Technical Note FL16

File Manager Performance and Caching

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This Technote discusses Mac OS file system input/output performance issues and the File Manager's volume cache. It is assumed the reader of this technote has a good understanding of basic File Manager I/O routines.

This technote is directed at application developers who are interested in getting the most performance out of the traditional Mac OS file system.

[Sep 05 2000]

Introduction

The File Manager's input/output programming interface hasn't changed much since 1984. There are a half dozen new ways to open a file, but when it gets down to accessing the data in a file, you still end up using the same read and write calls the Mac OS started with. Since little has changed, most programmers pay little or no attention to how their programs access files until they find the overall performance of their program depends on file access speed. This technote shows you how to get the best throughput from the file system using a variety of techniques.

Although this technote's primary focus is on the built-in HFS and HFS Plus file systems, the techniques described will likely improve performance when used with any other file system.

> **Note:**
> The intent of this technote is to tell how to use the File Manager API to improve the performance of file I/O, not to describe in detail the processes and steps taken by the file system to perform file I/O. Thus, the descriptions of the processes and steps taken by the file system to perform file I/O are much simpler than what actually take place.

Each time you read or write data to a file, a file system must perform several steps which ultimately end up transferring data between your buffer and the disk. For the purposes of this technote, we'll divide that time up into two categories: data transfer time and request overhead time. The first step to improving file I/O performance is to reduce the amount of request

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Increase the Size of I/O Requests

The size of your read and write requests can make more difference to file I/O performance than any other factor under your control. Here's why:

- Each request will incur some request overhead time.
- Each request will involve one or more calls to a disk driver through the file system cache, or to a network device

through a network driver.
- Each request may cause one or more data transfers from the disk driver and the disk device, or the network driver and network device. A device access may be very fast (reading data from or writing data to a disk device's or disk driver's cache), or very slow (waiting for a stopped floppy disk drive to come up to speed and then reading or writing the data).

Let's look at an example: reads from a fast (by the standards of the time this technote was written) SCSI hard disk drive with an average access time of approximately 10 milliseconds and a Power Macintosh class system with a SCSI transfer rate of approximately 5 megabytes per second or 0.1 milliseconds per 512-byte disk block. When a single disk block (512 bytes) is read, the time spent reading the block looks like that shown in Figure 1.

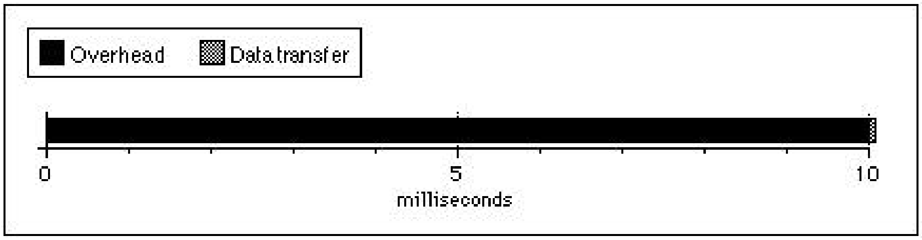

Figure 1. One block transfer with 10 ms average access time

The overhead time on this single block read is over 99% of the total time, giving you a throughput of 49.5K per second (that's about half the transfer rate of a SuperDrive floppy disk drive!). However, when the size of the read is increased to 450K (Figure 2), the overhead time is reduced to approximately 10% of the total time. That's because the overhead remains essentially the same while the total number of bytes transferred increases. This change makes the adjusted throughput for this transfer 4.5 megabytes per second.

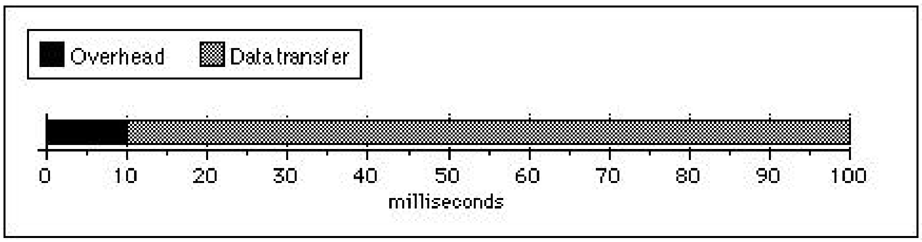

Figure 2. 900 block transfer with 10 ms average access time

If you were to make a graph comparing the size of your I/O requests to the throughput of that request, you'd see a curve like that shown in Figure 3.

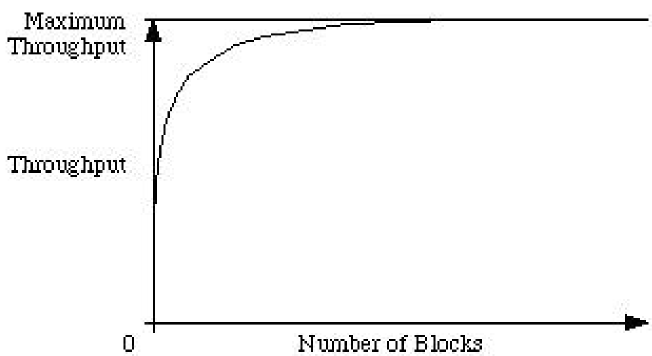

Figure 3. Size of transfer versus throughput of transfer

> **Important:**
> By increasing the size of your I/O requests, you can maximize your usage of the device's ideal throughput. DTS strongly recommends an I/O size of at least 4 KB. 16 KB is better. 64 KB is even better, although it's approaching the point of diminishing returns.

One last note on the size of I/O requests. In some cases, you may actually want to limit the size of your I/O requests. For example, large reads and writes to a file over a slow network connection may make it look like the system has locked up to the users of your program. Your program can use the `vmVolumeGrade` field of the `GetVolParmsInfoBuffer` structure (returned by `PBHGetVolParms`) to scale the size of its I/O requests for a particular volume's speed. See DTS Technote 1121 Mac OS 8.1 for more information about how the Finder uses this field.

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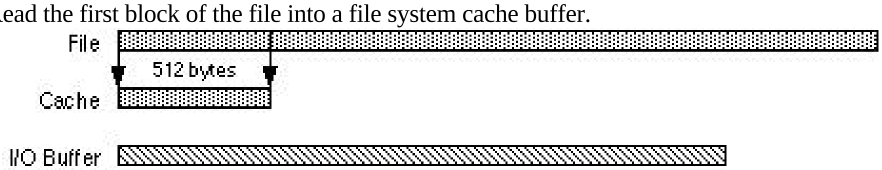
Block Align I/O Requests

After increasing the size of your I/O requests, the next thing you should look at is the block alignment of your requests.

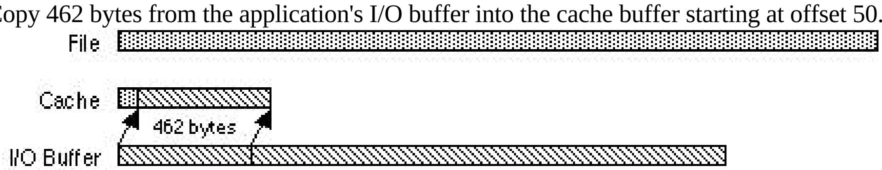
When reading from or writing to a file on file systems that use block devices, data is read or written in complete disk blocks. When a read or write begins or ends in the middle of a disk block, the file system must read that entire block into a buffer owned by the file system (a cache buffer) and then move data to or from your application's I/O buffer. The worst case is a write that doesn't begin or end on a block boundary, but is large enough to write one or more full blocks.

For example, here are the steps the HFS Plus file system must take to write 2048 bytes starting at offset 50 in the file:

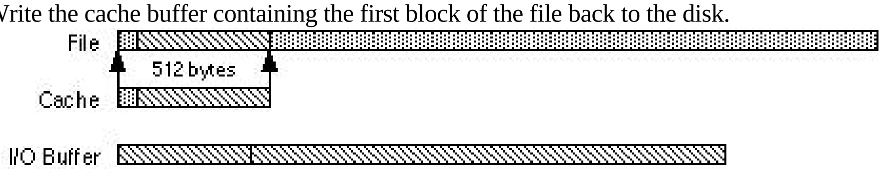
1. Read the first block of the file into a file system cache buffer.



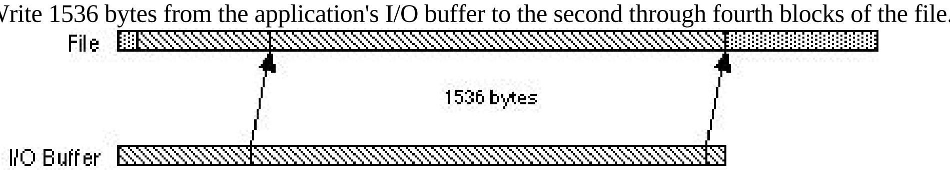
2. Copy 462 bytes from the application's I/O buffer into the cache buffer starting at offset 50.



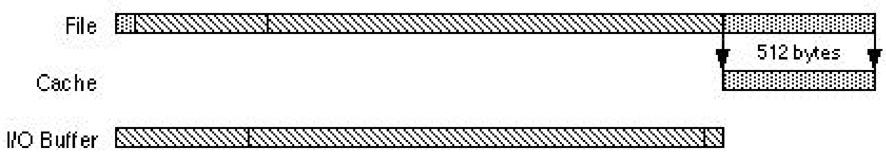
3. Write the cache buffer containing the first block of the file back to the disk.



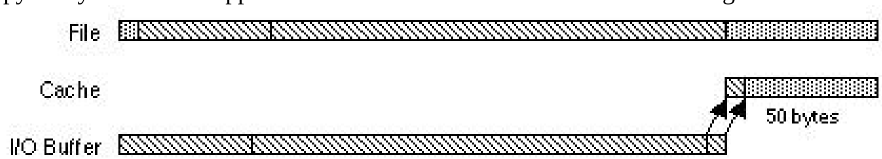
4. Write 1536 bytes from the application's I/O buffer to the second through fourth blocks of the file.



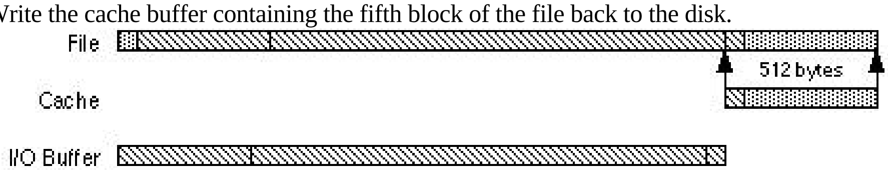
5. Read the fifth block of the file into a file system cache buffer.



6. Copy 50 bytes from the application's I/O buffer into the cache buffer starting at offset 0.



7. Write the cache buffer containing the fifth block of the file back to the disk.



By not block aligning your I/O, your program's single non-block aligned write request generated two read request and three write requests to the disk driver. The extra two reads and two writes increased the request overhead time by 400%. If the same size write request started at offset 0 in the file, then there would have been only one write to the disk driver.

Important:
If you make your reads and writes start on a 512-byte boundary and read or write in multiples of 512-bytes, you'll avoid extra read and write requests and the request overhead time they generate. For even better results, align your I/O to 4 KB boundaries.

Note:
Why is 4 KB alignment better than 512 byte alignment? On traditional Mac OS alignment beyond 512 bytes is irrelevant. However, the Mac OS X file system is closely tied with the virtual memory system, and the virtual memory system uses a 4 KB page size. If you transfer data in 4 KB or larger requests and align those requests on 4 KB boundaries, you will get the best performance from the Mac OS X file system. This technique will also perform well on current and future traditional Mac OS File Manager implementations.

While this note does not cover all possible Mac OS X file system performance optimizations, this advice is sufficiently simple that it's worth covering here.

Note:
One particularly interesting case of unaligned I/O occurs when you copy a file. A typical file copy algorithm is shown below.

```
on copyFile source, dest
  set bytesRemaining to size of source
  while bytesRemaining > 0 do
    if bytesRemaining > size of buffer
      set bytesThisTime to size of buffer
    else
      set bytesThisTime to bytesRemaining
    end-if
    read bytesThisTime from source into buffer
    write bytesThisTime from buffer into dest
    set bytesRemaining to bytesRemaining - bytesThisTime
  end-while
end copyFile
```

If the size of the copy buffer is a multiple of 512 bytes, this algorithm does all of its I/O aligned on block boundaries and is very efficient. However, the last transfer can cause a loss of efficiency. If the source file is not an even multiple of 512 bytes long, the last write will often result in two disk operations. The first disk operation will write the bytes in the buffer that even fit into 512-byte blocks. The remaining bytes in the buffer will be placed in a disk cache block and will eventually be written in a separate disk I/O when that cache block is flushed. If you are copying a lot of files, these cache block flushes can represent a significant overhead.

One interesting workaround is to round up the last write to the nearest 512-byte boundary -- which actually writes extra data to the end of the file -- and then call `SetEOF` to trim off the extra bytes. The exact algorithm is too complex to show here (for example, it only makes sense to do this on non-network volumes), but it is codified in the MPFileCopy sample code.

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File System Cache Control

Next, you should look at how your programs use the data they read and write.

The File Manager's cache is a buffer in RAM memory that holds recently accessed disk blocks. When data is read from the disk into the cache, subsequent accesses to those disks blocks can come from the cache instead of causing additional disk accesses. When data is written into the cache instead of going directly to the disk, subsequent writes to the same disk block won't cause an additional writes to those disk blocks. (Cache blocks that contain different data than the disk block they are associated with are "dirty" cache blocks.) When used this way, the cache can greatly improve the performance of your file I/O.

However, the File Manager's cache doesn't know *how* the data in the cache is going to be used. When the File Manager sends multi-block file I/O requests through the cache, it always caches the blocks unless the size of the request is very large or unless it's told not to in the read or write request. The cached blocks stay in the cache until they are reused, until the file is closed, or until the volume is put offline, ejected, or unmounted.

Unless you do something about it, *reads and writes that have no reason to be cached will be cached* and that can cause increases in request overhead two ways: cached I/O requests have more request overhead and cached I/O requests can force other more useful cached data out of the cache.

Cached I/O request overhead can be minimal as in the case where the request is small enough to use only unused blocks in the cache. Or, the request overhead can be very large as in the case where all of the blocks in the cache are in use and dirty, and must be flushed to the disk before they can be reused.

Cached I/O requests can force other more useful cached data out of the cache. As an example, if you fill the cache with data blocks from your file (that you won't be using again in the near future), then cached catalog and volume information used by the HFS Plus file system is flushed out of the cache. The next time the HFS Plus file system needs to read the catalog, it will have to flush your cached blocks out of the cache just to reload the data it needs.

Important:
By following the following simple guidelines, most applications can avoid both of these problems and increase the file system performance for everyone.

- You should cache reads and writes if you read or write the same portion of a file multiple times.
- You should not cache reads and writes if you read or write data from a file only once.

Warning:
An older version of this technote recommended manipulating the low-memory global `CacheCom` to control the File Manager's cache. This method should be avoided because:

- `CacheCom` is no longer supported on Power Macintosh systems for native applications (it isn't in "LowMem.h") and it won't be supported by future versions of the File Manager.
- `CacheCom` affects the system globally. That means that your code affects all other running programs that read or write and that's not a friendly thing to do in a multi-process environment.

So, how do you control what gets cached and what doesn't? In a `PBRead` or `PBWrite` request, bits 4 and 5 of `ioPosMode` are cache usage hints passed on to the file system that handles requests to the volume the file is on (the cache control bits are also documented on pages 2-89 and 2-95 of *Inside Macintosh: Files* and in DTS Technote 1041 Inside Macintosh--Files Errata). Bit 4 (`pleaseCacheBit`) is a request that the data be cached. Bit 5 (`noCacheBit`) is a request that the data not be cached. Bits 4 and 5 are mutually exclusive -- only one should be set at a time. However, if neither is set, then the program has indicated that it doesn't care if the data is cached or not.

Bit Number	Bit Mask	Description
n/a	0x0000	I don't care if this request is cached or not cached.
`pleaseCacheBit` (4)	`pleaseCacheMask` (0x0010)	Cache this request if possible.
`noCacheBit` (5)	`noCacheMask` (0x0020)	I'd rather you didn't cache this request.

Note:
A particular file system (HFS Plus, AppleShare, ISO-9660, and so on) may choose to ignore one or both of the cache usage hint bits. For example, the HFS Plus file system ignores bit 4. File systems may cache when you set bit 5, may not cache when you set the bit 4, may cache everything, or may cache nothing. However, if a program leaves both bits clear, then file systems which *do* respect the cache hint bits have no way of knowing if the data being read or written will be needed again by your program.

The following high-level functions show how to read and write with the no cache hint bit turned on. These routines were taken from the MoreFiles sample code.

```
pascal  OSErr   FSReadNoCache(short refNum,
                              long *count,
                              void *buffPtr)
{
    ParamBlockRec pb;
    OSErr error;

    pb.ioParam.ioRefNum = refNum;
    pb.ioParam.ioBuffer = (Ptr)buffPtr;
    pb.ioParam.ioReqCount = *count;
    pb.ioParam.ioPosMode = fsAtMark + noCacheMask;
    pb.ioParam.ioPosOffset = 0;
    error = PBReadSync(&pb);
    *count = pb.ioParam.ioActCount;       /* always return count */
    return ( error );
}

pascal  OSErr   FSWriteNoCache(short refNum,
                               long *count,
                               const void *buffPtr)
{
    ParamBlockRec pb;
    OSErr error;

    pb.ioParam.ioRefNum = refNum;
    pb.ioParam.ioBuffer = (Ptr)buffPtr;
    pb.ioParam.ioReqCount = *count;
    pb.ioParam.ioPosMode = fsAtMark + noCacheMask;
    pb.ioParam.ioPosOffset = 0;
    error = PBWriteSync(&pb);
    *count = pb.ioParam.ioActCount;       /* always return count */
    return ( error );
}
```

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Cached I/O versus Data Integrity

The File Manager's cache can increase the performance of certain I/O operations. However, it does open a window of time where data can be lost if a system crashes. If the system crashes when cache blocks hold data that hasn't been flushed to disk (dirty blocks), the data in the cache is lost. That can cause lost file data, or can cause volume catalog corruption problems.

> **Note:**
> In Mac OS 7.6 the disk cache was modified to periodically flush dirty blocks if the disk is idle. See DTS Technote 1090 Mac OS 7.6 for details.

Flushing Files and Volumes

The File Manager provides routines you can use to flush cached file and volume blocks to disk. When a file or volume is flushed, the dirty cache blocks associated with the file or volume are written to disk. However, indiscriminate flushing can affect performance, so an understanding of what the flush calls actually do is an important part of using the flush calls correctly.

- `PBFlushFile` flushes an open file fork's dirty cached data blocks, but may not flush catalog information associated with the file. To ensure data written to a file with `PBWrite` or `FSWrite` is flushed to the volume, use `PBFlushFile`.
- `PBFlushVol` flushes all open files on the volume, and then, flushes all volume data structures. So to ensure all changes to a volume, including the volume's catalog and block allocation information, are flushed to the volume, use `PBFlushVol`.

In addition to handling to `PBFlushFile` and `PBFlushVol` requests, the file system flushes files and volumes at other times:

- When a file fork is closed, the file is first flushed and then, all cache blocks associated with the file are removed from the cache. You don't need to flush a file before closing it.
- When a volume is unmounted, ejected, or put offline, the volume is first flushed and then, all cache blocks associated with the volume are removed from the cache. You don't need to flush a volume before unmounting it, ejecting it, or putting it offline.

File Block Preallocation

Preallocating the space for a file can keep the file and the volume from being fragmented. Accessing the data in an unfragmented file will be faster. The File Manager's `Allocate` and `AllocContig` functions allow you to allocate additional space to an open file. However, there are two important points to note:

- The space allocated with `Allocate` and `AllocContig` is not permanently assigned to that file until the file's logical EOF is changed to include the allocated space. You can use `SetEOF` to change the file's logical EOF to include the allocated space. When a file (or volume) is flushed or closed, the space beyond the file's logical EOF is made available for other purposes.
- `Allocate` and `AllocContig` are not supported by all file systems. For example, remote volumes mounted by the AppleShare file system do not support `Allocate` and `AllocContig`. To allocate space for a file on any volume, use `SetEOF`.

A Simple Example of Balancing Cached I/O Performance and Data Integrity

Given the information just provided, you should be able to use the flush calls along with preallocating space for your file to ensure that your data is safely on a disk without incurring performance penalties during your I/O operations. However, a small commented example can't hurt, so...

```
enum
{
    /*
    **  Set kMaxWrite to the largest amount of data your write proc will
    **  write in one call. Then, set kMinWritesPerAllocate to the minimum
    **  number of writes you want before more space is allocated.
    */
    kMaxWrite             = 0x10000,
    kMinWritesPerAllocate = 4
};

/*****************************************************************************/

/*
**    Prototype for the routine that writes data to a file.
**    Your write procedure can make sure data is really written to disk by
**    calling PBFlushFile, or you can block-align your requests and set the
**    noCache ioPosMode bit in your calls to PBWrite (with the HFS file system,
**    block-aligned requests with the noCache bit set are not cached).
*/
typedef pascal OSErr (*WriteProcPtr) (short refNum, Boolean *doneWriting,
                                      void *yourDataPtr);

/*****************************************************************************/

/*
**    MoreSpace checks to see if more space should be allocated to an
**    open file based on the current position and the current EOF and
**    if so, then allocates the space by extending the EOF.
**    If more space is allocated, the volume is flushed to ensure
**    the additional space is recorded in the catalog file on disk.
*/
OSErr    MoreSpace(short    refNum, short vRefNum)
{
    OSErr    result;
    long    filePos, logEOF;
```

```
    result = GetFPos(refNum, &filePos);
    if ( result == noErr )
    {
        result = GetEOF(refNum, &logEOF);
        if ( (result == noErr) && ((logEOF - filePos) <= kMaxWrite) )
        {
            result = SetEOF(refNum, logEOF + (kMaxWrite * kMinWritesPerAllocate));
            if ( result == noErr )
            {
                result = FlushVol(NULL, vRefNum);
            }
        }
    }
    return ( result );
}

/******************************************************************************/

/*
**    Simple example of creating and writing to a file.
*/
OSErr    SafeWriteFile(const WriteProcPtr writeProc, void *yourDataPtr)
{
    OSErr              result;
    Str255             prompt       = "\pSave this document as:";
    Str255             defaultName  = "\puntitled";
    StandardFileReply  reply;
    OSType             creator      = '????';
    OSType             fileType     = 'TEXT';
    short              refNum;
    Boolean            doneWriting;
    long               filePos;

    StandardPutFile (prompt, defaultName,& reply);
    if ( reply.sfGood )
    {
        if ( reply.sfReplacing )
        {
            /* Delete old file */
            (void) FSpDelete(&reply.sfFile);
        }

        result = FSpCreate(&reply.sfFile, creator, fileType, reply.sfScript);
        if ( result == noErr )
        {
            result = FSpOpenDF(&reply.sfFile, fsRdWrPerm, &refNum);
            if ( result == noErr )
            {
                /*
                **    Preallocate some space and flush the volume.
                **
                **    Flushing the volume here makes sure the newly
                **    created file in the catalog file is flushed to
                **    disk and makes sure the space preallocated for
                **    file data is allocated on disk.
                */
                result = MoreSpace(refNum, reply.sfFile.vRefNum);

                /*
                **    Write file in pieces until we're done writing, or until
                **    an error occurs.
                */
```

```
                doneWriting = false;
                while ( (result == noErr) && !doneWriting )
                {
                    result = (*writeProc) (refNum, &doneWriting, yourDataPtr);
                    if ( result == noErr )
                    {
                        if ( !doneWriting )
                        {
                            /*
                            **    We're not done writing. Check allocated space,
                            **    then allocate more space and flush the volume
                            **    (to make sure the space is really allocated
                            **    on disk) if needed.
                            */
                            result = MoreSpace(refNum, reply.sfFile.vRefNum);
                        }
                        else
                        {
                            /*
                            **    We're done writing. Truncate file to current
                            **    file position.
                            */
                            result = GetFPos(refNum, &filePos);
                            if ( result == noErr )
                            {
                                result = SetEOF(refNum, filePos);
                            }
                        }
                    }
                }

                /*
                **    Close the file (which flushes the file) and then
                **    flush the volume to ensure the file's final EOF
                **    is written to the volume catalog.
                */
                (void) FSClose(refNum);
                (void) FlushVol(NULL, reply.sfFile.vRefNum);
            }
        }
    }
    return ( result );
}
```

As shown in the example above:

- If changes are made to space that already exists in a file (you are overwriting existing data before the file's EOF), `PBFlushFile` will ensure everything written to the file is written to disk. In this case, the only possible data loss in a system crash will be the file's modification date.
- If changes are made to a file that affect the file's EOF, the file's name, the file's Finder information, or the file's location on the volume, then `PBFlushVol` must be used to ensure the changes to the file are written to disk.

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Summary

To get the best performance from the Mac OS File Manager, you should:

- buffer data so that transfers are 4 KB or larger,
- align all transfers to at least 512-byte boundaries (better yet 4 KB), and
- disable caching on requests where you will be only looking at the data once.

In addition, you may want to examine how and why you flush files or volumes, and preallocate space for new files.

There are other useful techniques not discussed in this technote that you may want to consider.

- You could implement your own buffering scheme above the File Manager. For example, the file stream libraries supplied by many object-oriented development environments allow you to perform file I/O using a pointer or handle to a RAM buffer.
- You can use asynchronous read or writes that overlap with other non-File Manager operations, allowing your program to do something besides show the watch cursor while file I/O is performed. For example, the article, "Concurrent Programming with the Thread Manager" in *develop* issue #17 shows how to perform asynchronous I/O in cooperative threads.

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References

Inside Macintosh: Files

DTS Technote 1041 Inside Macintosh--Files Errata

DTS Technote 1090 Mac OS 7.6

DTS Technote 1121 Mac OS 8.1

Asynchronous Routines on the Macintosh, Jim Luther, *develop* Issue 13

Concurrent Programming with the Thread Manager, Eric Anderson and Brad Post, *develop* Issue 17

MoreFiles sample code

MPFileCopy sample code

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Change History

Add this section if there are changes. If you're writing a new technote, then you can remove this section.

01-June-1986	Originally written.
01-March-1988	Completely rewritten.
01-April-1995	Revised.
01-August-2000	Updated to include a specific hint about avoiding extra disk writes while copying files. Also made numerous minor updates and cosmetic changes.

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