Dynamic Lock Dependency Analysis of Concurrent Systems

by

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Chapter 1

Introduction

Since the early days of multiprogramming, programmers have had to deal with the particularly difficult problem of system deadlocks [7]. In any multithreaded system where different threads need to share resources, some form of concurrency control is needed to prevent simultaneous access. Some form of locking scheme is used that inevitably suffers from possible deadlock. A deadlock occurs when a set of threads is stopped because each needs a resource that is held by another. Since none of the resources can be released, the threads in the set cannot continue execution, this usually has the effect of bringing the entire system (whether it be a user program or an operating system kernel) to a halt.

In a well-formed concurrent system, there is an implicit locking order, and concurrency controls are used in such a way so as to make deadlock impossible. In theory this is a simple policy to describe, but in practice it becomes increasingly difficult for large programs. Historically, deadlocks have been difficult to detect[10], because they happen so infrequently and are difficult to reproduce under controlled situations. This is because a thread can execute the same sequence of locking operations a million times over without deadlock before a different thread happens to have the right locks and the right sequence of upcoming actions so as to cause a deadlock. Locks are typically held for very short periods of time, and the scheduling of threads is effectively arbitrary, requiring a very specific schedule to occur between multiple threads in order to produce a deadlock.

The typical approach to finding and determining the source of a deadlock is what's known as a "stress test." In this test, many threads are executed repeatedly over a very long period of time, with the hope that any unlikely interaction will surface by sheer probability during the execution of the test. Once the deadlock occurs, the system can be stopped and the thread states examined in order to determine the source. This is an inefficient means of resolving these bugs.

The program and algorithms outlined in this thesis attempt to address this issue in the field of large concurrent systems. There have been many published strategies concerning deadlock detection and avoidance [8], but the majority of these rely on the fact that the conditions leading to the deadlock must still be produced in order to detect its existence. The main benefit of these algorithms is that they provide a means by which the system can recover before the deadlock is actually produced. Some of these strategies also break down when confronted with the size and complexity of modern concurrent systems. Rather than forcing the programmer to design stress tests (and having to spend time analyzing the resulting state of the system), the method described here attempts to predict the existence of deadlocks without requiring them to occur. This problem of deadlock prediction is significantly more difficult than detecting deadlocks as they occur. Most algorithms require extensive modifications to the programming paradigm [14] [15], an unattractive solution for large systems.

This thesis attempts to define a generic means of deadlock prediction suitable for large and complex concurrent systems. The analysis is not tied down to a specific system, allowing for an independent means of analyzing user programs (regardless of the language in which they are written), as well as operating systems. Existing commercial analysis tools are tightly coupled with the target system [22] [23], preventing the adoption of new systems. The ultimate goal is to design a system capable of predicting deadlocks within the Solaris kernel, a highly concurrent system where traditional methods of data gathering and analysis break down. Once this is achieved, it should be possible to apply the analysis to a variety of other systems, including the Linux kernel and user programs.

Chapter 2

Design Goals

In designing a system for deadlock analysis, there were several goals that needed to be satisfied in order to make the system practical. The overall goal is an extensible, easy-to-use, and efficient program that can be applied to a variety of different target systems.

2.1 No Code Modification

The stated target for this analysis is large, concurrent systems. Presumably, this means that there is already a large, well-established code base. It is impractical to demand any change in the source code, since this would require far too much work. Instead, the program must be able to run on an unmodified system. This is important for operating system kernels and systems built on top of existing frameworks, because the original source code may not always be available. The extraction and analysis of data must be transparent to the programmer.

Some existing systems (especially deadlock avoidance schemes) require extensive changes to the programming paradigm in order to implement them correctly. At the very least it involves recompiling the source code linked with a new library (something impossible for kernels), and at the worst it involves changing the entire locking mechanism upon which the system is built. Tying the program to a specific programming model also constrains the implementation to a certain language and system, destroying its application to alternative systems.

2.2 Negligible Run-time performance

For large systems, there can be tens of thousands of locks, with millions of locking operations performed every minute. In order to keep the system functioning efficiently, the extraction of data must have limited impact on the execution speed of the system. In order to perform deadlock prediction in real time, the past behavior of all threads in the system must be kept, requiring extensive data structures that would consume resources and impact performance.

The goal is to devise a system for which every operation takes constant time, regardless of the number of locks or threads in the system. The simplest way to accomplish this is to have the event data offloaded to some external destination (typically a file) and saved for later analysis. This requires no run-time resources, and has little negative impact on performance. It also offers the ability to operate on non-terminating programs (such as system daemons or operating system kernels), since the event data can be grabbed from the executing system at any point for any period of time. The downside is that the analysis must be performed separately.

2.3 System Independent Analysis

In order to develop an extensible and open system, the analysis tools must be made system-independent. The data gathering tools must be tailored to the individual systems from which they extract data, because the methods are unique to each system. In order to support multiple data sources efficiently, a separate analysis tool cannot be required for each target system. Such a requirement would severely hinder application to novel systems. Since the analysis is identical regardless of the data source, the data sources can be streamed to a file in a source-independent format. These files can then be accessed by any analysis program, regardless of the source of the data. This also allows for data to be gathered from systems (such as embedded systems or custom operating systems) that cannot support the analysis program. The data files can be offloaded onto a larger or more capable machine, reducing the need to port the analysis program to every target architecture.

2.4 Scalable Analysis

Due to the nature of large concurrent systems, the analysis program must be capable of dealing with very large data sets. These data sets can be on the order of a hundred million events (section 8.4). In order to make processing these files practical, the analysis program (which relies on constructing a data structure of an order roughly based on the number of unique events in the input) must be efficient. With large multi-processor systems becoming more common, this means that the program must scale well up to a number of processors. This requires creating the analysis tool as a multithreaded program, choosing proper data structures to minimize time complexity, and providing a fine-grained or lock-free means of accessing common data structures.

Chapter 3

Deadlock Analysis

In the past several decades, a number of solutions to the problem of deadlocks have been proposed. The initial graph theory describing deadlocks has been around since the 1960s [7]. The two main problems with analyzing deadlocks is extracting the necessary data from the system, and formulating it into a mathematical representation suitable for analysis by a program. This chapter outlines several of the main forms of deadlock analysis. There are several approaches to each form of analysis, with some specific approaches described in chapter 4.

3.1 Deadlock Detection

The simplest form of analysis is that of deadlock detection. Whenever a lock is about to be taken, the system determines if taking the lock would cause the system to deadlock, in which case it takes some alternative action. This is usually accomplished by recording the thread that owns the lock and the current state of each thread [14]. Most approaches rely on detecting this type of problem at run-time, since a minimal amount of information is needed in order to determine whether a deadlock will occur. This nevertheless impacts run time performance [5] [1]. This scheme is typically employed on systems where deadlocks cannot be avoided. One common application is database systems, since the database software's developer cannot predict the interactions between records and tables from user queries. Many deadlock detection algorithms have been proposed and implemented over the years in the area of database systems [8].

3.2 Deadlock Avoidance

An extension of classic deadlock detection, this scheme is also commonly used in database systems. It builds on the deadlock detection scheme by allowing for a means of rescheduling or reformatting tasks in such a way so as to avoid a deadlock. Ordinarily, this involves stopping the task about to deadlock and rescheduling it to run at a time when it cannot cause a deadlock. The main problem with this approach is that it requires detailed knowledge of the task structure and the methods in which they can be scheduled. This makes it appropriate for systems such as databases, where the tasks are easily modeled as queries whose execution the database can control. It is generally not suitable for most operating systems, since the developer cannot control the method by which threads are scheduled, destroying its usefulness. Since this method also requires the ability to avoid the deadlock in an appropriate manner, it is significantly more complex than simple deadlock detection.

3.3 Deadlock Prediction

In this method, any deadlock is a bug, since it can bring a part of the system to a grinding halt. This makes sense for operating systems or user programs, where the programmer does not have control over the scheduling of tasks or their interaction. Detecting a deadlock and stopping the offending process is not an acceptable solution, since the stopped thread is completely lost, and most likely the functionality of the system is impaired.

With deadlock prediction, certain actions taken by the program are traced or recorded. These actions are then quantified and modeled so that any possible interactions of all the threads can be produced. In effect, the analysis simulates all possible execution schedules, although this is almost certainly not the most efficient means of detecting a deadlock. If some sequence of actions combined with the appropriate scheduling results in the possibility of a deadlock, then the program reports the source of the problem in as clear a way as possible. It is the responsibility of the programmer to go back to the source code and fix the offending code. The benefit of this system is that it can predict deadlocks without actually having to cause them to occur, finding those which are not immediately apparent to the programmer. Some commercial implementations of this exist [13] [23], but it is a difficult problem, and most available solutions are tied to a particular system.

There is a lot to gain from being able to *predict* deadlocks, since otherwise a programmer will have to stress the system to the point where a deadlock occurs. Post-mortem analysis tools (such as analyzing crash dumps) are then used to determine which threads were the cause of the deadlock, and the source of the dependencies which caused the threads to deadlock. This is a long and difficult process, and prediction allows for a more precise explanation of the source of the problem, without requiring the programmer to cause the deadlock to occur.

3.4 Run-time Analysis

In order to implement deadlock detection and avoidance, it is usually necessary to perform the analysis at run time. In this scheme, metadata are kept whenever a lock is acquired or released. In this manner, whenever a lock is about to taken, it can be compared against the current or past state of other threads to detect the possibility of deadlock. Example uses of run-time analysis are wait-for graphs (section 4.1) and resource allocation graphs (section 4.2). Unfortunately, this metadata does require time and space to maintain, so that locking operations are slowed during execution. The benefit is that the state of the system is immediately available, allowing it to be examined at any point in time.

Since run-time analysis typically runs hand-in-hand with deadlock avoidance and prediction, it is found in the same types of systems. Most commonly found in database systems, run-time deadlock analysis is even implemented in hardware [21] for systems where deadlocks are a regular and unavoidable problem. It is not a suitable tools for operating systems kernels because run-time performance is extremely important, and deadlocks are not expected to occur. Run-time analysis is typically only used for detection and avoidance, because the metadata required to perform deadlock prediction would likely be too great.

3.5 Static Analysis

This is a rather specialized form of deadlock prediction, since it does not require the examination of data from a running application. Instead, the possibility of deadlock is examined through static code analysis. There exist some commercial tools (such as Sun Microsystems' LockLint [23]) that can do this prediction based on source code. The analysis tools compiles code into an intermediate state, searches for lock acquisitions, and theorizes possible interaction between various threads. In this way, a static code set is reduced to a mathematical model, and the model can then be analyzed to see if if it matches the criteria for a deadlock-free system.

Some of the common tools for performing this analysis were outlined by Taylor in [30]. This type of analysis is suitable for detecting deadlocks in most basic programs, but they often break down when faced with the rising complexity of a large concurrent system [29]. This is because, in essence, the analysis must simulate all possible schedules for the entire system. The way this is typically accomplished, through a concurrency history graph [2] or task interaction concurrency graph [34], has a size that grows exponentially with the number of tasks and synchronization operations in the system. In order to combat this situation, some technique must be employed to reduce the system to a manageable size. There have been several attempts to combine static analysis with some sort of run time analysis [31] [2], which have met with limited success. Due to the enormous complexity issue inherent in this system, it is unlikely that it will ever be suitable for performing static analysis of a system such as an operating system kernel, which can have millions of lines of code and thousands of possible tasks. The other problem with these systems is that they are inextricably tied to the system being analyzed, since an intimate knowledge of the compiled source code and possible executions of that code must be known. The advantage of these systems is that they are fairly exhaustive, providing a reasonable guarantee that the system is deadlock-free (at least among those deadlocks that are detectable). They also have the advantage of being extendable, so that other concurrency problems, such as race conditions and unprotected memory accesses, can also be detected within the same framework.

3.6 Dynamic Tracing

In order to remedy the deficiencies of the previous methods, this thesis uses dynamic tracing to serve as a data source for deadlock detection. With dynamic tracing, important events (such as lock acquisitions and releases) are extracted from the system during execution, to be analyzed at a later time. The basic method of analysis by tracing is summarized in [20]. Tracing has the benefit of having very little impact on run-time performance. The data can simply be streamed to some external location for later analysis. The amount of time it takes to perform the analysis at a later date is immaterial when compared to the cost to run-time performance. This is because with large systems, such as an operating system kernel, locking operations occur tens of thousands of times per second. These locking operations are by necessity optimized for the common (non-contention) cases, requiring only a minimal number of instructions to execute. Adding even a minimal amount processing to every lock operation already slows the system down considerably. If the time taken grows with the number of tasks or locks in the system, then the time to execute locking operations will become unacceptably slow, and may affect the usability of the system. If the analysis is performed at a later time, then the amount of time it takes cannot possibly affect the running system. On the other hand, this makes the task of analyzing the system more complex, potentially increasing the overall time needed to perform the analysis. often take a large amount of time.

The actual method by which dynamic tracing is accomplished varies from system to system. Possibilities include specially instrumented code, library interpositioning, or dynamically modified program text. No matter what the method, the resulting event stream can be seen as an independent data source, so that the analysis can be kept separate from the gathering of data. This allows for a more generic analysis tool and does not tie the implementation to a specific system. In this type of analysis, the offending source code paths must still be executed at some point during the trace. The task of the programmer becomes creating a coverage test of as many code paths as possible. The benefit is that this need not be a stress test, since the code paths don't have to be forced to occur at the same time. In the end, dynamic tracing makes for a more extensible and efficient system.

3.7 Distributed System Deadlocks

The problem of deadlocks becomes even more difficult when applied distributed systems. Programs are written to run across many different computers via a network, and locks take on a whole new meaning. Solutions to this problem have been proposed before [32] [8] [18], usually focusing on run time analysis in order to provide a deadlock avoidance scheme for distributed databases. These solutions are typically very complex, since a number of issues (communication between computers, unified time scale, etc.) are not present in the single-system point of view. A full treatment of this subject cannot be adequately expressed in this limited amount of space. With deadlock prediction and dynamic tracing, the entire problem can be side-stepped, assuming that there exists a means by which various events can be coordinated into a universal time line. Given this assumption, it doesn't matter whether the system is distributed or local: the data source can still be analyzed in the same manner. This is a consequence of the separation of data source and analysis tools that is inherent in dynamic tracing methods. Unfortunately, distributed systems are very complex, and as a consequence there was not enough time to adequately explore the problem in this thesis. It remains an open area of possibility.

Chapter 4

Graph Theory

Historically, there have been a number of attempts to model the concurrency constraints of a system. This problem is usually reduced to modeling the lock dependencies of the system, since it is a much simpler problem and accounts for the large majority of concurrency constraints of most systems. The dominant model is graph-based, though the means of constructing the graph and the interpretation of the result varies between approaches. In each case, the goal is to reduce a system to a sequence of operations or statements which can be mathematically transformed into a structural representation suitable for analysis.

At the heart of almost any graph construction is the idea of a "task", an abstract sequence of localized operations. In the ideal sense, a task can be started and stopped as necessary, enumerate resource needs, and rescheduled to run at its beginning by some external entity. In reality, when confronted with large concurrent systems, this idealized task must be broken down into the much more realistic notion of the "thread". A thread has many similarities with an abstract task, but is more constrained. A thread can (and most likely will) perform a variety of disjoint operations in a serialized fashion that otherwise might be logically broken up into individual tasks. Threads can be started and stopped at will in a preemptive system, but not arbitrarily restarted at the beginning of their execution. The task of 'undoing' a thread's execution so that it can re-start at a previous point is difficult, if not impossible, on most systems.

This idealized task can be implemented in database systems and other restricted scenarios. In these cases, a task can be precisely described so that operations can be undone, tasks can be rescheduled, and a variety of other manipulations that make deadlock avoidance possible. For generalized systems, we must abandon this ideal notion and deal only with threads. In large concurrent systems, it becomes impossible to enumerate or anticipate the needs of all threads. Some proposed deadlock detection schemes rely on the fact that the resources for each thread can be presented in a clean, mathematical manner. This makes sense for isolated tasks, but complex threads perform a number of tasks, destroying the usefulness of this method of analysis.

Given these constraints, the problem is reduced to taking an arbitrary sequence of events associated with specific threads and translating them into a graph representation. Once the graph has been constructed, we can use standard analysis tools to detect and identify deadlocks.

4.1 Wait-For Graphs

One of the simplest methods of describing a system's state is the use of a "Wait-For Graph". This type of graph is often used in databases to perform deadlock avoidance. Each vertex is a task in the system, and each edge is an indication that one of the tasks is waiting for a resource held by the other. When a task blocks waiting for a resource, an edge is added between the two tasks. When this resource is later obtained, the edge is removed from the graph, indicating the task is no longer waiting for the resource.

Task t1	Task t2
`Lock(A)`	
	`Lock(C)`
	`Lock(A)`
`Lock(C)`	

produces

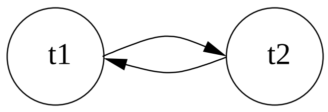


Figure 4.1: Two tasks deadlocked in a wait-for graph

Consider the sequence of operations presented in Figure 4.1. When task $t2$ attempts to take lock A, the system identifies that such an operation will cause $t2$ to block waiting for $t1$, since $t1$ is the current owner of the lock A. This causes the edge $(t2, t1)$ to be added to the graph. When task $t1$ attempts to take lock C, $t1$ blocks waiting for $t2$ and the edge $(t1, t2)$ is added to the graph. This is a simple example of a system deadlock. Deadlock detection and avoidance systems determine if adding an edge would create a cycle within the graph, at which point a deadlock will result. The action taken depends on the particular approach, but usually the offending task is rescheduled to run at its beginning at some later time. The limitation of this approach is that it is suitable only for run-time analysis. The graph represents the state of the system at a single point in time, as edges must be removed when the resource is acquired. The consequence is that it is incapable of predicting deadlocks. The events leading to the deadlock must still be executed in the appropriate sequence to cause the deadlock, the exact problem that deadlock prediction seeks to avoid.

4.2 Resource Allocation Graphs

This type of graph is an extension of the wait-for graph. It was first described by Holt in [11], though in a more generic form than is commonly used today. Most modern locking systems can be described, in Holt's terms, as a single-unit reusable resource system. A more complete introduction to this subject is given in [28]. The main benefit of this type of graph is that it provides more information about exactly which resources are involved in the deadlock, and separates the notion of processes and resources. It also allows for semaphores (section 5.1) by allowing multiple units of each resource. In this system, there are *resource* and *thread* nodes, represented by squares and circles, respectively. When a resource r is requested by a thread t, the edge (t, r) is added to the graph, indicating that the thread is blocked waiting for the resource. When the resource is acquired, then the edge (t, r) is removed, and the opposite edge (r, t) is added to the graph. When the resource is released, the edge (r, t) is deleted. The result is shown in figure 4.2.

Task t1	Task t2
`Lock(A)`	
	`Lock(C)`
	`Lock(A)`
`Lock(C)`	

produces

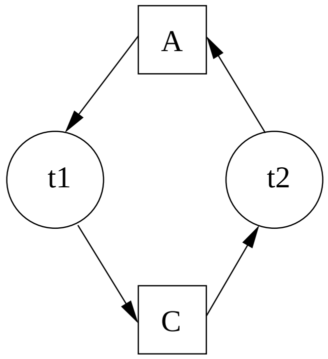


Figure 4.2: Two tasks deadlocked in a resource allocation graph

In this case, the edges $(A, t1)$ and $(C, t2)$ indicate that the locks are held by the respective threads, and edge $(t2, A)$ indicates that thread $t2$ is waiting to acquire lock A. When thread $t1$ attempts to get lock C, the edge $(t1, C)$ is added, and the system deadlocks. The method of analysis and actions taken are similar to that of the wait-for graphs. If a cycle would be formed by adding an edge, then a deadlock will occur. Note that if we allow multiple unit resources (as with semaphores), then the correct detection of a deadlock requires that a knot exists [11], a more stringent restriction than simply a cycle. The same drawbacks from wait-for graphs still apply to this system, most notably that it can only represent the system at a given point in time, and still requires the deadlock to be produced in practice. This system also does not correctly describe reader-writer locks (section 5.2). The advantage is that semaphores are modeled correctly, and that individual locks are part of the cycle, so more information about the deadlock can be extracted.

4.3 Historical Dependency Graphs

In order to provide a means for performing true deadlock prediction, the approach adopted in this thesis is that of historical dependency graphs. The main advantage of this type of graph is that it represents dependencies *over the course of the entire program.* This allows us to theorize possible interactions of different threads, even if these interactions did not actually occur during the course of the program's execution.

The first conceptual difference from the previous graph types is that nodes represent resources. Threads are considered a transient phenomenon, and provide an inadequate method for predicting deadlocks over the lifetime of the program. A deadlock is instead reduced to the fact that if the currently running thread is to deadlock, it owns a resource needed by another thread and it is in a state where it cannot release the lock. Since we assume that a thread can only be stopped due to resource contention (section 4.4), this implies that it is blocked waiting for some other resource owned by a thread that can't release it. An edge $(r1, r2)$ indicates that at some point during the program's execution, lock $r2$ was owned when lock $r1$ was taken. This is the dependency modeled by the graph. Any number of threads may generate this dependency (identifying the source of the dependency is outlined in section 4.6), and it can occur many times during the course of the program. No matter how many times it occurs, it is represented by a single edge in the graph. The important fact is that the dependency exists, not how many times it occurred.

In order to generate such a graph, data needs to be processed in a time-ordered event stream, where each event is associated with a given thread. Each thread maintains a list of all currently held resources. When a thread acquires a new resource, a dependency is added (if it doesn't already exist) between the new resource and all currently held resources. When a resource is released, it is removed from the thread's list of currently held locks. During the course of the system's execution, every possible dependency is recorded in the graph. This is shown in figure 4.3.

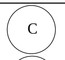
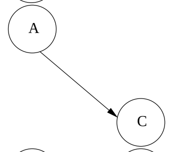
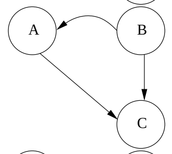
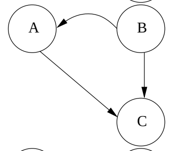
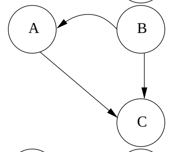
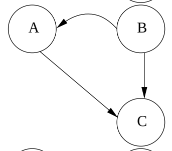
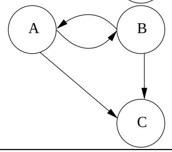
Thread t1	Thread t2	Graph
`Lock(C)`		
`Lock(A)`		
`Lock(B)`		
`Unlock(B)`		
`Unlock(A)`		
	`Lock(B)`	
	`Lock(A)`	

Figure 4.3: Three locks in a historical dependency graph

Note that the threads do not deadlock in the situation shown here. But given the right circumstances, there is potential for a deadlock in this schedule. It is possible for thread $t1$ to hold locks

A and C and thread $t2$ to hold just B, at which point both threads will deadlock. This schedule is shown in figure 4.4. The main benefit is that this deadlock didn't actually have to be created in practice. These two threads could have run at vastly different times so there was no possibility of deadlock. Implicit in the assumptions about concurrency (section 4.4) is the fact that these threads could have been scheduled to run in such a way as to cause a deadlock.

Thread t1	Thread t2
`Lock(C)`	
	`Lock(B)`
`Lock(A)`	
`Lock(B)`	
	`Lock(A)`

Figure 4.4: Basic deadlock schedule

The second feature of the graph is that the deadlocks are reduced to dependencies between locks, rather than processes. It doesn't matter how many processes acquire A and then B; all that matters is that somewhere this dependency exists. The fact that lock A is taken in between locks C and B does not diminish the fact that there exists a dependency between B and C.

4.4 Concurrency Assumptions

In order to make the structure and analysis of the graph correct, it is necessary to make several assumptions about the concurrent nature of the system being analyzed. The first assumption is that it is a preemptive system with some type of pseudo-arbitrary scheduler. Any sequence of events can be preempted, allowing any number of other threads to execute. In reality, there are scheduling constraints on many systems, such as thread priorities and realtime threads. Even with threads of different priorities, priority inversion (where a lower priority thread is temporarily raised because it owns a resource needed by a higher priority thread) can induce a different schedule. In the general case, the schedule is effectively arbitrary. The implication is that there is no sequence of locking events that can be considered atomic. If there are such operations in the system, then it the responsibility of the data source to model these operations as a single locking operation.

The second assumption is that there can be any number of threads running the same procedures at any time. In many systems, there can be only one thread that executes a certain sequence of operations. For highly concurrent systems such as those that we are trying to model, we assume that this is not true. The only time when this can cause inconsistencies in the data is when a thread is predicted as causing a deadlock through some scheduling interaction with itself. This is already an unlikely case, and is usually easily identified by the programmer as not a deadlock. Since the number of these threads is very small, and the chances of the deadlock occurring with the same thread are unlikely, this is a valid assumption. The alternative, detecting when multiple copies of the same thread are running at the same time, is impractical and reduces the scope of the deadlock predictions.

The final assumption is that locks are released from the same thread that acquired them. This is the case with any well-organized locking scheme, so it should not be an issue with the majority of systems. If a lock release is missed because it was recorded as happening from another thread, then the original lock will still be assumed to be held, and false dependencies will be created for each new lock acquired. If, for some reason, the locking strategy allows for this sort of behavior, it is up to the data gathering source to ‘spoof’ the holder of the original lock in order to make it seem like it was released from the original thread.

4.5 Deadlock Detection

Detecting deadlocks in a historical dependency graph is a relatively simple process. A deadlock is identified by a cycle within the dependency graph. This can already be seen with the example in figure 4.3, but a more interesting example with three threads is shown in figure 4.5. Note that in this figure, the notion of a universal time line is not shown in the interaction of the three threads, since we assume that the individual events can happen at any point. This particular deadlock is very difficult to produce in practice, but shows up as an easily detectable cycle in the dependency graph.

Thread 1	Thread 2	Thread 3
`Lock(A)`	`Lock(B)`	`Lock(C)`
`Lock(B)`	`Lock(C)`	`Lock(A)`

produces

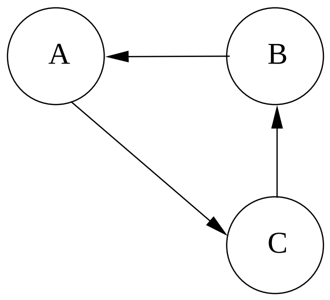


Figure 4.5: Three way deadlock in a historical dependency graph

This analysis depends on several assumptions, and only detects the possibility of a deadlock. Given our assumption of maximum concurrency, for any given edge $(r1, r2)$, we have to assume there can be a thread that owns lock $r2$ and is waiting for $r1$. This assumption generalizes to an arbitrary path in the graph. For any path P, it can then be assumed that for any vertex P_i, there can be a thread that owns lock P_{i+1} and is waiting to acquire lock P_i. If the same lock appears twice in a path, it is possible to have threads blocked on each intermediate vertex, but unable to continue because the first thread is (by the transitive nature of dependency) blocked waiting for itself.

These assumptions made by the analysis can falsely identify deadlocks in theory, though they are correct for nearly all deadlocks typically found in practice. For one thing, the assumption that there can be multiple threads running the same code at a given time is not always true. This means that conflicting actions taken by a single thread can be erroneously identified, as in figure 4.6.

If there are two threads running this same code, then there is the potential for the two threads to deadlock. If there is no other thread contending for both A and B at the same time, and this

Thread
`Lock(A)`
`Lock(B)`
`Unlock(A)`
`Lock(A)`

produces

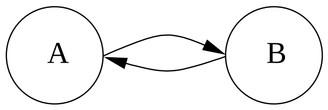


Figure 4.6: Potential deadlock misidentified

is the only thread in the system that executes this code, then there is no possibility of deadlock. In reality, most concurrent systems can have any number of threads running the same procedures, which is especially true of kernel code. Additionally, this can still deadlock if another thread ever takes both A and B, regardless of the order.

Another possible scenario is one in which the offending actions are enclosed by some higher-order locking principle, which may either be a lock in the system, or some interaction not capable of being described by the data source. For example, consider the two different cases in figure 4.7.

Thread 1	Thread 2
`Lock(A)`	`Lock(A)`
`Lock(B)`	`Lock(C)`
`Lock(C)`	`Lock(B)`

Thread 3	Thread 4
`Lock(A)`	`Lock(A)`
`Lock(B)`	`Unlock(A)`
`Lock(C)`	`Lock(C)`
	`Lock(B)`

both produce

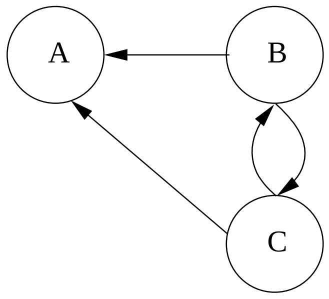


Figure 4.7: Identical graphs from different sources

If no other threads ever lock both B and C, then there can never be a deadlock between threads 1 and 2. This is because the common lock A is needed in order to acquire both of these locks, superimposing a critical section on their access. This enforces an artificial scheduling constraint that is not detectable during graph construction. The interaction of threads 3 and 4, however, does allow for a deadlock. The difference is that the scheduling constraint has been removed. In either case, a potential deadlock will be reported, and it is up to the programmer to discern between the two different cases. In reality, it is unlikely to see the first situation, because with the overarching critical section lock, there is no reason to lock B and C in the opposite order. It is also unlikely that both B and C are never acquired anywhere else. While it cannot deadlock, this behavior should not occur in a typical system.

4.6 Metadata

Since the nodes of the graph are only resources, the original information about where the dependencies were generated in the system is lost. From the basic form of the graph, it is impossible to tell where or when the original events occurred, only that they happened in such a way as to generate the edge dependencies. Unlike the wait-for graphs and resource allocation graphs, which allow the system to stop processes in real-time as they are about to cause a deadlock, the deadlocks predicted by this scheme don't occur. In order to analyze deadlocks effectively, we need to be able to identify all possible sources of each dependency involved in the cycle. This means that additional metadata must be kept in the graph in order to make identifying the deadlock useful. This is done by associating some sort of snapshot of the current thread (typically in the form of a stack trace) with each locking event. When a new lock is added to the list of currently held locks, the point at which is was acquired is remembered by the graph construction system. Whenever a dependency is created, the construction algorithm checks to see if the pair of events created by the newly acquired lock and the previous lock is associated with the given edge. If not, then this pair is attached to the edge, so later it can be used to determine how the dependency way generated. For example, consider figure 4.8.

Thread t1	Thread t2
1 `Lock(A)`	1 `Lock(B)`
2 `Lock(B)`	2 `Lock(A)`
3 `Unlock(B)`	3 `Unlock(A)`
4 `Lock(B)`	4 `Unlock(B)`
5 `Unlock(B)`	
6 `Unlock(A)`	

produces

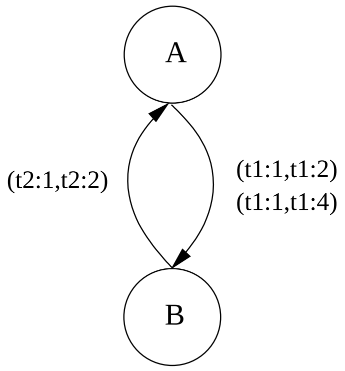


Figure 4.8: Metadata kept during graph construction

In this example, the *lock event pairs* are shown next to each edge in the graph. The first element of the pair is where the first lock (the destination of the edge) was acquired. The second element is where the second lock (the source of the edge) was acquired. Note that in this example, the data that is attached to each event is the owning thread and line number in the example source. In a real system, this would be a stack trace detailing exactly where the event occurred during execution. Also note that there can be more than on pair of events associated with each edge, as demonstrated with the edge (A, B). In this case, that dependency exists in two different places, but there is only one edge. Each edge can therefore have any number of these lock event pairs. Once a cycle is found, these lock event pairs are used to display the source of the dependency to the programmer in a meaningful way.

Chapter 5

Locking Specifics

In the abstract sense, a historical dependency graph represents dependencies between resources shared by different threads. The only required features of these resources is that there is a potential for the requesting thread to be stopped when an attempt is made to acquire the lock. Traditionally, this is represented as a a mutually exclusive lock which can be owned by only a single thread. If a thread tries to acquire a lock that is held by another thread, it will be stopped until such a time when it can acquire the lock.

This view describes only the most basic locking mechanisms that are present in modern systems. There are different primitives, methods of accessing them, and ways in which events can be modeled as locks. Up until this point, the locks have been dealt with as abstract named resources. In this chapter the specifics of how real world implementations of various locking ideas can be translated into the appropriate resource-dependent form needed to construct the graph. Example functions are shown for the C language using the POSIX threads library, the Linux kernel, and the Solaris kernel.

5.1 Mutually Exclusive Locks and Semaphores

The most basic lock is a mutex. The mutex is a specific form of the semaphore, which allows for an arbitrary number of threads to have access to the resource at the same time. The mutex is a semaphore that allows only a single owning thread. Regardless of the number of threads that are allowed access to the mutex or semaphore, it is presumed that any operation can block if there enough owners of the resource, or else why have a lock at all. The common functions used to manipulate these primitives are shown in table 5.1. Note that for kernel implementations (and newer POSIX implementations), there are two types of locks, adaptive locks and spin locks. With spin locks, the thread does not actually get suspended by the scheduler, it merely waits until the lock is free, tying up the processor upon which it's scheduled until the lock is released. This is equivalent to being blocked, because it is assumed that if the system is using spin locks, then it is a multi-processor system or code executing in user mode. Other threads will still be capable of running, and the controlling process will behave exactly as if it were stopped. This functionality has been added to

POSIX threads in the IEEE 1003.1-2001 standard [12].

	POSIX	**Linux Kernel**	**Solaris Kernel**
Lock	`pthread_mutex_lock`	`down`	`mutex_enter`
	`pthread_spin_lock`	`spin_lock`	`lock_set`
			`lock_set_spl`
Unlock	`pthread_mutex_unlock`	`up`	`mutex_unlock`
	`pthread_spin_unlock`	`spin_unlock`	`mutex_destroy`
		`spin_unlock_wait`	`lock_clear`
			`lock_clear_splx`

Table 5.1: Common mutex and semaphore locking functions

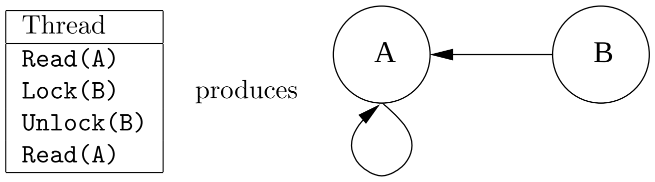
5.2 Reader-Writer Locks

An extension of the basic semaphore is that of the reader-writer lock, in which there can be multiple readers that hold the lock, but only one writer. If there are no waiting writers, then a read attempt will immediately acquire the lock, regardless of how many other readers currently own the lock. If a thread owns a write lock, or is blocked waiting for a write lock, then the read attempt will block until the writer has released the lock. A write attempt will block if any thread owns the lock (regardless of the type of lock currently held). This type of lock is simple to integrate into the dependency graph based on our assumptions about concurrency. Given a reader-writer lock, any write attempt can always block. In a highly concurrent system, we assume that at any given point in time there may be a writer that owns the lock, or is waiting to acquire it. This means that any read attempt can also block. Therefore, any operation, whether a read attempt or a write attempt, has the possibility of blocking. The common functions to manipulate these locks are shown in table 5.2. Note that the POSIX functions are not part of the original standard, but the IEEE 1003.1-2001 standard [12].

	POSIX	**Linux Kernel**	**Solaris Kernel**
Lock	`pthread_rwlock_rdlock`	`down_read`	`rw_enter`
	`pthread_rwlock_wrlock`	`down_write`	
Unlock	`pthread_rwlock_unlock`	`up_read`	`rw_exit`
		`up_write`	

Table 5.2: Common reader-writer lock functions

Since read lock can always block, the analysis catches the common bug of recursively acquiring a read lock. Under normal circumstances this will have no effect, since the second read lock will silently succeed. Typical implementations do not keep track of which threads own read locks, only the number of active readers, so it is impossible to tell if a thread that is attempting to acquire the lock already has a read lock. If an intervening write request were to occur, the thread would deadlock with itself when it attempted to get another read lock. The writer will also be blocked waiting for the the original thread to release the read lock, resulting in a deadlock. This situation is shown in figure 5.1. Note that there is a cycle between lock A and itself.



Thread
Read(A)
Lock(B)
Unlock(B)
Read(A)

Figure 5.1: Recursive reader-writer lock

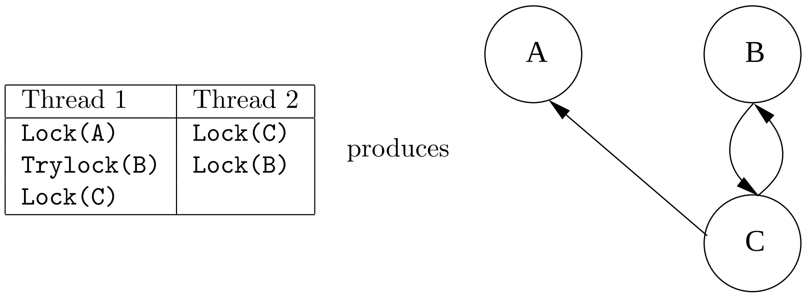
5.3 Non-blocking Locks

In most locking systems, locks can be acquired by methods that do not block. These functions attempt to acquire the lock (sometimes continuously for a given time period), but if they are unable to acquire the lock, then they return to the calling function with a status code indicating that the lock could not be obtained. The common functions are shown in table 5.3. These functions present some difficulty because they cannot possibly be a point of deadlock, since the thread cannot block while waiting for one of these functions to complete. It is possible for future events to depend on the lock being owned, however.

POSIX	**Linux Kernel**	**Solaris Kernel**
`pthread_mutex_trylock`	`down_trylock`	`mutex_tryenter`
`pthread_spin_trylock`	`spin_trylock`	`lock_try`
`pthread_rwlock_tryrdlock`		`rw_tryenter`
`pthread_rwlock_trywrlock`		

Table 5.3: Common non-blocking lock functions

In order to deal with this problem effectively, non-blocking acquisitions have to be identified in the data source. When one of these events is processed, the target lock is added to the thread's list of currently owned locks, but no dependencies are created to currently held locks. By adding it to the known lock list, subsequent locking events will still create dependencies to the non-blocking lock. This is outlined in figure 5.2. Note that there is no dependency between B and A, but there still is the possibility of a deadlock between B and C, even though B is acquired in a non-blocking fashion.



Thread 1	Thread 2
Lock(A)	Lock(C)
Trylock(B)	Lock(B)
Lock(C)	

Figure 5.2: Non-blocking locks

5.4 Interrupts as Locks

In a operating system kernel, interrupts play a crucial role in the system. Their asynchronous nature makes them difficult to analyze, especially in highly preemptive kernels such as Solaris, where locks can be taken at raised interrupt levels.

In an operating system, an interrupt is an asynchronous signal passed to the kernel, usually from a hardware device (although software interrupts are also possible). Each interrupt is associated with a number, called the *interrupt level.* There can be any number of different interrupt levels depending on the processor and operating system. The Solaris kernel (on SPARC platforms), for example, has 15 interrupt levels. When an interrupt occurs, the operating system passes the interrupt off to a special handler for that level. The mechanism used to accomplish this differs from system to system, but the mechanics do not affect the theory. In order to prevent multiple interrupts of the same level from occurring at the same time, each processor maintains the notion of the current "interrupt priority level," or IPL (also sometimes abbreviated PIL, processor interrupt level). When the IPL is set to a non-zero level, then no interrupts of an equal or lower level will be serviced on that processor (they are instead queued and handled when the IPL is later lowered). If the IPL is 10, then no interrupts of levels 1-9 will be serviced. When an interrupt is handled, the IPL is automatically set to the level of the current interrupt. One important fact about the IPL is that it is local to a specific processor. In a multiprocessor system, one processor may have an IPL of 10 and therefore be incapable of servicing interrupts below that level, while another processor may have an IPL of 0, and can still receive interrupts.

By themselves, interrupts do not present much of a problem in the area of deadlock prediction. Interrupts can be modeled as traditional threads, since the interrupt handler's execution can be seen as a very short lived thread. The actual mechanics of executing an interrupt handler are somewhat tricky, since it involves borrowing the current stack from whatever thread is executing. Under the Solaris model when an interrupt handler blocks on a synchronization primitive, it is converted into a full-fledged thread. This means that they can be analyzed in the same fashion as any other threads in the system. Because of our concurrency assumptions, there is no difference between an interrupt thread and a normal thread.

Function	**IPL Required**
`biowait()`	7
`cv_timedwait()`	10
`kmem_alloc(KM_SLEEP)`	7

Table 5.4: Interrupt-Dependent functions in the Solaris kernel

This situation becomes complicated with the introduction of interrupt-dependent functions. There are various functions throughout the kernel that implicitly require interrupts of a certain level to be serviced in order for the function to complete. Some of these functions are shown in table 5.4.

For example, the `biowait` function is used to wait for binary I/O operations to complete. In order to do this, the hardware device being used (whether it be a network card or a hard disk) signals the operating system that the operation is completed via an interrupt. The kernel then runs the appropriate handler (which can be at an IPL of up to 7), which calls the I/O completion routines that signal the caller of the `biowait` function that the operation is complete. Until this interrupt is received, the caller of `biowait` is effectively blocked, though it is not blocked on a traditional synchronization primitive. If the processor cannot service interrupts of level 7 or below, then the function will never return, and the thread will stop. If an interrupt handler of level 7 or higher is blocked on a resource that it cannot get (perhaps because the thread calling `biowait` holds it), then the system is deadlocked, since the interrupt handler can never complete. This example is shown in figure 5.3.

Thread	Interrupt Handler	Notes
`Lock(A)`		
	Receive Level 10 Interrupt	IPL is now set at 10
	`Lock(a)`	Interrupt Handler now blocked (IPL remains at 10)
`biowait()`		Requires interrupts of level 7 in order to return
blocked	blocked	Level 7 interrupts cannot be received; system is deadlocked

Figure 5.3: Deadlocked on the `biowait()` function

Similarly, the there is a special clock handler that runs at IPL 10 on a regular basis and performs various routine tasks. One of the additional synchronization primitives that hasn't been mentioned yet is the condition variable. A condition variable isn't like most other synchronization primitives, in that it is not something that is owned or acquired by a thread. Instead, a thread waits for a signal to be passed from another thread via the condition variable. One of the methods of accessing these primitives is through the use of a function with a timeout. If no signal is received within the timeout period, then the function returns anyway indicating that it did not receive a signal. The condition variables in the kernel are implemented around this clock handler when trying to do a timed operation. If `cv_timedwait` is called, then the clock handler must be able to run in order to signal to the calling function that the given timeout has expired. Otherwise, the function will never return (unless the condition variable is actually signalled), and the purpose of the function will be destroyed. This is not truly a deadlock in any traditional sense, since it is still possible for the condition variable to be signalled from another thread, but until this point, the clock interrupt handler will be unable to run and the whole system will be impaired.

The most complicated example, and the most difficult to produce in practice, is if `kmem_alloc` is called with `KM_SLEEP`. This is what is called a *sleeping allocation*. This informs the memory system that if there is no memory available, then the thread should be put to sleep until such a time as more memory can become available. In a system using virtual memory (which is almost all modern operating systems today), memory is divided up into larger chunks called *pages*. These pages can be brought into physical memory or written to disk as needed, so that the system can appear to have more memory than is physically available. In order to free up memory, the pages of memory must be written out to a *backing store*, which is usually a file or disk partition somewhere, to be recalled at a later date if necessary. In a memory-stressed system, a special process known as the pageout daemon is responsible for maintaining an adequate amount of free space. In order for this process to write data to the backing store, the I/O completion routines (`biowait`) need to be able to run, which implies that interrupts of level 7 need to be serviceable. If these interrupts cannot be handled, then the system will not be able to free up any memory, and any sleeping allocations will cause the calling thread to block. This is shown in figure 5.4.

Thread	Pageout Daemon	Interrupt Handler	Notes
`Lock(A)`			
`kmem_alloc(KM_SLEEP)`			There is no physical memory available, wait for more
	Write page to disk		An inactive page of memory is chosen
		Level 10 Interrupt	IPL is now set at 10
		`Lock(A)`	Interrupt Handler now blocked (IPL remains at 10)
	`biowait()`		Level 7 interrupts are needed for this function to return
blocked	blocked	blocked	Level 7 interrupts cannot be received; system is deadlocked

Figure 5.4: Deadlocked on the `kmem_alloc()` function

Whenever one of these functions is entered, the thread is put to sleep until an external source (an interrupt handler) is able to signal that an appropriate condition is satisfied. In this way, these functions can be interpreted as sleeping on a condition variable and signalled from an interrupt handler, although the actual mechanics are very different. The key fact is that in order for the waiting thread to be signalled, the IPL of the system must be able to drop below a certain level so that the needed interrupts can be serviced. To translate this fact to the graph model, whenever one of these functions is called, the system acquires a pseudo-lock for the needed interrupt level and immediately releases it, generating dependencies to all of the currently held locks. When an interrupt thread runs, it first "acquires" the pseudo-lock for the current interrupt level, and releases it when the handler is finished. In this way, if an interrupt handler becomes blocked, it will be unable to release the pseudo-lock, and any interrupt-dependent functions will be unable to acquire it, resulting in a simulated deadlock. So if a thread acquires a lock and calls an interrupt-dependent function, and that lock is also acquired by some interrupt handler at an IPL greater than or equal to the needed interrupt level, then the system can deadlock (as seen in figures 5.3 and 5.4. This is only noticeable on single-processor systems, since in a multiprocessor system the needed interrupts will still be serviceable on another processor. It is still possible to have this effect on a multiprocessor machine given the right circumstances, though it is much more unlikely.

In order to make the analysis robust, each interrupt level is modeled as depending on the next lower interrupt level being "owned". If a processor is at IPL 7, it implies that interrupts of level 7 and below (by transitive dependency) are unserviceable. This is done at the beginning of the data set by means of implicit dependencies - arbitrary relationships that do not actually appear in the data itself.

One common example in the Solaris kernel is with `kmem_alloc` and the interactions of the clock handler, as described previously. The clock handler runs at IPL 10, and acquires the process lock (`p_lock`), among other locks, in order to calculate process usage statistics. Therefore, if a thread acquires `p_lock` and then does a sleeping allocation (with `KM_SLEEP`), this could potentially deadlock the system in heavy-memory situations. This particular bug is extremely difficult to produce in practice, often requiring runs of many days in order to produce. By modeling the interrupts as locks, the deadlock can be found simply by running a coverage test once. This example is shown in figure 5.5. Note the implicit dependencies between the various interrupt levels.

Thread	Clock Interrupt

`Lock(p_lock)`
`biowait()`
	`Lock(p_lock)`

produces

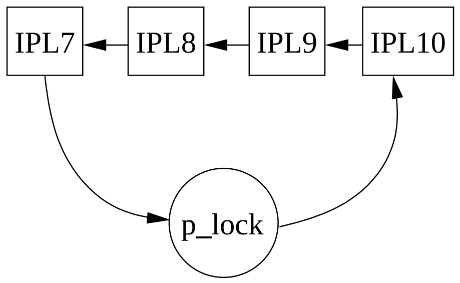
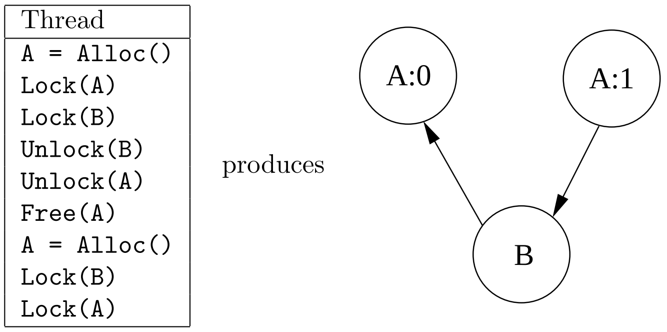


Figure 5.5: Interrupt-Dependent Functions

5.5 Dynamic Memory

In almost every system, dynamic memory allocation is used for some data structures. For most concurrent systems, these data structures typically contain synchronization primitives in order to share the contents of the data structure. This presents a problem, since the memory address (whether virtual or physical) is not sufficient to uniquely identify a lock in the system over the course of the entire execution. Two logically independent locks may end up sharing the same physical address at different points in time, depending on the way in which they are allocated. One method of avoiding this situation is to keep track of lock allocations and deallocations at run-time, and then assign unique IDs to each lock regardless of the address used. Without extensive modifications to the programming interface (a violation of the stated design goals), it would require maintaining a large amount of metadata at run time. This would affect the runtime performance in an unacceptable way.

In order to deal with this situation, each lock is referenced by a memory address, and then a separate "generation count" is maintained while the graph is being built in order to differentiate between logically different locks sharing the same address. In order to determine when the generation count must change, any events which free a range of memory are recorded in the event stream. The runtime gathering tools are not responsible for detecting whether these events actually affect any locks. While the graph is being constructed, a global list of all known locks is maintained, including their generation counts. When a memory free event is processed, this global list is checked to see if any known locks fall within the specified range. Each of these locks is then checked to see if it has been accessed since the last time the generation count was updated. If there were no events using the lock, then the lock is 'clean', and there is no need to update the generation count. If the lock is dirty, then the generation count is increased by one, and the lock is marked as clean. Whenever any lock is used, it is internally translated to a (address, generation) pair according to the global table before it is passed on to the rest of the graph construction algorithm. This is shown in figure 5.6.



```
Thread
A = Alloc()
Lock(A)
Lock(B)
Unlock(B)
Unlock(A)
Free(A)
A = Alloc()
Lock(B)
Lock(A)
```

Figure 5.6: Dynamically allocated locks

This assumes that the lock A is an address returned from a dynamic allocation routine, and that the second time the routine returns the same address just freed. If the address was the single identifying characteristic of a lock, then this would be misidentified as a deadlock. Notice that the second time the lock is used, the generation count has increased.

Under most systems, it is possible for a programmer to release memory for a lock while it is still locked. In general, this is poor programming practice, but it doesn't mean that it can't happen. In order to combat this lazy programming style, it is necessary to 'spoof' the release of any lock that is freed in a locked state. Unfortunately, the multithreaded way in which the graph is constructed (section 7.1) makes it impossible to know whether a lock is being held at the time the free event is processed. The solution is to spoof a release event for the given lock on every known thread in the system. Since a release event does nothing if the lock isn't currently held, this does not affect the correctness of the construction.

Chapter 6

Gathering Data

Since the analysis of the dependency graph is independent of the system that was used to produce the data, the analysis program can be kept separate from the data gathering program. This creates a cross-platform, source-independent system for analysis of potential deadlocks. The program can be deployed on a large variety of systems, such as user programs on various operating systems, operating system kernels, and distributed systems. The locking events are streamed to a common file format, which is then fed to the generic analysis program in order to construct the graph. This chapter details the structure of this file, and the different data sources that can be used.

6.1 File Format

In order to make generic analysis possible, the locking events must be streamed to common data file format. The basic format is a time-ordered sequence of generic locking events. Since we are dealing with potentially very large data sets (on the order of hundreds of millions of records), a compact binary form is needed. While it may be more portable to use a text-based standard such as XML, this would make the file extremely large and severely cripple the speed at which the file could be processed. The binary format is made slightly more complex by the fact that the primitives in the system (locks, threads, and symbols) are not a fixed size, and can vary from system to system. The records are all variable sized, and a header at the beginning of the file indicates the size of each primitive type. These primitives are logically limited to sizes that are a multiple of 4 bytes, since we are typically dealing with addresses. This restriction could be removed at the expense of more complex processing code. In order to indicate what the primitive sizes are, there is an initial header at the beginning of every file, shown in figure 6.1.

Magic Number	Version Number
Lock ID Size	Thread ID Size
Symbol Size	Endianness

Figure 6.1: File information header

The magic number is used to identify that the file is actually a data file, and the version information is used to match the data file to the appropriate analysis program. The endianness flag determines whether the data in the file is stored in big endian (most significant bit first) or little endian format. The analysis program can convert between the two during processing, but if the data is in the native system's endianness this translation can be avoided. The remaining fields of the header describe the size of each of the primitives used in the system. These primitives are described in further detail in section 6.2. After this general header is any number of variable-sized records.

6.2 Source Independent Records

Each record contains some information about the nature of the lock event, and is built from three locking primitives. These primitives are an abstract value that are used to identify resources in the system.

- **Lock ID** - This uniquely identifies a lock in the system (discounting different generations of the same ID). For user programs this is the virtual address of the lock in the program's memory. For operating system kernels, this can either be a virtual address or a physical address, depending on how the kernel address space is setup. For more complicated systems (such as distributed systems), a more complex scheme could be devised. Note that it is assumed that locks are laid out linearly in the ID space, so that when a generation count increment event (freeing of dynamic memory) occurs, it will update the generation counts of of all locks sharing IDs in the given range.

- **Thread ID** - A unique identifier for a thread in the system. Most locking events are associated with a given thread, so each thread needs to have a unique identifier throughout the execution of the system. For a user program using POSIX threads, this is the identifier returned from the `pthread_self()` call. For a kernel, it is often not enough to use the address of the thread structure in kernel memory to identify the thread, since this must be unique across the lifetime of multiple threads. For the Solaris kernel, the only appropriate value to use is the `t_did` field of the `kthread_t` structure, since it is guaranteed to be unique across the life of the entire system.

- **Symbol** - Certain locking events can have symbols associated with them. This sequence of symbols is used by the programmer to identify where in the program the event occurred when the deadlock is later examined. These symbols are typically translated into symbolic strings, which are easier to understand than the numerical values. For most systems, a symbol is an address in the stack trace of a call. This address is translated into a string representing the (symbol,offset) pair that the programmer can then use to determine where in the source code the event occurred.

With these primitives, all possible locking events can be appropriately modeled. Some of these records correspond to actual locking or memory events during the execution of the program, and

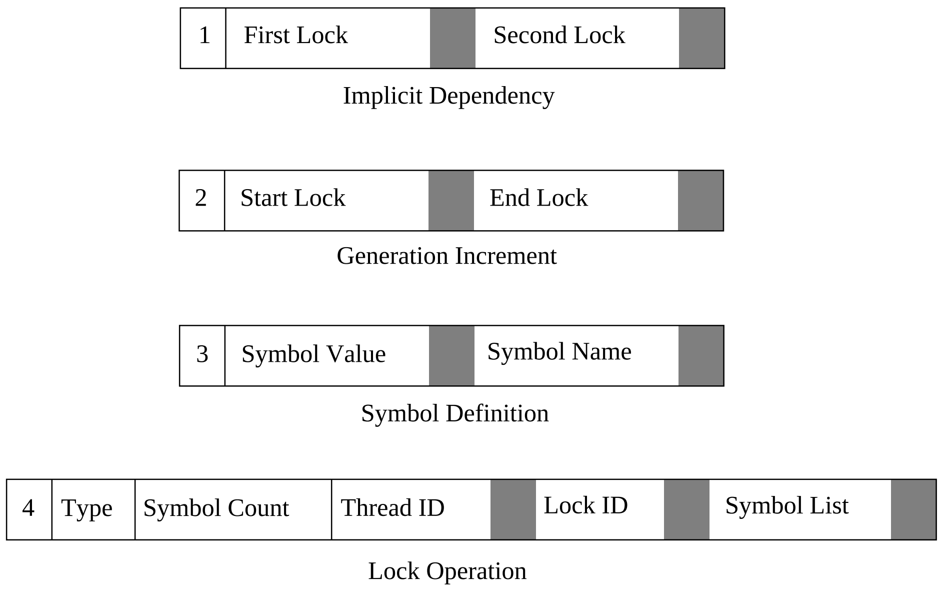


Figure 6.2: Record types

other records are external to the execution of the program, and affect implicit dependencies or the symbol table. The structure of each record is shown in figure 6.2. The gray dividers indicate variable-sized fields. A more detailed description of each record type follows.

- **Implicit Dependency** - This is a special record that sets up an absolute dependency between two locks in the graph. This dependency is not associated with a particular thread or point in time. Normally, these implicit dependencies are used at the beginning of the data source to describe a relationship that is not present in the data. An example of this is modeling interrupts as lock, as described in section 5.4. The only fields in the record are two lock IDs, where the second depends on the first.

- **Generation Increment** - A record indicating a memory free event. This event is not associated with a thread, since the lock ID space is shared by all threads. It still must be ordered in time with the rest of the events, since it affects the generation count of all subsequent locks. The two fields of the record are the starting and ending lock IDs which denote the range of memory to check for changes to generation counts. See section 5.5 for more information. The ending lock ID is non-inclusive, so it checks all the memory until just below the second lock ID.

- **Symbol Declaration** - Used to associate a numerical symbol with a plaintext string, in order to make results more readable. This adds an entry to the global symbol table, which is used when displaying results (section 7.3). The record includes the length of the string, padded out to 4 bytes so that the records always lie on word-aligned boundaries. The string itself is null-terminated to indicate the end of the string (extra padding is ignored).

- **Lock Operation -** This is the typical data record, operating on a specific lock in a given thread. There are several types of this record, indicated by an enumerated field. The possible types are BLOCKING, NONBLOCKING, or RELEASE. The difference between blocking and nonblocking lock acquisitions is described in section 5.3. Each record is associated with a specific thread, indicated by a thread ID, and each record can have any number of symbols attached to it. As described previously, these symbols are used to identify where the event occurred after the fact. For release events, the symbols are ignored during graph construction, so there is no need to attach symbols.

An example translation between a POSIX thread program and the corresponding locking events is shown in figure 6.3. Note that in this case, the 'symbols' being used are the line numbers of the program. More typically, there would be multiple symbols associated with each event, where each symbol was an address in the stack trace at the time of the event.

Source Code
`1  pthread_mutex_t *a;`
`2  a = malloc(sizeof(*a));`
`3  pthread_mutex_initialize(a,NULL);`
`4  pthread_mutex_lock(a);`
`5  pthread_mutex_unlock(a);`
`6  free(a);`

Event Translation
Lock Operation
Type = Blocking
Lock ID = addr(a)
Symbol List = (4)
Symbol Definition
4 = "Line 4"
Lock Operation
Type = Release
Lock ID = addr(a)
Generation Increment
Start = addr(a)
End = addr(a) + sizeof(*a)

Figure 6.3: Translation from source code to events

6.3 Library Interpositioning

The most immediately obvious target for deadlock analysis is programs running in user mode in an operating system environment. While it is possible to accomplish this through dynamic tracing (section 6.4), there is already a mechanism for intercepting library calls built into most UNIX systems. With a UNIX system and dynamically linked executables, it is possible to interposition a custom library in between the program binary and a system library, using the `LD_PRELOAD` environment variable as demonstrated in figure 6.4. This can then be used to intercept system thread calls [6]. Note that for this particular implementation, the data is streamed out to a file with the name "lockgrab.pid," where 'pid' is the process ID of the command. This can be controlled through flags in the environment, but the actual specifics are not important. Once the library is preloaded, the dynamic loader will resolve symbols originally targeted for the system shared library into the custom library. These functions can then do whatever they need to do before calling the real system function. The typical method by which this is done is shown in figure 6.5.

```
$ ls -a
.  ..
$ LD_PRELOAD=liblockgrab.so command;
$ ls -a
.  ..  lockgrab.21354
```

Figure 6.4: Example use of LD_PRELOAD

```
static int (*_pthread_mutex_lock)(pthread_mutex_t *mtx);
int pthread_mutex_lock(pthread_mutex_t *mtx) {
     int ret;
     if (_pthread_mutex_lock == NULL)
         _pthread_mutex_lock = dlsym(RTLD_NEXT, "pthread_mutex_lock");
     /* Do something here */
     ret = _pthread_mutex_lock(mtx);
     /* Or do something here */
     return ret;
}
```

Figure 6.5: Sample interpositioning function

Most modern operating systems and programs use the POSIX threads library, since it the most widely supported cross-platform library available. It makes the most sense to interposition on this library in order to generate the needed locking data. Some programs may have implemented their own locking systems, but the large majority use the provided system library. The downside of this is that on some systems (most notably Linux), the dynamic loader functions such as `dlsym` and `dladdr` require the use of POSIX functions, so that the program often gets stuck in an infinite loop where the dynamic functions need the POSIX functions to complete, but these POSIX functions are stubs that need to resolve the symbols using dynamic loader functions before they can execute. This can be avoided by writing custom dynamic loader functions that aren't as versatile and well-integrated as the system provided ones, but can safely execute without recursively depending on themselves. The stack traces are easily obtained depending on the running system and the Application Binary Interface. The virtual addresses in the stack can be translated into strings via the `dladdr` call.

6.4 Dynamic Tracing

Gathering event data from a kernel is a difficult problem at best, since there are no simple I/O mechanisms and no way to interpose on locking primitive calls without creating a specially instrumented kernel. Instrumenting a kernel to provide probe points is no simple task either. Since one of the design goals is no source code modification, the use of statically defined probes in special kernels is not an acceptable solution. Unfortunately, this may be the only solution for a large number of platforms. A better solution is to use dynamic probe points, where probes are enabled at runtime by rewriting the text code.

Very few systems like this exist, in part because it is a very difficult problem, and detailed knowledge of a system's assembly language and execution semantics is needed in order to implement it correctly. More information on the semantics and difficulties of dynamic instrumentation can be found in [33] [26] and [27]. A few tracing frameworks have existed for the Solaris kernel over the years, including the deprecated VTrace and, more recently, TNF tracing [24]. These implementations still rely on defining static disabled probes within the kernel, and any change in the probes requires a re-compilation of the kernel. Limited lock information can be gathered on Solaris using the lockstat utility [25], although this is not suitable for creating a robust implementation suitable for analysis. A recent implementation of true dynamic kernel probes is KernInst, a dynamic trace facility for the Sparc platform. For the kernel tracing done in this project, a specially instrumented Solaris kernel was used, courtesy of Sun Microsystems' Solaris Kernel Group.

Unfortunately, the selection of open-source tracing frameworks for the Linux kernel are wholly inadequate for the type of tracing required by this project. The most promising is a combination of the Linux Tracing Toolkit [33] and IBM's DProbes facilities [16] [3]. Unfortunately, these systems are still under development, and although they are largely functional, they do not provide enough facilities to extract the necessary information from the Linux kernel. A number of tools exist for doing Linux kernel profiling, such as SGI's lockmeter [4] and kernprof [19], but these are intended for performance monitoring, not generic event gathering.

It is also possible to use dynamic tracing for user space programs. This is potentially easier, since the instructions can be changed to simply trap into the kernel on most platforms, although this still requires extensive kernel modifications. Since reasonable functionality can already be achieved using library interpositioning, dynamic tracing's greatest benefit providing kernel-level tracing.

6.5 Other Possibilities

Since the data source gathering tools and the analysis tools are intentionally kept separate, there is unlimited potential for the number of systems that the program can be applied to. The only stipulation is that the system follows the assumptions and locking consistency outlined in section 4.4. Due to the scope of this project, it was unreasonable to pursue any more methods than the library interpositioning and Solaris kernel tracing presented here. Some of the future possibilities include java (or other language) based programs, distributed systems analysis, or the Linux kernel. All of these systems can be modeled in the same way, as long as the data gathering tools are correctly implemented.

Chapter 7

Analysis and Display of Results

In order to predict possible deadlocks from a given data source, we must first construct the historical dependency graph, and then search for the necessary cycles. Because we are dealing with very large data sets, the graph produced will be large and time-consuming to build. Therefore, not only must the graph be built correctly, but it must be built in an efficient manner. Once the graph is constructed, it then becomes necessary not only to detect the cycles within the graph, but also to display the results in a meaningful manner. This chapter details some of the specifics of graph construction and analysis.

7.1 Graph Construction

In recent years, multiprocessor machines have become more and more common. In order to satisfy the design goals, the program must scale with additional processors. This implies that there must be multiple threads running concurrently to produce the graph, cutting down construction time for multiprocessor systems.

Unfortunately, since the data stream is time-ordered, and the generation count of locks is a global property, there there must always be a single thread processing the data source. The existence of a generation-count increment event can affect the interpretation of future events. This single thread does only the minimal required work, which is maintaining generation counts for locks in the system and passing on events to threads. Symbol definition records are handled by a special thread, but all of the 'normal' locking events are localized to a specific thread. Rather than having a single execution thread correspond to every thread structure in the data source, idea of a worker thread is used instead, where each worker manages several data-source threads. The number of worker threads created is directly related to the number of processors on the system.

Rather than having each worker share a common graph (which would require locking and increase contention), there is a graph local to each worker. This has the benefit of creating lockless data structures, but has the downside of increasing the memory footprint (since the same vertices and edges may appear in multiple graphs) and forcing the implementation to merge all of the graphs into a final representation. Due to the large number of events, the addition of vertices and edges will be fairly common, suggesting that there will be a great deal of contention between worker threads if they were to share a common graph. It makes more sense to perform one time-consuming merge operation at the end of construction, rather than forcing workers to contend for common resources. The edges and vertices are kept in dynamic hash tables, yielding approximately constant access time. The lock event pairs (described in section 4.6) are maintained in a linked list for each edge, since there will be relatively few cases where a dependency is established in multiple places. The overall layout of the system is shown in figure 7.1.

The algorithm used to process the "normal" locking events is shown in figure 7.2, and runs locally for each worker. Generation count increment and symbol definition events are handled separately. In this algorithm, the `thread` parameter is the local thread structure, the `graph` parameter is the worker-local graph, `lock` is the (address,generation) pair identifying the lock, `operation` is the type of operation, and `lockevent` is a (address,generation,symbol list) tuple that can be used to identify where the event occurred within the system.

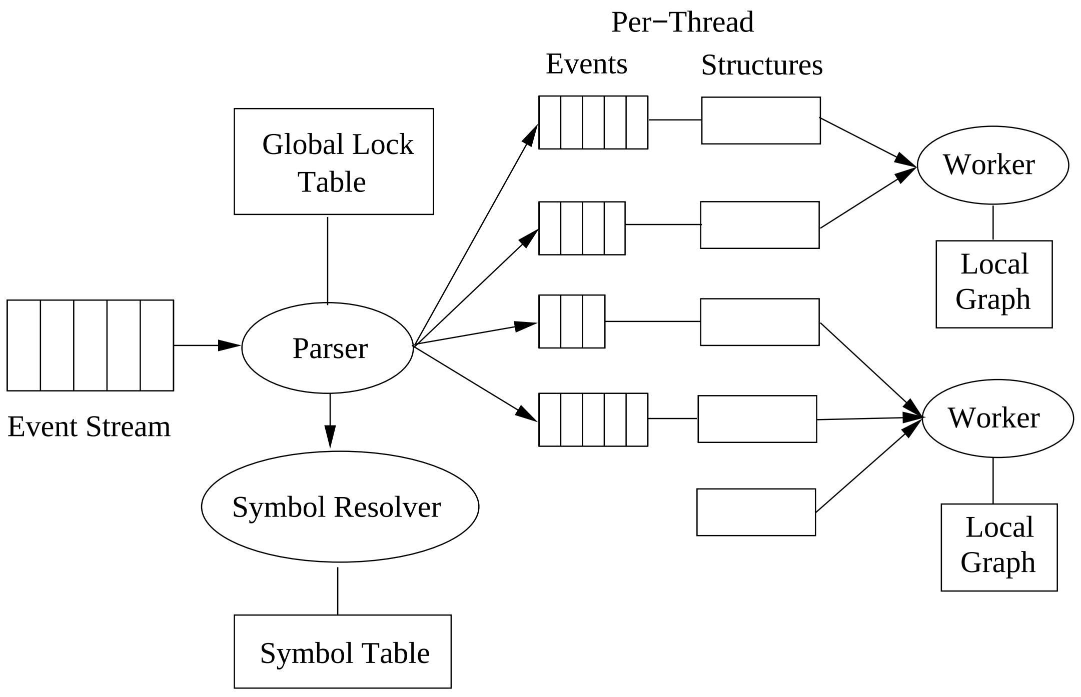


Figure 7.1: Graph Construction System

The global lock list and symbol table implementations are relatively straightforward. Every lock that passes through the parsing thread is checked to see if it exists in the global list. This list is an AVL tree, since whenever a generation count increment event is received, the entire range of addresses must be checked. This makes a hash table unusable. The symbol table is simply a hash table between symbol addresses and strings. Internally, the numerical addresses are used to identify and compare symbols, but when the data needs to be printed out, the string translation is used.

```
ProcessThreadEvent($thread, graph, lock, operation, lockevent$)
 1  if $lock \notin Vertices[graph]$
 2     then $Vertices[graph] \leftarrow Vertices[graph] \cup lock$
 3  if $operation =$ BlockingAcquisition
 4     then for $\forall\ l \in HeldLocks[thread]$
 5              do if $(lock, l) \notin Edges[graph]$
 6                    then $Edges[graph] \leftarrow Edges[graph] \cup (lock, l)$
 7                 $e \leftarrow e \in Edges[graph]$ such that $e = (lock, l)$
 8                 if $(LockEvent[l], lockevent) \notin Events[e]$
 9                    then $Events[e] \leftarrow Events[e] \cup (LockEvent[l], lockevent)$
10  if $operation =$ NonBlockingAcquisition $\vee$ $operation =$ BlockingAcquisition
11     then $HeldLocks[thread] \leftarrow HeldLocks[thread] \cup lock$
12          $l \leftarrow l \in HeldLocks[thread]$ such that $l = lock$
13          $LockEvent[l] = lockevent$
14  if $operation =$ Release
15     then $HeldLocks[thread] \leftarrow HeldLocks[thread] - lock$
```

Figure 7.2: Per-thread event processing algorithm

7.2 Cycle Detection

In order to detect cycles, a modified depth-first search algorithm is used. In this algorithm, every vertex is marked as either unknown, visited, or active. Initially, all vertices are marked as unknown. Then, for each unknown vertex, we push it onto a stack, and mark the vertex as active, indicating that it is currently in the stack. We then look at each outgoing edge from the vertex. If the destination vertex is active, then we have found a cycle. If the destination vertex is unknown, then we continue with the algorithm recursively with the next destination vertex. If the vertex is visited, then we ignore it. This prevents us from inadvertently searching down paths that we have already seen. Once all of the neighbors have been visited, the current vertex is removed from the stack and marked as visited. This algorithm is shown in figure 7.3, and is called on every vertex in the graph in order to find all possible cycles.

```
FindCycle($graph, vertex, stack$)
 1  if $mark[vertex] =$ VISITED
 2     then return
 3  if $mark[vertex] =$ ACTIVE
 4     then print cycle
 5  if $mark[vertex] =$ UNKNOWN
 6     then push $vertex$ on $stack$
 7          $mark[vertex] \leftarrow$ ACTIVE
 8          for $\forall\ e \in outgoing[vertex]$
 9          do FindCycle($graph, end[e], stack$)
10          pop $vertex$ from $stack$
11          $mark[vertex] \leftarrow$ VISITED
```

Figure 7.3: Cycle detection algorithm

This algorithm fails for certain cases of multiple cycles. Specifically, if two vertices are both part of two different cycles, then only one of the cycles will be found. This is demonstrated in figure 7.4. The smaller 3-vertex cycle is detected, but then the larger cycle is not found because one of the vertices has already been marked as visited. This is not a problem for two reasons. First, the system being analyzed is expected to be largely correct, since most of the common deadlocks would have been produced through normal testing. Therefore, the graph is going to be largely acyclic, with only a few cycles to be found. Second, the majority of cycles will contain only two vertices. The most common deadlock by far is a mixed dependency between two threads. Any cycle of more than two vertices implies multiple threads with cascading dependencies, an unlikely scenario. Combined with the low probability that two vertices are part of two different cycles, this is an unlikely situation. The simplicity and speed of the algorithm are more important.

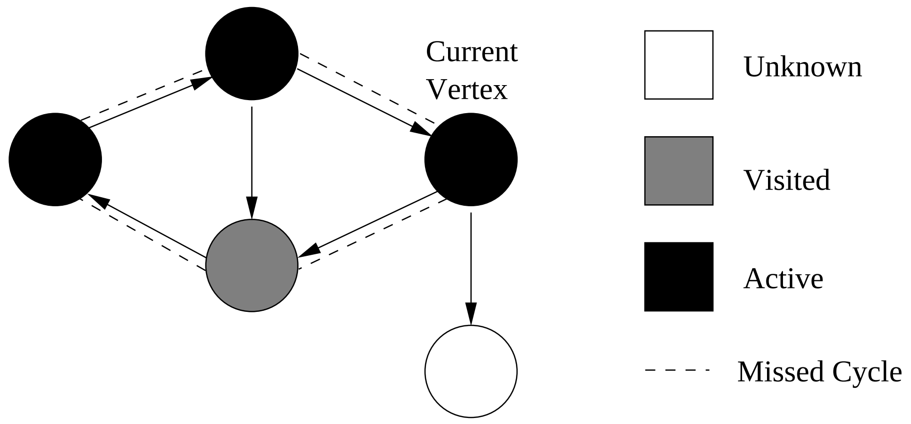


Figure 7.4: Cycle missed by detection algorithm

7.3 Displaying Meaningful Data

Once a cycle has been found, it becomes important to display the cycle in a meaningful way to the user of the program. Section 4.6 describes the method by which individual events are stored with each edge. We go through each edge in the cycle and print out the event information about when each lock was acquired. This event information is typically a stack trace at the point that the lock was acquired, although it is completely arbitrary and up to the data source to provide meaningful event data. We print out the identifier and generation count of the lock. It is doubtful that meaningful data can be extracted from the address, but it's necessary to identify the lock. It would be possible, as an extension to the analysis, to provide a lock symbol table in addition to the arbitrary symbol table (they cannot share the same table because the primitives can be different sizes). This would allow symbolic names to printed out for some locks, such as implicit dependencies and statically defined locks. For each edge, we look at all known event pairs associated with the edge. For each event, we print out the symbol list, first by trying to find the symbols in the symbol table, and then resorting to the numerical value in the case that it cannot be found. An example is shown in figure 7.5.

```
Cycle found:
  000002a100571968:0                     -> 000002a100571970:0

  unix‘mutex_enter                          unix‘mutex_enter
  badlock‘badlockdrv_ioctl+0x7c             badlock‘badlockdrv_ioctl+0x8c
  genunix‘ioctl+0x1f8                       genunix‘ioctl+0x1f8

  000002a100571970:0                     -> 000002a100571968:0

  unix‘mutex_enter                          unix‘mutex_enter
  badlock‘badlockdrv_ioctl+0x74             badlock‘badlockdrv_ioctl+0x7c
  genunix‘ioctl+0x1f8                       genunix‘ioctl+0x1f8
```

Figure 7.5: Sample data display

One thing to note is that the edges are displayed backwards, with the source of the edge (the second lock taken) being displayed as the second lock rather than the first. This is because it makes more logical sense to the user to see the data in a time-ordered fashion, where the first event that happened is on the left, and the next event is on the right. There can be more than one event pair for each edge, and there can be more than one cycle found for each graph. From this data, the programmer can determine the corresponding points in the source code where the locks are taken, and take appropriate steps to fix it.

7.4 Prediction Limits

Deadlock prediction can only be taken so far. At some point, the automatic analysis breaks down and the programmer must intervene. There are several points about the analysis that should be noted. First of all, as mentioned in section 4.5, the deadlocks are merely *possible* deadlocks, and it can never be asserted without doubt that a deadlock can occur except by demonstrating it in practice. Upon closer analysis, it may turn out that the predicted deadlocks are in fact not possible. Second, the analysis hinges on the fact that all possible code paths must be stressed in the program. More places where a deadlock could occur may exist in the code, and just weren't traced by the original data source. This means that programmers must still try and write a good coverage test in order to hit all the code paths in the system. The advantage of using this system is that they need not write a full stress test to try to get the bugs to occur in practice. In the end, the programmer is presented only with a list of symbolic addresses, and the true cause of the deadlock (or lack thereof) must be extrapolated by looking at the source code for those particular areas and determining how they occurred in the given sequence.

One possibility for extension of this program in order to make it more useful to programmers would be to provide a more complete trace of the program's execution between lock acquisitions.

Under the given system, the programmer is only presented with the point where each lock was taken in the system. What happened in between is unknown, and if a lot of code is covered, it may not be immediately obvious how the deadlock could occur. In order to make this more informative, the program could keep track of all events in between the two acquisitions, or go back and re-examine the data source to get this information. Then, the programmer would see a series of locking operations that hopefully could provide more details to the program's execution that otherwise were not immediately apparent. A more complete solution would be to record every function entry and exit in between the two events, but this begins to generate too much data for the program to handle. One possibility would be to take the information about the cycle, and then run the program again, tracing only those events that are in between the given lock acquisitions. This would add another step to the process, but done correctly it would make the exact sequence of operations that lead to the deadlock very clear. The best possible solution would be an interactive one, where the programmer could trace through the program's execution based on source code and see exactly what happens. This is an order of magnitude more difficult than just printing out the source of the deadlock, and can be a difficult problem [9] [2].

Chapter 8

Sample Results

In order to demonstrate the correctness and usefulness of the program, the data gathering tools and analysis program was run on a variety of contrived and existing systems. For all of these examples, the full source code to each program can be found in Appendix A. The graphs presented in this chapter are extracted directly from the source and produced using the graphviz [17] program. In this chapter, the results of running the program on each system will be examined and interpreted in the context of the source program.

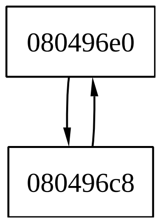
8.1 Application bugs

The program can be most easily demonstrated using data gathered from user programs. Rather than trying to analyze an existing program, for which source code may or may not be available, simple custom-made programs are used in order to demonstrate the features and limits of the analysis.

8.1.1 Simple Deadlock

The most basic form of a deadlock is shown in section A.1. In this somewhat contrived example, two threads each lock two mutexes in a different order. Under normal circumstances, since the running time of each thread is very short and the locking operations occur very quickly, this will most likely not deadlock. But this does not diminish the fact that there is a possibility, no matter how remote, that the two threads could be scheduled in such a way as to cause a deadlock. The results of the analysis are shown in figure 8.1.

From these results, it can be seen that in one case (threadone), lock $0x080496c8$ is taken before lock $0x080496e0$, and in the other case (threadtwo), they are taken in the opposite order. By examining the disassembled source code (or using debugging symbols, if present), the source of each lock can be traced to a line in the source file. For example, `threadone+0x13` corresponds to line 9 in the source file. Once the programmer has determined this, it is up to him or her to fix the source code. For this example there is no real "fix," since it is a contrived and deliberate bug. In a real



```
Total Vertices: 2
   Total Edges: 2

Cycle found:
  080496c8:0                           -> 080496e0:0

  ‘liblockgrab.so‘pthread_mutex_lock      ‘liblockgrab.so‘pthread_mutex_lock
  threadone+0x13                          threadone+0x20
  0x40032fa5                              0x40032fa5
  ‘libc.so.6‘__clone                      ‘libc.so.6‘__clone

  080496e0:0                           -> 080496c8:0

  ‘liblockgrab.so‘pthread_mutex_lock      ‘liblockgrab.so‘pthread_mutex_lock
  threadtwo+0x13                          threadtwo+0x20
  0x40032fa5                              0x40032fa5
  ‘libc.so.6‘__clone                      ‘libc.so.6‘__clone
```

Figure 8.1: Results of tracing a simple user deadlock

system there would be a more complex solution to the problem.

8.1.2 Dynamic Memory

The source code in section A.4 demonstrates the effect that dynamic memory allocation has on the construction of the graph and subsequent analysis. We allocate lock *a* dynamically, and lock *a* and then *b*. Then, we free and allocate the same lock (making sure that the address is the same), and lock *b* and then *a*. Without generation counts, they would be treated as the same lock (since they share the same address), and there would be a possible deadlock (as in figure 8.1). Instead, this produces the set of events and resulting graph shown in figure 8.2.

These events are extracted from the original data and displayed in a human-readable format. Note that the majority of the events are symbol declaration (`SYM`) events. For a complete description of each event type, and the meaning of each parameter, consult section 6.2. The important event in this data set is the generation count (`GEN`) event. This causes the generation count of 08049a10 to be incremented to 1. In the graph, this creates a new node, and the resulting dependency does not create a cycle.

```
SYM 4001774e ‘liblockgrab.so‘pthread_mutex_lock
SYM 0804859b main+0x3b
SYM 4005a0bf ‘libc.so.6‘__libc_start_main
SYM 080484a1 ‘test2‘pthread_mutex_unlock
BLK 00000400 08049a10
SYM 080485a7 main+0x47
BLK 00000400 bffff744
SYM 400179af ‘liblockgrab.so‘pthread_mutex_unlock
SYM 080485b3 main+0x53
REL 00000400 08049a10
GEN 08049a10 08049a28
SYM 080485fc main+0x9c
BLK 00000400 08049a10
SYM 08048608 main+0xa8
REL 00000400 08049a10
SYM 08048611 main+0xb1
REL 00000400 bffff744
```

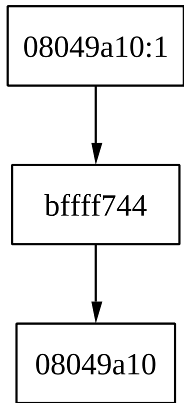


Figure 8.2: Example of dynamic memory usage

8.1.3 The Dining Philosophers

One of the classic problems mentioned when discussing concurrency control is that of the dining philosophers. In this problem, there are a number (N) of seats at a table with a place setting at each seat. There is a fork on either side of the place setting, but the forks are shared between adjacent place settings, so there are only N forks on the table. There are also N philosophers that want to come and eat at the table. In order to eat at the table, the philosophers must grab both the left fork and the right fork of a particular place setting. They cannot reach across the table, and must wait until they have both forks before they can start eating. Once they pick up a fork, they cannot put it down until they are done eating. The simplest solution is to have all the philosophers sit down at the table, and grab the left fork and then the right fork. This is system in section A.2. There is the possibility of a deadlock, however, if every philosopher picks up the left fork, at which point no one can pick up their right fork or put down their left fork, and the entire table is in a deadlock. The output from the program when it reaches the deadlock state with 3 philosophers is shown in figure 8.3.

As the number of philosophers increase, and the amount of time spent eating decreases, the chances of a deadlock being produced drop significantly. The analysis program should still be able to detect the possibility of the deadlock, even if it isn't produced during the execution of the program. The results of the analysis are shown in figures 8.4 and 8.5 respectively. This analysis was performed on a dining philosopher problem with 4 philosophers. One of the possible resolutions to this deadlock problem is explained in the next section.

```
Running with 3 philosophers
Philosopher 1 waiting for left fork
Philosopher 1 left fork up
Philosopher 0 waiting for left fork
Philosopher 0 left fork up
Philosopher 2 waiting for left fork
Philosopher 2 left fork up
Philosopher 1 waiting for right fork
Philosopher 0 waiting for right fork
Philosopher 2 waiting for right fork
```

Figure 8.3: Dining philosophers in a deadlock

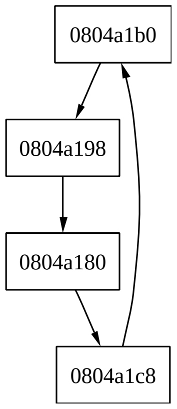


Figure 8.4: Graph of Dining philosophers

8.1.4 Dining Philosophers With a Butler

One of the possible solutions to the deadlock problem with the dining philosophers is the use of a butler that effectively limits the number of people that can sit at the table. As long as there are fewer philosophers at the table than there are place settings, the system cannot deadlock. The source code for this example is given in section A.3. The difference between this example and the previous dining philosopher solution is that the philosophers will pick up either fork first (a fact that does not avoid the deadlock), as well as having the number sitting at the table limited to one less than the total number of philosophers.

This example illustrates some of the shortcomings of the prediction mechanism. First of all, it will predict the possibility of a deadlock between all of the philosophers, even though it cannot actually occur. This is because it is impossible for the analysis program to know that there is an overarching locking order that limits the number of threads that can be involved in the deadlock. The deadlock is still reported due to the concurrency assumptions made about the system. Similarly, the analysis will report a potential deadlock between each of the threads and itself, since in one case it grabs the left fork and then the right fork, while in another instance it grabs the right fork and then the left fork. This cannot actually occur in practice because there can only be one copy of each

```
Total Vertices: 4
   Total Edges: 4

Cycle found:
  0804a198:0                        -> 0804a1b0:0

  ‘liblockgrab.so‘pthread_mutex_lock     ‘liblockgrab.so‘pthread_mutex_lock
  philosopher+0x84                       philosopher+0xf9
  0x40032fa5                             0x40032fa5
  ‘libc.so.6‘__clone                     ‘libc.so.6‘__clone

  0804a180:0                        -> 0804a198:0

  ‘liblockgrab.so‘pthread_mutex_lock     ‘liblockgrab.so‘pthread_mutex_lock
  philosopher+0x84                       philosopher+0xf9
  0x40032fa5                             0x40032fa5
  ‘libc.so.6‘__clone                     ‘libc.so.6‘__clone

  0804a1c8:0                        -> 0804a180:0

  ‘liblockgrab.so‘pthread_mutex_lock     ‘liblockgrab.so‘pthread_mutex_lock
  philosopher+0x84                       philosopher+0xf9
  0x40032fa5                             0x40032fa5
  ‘libc.so.6‘__clone                     ‘libc.so.6‘__clone

  0804a1b0:0                        -> 0804a1c8:0

  ‘liblockgrab.so‘pthread_mutex_lock     ‘liblockgrab.so‘pthread_mutex_lock
  philosopher+0x84                       philosopher+0xf9
  0x40032fa5                             0x40032fa5
  ‘libc.so.6‘__clone                     ‘libc.so.6‘__clone
```

Figure 8.5: Analysis of dining philosopher

philosopher thread running at any given time, but one of the concurrency assumptions was that it is possible to have multiple copies of the same thread running at the same time. The existence of these smaller cycles also shows the limitation of the cycle detection algorithm, because the smaller cycles are not detected once the larger cycle is found. The results of the graph and the analysis are shown in figures 8.6 and 8.7 respectively. Note that only one of the possible smaller cycles is detected.

8.2 Kernel Bugs

Part of the inspiration for this program was to provide a method of predicting deadlocks within an operating system kernel. Two kernels were examined, the Linux kernel and the Solaris kernel, to determine if either had an appropriate means of extracting lock data from a running system. The Linux kernel has the beginnings of dynamic tracing facilities (see section 6.4) but they are not quite

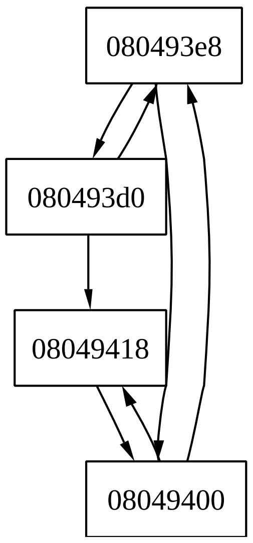


Figure 8.6: Graph of dining philosophers with a butler

adequate, and a full implementation would still be a reasonably large task. On the other hand, a specially instrumented Solaris kernel was provided by the Solaris Kernel Group at Sun Microsystems, providing a simple method of extracting data from an executing kernel. Therefore, all of the kernel analysis is performed on the Solaris kernel, for the sake of simplicity.

Since the Solaris kernel has been around for a long time (and is one of the earliest fully preemptive UNIX kernels), it has undergone a rigorous test regimen during its evolution. It is highly unlikely that there are any existing bugs in the common kernel code. It is much more likely that deadlocks exist in some of the newer and more esoteric modules that are not used very often. Without access to some of the newest hardware and modules, a special kernel driver was instead created in order to artificially insert deadlocks into the kernel. The complete source code for this driver is given in sections A.5 and A.6. This driver was then installed in the system as `/dev/badlock`, and tested with the code in section A.7. The device allows for several different tests through the `ioctl()` call, the specifics of each which is discussed here.

8.2.1 Locking Order

This test (`BADLOCK_CHECK_ORDER`) is the kernel version of the test described in section 8.1.1. It merely locks two different locks in two different orders, using the kernel-level functions `mutex_enter` and `mutex_exit`. If two different user programs were to issue this `ioctl` at precisely the right moment, it would be possible that they would both deadlock, and the rest of the driver becomes unusable (a bigger problem with realistic systems). The results of the analysis on this section of the driver is shown in figure 8.8.

Note that in this particular test, the mutexes are actually on the stack, so it is impossible for any two threads to ever deadlock on these mutexes. This makes the code simpler, although the analysis

```
Total Vertices: 5
   Total Edges: 8

Cycle found:
  080493d0:0                           -> 080493e8:0

  `liblockgrab.so`pthread_mutex_lock      `liblockgrab.so`pthread_mutex_lock
  philosopher+0xc0                        philosopher+0x15a
  0x40032fa5                              0x40032fa5
  `libc.so.6`__clone                      `libc.so.6`__clone

  08049418:0                           -> 080493d0:0

  `liblockgrab.so`pthread_mutex_lock      `liblockgrab.so`pthread_mutex_lock
  philosopher+0xc0                        philosopher+0x15a
  0x40032fa5                              0x40032fa5
  `libc.so.6`__clone                      `libc.so.6`__clone

  08049400:0                           -> 08049418:0

  `liblockgrab.so`pthread_mutex_lock      `liblockgrab.so`pthread_mutex_lock
  philosopher+0xc0                        philosopher+0x15a
  0x40032fa5                              0x40032fa5
  `libc.so.6`__clone                      `libc.so.6`__clone

  080493e8:0                           -> 08049400:0

  `liblockgrab.so`pthread_mutex_lock      `liblockgrab.so`pthread_mutex_lock
  philosopher+0xc0                        philosopher+0x15a
  0x40032fa5                              0x40032fa5
  `libc.so.6`__clone                      `libc.so.6`__clone


Cycle found:
  08049400:0                           -> 08049418:0

  `liblockgrab.so`pthread_mutex_lock      `liblockgrab.so`pthread_mutex_lock
  philosopher+0xc0                        philosopher+0x15a
  0x40032fa5                              0x40032fa5
  `libc.so.6`__clone                      `libc.so.6`__clone

  08049418:0                           -> 08049400:0

  `liblockgrab.so`pthread_mutex_lock      `liblockgrab.so`pthread_mutex_lock
  philosopher+0xc0                        philosopher+0x15a
  0x40032fa5                              0x40032fa5
  `libc.so.6`__clone                      `libc.so.6`__clone
```

Figure 8.7: Analysis of dining philosophers with a butler

```
Cycle found:
  000002a100571968:0                     -> 000002a100571970:0

  unix‘mutex_enter                          unix‘mutex_enter
  badlock‘badlockdrv_ioctl+0x7c             badlock‘badlockdrv_ioctl+0x8c
  genunix‘ioctl+0x1f8                       genunix‘ioctl+0x1f8

  000002a100571970:0                     -> 000002a100571968:0

  unix‘mutex_enter                          unix‘mutex_enter
  badlock‘badlockdrv_ioctl+0x74             badlock‘badlockdrv_ioctl+0x7c
  genunix‘ioctl+0x1f8                       genunix‘ioctl+0x1f8
```

Figure 8.8: Kernel locking order deadlock

is technically incorrect. In reality, it makes little sense to have mutexes on the stack, and these would more likely be allocated from some shared memory (or declared statically) so that they could be shared between threads. Note also that in the results the addresses are 64 bits (since the kernel is a sun4u 64-bit kernel), demonstrating the ability to deal with different sizes for the primitive types.

8.2.2 Dynamic Memory

This call (`BADLOCK_CHECK_FREE`) is the kernel-level equivalent of the example shown in section 8.1.2. It allocates a mutex *a* from a cache using `kmem_cache_alloc`, locks *a* and then another static mutex *b*. The dynamic mutex is freed using `kmem_cache_free` and then allocated again, returning the same address. The locks are then locked in the reverse order, but since the new *a* is logically a different lock (even though is shares the same address) it is not a deadlock. Running the analysis tools doesn't show any deadlock in this section of code, demonstrating that the dynamic allocation is correctly handled. Unfortunately, the number of events (and the resulting graph) are so large that they cannot be shown here in order to prove that the cycle doesn't exist in the graph.

8.2.3 Recursive Reader-Writer Lock

As described in section 5.2, the problem of recursive read locks on a reader-writer lock is a relatively common problem in large systems. This test (`BADLOCK_CHECK_RWLOCK`) takes two consecutive read lock using `rw_enter(&lock, RW_READER)`. Under normal circumstances, the second call will almost never block, since it would require an intervening write call to occur at just the precise moment between the two locking attempts. There is this slight chance, leading to the possibility of a deadlock. The results of running the analysis is shown in figure 8.9.

Note that the cycle is detected between the lock and itself. This is the only situation where this can occur in normal locking systems, except for the case of semaphores. Otherwise, the second call to the acquisition function would have blocked, and the system would have deadlocked instantly. Again, in this contrived situation, the locks are located on the stack, and there is no way for an intervening

```
Cycle found:
  000002a100571958:0                  -> 000002a100571958:0

  unix‘rw_enter                          unix‘rw_enter
  badlock‘badlockdrv_ioctl+0x1fc         badlock‘badlockdrv_ioctl+0x208
  genunix‘ioctl+0x1f8                    genunix‘ioctl+0x1f8
```

Figure 8.9: Recursive reader-writer locks in the kernel

write attempt to happen, so there is technically no possibility of a deadlock. In a real situation, these locks would be shared by threads, and there is an implicit assumption that somewhere, a write lock will be taken.

8.2.4 Interrupt Dependent Functions

This type of locking violation is described in section 5.4. As outlined there, the `kmem_alloc` function requires interrupts of level 7 to be able to complete when passed the `KM_SLEEP` flag. This is because in low memory situations, the pageout daemon needs to run, which requires the I/O completion routines need to run at interrupt level 7. In order to test the functionality of this detection, the driver takes a lock (`thread_free_lock`) that is known to be taken in the clock handler. The current process `p_lock` could have been used as well, but it doesn't matter, since the dependency is automatically detected. Once this lock is acquired, `kmem_alloc` is called with the `KM_SLEEP` flag. The original lock is then released. The results of the analysis are shown in figure 8.10.

```
Cycle found:
  0000000000000009:0                  -> 000000000000000a:0
  0000000000000008:0                  -> 0000000000000009:0
  0000000000000007:0                  -> 0000000000000008:0
  0000000001899720:0                  -> 0000000000000007:0

  unix‘mutex_enter                       genunix‘kmem_cache_alloc
  badlock‘badlockdrv_ioctl+0x24c         genunix‘kmem_alloc+0x28
  genunix‘ioctl+0x1f8                    badlock‘badlockdrv_ioctl+0x258
                                         genunix‘ioctl+0x1f8

  000000000000000a:0                  -> 0000000001899720:0

                                         unix‘mutex_enter
                                         genunix‘clock+0x36c
                                         genunix‘cyclic_softint+0x368
                                         unix‘cbe_level10+0x8
```

Figure 8.10: Interrupt Dependent Functions in the Kernel

The pseudo-locks for each interrupt are represented as their numerical identity. This is safe because in the Solaris kernel we are assured that there is no memory mapped in the first page of memory, so these pseudo-locks will never conflict with the address of any real lock. The implicit dependencies are shown between each interrupt level (notice that there are no events associated with the implicit dependencies). The clock interrupt occurs at level 10, but the implicit dependencies connect this to the dependency created at level 7 by the driver. In the future, the program could be modified so that locks can have symbolic names attached to them, so that the interrupts would appear as "IPL 9", "IPL 10", etc, and the lock itself could appear as "thread_free_lock" (since it is statically defined).

8.3 Existing Solaris Bugs

Despite the claims made at the beginning of this chapter, some potential deadlocks still exist in the Solaris kernel, and a few were found using this tool. Most notably, two potential deadlocks were found in the UFS (Unix File System) subsystem.

While it may seem that deadlocks in such a common subsystem should have been long since fixed, the deadlocks are in fact extremely unlikely to occur, since they rely on several infrequently used features of UFS. UFS supports quotas, allowing filesystems to be limited in their size, as well as access control lists (ACLs) and attribute directories. To begin with, both deadlocks involve a global reader-writer lock designed to prevent simultaneous access to quota data. The quota data is accessed by acquiring a read lock whenever a file is added or deleted. Normally, when a file is deleted, a read lock on the quota is taken (to prevent it from changing value) and the file is removed from the system. If the directory contains ACLs or an attribute directory, then a recursive read lock ends up being taken. The code to remove the file from the directory gets a read lock on the global lock, but then calls another subroutine with it held, and that subroutine ends up taking the same lock again. Normally, this function is called from routines that do not already have the lock. The only time a write lock is taken on the global lock is via the `quotacheck` and `edquota` commands, so if one of these commands is run at just the right time and the write lock occurs between the two read locks, while an ACL or attribute directory is being deleted, then the entire UFS subsystem will deadlock.

It is apparent that this is a highly unlikely bug, since it requires that the administrator have access control lists and/or attribute directories, and that a certain command be run at precisely the same time that a file is being deleted. Nevertheless, it is a potential deadlock, and any such situation is a hurdle to achieving the elusive goal of 100% uptime. In order to find this bug, a UFS stress test was run while data was gathered from the entire kernel. In order to keep the file sizes manageable, data was gathered into 2 or 3 minute groups, where each file was about one to two gigabytes long (see section 8.4). Each of these files was then analyzed independently, and these cycles were detected in the graph. From looking at the stack traces, it was apparent that the subroutine was being called with the same lock held. From this point, it was a relatively simple matter to trace through the source code to determine exactly how it got there.

8.4 Kernel Complexity

Some passing references have been made to the complexity of analyzing locks in a preemptive kernel. To shed some light on the subject, a few arbitrary tests were done in order to gather basic statistics about the number of locks to expect in a typical trace of the Solaris kernel. To begin with, a simple trace of all the mutex operations (not including spin locks) when running the "date" command was done. From the kernel view, this command simply maps some memory, makes a system call to find out the current time, and then makes another system call to write to the screen device. To acquire this data, operations were only recorded if `curthread->t_procp->p_user->u_comm` was equal to "date". Running the command once produced 9000 events, and the resulting graph had 500 vertices and 14,000 edges. This is one of the simplest traces possible and already the graphviz program requires 180 pages to display the resulting graph.

For a more general situation, a trace of the entire kernel (without spin locks) on an "idle" system (one in which the majority of processes are blocked waiting for I/O and not actively consuming system resources) yields more realistic results. In a 5 second trace, a graph with 3700 locks and 27000 edges is produced. A minute of tracing an idle system produces approximately half a gigabyte of data, or 1 million records. More moderately loaded systems, when including spin locks, generate about 10 million records per minute, and the resulting graphs can have upwards of 25,000 vertices and 250,000 edges. Since a typical coverage test can be expected to run for times ranging from 5 minutes to an hour for complicated systems, we can expect to see traces with hundreds of millions of events and millions of dependencies. At this point, the current implementation starts to reach the limits of the hardware available to the author. Significant work can still go into optimizing the source code (the first step being to turn debugging information off), and more powerful hardware (including multiprocessor machines) can be used to construct more comprehensive analyses.

Chapter 9

Concluding Remarks

Deadlock detection and prediction is not a new idea, and has been around since multiprogramming was first introduced. The problem of deadlock prediction is an especially important one, since most systems need to be deadlock-free. This problem is unfortunately also a very difficult one. Throughout the course of this thesis, a practical and extensible solution to this problem has been presented.

The main benefit of this system is that it allows for prediction and modeling of systems that were previously inaccessible. Large concurrent systems can be easily analyzed for possible deadlocks, including operating system kernels. The separation of the analysis and data gathering tools allow for data to be extracted from a variety of systems and all analyzed using the same program, making it easy to expand the analysis to novel systems. In addition, a variety of other synchronization tools can be modeled effectively, including interrupt handlers and non-blocking locks. With the automatic handling of dynamic memory, this system can effectively model situations that historically have been unassailable.

Using a dynamic tracing framework, data can be directly extracted from sources, without requiring the programmer to change any code or recompile any software. This trace-driven technique also allows for data to be extracted from an executing kernel, which makes kernel analysis possible. This reduces the overhead at run time, instead opting to stream the data to an external source for later analysis.

The analysis of the system is not perfect, since it relies on several assumptions about the concurrent nature of the system that may not always hold true. Some deadlocks may be reported that can in fact never occur, since there are constraints on the system beyond the traditional model, or violations of the concurrency assumptions. Once these deadlocks are reported, then, it becomes the responsibility of the programmer to return to the source code and determine if the deadlock in fact exists, and what can be done to fix it.

The overall system demonstrates that it is possible to predict deadlocks in a complicated system such as an operating system, without impacting the run time performance. A great deal more work can be done into making the interface more accessible, with the possibility of integrating the analysis into a coherent development tool. The algorithms used could also be optimized or extended, though the basic concepts are sound. The largest area where this research can be extended is applying to new and novel systems, such as the Linux kernel or distributed systems. As long as the concurrency constraints follow the assumptions laid out, and the concurrency controls follow traditional semantics, then any system can be targeted.

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Appendix A

Source Code Examples

A.1 Simple User Deadlock

```
#include <pthread.h>
#include <assert.h>

static pthread_mutex_t a = PTHREAD_MUTEX_INITIALIZER;
static pthread_mutex_t b = PTHREAD_MUTEX_INITIALIZER;

static void * threadone(void *param)
{
        pthread_mutex_lock(&a);
        pthread_mutex_lock(&b);
        pthread_mutex_unlock(&b);
        pthread_mutex_unlock(&a);
}

static void * threadtwo(void *param)
{
        pthread_mutex_lock(&b);
        pthread_mutex_lock(&a);
        pthread_mutex_unlock(&a);
        pthread_mutex_unlock(&b);
}

int main(int argc, char **argv)
{
        int ret;
        pthread_t t1, t2;

        ret = pthread_create(&t1, NULL, threadone, NULL);
        assert(ret == 0);
        ret = pthread_create(&t2, NULL, threadtwo, NULL);
        assert(ret == 0);
        pthread_join(t1, NULL);
        pthread_join(t2, NULL);
        return 0;
}
```

A.2 Dining Philosophers

```
#include <pthread.h>
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <signal.h>
#include <assert.h>
#include <time.h>

typedef struct placesetting {
        pthread_mutex_t         *forks[2];
        int                     number;
} placesetting_t;

static int g_stopped;

void *
philosopher(void *param)
{
        placesetting_t *place = (placesetting_t *)param;
        struct timespec delay;

        delay.tv_sec = 0;

        while (!g_stopped) {
                /* Wait for up to 100 ms */
                delay.tv_nsec = rand() % 100000000;
                nanosleep(&delay, NULL);

                /* Get left fork */
                printf("Philosopher %d waiting for left fork\n",
                        place->number );
                pthread_mutex_lock(place->forks[0]);
                printf("Philosopher %d left fork up\n",
                        place->number);

                /* Wait for up to 100 ms */
                delay.tv_nsec = rand() % 100000000;
                nanosleep(&delay, NULL);

                /* Get right fork */
                printf("Philosopher %d waiting for right fork\n",
                        place->number);
                pthread_mutex_lock(place->forks[1]);
                printf("Philosopher %d right fork up\n",
                        place->number);

                /* Wait for up to 100 ms */
                delay.tv_nsec = rand() % 100000000;
                nanosleep(&delay, NULL);

                /* Release forks */
                printf("Philosopher %d right fork down\n",
                        place->number);
                pthread_mutex_unlock(place->forks[1]);
                printf("Philosopher %d left fork down\n",
                        place->number);
                pthread_mutex_unlock(place->forks[0]);
        }
}

int
main(int argc, char **argv)
{
        int             count;
        pthread_mutex_t *forks;
        placesetting_t  *places;
        pthread_t       *philosophers;
        int             i;
        int             ret, sig;
        sigset_t        set;

        if (argc != 2) {
                printf("usage: %s count\n", argv[0]);
                return EXIT_FAILURE;
        }

        count = atoi(argv[1]);
        if (count <= 1) {
                printf("usage: %s count\n", argv[0]);
                return EXIT_FAILURE;
        }

        printf("Running with %d philosophers\n", count);
        srand(time(NULL));

        /* Create the placesettings */
        forks = malloc(count * sizeof(pthread_mutex_t));
        places = malloc(count * sizeof(placesetting_t));
        philosophers = malloc(count * sizeof(pthread_t));

        for (i = 0; i < count; i++) {
                pthread_mutex_init(&forks[i], NULL);
                places[i].number = i;
                places[i].forks[0] = &forks[i];
                places[i].forks[1] = &forks[(i+1)%count];
        }

        /* Create the philosopher threads */
        sigemptyset(&set);
        sigaddset(&set, SIGINT);
        pthread_sigmask(SIG_BLOCK, &set, 0);

        for (i = 0; i < count; i++) {
                ret = pthread_create(&philosophers[i], NULL, philosopher,
                    &places[i]);
                assert(ret == 0);
        }

        sigwait(&set, &sig);
        /* This is not technically thread-safe, but it will do */
        g_stopped = 1;

        for (i = 0; i < count; i++) {
                ret = pthread_join(philosophers[i], NULL);
                assert(ret == 0);
        }

        return EXIT_SUCCESS;
}
```

A.3 Dining Philosophers With a Butler

```
#include <pthread.h>
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <signal.h>
#include <assert.h>
#include <time.h>

typedef struct butler {
        pthread_mutex_t         mtx;
        pthread_cond_t          cond;
        int                     count;
} butler_t;

typedef struct placesetting {
        pthread_mutex_t         *forks[2];
        int                     number;
        butler_t                *butler;
} placesetting_t;

static int g_stopped;
static void
butler_init(butler_t *b, int count)
{
        pthread_mutex_init(&b->mtx, NULL);
        pthread_cond_init(&b->cond, NULL);
        b->count = count;
}

static void
butler_enter(butler_t *b)
{
        pthread_mutex_lock(&b->mtx);
        while(b->count == 0)
                pthread_cond_wait(&b->cond, &b->mtx);
        b->count--;
        pthread_mutex_unlock(&b->mtx);
}

static void
butler_leave(butler_t *b)
{
        pthread_mutex_lock(&b->mtx);
        b->count++;
        pthread_cond_broadcast(&b->cond);
        pthread_mutex_unlock(&b->mtx);
}

void *
philosopher(void *param)
{
        static char * fork_names[2] = { "left", "right" };
        placesetting_t *place = (placesetting_t *)param;
        struct timespec delay;
        int first;

        delay.tv_sec = 0;

        while (!g_stopped) {
                /* Request permission from the butler */
                butler_enter(place->butler);

                /* Randomly pick which fork to choose */
                first = rand() & 1;

                /* Wait for up to 100 ms */
                delay.tv_nsec = rand() % 100000000;
                nanosleep(&delay, NULL);

                /* Get first fork */
                printf("Philosopher %d waiting for %s fork\n",
                        place->number, fork_names[first]);
                pthread_mutex_lock(place->forks[first]);
                printf("Philosopher %d %s fork up\n",
                        place->number, fork_names[first]);

                first = !first;

                /* Wait for up to 100 ms */
                delay.tv_nsec = rand() % 100000000;
                nanosleep(&delay, NULL);

                /* Get second fork */
                printf("Philosopher %d waiting for %s fork\n",
                        place->number, fork_names[first]);
                pthread_mutex_lock(place->forks[first]);
                printf("Philosopher %d %s fork up\n",
                        place->number, fork_names[first]);

                /* Wait for up to 100 ms */
                delay.tv_nsec = rand() % 100000000;
                nanosleep(&delay, NULL);

                /* Release forks */
                printf("Philosopher %d %s fork down\n",
                        place->number, fork_names[first]);
                pthread_mutex_unlock(place->forks[first]);
                first = !first;
                printf("Philosopher %d %s fork down\n",
                        place->number, fork_names[first]);
                pthread_mutex_unlock(place->forks[first]);

                /* Tell the butler we're leaving */
                butler_leave(place->butler);
        }
}

int
main(int argc, char **argv)
{
        int             count;
        pthread_mutex_t *forks;
        placesetting_t  *places;
        pthread_t       *philosophers;
        int             i;
        int             ret, sig;
        sigset_t        set;
        butler_t        butler;

        if (argc != 2) {
                printf("usage: %s count\n", argv[0]);
                return EXIT_FAILURE;
        }
        count = atoi(argv[1]);
        if (count <= 1) {
                printf("usage: %s count\n", argv[0]);
                return EXIT_FAILURE;
        }

        printf("Running with %d philosophers\n", count);
        srand(time(NULL));

        /* Initialize the butler */
        butler_init(&butler, count-1);

        /* Create the placesettings */
        forks = malloc(count * sizeof(pthread_mutex_t));
        places = malloc(count * sizeof(placesetting_t));
        philosophers = malloc(count * sizeof(pthread_t));

        for (i = 0; i < count; i++) {
                pthread_mutex_init(&forks[i], NULL);
                places[i].number = i+1;
                places[i].forks[0] = &forks[i];
                places[i].forks[1] = &forks[(i+1)%count];
                places[i].butler = &butler;
        }

        /* Create the philosopher threads */
        sigemptyset(&set);
        sigaddset(&set, SIGINT);
        pthread_sigmask(SIG_BLOCK, &set, 0);

        for (i = 0; i < count; i++) {
                ret = pthread_create(&philosophers[i], NULL, philosopher,
                        &places[i]);
                assert(ret == 0);
        }

        sigwait(&set, &sig);
        /* This is not technically thread-safe, but it will do */
        g_stopped = 1;

        for (i = 0; i < count; i++) {
                ret = pthread_join(philosophers[i], NULL);
                assert(ret == 0);
        }

        return EXIT_SUCCESS;
}
```

A.4 Dynamic Memory

```
#include <assert.h>
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

int
main()
{
        pthread_mutex_t *a, b = PTHREAD_MUTEX_INITIALIZER, *save;

        save = a = malloc(sizeof(pthread_mutex_t));
        pthread_mutex_init(a, NULL);
        pthread_mutex_lock(a);
        pthread_mutex_lock(&b);
        pthread_mutex_unlock(a);
        free(a);
        a = malloc(sizeof(pthread_mutex_t));
        assert(a == save);
        pthread_mutex_init(a, NULL);
        pthread_mutex_lock(a);
        pthread_mutex_unlock(a);
        pthread_mutex_unlock(&b);

        return (0);
}
```

A.5 Solaris Kernel Module

```
#include <sys/types.h>
#include <sys/stat.h>
#include <sys/modctl.h>
#include <sys/cmn_err.h>
#include <sys/errno.h>

#include <sys/systm.h>
#include <sys/ddi.h>
#include <sys/sunddi.h>
#include <sys/devops.h>
#include <sys/conf.h>

#include "badlock.h"

static dev_info_t *badlockdrv_devi;

static int
badlockdrv_open(dev_t *devp, int flag, int otyp, cred_t *cred_p)
{
        return (0);
```

```
}

static int
badlockdrv_close(dev_t dev, int flag, int otyp, cred_t *cred_p)
{
        return (DDI_SUCCESS);
}

static int
badlockdrv_ioctl(dev_t dev, int cmd, intptr_t data, int flag, cred_t *cred,
    int *rvalp)
{
        switch(cmd) {

        /*
         * This checks the obvious case, where we acquire A then B in one case,
         * and later acquire B then A.  This should be recognized as an error.
         */
        case BADLOCK_CHECK_ORDER:
        {
                kmutex_t a, b;

                mutex_init(&a, NULL, MUTEX_DRIVER, NULL);
                mutex_init(&b, NULL, MUTEX_DRIVER, NULL);

                mutex_enter(&a);
                mutex_enter(&b);
                mutex_exit(&a);
                mutex_enter(&a);
                mutex_exit(&a);
                mutex_exit(&b);

                mutex_destroy(&a);
                mutex_destroy(&b);
        }
        break;

        /*
         * This checks that memory that we free is not erroneously identified
         * as the same lock.  This should NOT produce an error.  What we are
         * going to do is:
         *
         * allocate A from cache
         * lock X
         * lock A
         * unlock A
         * unlock X
         * return A to cache
         *
         * allocate B from cache (same address)
         * lock B
```

```
 * lock X
 * unlock X
 * unlock B
 * return B to cache
 *
 * By address, this would be a locking violation.  But by the fact that
 * it is freed, A and B should be considered different locks.
 */
case BADLOCK_CHECK_FREE:
{
        kmutex_t x;
        kmutex_t *a, *b;
        kmem_cache_t *mutex_cache;


        mutex_init(&x, NULL, MUTEX_DRIVER, NULL);
        mutex_cache = kmem_cache_create("badlock_cache",
            sizeof (kmutex_t), 0, NULL, NULL, NULL, NULL, NULL, 0);

        a = kmem_cache_alloc(mutex_cache, KM_SLEEP);
        mutex_init(a, NULL, MUTEX_DRIVER, NULL);
        mutex_enter(&x);
        mutex_enter(a);
        mutex_exit(a);
        mutex_exit(&x);
        mutex_destroy(a);
        kmem_cache_free(mutex_cache, a);

        b = kmem_cache_alloc(mutex_cache, KM_SLEEP);
        mutex_init(b, NULL, MUTEX_DRIVER, NULL);
        mutex_enter(b);
        mutex_enter(&x);
        mutex_exit(&x);
        mutex_exit(b);
        mutex_destroy(b);
        kmem_cache_free(mutex_cache, b);

        kmem_cache_destroy(mutex_cache);
        mutex_destroy(&x);

        /*
         * We want to make sure that we did in fact allocate to the
         * same address.  This should always be true, considering that
         * no one else if using this cache.
         */
        if (a != b)
                return (-1);
        else
                return (0);
}
break;
```

```
        /*
         * This case checks that recursive read locks on rwlocks are correctly
         * identified.  If a read lock is taken on a rwlock that is already
         * owned for reading, an intervening write lock could result in a
         * deadlock.
         */
        case BADLOCK_CHECK_RWLOCK:
        {
                krwlock_t lock;

                rw_init(&lock, NULL, RW_DRIVER, NULL);
                rw_enter(&lock, RW_READER);
                rw_enter(&lock, RW_READER);
                rw_exit(&lock);
                rw_exit(&lock);
                rw_destroy(&lock);
        }
        break;

        /*
         * This case checks that IPL-dependent functions are detected.  Any
         * allocations with KM_SLEEP cannot be done with thread_free_lock held,
         * because it implicitly relies on I/O completion routines for
         * the pageout daemon, which require Interrupts at level 7 to be
         * serviceable.  Since the clock routine runs at level 10 and requires
         * thread_free_lock, we have a potential deadlock.
         */
        case BADLOCK_CHECK_PIL:
        {
                void * mem;

                mutex_enter(&thread_free_lock);

                mem = kmem_alloc(1, KM_SLEEP);
                kmem_free(mem, 1);

                mutex_exit(&thread_free_lock);
        }
        break;

        default:
                return (-1);
        }

        return (0);
}

static int
badlockdrv_info(dev_info_t *dip, ddi_info_cmd_t infocmd, void *arg, void **result)
{
        int error;

        switch (infocmd) {
        case DDI_INFO_DEVT2DEVINFO:
                *result = (void *) badlockdrv_devi;
                error = DDI_SUCCESS;
                break;
        case DDI_INFO_DEVT2INSTANCE:
                *result = (void *)0;
                error = DDI_SUCCESS;
                break;
        default:
                error = DDI_FAILURE;
        }
        return (error);
}

static int
badlockdrv_attach(dev_info_t *devi, ddi_attach_cmd_t cmd)
{
        switch (cmd) {
        case DDI_ATTACH:
                break;

        case DDI_RESUME:
                return (DDI_SUCCESS);

        default:
                return (DDI_FAILURE);
        }

        if (ddi_create_minor_node(devi, "badlock", S_IFCHR,
            0, DDI_PSEUDO, 0) == DDI_FAILURE) {
                ddi_remove_minor_node(devi, NULL);
                return (DDI_FAILURE);
        }

        badlockdrv_devi = devi;

        ddi_report_dev(devi);
        return (DDI_SUCCESS);
}

static int
badlockdrv_detach(dev_info_t *devi, ddi_detach_cmd_t cmd)
{
        switch (cmd) {
        case DDI_DETACH:
                break;

        case DDI_SUSPEND:
                return (DDI_SUCCESS);

        default:
                return (DDI_FAILURE);
        }

        ddi_remove_minor_node(devi, NULL);
        return (DDI_SUCCESS);
}

/*
 * Configuration data structures
 */
static struct cb_ops badlockdrv_cb_ops = {
        badlockdrv_open,        /* open */
        badlockdrv_close,       /* close */
        nulldev,                /* strategy */
        nulldev,                /* print */
        nodev,                  /* dump */
        nodev,                  /* read */
        nodev,                  /* write */
        badlockdrv_ioctl,       /* ioctl */
        nodev,                  /* devmap */
        nodev,                  /* mmap */
        nodev,                  /* segmap */
        nochpoll,               /* poll */
        ddi_prop_op,            /* cb_prop_op */
        0,                      /* streamtab */
        D_MP | D_NEW            /* Driver compatibility flag */
};

static struct dev_ops badlockdrv_ops = {
        DEVO_REV,               /* devo_rev, */
        0,                      /* refcnt */
        badlockdrv_info,        /* getinfo */
        nulldev,                /* identify */
        nulldev,                /* probe */
        badlockdrv_attach,      /* attach */
        badlockdrv_detach,      /* detach */
        nulldev,                /* reset */
        &badlockdrv_cb_ops,     /* cb_ops */
        (struct bus_ops *)0,    /* bus_ops */
};

static struct modldrv modldrv = {
        &mod_driverops,         /* Type of module.  This one is a driver */
        "Bad Lock Driver",      /* name of module */
        &badlockdrv_ops,        /* driver ops */
};

static struct modlinkage modlinkage = {
        MODREV_1, (void *)&modldrv, NULL
};

int
_init(void)
{
        return (mod_install(&modlinkage));
}

int
_fini(void)
{
        return (mod_remove(&modlinkage));
}

int
_info(struct modinfo *modinfop)
{
        return (mod_info(&modlinkage, modinfop));
}
```

A.6 Solaris Kernel Module Header

```
#ifndef _BADLOCK_H
#define _BADLOCK_H

#ifdef  __cplusplus
extern "C" {
#endif

#define BADLOCK_CHECK_ORDER     1
#define BADLOCK_CHECK_FREE      2
#define BADLOCK_CHECK_RWLOCK    3
#define BADLOCK_CHECK_PIL       4

#define BADLOCK_MIN             1
#define BADLOCK_MAX             4

#ifdef  __cplusplus
}
#endif

#endif  /* _BADLOCK_H */
```

A.7 Solaris Kernel Driver

```
#include <stdio.h>
#include <sys/ioctl.h>
#include <stdlib.h>
```

```
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <unistd.h>

#include "badlock.h"

int
main(int argc, char **argv)
{
        int fd;
        int i;

        if ((fd = open("/dev/badlock", O_RDWR)) == -1) {
                fprintf(stderr, "Unable to open /dev/badlock\n");
                return (EXIT_FAILURE);
        }

        for (i = BADLOCK_MIN; i <= BADLOCK_MAX; i++) {
                if (ioctl(fd, i) < 0) {
                        fprintf(stderr, "ioctl() %d failed\n", i);
                        return (EXIT_FAILURE);
                }
        }

        if (close(fd) < 0) {
                fprintf(stderr, "close() failed for /dev/badlock\n");
                return (EXIT_FAILURE);
        }

        return (EXIT_SUCCESS);
}
```