters a second stage of this limbo. There are no pointers to `pos` that should keep its memory around, but the memory will stay around until the next garbage collection. Only when the garbage collector performs a sweep over memory, looking for reclaimable objects, will the memory for `pos` be ready for new objects. Most of the time, this second stage of limbo is short, because garbage collections typically run ever few seconds.

However, if there is a long interval of time during which your application allocates very few objects in the Java heap, it could be quite a while before these dragging objects are reclaimed. You should be cautious here if, during these lulls in Java object creation, your application is heavily exercising the native heap. For example, say your application has small Java objects that hold on to large native resources. Even if, once the Java objects are collected you can up the associated nativ resources, you may still exhaust native resources. This is because dragging Java objects will only be collected when you run out of Java heap space. The JRE doesn't know to schedule a garbage collection when you exhust native resources.

12.4 The Basic Ways of Keeping an Object Alive

An object will stay around as long as it is reachable from some chain of references. The nature of the references along any chains (for there may be multiple such chains!) leading up to your object will determine how long it'll stick around. After your program creates an object, it references the object in one or more of three basic ways shown on the right. Each comes with its own guidelines as to how it governs lifetime, and how you can control it.

The basic ways of referencing an object:

- instance field of any other object
- static field of a class
- local variable of a method
- a *shared* combination of the above

The Lifetime of Instance Field References If object `B` is dominated by an instance field of object `A`, then `B` will become garbage collectable only under two circumstances. Once `A` becomes collectable, then so will `B`. Notice how, in this way, a dominating reference is one way to implement the correlated lifetime pattern of Section 11.3. The

other possibility is that you insert code that, at some point, assigns this reference to `null`. Since `A` dominates `B`, therefore, at this point, there will be no way for the garbage collector to reach `B`, and so it will become garbage collectable.

The Lifetime of Statics, and Class Unloading The JRE allocates memory for every class, to store its static fields, such as the one on line 13 in the above example. This memory, to store all static fields plus some bookkeeping information, is often referred to as the *class object* for the class. It is possible for the same class to be loaded into multiple class loaders; in this way, using more than one class loader lets you avoid the problem of colliding use of static fields in separately developed parts of the code. A static field therefore only exits scope when the class object is reclaimed, which occurs when the respective class is unloaded, by the JRE, from its class loader.

If a class is never unloaded, which is likely to the be case for your application, then that class object will remain permanently resident. The *default* class loader, which is the one that will be used unless you specify otherwise, never unloads application classes.

If you need classes to be unloaded, then you must manually specify a class loader to use. Unloading a class is then accomplished by ensuring that all references to both the class object and your custom class loader, are set to `null`. This will render the class unloadable, and will also render objects referenced by static fields all classes loaded into that class loader as garbage collectable. There exist module management systems, such as OSGi [4], that facilitate this task.

Due to these complexities, your design should generally anticipate that the memory for these static fields is permanently resident. This means that any static fields referencing an instance, rather than containing primitive data, will render that instance also permanently resident. Unless, that is, you take action to explicitly clip the static field reference, by assigning the field to null. Otherwise, that instance will be forever reachable along a path from some garbage collection root through the static field reference. In this way, storing a reference in a `static` field of an class is one way to implement a permanently resident lifetime policy.

```
class F {
  static Object static_obj;

  void f() {
    Object obj = new Object();
    static_obj = obj;
    ...
  }
}
```

Figure 12.6. When `f` returns, `obj` ownership automatically ends, but `static_obj` ownership persists.

The Lifetime of Local Variables Variables that are declared within a method body often have a lifetime that is bound to, at most, the duration of an invocation of that method. Common examples of this are local variables, loop variables, and variables declared within some inner scope such as within the body of a loop or `if` statement. For these variables, when a loop continues to the next iteration, when the body of a clause of an if/then/else state-

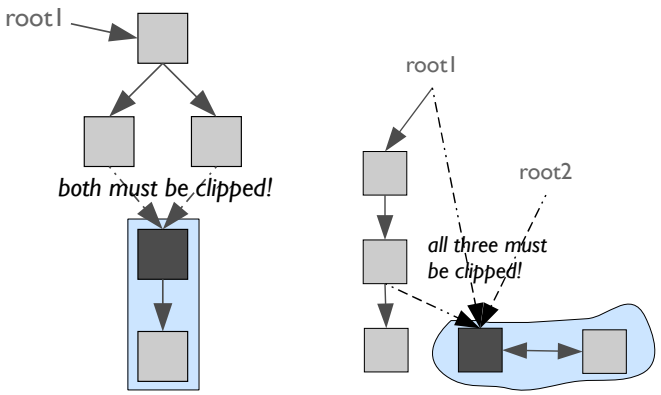
ment finishes, or when the method invocation returns, there is a good chance that the object referenced by that variable will be reclaimable. If the local variable was the sole owner of the object, it will indeed become reclaimable.

There are situations where an object may *escape* the local scope in which it was declared. This is an example of an object escaping a local variable scope, so that, beyond the duration of the local scope, it will remain alive, now owned by a static field of a class object: The next section discusses the lifetime of static fields.

The minimum that the Java language specification requires is that non-escaping objects that are declared within some scope inside of a method will be reclaimable by the time that scope exits. Many modern JREs try to optimize this, by attempting to infer a more precise line of code after which an object will not be used. For this reason, a *few* cases of memory drag that would have been a problem with older JREs, are no longer an issue. If you're curious to know whether your JRE does something clever, you can run the test program on the right. The `obj` object is owned by a local variable that is declared in the scope of the `main` method. This method does not return until the program exits. If you see the message before the program terminates, this means that the JRE has smartly determined that `obj` is not used beyond a certain point. If you see the `Yes` message before the end of loop message, this is a sure sign that the JRE is being clever. Be careful to remember that seeing the message is definitive evidence, but not seeing that message might only mean that your loop doesn't iterate enough times to cause a garbage collection to occur. You may need to experiment with the number of loop iterations, before coming to a conclusion.

```
void main(String[] args) {
  Object obj = new Object() {
    protected void finalize() {
       System.out.println("Yes");
    }
  };
  for (int i=0; i<1000000; i++) {
     new HashSet().add(i);
  }
  System.out.println("End");
}
```

Shared Ownership When you invoke a library method, there is no way in Java to know what the called method does with your object. It could very well squirrel away a reference to any object reachable from arguments you pass to the invocation. Despite your best efforts at keeping track of which references exist to an object, it can easily become an uncontrolled mess once you pass these objects to third-party libraries. In the above example, if you call the `parse` method of a `SimpleDateFormat` object, the method contract says nothing about how it treats the given string or `ParsePosition` passed as parameters. Consider the case where you need the string to become garbage collectable soon after having parsed it, but the formatter maintains a reference in order to avoid reparsing the same string in back to back calls.



(a) Diamond sharing. (b) Root sharing.

Figure 12.7. When an object is shared, such as the shaded ones shown here, care must be taken to clip all edges from emanating from outside of the region you wish to reclaim.

This calls to mind the worst of the days of explicitly managing memory in a language like C.

In the case where there is more than one reference to the object, the story gets more complicated. In contrast to C, where a `free` of *any* pointer suffices for deallocation, in Java *all* paths to an object must be clipped. This is tricky in many cases, because it may not be easy to know where all of path paths emanate from. Figure 12.7 illustrates a situation where three references must be clipped before an object, the darkly shaded one, becomes a candidate for garbage collection. There are two other important things to note in this example. First, just as in Figure 12.3(b), after clipping the three indicated references, an entire data structure, not just that darkly shaded object, becomes a candidate for reclamation. This structure consists of the two objects contained within the lightly shaded region. The second important thing to note is that you needn't clip the backwards edge, or any edge contained entirely within the data structure you no longer need.

12.5 The Advanced Ways of Keeping an Object Alive

The Java language provides mechanisms that allow you more flexibility in implementing lifetime management policies. These advanced features are exposed via soft, weak, and phantom references, finalization, and thread-local storage. In contrast, the term used for the normal way of referencing objects is a *strong* reference; i.e. this is what you get when you use fields of objects or local variables,

Soft and Weak References An object is *strongly reachable* if it is reachable only from strong references. For a strongly reachable object, the normal garbage collection rules apply: when it is no longer reachable from the current set of roots, it is a candidate for garbage collection. Soft and weak references are features of the

Advanced Reference	Purpose	Chapter
weak	correlated lifetimes	Chapter 13
soft	caching, safety valves	Chapter 14
final, phantom	cleaning up external resources	Chapter 13
thread-local	avoiding lock contention	Chapter 14

Table 12.2. Java offers several more advanced ways of referencing objects.

Java language that let you guide the normal process, so that you can more easily implement certain lifetime patterns. Programmers are often confused by these two, and web searches will reveal some degree of misinformation. It is common for web sites misdefine these two mechanisms, e.g. by swapping their roles.

Soft references are useful when you need to implement any kind of logic that needs reclamation only when memory is tight. In this way, soft references can form the basis of caching, or to implement safety valves. If an object is reachable by only a soft reference, then the garbage collector is free to reclaim it whenever it wants.

Softly and Weakly Reachable

An object is *softly reachable* if it is not strongly reachable, but there is at least one path that contains a *soft reference*. An object is *weakly reachable* if it is neither strong nor softly reachable, but there exists at least one path that contains a *weak reference*.

The Java language specification places no firm criteria upon JRE implementations as to when they should clip soft references. In practice, soft references won't be clipped at the random whim of the JRE. All JREs these days make a partial effort to clip soft references in a least-recently used (LRU) fashion: soft references that haven't been traversed in a while will be clipped before those that are frequently used. This is why soft references can form the basis for cache implementations. In reality, no contemporary JRE uses a true LRU policy for clipping soft references. For example, with Sun JREs, it is possible that all soft references that haven't been used in 6 minutes will be automatically cleared, even though the heap has 500MB of space free, out of a 600MB heap. Section 14.1 has more details on this subject. Soft references are still useful, despite this limitation, but you will need to design around this limitation.

Weak references can help you implement a correlated lifetime pattern. If an object is referenced by both a strong and a weak reference, then of course the object remains live, due to the strong reference. Your code has two ways to access the object, via either the strong or the weak reference, but only one of them is keeping the object alive. As soon as the strong reference goes away, the referenced object will become garbage collectable.

If it's not immediately obvious to you how this behavior can be used to implement a correlated lifetime pattern, you're not alone. It's tricky! Say you'd like to correlate an annotation `A` with an object `X`. How should you link these together with strong and weak references to make the magic happen, i.e. that when `X` is reclaimed, then `A` must also be reclaimed? Should the weak reference point to `A`, since it is the object you'd like to go away automatically? You can't just only weakly reference `A`, otherwise it'd be reclaimed in very short order (at the next garbage collection). It turns out that getting this correct isn't easy. Section 13.2 goes into more detail on

this topic, and shows you how to use the standard `WeakHashMap` class to avoid most of the messy details.

In real code, things will be a bit more complicated. It is possible that an object is directly referenced ownly by strong references, but that it is *reachable* only from a soft reference. In this case, everything dominated by that soft reference will become garbage collectable as soon as memory gets tight.

```
void foo(DateFormat f) {
   SoftReference<DateFormat> ref;
   ref = new SoftReference<
       DateFormat>(f);
   ...
}
```

Figure 12.8. Creating soft references.

You should not use these references lightly. Table 12.3 summarizes the costs of the ways of one object referencing another. A strong reference costs one pointer, which is 4 bytes (32 bits) on a 32-bit JRE. In comparison, a weak reference is *seven times* more costly, at 28 bytes per reference, and a soft reference is nine times more costly. The reason for these expenses is that you must create an extra `Reference` object for every soft or weak reference you use. To softly reference a date formatter, you would write code such as appears in Figure 12.8.

Reference Queues Normally, when you create a soft reference, and the JRE decides to clip it, then the associated `Reference` object becomes immediately garbage collectable. You get no warning that the JRE has clipped this reference. Sometimes, this is good, because it lets you very easily take advantage of the soft and weak referencing mechanisms. More often, however, your code will need some warning that a reference has been clipped. For example, if you are using soft references to implement a cache (this is discussed in more detail in subsequent chapters), then you will probably need to perform some cleanup work when the reference is clipped.

reference type	memory cost
strong	4 bytes (one pointer)
finalization	28 bytes
phantom	28 bytes
weak	28 bytes
soft	36 bytes

Table 12.3. The per-reference cost one object referencing another.

Java provides reference queues for exactly this purpose. When you construct a soft or weak reference, and associate it with a reference queue, then something different happens when the reference is clipped. Instead of becoming collectable, when clipped, it is placed on the associated reference queue. It is your job to periodically *poll* the reference queue in order to enquire as to whether any references have been clipped. If this sounds tedious and error prone, it is! For some use cases, the standard library provides mechanisms that hide some of these details. For example, `WeakHashMap` does a good job of completely hiding reference queues and weak references from you.

If you do find a need to use reference queues directly, there are a few points

of caution you should incorporate into your design. First, if you don't poll your reference queue at a rate that at least equals the worst case rate at which they will be queued, then the size of your reference queue will grow unboundedly. The worst case rate of objects queueing up is the rate at which they are created. Therefore, you should make sure to poll the queue in all code contexts that create any of the special kinds of references.

Reference Queue Polling Rule

A reference queue must be polled at least as often as `Reference` objects are created, that are destined for that queue. Otherwise the queue will leak memory, growing unboundedly.

Second, since you need to poll wherever a queueable item is created, you may run into a severe degree of lock contention. The `poll` method of `ReferenceQueue` does synchronize access to the queue, so you don't need to worry about race conditions, but this can result in a major impediment to multithreaded scalability. Section 14.1.1 gives an example of how to solve this problem, when implementing a concurrent cache.

Finalization and Phantom References Weak references can help you to correlate the life of one object with that of another. Sometimes, it is necessary instead to correlate an cleanup action with the reclamation of an object. For example, this is helpful if there are non-Java resources associated with a Java object that need to be cleaned up along with that object. The JVM knows nothing about those resources, since they aren't Java objects; they may not even be memory, per se, or may be memory on an entirely different machine. For example, a Java `DatabaseConnection` object has implicit linkage to many resources, possibly scattered across several machines. There are operating system resources, for managing connections, on the local machine that are involved. The remote database machine has these, too, and the database process also has some internal state about that connection. All of this state needs to be cleaned up when the Java facade for it is reclaimed.

Java provides *finalization* and *phantom references* as two ways around this problem. With the mechanisms, you can install cleanup hooks. Finalization lets you associate a cleanup hook with a class. Phantom references let you associate a cleanup hook at a finer granularity, on an object-by-object basis. Invocation of a finalization cleanup hooks is managed by the JRE, so your cleanup code operates at the whim of the JREs scheduling decisions. If it does not run the finalization cleanup hooks in a timely enough manner, there's pretty much nothing you can do. In contrast, you are in charge of invoking the phantom reference-based cleanup hooks, primarily via the reference queue mechanism.

Thread-local Storage When you reference an object from a static field of a class, the object will stay around pretty much for the life of the program. While this lets

you implement a permanently resident lifetime pattern, it is not thread safe. In order to protect write access to static fields, you will need to guard these operations with locks. This is possible, but tedious, and often results in poor performance due to contention of threads trying to acquire those locks. The threads need to sleep or spin-lock before they can enter the contended critical section.[6]

Java provides an alternative way to implement a permanently resident pattern called *thread-local storage*. Thread-local storage provides a easy way to store cloned data, so that each thread has its own copy. It is impossible for one thread to access another thread's local storage. When you store objects in a thread's local storage, the objects will live for as long as the thread does, unless you explicitly `null` them out or otherwise otherwrite the entries first.

To use thread-local storage, you need to create a *thread-local variable*. A thread-local variable represents a piece of data that you want to clone across threads. For example, if you'd like each thread to have it's own date formatter, because your date formatter isn't thread safe, then you would create a thread-local variable for it: `ThreadLocal<DateFormat>`.

12.6 Summary

- Every Java process has multiple memory regions, each with separate size limits and separate configuration options for adjusting these limits.
- Local variables in Java programs can only store primitive data and pointers to heap-allocated objects.
- Memory leaks can easily occur in a Java application, despite it having a garbage collector.

[6] Spin-locking, optimistically assuming that the lock will be available in the near future, retries the lock acquisition a few times in a tight loop. This can help, in the case of limited lock contention, but can result in wasted CPU cycles in the case of severe contention.

Chapter 13

AVOIDING MEMORY LEAKS BY CORRELATING LIFETIMES

The normal flow of method invocations renders many objects reclaimable, without any special effort on your part. All temporary objects (see Section 11.2) fall into this camp. These objects are created and only reachable from local variables of the current method, or of a recent invocation on the stack. Once these local variables go out of scope, these temporaries can be reclaimed. A *memory leak* occurs when an object is not reclaimed in the normal course of method invocations.

If you expect an object to be reclaimable at some point, and normal control flow does not do the right thing, then you need to take a step back and determine how to properly ensure the lifetime correlation that you expect. In some cases, you may need an object to survive for a period of time that is not bound to any one method invocation, but rather to the lifetime of another object. In others, the lifetime of an object may actually be correlated with an invocation, but simultaneously referenced by global variables that inhibit its timely reclamation. This is a common, and often requisite coding practice. Oftentimes, the invocation that marks the beginning of a request is in a part of the code outside of your control, or is distant from the allocation site of the objects that must go away when the request finishes. In these cases, you should not, or can not, pass objects around as parameters.

To handle correlated lifetimes in a more robust way requires careful use of some advanced features of Java. This chapter covers five important cases of correlated lifetime: annotations, sharing pools, listeners, phase/request-scoped objects, and external resources.

13.1 The (Unachievable) Ideal: The Single Strong Owner Pattern

A *dominating* (see Figure 12.2) reference from object `A` to another `B` naturally correlates the lifetime of the two objects. When `A` is reclaimed, then `B` becomes reclaimable, because there is no other way to reach it. This is nice, but requires lining up many dominoes in order for things to work as you'd expect. You need to be willing and able to modify the class definition of `A` to add a field, and, what is much more difficult, you need to ensure that this reference is *the* dominating reference.

Java gives you no way to ensure that the latter is actually the case — it's totally up to you, and your careful coding practices. If `A` does not dominate `B`, the `B` will remain alive, longer than you had anticipated.

If `B` is simultaneously part of multiple data structures, then there's a good chance that it won't be dominated by `A`. The listener pattern, covered in more detail below, is a common case of this; e.g., the registrar of listeners for window events becomes a second owner for the window objects. If so, it becomes hard to keep track of what actions need to be taken in order to make that object reclaimable by the JRE. From which collections does `B` need to be removed?

It would certainly much be simpler if every object were part of only one data structure at a time. A more relaxed, and achievable, policy would ensure that every object has a *home base*.

The Home Base as Single Strong Owner

If an object simultaneously is part of multiple data structures, then identify one of these as its *home base*. If possible, you should design for the home base data structure to be the *single strong owner* of this shared object. Every other data structure should only weakly reference the object.

For example, consider an object that is part of a cache. The lifetime policies of the cache should dictate the lifetime of its entries. When the object is not in use, the cache is its sole owner, and so this policy is in place. While being used by the program, it may also be part of other data structures. If these other structures are reachable from non-stack variables, then things can go wrong. Due to bugs or a developer's oversight, those other data structures maintain strong references to the object longer than anticipated. The cache is a natural home base, and any other transient owners of the objects should be designed so that their ownership is indeed transient: either by being referenced from the stack, or by being (other than the cache) weakly reachable.

While this design, for practical reasons, is not always feasible, it is nonetheless something you should keep in mind. Storing strong references to an object for purposes that are only transient, and forgetting to remove these references in a timely fashion, is *the* source of memory leaks.

13.2 Patterns Based on Weak References

As introduced in Section 12.5, Java offers a feature called *weak references*. Weak references can help you to implement correlated lifetime patterns in a more flexible way than is possible with normal (strong) references. They are powerful, but there are "gotchas", surprises and intricasies, that you will need to navigate in order to

use them well. Incautious use of weak references can result in memory leaks that are harder to debug than the ones you are trying to avoid.

A weak reference is manifested as a wrapper object. To weakly reference an object `obj`, you create an instance `new WeakReference(obj)`. For the most part, this weak reference is like any other reference, in the sense that you can traverse it to access other objects. The only difference is that it does not inhibit `obj` from being reclaimed. This means that, if *all* paths of references leading to an object contain at least one weak reference, then it is an immediate candidate for reclamation. Suc an object is said to be *weakly reachable*.

```
WeakReference<String> r = new
    WeakReference("cabbage")
String s = r.get();
```

To unwrap a weak reference, and retrieve the weakly referenced object, call its `get` method. If this method returns `null`, then you know that the referenced object has been reclaimed. Otherwise, by calling the `get` method on a weak reference, you have now acquired a *strong* reference.

Weak References: Gotchas There are many ways to spoil the benefits of weak references. Many of the issues boil down to having strong references to the weakly referenced object that inhibit it from becoming reclaimed. When you call `get`, you acquire a strong reference. As long as this strong reference is temporary, say if it is bound only to the current method invocation, then this new strong reference shouldn't alter the intended lifetime of the object. If you were to squirrel away the resulting strong reference in some other long-lived data structure, you now have to remember to clip *both* references (this new one, and the original one that was keeping the object alive up till now), in order to render the object reclaimable.

You also need to be careful to avoid race conditions. The `get` method can return null at any time, and so you must not expect that a single check for `null` suffices; in-between the first call to `get` and the second, the garbage collector may have, behind the scenes, reclaimed the referenced object. Instead, call `get` once in a basic block, and store the result in a local variable, as shown on the right.

```
class A {
  WeakReference<B> wrapper;

  B getB() {
    B b = wrapper.get();
    if (b != null) {
      return b;
    } else {
      // clean things up
    }
  }
}
```

It gets worse, though. In that code on the right, the `else` clause is intended to do some cleanup in the case that the referenced object is reclaimed. But the object is gone! The reference is already null, and so you have no way to pursue any cleaning action. If you need to be informed that the underlying object has been reclaimed, you must use the *reference queue* mechanism, introduced in Section 12.5.

The standard library, and some third party libraries as well, help with using

weak references correctly. Even then, some care is required.

Weak Maps The Java standard library includes `WeakHashMap`, a class that hides most of the complexity of managing weak reference queues. This hashmap is a normal map, excep that it weakly references its keys and strong references its values. When a key is ready to be reclaimed, the map evicts the corresponding entry. Behind the scenes, it uses a reference queue, making sure to poll it at the right times, to know when keys are otherwise reclaimable — the nice part is that you needn't worry about any of these details. Your own code is not polluted by mention of `WeakReference` and `ReferenceQueue`, nor of the polling complexities necessary to keep the reference queue from overflowing with reclaimed keys.

```
new MapMaker().
    concurrencyLevel(8).
    weakKeys().makeMap();
```

Figure 13.1. The Guava `MapMaker` factory facilitates creating almost any form of map that you will need. This code creates a concurrent version of the standard `WeakHashMap`.

The Google Guava library [5] includes a `MapMaker` factory class that provides more general control of the Java advanced referencing mechanisms. This factory class lets you easily configure whether you want concurrency or not, whether you need an eviction policy, and whether you need the keys or values to be specially referenced. The standard Java `WeakHashMap` is not concurrent. You can synchronize it, by using a `Collections.synchronizedMap` wrapper, but it will not be a truly concurrent map. To make a concurrent analog to the standard `WeakHashMap`, you would use the code in Figure 13.1.

More Weak Reference Gotchas: The Danger of Diamonds Using a construct such as `WeakHashMap` or `MapMaker` is not a guarantee of success. These maps don't control the structure of your keys and values. A `WeakHashMap` weakly references its keys, with the implicit understanding that the strong owners of the key will properly govern each key's lifetime. Trouble happens, though, when the value associated with a key strongly references (possibly indirectly) the key. If you insert values that strongly reference the key, as illustrated in Figure 13.3 then the key will very likely never become weakly reachable, even after the expected strong reference is reclaimed.

As is shown in the figure, this problematic reference structure has a diamond shape. The top of the diamond is the `Entry` object of the map, from which emanate two paths to the key,

```
class Key {
  protected void finalize() {
    println("Good");
  }
}
class Value {
  Object key;
}
void add(WeakHashMap map,
    Value value, boolean
    diamond) {
  Key key = new Key();
  if (diamond)
    value.key = key;

  map.put(key, value);
}
```

Figure 13.2. If `diamond` is true, then the `Good` message will never appear.

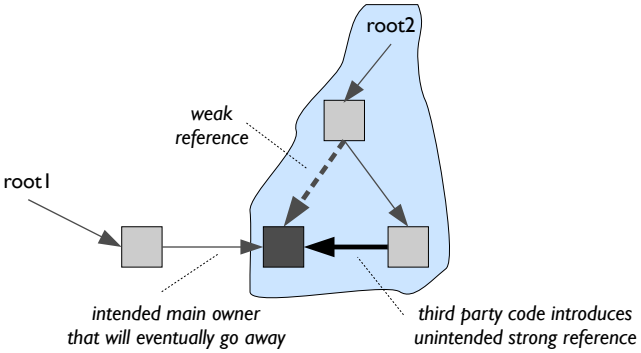


Figure 13.3. Despite your best efforts to use weak references correctly, if you introduce a second strong reference in a way that forms a *diamond* shape (the shaded region), it will likely never be reclaimed.

the weak reference from the `Entry` to the key, and the strong reference path that flows through the value. In Figure 13.3, the darkly shaded object has a good chance of never being reclaimed.

13.2.1 Annotations

Normally, to associate information with an object, you would add fields to its class definition. If you don't have the luxury to change a class definition, but need to associate some information with it, then your only choice is to use a side map. The side map is keyed by the object you wish to annotate, and the value is the annotation itself. Usually, you need the annotation to live no longer than the annotated object.

```
class AnnotationMap<T,A>
    extends WeakHashMap<T,A> {
  void annotate(T t, A a) {
    super.put(t, a);
  }
}
```

Figure 13.4. Annotations can make direct use of the `WeakHashMap`.

```
class TimeAnnotation<T> {
  WeakReference<T> t;
  Date date;

  TimeAnnotation(T t) {
    this.t = new
        WeakReference<T>(t);
    this.date = new Date();
  }
}
```

To ensure that the lifetime of the annotation is correlated with the lifetime of the annotated object, you can use a `WeakHashMap`. For the most part, you can use it pretty much in its unadulterated form, as shown in Figure 13.4. Soon after an annotated `T` instance is reclaimed, the `WeakHashMap` will automatically take care of removing the annotation entry from the map. If your code updates the annotation map concurrently with other uses of the map, then you either need to use a `Collections.synchronizedMap` wrapper, from

the standard library, or use the Guava `MapMaker` factory (see Figure 13.1). Even then, you may suffer some concurrency issues. Section 14.1.1 discusses this issue in more detail.

You have to be careful to avoid the strong-weak diamond problem described in Section 13.2. This is a common and innocent mistake, because very often it is necessary for the annotations to reference (perhaps indirectly) the annotated object. This reverse mapping, from annotation to annotated object, is sometimes necessary to properly implement the annotation's functionality. Just make sure that the reverse mapping uses a *weak* reference, otherwise the annotation map will leak memory.

13.2.2 Registrars and Listeners

Applications that process asynchronous events need a way to decouple event generation and event handling. For example, it is nice to separate the event generators, such as windows that generate mouse click events, from the drawing canvas that will paint the appropriate elements on the screen. This separation allows for greater flexibility, in case event handlers come and go as the application runs, or as features are added to the application. It also keeps the implementations clean of everything but the essential details of the communication pipe; this example communication pipeline involves only mouse click events, with no mention of windows or canvases.

The design pattern behind this is called the Listener pattern. Any implementation of this pattern requires that event handlers register themselves with an event source. The implementation must keep a registrar of the subscribed listeners.

This pattern is elegant, but highly prone to memory leaks. The Java Swing implementation of `JComponent` stores an `EventListenerList` instance, which has an array of strong references to the callback handlers. Because the registrar maintains *strong* references, this approach requires that you maintain and debug code that explicitly deregisters the callback hook from the listener queue.

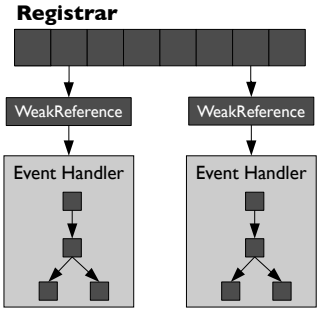


Figure 13.5. If possible, registrars should weakly reference event handlers.

To avoid this source of bugs altogether, you should consider implementing all registrars to maintain weak references to the event handlers. With this referencing structure, there may be no need to explicit deregister event handlers. Whether or not handlers need to deregister themselves explicit depends upon the internal structure of the registrar. If the registrar is implemented as an array-based list, then explicit deregistration is not necessary. When the handler is reclaimed, the entry in the array will become `null`. As long as you implement the registrar to handle this scenario, everything will work just fine, without explicit deregistration. If the registar has a more complex, link-based, structure (such as a `LinkedList`), some code must periodically cull the stale

link entries. This is doable, but more difficult to get right. You may feel safer with explicit deregistration, in this case.

13.2.3 Sharing Immutable Data Without Exhausting Memory

Storing multiple copies of long-lived data in your heap is wasteful, but thankfully a relatively straightforward problem to solve. Chapter 6 introduced the topic of sharing immutable data. That earlier chapter discussed how to eliminate duplicate data structures, such as strings, through the use of sharing pools. Pooling the underlying data allows you store only one canonical copy, and reference it as needed. The cost of a reference, in Java, will almost always be less than the cost of duplicating the data in Java objects.

Once you have eliminated duplicate data in your heap, the biggest remaining concern is that the pools may contain stale data, or even grow in size without bound. A pool can suffer from memory *drag* (see 12.3 for an introduction to memory drag) if a pooled data item persists beyond any point in the code that will use it.

Sharing pools may even suffer from memory leaks (see Section 12.2 for an introduction to memory leaks in Java). In general, if a pool leaks memory, this is likely to be a sign that your code is misusing the pools. A pool should contain a bounded number of canonical data items. If it grows without bound, then either: you were wrong in your assumption that the set of data items was bounded; or, your lookup mechanism is flawed, and incorrecty indicates that the pool does not contain a given data item.

In either case, you should protect yourself from the worst effects of memory drag or memory leaks in your sharing pools. It is pretty easy.

Avoiding Stale Entries in Sharing Pools Section 6.5 introduced the canonicalizing map construct. A canonicalizing map is simply a map from a given instance to the canonical equivalent (shared) instance. The basic construct is straightforward, but it takes some care to avoid memory issues. For example, say you are annotating nodes in a graph. You have an `Annotation` for each `Node`, and need the annotation instance to go away when its associated `Node`s are no longer used. This can be implemented by a `WeakHashMap<Node, Annotation>`. Remember that this kind of map weakly references the keys, which means that it will not, on its own, prevent the node instances from being reclaimed. So, this looks like all you will need to store the mapping itself. How about storing the annotations? If every node has its own distinct annotation, then you are done.

If many nodes have the same annotation, then it is worthwhile figuring out how to share them. If the set of distinct annotations is known statically, then you can use an enumerated type. If not, then you will need to set up a *second* map, a canonicalizing map, to maintain the distinct annotations.

The first map, from nodes to annotations, will strongly reference the annotations. Since you need the annotations to be reclaimed when a node is, therefore this second map, the annotation canonicalizing map, should only weakly reference

them. This means that the sharing pool of annotations can be implemented by: `WeakHashMap<Annotation, Annotation>`.

This should do it. Wrong! This map suffers from the diamond structure problem described in Section 13.2. Both the key and the value of the sharing pool reference the same (canonical) `Annotation` object. The key is a weak reference, but the value is a strong reference, which prevents an `Annotation` object from every being released. The value must also be a `WeakReference`. Here is the correct implementation of a sharing pool for `Annnotation`s:

```
class AnnotationFactory {
   WeakHashMap<Annotation, WeakReference<Annotation>> sharingPool =
       new WeakHashMap<Annotation, WeakReference<Annotation>>();

    public Annotation canonicalize(Annotation annotation) {
        WeakReference<Annotation> wref = sharingPool.get(annotation);
        if (wref != null) {
            Annotation oldAnnotation = wref.get();
            if (oldAnnotation != null) return oldAnnotation;
        }
        sharingPool.put(annotation, new WeakReference(annotation));
        return annotation;
    }
}
```

As this example shows, Java's weak referencing capability has subtle semantics and is not easy to use.

TODO: show (briefly) second style of canonicalizing map, and show how that would be implemented using a map with strong keys and weak values.

Avoiding Unbounded Growth in Sharing Pools (Capacity Safety Valves) TODO: (GSS) Can we move this to the next chapter?

If you already know that your sharing pool has the possibility of growing without bound, then you should engage the developers to find and fix the underlying problem. For example, perhaps there truly is not a finite number of annotations. If, for every new node comes a new annotation, and you have a steady stream of new nodes, then your sharing pool will leak memory; you will eventually run out of heap space, and your application will fail.

In some cases, you can protect against this problem. For example, if the map from node to annotation can be recreated, say from some secondary store, then you should consider using *soft references*. The node-to-annotation map should weakly reference the annotations, and the sharing pool should weakly and softly reference the annotations, as shown in Figure 13.6.

In this way, the value of the sharing pool map will be the sole reference keeping the annotations alive (every other reference is weak). When the JRE finds that it

```
WeakHashMap<Node, WeakReference<Annotation>> map;
WeakHashMap<Annotation, SoftReference<Annotation>> sharingPool;
```

Figure 13.6. A modified form of the sharing pool example that uses soft references as a safety valve on the maximum memory consumption of the structures.

needs space, that sole non-weak reference will be clipped, thus starting a cascade that will lead to both weak maps cleaning up the entries. You will then need to update the node-to-annotation map to detect this case, and recreate the mapping on demand. Chapter 14 goes into more detail on the use of soft references.

13.2.4 Phase/Request-Scoped Objects

Many objects are created within a phase or request and are (or should be) reclaimable when the phase or request completes. For many such objects, this expected flow of creation and reclamation proceeds naturally. This is especially true for objects that are created in a method and do not escape that invocation. For example, if an object is created at the top level of the request method, and is never stashed into any static fields or fields of objects which are bound to enclosing method scopes, then the normal local variable scoping rules (see Section 12.4) would apply.

```
void doLogin() {
  Object obj = new Object();
  restOfWork(obj); // if obj does not escape ...
} // ... then lifetime of obj automatically ends here
```

If, during the execution of the `restOfWork` method, `obj` does not escape into some other scope outside of `doLogin`, then its lifetime ends when the `doLogin` method returns. In this example, the lifetime of the object `obj` will be correlated with the `doLogin` request, by the natural local variable scoping rules.

Unfortunately, the lifetime requirement, that the lifetime of `obj` be correlated with the `doLogin` request, is not guaranteed by the code. In Java, this is pretty hard to do. Nothing in that `doLogin` method forces this non-escaping property that is necessary in order for the correlated lifetime pattern to play out properly.

It is easy to write code that alters the lifetime of `obj` in unexpected ways. Rather than pass `obj` around everywhere, as a parameter, it is convenient to stash it in a global variable, or a map that is shared by disparate bits of code, such as is shown in Figure 13.7. When stored in this global map, `obj` will survive for an indefinite period of time. If some exception path does not properly clean up this map, then `obj` will leak.

```
static ConcurrentMap
    requestState;
void restOfWork(Object key) {
  requestState.put(key, ...);
}
```

Figure 13.7. It is convenient to pass around request variables in a global map, rather than via method parameters. You just have to make sure to clean up the map when the request is finished.

If you stash the object into a map, in this case as a key, you must plan out a way to remove it when the `doLogin` request is done. If the request-scoped objects are also created and used by a single thread, there are some straightforward solutions to this problem.

The Thread-local Storage Trick Since these objects are confined to one thread, you can use thread-local storage. The Java thread-local storage mechanism (see Section 12.5) gives you a way to store and access data in a way that is confined to a thread. If you create a thread-local variable `ThreadLocal<String>`, then each thread has its own copy of that string. Normally, thread-local storage is used to avoid lock contention. This is an interesting use of thread-local storage, because you won't be using it to reduce contention, but rather to avoid a potential memory leak.

```
ThreadLocal<RequestState> state;

void doLogin() {
  state.set(new RequestState());
  restOfWork();
}
```

Figure 13.8. This implemenation avoids unbounded leakage of `RequestState` objects, since each request overwrites the state from the previous request.

Let's say that you need to store a data structure of request-scoped objects, and that the class `RequestState` manages the state of the current request being processed. If you store this in thread-local storage, then there is no way for the request state to leak, occupying more and more memory over time. This is because the next request service by that thread will overwrite the thread-local entry of request state from the previous request.

There are other possible solutions that involve more complex implementations. For example, you may consider using the listener pattern. The end of each request is an observable event; in Java, you can manifest this as an instance of `Observable`. Each data structure that contains request-scoped objects is an observer of these events, and so should implement the `Observer` interface.

Make Sure Shared Owners Weakly Reference the Request-scoped Objects In either case, you should make sure that either thread-local storage, or the `Observer`s have the only strong references to the request-scoped objects. Due to some programming necessity, you may find that there are other structures in which you need to store phase- or request-scoped objects. If this is the case, then you should ensure that these other structures only weakly reference these scoped objects. If you structure things this way, then you can allow a more relaxed structure, where phase/request-scoped objects can be stored anywhere they need to be, while maintaining the lifetime pattern you desire.

13.3 Patterns Based on Finalization or Phantom References

Java provides two closely related facilities that allow you to install a cleanup hook that is invoked when an object is reclaimed: finalization and phantom references. These hooks are called just after the garbage collector has discovered that the object is collectible, but before its memory is reclaimed. The most important correlated lifetime scenario that finalization and phantom references help with is releasing any external resources that are implicitly associated with a Java object. For example, there is no direct reference between a the Java representation of a database connection and the resources inside the database server; they certainly lie in separate processes, which probably run on separate machines.

Finalization is the easier of the two to use, but the most fraught with danger. If you implement a `finalize` method in a class, then every instance of that class will go through a process known as finalization. Except for the logic of the final cleanup hook, finalization is entirely managed by the JRE. After an object is discovered to be garbage, the JRE enqueues it on a special queue, called the *finalizer queue*. This queue is completely outside of your control, but it does reside in Java heap. While the garbage collector is responsible for enqueueing objects, a separate thread, spawned by the JRE, periodically scans the finalizer queue. This solitary finalizer thread invokes the `finalize` method of the enqueued objects.

The Java phantom reference feature provides a more powerful, and less dangerous, alternative to finalization. If you decide to use phantom references, you will be in greater control of the queueing and scanning aspects of cleaning up reclaimed objects. With phantom references, you can associate a cleanup hook on a per-object basis, rather than, as is the case with finalization, on a per-class basis. Furthermore, you can use separate queues for different groups of objects, and manage how often to poll the queues, rather than having a single queue and relying on the JRE to poll the queue when it feels like it.

Finalization Gotchas Finalization is filled with potential dangers. The JRE doesn't know about inherent limits on the capacity of external resources. If the availability of an external resource becomes constrained, it'd be great if the JRE would recognize this, and increase the priority of the finalization process. This is not the case, unfortunately. The finalizer thread always plows along at drip-like clip, independent of any impending catastrophes outside of the Java heap. This is in stark contrast to the closed world of the Java heap: the JRE knows when the heap is exhausted, and can make educated guesses, such as to when it should increase or decrease the size of the heap.

The Java language specification provides no assurances of how often, or even whether, finalization will be run on an object. Furthermore, the specification is very lax about whether finalizers will be run before program termination. If your external resources require a proper "dispose" call, and you have a short-running application, then you will probably be in some amount of trouble. It is very likely

that your program will terminate with many unprocessed finalization tasks.

You can ask the JRE to attempt to finalize objects before the program terminates, by calling `System.runFinalizersOnExit(true)`. This is a deprecated part of the `System` API. However, it is hard for the JRE to do the right thing in a deadlock free manner. Should it only schedule the finalizer thread, which would run any pending finalization? This would be safe, and is what the JRE will do if you ask. But this misses all the currently-live objects that would have have been finalized, had the program reached a point where they were reclaimable. Hence, even for those objects which are actually ready to be finalized, the JRE won't do so on exit. It is for these reasons that the API has been deprecated.

Overwhelming the Finalizer Thread It is also possible to overwhelm the finalization thread. This can happen if your program creates instances of objects with `finalize` methods at a high rate. Such is the case in the loop on the right. Since each loop iteration's instance of `font` is not used beyond the execution of that iteration, it seems like one could run this program on a small heap, for any value of `N`. Instead, you will find that, as `N` increases, you will very likely need to increase the maximum heap size allotted to the JRE. If you don't, this code will fail with a `java.lang.OutOfMemoryError`.

```
for (int i = 0; i < N; i++) {
   Font font = new Font("SansSerif
       ", Font.BOLD, 12);
   // some small amount of work
} // font does not escape the loop
```

The problem, in this case, is that `Font` class has a `finalize` method. Every instance of a font has an implicit linkage to some native resources. The Java object and the native resources need to be cleaned up in tandem. The developers of this class decided to implement this case of correlated lifetime by using finalization. Therefore, as the loop iterates, instances of `Font` begin to pile up the finalization queue. You can put your application's threads to sleep in order to let the finalizer thread catch up. Try sticking in this code: `if (i % 100000 == 0) System.runFinalization()`. This change works around the problem.

An Alternative: Explicit Dispose/Close One recourse is to fall back to the C style of resource management, at least for the case of external resources. You can design the API specifications so as to require users of the API to adopt a convention that requires explicit closing, or freeing, of resources. Such APIs do indeed exist in the Java world, primarily because Java does not offer any especially palatable alternatives.

13.3.1 Using Finalization as a Safety Valve

```
void close() {
  socket.close();
  socket = null;
}
void finalize() {
  if (socket == null) return;
  logger.severe("Oops!");
```

Due to the dangers of finalization, you must not rely on it. Even so, it can be helpful as a back-up mechanism, a kind of safety valve, to protect against some occurrences of bugs

in your code. For example, if you do decide to use explicit cleanup hooks, you should consider using finalization as a safety valve. Such a finalization safety valve can protect against bugs where the cleanup hooks are, mistakenly, not called. The finalize method of a resource can warn you of failures to explicitly call the dispose/close method, and then perform the correct action. Failure to clean up external resources can result in failures, due to exhaustion of the capacity of that underlying resource, so you should strongly consider installing these kinds of safety checks.

13.3.2 Cleaning Up with Phantom References

You can use the hooks offered by phantom references to free up external resources that are implicitly associated with an object. The way to leverage phantom references is a bit different from the way you use weak references. They share much in common, including the ability to associate a reference with a reference queue. Both have a `get` method. When you invoke this method on a weak reference, you get back the referant object, or `null` if the JRE has clipped the reference.

```
class MyPhantom<T extends Closeable>
    extends PhantomReference
   implements Closeable {
  T associatedData;

  public void close() {
     associatedData.close();
  }
}
```

In contrast, the `get` method of a phantom reference always returns `null`. This seems strange, but is a necessary part of ensuring that the referant object is dominated by the reference queue. If the reference queue is not the unique owner of the obect, then it can come back to life, transitioning from being ready for reclamation (which is the whole reason for it being enqueued on the phantom reference queue of your choosing) to being an active object.[1]

In order to do any kind of cleanup work, you certainly will need some information about the referant object, but the `get` method does not give you anything. One way around this problem is to implement a subclass of `PhantomReference` that stores that necessary information. The only restriction on what data you can associate with a phantom reference is that it can't be the referant itself. If you were to have a subclass of `PhantomReference` that strongly referenced the referant, then the referant would never become a candidate for reclamation.

[1] Oddly, if you use finalization, rather than phantom references, there is nothing to stop you from revivifying objects.

13.3.3 Using Phantom References to Manage Pools (Dangerous!)

You may be tempted to use phantom references to help manage pools. For example, when pooling connections to a remote data source, you will probably implement facades around the connection instances. A call to `close` on a raw connection instance actually closes the underlying connection. A call to `close` on a connection facade merely returns it to the pool, making it available for the next use. It is indeed tempting to try to avoid the need for an explicit call to `close`. After all, the connection facade object should be naturally correlated with local variables of the request. When the request exits scope, the facades will become garbage. As soon as the next garbage collection runs, these facades will become phantom reachable, and so the cleanup handler can return them to the pool — all without any need for an explicit call to `close`. This sounds nice.

Unfortunately, this design is prone to livelock failures. The facade objects will only become phantom reachable after a garbage collection runs. Garbage collections pretty much only run when the JRE finds that it is low on Java heap. Therefore, there is a window where the connection pool is empty, and so incoming requests queue up, and yet existing connection facades are not returned to the pool, because requests are not being processed and hence garbage collections do not occur. The only, and ugly, possible way around this problem is to periodically invoke the garbgage collector in a separate background thread. You have been warned!

At most, phantom references should be used in this capacity as safety valves, to warn you when the proper `close` method was not invoked. If you do only use phantom references as safety valves, then you might be better off using plain old finalization. It may be easier to manage, and the extra downsides of finalization won't really hurt too much: phantom references will provide no firm assurances of correctness, either.

13.4 Summary

- A desirable goal is to aim for as few strong references to objects whose lifetime falls into one of the correlated lifetime patterns. As much as possible the strong owners should be those whose lifetime is naturally correlated in the expected way. Every other reference, whose lifetime follows other principles, should ideally be a weak reference.

- As much as possible, you should avoid using weak references directly, and instead use the built-in `WeakHashMap` or similar functionality from other libraries, such as the Guava `MapMaker`.

- Weak references can help you implement annotations, the listener pattern, sharing pools, and phase/request-scoped objects.

- Finalization and phantom references should be avoided at all costs, except

as safety valves. These safety valves can alert you when the proper cleanup methods have not been invoked.

Chapter 14

TRADING SPACE FOR TIME: CACHES, RESOURCE POOLS AND THREAD-LOCAL STORES

Sometimes, you need to consume more memory, not less, in order to make your application run well. There are two main reasons to trade off increased memory consumption for increased overall application performance: caching and cloning. A cache stores the output of expensive operations. A resource pool is a cache whose elements are interchangeable. For example, a connection pool caches the outcome of establishing of a connection to a remote data source. A memory pool amortizes the costs associated with allocation and reclamation of memory. These are caches, except that each connection to a particular machine, or each allocation of a particular size or type, is interchangeable with any other. Finally, cloning allows concurrent, rather than synchronized, access to data. All of these mechanisms trade space for time. They require extra memory, say, on top of establishing a new connection for every remote access. But this trade-off often pays off when the increase in performance is more important than increase in memory consumption.

When you implement your own time-space trade-offs, you will leverage underlying mechanisms provided by Java. Soft references and thread-local storage can help with caching, resource pooling, and cloning, but misuse of them can result in memory issues such as leaks and memory drag.

14.1 Patterns Based on Soft References

Java offers soft references as way to manage bounded-size caches. Section 12.5 introduced soft references. You can use soft references to reference objects in place of normal references via instance fields. When you do so, you are informing the JRE that this reference should not inhibit the object from being reclaimed, but that it should only be reclaimed when heap memory grows tight.

To use soft references, you will employ the `SoftReference` class. The constructor for a `SoftReference` takes, as a parameter, the object you would like to softly reference. That object lives as it normally would until the point in time when it is

soft reference clipping policy	JRE versions
LRU heuristic	IBM 1.4 and higher, Sun 1.3.1 and higher
clip all when memory is tight	IBM prior to 1.4
treat as weak references	Sun prior to 1.3.1

Table 14.1. Depending on your JRE, you may not be able to employ soft references as you might hope. Only some JREs discard of soft references in an LRU-like fashion.

only reachable by traversing soft (and possibly also weak) references. This means that the there is no way to reach the object from your code, as you traverse fields and local variables, through only normal (strong) references; all chains of traversals must go through at least one soft reference, and possibly weak references, too.

While an object is softly reachable, the JRE will keep it around, for as long as there is enough free Java heap. At least, this is what the Java language specification requires. The only requirement imposed by the language specification is that the JRE must clear all soft references before it throws an `OutOfMemoryException`. In practice, most JREs also impose a freshness criterion on softly reachable objects. These JREs will first discard those softly reachable objects that have been least recently used. Most, if not all, Java 5 and Java 6 JREs use a rough approximation a least recently used (LRU) eviction policy. Early JREs tended to make poor decisions, when choosing how to clear soft references. One such JRE would wait until the heap was exhausted, at which point it would clear all soft references. On early Sun JREs, a soft reference behaves like a weak reference, which means that such softly referenced objects will probably be collected in the very near future, independent of demand for memory, or how recently used the referenced objects are. Table 14.1 summarizes the treatment of soft references by various JREs.

Be Cautious with Soft References Most contemporary JREs measure freshness relative to the amount of free memory. For example, the Sun JREs, after version 1.3.1, the default behavior is to clip all soft references that haven't been used for 1 second, for each megabyte of free heap. This means that, if you have 500MB of free heap, any cache entries that haven't been used in 6 minutes will be evicted after the next garbage collection. This is true, even if the total size of your heap is 600MB: despite the heap being 83% unoccupied, the JRE will begin to evict some cache entries. This value can be tweaked, at least on Sun JREs, via the command-line argument `-XX:SoftRefLRUPolicyMSPerMB`. This value is in milliseconds, so passing 5000 would change the above eviction example from 6 minutes to 30 minutes (since the default is 1000 milliseconds per megabyte of heap).

This is a reasonable approximation to a true LRU eviction policy. For those JREs that use some a freshness heuristic, soft references can still form the basis for implementing caches. However, you must not depend on this heuristic blindly.

```
<refs soft="27801" weak="3"
    phantom="0" ... />
```

Figure 14.1. Verbose garbage collection data from an IBM JRE tells you if a misuse of references is causing a pile-up of reference objects.

You should monitor the behavior of soft references in your application. On an IBM JVM, you can see whether soft references are piling up: enable verbose garbage collection (by adding `-verbose:gc` to the command line), and track the output of the form shown in Figure 14.1. If the LRU heuristic is not working well, then you will observe a ragged sawtooth pattern in the number of soft references. If so, then you must not depend on soft references for implementing your caches! On Sun JREs, you should also monitor the hit rate of you caches, relative to the value of the `-XX:SoftRefLRUPolicyMSPerMB` tuning parameter.

Consider Establishing a Bound, Too Because of the potential limitations of the LRU heuristic, you may want to treat soft references as more of a safety valve, rather than as the primary means for ensuring that the cache stays at a reasonable size. With soft references only, it is possible that your cache will be entirely cleaned up, if there is a lull of only a few minutes. With only a pre-established capacity bound on the data structure, you avoid this problem, but are subject to memory exhaustion. If you choose a bound of, say, 10,000 entries, you do have some assurance that this will indeed by the occupancy level, in the steady state. However, unless you do the careful analysis described in Part I, combined with the scalability analysis described in Part III, you have no way of knowing how many bytes those 10,000 entries consume. If the unit cost of each entry of the cache is 100 kilobytes, then you cache, in the steady state, will occupy 1 gigabyte of heap. You may be left with excessive garbage collection, because you have left little room for temporary object creation. You may even suffer out of memory exceptions under certain conditions.

Soft references can serve as a safety valve, to protect against these memory problems. With some careful experimentation, you should be able to combine capacity bounds with soft references to achieve the desired effect.

What to Reference, Softly If you do use soft references to help bound the size of a data structure, you need to be cautious about how you use soft references. If you reference the wrong objects, using soft references, you may foil the LRU heuristic of the JRE. For example, say you are using a `HashMap`, and decide to softly reference the keys. Whenever the map has hash collisions, then each call to `get` or `put` may update the last-used field of the soft reference for objects that are not `equal` to the given key, but that hash-collide with it.

Soft Reference Rule

Soft references must always be over values, not keys. Otherwise, testing equality of keys will trigger a use of the reference. This will extend the lifetime of the value, even though the only use of the entry was in checking to see if its key matches another.

14.1.1 Example: Implementing a Concurrent Cache

A cache is a map, usually of bounded size, with an eviction strategy for maintaining that bound. The Java standard library provides a concurrent map implementation, in the form of the `ConcurrentHashMap` class, but this is not a cache, because it has no eviction hooks with which one can bound its size.

```
new MapMaker().
    concurrencyLevel(4).
    softKeys().
    maximumSize(1000).
    createMap();
```

Figure 14.2. Using Google's Guava library to create a concurrent cache.

The Java standard library does not provide a concurrent cache implementation. Thankfully, there are other libraries at your disposal, such as `MapMaker` from the Google Guava libraries [5]. With `MapMaker` you can create a concurrent cache by calling the sequence in Figure 14.2. It is nonetheless useful to step through what it takes to make this work. In doing so, you will learn about managing soft references and reference queues.

Eviction Mechanisms To implement the eviction aspect of a cache, you can leverage soft references. You need to follow the soft reference rule from earlier in this chapter: softly reference the values, never the keys. You can extend the basic `ConcurrentHashMap`, wrapping the map's values with soft references. You also need to follow the reference queue polling rule from Table 12.5: poll the queue at least as often as soft references are created — in the steady state, `put` calls are likely to cause evictions. This leads to the first attempt at a concurrent cache implementation, shown in Figure 14.3. The first thing you will discover is that your cache implementation cannot inherit from the concurrent hash map with softly reference values, because then the `put` and `get` methods would have to expose the soft references. Instead, your cache must delegate to the underlying map.

```
class Cache<K,V> {
  ConcurrentHashMap<K,SoftReference<V>> m;
  ReferenceQueue<V> q;

  void put(K k, V v) {
    cleanupQueue();
    m.put(k, new SoftReference(v, q));
  }

  void cleanupQueue() {
    Reference r;
    while((r = q.poll()) != null)
       m.remove(???); // oops!
  }
}
```

Figure 14.3. A first attempt at a concurrent cache.

Unfortunately, this doesn't quite work. The variable `v` references the value, not the key. Therefore, this first implementation provides no way to remove evicted value from the map. To fix this, you'll need to stash, in the a subclass of the soft reference

wrapper, a pointer to the key.[1] Then, you can update the `Cache` implementation to extend `ConcurrentHashMap<K, CacheValue<K,V>>`, as shown in Figure 14.5.

The Need for a Cleanup Thread This updated implementation still suffers from two critical problems. First, the reference queue `poll` method is internally synchronized. Every call to `put` and `get` must poll the reference queue at least once, to avoid unbounded pile-up in the queue. This can result in severe lock contention, which pretty much foils the concurrency aspect of the `ConcurrentHashMap`. Also, if the cache as a whole goes unused for a long period of time, then the objects already queued up in the reference queue will suffer from memory drag (see 12.3). These queued up objects will never be polled, since neither `put` nor `get` will be called. The good news is that this won't result in a memory leak, where objects pile up without bound, but it is still a potential source of memory problems. You may find that you are wasting quite a bit of memory in the reference queues of quiescent caches.

```
class CacheValue<K, V>
   extends SoftReference<V> {
  K key;

  CacheValue(K k, V v,
      ReferenceQueue<V> q) {
    super(v, q);
    this.key = k;
  }
}
```

Figure 14.4. You will need a special value reference that keeps a reference to the key, to allow you to remove the entry when it is evicted from the cache.

```
class Cache<K,V> {
  ConcurrentHashMap<K,CacheValue<K,V>> m;
  ReferenceQueue<V> q;

  void cleanupQueue() {
    Reference r;
    while( (r = q.poll()) != null)
       remove(((CacheValue)r).k);
  }

  void put(K k, V v) {
    cleanupQueue();
    m.put(key,new CacheValue<K,V>(k,v,q));
  }
}
```

Figure 14.5. A second attempt at a concurrent cache.

One way to fix the lock contention problem is to have a separate thread be responsible for polling the reference queue. This will also fix the second problem, as long as the polling thread is active for as long as the cache itself is around. This spawned thread's `run` method will look just like the `cleanupQueue` method above, except that it should loop indefinitely.

Avoiding Spikes At first sight, it would seem that you should be able to remove the calls to `cleanupQueue` from the `put` and `get` methods. The

[1] It would be nice if the `ConcurrentHashMap` implementation let you extend its implementation so that its `$Entry` class extended soft reference; the `$Entry` would serve this role perfectly.

cleanup thread should take care of all necessary polling, right? However, when there is a large spike of `put` calls in a short period of time, you are at risk of running out of Java heap due to a large pileup of pending evictions.

You must have a safety valve in place to prevent this situation. One possibility is to keep an approximate count of the number of `put` calls, and call `cleanupQueue` only periodically. In order to avoid lock contention in maintaining this count, you can do so in an unsynchronized way. There is still a pathologic possibility that every racey increment of the put counter won't actually increment the counter. If this worries you, you can use an `AtomicInteger`, at increased expense. A new `cleanupQueueHelper` method is shown in Figure 14.6, and `poll` now calls this method. There is no reason for `get` calls to call this method. The only point of this safety valve is to avoid a sudden large influx of `put` calls.

```
AtomicInteger putCount;
void cleanupQueueHelper() {
  if (putCount.
      incrementAndGet() >=
      1000) {
    putCount.set(0);
    cleanupQueue();
  }
}
```

Figure 14.6. To avoid spikes, `put` must call this method.

14.2 Patterns Based on Thread-local Storage

To avoid synchronization, you often need to replicate data structures. Thread-local storage is a built-in mechanism that Java provides to facilitate this kind of cloning across threads.

Consider an example of generating random numbers, using the `SecureRandom` class. Instances of this class provide a stream of pseudo-random numbers, in a way that is cryptographically strong. If you have a singleton instance of this class, you may experience scalability problems due to lock contention; the contention is hidden within the `SecureRandom` implementation. You can use thread-local storage

```
class ThreadLocalRandom {
  ThreadLocal<SecureRandom> rng = new
      ThreadLocal<SecureRandom>() {
    SecureRandom initialValue() {
      SecureRandom random = new SecureRandom();
      random.setSeed(...);
      return random;
    }
  }

  public int next() {
    // need 32 bits of data
    return rng.get().next(32);
  }
}
```

to avoid this contention, at the (in this case, small) expense of having one instance per worker thread. Java 7 adds a `ThreadLocalRandom` implementation to the standard library.

Thread-local storage: Reentrancy Gotchas A thread-local variable allows you to store one copy of a data structure per thread. If your code is structured so that one method invokes another, and the both need to make use of the thread-local variable, you should be cautious of reentrancy problems. A reentrancy problem is like a race condition, but within one thread. If first one invocation begins to modify the thread-local variable, and, before it is done with its modifications, calls another method that begins its *own* modifications, then you will see unexpected results.

One way to protect against the potential for this problem is to adopt a *fail-fast* approach. When you grab an entry from thread-local storage for modification, then assign the thread-local variable to `null` for the duration of the modifications. That way, any reentrancy problems will be exposed as quickly as possible, as a `NullPointerException`. Here, you will get an exception thrown at the very point of the bug, rather than further down the line, as is often the case with race and reentrancy bugs.

Thread-local storage: Memory Drag Gotchas When using thread-local storage, you need to be cautious of memory drag. Data stored in thread-local storage will, unless you take some action, live as long as the thread. If you store a large structure in the local storage of a thread that lasts for the duration of the program, but only use the structure early in your program's execution, then that structure will be needlessly consuming space.

To avoid drag you can explicitly overwrite the entry, by calling `rng.put(null)`. This must be done by the thread itself, since there is no way for one thread to access another thread's local storage. You can put this call at the end of a phase in your program, or when the program terminates. If you are using the `java.util.concurrent` thread pool framework, then you can use its hooks that are called after a task, or after a thread, terminates. You can do so by extending the `ThreadPoolExecutor` and overriding the `afterExecute` and `terminated` methods, respectively.

Another option is to have your thread-local variable store a soft reference to the data. If you adopt this design, then each thread's copy of the random number generator will be cleaned up by the garbage collector if it ever needs the space, and the generator hasn't been used in a while.

```
ThreadLocal<SoftReference<SecureRandom>> rng;
```

This design does not clean up every last bit of memory associated with a thread's entry. Each thread-local variable is a map, from thread to the value, and so the per-entry objects of the map will stick around. Still, at least you will not be keeping around a potentially very large structure. You also need to take care to handle the case when the JRE does get around to clipping the soft reference, and you come

back to generate more random numbers. Still, this hybrid approach, of combining soft references and thread-local storage, can be quite powerful.

Thread-local storage, like the `WeakHashMap`, is an example of the JRE hiding some of the complexity of managing weak references. Under the covers, the thread-local storage implementation uses weak references so that, if a `ThreadLocal` object is reclaimed, then the storage associated with it, for all threads, will be reclaimed, too. In some implementations, this will not happen immediately, because these implementations do not use reference queues. They use an alternative approach that at least keeps the amount of memory spent on stale thread-local storage bounded.

14.3 Summary

- Soft references can be a useful tool to bound the size of caches, but you should not depend solely on it. Some JREs do not implement an LRU heuristic at all. Others implement one that may give you unexpected evictions, despite there being plenty of free Java heap.
- Implementing a concurrent cache is surprisingly difficult!
- Thread-local storage is an easy way to keep around clones of data, in order to avoid lock contention.

Part III

Scalability

Chapter 15

ASSESSING SCALABILITY

Despite heroic efforts at tuning classes and optimizing the use of collections, you may still be unable to fit your application into available physical memory or address space. Sometimes, heroic efforts are not even possible, because this problem was discovered very late in the development cycle. If you don't discover till the final stages of testing that your application won't fit, you will have difficulty finding the resources to perform extensive tuning. Optimizing earlier in the development process would help, but these things need to be budgeted. Resources spent on earlier tuning are resources taken away from other aspects of development, such as architectural design and coding. To avoid wasting time blindly tuning everything, it is helpful to have a quick way of knowing whether an inefficient data structure will really matter in the grand scheme of things. A particular structure might have a bloat factor of 95%, being composed of only 5% actual data, but if that structure only contributes to a few percent of overall memory consumption, who cares?

You can focus your tuning efforts by adopting a design strategy that assesses the *scalability* of your data structures. By focusing on scalability, you can answer two kinds of questions:

- **Will It Fit?** As you scale up your application, adding more users for example, it'd be nice to know whether it will fit within a given memory budget.
- **Should I Bother Tuning?** Your tuning efforts should focus on those structures that can benefit from the tuning tasks described in the Part I.

The rest of this part of the book will help you in answering these questions, and in developing solutions for the cases when the answers to both questions are no. If so, then you need to consider stepping outside of the Java box.

Will My Design Fit? Chapter 16 introduces a metric that you can use to estimate the answers to these questions. The metric, called the Maximum Room For Improvement, quantifies how much your design can benefit from tuning. From this number, you can extrapolate how much memory will be required to fit your data. If the room for improvement is high, then you should consider applying the tuning regimen detailed in Part I.

If your design doesn't fit in physical memory constraints, but you still have address space available (see Section 12.1), then the first solution you should consider is buying more physical memory. If your budget allows for this, then by all means you should strongly consider doing so.

Making it Fit by Breaking the Java Mold Despite being an object-oriented language, there are still some tricks you can use that let you continue to program in Java, but store objects in a non-object oriented way. These tricks come at the expense of some xtra programming time and maintenance expense, but can dramatically increase the scalability of your data models. Chapter 17 describes these *bulk storage* techniques.

It Still Won't Fit Rather than attempting to fit all of your objects into a single heap, you can store them outside of the Java heap, and swap them in (and out), on demand. If the logic of your application allows for recomputing the data stored in these objects, you need to be careful to compare the recreation cost with the costs of marshalling objects. You can choose to marshall objects to and from a local disk, or you can use one of several frameworks that provide a distributed key-value map.

Chapter 16

ESTIMATING HOW WELL A DESIGN WILL SCALE

It would be nice to be able to predict how well a data model design and implementation will scale up, as you increase the complexity or number of entities. The bloat factor of a data structure tells you, for a given size, what fraction of its size is overhead versus actual data. To judge whether it will scale requires extrapolating these costs out. This chapter introduces a metric, and some facilitating techniques, that enable you to more quickly make these predictions. The metric is called the Maximum Room for Improvement, which is the highest factor of improvement in scalability you can expect to wring out of a given design, after all possibly amortizable costs have been amortized away.

16.1 The Asymptotic Nature of Bloat

Up till now, bloat factor has been treated as a scalar quantity: e.g., 95% of space is devoted to implementation overhead rather than actual data. More accurately, the bloat factor of a data structure is a function of its size. The bloat factor of a collection of objects decreases until it reaches an *asymptote*, the lowest bloat factor a data structure car achieve, no matter how big it grows.

Data Structure Scaling: Asymptotic Bloat Factor

A data structure scales well, or not, depending upon how its bloat factor changes as it grows. It starts by decreasing, as the collection's fixed costs are amortized over a larger amount of actual data, and soon levels off. This *asymptotic bloat factor* is governed by the collection's variable cost and the bloat factor and *unit cost* of the contents.

Figure 16.1 illustrates an example of the asymptotic behavior of bloat factor for two collection types. With a small number of elements, the fixed costs dominate. For this example, for a `HashMap`, with more than about 10 elements, fixed costs are pretty much fully amortized; the fixed cost of a `ConcurrentHashMap` requires more

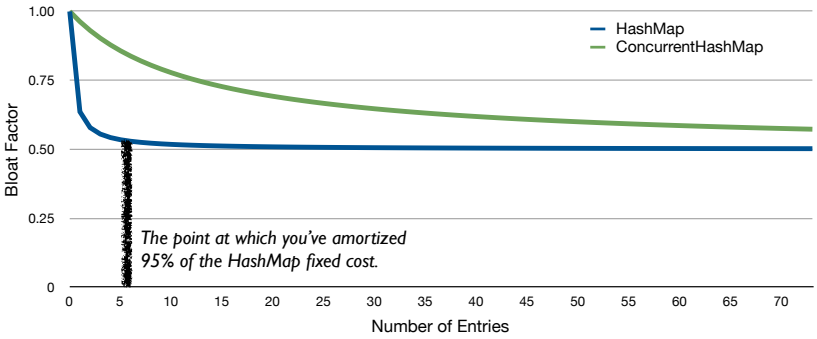


Figure 16.1. An example of the asymptotic behavior of bloat factor.

elements to amortize away. In either case, at this point, the bloat factor of the elements being stored in the collection, along with the collection's variable costs, become the dominant factors. In this example, the total cost per element is 128 bytes, 64 bytes of which is overhead. Ultimately, it is that ratio of 64/128, or 0.5, which governs the asymptotic bloat factor of this structure.

Amortizing Fixed Costs Data structures that can change in size, as opposed to having a fixed size, do so because they make use of collection. As you learned in Part I, collections of objects have a *fixed cost* that is independent of the number of entries in contains. For a simple array, this is the JRE object header. For more complex collections of objects, such as `java.util.HashSet`, the fixed cost includes a extra wrapper cost. This fixed cost is quickly amortized, usually once the data structure grows to have more than a dozen or two elements.

The number of elements that it takes to amortize a collections fixed cost depends on that cost in comparison to the memory cost of storing elements. If the collection's fixed cost is 48 bytes, and it costs 128 bytes per stored element, then the collection must have at least 6 elements before the fixed overhead contributes less than 5% to the overall size of the collection:

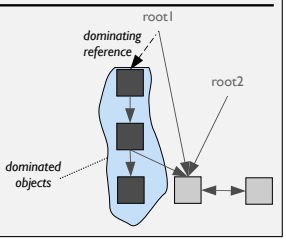
$$\frac{\text{collection fixed cost}}{\text{collection total cost}} = \frac{48}{48 + 128N} \leq 0.05 \implies N \geq 5.45$$

Once fixed costs have largely amortized, the asymptotic bloat factor is reached. For this reason, at least for collections that you expect to be at least moderately sized, it is the asymptotic bloat factor that should be your primary concern.

Unit Costs However, the fixed costs of collections still play an important role in the ultimate scalability of most data structure. When one collection is nested inside of another, the fixed cost of nested collection contributes to the *unit cost* of storing things in the outer collection.

The Unit Cost of Storing Data in Collections

The *unit cost* of storing elements in a collection is the average size of each contained element. This cost includes everything uniquely owned by the elements. See Figure 12.2 for more discussion of *dominance*, which is a property of a graph of objects as illustrated on the right.



Every class has a *unit cost*, the cost for every additional instance. You can determine the unit cost of a class by counting up the size of its fields, taking into account JRE-imposed costs. Similarly, every interconnected group of instances has a unit cost, the sum of the sizes of the classes involved in that group. Section 3.1 introduced this style of accounting. Figure 16.2 gives an example EC diagram of a HashMap that contains an interconnected group of four objects. The unit cost of each entry in this structure is given by the sum of the sizes of those classes: 88 bytes, in this case.

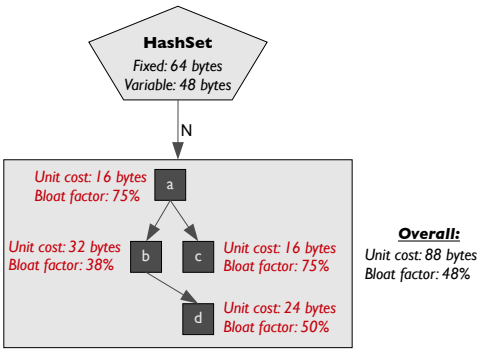


Figure 16.2. EC diagram for a `HashSet` that contains data structures, each composed of four interconnected objects.

Quite often, the elements you are adding themselves consist of nested collections. If you don't expect those nested collections to grow, then they contribute to the unit cost of additional elements in the structure that *is* growing. A fixed-size collection has a unit cost which is that collection's fixed cost, plus the total size of all of the variable costs and unit costs, counted once for each entry. So, if you have a fixed-size collection with four entries, then the total cost is the fixed cost plus four times the sum of the variable costs of the collection plus the unit cost of what's inside.

Determining the Maximum Room For Improvement Figure 16.2 is annotated with the four numbers that govern the scalability of this structure: the fixed and variable costs of the collection you use, and the unit cost and bloat factor of the data you're storing inside of it. The maximum room for improvement of a collection of data structures is given by:

$$V = \text{collection variable cost}$$
$$U = \text{unit cost of actual data}$$
$$B = \text{bloat factor of contained structures}$$
$$\textbf{maximum room for improvement} = \frac{V}{U} + \frac{1}{1-B}$$

Rule of Thumb: When Should I Bother Tuning?

A good rule of thumb to following, when deciding whether to tune or to buy more hardware in order to increase scalability, is to look at the asymptotic bloat factor of your dominant structures. For each data structure that are expected to grow the largest, tune it only when its asymptotic bloat factor is above 50%. You can estimate which structures are the dominant ones by looking at the unit cost of each, and multiplying these figures out by how many elements you'd like to have in each.

For example, the variable cost of a `HashMap` is 48 bytes. If you're storing structures with a unit cost of 40 bytes each with a bloat factor of 50%, then the maximum room for improvement is $\frac{48}{40} + \frac{1}{1-0.5}$ or 3.2x. This means that there is a fairly good scalability benefit you'll see from tuning.

Will It Fit? Should I Tune? From unit costs and the maximum room for improvement, you can estimate answers to the these two important scalability questions. If you have a fixed amount of heap size that each process has access to, then your data model designs will fit if memory capacity divided by unit cost, which is the number of elements you can afford, is at least as large as you need. For example, if you have one gigabyte of memory available, and each user comes with a unit cost of one megabyte, then you can support at most 1000 simultaneous users. Is this enough?

If not, then you have two options: buy more hardware, or tune. If possible, you could buy more memory, or more machines if your current machines cannot accept any more physical memory. You must also pay attention to address space limits, as discussed in Section 12.1: if your 32-bit processes cannot fit anything more into the constrained address space, then the answer to "Will It Fit?" is no! In this case, buying more physical memory won't help, and your only option is to tune your data models.

The maximum room for improvement of your dominant data structures can help you to understand whether you should bother tuning. If a data structure has a low bloat factor, then there isn't much bloat to optimize away. For example, in a web application server, session state will scale up roughly depending on the number of concurrent users. If the unit cost per user is one megabyte, and you'd like to support 1000 concurrent users, then this is clearly a dominant structure. If you can't afford one gigabyte for session state, then and if the bloat factor of your session state data models is greater than 50%, then you should consider tuning these models.

16.2 Quickly Estimating the Scalabilty of an Application

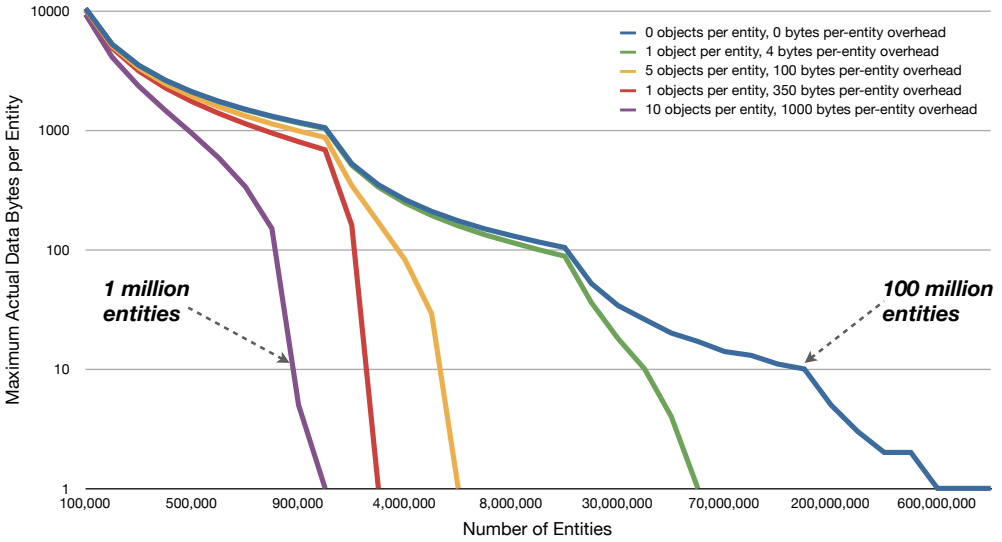
It can be tedious to construct formulas in order to estimate the scalability of your data models. Estimating scalability can require navigating a space with many dimensions of freedom. Sometimes, you have a fixed amount of memory, and a fixed amount of actual data to store, and want to know how much you need to tune, in order to make it fit. Sometimes, you have some flexibility in how much data you're keeping around. Luckily, there are some simplyfing studies that you can do, where you fix certain parameers, and let others vary. Figure 16.3(a) and Figure 16.3(b) show two of these. In both cases, the amount of memory available is fixed at one gigabyte. The first chart plots how much actual data you can afford to keep around, for various degrees of bloat (the four level curves). The second chart plots how high an asymptotic bloat factor you can afford, for various amounts of actual data (the four level curves). For many cases, you can simply consult these charts. However, it isn't difficult to construct your own, as described in Figure 16.2.

16.3 Example: Designing a Graph Model for Scalability

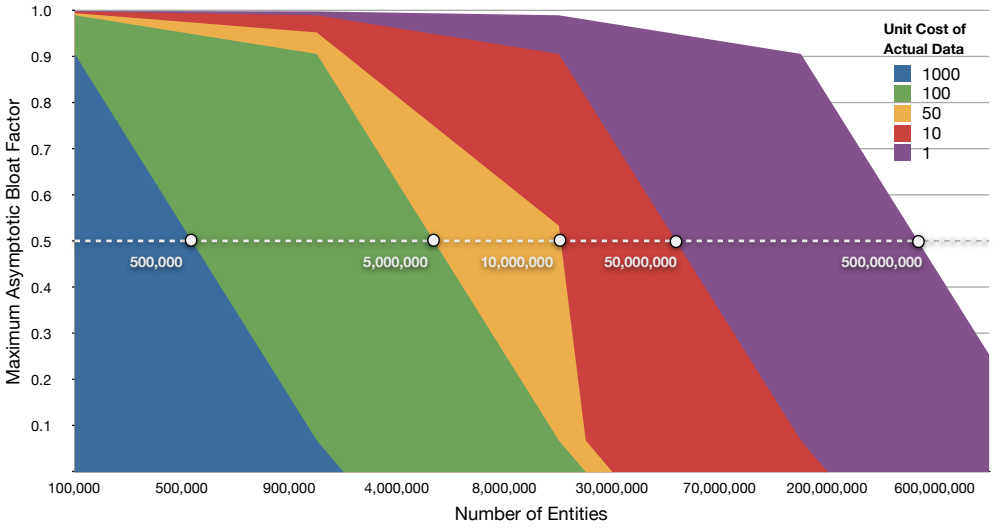
Let's step through an example of getting a data model to scale. This extended example focuses on modeling relationships between entities, like the employees within a department, or the books on a certain topic. This is a modeling task you face whenever bringing in data from some relational data store, loading in trace or log data, or modeling XML information. There are many examples that fall into this general space.

This is a task you'll often face, but getting a relational data model design to scale is hard. Database developers from Oracle, IBM, and others, have worked for decades to tune the way their databases store this kind of information. When this data is loaded into Java, we all pay much less attention to the way that same data is laid out in the Java heap. A general-purpose storage strategy, using Java objects in the natural way, is very likely not to scale well. Something you should keep in mind is that, at each step along the way, as you tune your data model for certain use cases, is to keep a focus on the two important aspects of scalability: unit costs and asymptotic bloat factor. These factors will determine the scalability success of your design.

Modeling Relationships Means Modeling Graphs Representing relationships between entities is no different than representing a graph of nodes and edges: entities are nodes, and relationships are edges. A small graph is illustrated in Figure 16.4. When caching data from a relational database in the Java heap, each database row is an entity. Columns containing numbers, dates, string, and binary large objects (BLOBs) data are all attributes of these entities. So far, the way you'd store this entity information in Java is somewhat similar to the way you'd store things in a relational database.



(a) The amount of actual data you can store in your entities depends on the degree of delegation in your entities, and the per-entry overhead of the collection in which these entities reside.



(b) The area under each curve shows the bloat factor you can afford, for various amounts of actual data that you need to store.

Figure 16.3. You can consult these charts to get a quick sense of where your design fits in the space of scalability. These charts are based upon having 1 gigabyte of Java heap. Note the logarithmic scale of the horizontal axis.

Deriving Scalability Formulas [For Experts]

It isn't hard to make your own scalability charts, with some simple algebra and your favorite spreadsheet software. Before you can plot anything, you will need to construct a formula that governs how things scale. Consider the chart in Figure 16.3(b), which plots the bloat factor that will let you fit *at least* one element of data in memory. The formula behind this chart depends upon these quantities: let M be the bytes of memory available, N be the number of entities, and D be the unit cost of your actual data, and x be the unknown maximum room for improvement that you need to solve for.

The *maximum* number of bytes per entity you can afford is the ratio of memory capacity to the number of entities: M/N. The exact cost per entity, including overhead is $\frac{1}{1-x}D$; e.g. 20 bytes of actual data with a bloat factor of 60% means the total size per entity is 50 bytes.

$$\frac{M}{N} \geq \frac{1}{1-x}D \quad \Longrightarrow \quad x \leq 1 - \frac{ND}{M}$$

```
interface INode {
  Color color();
  Collection<INode> children();
  Collection<INode> parents();
}
enum Color {
  White, LightGray, DarkGray
}
```

(a) If you don't need edge properties.

```
interface INode {
  Color color();
  Collection<IEdge> children();
  Collection<IEdge> parents();
}
interface IEdge<Property> {
   Property property();
   INode from();
   INode to();
}
```

(b) If you do!

Figure 16.5. Java interfaces that define the abstract data types for nodes and edges.

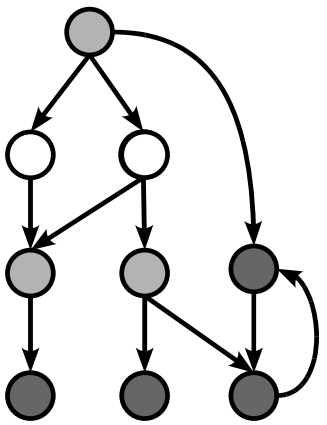


Figure 16.4. Example graph.

Storing relationships is where things start to diverge. In Java, it is natural to store the relationship information, such as the employees under a manager, as references to collections of other entities: a manager object points to a set of employee objects. In a database, this information is usually stored in a separate table; e.g. a table that maps managers to the employees they supervise. In Java, this isn't a very natural way to model things.

The implementation strategy you choose depends heavily upon the use cases that you need to handle. Do your edges have properties, such as an edge weight? Do you need random access to the edges? Do you need edges at all, or only nodes along with edge fanouts? How will you be traversing the edges? The Java interfaces help to shape your implementation to these use cases.

Every interface fixes some things, while sitll allowing some degree of freedom in the implementation. Figure 16.5 shows two interfaces that this example will work through. In one case, there are no edge properties, and in the second case, each edge as an associated weight. If your edges don't have any properties associated with them, then there is no need for an `IEdge` interface.

16.3.1 The Straightforward Implementation, and Some Tweaks

A reasonable place to start is with a straightforward mapping of interfaces to concrete classes. Figure 16.6 shows such an implementation for the `Node` data type. Following this strategy, the `Node` class has three fields, one to store its `Color`, and two for the relations to children and parents. These two relations are implemented

```
class Node<E> {
   Color color;
   Set<E> parent = new HashSet<E>();
   Set<E> children = new HashSet<E>();
}
```

(a) Node implementation.

```
class Edge<Property> {
   Property property;
   Node<Edge> from, to;
}
```

(b) Edge implementation, if you have edge properties.

Figure 16.6. A straightforward implementation of the `INode` interface, one that is parameterized the type used for parents and children; e.g. a node without edge properties would be a subclass of `Node<Node>`, because the parents and children point directly to other nodes.

with a standard `HashSet` collection. In the case where the design requires edge properties, there is an `Edge` class with one field that stores the edge property, and two reference fields that store the source and target nodes.

This is a pretty natural expression of a graph in Java, and it's easy to implement and maintain. There are no corner cases to handle, in terms of adding or removing nodes or edges. It's easy for new project members to map between interface and implementation, because the two are parallel versions of each other. The nodes and edges, and relations between them, are objects that can be manipulated using normal object oriented practices; e.g. you can write `node.children().get(5).getTo()-.color()` and, later, quickly understand what is going on. Contrast this with interacting with a non-object-oriented data storage, such as memcached[6] or a relational database. To access an attribute in this non-OO data would be more work, and would not read as cleanly.[1]

In this implementation, the unit cost per node is three pointers plus two collections of default size. If a typical node has one parent and two children, then the unit cost of a node will be 404 bytes: one object header, plus three pointer fields, plus two 136-byte collection fixed costs, plus three 28-byte collection variable costs (Table 8.1 shows the fixed and variable costs of standard collections). At this unit cost, you can fit at most 2.6 million nodes into one gigabyte of Java heap. Is it worth tuning? That depends on the maximum room For improvement of this design, as things scale up.

Every node stores 16 bytes of actual data (its color, parent, and two children), compared to its 380 byte total unit cost. Let's assume that the nodes are stored in a simple array. From these values, we can compute the maximum room for

[1]There are frameworks that hide the details of accessing this information, such as Hibernate[7]. Under the covers, though, the same mismatch exists, and now you are faced with the added complexities of interacting with these APIs.

improvement:

$$V = 4 \quad \text{(variable cost of node array)}$$
$$U = 16 \quad \text{(actual data per node)}$$
$$B = 1 - 16/380 \quad \text{(bloat factor of node)}$$
$$\textbf{maximum room for improvement} = \frac{V}{U} + \frac{1}{1-B} = 24x$$

The maximum room for improvement is a factor of 24x, which is very high. Table 16.1 tracks the maximum room for improvement of various storage designs.

If you need to support edge properties, then the scalability story gets worse. In this case, In addition to the cost of the nodes are the cost of the edge objects. By objectifying each edge, this implementation pays a cost of one object header, one 4-byte data field (let's assume that the edge properties are simple weights, and you store the primitive integer inline with the edge object), and two pointers, or 24 bytes. For the example an average of one parent and two children per node means three `Edge` objects per node. This increases the effective cost per node to $380+3*24$, or 428 bytes. In this case, the Maximum Room for Improvement is 27x.

An easy way to increase scalability is to use a list, rather than a set, to store the edges. An `ArrayList` has much lower fixed and variable costs than a `HashSet`. This should be a fine replacement, as long as you don't need the ability to randomly delete edges from the graph, or check for duplicate edges in a node with many edges. An `ArrayList` handles random deletions just fine, but deletions from the middle of a list are a hidden cost of which you should be cautious. What's worse, whereas a `HashSet` quickly and transparently eliminates duplicates, you have to manage duplicate elimination yourself, and with expensive linear scans. This linear scans won't be a problem if the number of parent or child edges per node is less than around three. Using `ArrayList` instead of a hash map would lower the total unit cost per node from 404 bytes down to 224 bytes. This small change has increased the number of nodes you can fit in a gigabyte from 2.8 million up to 4.8 million. The maximum room for improvement of this design is 14x (19x with edge properties).

storage design	MRI without edge properties	MRI with edge properties
`HashSet`	24x	27x
`ArrayList`	14x	19x
`ArrayList`(2)	10x	15x
no collections	2x	7x

Table 16.1. The Maximum Room For Improvement (MRI) of storage designs for a graph, both without and with edge properties.

This means that there remains quite a bit more bloat to be squeezed out. If you know that the number of parents and children will be typically no more than two, then you can use a smaller initial size for the edge lists. If you update the constructor call for the `ArrayList`s to request an initial capacity of two elements, then the total unit cost of the nodes drops to 160 bytes. You can now fit 6.7 million

nodes in a gigabyte heap, and the remaining maximum room for improvement is now 10x (15x with edge properties).

These easy tweaks can bring you a great return on a minimal investment of your time. They don't in any great way negatively impact the maintainability of the code. But there's still a very large amount of bloat remaining. The variations so far haven't greatly impacted the functionality of the implementation. By specializing your code to handle only a limited degree of functionality, you can achieve a fair degree of compactness without much additional effort.

16.3.2 Specializing the Implementation to Remove Collections

One of the main remaining sources of bloat lies in the use of collections to store edges. Every node has two collections, even if it only has one or two outgoing edges. As a result, every node pays for the fixed cost of a collection and, with only a small number of incident or outgoing edges, does not amortize these fixed costs.

If every node has exactly the same small number of incoming and outgoing edges, an alternative implementation presents itself. Figure 16.7a shows an implementation of the `Node` interface that does away with collections. Even if many nodes have no parents, or fewer than two children, this specialized implementation remains preferable to the original one that uses collections. The flexibility of collections simply does not pay off at this small scale. For each node, on top of the 16 bytes of actual data ideal cost, this implementation costs only one object header. The bloat factor is 43%, which reduces the maximum room for improvement to $\frac{V}{U} - \frac{1}{1-B} = \frac{4}{16} - \frac{1}{1-.43}$, or 2x. You can now support around 38 million nodes per gigabyte of heap! If you need edge properties, then the maximum room for improvement is still high, at 7x.

```
class Node<E> {
   Color color;
   E parent;
   E child1;
   E child2;
}
```

Figure 16.7. No collections: a specialized design for the case that no object has more than one parent and two children.

Though quite scalable, this implementation presents several complications. The `INode.parents()` interface is specified to return a `Collection`. How can one efficiently support an interface that expects a collection, if the storage contains only a single pointer? If you don't make this API change, and instead choose to return a *facade* that routes the edge operations to the underlying storage, users of the API will be in for some surprises:

```
public Collection<E> parents() {
   return Collections<E>.singletonList(parent);
}
public Collection<E> children() {
   List<E> l = new ArrayList<E>(2);
   l.add(child1); l.add(child2);
```

```
    return l;
  }
```

Firstly, if a caller of `children()` does so in a loop, then making this change will result in a potentially big slowdown. A loop that depends heavily upon calls to this method run an order of magnitude slower after this change. Secondly, this implementation will not reflect any updates that the caller makes to the returned collections. Finally, it violates a contract that is implicit in the interface: that two calls to the `parents()` interface have reference (i.e. `==`) equality. The only solution, short of caching these collections (and thus undoing this optimization entirely), requires that you revise the `INode` interface. This is not a very appealing requirement, to expose implementation details to the interface.

Third, in addition to being quite expensive, in creating a set for every call to `parent()`, this implementation lacks in expressive power compared to the other implementations presented so far. For example you will find it more difficult to extend the graph interface to support edge labels. Adding edge labels with low overhead is not impossible, but requires some careful planning.

16.3.3 Supporting Edge Properties in An Optimized Implementation

If you do need edge properties, but want to avoid the expense of `Edge` objects, things can get tricky in a language like Java. In this design, the API method `Node.children()` returns a collection of nodes, not one of edges. Thus, the code to access an edge label requires an API change. You could play a trick similar to the one above, where transient collections were created in order to avoid the cost of persistant collections while preserving a collections-oriented API for accessing edges. This change also requires that you store the edge properties somewhere other than in `Edge` objects:

```
class Node<Property> {
   Node parent, child1, child2;
   Property parentEdgeProp;

   public Collection<IEdge> parent() {
      return Collections<IEdge>.singleton(new EdgeFacade(
          parent, this, parentProperty));
   }
}
```

Notice how, since, in this special form of a graph, each node has at most one parent, therefore you needn't store edge properties of a node's outgoing (children) edges. These edge properties can be accessed from `child1.parentEdgeProp`. With this design, you add no bloat in supporting edge properties, and so you can achieve the same maximum room for improvement with or without edge properties. The

downside comes from the computational expense of the `parent()` and `children()` calls. These can be quite expensive, as each call to these methods entails creating and initializing two temporary objects. Also, as with the previous facade-based solution, the breakage of reference equality needs to be strongly documented along with the API.

An alternative is to store edge properties in a side map. This makes sense only if a small fraction of the edges have labels. Otherwise, the costs of the map infrastructure may very well overwhelm the cost of the labels. Each edge property now consumes an extra 28 bytes for a `HashMap` entry object, plus an object header (you will be forced, if you use the standard Java collections, to fully objectify the property values, even if each is a scalar quantity), or 30 bytes more than the clever implementation that inlines the properties into the node object.

This activity of tuning the original graph implementation has raised two problems. First, it is difficul to support nodes with widely varying numbers of parents and children. If all nodes had only a very small number of incident edges, or a very large number, then specialized implementations are possible. But even these have issues, such as requiring users, via documentation rather than compiler assisted analysis, to avoid using reference equality. Second, optimizing storage has come at the expense of easy extensibility; one can remove the use of `Edge` objects, but, to support edge labels requires either expensive maps to parallel data structures, or pollution of data types not directly connected to the planned extension.

16.3.4 Supporting Growable Singleton Collections

Section 16.3.2 shows how to specialize an implementation for the case when nodes have only one or two incident and outgoing edges. This implementation is pretty efficient, but inflexible: it has to be the case that every node has this property. If, as you populate the graph, you realize that even one node violates it, then you'll need to code up complicated fallback cases. You would need to create a more general-purpose form of the node, copy over the edges you've added up until this point, remove the old node instance from the node set of the graph, and then iterate over all of the existing nodes, rerouting their edges to point to the new node instance. This is tedious code to write and maintain. Plus, if this happens even moderately often while populating the graph, can result in bad performance.

It is possible to maintain a degree of flexibility, allowing nodes with widely varying edge counts, while keeping the updates localized to a node, as its edge counts exceed special case boundaries. This is especially true for the special case of single-element collections. A node can also be a singleton collection if it obeys a simple contract, the *singleton collection pattern* shown in Figure 16.8: `class Node`

```
interface Singleton<T> extends Collection<T> {
}
```

Figure 16.8. The Singleton Collection pattern.

`implements Singleton<Node>`.

In this way, it becomes possible to have a single node implementation that supports arbitrary numbers of parents, while remaining optimized those nodes with only a single parent. Furthermore, you needn't change the fields of the `Node` class from the straightforward, most general, implementation of Section 16.3.1: a field `Collection<Node> parents` can, transparently, be either a single node or a more general collection.

In order to take advantage of this technique, you will need to modify the node's `addParent()` method. Here is an implementation that optimizes both for empty and singleton sets:

```
class Node {
  public Node() { // constructor
     this.parents = Collections.emptySet();
  }
  public void addParent(Node parent) {
     if (parents.size() == 0) parents = parent;
     else if (parents.size() == 1) {
        Node firstParent = parents.iterator().next();
        parents = new ArrayList<Node>(2);
        parents.add(firstParent);
     } else {
        parents.add(parent);
     }
  }
}
```

It would be nice if this transition, from a singleton to a fully formed collection, could be done more transparently. But this would involve rerouting all pointers to this singleton to point to a proper set. In Java, it is not possible to write a program that transparently changes an object's reference identity, without using wrapper objects. An `ArrayList` does this, by wrapping an object around the underlying array, thus allowing the identity of the array to change as it is reallocated to be of larger or smaller size.[2]

16.4 Summary

- When designing and implementing your data models, you should keep two questions in mind: "Will it Fit?", and "Should I Bother Tuning?".

[2]The Smalltalk language provides a `become` primitive that allows for pointer rerouting, without the use of handles, though at a nontrivial runtime expense. In the worst, but common, case, every call to `become` requires a full garbage collection.

- It is often not possible to fully amortize the amount of bloat in a data structure. Eventually, the amount of bloat will reach an asymptote, no matter how many elements you add to it.
- The Maximum Room For Improvement is a useful metric in helping you to answer the two important questions. It is based on the asymptotic value of bloat in a data structure.
- Using a fully object-oriented Java design, it is impossible to achieve both compactness of storage and the generality to handle a variety of graph structures.

We are left in a bit of a hard spot. If your nodes have no attributes, then you needn't waste any space on `Node` objects. All of the information lies in the edges, yet a design that includes a `INode` interface (which supports `getChildren()` and related calls such as shown in Figure 16.5), is forced to creation node objects at some point. You could overhaul the design to optimize for this case, but the new design will be foiled as soon as a use case comes along that requires node attributes. There is no degree of flexibility here. Achieving this kind of flexibility requires coding in a style that is not conventionally object oriented. This is the subject of the next chapter: bulk storage.

Chapter 17

WHEN IT WON'T FIT: BULK STORAGE

There are limits to how well an object-oriented data model can scale. At some point, you will be faced with the ineluctable limits of tuning objects. Each object has its header, and this is an unavoidable cost. The only way to avoid delegation costs, and thus amortize the cost of a header over more data fields, is to go through the manual, iterative, process of inlining the fields of one class into another. Some amount of this manual inlining makes sense, but too much runs counter to principled engineering. Often, you are blocked because you run into code that you do not own, or classes whose field layout is, for one reason or another, set in stone.

In this way, a conventional storage strategy, one which maps entities to objects and relations to collections, suffers from two problems that impact scaling up the size and complexity of a design.

Amortizing away header costs. Since entities are objects, and each object pays a header cost imposed by the JRE, you need to craft your design so that there is enough data in each object to amortize the cost of the headers, and to avoid high delegation costs.

The Fragile Base Class problem. You may (wisely!) be unwilling to touch a class that is also used by other teams for fear of adversely impacting their correctness or memory footprint. For example, say class `X` delegates some of its behavior to an instance of class `A`, and that both `B` (your class) and `C` (the other team's class) are instances of `A`. Ignoring the other teams needs, you might prefer to collapse the fields of `B` into the `X` class, removing this need for delegation and that extra object header. To do so requires either modifying the implementation of `X`, or duplicating the implementation of `X` into a modified version of `B`. Neither alternative seems very appealing. This is a variant of what is known as the *fragile base class problem.*

```
class X {
  A a;
}
class B extends A {
  int w, x;
}
class C extends A {
  int z;
}
```

Figure 17.1. Delegation costs one object header, a cost that is easy to amortize.

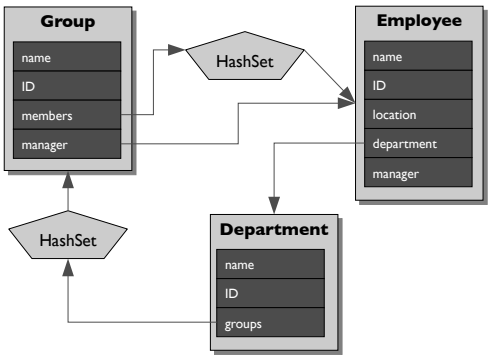


Figure 17.2. A conventional storage strategy maps entities to objects, attributes to fields, and relations to collections.

If you break out of the Java mold, you may be able to overcome these issues. An Entity-Collection diagram such as Figure 17.2 maps pretty inefficiently to a straightforward Java implementation. Each entity pays a header cost, but has only a few data fields. Most of the collections, representing relationships such as the number of employees under a manager, will be small.

Storing data in bulk form means that the relations are stored in a small and fixed number of collections, and the entities are stored in a small and fixed number of objects — across *all* entities and relations between them. They key is that the number of allocations is small and fixed, and therefore object header overheads (and allocation costs) are easily amortized. The trick to accomplishing a bulk storage approach is to store data in large arrays. This can be accomplished in two ways: arrays of records and column-oriented storage. An array of records stores the fields of the entities back to back in the array, without intervening pointers or headers. Arrays of records are not an option in Java (they are in languages such as C, Pascal, COBOL, and C#) and so this chapter focuses on the latter approach: column-oriented storage.

Warning! Bulk storage violates some basic tenets of object-oriented data modeling. Everything is a stored in an array, and thus there are no objects to encapsulate the state of an individual entity. You will learn that subclassing is more difficult to express, and that a column-oriented approach may not suit the way your data is accessed and updated. Nonetheless, with careful consideration of these issues, you can reap substantial benefits.

```
struct Node {
  enum Color color;
} nodes[20]
```

Figure 17.3. In C, `nodes` is an array of 20 integers, not pointers to 20 separate heap allocations.

17.1 Storing Your Data in Columns

In a column-oriented storage strategy, attributes are stored as arrays of data, and an entity is implicitly represented by an index into these parallel arrays. Figure 17.4 gives an example which takes the graph of objects from Figure 17.2 and represents the attributes of the `Employee` entities in this fashion. Every group of entities, such as the set of all employees, is stored in what amounts to a table of data. The range of indices, 0 to 6 in this case, over the domain of attributes (`name`, `ID`, etc.), altogether represent what was previously a graph of individual objects.

Column-oriented Storage

A column-oriented strategy stores everything, your data and the relations between them, as sets of parallel arrays. Entities, rather than being individual allocations, are indicies into these arrays.

A column-oriented storage strategy consists of four tasks. First is storing the primitive attributes of your entities, such as the `boolean` and `int` data. Second is storing the relations between entities. Third is storing variable-length attributes, such as string data. Finally is the task of establishing the set of tables. There will be one per set of entities, one per relation between entities, and one per source of variable length data. Let's step through these tasks now, continuing the example from the previous chapter: storing a graph model.

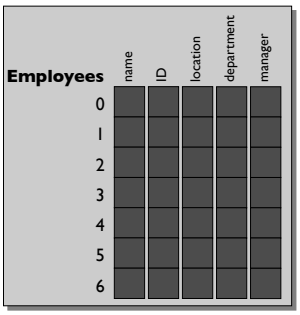


Figure 17.4. Storing attributes in parallel arrays.

17.2 Bulk Storage of Scalar Attributes

The example graph of the previous chapter finished with a bit of a condundrum. You could store a flexible number of nodes and edges, but at high level of memory bloat. Alternatively, by severely restricting the flexibility of the implementation, could you achieve a pretty good level of scalability. Within the normal confines of Java, these were the two choices. You should be able to achieve a better balance by storing the graph in a bulk form.

```
class Attribute<T> {
  T[] data;
  T get(int node) {
     return data[node];
  }
  int extent() {
    return data.length;
  }
}
```

A graph model is a good candidate for storing in a column-oriented fashion. Stored in this way, a graph without node attributes is simply one that has no arrays to store node attributes. The is a direct correspondence between need for and the existence of storage. This feature is hard to achieve in a purely object-oriented approach, where having an interface for an entity at some point demands that instances of that entity be created.

Figure 17.5(a) repeats the example graph from Figure 16.4, this time including an identifier for each node. Each identifier is a natural number that ranges, in this example, from 0–8 with no gaps. As far as node attributes are concerned, the identifier of each node need not be stored anywhere. The figure illustrates the identifiers for clarity, only. Once every node has been assigned a dense identifier, then the attribute value of a given node attribute can be stored and accessed in with that identifier.

```
interface INodes {
  int numNodes();
}

class ColorNodes implements INodes {
  Attribute<Color> colors;

  int numNodes() {
    return colors.extent();
  }

  Color getColor(int node) {
    return colors.get(node);
  }
}
```

In a column-oriented storage approach, rather than having interfaces and implementations for individual nodes, you instead have them for a *set* of nodes. An instance of `INodes` defines the range of node indices for the nodes of that model, and includes whatever combination of node attributes that you need for your given purpose. If, for one use case, your nodes have colors, then you include that attribute in your `INodes` model.

Freedom from Concensus Building If an object-oriented design is expected to be used by multiple groups, there is usually a painful, iterative, process of reaching a concensus. Many groups, with possibly competing trade-offs of time and space, and of what attributes are necessary or optional, must reach a consensus as to how to lay out the data in a class hierarchy. Deciding which attributes belong in base classes versus inherited classes, and of when to store attributes as fields or in a side object, cannot be made in isolation, one group at a time.

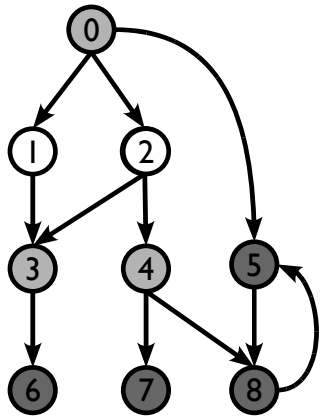
For the most part, these issues are much simpler when using column-oriented storage. Adding new attributes to nodes or edges is a trivial operation. Adding a new node attribute requires an extra array. You needn't reach a concensus among developers as to whether this is a good idea.

Transient Need for Attributes If you only need node colors for the first phase of a multi-step algorithm, then you can `null` out the colors attribute when you're done with it. This will clear out all memory associated with that attribute. If the colors were spready out into many individual node objects, rather than a single array, this would require essentially reforming the entire graph. Assigning the color fields of node objects to `null` would have no benefit, because in this case the color is a enumerated type.

Transient Boxing Since individual nodes are now just numbers, you may quickly run into some coding and maintenance problems. The Java compiler won't be of much use in giving you static typing guarantees, because a node is an `int` (serving as an index into arrays) just as much as integers that represent other quantities. Imagine code where methods commonly have 5 `int`

```
class TransientNode {
  ColorNodes nodes;
  int node;

  Color getColor() {
    return nodes.getColor(node);
  }
}
```



(a) Each node has an identifer.

id	Color
0	LightGray
1	White
2	White
3	LightGray
4	LightGray
5	DarkGray
6	DarkGray
7	DarkGray
8	DarkGray

(b) Node attribute.

source → target
0 → 1
0 → 2
0 → 5
1 → 3
2 → 3
2 → 4
3 → 6
4 → 7
4 → 8
5 → 8
8 → 5

(c) The edges.

Figure 17.5. A graph of stored in a column-oriented fashion.

parameters, and trying to make sure you're passing the integer values in the proper order.

Using transient node facades can help here. Instead of passing around integers to represent nodes, you can pass around temporary `Node` objects. As long as manage the lifetime of these facades properly, being careful never to store them in long-lived collections, then it is possible that you won't see a huge performance hit by using them. With transient node facades, you are trading off more time spent in garbage collection for convenience and the greater assurances you get from strong typing.

These transient node objects act as facades to the `INodes` model, and so most store both a reference to the `INodes` model and the node's identifier. Notice that these facades have two fields. If your nodes have only one attribute, a purely object-oriented implementation would have only a single field. Though it has one extra field, on top of the earlier node implementations, for the `INodes` reference, as long as it is transient, there is some chance that this won't result in an increase in garbage collection overhead. This is something that requires experimentation in your setup. If these result in big drags in performance for your use cases, remember that there is no absolute need for these transient node facades.

You must also be careful to disallow, by convention, reference equality checks against transient nodes. If you are not careful, you will need to persist the transient facades, ruining any benefits of the column-oriented approach. Similarly, if the lifetime of the facades is neither temporary, nor correlated with a short-running method, you will certainly see negative impacts on garbage collection overheads.

17.3 Bulk Storage of Relationships

```
class WeightedEdges {
  int[] source, target,
      weight;

  int source(int edge) {
    return source[edge];
  }

  int target(int edge) {
    return target[edge];
  }

  int weight(int edge) {
    return weight[edge];
  }
}
```

The edges of a graph can be represented as two parallel arrays, storing the source and target node indices of each edge, as shown to the left. Figure 17.5c illustrates a concrete example for a graph with 11 edges. For example, row number 4 represents the edge from node 1 to node 3. Any edge attributes, such as an edge weight, can easily be represented as attributes parallel to the source and target arrays.

This representation is a nice first step towards storing relations in a bulk form, but it cannot efficiently support graph traversals. In order to traverse the edges of a graph from a given node, you need to know the outgoing edges of a given node. In this edge layout, the only way to get the outgoing edges of a node is to scan the entire edge table, pulling out those rows whose `source` attribute matches the given node identifier.

Indexing the Edges To allow for efficient traversals of the edges, you must index them, as a database would. First, consider the outgoing edges from a node. If the `source` and `target` arrays are sorted by the **source** attribute, then all of the children of a node will be stored as contiguous rows. This is a nice trick, and is what is shown in Figure 17.5c.

Having sorted the edges, you can now leverage this property to allow for more efficient traversal, as well as more efficient storage of the edge data. Notice how the outgoing edges of node 2 start at row 5, and stop at row 6 (inclusive). To visit the children of this node, without having to traverse the entire edge model, you need to store these two row numbers somewhere. These two boundary values, 5 and 6, are attributes of node 2. This means that a natural place to store the edge index is as integer attributes in the node model; let's call these `start` and `end`.

Also notice how the `source` attribute of Figure 17.5c contains lots of duplicate data; e.g. the two rows that represent the outgoing edges of node 2 have the same `source` value (the value 2!). The `start` and `end` node attributes, combined with the `target` edge attribute is all you need to traverse the graph.

Therefore, a more compact representation can eliminate the `source` attribute entirely. Figure 17.6 shows an update to Figure 17.5, where the node model now has, for the outgoing edges, the two new attributes: `start` and `end`.

Parent Edges The same thing can be done for the incoming edges, if we instead sort the edges of Figure 17.5c by the **to** attribute. Figure 17.6a also shows the two new attributes for the incoming edges. For example, node 2 has two children and one parent. The children start at index 4 in Figure 17.6b, which shows the two

node id	Color	Children start	Children end	Parents start	Parents end
0	LightGray	0	3	–	0
1	White	3	1	0	1
2	White	4	2	1	1
3	LightGray	6	1	2	2
4	LightGray	7	2	4	1
5	DarkGray	9	1	5	2
6	DarkGray	–	0	7	1
7	DarkGray	–	0	8	1
8	DarkGray	10	1	9	2

(a) Node attributes. `start` and `end` are edge identifiers.

edge id	node id
0	1
1	2
2	5
3	3
4	3
5	4
6	6
7	7
8	8
9	8
10	5

(b) Children edges.

edge id	node id
0	0
1	0
2	1
3	2
4	2
5	0
6	8
7	3
8	4
9	4
10	5

(c) Parent edges.

Figure 17.6. In order to support efficient traversal of the graph edges, you will need to index them. These tables update the example of Figure 17.5 to do so. For example, node 2 has two children and one parent. The children start at index 4 in Figure 17.6b, which shows the two children to be nodes 3 and 4.

children to be nodes 3 and 4.

17.4 Bulk Storage of Variable-length Data

The last remaining type of data is the strings and other data of variable length. Storing a node or edge attribute in an array works well for any attributes each of whose values is one of Java's primitive data types. If each attribute value is an array, such as the case with string attributes, then a single attribute array does not suffice.

Even though the standard column-oriented storage strategy doesn't suffice, there is still a big gain to be had to finding some way to store this data in a bulk form. If the length of an array is 10 characters, then it has a memory bloat factor of 61%. The problem grows worse if these primitive arrays are wrapped inside of objects such as `String`. If wrapped inside of `String` objects, then your the string has a bloat factor of 83%. This is a pretty common problem, and so you should consider bulk storage of your variable-length data, eve if you decide not to store your entities and relations in bulk form.

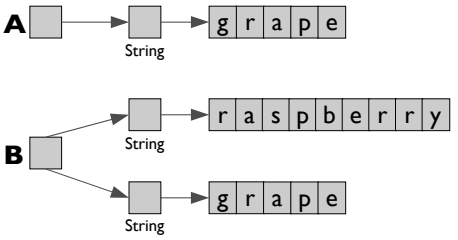
There are several ways, within the constraints of Java, to avoid the object headers of many small character arrays. One possibility is to use the built-in string interning mechanism covered in Section 6.3. By interning strings, your code will pay for the string wrapper and the character array only once, rather than once per occurrence of that string in the heap. Interning works well in reducing overall heap consumption — you're removing not only the many primitive array object headers, but the entire content of duplicated arrays. As discussed in that earlier chapter, you must pay careful attention, because interning is an expensive process, and you only see reductions in memory footprint if there are indeed duplicates to be found.

Figure 17.7(a) and Figure 17.7(b) illustrate a simple case of interning. Of three strings, there are two duplicate "grape" sequences. The residual high overhead is due to the remaining primitive array object headers; all of the `String` objects are eliminated by interning. Interning removes only the primitive array overheads of *duplicate* strings.

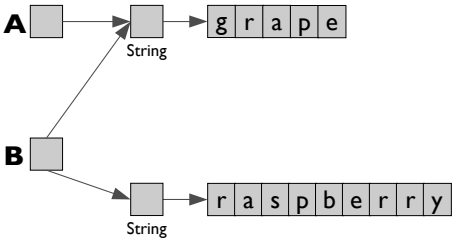
Of course, you can only use this built-in mechanism for `String` data. For non-string data, or when there isn't much in the way of duplication, you can still implement a solution that stores this data in a bulk form.

Bulk Sharing Pools If you will never synchronize or reflect on sequences, as objects, then the primitive array header and string wrapper are a needless expense. Another possibility is to concatenate your many small arrays into fewer, longer, arrays. Figure 17.7(c) illustrates this bulk storage of the sequences in a single large array. You pay the primitive array overhead just once, across all pooled sequences, rather than for every sequence.

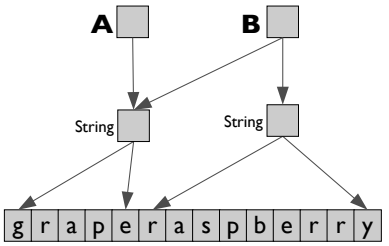
To achieve the ultimate in memory efficiency, you must also eliminate the `String` wrapper objects, as shown in Figure 17.7(d). This last step requires the most work



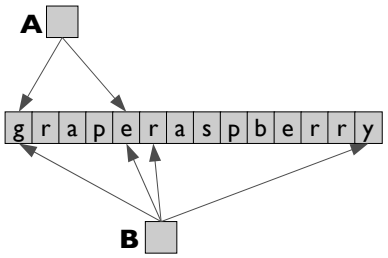
(a) Three normal `Strings`.



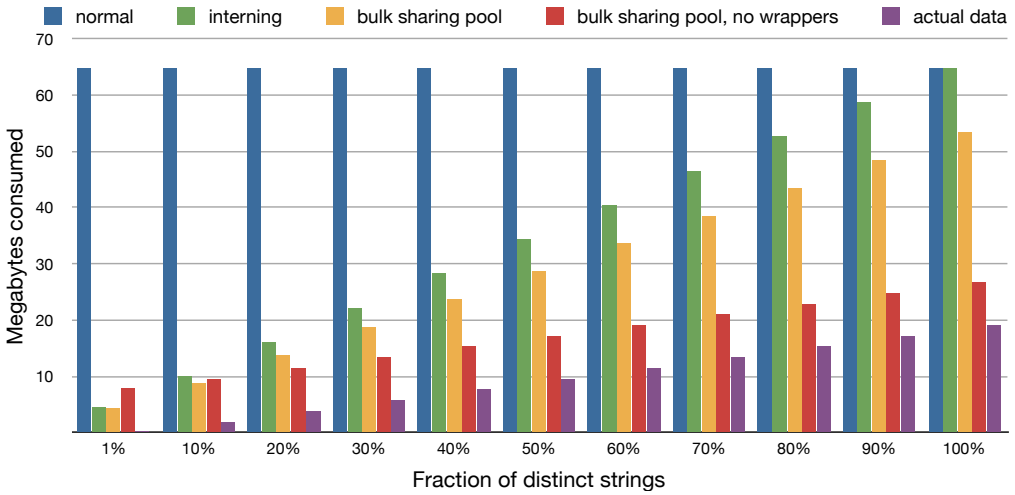
(b) Interning.



(c) Bulk sharing pool.



(d) Bulk sharing pool, no wrappers.



(e) The memory consumed by one million strings, each of length 10 bytes, for varying degrees degrees of distinctness; e.g. 10% means that there are only 100,000 distinct strings.

Figure 17.7. If your application has many long-lived, but small, arrays of primitive data, it could suffer from high overhead. Interning avoids duplication. On top of interning, a Bulk Sharing Pool offers the additional potential for you to eliminate the primitive array wrappers, and so can be beneficial if there are still a large number of unique sequences.

on your part. If you have the luxury of modifying the class definitions for the objects that contain the string wrappers, then you can replace every pointer to a string with two numbers. These numbers store indices into the single large array of bulk data, and demark the sequence that the string wrapper would have contained. You are essentially inlining the offset and length fields that every Java `String` object has, and doing away with the hashcode field and the extra header and pointers. This eliminates almost all sources of overhead.

This last, most extreme, optimization can reap large benefits in scalability, but not always! You are paying an offset and length field in every object, even when the strings are the same. For example, in Figure 17.7(d), the offset and length fields for the two uses of "grape" contain the same data. In the previous two optimizations, these two fields are factored out into a separate `String` object, and so only stored once. If the fraction of distinct strings is small, then the cost of these duplicated fields outweighs the benefit of removing the wrappers; it even outweighs the cost of removing the character array headers. Where is the cross-over point?

Figure 17.7(e) shows the memory consumption of the four implementations: using normal Java `Strings` without any attempt to remove duplicates; using Java's built-in string interning mechiansm; using a bulk sharing pool; and using a bulk sharing pool without any `String` wrappers. The chart also includes a series comparison with the amount of memory consumed by actual data. The chart shows memory consumption of each implementation for varying degrees of distinctness of the strings, for an case with one million strings of length 10 characters each. For example, if 500 thousand of the million strings are distinct (which corresponds to the 50% point in the chart), the normal implementation consumes 65 megabytes, the interning implementation consumes 34 megabytes, the bulk sharing pool implementation consumes 27 megabytes, and the bulk implementation without string wrappers consumes 17 megabytes. There are 500 thousand distinct characters, so the actual data consumes about 10 megabytes. You can see that the cross-over point, where the most extreme optimization begins to pay off, occurs when about 10% of the strings are distinct.

The chart shows just how much a few headers and pointers can affect the scalability of your application. With only a bit of work, you can have an implementation that scales very well, with only minimal overhead on top of the actual data.

17.5 When to Consider Using Bulk Storage

The choice between bulk storage and using normal objects is analogous to the choice between using an `ArrayList` versus a `LinkedList` to store a list. An array-based list makes more efficient use of memory than its linked counterpart, but does not support efficient insertion and deletion of random list elements. Analogously, bulk storage removes all of the delegation links, and stores data and relations in arrays. Removing an entity therefore entails removing an entry from the arrays that stores

the attributes of that type of entity.

There are two main problems you will run into, with a column-oriented approach. The first has been touched on briefly: the lack of strong typing for nodes and edges. If everything is just an integer, your code will be buggy and hard to maintain. Java does not have a facility for naming types, such as `typedef` in the C language. The Java `enum` construct seems like it could help, but this use case would require a permanent object for every node, and, besides, this construct is limited to around 65,000 entries per enumeration. You can use transient nodes, with some cost to performance, but your code must still obey an implicit contract, one not enforced by the `javac` compiler, that reference equality is never used on these transient facades.

The second problem centers around modifications to the node or edge model. This style of storage works fantasically well, much better than normal Java objects, for certain kinds of modifications. Adding attributes to models is easy. Adding nodes is straigtforward. However, deleting nodes, and adding or removing edges from existing nodes can only be done with some extra work. For deletions, you would have to implement a form of garbage collection yourself. Nodes and edges can be marked as deleted; deleted elements would be ignored by normal access mechanisms. Adding edges to existing nodes is even more difficult. For these reasons, it is highly recommended that you only employ column-oriented storage for data structures that do not change in these ways.

17.6 Summary

- Bulk storage is a technique for storing large volumes of data. It eliminates many of the usual overheads of storing objects, such as headers and delegation. Column-oriented storage is one way to store data in bulk form, and is well suited for use in Java applications. With this storage strategy, you can still program in Java and enjoy many of the benefits of the language, while simultaneusly enjoying large improvements in scalability.

- There are restrictions that will limit performance of column-oriented storage under certain circumstances. If the set of entities is in constant flux, then this strategy may not pay off.

- Your code quality will suffer somewhat. Entities are passed around as numbers, reducing the benefits of static type checking.

Chapter 18

WHEN IT WON'T FIT: WORKING WITH SECONDARY STORES

When you've tried every trick in the book, and your data still does not fit within the constraints of available memory or address space, your remaining option is to shuttle it in and out of the heap. While a subset of your data is stored in the heap, the entirety of the data needs to be persisted on some kind of *secondary storage* device. Commonly, data is persisted as files on a local filesystem or a distributed filesystems such as Hadoop's HDFS, in flat-file data stores such as sqlite or Berkeley db, as key-value pairs in distributed in-memory caches such as memcached, as tuples in a directory server, or tables in a relational database. You have lots of options!

Most often, the choice you make of how to store the data dictates how you get the data to and from the secondary store. The provider of the storage mechanism usually provides a Java library that implements a data access API. For example, every relational database comes with code that implements the Java DataBase Connectivity (JDBC) API. This API takes care of the task of turning database query results (a list of rows) into Java objects, and vice versa. These processes are termed *deserialization* and *serialization*. These terms are sometimes synonymously referred to as the steps of *marshalling* data.[1]

On top of the basic data access layers, there exist a number of libraries that hide the low-level details that are particular to any one secondary store. Most JDBC libraries will marshall data to and from Java objects, but these objects are not the objects you care about. THey are instead quite literal Java manifestations of relational database concepts: connections, prepared statements, and result sets. Hibernate, for example, raises the level of interfacing with relational databases so that you needn't be concerned with these lower level details.

[1]Some sticklers distinguish marshalling to be serialization and deserialization along with a protocol for ensuring compatibility between code releases. In this lexicon, a marshalled object is a record not only of the data, but also of the version, or even the schema itself, of serialized form.

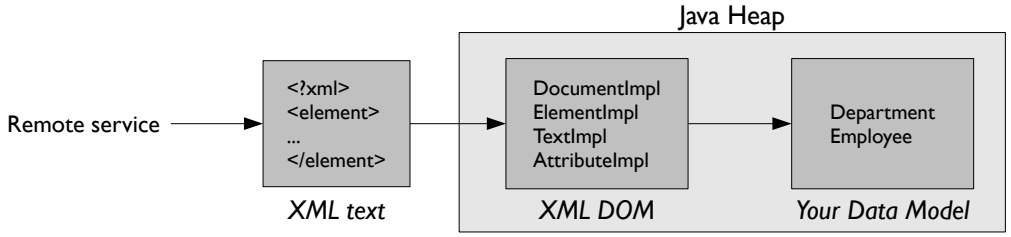


Figure 18.1. An example of data that takes on three forms as it flows from a secondary data source (in this case, a remote service) eventually into your Java data model.

18.1 Serialization: Copying Data in and Out

When interacting with secondary stores, there are three possible stages of the data between the in-transit form and your initial java objects: the serialized form, the in-memory intermediate form, and the initial form of your Java data modles. There of course may be even more forms of java objects, as the data flows through the Java code, but these are the three forms of data that are involved with communicating with secondary stores.

- **Serialized Form** This is the data format that flows over the wire, or is stored to disk. Examples include the standard Java binary serialized form, relational database result sets, XML text (e.g. "`<element></element>`"), Google Protocol Buffers [8], and the key/value string pairs that come back from a distributed map such as memcached [6].

- **In-memory intermediate form** If the data access API requires random access to the elements of the data being streamed in, then the deserialization library needs to keep some sort of indexing structures, and probably even the entirety of the data, in some form that can be efficiently accessed. the important point here is that this form of the data won't be instances of *your* data model, but rather instances of some data structures that the deserialization library provides. Examples include the XML DOM, which provides an objectified, in-memory, form of XML text.

- **One or more of your Java objects** After the data comes over the wire, you must populate an initial form of your Java data models. These model instances must be populated by copying, usually one field at a time, the serialized data or intermediate-form data, into your own Java objects. the reason that this copying needs to happen at such a fine granularity, rather than in bulk (either whole objects at a time, or, even better, whole result sets at a time), is that, in Java, there is no way to map an abstract data type onto existing memory. For this reason, in Java, it is difficult for the serialized form and the *operational* form, i.e. the form that your Java code accesses, to be the same. In a language

such as C, this *is* possible, either through unions or by typecasting a pointer to a struct.

This mismatch between the various forms can result in expensive translation steps. For example, in a version of the Apache Daytrader benchmark [9], turning a single date field of SOAP message (which comes over the wire as XML text) into Java objects requires 268 method calls and the creation of 70 new objects.

Example: Google Protocol Buffers Google Protocol Buffers do a good job at reducing these expenses. The Google designers mostly optimized for performance, at some cost in features. There are two main tricks that Protocol Buffers uses to lower the costs of marshalling. First, the serialized form stores, for many common cases, pure data. The serialized form is not self describing: each end of the communication must know the schema. This data is also transported in a binary form, in contrast to XML text. In addition to it being binary and pure data, the binary data is written out in a compact form. With Protocol Buffers, not all numbers require the same number of bits. Common integers require only one byte, compared to 4 bytes in a naive encoding scheme.Google calls these variable-width integers *varints*. Because the resulting serialized form is smaller, less effort is required to get data into and out of it.

The second trick that Protocol Buffers employs is static compilation of specialized marshalling code. You specify the protocol, and then *statically* generate Java classes that are specialized to the task of serializing and deserializing that kind of data. An XML parser knows nothing about the field layout of your specific classes. In contrast, with Protocol Buffers, the generated code that can marshal only that protocol. There is no introspection needed, to determine the type of the next field.

18.2 Memory mapping: Avoiding Copying

One way to bring data in and out of Java without paying a marshalling expense is via memory mapped I/O. When you *memory map* a file into your address space, you can treat the file as if it were an array. Reads and writes to the array are reflected as disk reads or writes, and these operations are usually done at a page granularity. Actual disk I/O may not occur with every array access. This is the case if the operating system decides that it has enough physical memory to keep the written pages in memory, and you haven't specified that array writes should be written through to disk every time. Reads may be serviced from this cache, as well. In this way, memory mapped I/O can have the benefit of well-tested caching that balances that performance needs of all processes running on your machine, without any work on your part. Memory mapping is a common trick used that is used by C programmers seeking a high level of performance.

Additional Benefits of Memory Mapping Since the cache is managed by the operating system, cached pages persist across process boundaries. Therefore, if your

application runs as multiple steps, each in a separate process, then storing your data structures in memory mapped files can result in a combination of caching and serialization-free persistence. The unwritten buffers may eventually find their way to disk (if the underlying file is not deleted first), but this needn't happen when one process terminates.

Used to its utmost, memory mapping can additionally offer one-copy bulk transfers of memory to and from other processes, disk, or the network. For example, say your application takes data from the network and writes it to disk. If you memory map the network input buffers and the output file, and issue bulk transfers from the input to the output, then it is possible that the operating system will transfer the data directly from the network buffers to the disk buffers, without first copying them out of the kernel, or into the Java heap.

Memory Mapping in Java As of version 1.4, Java offers a memory mapping facility through the `java.nio` library. This Java library provides a `ByteBuffer` API for accessing data. This interface acts like an array of primitive data, even though the data may not be stored in the Java heap at all. It provides both random access and bulk `get` and `put` methods, but no insertion or deletion operations.

Using the `ByteBufer` interface, you can access data from four sources: network transmissions, files on disk, memory allocations in the native heap, and allocations in the Java heap. On UNIX platforms, these last two are often called *anonymous* maps. They have the same API and mostly the same performance characteristics as memory-mapped files, without the benefits and liabilities of a persistent backing store. While the latter two can serve only as transient repositories for your data, they avoid the expense of having to create a file on disk — an expensive operation, on most file systems, if done frequently.

You may find it useful to have the option to have some data stored in transient storage, and others in persistent storage, backed by files on disk, and interact with both using the same API. The `java.nio` library lets you do this. An important advantage of using native `ByteBuffer` storage, over Java heap storage, is that your application can run on arbitrarily large inputs without the constraints of a fixed-maximum size Java heap.

You also have a choice of whether to use standard Java byte ordering, or the byte ordering of the platform on which the application is executing. Of course, this only matters if the data values you are accessing are larger than a byte. On top of a `ByteBuffer`, you can layer other primitive-type views. For example, the instance method `ByteBuffer.asIntBuffer()` returns an `IntBuffer` that takes care of any bit manipulations that are necessary to access the data as Java integers; 18.2 shows what your code might look like. If you don't force native byte ordering, and are running on hardware configured to run with little-endian bytes (e.g. an x86 core), then every call to `getInt` or `putInt` requires expensive byte swapping; if you do force native byte ordering, then the JIT compiler will compile away these method calls entirely, thus rendering `getInt` and `putInt` no more expensive than accessing

```
ByteBuffer mapAnonymous(int numBytes) {
  return ByteBuffer.allocateDirect(numBytes);
}
```

(a) Mapping a native heap allocation into Java.

```
ByteBuffer mapFile(String file) {
  return new RandomAccessFile(file).getChannel().map(MapMode.
      READ_WRITE, 0, file.length());
}
```

(b) Mapping a file into Java.

```
IntBuffer asInts(ByteBuffer buffer) {
  return buffer.asIntBuffer().order(ByteOrder.nativeOrder());
}
```

(c) Java offers facades that let you operate on the underlying bytes as larger primitives. It is highly recommended that you use native byte ordering when possible.

Figure 18.2. Some of the memory mapping facilities offered by Java.

an array. There can be an order of magnitude difference in performance hinging on the decision to use native byte ordering.

Memory Mapping is not Marshalling! The data being read and written is limited to the Java primitive data types, such as integers and floating point numbers. For this reason, memory mapping is not an immediate replacement for object serialization. If you already have code that is using, say, built-in Java object serialization, then don't expect the `java.nio` memory mapping facilities to provide a drop-in replacement for your marshalling needs. Any preexisting code that is expecting to interact with Java objects will either require modification. Either that code must be modified so that it operates directly on data stored in a memory mapped form, or the users of that code must be modified to create temporary facade objects that implement the expected interfaces.

Memory Mapping Your Column-oriented Bulk Storage If you've *already* committed to a column-oriented bulk storage approach (see Section 17.1) to storing your data, then you are in for a treat. In the context of a column-oriented approach, you've already made the necessary switch away from storing data as objects, and so any requisities for marshalling have already been done away with. What's better is that memory mapping and column-oriented bulk storage go hand-in-hand: the interface to all memory mappings is an array, and a column-oriented storage structure stores data as arrays. There are two variants to consider, depending on whether or not you need the data to be persisted.

```
class WeightedEdges {
 IntBuffer source, target, weight;

 WeightedEdges(String name) {
   from = asInts(mapFile(name+"from"));
   to = asInts(mapFile(name+"to"));
   weight = asInts(mapFile(name+"weight"));
 }

 int source(int edge) {
   return source.get(edge);
 }

 int target(int edge) {
   return target.get(edge);
 }

 int weight(int edge) {
   return weight.get(edge);
 }
}
```

Figure 18.3. A memory-mapped implementation of an edge model with edge weights.

If you don't need your column-oriented storage to be persisted, then the change required to shift from storing data as arrays to storing data as anonymous maps is minimal. For an integer-valued attribute over 100 elements, instead of allocating an array via `new`

`int[100]`, you call `asInts(mapAnonymous(100))` (using the helper routines from Figure 18.2). This change should be minimal, and nicely localized.

With only a few more coding changes, you can have your models persisted. This is one of the several strengths of a storage approach that is based on memory mapping. The decision of whether or not to persist data to a file system does not involve extensive code work, nor does it require establishing and maintaining versions of serialized forms and all of the associated marshalling code.

To persist an attribute, you have to specify a place to persist it. The helper routine `mapFile` from 18.2 requires a `File` in which to store the data. If your application has a graph model such as the one discussed in Chapter 17, and needs only one of them, then choosing file names isn't very difficult. For example, the edge model can be stored in a file called "edges"; the nodes' weight attribute can be stored in a file called "nodeWeights". You need only choose an appropriate directory in which to keep these files.

If your application has multiple instances of graph models alive simultaneously, then the naming problem becomes more difficult. Now, the choice of directory becomes a critical one, so that you can avoid collisions of the edge and node models. To solve this problem, you will need to give a *name* to each graph model. For example, you may have two edge models, one that stores the department to employee relation, and one that stores the manager to employee relation. It should be easy to come up with distinctive names for these. The `WeightedEdges` example from Section 17.3, shown in Figure 18.3, here updated to use file-backed memory mapping, looks nicely very similar to the original one that used Java arrays to store the data — using a memory mapped backing store needn't radically change the way you code.

Difficulties with Memory Mapping in Java Each memory mapped file consumes only as much *physical* memory as is available and which the operating system decides, in its balancing act, is worthy to allocate to the mapping. While all major operating system manage consumption of physical memory, they do not similarly manage address space consumption. Thus, each mapped `ByteBuffer` consumes a swath of address space equal to the *full* size of the map. For this reason, if you decide to use memory mapping, you will run into several pernicious and interconnected problems. These problems are orthogonal to any problems that stem from a choice to use column-oriented storage.

The primary problem comes from the lack of an unmapping facility in the `java.nio` library. You can not explicitly unmap a mapped area. Instead, and, quite oddly, in direct contradiction of widely published best practices, the library takes care of unmapping in the `finalize` method of the mapped `ByteBuffer`. This leaves the timing of unmapping at the whim of garbage collection and the subsequent scheduling of the finalizer thread. If you application allocates very little in the way of temporary objects, but uses memory mapping extensively, you will have failures due to address space exhaustion. The garbage collector won't run, because

plenty of Java heap is available for allocation. However, memory mappings fail, because the process's address space is fully consumed by older mappings, many of which would be unmapped if the garbage collector were only to run.

What's worse, the JRE does not, upon address space exhaustion, attempt to run a garbage collection and finalization pass in order to clear out mapped byte buffers that are ready to be cleaned up. Therefore, you may suffer from `OutOfMemoryError` failures, due to running out of address space, despite the fact that many of your mapped regions are actually ready to be unmapped.

The second major problem you may encounter is primarily to be found on Windows platforms. The Windows operating system does not allow a file to be removed from the file system if there are existing memory maps over any part of the file. This, combined with the inability to explicitly unmap a mapping, can lead to a situation where files remain on disk when you no longer need them. For example, this can happen if there is a point in your code where you know the file is no longer necessary, but there exist references from live objects or the stack to the `ByteBuffer` object that represents the memory mapping. Since the `ByteBuffer` facade is not garbage collectible, then its `finalize` method will not be called, and hence the unmapping will not occur.

There is a set of policies you can follow to reduce the likelihood of such problems. First, if possible, you should implement a correlated lifetime pattern for the `ByteBuffer` objects. If these objects become garbage collectible as soon as a phase or request completes, or correlated object is collected, then the `ByteBuffer.finalize` method will be called as soon as possible after that correlated event occurs. Next, you must trap all memory mapping failures, force a garbage collection and finalization pass, and then retry the memory mapping; doing this several times in a loop is recommended. Third, on some versions of the JRE, you will find that a memory mapping failure results in the JRE terminating the process. This was one, by the JRE developers, with the thought that a memory mapping failure was a sign of catastrophic failure. To work around this problem, you can set up a security policy that disables calls to `System.exit`, though you must be careful that your own code does not rely on this call.

The last good design principal, when using memory mapping in Java, is to rely on file-based memory mappings as little as possible. If you need only temporary mappings, then consider using the anonymous mappings described earlier:

```
IntBuffer allocateAnonymousInts(int numBytes) {
   ByteBuffer buffer = ByteBuffer.allocateDirect(numBytes);
   buffer.order(ByteOrder.nativeOrder());
   return buffer.asIntBuffer();
}
```

When using anonymous maps, you must be aware of the default limits on these native allocations. With Sun JREs, you can configure the maximum allowed number of

bytes allocated in this way via the command line argument `-XX:MaxDirectMemorySize`; this option takes the same arguments as the `-Xmx` setting. With IBM JREs, you do not need to specify a maximum value.

Appendix A

A COMPARISON OF SIZINGS ON JREs

TODO: Let's make a clear separation of information readers need to estimate the size of their applications vs. the maximum address space issues. Otherwise the tables will be too large. That will also make the text more problem-oriented. We need three tables:

- Object-level overheads: (32 vs. 64 vs. compressed) x (Sun vs. IBM), showing (object header size, array header size, object alignment size, bytes per reference)
- Field-level overheads, in two parts.
  - a. (type) x (arch) show field alignment
  - b. Show the field-packing rules for each each JRE (may be a bullet list rather than a table)
- Addressable bytes: (Sun vs. IBM) x (OS), showing bytes. Some slots will be blank.

The majority of the body of this book focuses on the Sun 32-bit JRE. This appendix provides supplementary material regarding the sizing criteria used by other JREs, and how various configuration choices affect these parameters.

A.1 Sizing Criteria

Table A.1 summarizes the important sizes that JREs use. These include the number of bytes each reference consumes, the number of bytes each object header consumes, the boundary (in bytes) to which each object allocation is aligned, and the maximum number of bytes a Java application can address. These values vary fairly widely, from one JRE to another.

The value that varies most is the maximum heap size a Java application can use. If you aren't running on a 64-bit JRE, you should exercise extreme caution in

Platform	Bytes per Reference	Bytes per Header	Alignment	Addressible Bytes
IBM zOS 31-bit	4	12	8	1.3GB
Windows 32-bit	4	8–12	8	1.8GB
AIX 32-bit	4	12	8	2.5-3.25GB
Solaris 32-bit	4	8	8	3.5GB
Linux 64-bit	8	24	16	128TB
AIX 64-bit	8	24	16	> 1PB
compressed refs	4	12	8	28-32GB
extended compressed refs	4	12	16	64GB

Table A.1. Sizing information for various platforms.

setting the heap size too high. For example, on a 32-bit Windows platform, if you request a heap size of 1.8GB, then your application will only have a few hundred megabytes of address space left over for native resources. All of your byte code, compiled code, and all of the JREs metadata about classes and the heap, need to fit into this small window. On AIX, if you request 3.25GB of Java heap, the story is similar.

A.2 Compressed references

TODO: This duplicates discussion we have in the Objects and Delagation Chapter. - let's move info that we really need to that chapter, unless it's very detailed. Let's keep the Appendix mainly for reference details.

Provider	Command-line Argument
IBM	-Xcompressedrefs
Sun	-XX:+UseCompressedOops
JRockit	-XXcompressedrefs

Table A.2. Options for specifying that you wish the JRE to use compressed references. This is only relevant for 64-bit JREs.

One potential downside to switching to a 64-bit JRE is an increase in memory consumption. Each reference will consume 8 bytes, and each object header will consume as much as 24 bytes. Luckily, most JREs support *compressed references*. When using compressed references, references and object headers consume as much as they would on a 32-bit platform, which is nice. There are two downsides. One is that the maximum heap size is far lower than it would be with full 64-bit pointers, though still higher than with a 32-bit JRE. For example, the Sun and IBM Java 6 JREs support heap sizes of only up to 32GB; in some cases, the limit is 25 or 28GB. The other downside is a potential, though small, decrease in performance. THe hardware expects 64-bit pointers, but the heap only stores 32 bits. Therefore, each memory operation may require an extra shift operation. Some JREs are clever enough to avoid this expense, if the requested maximum heap size is less than 4GB.

For some JREs, if you are willing to pay a higher memory overhead, then you can support up to 64GB of memory, while still using only 32-bit references. When JREs operate in this mode, each object is aligned to a 16 byte boundary. This may result in an increase alignment overhead, compared to the normal 8-byte alignment. For example, say a `Double` boxed scalar has 8 bytes of data and a 12-byte header. This adds up to 20 bytes. With 8-byte alignment, you will pay 4 bytes for alignment cost. With 16-byte alignment, the alignment overhead is 12 bytes. On the other hand, for a `String` or `Integer`, the alignment costs remain unchanged, whether the JRE aligns to 8- or 16-byte boundaries.

Many JREs will automatically enable this support for compressed references. You should consult the documentation of your specific JRE provider to know whether this is the case.[1]

[1]On Java 7, 64-bit Sun JREs have this enabled by default, as long as your heap size is smaller

A.3 Identity Hashcode in Object Headers

Depending on the JRE, the object header may actually be 4 bytes smaller than indicated in Table A.1. Some JREs leave room for the identity hashcode in the header of every object. The identity hashcode is usually the address of the object. If the garbage collector decides to move the object to another address at some point, then it has to store the original address somewhere. This is necessary so that the `identityHashcode` method always returns the same value, for the lifetme of a given object. The values in the table assume that the JRE preallocates space for this identity hashcode, and so every object pays the expense, even if the object's identity hashcode is never used. Some JREs are clever enough to store the identity hashcode only when it is needed: if it is used, and, even then, only if the object is moved from its original location. The only way you can know whether this is the case is to write a small program that allocates a large number of `Integer` objects. You know how much space you expect the object to consume, based on the 4 bytes of actual data, and the expected header size. Try it, and see how many you can fit, in a given size of heap.

than 32 gigabytes.

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SUBJECT INDEX