# AN EXECUTION CONTEXT OPTIMIZATION FRAMEWORK FOR DISK ENERGY

by

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## ABSTRACT OF THE DISSERTATION

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Power, energy, and thermal concerns have had explosive growth in research over the past two decades. In servers, desktops, and mobile systems, the hard disk is among the top resources in power and energy consumption. Common techniques for reducing disk energy consumption have included caching, adaptive low power modes, batch scheduling, and data migration. Many previous software optimizations for single disk systems have assumed and experimented in uniprogramming environments. However, modern systems are typically multiprogramming, and the optimizations do not extend well from the uniprogramming model. Programs should be aware of concurrently running programs to enable cooperation and coordinate disk accesses from multiple programs. The set of concurrently running programs is referred to as an execution context. Execution context optimizations were introduced to target multiprogramming environments. My research introduces an optimization framework to provide execution context information and reduce disk energy consumption by effectively managing disk accesses.

Optimizing over all possible execution contexts is counter-productive because many contexts do not occur in practice. For an extreme example, users rarely, if at all, run more than twenty programs concurrently. Optimizations may be profitably targeted at the most common execution contexts for a given workload. A study was conducted of real workloads by collecting user activity traces and characterizing the execution contexts. Out of hundreds of contexts and over 50 unique programs, the study confirmed the intuition that users generally run only a small set of programs at a time.

Execution context optimizations were implemented on eight streaming and interactive applications. The optimizations were compared to previous best optimizations and evaluated on a laptop disk which is already designed for energy efficiency. The disk energy was measured while running synthetic traces of ten execution contexts. The results show up to 63% energy savings while incurring less than 1% performance delay. When compared to unoptimized versions, energy savings was up to 77%. If the optimizations were applied to comparable applications in the user study, an estimated 9% disk energy could have been saved. Execution context optimizations show significant promise for saving disk energy.

# Acknowledgments

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Most importantly, to the Creator and Savior, I have yet to know how I have made it thus far except to acknowledge Your grace poured out over me. I am profoundly indebted and hope that my profession of research demonstrates grace in the career of life.

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# Chapter 1

# Introduction

Energy, power, and thermal issues are important computing system design considerations for a variety of reasons. Energy efficiency and conservation is a popular trend as global energy demands outpace the growth in supply. Power and heat correspond to cooling issues which may require additional energy for external cooling systems. In battery-powered systems, the battery's energy supply gives a finite, useful computing time before recharging or replacement. Increasing energy efficiency means longer operational times, greater flexibility, lower cost, or smaller form factors, is desirable for computing systems in general, and can be addressed at various hardware and software levels. This research is a language level approach at reducing disk energy consumption in multiprogramming environments.

## 1.1 Disk Energy

For many computing systems, the display, processor, and disk are generally regarded as the largest power consumers on average. Different configurations will change the relative percentages of power consumption. For example, servers may not have dedicated displays yet include multiple processors with multiple disks attached. Smaller scale battery-powered systems have taken advantage of more power efficient devices, but the display, processor, and disk remain proportionally among the top power consumers. Besides hardware advances, much research has been devoted to software logic for managing the display (e.g., dimming, power off, and selective dimming) and minimizing resource usage (e.g., caching). Many previous optimizations have focused on disk energy management from individual programs, but real world multiprogramming environments need cooperation system-wide by all programs. That is, the disk is a single resource but accessed by many applications running (concurrently) on the system. Managing disk energy across all applications can provide significant energy savings.

## 1.2 Background

Resource energy management is challenging in multiprogramming environments. The large disparity in latency between the processor and memory storage devices led to the design of multiprogramming which allows multiple programs to run in batches. Operating systems (OS) use short time slices, on the order of ten milliseconds, before switching contexts to give the illusion of simultaneous execution. When programs want to access system resources, such as the memory or network, the OS mediates among them so their accesses can be interleaved yet remain independent. The OS provides the abstraction of a complete, virtual computing system to each program. The virtualized computing paradigm allows a programmer, in many cases, to develop a program as if it were in a uniprogramming environment. The uniprogramming model simplifies the programming abstraction since a program can be oblivious to how other programs operate. In turn, when applying optimizations on a program, compilers might be oblivious to its effects on other programs.

For disks, typical energy management techniques when workloads decrease involve voltage scaling, switching rotational speeds with multi-speed disks, or changing to lower power operational modes. The basic hibernation strategies rely upon the OS to monitor the disk's workload. When the workload has decreased for some period of time, then the OS may decide to reduce the power draw. However, if the time threshold is too long, many opportunities to save energy are missed. If the time threshold is too short, both performance and energy can suffer from too aggressive hibernation. Compiler optimizations have been developed to more precisely identify when the disk can profitably hibernate between a program's disk accesses, enable hibernation opportunities by clustering a program's disk accesses, and even increase the opportunities such as with prefetching.

Many of these optimizations were designed with a uniprogramming model. Yet most modern systems use a multiprogramming model of execution, and the benefits from the uniprogramming optimizations degrade when run in actual multiprogramming environments. Physical resources can hibernate only when no program is actively accessing it, but the uniprogramming model has no knowledge of other programs. For instance, program $A$ may be idle and hint for the disk to hibernate, but shortly afterward, program $B$ may access the disk. Program $B$ must then tell the disk to wakeup and perhaps waste more energy waiting for the transition. If the programs are aware of each other, they may cooperate to provide better hints about when the disk is truly in an idle period. I refer to a set of running programs as an execution context. The execution context inherently contains information which can aid programs to adapt their behavior and cooperate for better overall energy consumption.

## 1.3 Thesis

Execution context optimizations can significantly reduce disk energy consumption in multiprogramming environments. Clustering disk requests across multiple cooperating programs increases hibernation opportunities for saving energy. If programs categorize their types of disk request behaviors, a compilation and runtime framework can facilitate cooperation and adapt program behavior according to the execution context. Identifying the most common execution contexts will reveal the greatest opportunities for saving energy. The significant benefits of execution context optimizations can be verified through physical measurements of representative or actual workloads.

## 1.4 Contribution

Clustering disk requests within a single program is useful for saving energy in uniprogramming environments. I developed an optimization technique to cluster disk requests by adding user level buffering for streaming applications. In multiprogramming environments, disk requests from multiple programs should be clustered to save energy. I extended the clustering technique to multiprogramming by developing a synchronization policy for programs to cooperate.

With multiprogramming environments, execution contexts contain important information about how programs should adapt their disk request behavior to cooperatively save energy. I categorized the disk request behaviors into four types and designed new language keywords to expose these behaviors to a compiler. Another characteristic of multiprogramming environments is the changing state of concurrently running programs. Taken together, I modeled execution contexts and the transitions between them as states in a finite state machine. When a program exits or a new program starts, the execution context transitions to a new state. A state diagram conveniently encapsulates the information about execution contexts and provides the necessary information for programs to adapt their behavior.

My generalized framework for applying execution context optimizations on $n$ programs would consider the $2^n$ possible combinations of running programs. However, the optimizations can be targeted at the most common cases. I conducted a user study to identify some of the most common cases in actual user workloads. The user study also confirmed the intuition that many users typically run a small number of programs at a time. These activity profiles are important in demonstrating the feasibility of execution context optimizations. If people mostly use a single program at a time, then the uniprogramming model suffices. If people regularly use ten programs at a time, then there may likely be no opportunity at all to save energy.

I measured and verified disk energy savings by developing a physical measurement infrastructure. I implemented the execution context optimizations on eight programs and created ten combinations of programs. I generated synthetic traces for the ten states and compared the energy consumption of the optimized and baseline programs. The baseline programs used disk clustering optimizations from the uniprogramming model. On a laptop class disk, which is already designed for energy efficiency, execution context optimizations can save up to 63% energy than the baseline optimizations. Lastly, I developed a disk energy model to estimate energy savings based on disk activity profiles. If a representative synthetic trace can be generated for a state, then the energy model can help analyze expected energy savings and guide the optimization efforts.

# Chapter 2

# Literature Review

This thesis work consists broadly of three areas — disk energy management, execution context aware optimization, and surveying user activity. I will review the literature according to these areas. The existing literature on energy management is extensive over the past two decades, but the areas of execution context aware optimization and surveying user activity have received little attention and only within specific domains.

## 2.1 Disk Energy Management

In the early 1990's, computer system energy conservation became a major effort in the United States, spearheaded by the ENERGY STAR joint program of the Environmental Protection Agency and the Department of Energy. Hardware manufacturers began designing components with multiple power modes. The simple idea is that a component should switch to a lower power mode when not being used. However, performance and energy concerns are often at odds with each other, and tradeoffs must be evaluated to satisfy performance demands with minimal energy. Researchers have approached the problem by starting with power models of various components. The power characteristics of a component may influence the policies to manage a resource's power consumption. Different classes of disks may employ energy saving strategies tailored to their environment. Emerging and alternative disk technologies along with new applications have also led to new strategies for optimizing resource usage.

### 2.1.1 Modeling

Some of the earliest efforts at modeling the hard disk were done by Ruemmler and Wilkes [63], Ganger [27], and Greenawalt [29]. Greenawalt formulated the basic equations accounting for the power consumed at different operating modes. Without prior guidance, manufacturers began using fixed timeout thresholds on the order of minutes. Timeout thresholds monitor the length of past idleness before switching to a low power mode. For years, the timeout thresholds remained on the order of minutes even though Greenawalt's models showed that significant energy could be saved by using short timeout thresholds. Greenawalt's analysis agreed with earlier work by Douglis and Marsh for setting timeout values on the order of seconds.

Golding et al., motivated by disk hibernation issues, investigated the general aspect of predicting and detecting idle time [28]. Improving such analysis is useful to enlarge the opportunities for the OS to hibernate resources. Ganger developed the DiskSim project to simulate the disk storage subsystem while Shriver et al. formulated analytical performance models of many aspects in storage systems [69]. More recently, Zedlewski et al. used power modeling to augment DiskSim with a power dimension [76].

Multi-speed disks have attracted attention due to their unique ability for multiple power levels in active modes. Independently and simultaneously, Gurumurthi et al. [31] and Carrera et al. [12] developed the early power models for such disks. The low power active modes are analogous to a processor's reduced clock frequency modes. At lower speeds, energy may be saved proportional to the square of the reduced voltage.

### 2.1.2 Policies

System designers have collaborated to develop holistic system policies governing the power behavior of various components. The Advanced Power Management [39] specification sought to standardize and simplify power management between hardware and the OS. It has been superceded by the Advanced Configuration and Power Interface [40]. Many previous limitations have been eliminated, however the new interface is extensive, complex, and prone to implementation errors. It has found broad support, but simpler policies may prove more effective.

Douglis et al. developed and analyzed several static policies for managing energy consumption at the OS level [21]. They used a trace-driven simulator to demonstrate that shorter timeout values can approach an optimal case. However, they note that any optimal settings will depend on the workload and physical disk. Li et al. worked on a detailed quantitative analysis of disk power consumption under a range of timeout values [45]. Without naming a specific policy, their results concluded that a timeout of two seconds was optimal for their workload traces.

Since optimal timeout values vary with workload, some researchers have designed adaptive policies. Douglis et al. describe a method for monitoring disk accesses and adapting the timeout threshold to save energy while keeping performance within an acceptable level [20]. Helmbold et al. apply a machine learning technique which adapts the timeout based on the weighted average of other algorithms [34]. The weights and timeout are adjusted periodically to minimize energy usage. Lu et al. describe a comprehensive OS approach to manage power for many resources [48].

Adaptive policies attempt to predict future disk request arrivals based on recent history, but even the best algorithms will lag somewhat in predicting requests. Another approach is the use of scheduling policies to transform requests into more predictable patterns. These policies try to determine expected requests through compiler or programmer inserted hints. Considerable research has used hints to dynamically adjust processor frequency and voltage [70, 1, 8, 38]. Weissel et al. developed Cooperative I/O [71] which gives hints to the OS via modified I/O system calls. The OS may defer requests to be clustered with others or abort requests which have become unnecessary. Hints have also guided disk caches for performance and energy efficiency [54, 41, 2, 53, 80]. At the file system level, a new scheduling system [17] uses adaptive buffering and reservations to provide disk bandwidth guarantees for real-time applications. An extension of the system may implement scheduling for optimizing power consumption.

My research has developed a scheduling policy which clusters disk requests across multiple programs. The concept is similar to implicit co-scheduling [7] where a process infers the status of related jobs and decides whether to yield the processor. My technique to cluster disk requests is a variant on barrier synchronization [52]. The net effect of clustering is to optimize for bursts of activity, which contrasts the notion of scheduling for average utilization and throughput such as with the slotted ALOHA system [3, 57].

### 2.1.3 Management Techniques for Various Disks

Different classes of disks have very different performance and power characteristics. Their intended application use may influence which energy management techniques are suitable. Broadly speaking, disks are categorized for servers, desktops, laptops, and handhelds. Handheld class disks refer to the 1.8" or 1" form factors. Some systems may use a set of disks arranged as a Redundant Array of Inexpensive Disks (RAID).

Energy management of disk farms for server type systems are important because they account for a significant portion of the total power consumption [78]. Chase et al. devised a system to assign monetary costs to various subsystems and demonstrate the tangible financial costs associated with energy for each resource [13]. For enterprise computing clusters with many disks, Colarelli and Grunwald designed a new type of storage hierarchy using massive arrays of idle disks (MAID) [14]. They allocate some drives to serve as large caches and power manage the remaining drives. Zhu et al. [78] and Pinheiro et al. [55, 56] develop the idea further by adding data migration with multi-speed disks. Li et al. analyzed several parts of the storage hierarchy for both performance and energy [46]. Their technique adapts to changing activity workloads through the use of multi-speed disks and predicting expected slack times. A similar study investigates the same techniques in systems employing very large disk caches, on the order of gigabytes [79].

Desktop systems may not be so concerned with energy because the scale is much smaller than servers. Battery powered systems, typically with laptop and hand-held class disks, clearly have a prime concern with energy. Some energy conserving approaches have included remote processing [49, 61] and power management techniques. Power management also arises from strategies such as adaptive applications and caching. Write caching with the write-back policy is an effective technique for improving disk performance and energy [62, 80]. The write-back policy allows data to be written in batches to the disk, but there is a minor concern for data corruption or loss in the intervening time until the data is flushed to disk. The net effect of the write-back policy is similar to and overlaps with my technique for clustering disk requests. My experiments examined both the write-back and write-through policies, and their differences will be evaluated in Chapter 6.

### 2.1.4 Alternative Storage

Besides the traditional magnetic hard disk, flash memory has been considered as an alternative storage device. Douglis et al. explored this alternative and reported on the tradeoffs compared to the hard disk [19]. Historically, flash memory has had performance and energy advantages but has not been cost effective due to its high cost. Even today, flash memory still costs about an order of magnitude more than the hard disk. Disk technology has caught up to be competitive with flash in performance. Hence, the hard disk continues as the medium of choice for high performance large storage at low cost.

Flash memory has gained popularity in a variety of products such as video players, music players, digital cameras, and portable disk storage. High performance is less of an issue whereas small form factor, low energy use, and motion shock resistance have enabled emerging market opportunities. For instance, the Apple iPod [6] started as an audio player and has evolved into a general purpose system with a variety of applications such as a photo viewer, video player, web browser, and more with the upcoming availability of a software development kit.

## 2.2 Adaptive Applications

Energy management may occur at many levels within hardware and software. Several researchers have used the end-to-end argument [64] to suggest energy management at the application level. Lorch and Smith discuss the issues at various levels and note how application level management holds much potential [47]. A group of researchers developed the Odyssey platform which allows applications to adapt their behavior for network or energy concerns [50, 51, 25]. Zeng et al. and Ellis make the case for managing energy as a first class resource at the software levels [23, 77].

Mechanisms for adapting application behavior have been targeted towards quality of service issues. Such issues are prominent in mobile application domains where geographic location and wireless network connectivity changes. Katz gave a broad, seminal overview on the issues and challenges facing mobile systems [42]. Schilit et al. motivate the issues with practical examples and prototypes of context-aware applications [67]. As their ParcTab prototype device moves geographically, applications dynamically discover changes in location, neighboring devices, services, and network bandwidth. Campbell et al. [9] and Capra et al. [10] describe middleware platforms to expressly support adaptive mobile applications. Services have well-defined interfaces, appplications have profiles, and their interactions will be correlated through the current context. However, I am not aware of any other research investigating adaptive applications based on the runtime context of other applications. My approach for execution context aware adaptations aims to be applicable for servers, handhelds, and everything in between.

## 2.3 Surveying User Activity

Within experimental computer science, many researchers focus on measuring and quantifying hardware or software aspects. Entire conferences are devoted to measuring the very tools we work on. Yet little research goes into the interactions of users and software. The few studies I am aware of deal with characterizing human interactive behavior over different physical devices. Leland et al. provided one of the earliest studies on human activity as seen by ethernet traffic [44]. Crovella and Bestavros also study network traffic but more specifically on world wide web traffic [15]. Wolski et al. measured processor availability in remote systems [73] using their Network Weather Service [72]. Gribble et al. [30] and Roselli et al. [59] analyzed file system workloads with a perspective on how human activity patterns translate into actual file system activity. The conclusions drawn from all studies describe human interactivity patterns as self-similar. The inter-arrival times between significant events can be characterized by a Pareto distribution. In other words, activity is bursty. Either a user performs many events in a short period of time, or a user is idle for stretches at a time. The idle periods after bursts may be considered as human think time [15, 69]. My own user study on application usage patterns agrees with the self-similar characterizations of human activity.

# Chapter 3

# Optimization Framework

Clustering disk accesses is an important strategy for enabling hibernation opportunities. Disk caches and OS file system buffers employ this strategy to some degree of benefit. According to [62, 30, 59], most disk access patterns are small, bursty, and scattered across many files. Disk manufacturers, noting the benefits of caches, have added and increased cache sizes as technology improves. Larger caches increase the probability of containing relevant file blocks to be read in the near future or increase the potential efficiency of batched writes at a time. Modern disk caches are typically on the order of megabytes which can reasonably hold several blocks from many files. File system buffers replicate the effect of disk caching but use per file buffering typically on the order of hundreds of kilobytes. The size is smaller because the OS must consider there may be hundreds of open files in use, and many files tend to be small for system or metadata use. Applying the end-to-end argument for disk energy management suggests clustering disk accesses at the application level. I will start with a review of disk energy accounting. Then I will discuss optimization techniques in the uniprogramming model, followed by the challenges and possible solutions when extending the techniques to the multiprogramming model. Lastly, I will describe my implementation.

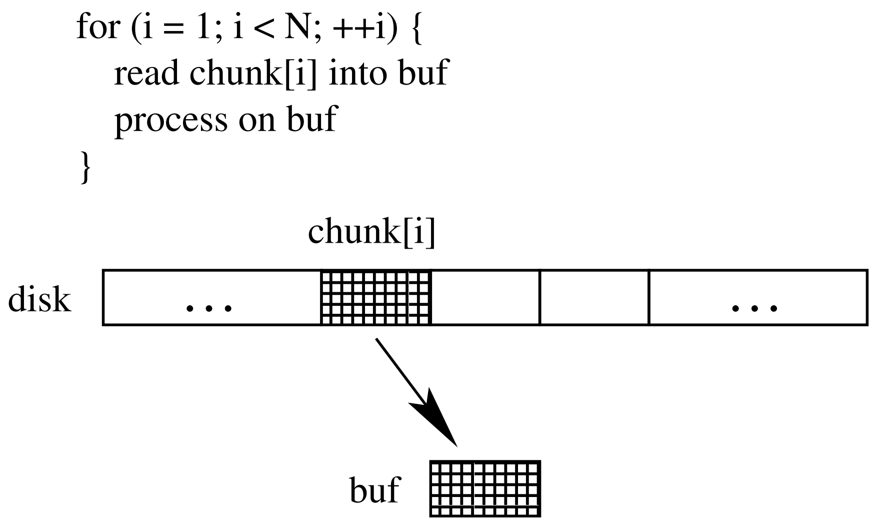
## 3.1 Disk Energy Accounting

Practically all hard disks support at least one low power operating mode with trade-offs between power consumed and time taken to switch between modes. When switching from the disk's idle mode to a low power mode, the lower the power mode requires more time to switch. The same is true for the reverse when switching from a low power mode to idle mode. The exact power modes, consumption, and switching time characteristics are unique to each disk model and generally provided by the manufacturer's specification sheet. For a given disk, let $P_m$ and $T_m$ be the power consumed and time spent in mode $m$. Most manufacturers do not specify transition mode costs or even average costs because they have a very wide range between the lower and upper bounds. Instead, I derived these average costs through physical measurement. The transition cost from mode $m$ to $n$ can be expressed in terms of average power ($P_{m \to n}$), time ($T_{m \to n}$), and energy ($E_{m \to n}$). Therefore, a disk's total energy consumption under a given workload period can be given by

$$E_{total} = \sum_i P_i \times T_i, \tag{3.1}$$

$$i \in \{\text{all operational and transitional modes}\}$$

With this analysis, a disk's energy break-even threshold can be calculated. The break-even threshold considers two cases for an idle disk. Either the disk remains in the idle mode or transitions to a low power mode, hibernates for some period, and transitions back to idle mode. The energy consumption in both cases can be plotted on a graph as linear functions of time. Their intersection point is the break-even threshold. Thus, if the disk will be idle for longer than the break-even threshold, the disk would save energy by hibernating in a low power mode. A more extensive treatment than is necessary here of break-even thresholds among multiple operational



```
for (i = 1; i < N; ++i) {
   read chunk[i] into buf
   process on buf
}
```

Figure 3.1: File access behavior of streaming applications.

modes can be found in [33]. Note that a disk's break-even thresholds are directly computed from its physical specifications which could either be stored on the disk or derived empirically [74, 68].

## 3.2 Uniprogramming

Application level clustering will benefit chiefly for accesses larger than the disk cache. Otherwise, the disk cache is sufficient for clustering. Hence, applications which use large data files are candidates. One such class of applications is characterized as streaming. Example programs include an audio player or file transfer. Their file access behavior consists of reading a chunk of data, processing it, and looping until the end. Figure 3.1 illustrates this behavior while Figure 3.2 shows the actual disk activity of an unmodified audio player.

The OS file buffer and the disk cache may have read-ahead policies which monitor for contiguous file reads. If consecutive file requests call for contiguous blocks, the file buffer and disk cache will read ahead and pre-fetch more than what is requested. However, the OS default file buffer is generally too small for streaming applications.

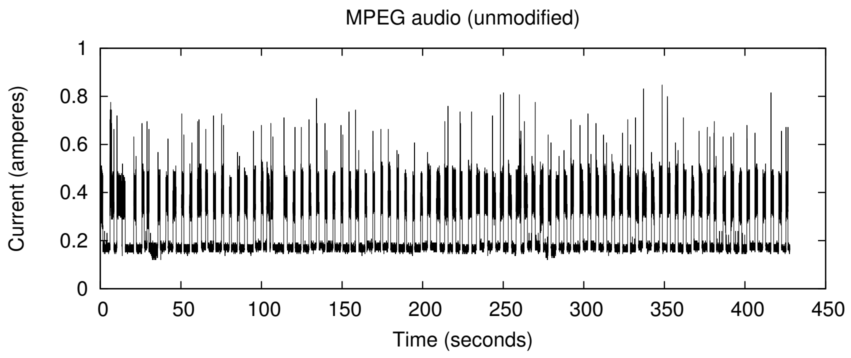


Figure 3.2: Disk activity of unmodified audio player.

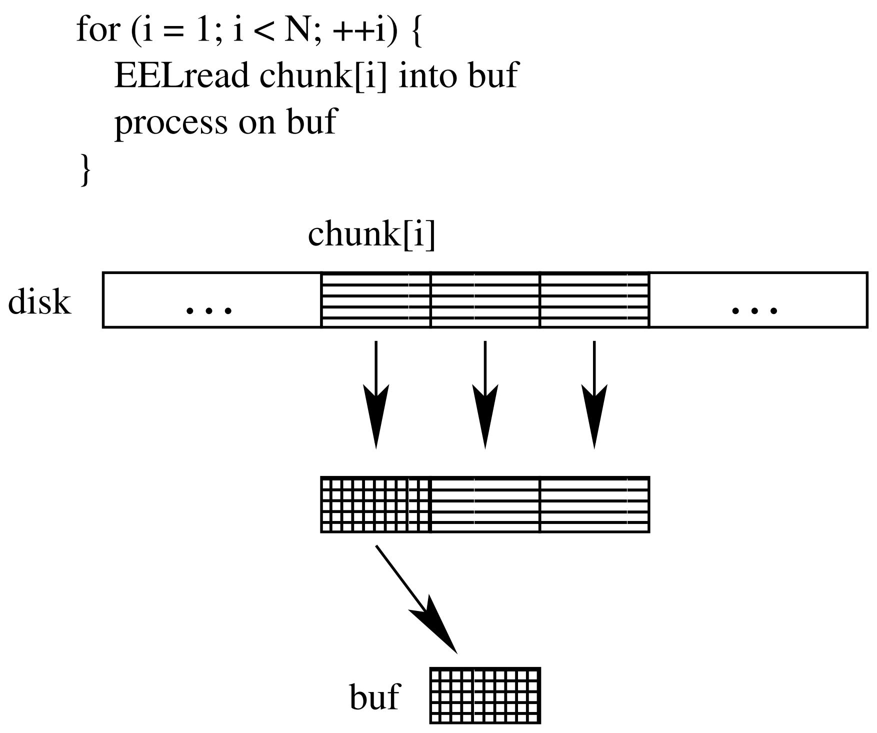
The pre-fetched data would not be enough to create idle time for hibernation. On the other hand, the disk's cache may hold enough data to support hibernation. Now the question is whether the idle period is greater than the break-even threshold. The disk knows its cache size, but crucially, it does not and cannot know when the next physical disk access will occur. In other words, when will the entire cache be consumed before pre-fetching again?

The information to answer that question resides at the application level. Another characteristic of streaming applications is their data consumption rate. For example, audio files may be encoded at different bit rates corresponding to their perceived playback quality. The encoding bit rate determines the runtime data consumption rate, which can be used to estimate when a buffer will be consumed. Therefore, the optimizations here are to add an application-level file buffer and use the data consumption rate to estimate the length of idle periods for disk hibernation. In order to add an application-level file buffer, I assume the system contains some amount of available memory. If at runtime there is not enough memory, then a buffer should not be added since doing so would induce virtual memory swapping to disk, which effectively destroys disk idleness.

My framework proposes a mechanism which is almost transparent to the programmer. Instead of implementing a buffer into the application directly, the programmer will use a new language keyword (e.g., `STREAMED`) to tag file descriptors with an attribute. The file descriptor corresponding to the stream data file may be prepended with `STREAMED`. A compiler transformation propagates the attribute tag across procedure boundaries to identify the `read` calls on this file descriptor. A `read` call is replaced with an enhanced read library function. For procedures which take a file descriptor as a formal parameter, they may be called with file descriptors without the `STREAMED` attribute. Those procedures can be modified to accept an additional parameter which explicitly indicates the attribute type. The compiler inserts code to choose the proper read operation based on the attribute. The enhanced read implements the application-level file buffer which is self-managing and can direct the disk into a hibernation mode. It manages itself by refilling when the buffer is consumed. Otherwise, the enhanced read behaves just as the original `read` by copying the requested bytes from the file buffer into the supplied local buffer. After transformation, Figure 3.3 depicts the buffered situation, and Figure 3.4 shows the disk activity of the buffered audio player.

When the original program calls the enhanced read, the key step is to first allocate a buffer. With the assumption of available memory, the process must determine how much is available. Although processes are normally oblivious to available memory because of the virtual memory abstraction, in this case, the process should be aware of memory constraints. A process may use a system call to query the OS about available memory. Using all available memory, if the allocated buffer can store the entire data file, then disk accesses are clustered into one, and the disk may hibernate for the maximum time.

Now suppose the allocated buffer cannot contain the entire file. The buffer must refill itself. However, the streaming application will block during the time to refill the buffer. Some streaming applications, such as an audio player, have a real-time aspect where a pause longer than some threshold significantly degrades the human



```
for (i = 1; i < N; ++i) {
   EELread chunk[i] into buf
   process on buf
}
```

Figure 3.3: File access behavior of buffered streaming applications.

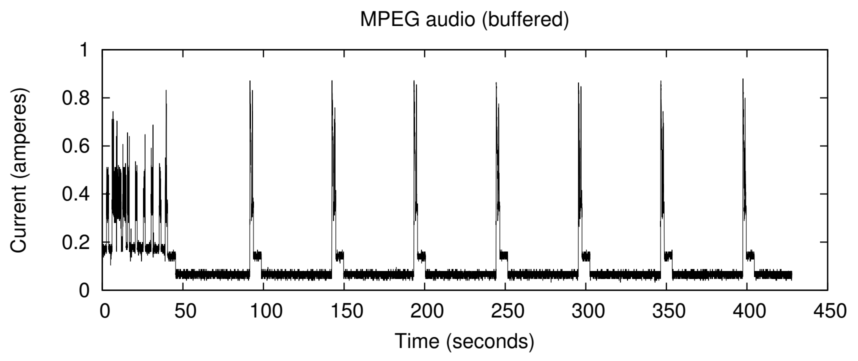


Figure 3.4: Disk activity of buffered audio player.

perceived performance of the application. In those cases, the buffer size should be set to the product of the disk's bandwidth and the pause threshold.

$$BufferSize = DiskBandwidth \times PauseLimit \tag{3.2}$$

The pause threshold may be a constant parameter in the compiler transformation, but the target disk's bandwidth is unknown at compile time. As with available memory, a system call would allow a process to query the OS for the disk's bandwidth, which should be a constant, as well as its break-even thresholds as noted above.

Once the buffer's size is set, the buffer needs to know only the data consumption rate to estimate the time until the buffer is consumed. As part of the buffer setup phase, the enhanced read function transparently profiles the main program's operation to estimate the consumption rate. With the buffer's size and consumption rate, the time until the buffer is consumed corresponds to the estimated idle period of the disk. Therefore, the buffer can compare the idle period with the disk's break-even thresholds to find the best hibernation mode and immediately direct the disk to that mode. In contrast to techniques using fixed or adaptive timeout thresholds, this technique takes advantage of the maximal hibernation time.

Lastly, the buffer should refill itself when empty. Various disk management techniques will have an inherent problem upon the disk's next access. The disk must first undergo a transition period from the low power to idle mode before servicing the next request. Yet the next access is generally unknown in advance, hence the wakeup transition is often initiated on demand. For streaming applications, the wakeup time cannot be factored into the buffer setup phase because it is already an order of magnitude greater than the pause threshold. However, the application-level file buffer contains a unique advantage by computing the idle time. In essence, the buffer does know when the next disk access will be as well as how long the disk's wakeup transition takes. The buffer can initiate the wakeup transition in advance such that the disk will be ready just when the next request arrives. The performance delay and energy penalty from wakeup is eliminated with just-in-time activation.

## 3.3 Multiprogramming

Multiprogramming with virtual memory and pre-emption allows many programs to run concurrently without worrying about interactions between programs. Managing disk energy is a different story since the disk is a shared, global resource. The OS pre-empts processes on short time slices to give multiple programs a chance to execute and give the illusion of simultaneous execution. Process execution is interleaved as scheduled by the OS. Hence disk access from multiple programs are also interleaved and increases disk utilization for overall performance. While one process waits for data from the disk, another process may execute on the processor. Yet for energy purposes, the disk should be given clustered requests as in the case for uniprogramming.

Now suppose two streaming programs have been optimized with buffering and run concurrently. The disk requests from each program will certainly be clustered, but the interleaving of even clustered disk requests disrupts and shortens the effective idle periods of the disk. Figure 3.5 shows the disk access pattern that results when buffered versions of an audio player and video player are run concurrently. Some profitable hibernation opportunities still exist, but several have been ruined. The access pattern begins to degenerate, vaguely resembling the unbuffered case of uniprogramming. There are a few problems to note. First, while one program's disk requests may occur periodically, they interleave with other programs and interfere with the idle periods. Second, one program's buffer, taking the uniprogramming view, assumed that the disk would be idle after a buffer refill and immediately directed the

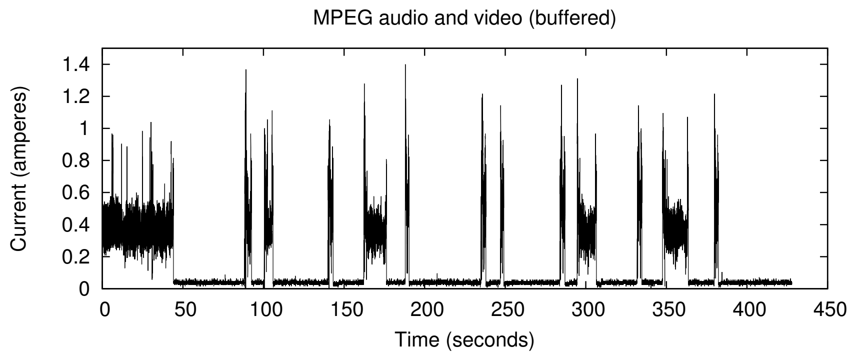


Figure 3.5: Disk activity of buffered audio player and video player.

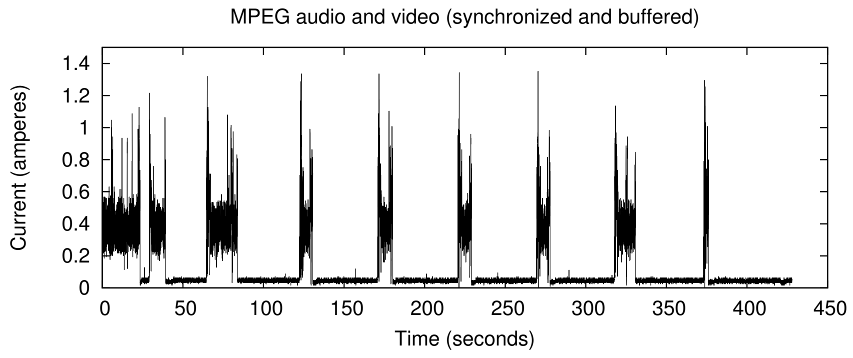


Figure 3.6: Disk activity of synchronized and buffered audio player and video player.

disk to hibernate while the other program's buffer became empty soon after and initiated a wakeup. If the accesses were aligned, the energy costs of transitioning from idle to low power and back to idle could have been saved. Third, disk requests from any two programs will never align except by chance because their frequencies are different. Even if their frequencies happened to be the same, they still need some way of first synchronizing their requests. Therefore, just as in the uniprogramming case, the solution is to cluster disk accesses but now across multiple programs. Figure 3.6 shows a disk access pattern where a buffered audio player and video player are cooperating to synchronize their disk requests.

### 3.3.1 Inverse Barrier

The notion of clustering disk requests from multiple programs shares a resemblance with scheduling jobs on a parallel processing system. To compare the problem domain with disk energy management, disk requests are like related jobs to be scheduled on the disk. The disk requests and jobs are unknown in advance when they will be ready to be scheduled. When jobs are ready on a parallel system, many techniques try to schedule related jobs together. Due to high communication and context switching costs, efficiency is increased when related jobs are scheduled together. For disks, Figure 3.5 demonstrates how each disk request from two applications incurs a transition cost of wakeup and hibernation. Clustering requests would eliminate transitions, amortize the costs, and lengthen the disk idle periods.

Many job scheduling policies revolve around some form of co-scheduling. Barrier techniques are well known and straight forward. A job will wait or suspend execution when reaching a barrier point until all jobs within its group has reached the barrier. Then they may be allowed to proceed or be co-scheduled on the ready queue. Using a barrier to cluster disk requests however will seriously impact performance for real-time applications. They should not wait for other applications to access the disk. Instead, quite the opposite should occur. A streaming application whose buffer is empty should certainly refill itself to maintain performance. Now that the disk has performed a wakeup transition, other applications may take advantage of the disk's ready state. For this purpose, I designed inverse barrier synchronization.

**Definition (Inverse Barrier).** Let a set of programs belong to a collective group. The protocol is a logical construct placed at an execution event and consists of a send and receive notification.

**Send** When a member program's execution reaches the inverse barrier, that member sends an announcement to all other members, informing them that the inverse barrier has been reached. The member may resume normal execution.

**Receive** When a member receives the announcement, it understands that the inverse barrier event has just occurred. It may take a relevant action based on its program state.

In contrast to regular barrier scheduling, the inverse barrier essentially causes all members to synchronize when one member reaches that point. Instead of waiting for other members, the inverse barrier conceptually pulls other members forward which implies that programs are always ready for the synchronization event. Figure 3.7 illustrates the differences between barrier and inverse barrier scheduling. Three programs $\{A, B, C\}$ are running concurrently. Programs $A$ and $B$ are streaming and exhibit periodic accesses while $C$ is interactive. Under barrier scheduling, $A$ and $B$ will wait for the other when they issue a disk request. Program $C$'s disk requests will wait for the other programs. The overall execution time is delayed. Under inverse barrier scheduling, when $A$ issues the first disk request, $B$ decides its buffer is near empty and pre-fetches early while $C$ decides its disk request can be issued early. In $B$'s case, early pre-fetches may require extra disk accesses, but the energy and performance costs remain the same. There were more disk accesses, but each disk access was shorter. The disk transition costs were already paid by $A$'s disk request. The following section will discuss the example of how $C$, an interactive program, may issue disk requests early.

### 3.3.2 File Descriptor Attributes

So far, the optimization for the uniprogramming model introduced one new keyword, `STREAMED`, to tag file descriptors with an attribute. To utilize synchronization in multiprogramming, the file buffer associated with the `STREAMED` attribute can be modified to implement synchronization. However, I would like to extend the opti-

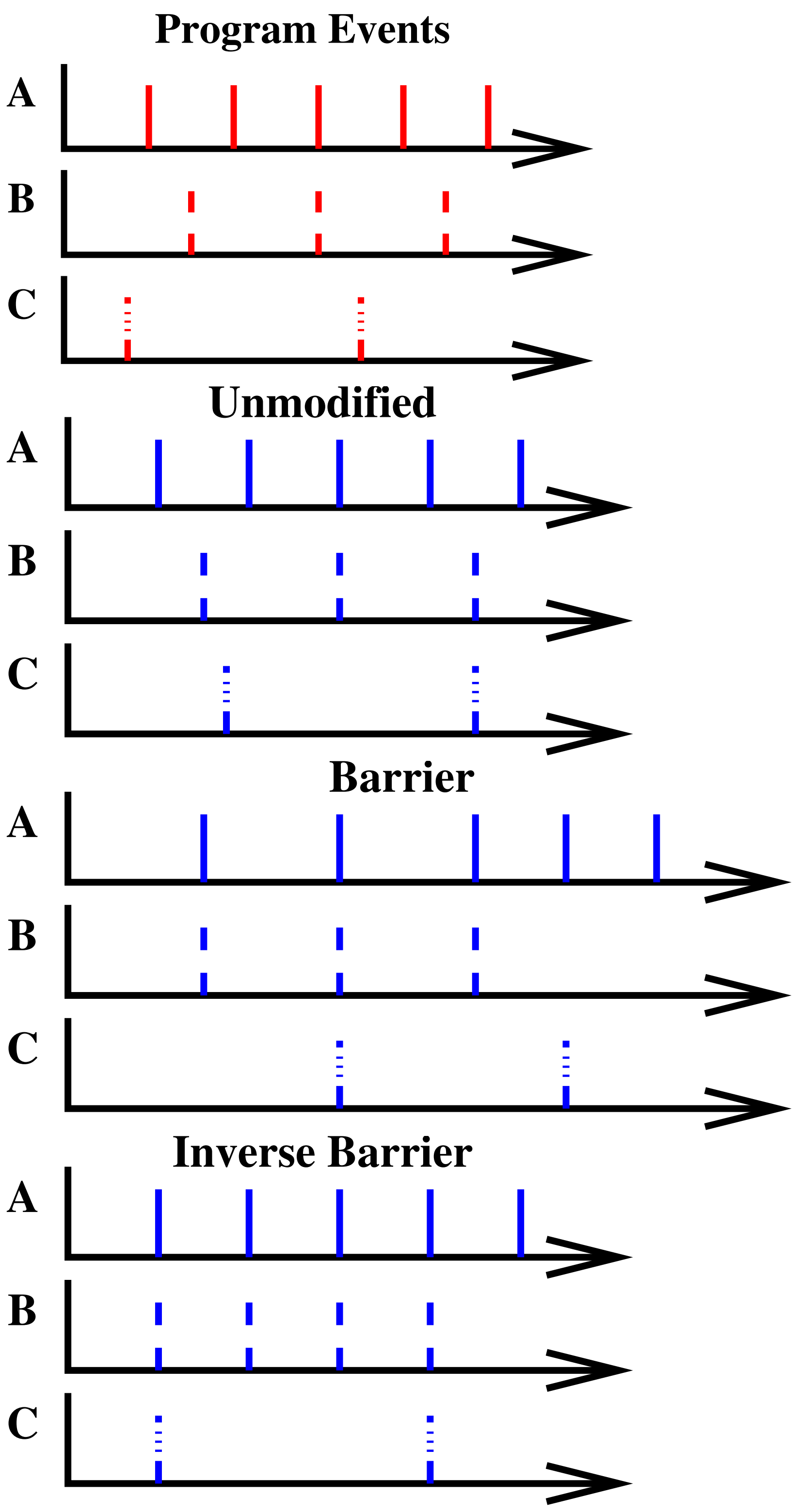


Figure 3.7: The effect of barrier and inverse barrier scheduling policies on disk accesses. Programs $A$ and $B$ are streaming while $C$ is interactive.

mization framework to include other classes of applications besides streaming. The goal is to have as many applications as possible be aware of synchronization and able to cooperate in the inverse barrier group. I have extended the framework by introducing three more file descriptor attributes: `BUFFERED`, `SYNC_RECV`, and `SYNC_SEND`.

The attributes are ordered hierarchically in that each attribute adds some new feature on top of those carried by the attribute below it. The `STREAMED` attribute is at the top and therefore already describes all the features of the other attributes. There is one new feature for `STREAMED` present in the multiprogramming model. Many systems use asynchronous disk access which can be exploited to remove the buffer size constraint. In uniprogramming, the size was limited according to Equation (3.2). For multiprogramming, I have introduced a child thread whose role is the Producer of a Producer-Consumer buffer. When the buffer is near empty, the child thread initiates a disk wakeup transition, refills the buffer, announces the inverse barrier, and initiates a disk hibernation transition. When receiving an inverse barrier announcement, the child thread checks whether the buffer is near empty. If yes, then follow the steps above. If no, then simply resume execution. The buffer's pre-fetched data will be ready, the original program will not experience any performance delay, and hence the buffer can use any available memory. Now I need only discuss the restricted set of features for the new attributes.

Many streaming applications are broadly categorized as non-interactive. The three new file descriptor attributes are designed for three kinds of interactive applications. For applications which read large data files but not in a streaming pattern, the `BUFFERED` attribute may be used. An example application is an Adobe PostScript (PS) viewer. A PS viewer displays a page of the document at a time. Deciding to display a new page and when is entirely dependent on the user's actions. I would expect that most PS documents are viewed sequentially, and adding a large file buffer with pre-fetching is suitable. There is no known data consumption rate since the user controls when to display a new page. Therefore, the compiler will replace original `read` calls with a version of the enhanced read which implements the buffer but does not include just-in-time activation.

The next category is a special class of applications. They do not access large data files in a sequential manner and hence cannot use the file buffer optimization. However, they can do a useful action when receiving a synchronization message. Example applications include document editors with an auto-save file backup feature. For example, after modifying a document, a program may set a timer. If the user is idle for that length of time, the program will automatically save the modifications to a backup version of the file. If the user has gone away or thinking very long about what to do next, then the auto-save operation could have occurred at any time with the same energy impact on the disk. But suppose that before the idle timer expired, another program accessed the disk. The auto-save feature could cluster its impending disk writes with the other program via synchronization and save energy from the extra transition costs. These applications are described above as program $C$ in Figure 3.7 and should use the `SYNC_RECV` attribute. An explicit save operation would trigger the synchronization send function. The special part for these applications is that the programmer must add a function to perform a useful task when receiving a synchronization message. At most, the compiler can add a dummy function which does nothing, but only the programmer will know an appropriate action to implement. The receive function would be similar to a signal handler waiting for synchronization messages. The `BUFFERED` and `STREAMED` attributes get a built-in receive function which refills the buffer. Since I developed the buffer, I knew the appropriate receive action.

Finally, almost any other application may access the disk in some regular way whether reading or writing a file. These applications may still participate in the synchronization protocol by using the `SYNC_SEND` attribute. Some example applications include document editors without auto-save, web browsers with file caching, and Adobe Portable Document Format (PDF) viewers. These applications access the disk in some predictable ways and can notify other applications for synchronized disk access. However, as far as I know, they do not have applicable receive actions. PDF viewers cannot use the `BUFFERED` attribute because the data layout uses a pointer-based index [5]. That is, page content is not stored sequentially as opposed to the PS format [4].

The file buffer from the `STREAMED` attribute, by knowing its buffer size and data consumption rate, could calculate the estimated idle time and immediately direct the disk to the optimal low power mode. The other three attributes have no such knowledge from interactive applications. The question remains then of when to hibernate the disk? With interactive applications, the best solutions from the literature suggest using a short fixed, an adaptive, or a predictive timeout. My experimental experience indicates that any of these solutions would be fine and approach optimal energy savings.

### 3.3.3 Execution Context

One area still missing from the treatment of adding file buffers to programs in a multiprogramming model concerns how much memory is available to allocate. Suppose one buffer optimized application begins execution, and its file buffer takes all available memory. If a second buffer optimized application starts execution, it will find no available memory and fall back to the unoptimized behavior without a buffer. If the second program is a streaming application, then its disk accesses will never hibernate and effectively ruin the optimizations in the first program. They may cooperate by synchronizing disk accesses, but buffered programs also need to cooperate in sharing the available memory. Optimized programs should be aware of which other programs are concurrently executing in order to adapt their behavior and cooperate for overall disk energy savings.

A general method for applications to adapt their behavior might use the Odyssey platform [24] or a similar runtime system where applications share information. One problem with general adaptive systems is the performance overhead. The Odyssey researchers capped the maximum adaptation rate to once every fifteen seconds. One strategy to reduce such overhead is to encode the execution contexts as a state diagram or table in the program. A state transition corresponds to a program exiting or a new program starting. Encoding the execution contexts is nontrivial since it requires unique program identifiers. Considering $n$ programs, there will be $2^n - 1$ possible combinations for execution contexts. However, much of this space may be pruned because many contexts are very unlikely to occur. For example, many users typically run a small number (less than five) of programs at a time. In addition, some contexts are much more popular than others. Targeting the most popular contexts is a prudent optimization strategy. Chapter 4 will discuss a user study to identify popular contexts.

For the moment, assume a set of popular contexts are known, and programs are ready for optimization. A compiler can generate a runtime module for the programs as follows. First, the execution contexts are enumerated and given unique identifiers. One method is to generate a bit vector where each program has been assigned a bit position. If a program is in the context, then its bit position should be 1, otherwise 0. Each program is also categorized according to the file desciptor attributes it uses. Now, a program knows the possible contexts, the programs within each context, and the types of expected file access from each program. On a transition, a program must be able to either discover the new state or communicate the new state to others. One possible implementation is to communicate via shared memory. The shared memory can be a bit vector representing the context. Each program must, upon start or exit, update its bit position in the shared memory vector. Extant programs will be notified of the transition via an announcement similar to the inverse barrier.

When a program is notified of a transition, it reads the new state and adapts its behavior as follows. If only one program is extant, then any synchronization mechanisms can be disabled. If more than one program is extant, and if at least one program uses the `SYNC_RECV` or higher attribute, then synchronization will be enabled. If any extant programs are buffered, then they will adjust their use of available memory according to any suitably fair or proportional policy. A conservative policy, Divide-by-N, would reallocate each program's share of memory to be the available memory divided by the number of buffered programs.

A more sophisticated policy, Proportional-Consumer, could treat streaming programs specially by allocating memory proportional to their data consumption rate. For example, let program $X$ use the `BUFFERED` attribute while programs $Y$ and $Z$ use `STREAMED`. Furthermore, let the consumption rates of $Y$ and $Z$ be 100 and 300 kilobits per second, respectively. If available memory is 30 megabytes, Divide-by-N would give 10 megabytes to each program. On the other hand, Proportional-Consumer could adjust the relative shares between $Y$ and $Z$. They have 20 megabytes between them, so $Y$ and $Z$ could be assigned 5 and 15 megabytes, respectively. The time for $Y$ and $Z$ to consume their buffers will be optimized for maximal hibernation time. Figure 3.8 shows how proportional buffers can lengthen the hibernation time and reduce the number of transitions as compared to Figure 3.6 which uses equally sized buffers.

The framework must also consider the situation where optimized programs execute concurrently with non-optimized programs. The safe option is to disable all optimizations because the presence of unknown disk access patterns can degrade overall disk energy consumption to actually waste extra energy. One alternative is to disable the buffer optimization but leave synchronization enabled which may help those applications using `SYNC_RECV`. Ultimately, execution context optimizations imply a

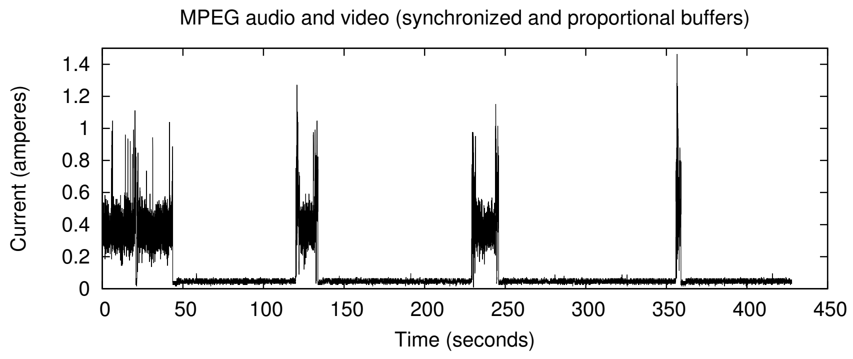


Figure 3.8: Disk activity of synchronized audio player and video player with buffer sizes proportional to their data consumption rates.

sensitivity to the context of executing programs. These optimizations will yield the most benefits, which may be significant for some workloads, through recompilation.

Finally, although the mechanisms discussed in this framework can be implemented independently of the OS, areas of overlap suggest that some functions can be more efficiently implemented in the OS. For example, an OS mechanism to discover and communicate the execution context can eliminate that part of the runtime modules from each program. Keeping in mind that energy aware resource usage often involves arranging activity into bursty patterns, a notification system on accesses to various physical resource, similar to the inverse barrier, may be invaluable for general energy management of system resources. My framework focuses on the compiler and language techniques to support execution context optimizations. Evaluating hybrid OS and compiler techniques is beyond the scope of this research.

## 3.4 Implementation

I used the Low Level Virtual Machine (LLVM) compiler infrastructure [43] to implement code transformations in various passes. LLVM is based on the GNU Compiler Collection (GCC). LLVM provides modified GCC front-end parsers to build a new intermediate representation. Many tools are also provided to support analyses, transformations, and back-end code generators for several popular architectures including source level C code. LLVM is robust enough to compile many C programs, but it lacks full support for C++. In addition, using LLVM would require modifying the build scripts to use LLVM's tools, and modifying the build system of even one program can be nontrivial. Thus, I used LLVM to perform source to source level transformations and kept the original build system of scripts unchanged.

### 3.4.1 Limitations

There are two limitations of my implementation, one of which is affected by how LLVM is structured. My framework introduces new file descriptor attributes which are to be propagated to call sites. An inter-procedural analysis would serve this purpose. LLVM does support inter-procedural analysis but currently only at the linking phase of compilation. The LLVM developers have plans to support inter-procedural analysis on their intermediate representation. Since I am performing source to source transformations, I emulate the inter-procedural analysis by hand and use the information to precisely target the code transformations.

The second limitation deals with application adaptation. I have not yet developed the runtime modules to support dynamic application adaptation according to the execution context. For now, the code transformations target a specific execution context when applying optimizations. Hence, multiple versions of program binaries may be generated depending on the context. Runtime adapation modules are left for future work.

### 3.4.2 Synchronization

I implemented inverse barrier synchronization via semaphores. Semaphores provide a simple way to mimic multicast. A true multicast mechanism with message queues would have been more flexible and elegant. Semaphores do not know which programs to send a message to and relies upon each program earnestly waiting to process the message. If programs do not process the message in a timely fashion, a race condition exists to degrade the semantics of the multicast-like semaphore. I set aside a global semaphore to be shared by all programs. Each program wanting to receive notifications will have a child thread to wait on the semaphore. The semaphore structure in Linux maintains a count of waiting processes. To send a notification, a process increments the semaphore by the number of waiting processes. Each waiting child thread will decrement the semaphore by one and take the appropriate action. The action will vary for `SYNC_RECV`, `BUFFERED`, and `STREAMED`.

### 3.4.3 Greedy Hibernation

Synchronization messages are sent after a program has accessed the disk. A variety of policies, such as fixed or adaptive thresholds, may be used to govern when a disk should hibernate. I have chosen to use an aggressive, greedy hibernation policy which directs the disk to hibernate immediately. Programs using the file buffer optimization will have finished pre-fetching data to fill their buffer. Programs using `SYNC_SEND` or `SYNC_RECV` are generally interactive, and the inter-arrival times between disk requests are described by a Pareto distribution. The activity profile of a program just finishing its disk access will likely be followed by human think time. Therefore, maximal energy savings is possible with immediate hibernation.

### 3.4.4 Optimization Passes

The overall transformations occur in two stages. Stage 1 is specifically for those programs using the `SYNC_SEND` or `SYNC_RECV` attributes. Programs are instrumented to collect profiling information which is passed to the next stage. Stage 2 transforms and

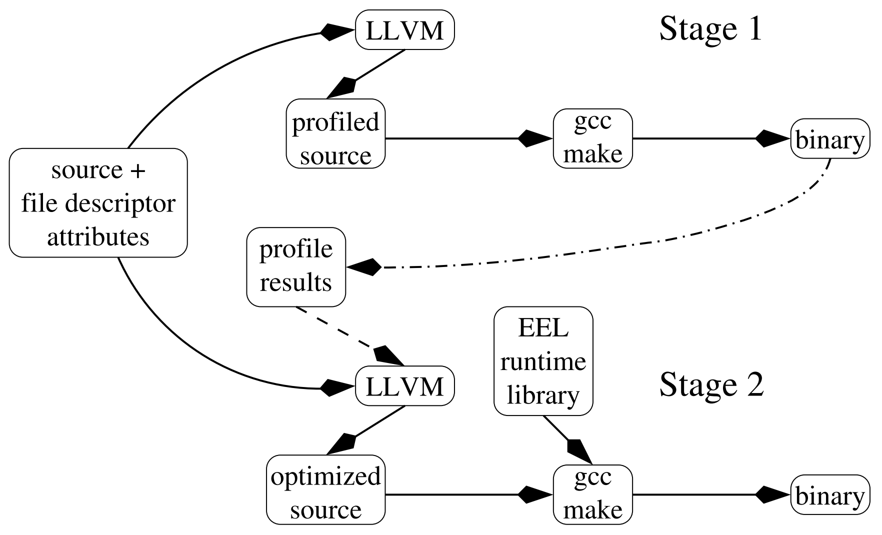


Figure 3.9: Optimization framework in two stages. Stage 1 is used only for `SYNC_SEND` and `SYNC_RECV` attributes. Stage 2 accepts profile information from Stage 1 to mark synchronization points. Stage 2 transforms and inserts code to implement inter-program synchronization, file buffers, and disk profiling.

inserts function calls according to the file descriptor attributes. The EEL[1] runtime library, which implements the synchronization mechanisms and file level buffers, is also linked in with the object code. Figure 3.9 depicts the sequence of both compilation stages which will be further described with each attribute.

`SYNC_SEND`

The new keywords provide a simple way for programmers to add cooperatively synchronized disk access. The most basic operation for the keywords to support is sending a multicast message to notify others about a just completed disk access. For example, if a user saves a file or advances to the next page of a document, the program invokes the corresponding procedure. Within the body of that procedure or its call chain will contain the actual read or write system calls. The notification message should be sent after an I/O operation.

However, the compiler should not simply insert the synchronization function af-

[1]The EEL name is taken from the Energy Efficiency and Low-power (EEL) Laboratory headed by Dr. Ulrich Kremer.

```
while (NOT FINISHED) {        //
    read (file, buffer, n);   //
    SYNCHRONIZE ();           //  CASE 1
    process (buffer);         //
}                             //

while (NOT FINISHED) {        //
    read (file, buffer, n);   //
    process (buffer);         //  CASE 2
}                             //
SYNCHRONIZE ();               //
```

Figure 3.10: Synchronization points should be placed at the end of a logical I/O operation. Finding such points is undecidable.

ter each marked I/O call because that may generate a flood of messages. A program operation, such as saving a file, may consist of multiple I/O calls at runtime. Even if there is only a single line of code for the I/O call, that line may be located within a loop body. Figure 3.10, Case 1 illustrates the situation. The pseudo-code is representative of the programming structure for logical I/O operations. They generally have a loop pattern and iterate until a delimiter has been reached. If a loop iteration takes longer than the disk's hibernation threshold, then Case 1 is appropriate. If a loop iteration takes shorter, then another approach might notice the loop and decide Case 2 is better. The problem is unchanged though because Case 2 may be enclosed within yet another loop. Searching backwards through loop nesting levels will eventually reach a procedure boundary. The problem continues because that procedure's call site may be within a loop. This line of reasoning leads back ultimately to the top-level main function.

Therefore, the compiler's task to insert synchronization points is described as finding the end of a logical I/O operation. Unfortunately, the problem is undecidable as the compiler has no way of determining via static analysis what a programmer considers as the logical operation. Only the programmer understands what constitutes the logical operation. In lieu of any other guidance, a compiler may use a heuristic of runtime profiling to estimate when a logical I/O operation has ended. In a generalized I/O operation containing multiple I/O calls, the calls will occur with short inter-arrival times. If the inter-arrival time between two calls is greater than a reasonable threshold, then the compiler assumes one I/O operation has completed. This heuristic is similar to the work in [32] for distinguishing interactive sessions.

For Stage 1, the compiler must first mark the candidate I/O calls. They are identified by using an inter-procedural analysis to build Definition-Use chains from the keywords. Uses of the file descriptor are marked. As mentioned above, I performed the inter-procedural analysis by hand. I instrumented the I/O calls and surrounding functions with timestamps. The program is run in a training phase where the logical I/O operations are specifically executed. I analyzed the profile timestamps using an inter-arrival threshold of ten seconds and identified the synchronization points. Stage 2 uses the profiling results to pinpoint where the synchronization function is inserted. The only operations include directing the disk to hibernate and sending a notification.

### `SYNC_RECV`

In addition to the above, the `SYNC_RECV` attribute lets the compiler know to add a child thread which will listen for synchronization messages. The child thread will dispatch to the program's handler and then go back to listening again for the next message.

### `BUFFERED`

Programs using at least the `BUFFERED` attribute will not need the profiling phase of Stage 1. The buffer optimization transforms and clusters the disk request patterns. The buffer has taken over control of the I/O resulting from the program's logical operations. In effect, the logical I/O operation is now mapped to the buffer's pre-fetch operation. Since I, as the programmer of the buffer, know where this operation ends, I also know the optimal location for the synchronization point. Thus, the buffer is entirely self-managed and the synchronization mechanism is built in. A child thread listens for messages and dispatches to a pre-fetch handler. The handler will check if the buffer is less than half full before initiating a pre-fetch; otherwise, do nothing.

### `STREAMED`

The `STREAMED` attribute inserts an enhanced buffer which takes into account the disk's bandwidth and the program's data consumption rate to implement just-in-time wakeup. Activating the disk early strives to prevent buffer underflow situations where real-time applications cannot tolerate pausing for data. Furthermore, the child thread operates asynchronously to pre-fetch data into the buffer for maximum energy savings and zero performance delay.

# Chapter 4

# Opportunity

Execution context optimizations are a promising new research area. A key enabler is observing how users interact with applications in routine ways. The computer is well suited for multi-tasking up to its available memory. Exceeding available memory causes the system to swap memory to disk to store information about future tasks when needed. Humans are also quite capable of multi-tasking up to a limit; beyond that, people may turn to writing notes to remind themselves of future tasks. Daily experience and psychology experiments demonstrate that humans are less efficient when multi-tasking with many tasks [60]. Thus, the intuition for computing is that most users run only a small number of programs at a time.

Computer multi-tasking may also be constrained by various other system resources. Many users recognize that their system's processor, disk, or network can handle only a finite number of tasks before the perceived system speed slows down. Hence, identifying the sweet spots of user activity will reveal the opportunities for execution context optimizations. Calculator applications may not access the disk much and consequently, may not merit attention for optimization. But if calculators often run with a streaming application, perhaps some common disk access operations could be optimized. To gain insight into actual user activity, I conducted a study on program usage from a population of computer science graduate students. The results provide a first step in confirming the intuition above and a direction for future optimizations.

## 4.1 Tracing Infrastructure

During the spring 2007 semester, with the cooperation and help of the Computer Science Department system administrators, 40 desktop machines were instrumented in a style similar to Roselli et al.'s setup to trace file systems [59]. The systems contain Pentium 4 processors clocked between 2.8–3.4 GHz with either 512 or 1024 MB main memory and a standard installation of Fedora Core 3 Linux. The kernel was upgraded to version 2.6.18 to support the instrumentation software. The systems are connected to the Computer Science graduate student network. All but five of the machines are located in offices designated for graduate student teaching assistants. Each office generally contains two machines and is shared by up to four students. The other five machines are located within a computing lab accessible to all Computer Science graduate students.

The Computer Science graudate network maintains user accounts across the networked machines via NFS mounts. All systems have full network access to the Internet and are suitable for general computing use. The only network restriction I am aware of is a byte transfer limit to guard against extreme abuse of network bandwidth. The systems also do not have external speakers. This is interesting to note because the types of applications used are influenced by the system capabilities. If users want audio output, they must connect their own speakers or earphones. Since all machines are in shared facilities, users may have been reluctant to use recreational or entertainment applications.

### 4.1.1 LTTng

The Linux Trace Toolkit next generation (LTTng) [18] version 0.6.33 was installed onto all 40 desktop machines. LTTng is a kernel module which monitors and records kernel events such as file system read and write, process signal and wakeup, and kernel interrupt. The events provide a fine-grain view of the system from the kernel's perspective. LTTng's maximum impact on system performance has been estimated by its developer to be 2% under high system load. LTTng does not significantly impede system performance or users' activities nor has any user complained about system lag.

LTTng is structured with three event rate channels: high, medium, and low. Events have been categorized into these channels based on their expected frequency and quantity. For example, most file system events are in the high rate channel while process events are in the medium rate channel. A partial listing of traceable kernel events is shown in Table 4.1. One goal for LTTng's event channels is to enable selectively switching a channel on and off, meaning that those events can be selectively recorded to the trace. A fully dynamic event multiplexing interface is a planned feature by the developer. For now, the rate channels are set according to the recording mode. Each channel has a buffer to store events. When the buffer is full, batches of events can be dumped to disk. The default buffer sizes for the high, medium, and low rate channels are 1 MB, 256 KB, and 64 KB, respectively, though they can be specified at runtime.

LTTng has three modes of operation: normal, flight recorder, and hybrid. Normal mode captures all event channels. Flight recorder mode maintains circular buffers for the event channels and may optionally write the buffers to disk when tracing has stopped. As its name implies, flight recorder mode is intended to capture the last buffer's worth of events after an interesting event has occurred such as a system crash. This mode can be integrated with the Linux Kernel Crash Dump (LKCD)

| Type | Subtype | Detail |
|---|---|---|
| Process | create kernel thread | Thread start address and PID |
| | fork | PID of created process |
| | exit | None |
| | wait | PID waited on |
| | signal | Signal ID and destination PID |
| | wakeup | Process PID and state before wakeup |
| | scheduling change | Incoming and outgoing task and state |
| | free | PID of freed process |
| File System | buffer wait start | None |
| | buffer wait end | None |
| | exec | File name |
| | open | File name and descriptor |
| | close | File descriptor |
| | read | File descriptor and quantity read |
| | write | File descriptor and quantity written |
| | seek | File descriptor and offset |
| | ioctl | File descriptor and command |
| | select | File descriptor and timeout |
| | poll | File descriptor and timeout |

Table 4.1: Partial list of traceable kernel events. Most events have been documented and published [75] but some are not yet officially documented.

[58] project to recover the buffer contents from memory after a system crash. Hybrid mode records the medium and low rate channels as in normal mode while the high rate channel is in flight recorder mode. Hybrid mode was a recent feature which made this user study feasible. The great advantage was in reducing the trace file size by recording, in effect, only the medium and low rate channel. The high rate channel in flight recorder mode can be discarded, if desired, when tracing has stopped. Tracing tests with earlier versions of LTTng in normal mode revealed that a ten hour trace generates about 5 GB of compressed data. At those sizes, several of the instrumented machines have only enough disk space to store a week's worth of traces. That would have necessitated weekly cleanup and maintenance of the storage systems. At 40 systems, 1000 GB per week would have been untenable. Alternatively, the scope of the tracing could have been limited by the number of hours per day or the number of traced machines in total. Hybrid mode reduced the file size of a ten hour trace by two orders of magnitude to about 50 MB.

### 4.1.2 Trace Time Setup

With hybrid mode, the tracing software could have run continuously 24 hours per day, yet for reporting purposes, a daily snapshot is useful and convenient. For efficiency's sake, the tracing should record when there is actual user activity as opposed to user idleness or when no user is logged in to the machine. I want to know when the most active hours of the day are for tracing. Unix, by default, tracks user sessions by recording when a user logs in and out. Average daily user activity can be approximated from these user session records.

I examined the user session logs of the 40 instrumented machines over a one week period. The user sessions recorded 55 distinct users. The one week in particular was considered ordinary; that is, there were no holidays or special events in the academic calendar. I divided the session times into 24 hourly buckets. For example, if a session

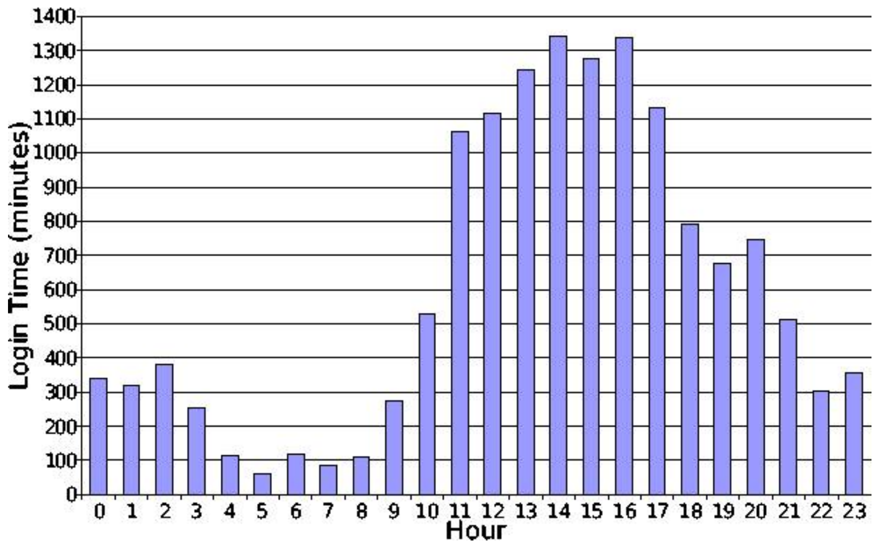


Figure 4.1: One week histogram of user login sessions.

started at 8:58 and ended at 9:03, then two minutes are added to bucket 8 while three minutes are added to bucket 9. A histogram of the 24 buckets represents the average daily user activity by hour as shown in Figure 4.1. Peak activity occurred between 10 A.M. and 10 P.M. while there was a small plateau between 11 P.M. and 3 A.M. In the interest of convenient calculations, administration, and maintenance, I set the tracing software to record for ten hours between 10 A.M. and 8 P.M. These ten hours cover 73% of daily activity. A twelve hour period from 10 A.M. to 10 P.M. would have covered 81% of daily activity. The tracing software ran daily for twenty-two weeks.

The histogram of user sessions was described above as an approximation of user activity because actual activity is difficult to quantify. If a user is browsing the web or reading a PDF document, the processor is mostly idle although the user is active. These situations can be referred to as *think* time. The user might also walk away from the machine, say for a bathroom break, and the system would still show the same processor activity. On the other hand, the user could have started a lengthy compilation job and proceeded to read a book while waiting for the compile. Hence, actual user activity time, which is bounded by the login session, is over-reported by session time because sessions include periods of idleness., I also noticed some sessions lasting many hours, sometimes days. Those users must have walked away from their systems while letting their login session continue. Activity from these extended sessions is impossible to even estimate, and consequently I excluded them. Excluding such sessions will under-report some user activity, which may counteract the effects of over-reporting. Of course, more sampling will help, but the coarse-grained sessions was sufficient to describe general activity trends and guide the setup of the tracing software.

### 4.1.3 Trace Analysis

Out of the twenty-two weeks worth of traces, I chose to focus on a four week period towards the end of the academic semester. Classes were still in session and activity workloads may be expected to be at the highest levels. I parsed the traces to extract user login sessions. The accumulated time of user sessions was over 860 hours, though 12% was attributed to the screen saver. Subtracting the explicit idle times leaves over 760 hours of user activity. The activity came from 73 unique users who were running over 50 different programs which do not include system programs such as finger, ping, spell, etc. Some programs are variations of the same code base (e.g., gpdf, kpdf, xpdf) and were counted together as one program.

#### Program Lifetime

The objective of the user study is to identify application usage patterns. Program lifetimes can be described almost exactly by keeping track of the **fork** and **exit** process events plus the **exec** file system event. These events are assigned to the medium rate channel and appropriately captured in hybrid mode. In most cases, a program's lifetime starts with a fork or exec call and ends with a corresponding exit call. The lifetime has clear delimiters, though flagging it has a few complications. I

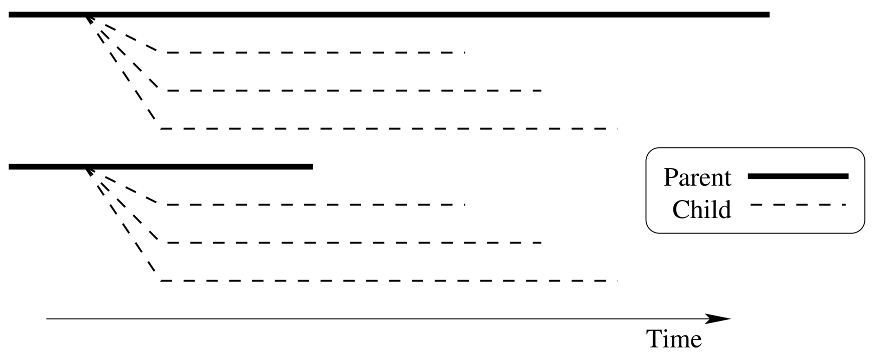


Figure 4.2: Examples of parent and child process lifetimes.

stored the fork and exec events along with their timestamps in a hierarchical list of parent-child processes. When parsing an exit event, if the matching process ID and name is found in the process list, then the difference in timestamps gives the process lifetime.

However, a program may also fork child threads, which may be responsible for core code, and let the parent process exit while the child threads continue executing. Figure 4.2 illustrates these situations. The latter case is typical of programs, such as Firefox and Xscreensaver, which run an initialization step before child threads run the program core. In some cases, flagging the lifetime may still be possible by correlating the process names - parent and child processes often have similar names - and parent process IDs. But in other cases, such as Xscreensaver, there is no obvious correlation with its child threads because the children processes are named according to the screensaver module. The name does not include any indication it is a screensaver module. In addition, since the child thread is spawned after some idle time, the child's lifetime does not overlap with the parent's lifetime and appears discontinuously. Therefore, the trace data was parsed in two ways: 1) by manual inspection to extract the most accurate program lifetimes and 2) by automatic parsing to quickly identify the most popular execution contexts.

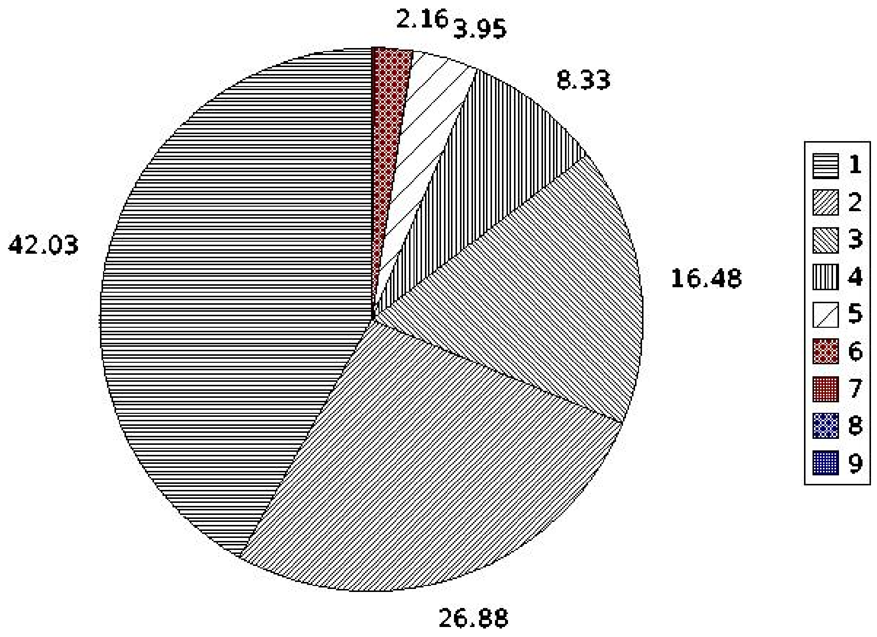


Figure 4.3: Percentage of time spent in execution contexts according to number of concurrent programs.

**Execution Context Time**

An execution context is defined as the set of programs running concurrently. Therefore, any fork, exec, or exit event marks the end of one execution context and the beginning of another. I aggregated the execution contexts according to the number of programs. The largest number of programs in an execution context was nine. In fact, there was only a single instance of this context whose accumulated activity time lasted less than a minute. The same user was also responsible, naturally, for running the sole execution context with eight programs, whose activity time was less than five minutes. Figure 4.3 shows the percentages of time spent in execution contexts according to the number of programs. Execution contexts with less than five programs accounted for over 90% of all active time and supports the intuition that users tend to run small numbers of programs concurrently. Execution context optimizations can feasibly focus on contexts with less than five programs.

An interesting issue for execution context optimizations is understanding the time

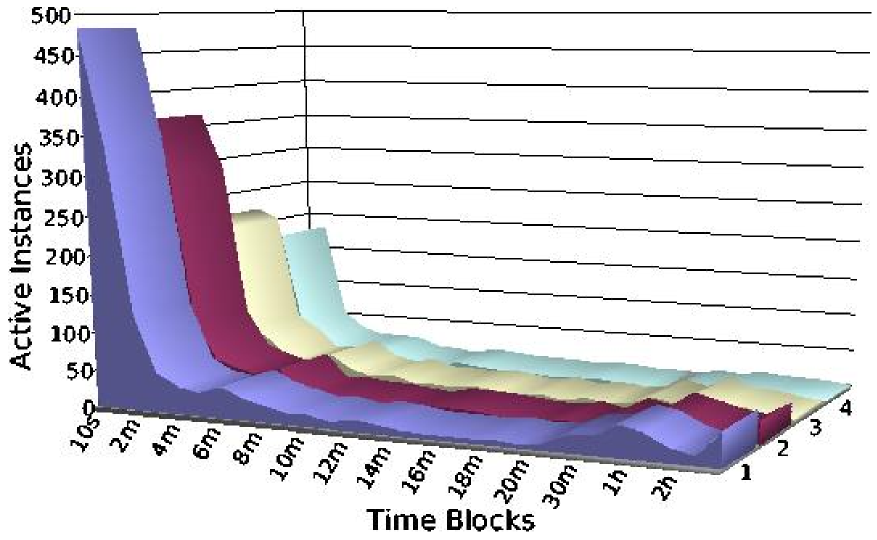


Figure 4.4: Histogram of transition times between execution contexts. Execution contexts are also grouped by the number of concurrent programs. Some time divisions are unlabeled for legibility.

spent within a given context before transitioning to the next. Every transition may incur application adaptations, for better or for worse depending on the time scale. If transitions occur on short time scales, then the adaptations may not be worthwhile. On the other hand, the overhead of adapting applications can be recouped if the user stays in the context for some time. Figure 4.4 shows a histogram on the time between transitions. The time between transitions is how long a user was active in a given context. The number of instances lasting a given amount of time are also grouped by the number of programs in the execution context.

The amount of time spent in a given execution context also indicates how task-oriented the users are. The distribution of times in execution contexts resembles a Pareto distribution. The time blocks domain uses nonlinear increments. The very first data point is 10 seconds, followed by one minute increments up to 20 minutes, while the remaining increments are increasingly larger up to 2 hours, and the last point collects all instances lasting beyond 2 hours. Each time point is a bucket for an accumulation of instances lasting more than the previous time and up to that amount of time. For instance, **6m** collects the number of instances lasting between five and six minutes. Since the right portion of the graph uses larger increments, it appears as though compressed in from the right side. If linear increments were used throughout, the curve would be a smooth distribution except for a bump at **6m**. The bump at **6m** is notable because most of the activity sessions were, in fact, idle. The screensaver program has a default idle threshold of five minutes before activating. That is, these sessions were the result of transitioning to a new context and then remaining idle for five minutes.

The **10s** and **1m** times also deserve mention. When ending a session, either the user will manually quit each program or select the logout function where the OS automatically kills all programs. The general effect is that the context transitions are in quick succession and describe most of the instances in **10s**. When starting a session, either the user will launch programs in succession until their desired execution context or the OS launches programs according to a login script. Programs starting execution generally require more time than exiting, and thus account for many instances in **1m**. If those two time points are ignored, then the average and median working times are 21 and 7 minutes, respectively. Those numbers could be slightly higher if the **6m** time is also ignored. Overall, the results and distribution of active times implies that users tend to transition quickly, but once reaching a steady state, remain so for several minutes. Adapting applications on 15–30 second intervals should be a reasonable tradeoff for adaptability and low amortized overhead. These findings agree with the Odyssey platform's settings [24].

### Popular Applications

As mentioned above, the most common execution contexts contain less than five programs. Analysis efforts can focus on such contexts. However, the number of possible contexts with less than five programs is still considerably large. With $n$

available programs, consider the contexts which contain up to four programs:

$$\sum_{i=1}^{4} \binom{n}{i} \tag{4.1}$$

The space of execution contexts for optimization can be pruned in two ways. Let us first consider the most commonly used applications. These popular applications will then guide the search for the most popular execution contexts.

The most popular applications are listed in Table 4.2 according to their active time as a percentage of all traced activity. The symbols are a shorthand notation to represent an application group. The web browser application, which encompases several programs such as Firefox and Konqueror, was the most popular by far. A web browser was active 62% of the time. The next most popular application was email at 34%. However, the growing popularity of web-based email may be shifting application use towards web browsers. These popular applications portray the average user as routinely gathering information, such as PDF files, over the web and using email. Common work related tasks involve a text editor, matlab, DVI viewer, or openoffice. Internet chat activity is similar to email in that it tends to run continuously as a background program until needed. Aside from internet chat, no other recreational applications such as games or multimedia were popular. The scarce activity may be partly due to the lack of external speakers.

## Popular Execution Contexts

The nine popular applications still present a large number of contexts to consider for optimization. If $n = 9$, then Equation (4.1) gives 255 possible contexts. However, just as with applications, some contexts are more popular than others. Users develop work habits and settle upon favorite sets of programs to accomplish tasks. Besides, even among popular applications, some combinations are very unlikely to occur. The

| Application | % | Symbol |
|---|---|---|
| web browser | 62 | W |
| email | 34 | E |
| PDF viewer | 23 | P |
| text editor | 15 | T |
| file transfer | 14 | F |
| internet chat | 13 | C |
| matlab | 7 | M |
| DVI viewer | 5 | D |
| openoffice | 5 | O |
| other | 31 | Z |

Table 4.2: Most popular applications by percentage of total active time. All others were less than 4%. Symbols are a shorthand notation to represent an application group.

traces also provide insight into the most popular execution contexts. Figure 4.5 represents these contexts as a lattice. The contexts are labeled by compositions of application symbols taken from Table 4.2. The symbol Z refers generically to any program not among the popular ones. Each context is also listed with its percentage of overall active time. Only contexts with at least 2% active time are shown. The popular contexts comprise 68% of all active time. If the threshold for contexts was lowered to at least 1% active time, then nine more contexts would have been added to cover 80% of active time.

The lattice structure serves to also describe the transitions between execution contexts. The bottom symbol $\perp$, which is omitted, would represent the system when no applications are running. The top symbol $\top$, which never occurs in practice, would represent all applications running. The rows of the lattice partition the nodes. Row $i$, from bottom to top, represents $i$ concurrently running applications. Edges between nodes represent context transitions — starting or exiting an application. Figure 4.5 shows three groups of contexts. Each group of connected contexts suggest a strong correlation of applications used together. Conversely, the lack of connections between groups indicate applications which are never or perhaps rarely used

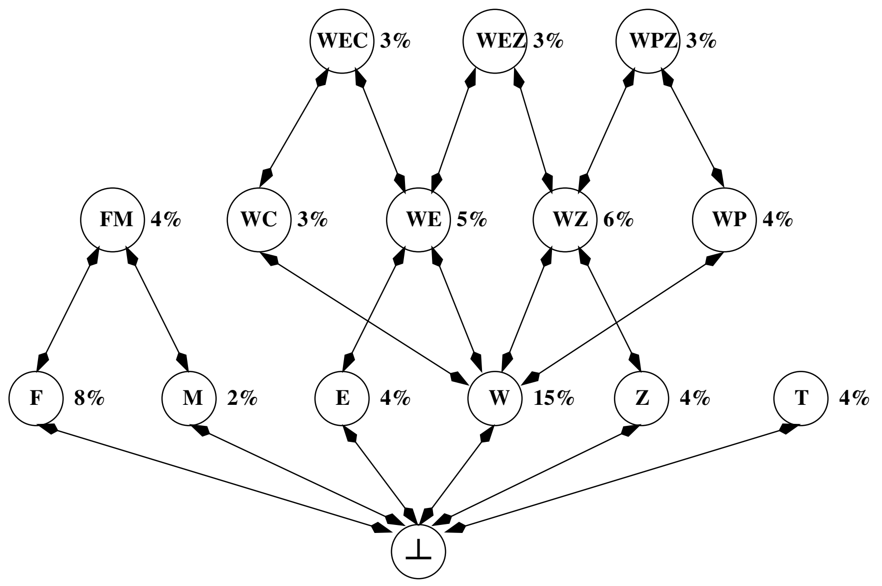


Figure 4.5: Most popular execution contexts by percentage (at least 2%) of total active time. Edges between nodes indicate a context transition — a program was started or exited. Programs not listed under Table 4.2 are given the generic symbol Z.

together. These nodes represent the most common execution contexts and correlate program usage patterns as opportunities for execution context optimizations. Furthermore, the greatest opportunities are identified by the connected contexts and merit further research. Realizing the benefits of execution context optimizations will be experimentally evaluated.

# Chapter 5

# Evaluation Infrastructure

The evaluation infrastructure consists of several hardware and software pieces to automatically control the measurement recording and experiment test sessions. The basic idea is to run the baseline and optimized versions of the test programs while measuring the disk energy. The tests must be repeatable to assure a fair comparison. However, testing interactive applications is particularly challenging since interactive implies human intervention. While a human could follow a script of actions, the precision and timing would be too poor to reliably repeat the tests. A robot who could emulate a human would be more suitable. Indeed, I will describe such a robot which greatly improved the precision of the experiments. Figure 5.1 depicts the entire measurement infrastructure.

## 5.1 Hardware

The host computer has an AMD Athlon processor operating at 1.2 GHz with a default workstation installation of Red Hat 9 Linux. The target disk is connected via Advanced Technology Attachment (ATA). The connector uses an adaptor to attach the computer's power supply plug into the disk. Experiments were conducted on two 2.5" disks, commonly referred to as laptop class disks: Fujitsu MHK2060AT and

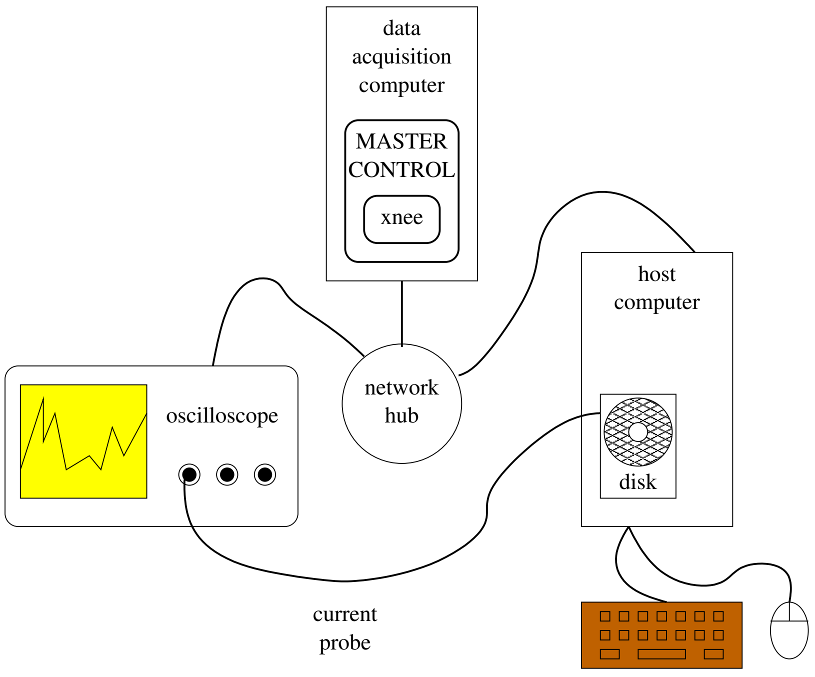


Figure 5.1: Power measurement infrastructure.

Hitachi Travelstar E7K60. The technical specifications are taken from manufacturers' specification sheets [37, 36, 26, 35] and listed in Table 5.1. Transition times may vary widely. The specification sheet for the E7K60 lists Standby→Idle time as 3.0 seconds (typical) and 9.5 seconds (max). The time spent and average energy consumption during transitions between Idle and Standby modes were measured and reported with standard deviations in parentheses. The break-even threshold describes the idle limit for which hibernation would profitably save energy. If the next disk request takes longer than the break-even time to arrive, then energy would be saved if the disk immediately transitioned to a low power mode after the last request.

For comparison, Table 5.1 also lists specifications for Hitachi 3.5" and 1.8" disks of comparable capacity. In general, a smaller form factor is designed for better energy efficiency than a larger one. The relative power levels are proportional. The optimizations in this research are applicable to all disks. Experiments on a 3.5" disk would have shown greater energy savings due to the higher operating specifications. The handheld class disk is intriguing because its specification recommends that usage

| | 7K80 | E7K60 | MHK2060 | C4K60 |
|---|---|---|---|---|
| Year | 2006 | 2004 | 1999 | 2004 |
| Form Factor | 3.5” | 2.5” | 2.5” | 1.8” |
| Capacity | 40 GB | 40 GB | 6 GB | 40 GB |
| Cache | 2 MB | 8 MB | 0.5 MB | 2 MB |
| Speed | 7200 RPM | 7200 RPM | 4200 RPM | 4200 RPM |
| Supply Voltage | 12.0 / 5.0 V | 5.0 V | 5.0 V | 5.0 V |
| Active | 9.7 W | 2.5 W | 2.3 W | 1.5 W |
| Idle | 4.7 W | 2.0 W | 0.85 W | 0.68 W |
| Standby | 0.9 W | 0.25 W | 0.28 W | 0.12 W |
| Sleep | 0.7 W | 0.10 W | 0.1 W | 0.11 W |
| Standby→Idle | — | 1.6 s (0.4) | 3.1 s (0.3) | — |
| | — | 4.9 J (1.1) | 6.9 J (0.5) | — |
| Idle→Standby | — | 0.6 s (0.2) | 5.8 s (0.2) | — |
| | — | 1.6 J (0.6) | 5.5 J (0.5) | — |
| Break-Even | — | 3.5 s | 17.4 s | — |

Table 5.1: Specifications, operation modes, and power levels for a variety of disks. Transition times can vary widely. The transitions between Idle and Standby modes were measured and reported with standard deviations. The 7K80 and C4K60 are listed for comparison. Sleep mode was not utilized during testing.

should not be continuous for several hours. The design tradeoffs for energy efficiency may influence which products it may be used in as well as which optimizations would be appropriate. Investigation into other storage classes is left for future work.

To measure the disk’s power, a Tektronix TDS3014 digital oscilloscope with a Hall effect current probe is attached to the wire supplying current to the disk. The host computer supplies power at a constant five volts; therefore, measuring the supply current readily translates into the disk’s power consumption. The TDS3014’s maximum sampling rate is 1.25 giga-samples per second, and I chose a reporting resolution of 20 milliseconds. That is, each data point represents an average of all the samples in the past 20 milliseconds. The oscilloscope buffers the data points and periodically flushes the buffer to the data acquisition computer. The data acquisition computer has a Pentium 4 processor operating at 2.8 GHz with a default workstation installation of Fedora Core 3 Linux. Both the host and data acquisition computers and the oscilloscope are connected to a 10 Mbps ethernet switch.

## 5.2 Software

The experiment test programs include several interactive programs such as a web browser or text editor. A key aspect for these programs is user interaction such as clicking on a link or typing a web address. User interaction is difficult to reliably repeat during experiment testing as noted by Crowley [16]. One solution is to have a robot mechanically perform the user interactions according to a timing-precise script. In the `X Window System`, each user interaction (mouse clicks or keyboard presses) corresponds to an X11 event processed by the `X Server`. The `X Window System` contains extensions, Record and XTEST [81, 22], which provide hooks to record and replay all keyboard and mouse events. A complete testing software solution exists in GNU Xnee. Xnee is described by its author as a robot and suitable as a testing infrastructure [65]. Xnee is designed to record and replay X11 events remotely to an `X Server`. The replayed events appear to the `X Server` as though coming from the physical keyboard and mouse. For that reason, Xnee is dubbed "Xnee is Not an Event Emulator".

Xnee uses a precision of one millisecond to record events with a time stamp. As a robot, Xnee can be expected to consistently replay events within a margin of ten milliseconds — the default length of a time slice. Such precision is useful for timing sensitive programs, but two issues reduce the usefulness, particularly for interactive programs. First, programs which communicate over the network are subject to latency which varies at any given moment. A repeated experiment will encounter different latencies and must allow for a range of latency delay between program events. For example, the act of typing a website address into a web browser comprises several keyboard events with very little delay, but waiting for the webpage to load may last on the order of tens of seconds. The next user action should wait for an amount of time on the upper end of the latency delay range. High-level program events, such as loading a web page or advancing to the next page of a document, require a settling time before the next program event. Second, processor response also has a variable delay due to the system load of background processes, overhead, disk latency, cache, and network traffic. The exact state of the system, in memory and cache, when replaying will be different than while recording. For these reasons, I experimentally found that when recording, high-level program events should allow a margin of at least five seconds from the end of the previous event before continuing.

Xnee has a synchronization feature which attempts to flexibly resolve the latency delay issues. The X11 protocol contains many response events which indicate graphical events with no direct causal event. For example, starting a web browser will require several seconds of loading before a window will appear. The window appearing is not directly related to the series of preceding keystrokes. The window will generate a response event. Xnee can record these events and use them during replay as synchronization markers. Xnee will try to match response events with recorded events and adjust the timing of future replay events accordingly. However, this feature was not yet robust enough for my purposes. After recording, the event timings may be fine-tuned as necessary. An actual experiment session script is listed in Appendix A. An understanding of Xnee's event encodings will reveal the account password I used at the time!

The oscilloscope may be remotely controlled from another computer. The basic operations are connecting to the oscilloscope, downloading data to a file, disconnecting, and closing the log file. I wrote a master control program running on the data acquisition computer to coordinate logging of the oscilloscope and Xnee's experiment sessions. I also wrote a client program running on the host computer to indicate when it is ready. The control program begins logging the oscilloscope, then runs Xnee with the next session script. Each session script corresponds to an experiment run. When the session script has finished, the host computer signals the experiment has ended, and the control program stops logging the oscilloscope. The host computer will then flush its disk, file, and memory caches before signaling ready again.

# Chapter 6

# Experiments

Using the file descriptor attributes of Section 3.3.2, I analyzed and categorized eight commonly used programs. The programs are listed in Table 6.1. The symbols are a shorthand notation to represent the programs in later figures. At the time I investigated OpenOffice, it was still at version 1 and suitable only for `SYNC_SEND`. With version 2, I suspect that it may be able to use `SYNC_RECV` because the auto-save feature was given a passive option. That is, in version 1, when the auto-save timer expired, OpenOffice would open a dialog box actively asking the user whether to save. In version 2, OpenOffice has the option of passively saving a backup copy of the document without asking the user, just as in programs like Emacs. All programs are written in C or C++ and passed through the LLVM compiler infrastructure as outlined in Section 3.4. OpenOffice and Firefox also have optional modules written in Java; they were disabled.

To test the interactions between optimized programs, I mixed the programs into ten combinations of two or three programs. Each combination represents an execution context. I designed the contexts to cover a range of interesting combinations. For example, a web browser and PDF viewer are common together, but a PDF viewer and video player are probably unlikely together. The execution contexts are listed in

| Program | Category | Description | Symbol |
|---|---|---|---|
| mpg123 | `STREAMED` | MPEG audio | A |
| mpeg_play | `STREAMED` | MPEG video | V |
| sftp | `STREAMED` | secure FTP | F |
| gv | `BUFFERED` | PS viewer | G |
| emacs | `SYNC_RECV` | text editor | T |
| ooffice | `SYNC_SEND` | spreadsheet | O |
| firefox | `SYNC_SEND` | web browser | W |
| xpdf | `SYNC_SEND` | PDF viewer | P |

Table 6.1: Test programs categorized according to the file descriptor attribute used. Symbols are a shorthand notation to represent the programs.

| Context | Description |
|---|---|
| OPG | spreadsheet, PDF, PS |
| VW | video, web |
| OT | spreadsheet, text |
| AF | audio, ftp |
| PT | PDF, text |
| OGT | spreadsheet, PS, text |
| WP | web, PDF |
| OV | spreadsheet, video |
| AWT | audio, web, text |
| GF | PS, ftp |

Table 6.2: Experimental execution contexts and their descriptions. Contexts are labeled as compositions of the symbols from Table 6.1.

Table 6.2 and appear in the figures below. Each context session consisted of several program events intended to either trigger disk accesses or demonstrate the various interactions between programs from different categories. For instance, `STREAMED` and `BUFFERED` programs react differently to synchronization messages than a `SYNC_RECV` program. The experiment sessions lasted between 4–10 minutes.

The programs were optimized to target specific execution contexts. The runtime modules to support adaptations has not been implemented yet. Therefore, an experiment session consists of a start-up phase where all programs are started in succession followed by a steady-state phase representing the execution contexts the programs were optimized for. The baseline for comparison includes previous buffering optimizations developed for the uniprogramming model [33]. There are two more topics to familiarize with before getting to the results. I will discuss high-level program events and the effects of write caching. After analyzing the results, I developed a model to describe the average expected energy savings from the optimizations.

## 6.1 Write Caching

The OS maintains a disk cache per open file via its virtual file system buffer cache. However the default maximum size at 128 KB is an order of magnitude smaller than the disk's onboard cache. For read performance, such a relatively small cache has negligible impact in our experiments. Any supported write cache policies will depend upon the file system type. The default, Second Extended File System [11], supports asynchronous and synchronous writes which are analogous to the disk cache's write-back and write-through policies. Asynchronous writes improve performance and energy in the exact same style as the disk cache's write-back policy. In continuing with our efforts to test our techniques independent of write-back caches and asynchronous writes, we set the file system to use synchronous writes.

Many disks have an onboard cache for data while reserving a small portion for control instructions. The data portion is further divided between reads and writes, each with their own page replacement policies. The impact of the read cache is insignificant on the file buffering optimization mainly because the file buffers are always larger. If not, then the system is likely low on available memory and file buffers should be disabled. With file buffers, disk accesses are clustered and sequential such that the disk's read cache will not experience any locality hits.

The write cache is a different story. Write caches often use the write-back policy which allows for asynchronous writes and offers performance and energy benefits. When the disk has received all data blocks into the write cache, it will report completion of the write command before actually writing the data to the physical disk. Writing to disk occurs when a flush command is issued. A flush may be either explicit from the host computer or implicit when the write cache is full and blocks must be evicted. Data may be lost if there is a loss of power. In contrast, write caches may use the write-through policy which forces synchronous writes. The disk will report completion of the the write command only when all blocks have been written to the physical disk. Data safety is ensured at the cost of performance.

## 6.2 Program Events

In all execution contexts, the recorded sessions followed the same pattern of launching two or three programs until reaching the target execution context (considered steady state behavior), performing actions to induce disk activity, then exiting all programs. Some typical actions or program events include saving a file, loading a web page, or scrolling to the next page of a document. Since we know the exact user actions recorded, we can correlate the causal effects between program events and disk activity. Figure 6.1 shows sample disk activity profiles from the OPG {ooffice, xpdf, gv} session. The graphs show the measured current over time. The area under the curves represent the total energy consumption. The experiment trace consists of starting all three programs in succession. The dashed line indicates where the execution context steady state begins. Thus, I will focus on the steady state portion of the graphs.

Figure 6.2 shows a zoomed view on the steady state execution after trimming away the start-up phase. The graphs are overlaid with horizontal ranges indicating when that program was running as the foreground application. The vertical markers indicate program events which may lead to disk accesses. The first three events from gv were advancing to the next page. The first event induced the buffer to refill while the next two events were buffer hits and did not need to access the disk. The next

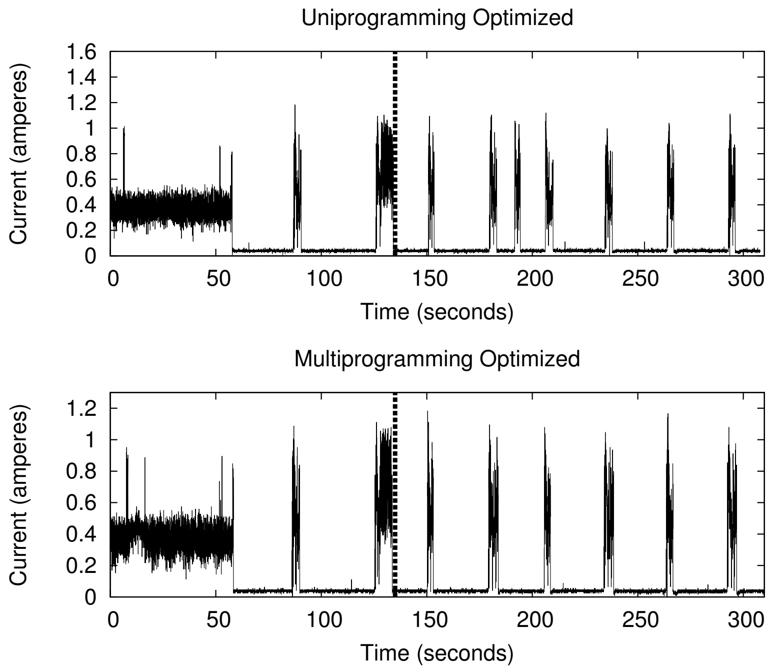


Figure 6.1: Comparison of disk activity traces resulting from program events under Uniprogramming and Multiprogramming optimizations. Execution context consists of ooffice, xpdf, and gv. Dashed line indicates beginning of execution context steady state.

two events from xpdf and gv also advanced to the next page. In the uniprogramming case, each incurred a disk access. However, in the multiprogramming case, the disk request from gv was synchronized with xpdf's disk request and gv could refill its buffer early. Hence, gv's disk request was a buffer hit and the transition was eliminated via synchronization.

## 6.3 Results

From the eight programs under investigation, I formed ten combinations to represent a diverse range of execution contexts. From a disk energy standpoint, the contexts are important in providing opportunities for savings. The actual program interactions according to the keyword optimizations employed are the direct factors towards realizing energy savings. The ten execution contexts are labelled in Figure 6.3 using

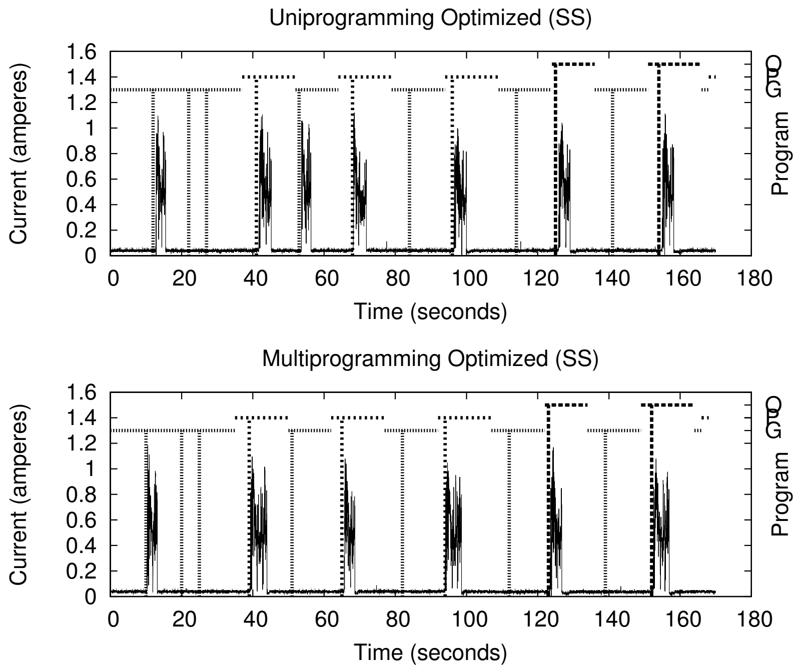
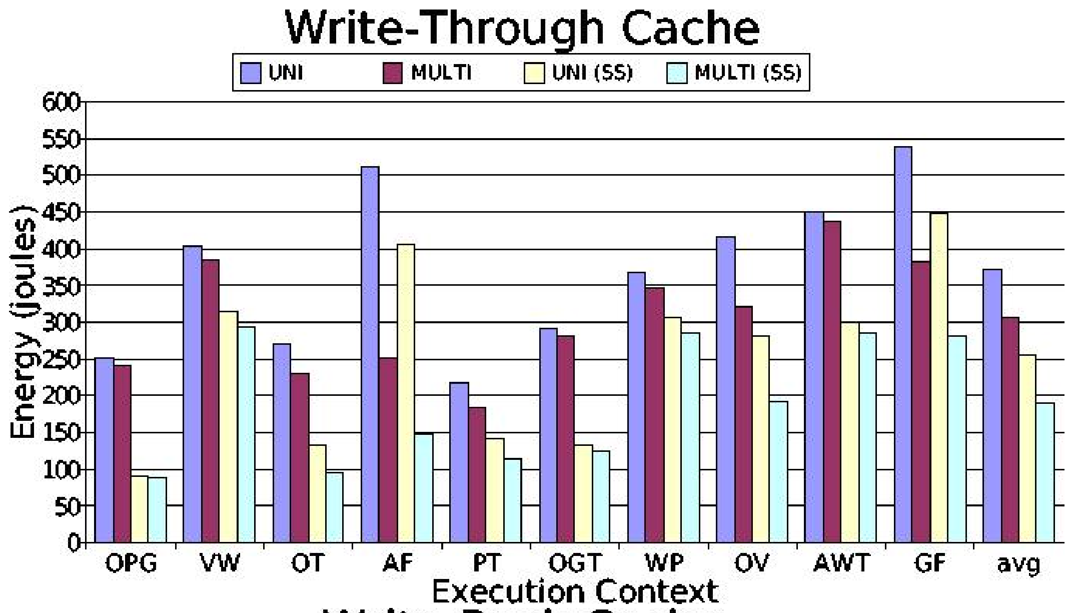


Figure 6.2: Comparison of steady state execution context disk activity traces from program events under Uniprogramming and Multiprogramming optimizations. Execution context consists of ooffice, xpdf, and gv.

compositions of the program symbols which are listed in Table 6.1. Each recorded session was replayed while the disk energy was measured on the oscilloscope. Each session could be replayed with either the uniprogramming or multiprogramming optimized versions of all programs. Figure 6.3 shows the experiment results when using the write-through and write-back cache policies. The results in either policy compare the total energy consumption for each session in two pairs. Both pairs compare the uniprogramming vs. multiprogramming versions. The first pair represents the entire session trace which includes the start-up phase while the second pair contains only the steady state phase. The results are averaged over nine runs.

The first emphasis is that the possible disk energy savings depends highly upon the user activity workload. These experiments are synthetic traces to show how program events interact in the resulting disk accesses. The interaction between disk requests reveals a range of opportunity for disk energy savings under various execution



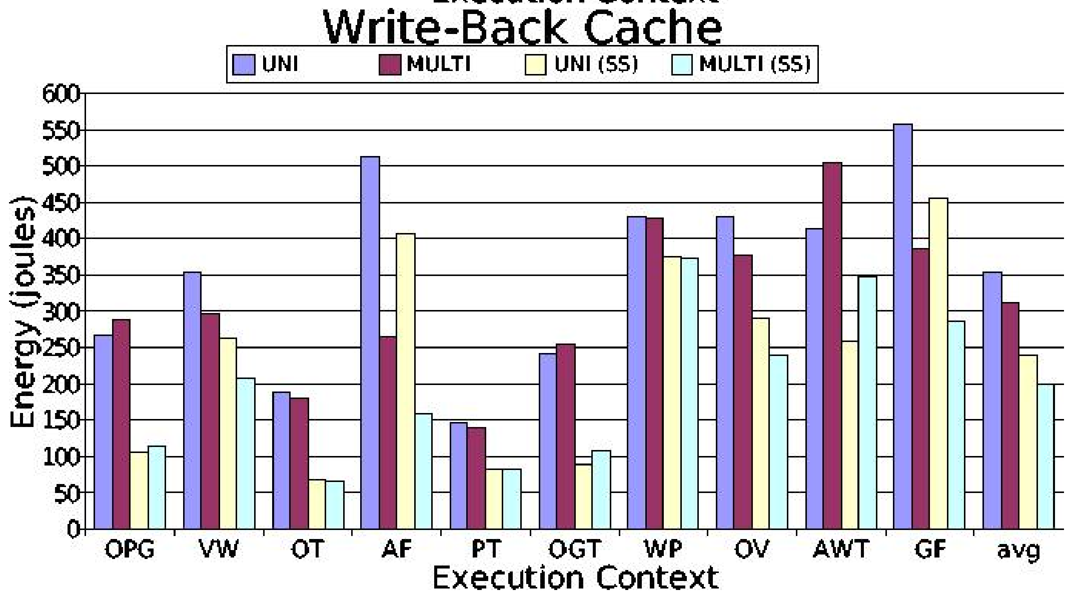


Figure 6.3: Experiment results when using write-through and write-back cache policies. An execution context represents the set of active programs. Each experiment group compares between the Uniprogramming and Multiprogramming optimized versions. The steady state (SS) results trim away start-up transition phases.

contexts. More representative traces would require a more detailed user study and is left for future work.

The experiments show that with mostly interactive programs such as WP, the opportunity for energy savings is small. Conversely, streaming programs such as AF offer plenty of opportunity for savings. Some contexts have moderate opportunity for savings, such as AWT, though the actual activity did not demonstrate all of the potential savings. I specifically tried maintaining a balance among the choice of experiments to span the range of activity. Using the write-through policy, the average savings was 21% with a range of 3% to 63%. Using the write-back policy, the average savings was 8% with a range of -33% to 61%.

These optimizations performed well in reducing disk energy consumption yet with negligible performance costs. The most harmful cases occur when extra disk accesses are triggered via prefetch and the data is not used, when the disk is repeatedly accessed at short intervals, or when small writes trigger early accesses. The last case is harmful only when using a write-back policy. An adversary could perform such activity, but the user study indicates that it is not typical behavior. User activity does follow a Pareto or bursty distribution. In all experiment runs, the overhead of synchronization communication between programs delayed total session execution times by no more than 1%. For real-time programs with buffering, just-in-time wakeup is necessary to maintain performance; previous optimizations are insufficient. Overall, these optimizations are beneficial for saving disk energy with insignificant performance penalty.

With the write-back policy, there were three sessions {OPG, OGT, AWT} in which these techniques performed poorly. Those three sessions all involved small writes, one of the harmful cases described above. There were three other sessions {OT, PT, WP} with small writes, but the results showed little or no appreciable energy savings. Of the remaining four sessions {VW, AF, OV, GF}, the results are similar to the write-through policy. The negative results under the write-back policy are unsurprising given that the multiprogramming optimization techniques perform a similar write clustering effect. The optimizations, in effect, perform a synchronous write operation while the write-back policy waits until necessary to flush the cache. As part of future work, identifying execution contexts with potentially harmful effects from multiprogramming optimizations may lead to a runtime heuristic which selectively disables optimizations.

## 6.4 Energy Model

The optimizations save disk energy via two forms of clustered disk accesses. A file buffer clusters accesses from the same program while synchronization clusters accesses from multiple programs. Both forms appear identical to the physical disk and are modeled as operational power modes over time. Figure 6.4 illustrates the disk activity of a typical access. Intuitively, the energy savings comes from eliminating wakeup ($E_{\nearrow}$) and hibernate ($E_{\searrow}$) transitions and combining the active periods together. The energy saved is proportional to the transition costs of a given disk. Laptop class and smaller disks are designed for fast transitions with lower energy costs then desktop or server class disks. The transition costs are

$$E_{transition} = E_{\nearrow} + E_{\searrow}$$

The baseline energy consumption with $M$ accesses is

$$E_{base} = M \times E_{transition} + E_{active} + E_{standby}$$

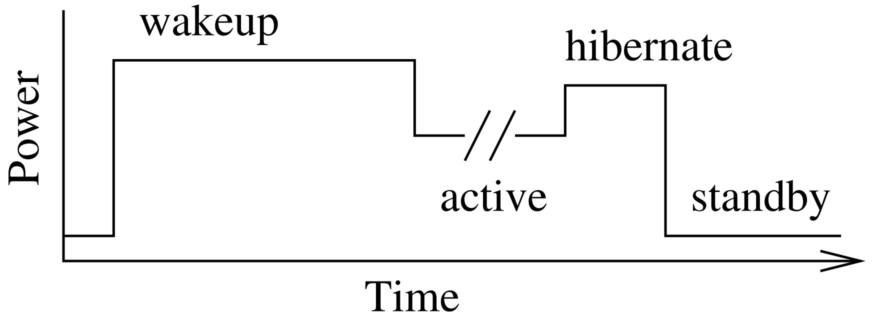


Figure 6.4: Disk activity behavior during typical access request from standby and then returning to standby.

The energy reduction by eliminating $N$ transitions is

$$\Delta E = N \times (E_{transition} - E_{standby})$$

Suppose an activity trace is given, such as in Figure 6.2, along with an estimate of which disk accesses can be clustered. A time period can be chosen over which to compute $\Delta E$. In this short trace with seven accesses, the entire trace is fine. With a longer trace, a representative activity pattern of average activity in the trace may be chosen. Finding representative patterns is challenging because $E_{active}$ and $E_{standby}$ can have wide variances. Longer time periods will increase accuracy because $M$ and $N$ are restricted to integral numbers.

A complete energy model would account for times when the disk is in idle mode or has different activity patterns than the typical pattern in Figure 6.4. For instance, a web browser may encounter network latency such that its logical I/O operation (writing to cache after loading all page objects) stalls, keeping the disk in idle mode. The parameters from Table 5.1 were used to analyze two traces, OPG and AF. These traces had the most stable activity patterns.[1] For OPG and AF, the model estimates energy savings of 2.6% and 55% compared to measured savings of 3.1% and 63%, respectively. The error rates are within one standard deviation.

[1]Measured current flow reveals large fluctuations and error margins, particularly when considering low power disks. Measured activity is in line with manufacturer's measurements.

Lastly, I used the energy model to estimate energy savings of the user study traces. Only some of the experiment contexts can be compared with the user study contexts. Referring back to Figure 4.5, the contexts F and FM are characterized by streaming applications and are similar to AF from my experiments. The opportunity for energy savings from streaming applications is high and limited mainly by the buffer size. The experiments with AF used moderate buffer sizes — not so large to buffer the entire file and not so small that the disk must immediately wakeup to refill the buffer. The optimized AF was able to save 63% energy. The contexts WP and WPZ of Figure 4.5 are characterized as a mix of reading PDF documents and web pages. They correspond most directly to WP from our experiments where the activity consisted of visiting a web page, reading an eight page PDF document (scrolling at regular intervals) linked from that web page, and visiting another web page. This context carries little opportunity for synchronizing disk requests but was able to cluster two accesses into one and save 7% energy. The four contexts {F, FM, WP, WPZ} accounted for 21% of the active time, and if optimized, may have saved about 9% energy over the 760 hours. If the workloads of emerging mobile systems include more multimedia applications, they may find greater advantage from streaming execution context optimizations.

# Chapter 7

# Summary and Future Work

Execution context information is important in maximizing disk energy savings in multiprogramming environments. Uniprogramming models for energy management optimization are insufficient when dealing with shared resources. I described an optimization framework designed for multiprogramming models of execution. For disk power management, I introduced language extensions in the form of file descriptor attributes. These attributes characterize the file access behaviors of programs, and provide information for a compiler to implement three optimizations. The optimizations include an inter-process communication framework for synchronizing disk requests, file-level buffers to pre-fetch and cluster disk accesses, and runtime application adaptations to transitions in execution context.

The execution context model was formulated as states in a finite state machine. Transitions between states correspond to starting or exiting a program. Execution contexts also encapsulate information about expected program interactions in disk requests. Although an exponential number of execution contexts exists ($2^n - 1$), optimization efforts may feasibly focus on only a small subset. I used LTTng to conduct a user study and collected over 760 hours of active traces. The user study investigated the program usage patterns of computer science graduate students and revealed that 94% of all activity occurred in execution contexts with fewer than five programs. Furthermore, the top 14 most popular contexts accounted for 68% of all activity.

Experiments with eight programs in ten execution contexts showed a range of disk energy savings. Actual energy savings will be capped by the potential opportunity available, and the experiments demonstrated a range of low to high opportunity. The optimizations are applicable to both streaming and interactive applications. I developed a measurement infrastructure with Xnee which can reliably repeat experiments on interactive applications. Using a write-through cache policy, execution context optimizations saved 3% to 63% disk energy with an average of 21%. Using a write-back cache policy, the savings ranged from -33% to 61% with an average of 8%. Further analysis to identify execution contexts where the optimizations are harmful may enable runtime heuristics to selectively disable optimizations based upon the execution context. In all cases, the runtime overhead from the optimizations resulted in less than 1% performance delay.

Lastly, I also formulated a simple energy model to estimate savings based on a disk's specifications, a disk access profile, and the expected interactions between programs' disk requests. The model helps to gauge which programs and execution contexts should be targeted for optimization. Applying the model to the user study estimates at least 9% disk energy could have been saved if the users were running optimized programs. This research has investigated real user workloads and the associated opportunities and benefits for disk energy savings via execution context optimizations.

There are several areas for further research. A more comprehensive user study would collect activity traces with disk events and evaluate the disk energy consumption over a measurement infrastructure such as the one I developed. Additionally, activity traces should capture user level program events to correlate with corresponding disk events. Evaluating activity traces will also require extending the existing optimizations to a wider range of programs. Analyzing more programs may lead to new file descriptor attributes for further characterizing disk access interaction. Analyzing program interactions for accessing other resources besides the disk is another avenue of research.

Execution context optimizations should be further investigated under different cache policies. The write-back policy is a competing technique for saving energy. For small working set sizes which fit in cache, the optimizations may be disabled, but larger working set sizes merit further analysis. An alternative idea to consider is adjusting the disk cache partition between read and write. With execution context optimizations out-performing the disk read cache, perhaps the disk might allow systems to specify a configuration where a greater portion of the cache is allocated for writes. In this way, file level buffering may work cooperatively with disk caching. Another optimization to explore is introducing a file level write buffer. Analogous to the existing file level read buffer, it may perform more efficient clustering of writes on a file level if data blocks are stored contiguously on disk.

Developing a complete, optimizing compiler infrastructure is a large task for future work. An infrastructure to support development of simple inter-procedural analysis will enable new areas for optimization research. I have focused on the disk as a system resource, but other resources should be explored. Besides power management techniques, execution context optimizations may also target performance aspects by clustering computation or working sets.

Research is also needed to compare OS approaches for clustering as well as how the OS may complement the techniques described here. Indeed, the runtime parts of the optimization framework may be more efficiently implemented as OS services to which applications register for. The file descriptor attributes will still provide compiler-directed hints, which can be more precise, to the OS about future disk requests while the OS manages the disk power. The execution context optimization framework has several parts which can be implemented in various layers between the OS, compiler, and runtime system, and the balance and tradeoffs for where to implement them should be investigated.

# Appendix A

# Xnee Session Script Sample

Xnee's session file format uses an 8-tuple for event replay directives. Table A.1 gives a partial listing of the directives taken from the Xnee Manual [66].

```
####################################
#         System information       #
####################################
# Date:                    2006:10:20
# Time:                    15:47:57
# Xnee program:            cnee
# Xnee version:            2.05
# Xnee home:               http://www.gnu.org/software/xnee/
```

| Directive | Description |
|---|---|
| 0,2,keycode,time | KeyPress with keycode to replay |
| 0,3,keycode,time | KeyRelease with keycode to replay |
| 0,4,button,time | ButtonPress on button to replay |
| 0,5,button,time | ButtonRelease on button to replay |
| 0,6,x,y,time | MotionNotify on position (x,y) to replay |
| 1,request,time | Request, used during synchronization |
| 2,reply,time | Reply, used during synchronization |
| 3,error,time | Error, used during synchronization |

Table A.1: Partial list of event replay directives.

```
# Xnee info mailing list: info-xnee@gnu.org
# Xnee bug mailing list:  bug-xnee@gnu.org
# X version:              11
# X revision:             0
# X vendor:               The XFree86 Project, Inc
# X vendor release:       40300000
# Record version major:   1
# Record version minor:   13
# OS name:                Linux
# OS Release:             2.6.9-1.667
# OS Version:             #1 Tue Nov 2 14:41:25 EST 2004
# Machine:                i686
# Nodename:               umbriel.rutgers.edu
# Display name:           ariel:0
# Dimension:              1024x768



##############################################
#      Xnee application arguments            #
##############################################
#  cnee -rec --keyboard --mouse -o audio-ftp.xns -e \
# audio-ftp.err -t 1 -d ariel:0 -sk Control_R



##############################################
#      Displays                              #
```

```
##############################################
# display ariel:0
distribute



##############################################
#      Files                               #
##############################################
out-file audio-ftp.xns
err-file audio-ftp.err



##############################################
#      Key Grabs                           #
##############################################
# stop-key          Control_R
# pause-key         0
# resume-key        0
# insert-key        0
# exec-key          0
# exec-key          xnee-exec-no-program



##############################################
#      Recording limits etc                #
##############################################
```

```
events-to-record        -1

data-to-record          -1

seconds-to-record       -1

first-last       0


# Record  all (including current) clients or only future ones

all-client

# future-clients


# Store the starting mouse position

# store-mouse-position




##############################################

#      Resolution                            #

##############################################


# Resolution

#recorded-resolution  1024x768

#replay-resolution  1x1

#resolution-adjustment  0




##############################################

#      Speed                                 #

##############################################
```

```
# Speed

#speed-percent  100



##############################################

#      Replaying limits etc                  #

##############################################


max-threshold 20

min-threshold 20

tot-threshold 40



##############################################

#      Feedback                              #

##############################################

#feedback-none

#feedback-stderr

feedback-xosd




##############################################

#      Various                               #

##############################################


# Plugin file (0 means none)
```

```
plugin       0

# Modes (currently not used)
#synchronised-replay       1

# Replay offset
#xnee_replay_offset 0x0

# Human printout of X11 data (instead of Xnee format)
human-printout  0

# Delay before starting record/replay
# 1

# Various
#########################################
#          Record settings              #
#########################################
#   data_flags          7
#   rState              149873200
#   xids[0]             35651584
#   xids[1]             4194304
# Number of Ranges      1
# RecordRange[0]
request-range            0-0
reply-range                   0-0
extension-request-major-range  0-0
```

```
extension-request-major-range  0-0
extension-request-major-range   0-0
extension-request-major-range   0-0
delivered-event-range         21-21
device-event-range            2-6
error-range                   6-6
0,2,0,0,0,58,0,686070317
0,3,0,0,0,58,0,686070416
0,2,0,0,0,33,0,686070451
0,3,0,0,0,33,0,686070557
0,2,0,0,0,42,0,686070635
0,3,0,0,0,42,0,686070725
0,2,0,0,0,10,0,686070981
0,3,0,0,0,10,0,686071101
0,2,0,0,0,11,0,686071204
0,2,0,0,0,12,0,686071341
0,3,0,0,0,11,0,686071371
0,3,0,0,0,12,0,686071431
0,2,0,0,0,20,0,686071875
0,3,0,0,0,20,0,686071968
0,2,0,0,0,39,0,686072202
0,3,0,0,0,39,0,686072270
0,2,0,0,0,23,0,686072661
0,3,0,0,0,23,0,686072721
0,2,0,0,0,12,0,686074341
0,3,0,0,0,12,0,686074431
0,2,0,0,0,20,0,686074875
```

```
0,3,0,0,0,20,0,686074968
0,2,0,0,0,23,0,686075661
0,3,0,0,0,23,0,686075721
0,2,0,0,0,46,0,686077009
0,3,0,0,0,46,0,686077112
0,2,0,0,0,31,0,686077229
0,3,0,0,0,31,0,686077312
0,2,0,0,0,23,0,686077692
0,3,0,0,0,23,0,686077765
0,2,0,0,0,50,0,686078684
0,2,0,0,0,16,0,686079008
0,3,0,0,0,16,0,686079086
0,3,0,0,0,50,0,686079153
0,2,0,0,0,36,0,686080318
0,3,0,0,0,36,0,686080378
0,2,0,0,0,36,0,686101906
0,3,0,0,0,36,0,686101976
0,2,0,0,0,39,0,686103177
0,3,0,0,0,39,0,686103282
0,2,0,0,0,41,0,686103381
0,3,0,0,0,41,0,686103466
0,2,0,0,0,28,0,686103579
0,3,0,0,0,28,0,686103649
0,2,0,0,0,33,0,686103788
0,3,0,0,0,33,0,686103891
0,2,0,0,0,20,0,686104068
0,3,0,0,0,20,0,686104161
```

```
0,2,0,0,0,39,0,686104264
0,3,0,0,0,39,0,686104356
0,2,0,0,0,23,0,686104597
0,3,0,0,0,23,0,686104687
0,2,0,0,0,12,0,686105264
0,3,0,0,0,12,0,686105356
0,2,0,0,0,23,0,686105597
0,3,0,0,0,23,0,686105687
0,2,0,0,0,44,0,686106430
0,3,0,0,0,44,0,686106503
0,2,0,0,0,43,0,686106614
0,3,0,0,0,43,0,686106712
0,2,0,0,0,32,0,686106844
0,2,0,0,0,58,0,686106938
0,3,0,0,0,32,0,686107001
0,3,0,0,0,58,0,686107056
0,2,0,0,0,62,0,686107297
0,2,0,0,0,11,0,686107439
0,3,0,0,0,11,0,686107537
0,3,0,0,0,62,0,686107561
0,2,0,0,0,54,0,686107745
0,3,0,0,0,54,0,686107845
0,2,0,0,0,26,0,686108009
0,2,0,0,0,27,0,686108200
0,3,0,0,0,26,0,686108215
0,3,0,0,0,27,0,686108294
0,2,0,0,0,26,0,686108417
```

```
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0,3,0,0,0,38,0,686108783

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0,3,0,0,0,46,0,686108977

0,2,0,0,0,36,0,686109421

0,3,0,0,0,36,0,686109506

0,2,0,0,0,62,0,686115540

0,2,0,0,0,41,0,686115738

0,3,0,0,0,41,0,686115830

0,3,0,0,0,62,0,686115913

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0,3,0,0,0,30,0,686116123

0,2,0,0,0,28,0,686116215

0,3,0,0,0,28,0,686116278

0,2,0,0,0,20,0,686116372

0,3,0,0,0,20,0,686116472

0,2,0,0,0,50,0,686116571

0,2,0,0,0,44,0,686116693

0,3,0,0,0,50,0,686116786

0,3,0,0,0,44,0,686116800

0,2,0,0,0,38,0,686116924

0,3,0,0,0,38,0,686117009

0,2,0,0,0,45,0,686117027

0,3,0,0,0,45,0,686117110

0,2,0,0,0,36,0,686117318

0,3,0,0,0,36,0,686117401
```

```
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0,2,0,0,0,28,0,686121472

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0,3,0,0,0,65,0,686121874

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0,3,0,0,0,39,0,686122142

0,2,0,0,0,41,0,686122215

0,3,0,0,0,41,0,686122300

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0,3,0,0,0,60,0,686123082

0,2,0,0,0,18,0,686123522

0,3,0,0,0,18,0,686123604

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```

```
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0,3,0,0,0,61,0,686126208

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```

```
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0,2,0,0,0,36,0,686580272

0,3,0,0,0,36,0,686580344
```

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# Curriculum Vita

## Jerry Yin Hom

### Education

09/1998–05/2008 Ph.D., Computer Science
Thesis: *An Execution Context Optimization Framework for Disk Energy*
Rutgers University
Piscataway, NJ

08/1991–05/1995 B.S., Electrical Engineering and Computer Science
University of California, Berkeley
Berkeley, CA

### Experience

09/1998–05/2008 Teaching Assistant
Computer Science Department
Rutgers University
Duties generally involved grading of exams, projects, and homeworks, answering questions about course work, and resolving complaints. Courses included:

- Programming Languages & Compilers (graduate)
- Compilers
- Principles of Programming Languages
- Numerical Analysis of Computing
- Introduction to Computer Science

For undergraduate courses, I also led recitations (up to three per course) which supplement the main lecture's instructional material. A recitation class ranged between 5–30 students.

09/1995–08/1998 Systems Programmer/Analyst
Information Technology Department
Acuson Corporation (now part of Siemens AG)

Developed and customized SQL databases, database client applications, and database reports.

## List of Publications

J. Hom and U. Kremer. Inter-program optimisations for disk energy reduction. *International Journal of Embedded Systems*, 3(1/2):8–16, 2007.

J. Hom and U. Kremer. Inter-program optimizations for conserving disk energy. In *Proceedings of the International Symposium on Low Power Electronics and Design*, pages 335–338, August 2005.

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