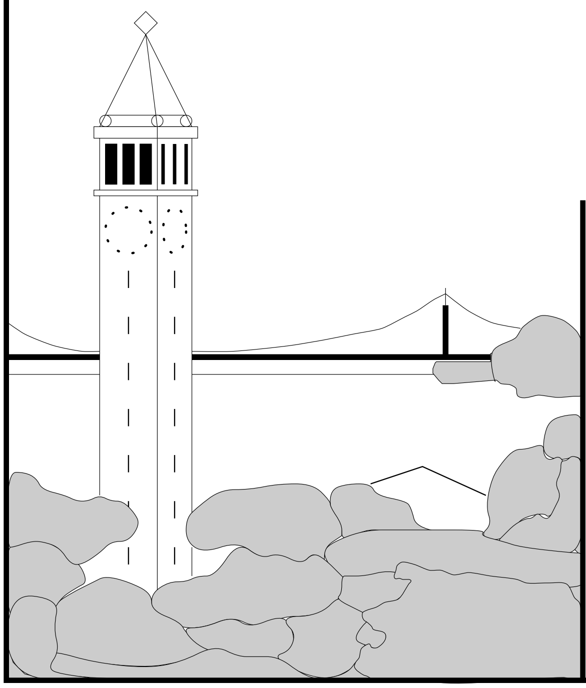
Energy Consumption of Apple Macintosh Computers

Jacob R. Lorch　　　　*Alan Jay Smith*



Report No. UCB/CSD-97-961

June 1997

Computer Science Division (EECS)
University of California
Berkeley, California 94720

Energy Consumption of Apple Macintosh Computers

Jacob R. Lorch and Alan Jay Smith*
Computer Science Division, EECS Department, University of California, Berkeley
Berkeley, CA 94720-1776

June 17, 1997

Abstract

The utility of a portable computer is critically dependent on the period it can be used while running off the battery. In this paper, we present a study of power consumption in Apple Macintosh computers. We measure the existing power consumption for each system component using built-in measuring tools. Since total power consumption is a function of user workload, we use eight user workload traces to determine power use as observed in practice. Apple currently implements some power-saving features, and the effectiveness of those features is estimated; we find typical power savings of 41–66%. After the use of basic power-saving techniques, we find that the major power users are the backlight (25–26%), the CPU (9–25%), the display (4–17%), the video circuitry (6–10%), and the hard drive (4–9%). We then evaluate possible changes in system hardware and software with regard to the power savings they might offer.

1 Introduction

One of the most important features of a portable computer system is its battery lifetime. Users would like a portable computer to last for a day, or even a week, without needing to be recharged, but a typical modern portable computer can only operate in this way for two to four hours [24]. Recognizing this, component and operating systems designers have had to consider ways to increase battery lifetime through special consideration of the portable environment.

There are two general approaches to reducing power use. First, one can design and/or use components that use less power, such as a low-power display, a display easily visible without a backlight, a low-power processor, a low-power disk, flash memory instead of mechanical disk, etc. Second, one can take better advantage of the low-power states of existing system components. For example, most hard drives made for portable computers can be made to stop spinning in order to save power, and operating systems can take advantage of this by spinning down the hard drive when it is not in use [17]. Another low-power state that can be taken advantage of is running the CPU at a lower voltage. Power consumption drops with the square of the voltage, but the maximum clock rate also drops with the voltage. By varying the voltage (and dropping the clock rate as necessary), it is possible to decrease overall power use while still permitting the CPU to meet its task completion deadlines [30]. Note that taking advantage of low-power states means making trade-offs between power and performance, since low-power states have associated disadvantages. For instance, spinning down the disk causes the subsequent disk access to have a high latency, and decreasing the CPU clock speed can increase response time.

In order to evaluate power-saving techniques, we need to know the power consumption of each system component for a "typical" workload while using existing (perhaps primitive or naive) power-saving techniques. To evaluate the effect of existing, proposed, and potential power-saving techniques, we have designed software tools to collect data on the power use of Macintosh portable computer components, and on the frequency of use of their low-power states. We use these tools to determine, for each machine studied, what its maximum power consumption is and how this is divided among its components. We then show how the use of power-saving modes reduces, and changes the breakdown of, this power consumption. Then, we show how this power consumption could be reduced even further through the use of additional software power-saving techniques. Finally, we consider how power consumption could be reduced further by changing the hardware configuration.

This paper is organized as follows. Section 2 gives

*The authors' research has been supported in part by the National Science Foundation under grants MIP-9116578 and CCR-9117028, by NASA under grant NCC 2-550, by the State of California under the MICRO program, and by Apple Computer Corporation, Sun Microsystems, Fujitsu Microelectronics, Sony Research Laboratories, Toshiba, and Intel Corporation. This material is also based upon work supported under a National Science Foundation Graduate Research Fellowship.

Machine	Features
Duo 230	68030 processor; 33 MHz top speed; supports 16 MHz operation; internal hard drive either 80 MB, 120 MB, or 160 MB; 9” backlit supertwist monochrome display with 16 levels of gray; optional internal modem; trackball; keyboard; 4 MB RAM expandable to 24 MB
Duo 270c	68030 processor with 68882 math coprocessor; 33 MHz top speed; supports 16 MHz operation; internal 240 MB hard drive; 8.4” backlit active-matrix color display; optional internal modem; trackball; keyboard; 4 MB RAM expandable to 32 MB
Duo 280c	68LC040 processor; 33 MHz top speed; internal 320 MB hard drive; 8.4” backlit active-matrix color display; optional internal modem; trackball; keyboard; 4 MB RAM expandable to 40 MB

Table 1: Features of the PowerBook Duos studied [5]

some background about the computers being studied: their components, their power-saving features, and their power-reporting features. Section 3 describes how our analysis tools work and how we used them. Section 4 presents the results of using these tools and some information that we collected from other sources. Then, Section 5 uses these results to perform the analyses described in the previous paragraph. Section 6 discusses directions for future research and development. Finally, Section 7 concludes.

2 Background

Machines studied

The Macintosh PowerBook Duos 230, 270c, and 280c are part of a line of portable computers produced by Apple Computer, Inc. While no longer the current product generation, they are still in wide use, and provide a good testbed for realistic modeling. To our knowledge, the power consumption patterns of these machines is still reasonably representative of existing designs, since as far as we know there have been no major shifts in technology that would lead to major changes in power consumption. Table 1 shows the major features of the Duos studied here [5].

Each of these computers uses a single battery. The highest capacity battery manufactured by Apple for operation on these machines was the PowerBook Duo Battery Type III, a NiMH battery whose capacity we measured at 16.94 W-h. More recent lithium-ion batteries manufactured by Apple have rated capacities of 29–32 W-h [5].

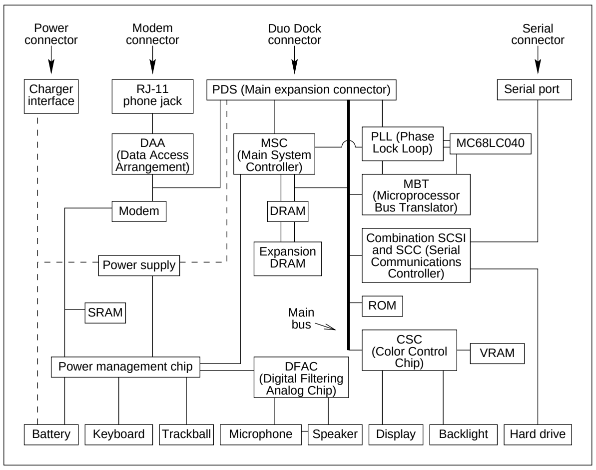


Figure 1: Block diagram of the Duo 280c main logic board functions

Figure 1 shows a block diagram of the main logic board functions of the Duo 280c [2, 3, 4]. The Duo 270c differs from this in that the MC68LC040 is replaced by an MC68030 and a 68882 coprocessor. The Duo 230 differs in that the CSC is replaced by the GSC (gray-scale controller), and the MC68LC040 is replaced by an MC68030. Also, in the Duo 230 and Duo 270c, the processor is connected directly to the main bus, so the PLL and MBT are not present.

We can use this block diagram to divide the computer into the following main components:

- Processor
- Hard drive (including SCSI controller)
- Backlight
- Display
- Modem (modem, DAA, and RJ-11)
- Sound (DFAC, microphone, and speaker)
- FPU, if present
- Video (CSC/GSC and VRAM)
- Power management support (power management chip and SRAM)
- Memory (DRAM and expansion DRAM)
- Serial communications (SCC and serial port)

- Input (keyboard and trackball)
- Power supply
- Miscellaneous glue logic and components (PDS, MSC, PLL, MBT, main bus, etc.)

When we talk about the power consumption breakdown of a machine, we will mean how much power is consumed by each of these main components. Since the serial communications and input components consume a negligible amount of power, they will not be considered further.

It is important to note that the power supply is not perfectly efficient, and only delivers about 85% of its input power to the system components [26]. This loss is, to our understanding, roughly linear in the amount of power used at any given time, and accordingly we attribute the power supply losses to the other individual components studied. If we wanted to consider alternative power supply designs, we would need to make a separate provision for power supply inefficiency, but in this paper we do not do so.

It is useful to break down the power consumption slightly further. When the processor is turned off, as it is during a power-saving mode to be described later, there is a consequent reduction in the power consumption of many motherboard parts other than the CPU and FPU. For example, when the CPU is inactive, the main bus has less to do and consequently consumes less power. It is thus useful to make a distinction between *reducible* and *nonreducible* components, where the reducible components are those whose power is reduced to zero when the processor is off. Note that if a component has its power reduced by 50% when the processor is off, we are considering half of this component to be reducible and the other half to be nonreducible. Most components do not have their work directly reduced when the processor is off, and so are assumed to be nonreducible. However, the FPU and, of course, the CPU are entirely reducible. The miscellaneous component has both reducible and nonreducible parts. We therefore further break down the miscellaneous component into a reducible miscellaneous component and a nonreducible miscellaneous component.

Power-saving features

In this section, we consider the existing low-power modes available on the Duos, and how the existing operating system takes advantage of them.

First, on each machine, the hard drive is capable of being "spun down", i.e. having its motor turned off. The user specifies an interval between 30 seconds and 15 minutes; if the specified amount of time goes by without any disk accesses, the operating system will spin down the disk. It will not spin the disk back up until the next disk access. The user may also set the interval to infinity, i.e. elect to have the hard drive never spin down.

```
save CPU state
loop
    check for user or network activity
    if there is activity
        exit the loop
    else
        turn off CPU until next interrupt
restore CPU state
```

Figure 2: Procedure for processor cycling

The backlight on each of the Duos can be set to many different levels, ranging from 0% to 100% of its maximum possible brightness. The user manually adjusts this brightness using buttons next to the screen. Furthermore, the user specifies an interval between 30 seconds and 5 minutes, after which amount of inactivity the operating system will begin to progressively dim the backlight, stopping when it eventually reaches 0% illumination. Note that here and in later contexts, activity is defined as any input, any indication by a process that it is busy, or any use of the disk, sound chip, or modem. When activity occurs again, the operating system will return the backlight immediately to the brightness level it was at before progressive dimming began. The user may also set the interval to infinity, i.e. elect to have the backlight never automatically dim.

The processor on the Duo 230 or the Duo 270c can be made to run at a lower speed; each supports 16 MHz operation in addition to the typical 33 MHz operation. The user indicates at what speed the processor should run, but any changes he or she makes do not take effect until the machine shuts down and restarts. Note that there is no voltage variation; slowing down the processor simply slows down the processor.

The processor on the Duos supports another low-power mode, called *cycling*. The operating system causes the machine to enter this mode by executing the processor cycling procedure described in Table 2. We use the term *halt cycle* to denote a single iteration of this loop. Thus, a halt cycle consists of an *on interval*, during which the machine checks for activity, followed by an *off interval*, during which the CPU is off. Note that when the CPU turns off, its cache is flushed. Also, as mentioned before, when the processor is off, not only is its power consumption reduced, but the power consumption of the rest of the motherboard is also significantly reduced. Usually, when the processor is cycling, the only interrupts that occur are the vertical-retrace interrupts. Since these interrupts occur roughly 120 times a second, a halt cycle typically takes about 8 ms. Since checking for activity takes a short amount of time, most of this 8 ms is spent in the off interval.

The user indicates whether or not processor cycling should be used. If it is to be used, the operating system will initiate the processor cycling procedure whenever no activity has occurred in the last 2 seconds and no disk activity has occurred in the last 15 seconds. The procedure will stop whenever activity is once again detected. This technique is used instead of a more aggressive power-saving technique for at least two reasons. First, it is difficult to determine when the processor is doing useful work and one does not want to turn it off while it is doing such work; because of peculiarities of both MacOS and the most common Macintosh applications, Macintoshes frequently experience busy waiting [20]. Second, even if one cycles the processor only when it is not doing useful work, there will still be a performance degradation from flushing the cache.

The sound chip on the Duos can be turned off. The operating system ensures that the sound chip is turned on when it is needed, and that it is shut off after about 8 seconds pass with no sound being produced. This is useful since the sound chip uses power even when not producing sound. The user has no control over the strategy used to turn the sound chip on and off.

The modem on the Duos can be turned on and off, but only explicitly by the user or by the applications he or she runs.

Finally, the system can have its power reduced as a whole by putting it in *sleep mode*. When the machine is asleep, all its components are off except for the DRAM. The user specifies an interval between 30 seconds and 15 minutes, after which period of inactivity the machine will be put in sleep mode. The machine automatically exits sleep mode whenever a key is pressed, taking about 12–15 seconds to return to normal operating mode. Note that the user may indicate an interval of infinity, i.e. make the machine never sleep.

Power-reporting features

The Duos have built-in hardware and software for monitoring their energy consumption. The software can be queried for the instantaneous power consumption, as well as the total energy consumption since the last time the battery was charged. These values are given in units of 0.06426 watts (W) and 0.06426 watt-seconds (W-s), respectively.

3 Methodology

There are two aspects to measuring the breakdown of power consumption on a portable computer: measuring how much power is consumed by each component in each state, and profiling how often each component is in each state. We designed a program called PowerMeasure to perform the former task and one called StateProfiler to perform the latter one.

The operation of PowerMeasure is as follows. For each component c, and for each pair of states s_1 and s_2 of c, it computes the difference in instantaneous total power consumption between when component c is in state s_1 and when all other component states remain the same but c is in state s_2. Note that this approach automatically accounts for power supply inefficiency as a part of each other component's power consumption, as discussed before. PowerMeasure also computes the energy savings from one halt cycle by subtracting the total energy consumption over a period of five minutes with processor cycling enabled from the total energy consumption over a period of five minutes with processor cycling disabled, then dividing by the number of halt cycles that occurred during those five minutes. Finally, it computes the energy consumption of spinning up (turning on) the hard drive by subtracting the energy consumption over an 8-second period while the hard drive is idle from the energy consumption during another 8-second period which is identical except that the hard drive is spun up once.

To validate the software power monitoring routines, we performed some measurements with hardware. A Duo 230 was instrumented with a voltmeter and ammeter so that battery current and voltage, and thus power consumption, could be observed while the PowerBook was running. The percentage differences found between software and hardware figures ranged from 0.1% to 5.6%. These differences seem small enough to warrant confidence in the values we obtained from PowerMeasure.

StateProfiler operates as follows. Every five seconds, it examines the state of each component and increments a counter for each such component state it finds as well as a global time counter. In addition, it arranges to be notified each time certain events of significant energy consumption take place so that it can count them. These events include the hard drive spinning down, the machine entering or leaving sleep mode, and a halt cycle starting.

Note that PowerMeasure needs to be run only once per machine type, while StateProfiler runs as a background application for a user throughout his or her participation in the study. Several users agreed to participate in this study and were asked to run StateProfiler on their machines for about a week. Each user works as an engineer or researcher at Apple Computer, Inc. and uses his

Item measured	Duo 230	Duo 270c	Duo 280c
. . .by PowerMeasure			
Maximum power consumption	7.84 W	10.08 W	12.08 W
Power saved by spinning hard drive down	0.96 W	1.22 W	1.48 W
Power saved by turning modem off	0.58 W	0.51 W	0.58 W
Power saved by turning sound system off	0.19 W	0.19 W	0.19 W
Power difference between CPU at 16 MHz and at 33 MHz	1.09 W	1.35 W	N/A
Power difference between backlight off and at full	2.38 W	3.21 W	3.40 W
Energy saved by cycling CPU once during 16 MHz operation	13 mW-s	14 mW-s	N/A
Energy saved by cycling CPU once during 33 MHz operation	19 mW-s	22 mW-s	28 mW-s
Energy consumed by spinning hard drive up	11 W-s	8.8 W-s	4.4 W-s
Maximum CPU cycling rate observed at 16 MHz	116 Hz	125 Hz	N/A
Maximum CPU cycling rate observed at 33 MHz	120 Hz	126 Hz	130 Hz
. . .by means other than PowerMeasure			
CPU power at 33 MHz	1.15 W	1.15 W	3.33 W
FPU power in typical operation	N/A	0.46 W	N/A
Power management power	0.12 W	0.12 W	0.12 W
Display power	0.20 W	0.75 W	0.75 W
Video power	0.35 W	0.46 W	0.46 W
Memory power	0.06 W	0.06 W	0.06 W
Reducible misc power at 33 MHz	1.19 W	1.23 W	0.41 W
Nonreducible misc power at 33 MHz	0.66 W	0.72 W	1.30 W

Table 2: Power consumption results obtained for all three machines

or her own PowerBook. Because power consumption is largely unimportant when running on wall power, results presented in this paper, unless otherwise noted, use only data collected while users were running on battery power. We further restricted consideration to the time the machines spent not asleep, since battery lifetime typically only refers to this kind of time. For the users studied, the average fraction of time on battery power was 16%. Another eight users, who spent less than an hour each running on battery power, were omitted from the study; these other users, however, spent a total of almost 243 hours running on wall power. As may be noted, at least for this set of users, portable computers spend only a small fraction of their time running on battery power.

4 Results

Component power consumption

PowerMeasure was run on three different machines to determine power and energy consumption. They were a Duo 230 with 80 MB hard drive, a Duo 270c with 240 MB hard drive, and a Duo 280c with 320 MB hard drive. The top half of Table 2 shows, for each of these machines, the total power consumption in the absence of power-saving modes, the power saved by entering various power-saving states, the energy saved or consumed by certain transient events, and the rate at which halt cycles occur during extended idle periods. Different machines generally use different components with different power consumptions; however, since the same modem is used for all three machines, the fact that we find a slightly lower modem power consumption on the Duo 270c is probably due to product variation or measurement error. Note that it is normal for different machines, even with the same processor, to have different maximum cycling rates, since these rates depend on how often interrupts occur. However, the rate differences observed between different CPU speeds on the same machine are also probably due to either product variation or measurement error.

We performed an additional experiment to determine the usable capacity of a Type III battery. The battery was run down from fully charged to the point at which the operating system forced the machine to sleep in order to preserve the contents of memory. Immediately before the machine went to sleep, the software was queried for the total energy consumption since charging. In this way, the usable capacity was determined to be 16.94 W-h.

Power of motherboard components

Since PowerMeasure cannot obtain power figures for machine states not currently supported, some data must be obtained through other means. To allow us to break down the power consumption of the motherboard, we obtained the following estimates from an engineer at Apple Computer [26]:

- 68030 at 33 MHz consumes 1.15 W.
- Duo 270c FPU, in typical operation, consumes 460 mW.
- 68LC040 at 33 MHz consumes 3.33 W.
- Power-management support chip consumes 120 mW.
- On interval duration is roughly 6600 clock cycles.
- Duo 230 display without backlight consumes 200 mW.
- Duo 230 video controller and VRAM consume 350 mW.
- Duo 270c/280c display without backlight consumes 750 mW.
- Duo 270c/280c video controller (color control chip) consumes 370 mW.
- Duo 270c/280c VRAM consumes 90 mW.

We also used our hardware instrumentation of a Duo 230 to measure its power consumption while asleep. Since only the 12 MB of DRAM is on while the machine is asleep, we attribute the 0.06 W we measured to the memory. We use the same result for the Duo 270c and Duo 280c, since they typically have the same amount of DRAM.

There are two additional things we must know in order to fully break down power consumption. First, we must know how to compute the power consumption of a reducible component given the rate at which halt cycles occur. Second, we must know how much of the miscellaneous component is reducible and how much is nonreducible.

We can compute the average power consumption of a reducible component by multiplying its full power consumption by the fraction of time the processor is on. One can compute the fraction of time the processor is off by multiplying the rate at which halt cycles occur by the amount of time the processor spends off per halt cycle. In summary, if the full power consumption of a reducible component is p, the cycling rate is r, and the duration of an off interval is d_{off}, then its average power consumption is

$$(1 - d_{\text{off}} r)\, p.$$

If we assume that the maximum cycling rate observed is the maximum achievable on the machine, i.e. the result of beginning a halt cycle as soon as the previous one has ended, then the reciprocal of this rate must be the sum of the on and off interval durations. Thus, we can compute the duration of an off interval from the maximum possible cycling rate possible $r_{\max}$ and the duration of an on interval d_{on} with the following equation:

$$d_{\text{off}} = 1/r_{\max} - d_{\text{on}}.$$

The energy savings e attained from each halt cycle are due to saving the power of all reducible components for a period of time equal to d_{off}. Thus, the full power consumption of all reducible components together is e/d_{off}. We can obtain the power consumption of the reducible miscellaneous component by subtracting from this value the power consumptions of the CPU and FPU.

The bottom half of Table 2 summarizes the results of our power estimates and computations for the motherboard components of each machine.

An interesting result of these computations is that the Duo 280c differs greatly from the other machines in the percent of miscellaneous power consumption that is reducible. This percent is 64% on the Duo 230 and 63% on the Duo 270c, but only 24% on the Duo 280c. The result of this lower percent on the Duo 280c is that it gets significantly less power savings from processor cycling than the other Duos. The lower percent may be because the Duo 280c has an MBT, a microprocessor bus translator that interfaces between the MC68LC040 and the main bus designed for use with the MC68030. This MBT lies between the processor and the rest of the motherboard, making it less apparent to the rest of the motherboard when the processor is off. Perhaps if the motherboard were designed differently, more power could be saved during processor cycling on the Duo 280c.

Frequency of component states

StateProfiler profiled seven users while their machines were awake and running on battery power, and the resulting data are shown in Table 3. Users 1–6 were engineers; user 7 was a researcher. In this table, cycling rates are expressed in hertz and backlight levels are expressed as percentages of the maximum possible power consumption of the backlight. Note that there was no use of the 16 MHz setting of the processor. Also, users 1 and 7 had different hard disk sizes than the machines we measured with PowerMeasure. For the purposes of later calculations, we will overlook this fact, since it seems likely

Item measured	User 1	User 2	User 3	User 4	User 5	User 6	User 7
Machine used	230	270c	270c	280c	280c	280c	280c
Hard disk size	120 MB	240 MB	240 MB	320 MB	320 MB	320 MB	240 MB
DRAM size	12 MB	12 MB	24 MB	12 MB	24 MB	12 MB	12 MB
Time profiled (h:m:s)	8:45:40	11:36:25	3:24:10	5:09:00	1:41:10	2:29:45	14:14:44
% time hard drive off	62.20%	91.27%	63.88%	77.02%	85.17%	54.03%	53.38%
% time modem off	88.43%	100.00%	97.06%	95.90%	0.00%	100.00%	0.26%
% time sound off	98.30%	99.92%	98.73%	99.35%	99.01%	95.10%	76.90%
Mean backlight level	48%	36%	32%	41%	46%	32%	67%
Max backlight level	100%	100%	50%	100%	77%	100%	100%
CPU cycling rate	42.33 Hz	111.75 Hz	0.00 Hz	101.52 Hz	130.01 Hz	41.71 Hz	31.71 Hz
Avg time b/n spindowns	6.41 min	23.1 min	6.80 min	6.31 min	12.6 min	3.94 min	5.27 min

Table 3: Profile data for users

that had these users been using the same hard disk sizes as the machines we studied, their usage patterns would not have changed. Similarly, users 3 and 5 had different memory sizes than the machines we measured, but hopefully this also did not have a noticeable effect on their usage patterns.

For most of the calculations in this paper (below), we will aggregate all the users on each machine into a composite by simply concatenating their profiles. We never aggregate users who worked on different machines, however, because usage patterns may be dependent on the machine used. For instance, a user might prefer a different backlight level on a color machine than on a black-and-white one. Also, a user with a faster processor will begin tasks that are dependent on the results of previous processing sooner.

5 Discussion

Maximum power consumption

The figures obtained by PowerMeasure and by other means allow us to break down the total power consumption of each machine when each component is in its highest-power state. Table 4 shows these breakdowns. We see that, when all components are active, the components consuming the most power are the backlight, the processor, and the hard drive. These three components account for 57% of the Duo 230 power, 55% of the Duo 270c power, and 68% of the Duo 280c power.

We can compare these results with an estimate of the power consumption breakdown of a hypothetical 33 MHz Am386 DXL system described by MacDonald [21]. This system is generally similar in architecture to the Duo 230, except that it has a floppy drive but no sound or modem. The estimates given by MacDonald for the machine with all components in their highest-power states, based on actual and estimated data for various components, indicate that out of a total power consumption of 13.03 W, 13% is due to the processor, 14% is due to the hard drive, 13% is due to the backlight, 4% is due to the display, 1% is due to the FPU, 16% is due to the video system, 1% is due to power management, 2% is due to memory, and 1% is due to the floppy drive. These percentages are similar to those given for the Duo 230, although the backlight on the Duo 230 consumes a noticeably greater percentage of total power and the video system consumes a noticeably lower percentage. Also, the Duo 230 has a total maximum power consumption 40% less than that of the hypothetical Am386 DXL system.

Effect of current power-saving features

The power consumption and user profile data can be combined to give a power consumption breakdown for each machine that takes into account the power-saving modes used in real environments. These breakdowns are presented numerically in Table 5. They are also shown graphically in Figure 3, in which they are compared to the corresponding breakdowns given no use of power-saving modes.

Comparison of Tables 4 and 5 reveals that users make significant use of the power-saving modes available when running on battery power. Power reduction attained from these methods amounts to 42% on the Duo 230, 56% on the Duo 270c, and 35% on the Duo 280c. Roughly 35% of these savings are due to backlight savings, 20% are due to hard drive savings, and 35% (25% on the Duo 230) are due to processor cycling. Thus, the existing, simple power-saving modes provided are together fairly effective, with spinning down the hard drive, backlight dimming, and processor cycling each accounting for a significant portion of the savings attained.

Component	Duo 230		Duo 270c		Duo 280c	
Processor	1.15 W	(14.67%)	1.15 W	(11.41%)	3.33 W	(27.57%)
Hard drive	0.96 W	(12.24%)	1.22 W	(12.10%)	1.48 W	(12.25%)
Backlight	2.38 W	(30.36%)	3.21 W	(31.85%)	3.40 W	(28.15%)
Display	0.20 W	(2.55%)	0.75 W	(7.44%)	0.75 W	(6.21%)
Modem	0.58 W	(7.40%)	0.51 W	(5.06%)	0.58 W	(4.80%)
Sound	0.19 W	(2.42%)	0.19 W	(1.88%)	0.19 W	(1.57%)
FPU	N/A	(0.00%)	0.46 W	(4.56%)	N/A	(0.00%)
Video	0.35 W	(4.46%)	0.46 W	(4.56%)	0.46 W	(3.81%)
Power management	0.12 W	(1.53%)	0.12 W	(1.19%)	0.12 W	(0.99%)
Memory	0.06 W	(0.77%)	0.06 W	(0.60%)	0.06 W	(0.50%)
Reducible miscellaneous	1.19 W	(15.13%)	1.23 W	(12.24%)	0.41 W	(3.37%)
Nonreducible miscellaneous	0.66 W	(8.47%)	0.72 W	(7.11%)	1.30 W	(10.79%)
Total (Type III battery life)	7.84 W	(2.16 hr)	10.08 W	(1.68 hr)	12.08 W	(1.40 hr)

Table 4: What the power consumption breakdown for each machine would be if power-saving modes were never used

Component	Duo 230		Duo 270c		Duo 280c	
Processor	0.75 W	(16.65%)	0.38 W	(8.66%)	1.96 W	(24.94%)
Hard drive	0.39 W	(8.64%)	0.19 W	(4.36%)	0.59 W	(7.55%)
Backlight	1.14 W	(25.22%)	1.16 W	(26.31%)	1.94 W	(24.75%)
Display	0.20 W	(4.42%)	0.75 W	(17.03%)	0.75 W	(9.56%)
Modem	0.07 W	(1.48%)	0.00 W	(0.08%)	0.40 W	(5.05%)
Sound	0.00 W	(0.07%)	0.00 W	(0.02%)	0.02 W	(0.36%)
FPU	N/A	(0.00%)	0.15 W	(3.46%)	N/A	(0.00%)
Video	0.35 W	(7.73%)	0.46 W	(10.45%)	0.46 W	(5.86%)
Power management	0.12 W	(2.65%)	0.12 W	(2.73%)	0.12 W	(1.53%)
Memory	0.06 W	(1.32%)	0.06 W	(1.36%)	0.06 W	(0.76%)
Reducible miscellaneous	0.78 W	(17.17%)	0.41 W	(9.29%)	0.24 W	(3.05%)
Nonreducible miscellaneous	0.66 W	(14.66%)	0.72 W	(16.27%)	1.30 W	(16.60%)
Total (Type III battery life)	4.53 W	(3.74 hr)	4.40 W	(3.85 hr)	7.85 W	(2.16 hr)

Table 5: Power consumption breakdown for each machine, taking into account observed use of power-saving modes

Component	Duo 230		Duo 270c		Duo 280c	
Processor	1.15 W	(23.79%)	0.65 W	(10.71%)	3.13 W	(31.98%)
Hard drive	0.96 W	(19.86%)	1.22 W	(20.18%)	1.19 W	(12.12%)
Backlight	0.14 W	(2.95%)	1.12 W	(18.55%)	2.09 W	(21.39%)
Display	0.20 W	(4.14%)	0.75 W	(12.38%)	0.75 W	(7.66%)
Modem	0.00 W	(0.00%)	0.00 W	(0.00%)	0.30 W	(3.05%)
Sound	0.00 W	(0.01%)	0.00 W	(0.01%)	0.00 W	(0.04%)
FPU	N/A	(0.00%)	0.26 W	(4.29%)	N/A	(0.00%)
Video	0.35 W	(7.24%)	0.46 W	(7.59%)	0.46 W	(4.70%)
Power management	0.12 W	(2.48%)	0.12 W	(1.98%)	0.12 W	(1.23%)
Memory	0.06 W	(1.24%)	0.06 W	(0.99%)	0.06 W	(0.61%)
Reducible miscellaneous	1.19 W	(24.54%)	0.70 W	(11.49%)	0.38 W	(3.91%)
Nonreducible miscellaneous	0.66 W	(13.74%)	0.72 W	(11.83%)	1.30 W	(13.31%)
Total (Type III battery life)	4.83 W	(3.51 hr)	6.06 W	(2.80 hr)	9.79 W	(1.73 hr)

Table 6: Power consumption breakdown for each machine given the composite usage pattern of the set of users who used that machine while they were running on wall power

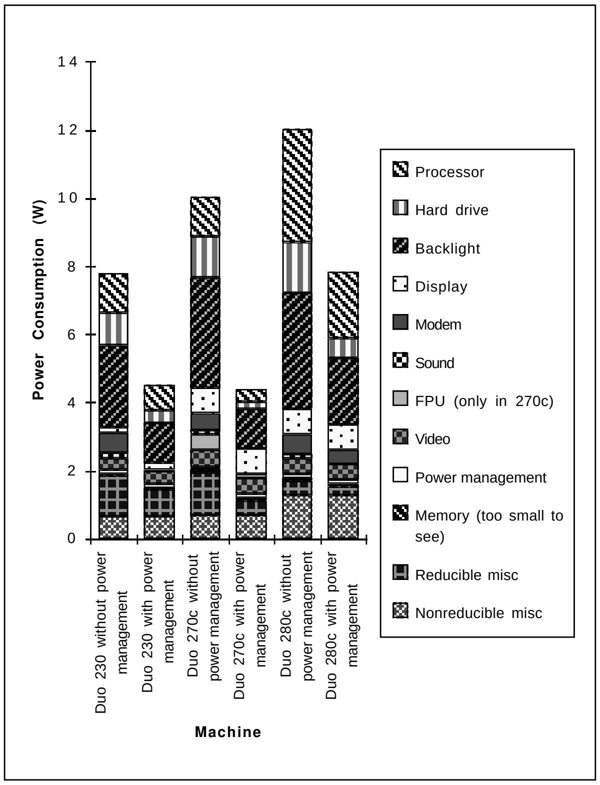


Figure 3: Power consumption breakdowns for each machine, given no use of power-saving modes and observed use of power-saving modes

Not only does the total power consumption of each machine decrease when power-saving modes are used, but the breakdown of this power consumption changes. For instance, the hard drive, which accounts for about 12% of maximum power consumption, only accounts for 4–9% of power consumption when power savings are taken into account.

We must be cautious when interpreting all of these figures, because as Table 3 shows, different users have significantly different usage patterns for each power-saving feature. Different users will have different total power consumptions and different breakdowns of power consumption. We can therefore expect the influence of a power-saving strategy will vary substantially depending on the workload.

One interesting finding is that users completely avoided the 16 MHz CPU speed. In fact, some brief thought shows that the slower CPU speed is not an energy-saving feature at all, but actually may increase the energy consumption while decreasing the CPU performance. Halving the CPU speed doubles the time for the CPU portion of a task, and increases the real time. The CPU energy is thus unchanged (half power times double time), but the increased real time makes it likely that other power-saving modes, e.g. disk spin-down, will be less effective; in this case, halving the CPU speed should spread the same number of disk accesses over twice as long a real time period. Thus, as long as the CPU does not run when there is nothing to do, and as long as the voltage is unchanged, decreasing the clock frequency does not decrease energy use.

We can compare these Duo results with those of the hypothetical Am386 DXL system described earlier, by taking into account MacDonald's estimates of the usage of low-power states of that machine [21]. His estimates lead to an average power consumption figure of 6.17 W, divided into 4% for the processor, 12% for the hard drive, 17% for the backlight, 4% for the display, 1% for the FPU, 26% for video, 3% for power management, 3% for memory, and 2% for the floppy drive. The main differences between these figures and those of the Duo 230 are that the Duo 230 has a significantly greater percentage of its power going to the processor, hard drive, and backlight, while the hypothetical Am386 DXL system has a greater percentage of its power going to video. Also, the Duo 230 consumes 27% less total power under average conditions than the hypothetical Am386 DXL system.

Although this paper studies the power consumption of machines while they are running on battery power, a comparison of these results with what happens when wall power is used is interesting. Table 6 shows the power consumption breakdown of each machine given the use of power-saving modes by our seven users while their machines were running on wall power. We observe, not surprisingly, that users use power management features less when they are running on wall power. Generally, the hard drive and CPU are allowed to consume nearly their maximum possible power, although roughly the same level of backlight savings are attained as when running on battery power. This may suggest that users are especially bothered by the processor cycling and hard drive spindown features. We also find that the lesser use of power-saving modes leads to a greater proportion of power consumption being attributable to the hard drive, CPU, FPU, and reducible miscellaneous components. Therefore, any new power-saving feature will have a different impact on a machine when it is running on wall power than when it is running on battery power.

Effect of different software techniques

Our figures allow us to evaluate the effect of other power-saving techniques on total power consumption. For example, Li et al. [17] suggest a way to reduce total hard drive power consumption by 90%. Our studies show that the average Duo 280c user already saves about 60% of hard drive power. Furthermore, currently about

7.6% of total power is due to the hard drive. Combining these figures, we find that Li et al.'s technique would reduce total Duo 280c power consumption by about 5.7%, increasing battery lifetime by about 6%. Of course, for different machines and for individual users these figures may be different; to get answers for such situations one must appropriately replace figures in the above calculation. We note that over the long term, the relative use of power between mechanical components such as disks and electronic components such as processors may shift. Such a shift may also result from designs optimized for power consumption rather than performance.

Weiser et al. [30] indicate that if their algorithms are used to reduce CPU speed and voltage simultaneously, they can save as much as 50% or 70% of CPU power, depending on whether the minimum voltage available is 3.3 V or 2.2 V. Let us assume that all reducible components, not just the CPU, would exhibit this 50% or 70% power reduction. As the reducible components account for 28.0% of the total Duo 280c power consumption, the new method could save as much as 14% or 20% of total power consumption, increasing battery lifetime by 16% or 24%.

Not only can we determine how much power savings are achievable through various software techniques, we can also determine upper bounds on how much savings could be achieved through such techniques. The percentages shown in Table 5 give upper bounds on the potential power savings achievable through better power-saving techniques for a given component. For example, since the hard drive on the Duo 280c only accounts for 7.6% of the total power consumption, the most reduction in power consumption possible through better hard drive power-saving techniques is 7.6%. We thus observe that more hard drive power reduction can save at most 4–9%, backlight power reduction 25–26%, and modem power reduction 0–5%. Greater processor cycling could save at most 33.8% on the Duo 230, 21.4% on the Duo 270c, and 28.1% on the Duo 280c. Reducing the video power consumption, perhaps by turning off the display when it is not in use, could save at most 7.7% on the Duo 230, 10.5% on the Duo 270c, and 5.9% on the Duo 280c. Note that different machines are affected differently by the power reduction of a given component.

Effect of different hardware

Our breakdowns of power consumption can also be used to estimate the impact of hardware changes, as long as one knows the power consumption of the alternative components to be used. Some examples of such information are presented in Table 7, which gives power consumption figures for a variety of components. These figures allow us to estimate how much power consumption

Description	Power
Processors	
33 MHz Motorola 68030	1.15 W
33 MHz Motorola 68LC040	3.33 W
72 MHz ARM810 [6]	0.58 W
200 MHz StrongARM SA-110 [6]	1.04 W
200 MHz PowerPC 603e [12]	4.03 W
250 MHz PowerPC 603e [12]	4.26 W
100 MHz microSPARC-IIep [27]	4.60 W
133 MHz Pentium [16]	4.95 W
166 MHz Pentium with MMX [16]	7.02 W
166 MHz Pentium Pro [15]	31.63 W
133 MHz PowerPC 620 [23]	34.50 W
200 MHz Pentium Pro, 512 KB L2 [15]	37.49 W
Backlit displays	
Used in Duo 230, 9", monochrome	2.58 W
Used in Duo 270c, 8.4"	3.96 W
Used in Duo 280c, 8.4"	4.15 W
IBM ITSV37N, 10.4" [11]	1.95 W
IBM ITSV34E, 11.3" [11]	2.53 W
IBM ITSV50N, 12.1" [11]	2.53 W
Toshiba LTM10C038, 10.4" [29]	3.22 W
Toshiba LTM12C263, 12.1" [29]	4.03 W
Hard drives	
Used in Duo 230	0.96 W
Used in Duo 270c	1.22 W
Used in Duo 280c	1.48 W
Road Warrior Slimline, 815 MB [25]	1.04 W
Maxtor MobileMax, 1.35 GB [22]	1.04 W
WD Portfolio, 1.0 GB [31]	1.09 W
Toshiba MK2720, 1.35 GB [28]	1.61 W
IBM Travelstar 4GT, 4.0 GB [13]	2.13 W
IBM Travelstar 5GS, 5.1 GB [14]	2.30 W

Table 7: Comparison of power consumption of components studied in this paper to power consumption of newer components described elsewhere; all figures described elsewhere have been inflated by 15% to account for power supply inefficiency

would be reduced by switching to these other components.

Suppose we used the newer IBM 12.1" backlit display on the Duo 280c. The figure given by IBM does not permit separation of the display and backlight power, so let us assume that, as on the Duo 280c, 82% of the backlit display power is due to the backlight. Under this assumption, using the new backlight would save roughly

$$\frac{2.69 \text{ W}}{4.15 \text{ W}} \times (4.15 \text{ W} - 2.53 \text{ W}) = 1.05 \text{ W},$$

or 13.4% of total power.

Suppose we used the more modern Maxtor MobileMax 251350 hard drive on the Duo 280c. This would save roughly

$$\frac{0.59 \text{ W}}{1.48 \text{ W}} \times (1.48 \text{ W} - 1.04 \text{ W}) = 0.18 \text{ W},$$

or 2.2% of total power. Note, however, that other features of a different hard drive could change this analysis. For instance, if the new hard drive had a larger cache in its controller, and thus needed to seek less often, its power consumption might be even lower.

Another technique for reducing the power consumption of the disk is to replace it with flash memory, as suggested by Douglis et al. [10]. They indicate that one such product can save 90% of hard drive power, even in the presence of disk power management. Given our figures, this would represent a total system power reduction for the Duo 280c of about 6.8%. Furthermore, our figures show an upper bound on the effectiveness of flash memory in this regard: if it eliminated 100% of hard drive power and consumed negligible power itself, then total Duo 280c power consumption would decrease by about 7.6%.

Limitations of the study

The following factors limit the results of this study. First, the model of power consumption we use does not account for transient events such as sound emissions, disk seeks, memory accesses, modem use, and bus activity. Second, PowerMeasure cannot separate the power consumption of two component states that are always coexistent in the computers studied; therefore we have had to use unverified estimates for the power consumption of individual motherboard components. Third, the results obtained from PowerMeasure have limited accuracy, as evidenced by the hardware validation and by the differences in values obtained for the same component in different trials. Fourth, we do not account for power savings achieved through use of the sleep mode.

6 Future and Related Work

Research

In this section, we discuss other work which we have done, are working on, or plan for the future, or which we anticipate will be done by others.

First, there is study which extends our results. Our measurements should be extended to take into account the energy consumed during such transient events as sound emissions, disk accesses, waking from sleep, and modem transmissions. We also need a better model for the breakdown of motherboard power consumption. We would like to obtain a larger and more diverse set of user profiles, since the current set comes only from technical employees at Apple Computer, Inc., and these users did not use battery power often. (A UC Berkeley student we work with is collecting profiles from Windows 95 users.) In addition, more work is needed to apply the principles of this paper to desktop machines. Power consumption is increasingly becoming an important issue for desktop machines, as the government and consumers demand machines consuming less power and dissipating less heat. The most visible evidence of this trend is the Environmental Protection Agency's Energy Star program, which is setting standards for power consumption on the desktop.

A second extension of our work is research that analyzes the relationship between the parameters of power-saving strategies, component power consumption, and system performance. For instance, more research is needed to describe how different hard drive inactivity time-out values simultaneously affect both the access latency and power consumption of the hard drive. Once such a relationship is known, it can be used along with the results of this paper to show a user what trade-off between battery lifetime and performance he would be making for each time-out value he could select. It is important to let the user indicate his preferences about power consumption, and to get the maximum benefit from his input one must provide him with enough information to make an informed decision.

A third category of further study is the development and evaluation of new software techniques for reducing the power consumption of laptops. Such study requires tools that obtain detailed, time-stamped traces of those user and system activities that have potential impact on the states of the system components. As described before, work has already been done on strategies to reduce disk power consumption by more frequent spinning down or replacement with flash memory, and on strategies to reduce processor power using voltage scaling and dynamic speed adjustment. Also, we have demonstrated a technique for improving the processor power savings in MacOS by 53%; this technique involves never scheduling processes to run when they are blocked, forcibly blocking processes that appear to be busy-waiting, and turning off the processor whenever all processes are blocked [20]. We hope that the results presented in this paper serve both as an indication of what power-saving techniques are most promising for future study and as a tool in the analysis of such techniques.

A fourth category of further study is in how to design hardware components that consume less power. Since the processor and backlight account for the largest percentage of total power, these are the components of which it is most important to develop lower-power versions. Other components whose power consumptions are significant are the hard drive and display.

Product development

The findings of this paper also suggest things that can be done immediately to improve portable computer design. First, support for multiple CPU speeds, all with the same operating voltage, seems to be useless; lower CPU speeds are generally only worthwhile if they allow simultaneous reduction in the operating voltage. Second, we have seen that the Duo 280c shows much less reduction in miscellaneous power consumption as a result of processor cycling than the Duo 230 and the Duo 270c. This suggests that the Duo 280c motherboard could be redesigned to improve the effect of processor cycling on the power reduction of other components. In general, when designing a motherboard, it is important to keep in mind how power reduction of the CPU will translate into power reduction of other components. Third, we have seen that the greatest sources of power consumption are the processor and backlight. Therefore, designers of new products should be especially eager to take advantage of new versions of these components that provide greater ratios of performance to power consumption, such as the PowerPC 603. To the extent that engineering resources are available, there appears to be a good rationale for designing much lower power, slightly lower performance processors (and other chips).

7 Conclusions and Summary

This paper shows, using the Duo line of portable computers, how power consumption in portable computers can be and is reduced by software and hardware techniques. The first part of this study is how power consumption is reduced by power-saving features currently available. Without power-saving modes, the Duo 230 consumes 7.84 W, the Duo 270c consumes 10.08 W, and the Duo 280c consumes 12.08 W. However, using the power-saving features currently provided reduces these to 4.53 W for the Duo 230, 4.40 W for the Duo 270c, and 7.85 W for the Duo 280c. About 35% of these savings come from dimming the backlight, 20% from spinning down the hard disk, and 35% (25% on the Duo 230) from processor cycling.

The next part of our discussion demonstrates how power consumption could be further reduced by additional software techniques. We find that aggressive spinning down of the hard disk could reduce power consumption of the Duo 280c by about 5.7%. We also compute that reducing the speed and voltage of the CPU simultaneously could reduce Duo 280c power consumption by as much as 14% or 20%, depending on how low a limit on voltage was imposed by the hardware. Finally, we show that there are upper bounds on the potential savings from additional software techniques, dictated by the percentages of total power attributable to each component. We see that depending on which machine he uses, the average user cannot hope to get more than an additional 21–34% from CPU cycling, 25–26% from backlight power reduction, 4–9% from hard drive power reduction, or 0–5% from modem power reduction.

Power consumption can also be reduced by substituting different components for those currently used.

An important point to emphasize is that there is no single item that dominates power consumption. To substantially reduce total power consumption, the power use of each of several components must be reduced. For the systems studied, the most significant power consumers are the processor, the backlight, the hard drive, and the display.

Designers of portable computers should also consider the effect of the power consumption of each component on the power consumption of others, e.g. how much motherboard power can be saved when the processor power is reduced.

Since the effect of a power-saving strategy can be strongly dependent on the user environment in which it is applied, user variability must be taken into account when evaluating a power-saving strategy. Also, a system that implements such a software strategy should measure and consider user preferences and activity patterns during its operation.

8 Acknowledgments

The authors owe a great deal of thanks to Apple Computer, Inc. for its contribution of information, equipment, and advice. Especially helpful at Apple were Phil Sohn, who offered aid and comments continuously during this project; Marianne Hsiung, who was a source of guidance and provided some funding; Clark Donahue, who provided extensive and detailed information about the workings of the Macintosh Power Manager; and Steve Sfarzo, who arranged the distribution of our profiler to, and the collection of data files from, many PowerBook users working with him. And, finally, we thank those users who ran the profiler on their machines to help us collect the data.

References

[1] Apple Computer, Inc. *Inside Macintosh, Volume VI*, Addison Wesley Publishing Company, Reading, MA, 1991.

[2] Apple Computer, Inc. *Macintosh Developer Note Number 2*, Developer Technical Publications, Cupertino, CA, 1992.

[3] Apple Computer, Inc. *Macintosh Developer Note Number 6*, Developer Press, Cupertino, CA, 1993.

[4] Apple Computer, Inc. *Macintosh Developer Note Number 9*, Developer Press, Cupertino, CA, 1994.

[5] Apple Computer, Inc. *Apple Computer*, on the World Wide Web at http://www.apple.com/, June 1997.

[6] Advanced RISC Machines. *ARM 810 Product Guide*, on the World Wide Web at http://www.arm.com/Pro+Peripherals/MicroP/ARM810/ProdGuide/, August 1996.

[7] Bertsch, J., Bernstein, K., Heller, L, Nowak, E., and White, F. Experimental 2.0 V power/performance optimization of a 3.6 V-design CMOS microprocessor — PowerPC 601. *1994 Symposium on VLSI Technology Digest of Technical Papers*, 83–84, June 1994.

[8] Boys, R. *Frequently Asked Questions (FAQ) for comp.sys.m68k*, on the World Wide Web at ftp://nyquist.ee.ualberta.ca/pub/motorola/m68kfaq, March 1995.

[9] Caruthers, F. Hue and cry for color stirs flat-panel makers. *Computer Design, OEM Integration section*, 11–16, July 1994.

[10] Douglis, F., Kaashoek, F., Marsh, B., Cáceres, R., Li, K., and Tauber, J. Storage alternatives for mobile computers. *Proceedings of the First USENIX Symposium on Operating Systems Design and Implementation*, 25–37, November 1994.

[11] IBM. *The IBM OEM On-Line TFT Products Guide*, on the World Wide Web at http://www.ibm.com/products/oem/products/tft_lcd/frames.htm, May 1997.

[12] IBM. *PowerPC 603e RISC Microprocessor*, on the World Wide Web at http://www.chips.ibm.com/products/ppc/DataSheets/603/ppc603e.html, May 1997.

[13] IBM. *Travelstar 4GT*, on the World Wide Web at http://www.storage.ibm.com/storage/oem/data/trav4gt.htm, May 1997.

[14] IBM. *Travelstar 5GS*, on the World Wide Web at http://www.storage.ibm.com/storage/oem/data/trav5gs.htm, May 1997.

[15] Intel Corporation. *Pentium Pro Processor Fact Sheet*, on the World Wide Web at http://www.intel.com/procs/ppro/info/techdtl/factsht.htm, May 1997.

[16] Intel Corporation. *Pentium Processors—Datasheets*, on the World Wide Web at http://developer.intel.com/design/pentium/datashts/, May 1997.

[17] Li, K., Kumpf, R., Horton, P., and Anderson, T. A quantitative analysis of disk drive power management in portable computers. *Proceedings of the 1994 Winter USENIX Conference*, 279–291, January 1994.

[18] Lorch, J. Measuring the energy consumption of portables: StateProfiler and PowerMeasure. *Apple Computer, Inc. Performance Evaluation Group Technical Report #145*, August 1994.

[19] Lorch, J. Upper bounds on potential power savings for laptops. *Apple Computer, Inc. Performance Evaluation Group Technical Report #155*, October 1994.

[20] Lorch, J. and Smith, A. J. Reducing processor power consumption by improving processor time management in a single-user operating system. *Proceedings of the Second ACM International Conference on Mobile Computing and Networking (MOBICOM 96)*, 143–154, November 1996.

[21] MacDonald, J. Power management for 386DXL-based notebook computers. *Proceedings of the Silicon Valley Personal Computing Conference*, 735–748, 1991.

[22] Maxtor Corporation. *251350, 251010 and 250840 Specifications*, on the World Wide Web at http://www.maxtor.com/products.html, February 1997.

[23] Motorola, Inc. *PowerPC 620 Microprocessor*, on the World Wide Web at http://www.mot.com/SPS/PowerPC/library/fact_sheet/620.html, February 1997.

[24] Riezenmann, M. The search for better batteries. *IEEE Spectrum*, 51–56, May 1995.

[25] Road Warrior International. *815 MB Slimline Hard Drive Functional Specifications*, on the World Wide Web at http://warrior.com/arihd/815.html, May 1996.

[26] Seibert, M. Personal communication, 1995.

[27] Sun Microsystems, Inc. *microSPARC*^{TM}*-IIep Highly Integrated 32-bit RISC/PCI Microprocessor Datasheet*, on the World Wide Web at http://www.sun.com/sparc/stp1100/datasheets/, March 1997.

[28] Toshiba America, Inc. *MK2720 Functional Specifications*, on the World Wide Web at http://www.toshiba.com/taisdpd/mk2720a.htm, January 1997.

[29] Toshiba America, Inc. *Notebook Type TFT-LCD Module Product Selection Guide*, on the World Wide Web at http://www.toshiba.com/taec/components/category/NotebookTypeTFT-LCDModule.shtml.

[30] Weiser, M., Welch, B., Demers, A., and Shenker, S. Scheduling for reduced CPU energy. *Proceedings of the First USENIX Symposium on Operating Systems Design and Implementation*, 13–23, November 1994.

[31] Western Digital Corporation. *WD Portfolio Specifications*, on the World Wide Web at http://www.wdc.com/acrobat/portfoli.pdf, February 1997.