XFS Algorithms & Data Structures

3rd Edition

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Contents

Part I

High Level Design

XFS is a high performance filesystem which was designed to maximize parallel throughput and to scale up to extremely large 64-bit storage systems. Originally developed by SGI in October 1993 for IRIX, XFS can handle large files, large filesystems, many inodes, large directories, large file attributes, and large allocations. Filesystems are optimized for parallel access by splitting the storage device into semi-autonomous allocation groups. XFS employs branching trees (B+ trees) to facilitate fast searches of large lists; it also uses delayed extent-based allocation to improve data contiguity and IO performance.

This document describes the on-disk layout of an XFS filesystem and how to use the debugging tools `xfs_db` and `xfs_logprint` to inspect the metadata structures. It also describes how on-disk metadata relates to the higher level design goals.

The information contained in this document derives from the XFS source code in the Linux kernel as of v4.3. This book's source code is available at `git://git.kernel.org/pub/scm/fs/xfs/xfs-documentation.git`. Feedback should be sent to the XFS mailing list, currently at `linux-xfs@vger.kernel.org`.

Note

All fields in XFS metadata structures are in big-endian byte order except for log items which are formatted in host order.

Chapter 1

Overview

XFS presents to users a standard Unix filesystem interface: a rooted tree of directories, files, symbolic links, and devices. All five of those entities are represented inside the filesystem by an index node, or "inode"; each node is uniquely referenced by an inode number. Directories consist of (name, inode number) tuples and it is possible for multiple tuples to contain the same inode number. Data blocks are associated with files by means of a block map in each index node. It is also possible to attach (key, value) tuples to any index node; these are known as "extended attributes", which extend beyond the standard Unix file attributes.

Internally, XFS filesystems are divided into a number of equally sized chunks called Allocation Groups. Each AG can almost be thought of as an individual filesystem that maintains its own space usage, index nodes, and other secondary metadata. Having multiple AGs allows XFS to handle most operations in parallel without degrading performance as the number of concurrent accesses increases. Each allocation group uses multiple B+trees to maintain bookkeeping records such as the locations of free blocks, the locations of allocated inodes, and the locations of free inodes.

Files, symbolic links, and directories can have up to two block maps, or "forks", which associate filesystems blocks with a particular file or directory. The "attribute fork" tracks blocks used to store and index extended attributes, whereas the "data fork" tracks file data blocks, symbolic link targets, or directory blocks, depending on the type of the inode record. Both forks associate a logical offset with an extent of physical blocks, which makes sparse files and directories possible. Directory entries and extended attributes are contained inside a second-level data structure within the blocks that are mapped by the forks. This structure consists of variable-length directory or attribute records and, possibly, a second B+tree to index these records.

XFS employs a journalling log in which metadata changes are collected so that filesystem operations can be carried out atomically in the case of a crash. Furthermore, there is the concept of a real-time device wherein allocations are tracked more simply and in larger chunks to reduce jitter in allocation latency.

Chapter 2

Metadata Integrity

2.1 Introduction

The largest scalability problem facing XFS is not one of algorithmic scalability, but of verification of the filesystem structure. Scalabilty of the structures and indexes on disk and the algorithms for iterating them are adequate for supporting PB scale filesystems with billions of inodes, however it is this very scalability that causes the verification problem.

Almost all metadata on XFS is dynamically allocated. The only fixed location metadata is the allocation group headers (SB, AGF, AGFL and AGI), while all other metadata structures need to be discovered by walking the filesystem structure in different ways. While this is already done by userspace tools for validating and repairing the structure, there are limits to what they can verify, and this in turn limits the supportable size of an XFS filesystem.

For example, it is entirely possible to manually use xfs_db and a bit of scripting to analyse the structure of a 100TB filesystem when trying to determine the root cause of a corruption problem, but it is still mainly a manual task of verifying that things like single bit errors or misplaced writes weren't the ultimate cause of a corruption event. It may take a few hours to a few days to perform such forensic analysis, so for at this scale root cause analysis is entirely possible.

However, if we scale the filesystem up to 1PB, we now have 10x as much metadata to analyse and so that analysis blows out towards weeks/months of forensic work. Most of the analysis work is slow and tedious, so as the amount of analysis goes up, the more likely that the cause will be lost in the noise. Hence the primary concern for supporting PB scale filesystems is minimising the time and effort required for basic forensic analysis of the filesystem structure.

Therefore, the version 5 disk format introduced larger headers for all metadata types, which enable the filesystem to check information being read from the disk more rigorously. Metadata integrity fields now include:

- **Magic** numbers, to classify all types of metadata. This is unchanged from v4.
- A copy of the filesystem **UUID**, to confirm that a given disk block is connected to the superblock.
- The **owner**, to avoid accessing a piece of metadata which belongs to some other part of the filesystem.
- The filesystem **block number**, to detect misplaced writes.
- The **log serial number** of the last write to this block, to avoid replaying obsolete log entries.
- A CRC32c **checksum** of the entire block, to detect minor corruption.

Metadata integrity coverage has been extended to all metadata blocks in the filesystem, with the following notes:

- Inodes can have multiple "owners" in the directory tree; therefore the record contains the inode number instead of an owner or a block number.
- Superblocks have no owners.
- The disk quota file has no owner or block numbers.

- Metadata owned by files list the inode number as the owner.
- Per-AG data and B+tree blocks list the AG number as the owner.
- Per-AG header sectors don't list owners or block numbers, since they have fixed locations.
- Remote attribute blocks are not logged and therefore the LSN must be -1.

This functionality enables XFS to decide that a block contents are so unexpected that it should stop immediately. Unfortunately checksums do not allow for automatic correction. Please keep regular backups, as always.

2.2 Self Describing Metadata

One of the problems with the current metadata format is that apart from the magic number in the metadata block, we have no other way of identifying what it is supposed to be. We can't even identify if it is the right place. Put simply, you can't look at a single metadata block in isolation and say "yes, it is supposed to be there and the contents are valid".

Hence most of the time spent on forensic analysis is spent doing basic verification of metadata values, looking for values that are in range (and hence not detected by automated verification checks) but are not correct. Finding and understanding how things like cross linked block lists (e.g. sibling pointers in a btree end up with loops in them) are the key to understanding what went wrong, but it is impossible to tell what order the blocks were linked into each other or written to disk after the fact.

Hence we need to record more information into the metadata to allow us to quickly determine if the metadata is intact and can be ignored for the purpose of analysis. We can't protect against every possible type of error, but we can ensure that common types of errors are easily detectable. Hence the concept of self describing metadata.

The first, fundamental requirement of self describing metadata is that the metadata object contains some form of unique identifier in a well known location. This allows us to identify the expected contents of the block and hence parse and verify the metadata object. IF we can't independently identify the type of metadata in the object, then the metadata doesn't describe itself very well at all!

Luckily, almost all XFS metadata has magic numbers embedded already - only the AGFL, remote symlinks and remote attribute blocks do not contain identifying magic numbers. Hence we can change the on-disk format of all these objects to add more identifying information and detect this simply by changing the magic numbers in the metadata objects. That is, if it has the current magic number, the metadata isn't self identifying. If it contains a new magic number, it is self identifying and we can do much more expansive automated verification of the metadata object at runtime, during forensic analysis or repair.

As a primary concern, self describing metadata needs some form of overall integrity checking. We cannot trust the metadata if we cannot verify that it has not been changed as a result of external influences. Hence we need some form of integrity check, and this is done by adding CRC32c validation to the metadata block. If we can verify the block contains the metadata it was intended to contain, a large amount of the manual verification work can be skipped.

CRC32c was selected as metadata cannot be more than 64k in length in XFS and hence a 32 bit CRC is more than sufficient to detect multi-bit errors in metadata blocks. CRC32c is also now hardware accelerated on common CPUs so it is fast. So while CRC32c is not the strongest of possible integrity checks that could be used, it is more than sufficient for our needs and has relatively little overhead. Adding support for larger integrity fields and/or algorithms does really provide any extra value over CRC32c, but it does add a lot of complexity and so there is no provision for changing the integrity checking mechanism.

Self describing metadata needs to contain enough information so that the metadata block can be verified as being in the correct place without needing to look at any other metadata. This means it needs to contain location information. Just adding a block number to the metadata is not sufficient to protect against mis-directed writes - a write might be misdirected to the wrong LUN and so be written to the "correct block" of the wrong filesystem. Hence location information must contain a filesystem identifier as well as a block number.

Another key information point in forensic analysis is knowing who the metadata block belongs to. We already know the type, the location, that it is valid and/or corrupted, and how long ago that it was last modified. Knowing the owner of the block is important as it allows us to find other related metadata to determine the scope of the corruption. For example, if we have a extent btree object, we don't know what inode it belongs to and hence have to walk the entire filesystem to find the owner of the block. Worse, the corruption could mean that no owner can be found (i.e. it's an orphan block), and so without an owner field in the metadata we have no idea of the scope of the corruption. If we have an owner field in the metadata object, we can immediately do top down validation to determine the scope of the problem.

Different types of metadata have different owner identifiers. For example, directory, attribute and extent tree blocks are all owned by an inode, whilst freespace btree blocks are owned by an allocation group. Hence the size and contents of the owner field are determined by the type of metadata object we are looking at. The owner information can also identify misplaced writes (e.g. freespace btree block written to the wrong AG).

Self describing metadata also needs to contain some indication of when it was written to the filesystem. One of the key information points when doing forensic analysis is how recently the block was modified. Correlation of set of corrupted metadata blocks based on modification times is important as it can indicate whether the corruptions are related, whether there's been multiple corruption events that lead to the eventual failure, and even whether there are corruptions present that the run-time verification is not detecting.

For example, we can determine whether a metadata object is supposed to be free space or still allocated if it is still referenced by its owner by looking at when the free space btree block that contains the block was last written compared to when the metadata object itself was last written. If the free space block is more recent than the object and the object's owner, then there is a very good chance that the block should have been removed from the owner.

To provide this "written timestamp", each metadata block gets the Log Sequence Number (LSN) of the most recent transaction it was modified on written into it. This number will always increase over the life of the filesystem, and the only thing that resets it is running xfs_repair on the filesystem. Further, by use of the LSN we can tell if the corrupted metadata all belonged to the same log checkpoint and hence have some idea of how much modification occurred between the first and last instance of corrupt metadata on disk and, further, how much modification occurred between the corruption being written and when it was detected.

2.3 Runtime Validation

Validation of self-describing metadata takes place at runtime in two places:

- immediately after a successful read from disk
- immediately prior to write IO submission

The verification is completely stateless - it is done independently of the modification process, and seeks only to check that the metadata is what it says it is and that the metadata fields are within bounds and internally consistent. As such, we cannot catch all types of corruption that can occur within a block as there may be certain limitations that operational state enforces of the metadata, or there may be corruption of interblock relationships (e.g. corrupted sibling pointer lists). Hence we still need stateful checking in the main code body, but in general most of the per-field validation is handled by the verifiers.

For read verification, the caller needs to specify the expected type of metadata that it should see, and the IO completion process verifies that the metadata object matches what was expected. If the verification process fails, then it marks the object being read as EFSCORRUPTED. The caller needs to catch this error (same as for IO errors), and if it needs to take special action due to a verification error it can do so by catching the EFSCORRUPTED error value. If we need more discrimination of error type at higher levels, we can define new error numbers for different errors as necessary.

The first step in read verification is checking the magic number and determining whether CRC validating is necessary. If it is, the CRC32c is calculated and compared against the value stored in the object itself. Once this is validated, further checks are made against the location information, followed by extensive object specific metadata validation. If any of these checks fail, then the buffer is considered corrupt and the EFSCORRUPTED error is set appropriately.

Write verification is the opposite of the read verification - first the object is extensively verified and if it is OK we then update the LSN from the last modification made to the object, After this, we calculate the CRC and insert it into the object. Once this is done the write IO is allowed to continue. If any error occurs during this process, the buffer is again marked with a EFSCORRUPTED error for the higher layers to catch.

2.4 Structures

A typical on-disk structure needs to contain the following information:

```
struct xfs_ondisk_hdr {
        __be32  magic;          /* magic number */
        __be32  crc;            /* CRC, not logged */
        uuid_t  uuid;           /* filesystem identifier */
        __be64  owner;          /* parent object */
        __be64  blkno;          /* location on disk */
        __be64  lsn;            /* last modification in log, not logged */
};
```

Depending on the metadata, this information may be part of a header structure separate to the metadata contents, or may be distributed through an existing structure. The latter occurs with metadata that already contains some of this information, such as the superblock and AG headers.

Other metadata may have different formats for the information, but the same level of information is generally provided. For example:

- short btree blocks have a 32 bit owner (ag number) and a 32 bit block number for location. The two of these combined provide the same information as @owner and @blkno in eh above structure, but using 8 bytes less space on disk.
- directory/attribute node blocks have a 16 bit magic number, and the header that contains the magic number has other information in it as well. hence the additional metadata headers change the overall format of the metadata.

A typical buffer read verifier is structured as follows:

```
#define XFS_FOO_CRC_OFF         offsetof(struct xfs_ondisk_hdr, crc)

static void
xfs_foo_read_verify(
        struct xfs_buf  *bp)
{
       struct xfs_mount *mp = bp->b_target->bt_mount;

        if ((xfs_sb_version_hascrc(&mp->m_sb) &&
             !xfs_verify_cksum(bp->b_addr, BBTOB(bp->b_length),
                                       XFS_FOO_CRC_OFF)) ||
            !xfs_foo_verify(bp)) {
                XFS_CORRUPTION_ERROR(__func__, XFS_ERRLEVEL_LOW, mp, bp->b_addr);
                xfs_buf_ioerror(bp, EFSCORRUPTED);
        }
}
```

The code ensures that the CRC is only checked if the filesystem has CRCs enabled by checking the superblock of the feature bit, and then if the CRC verifies OK (or is not needed) it verifies the actual contents of the block.

The verifier function will take a couple of different forms, depending on whether the magic number can be used to determine the format of the block. In the case it can't, the code is structured as follows:

```
static bool
xfs_foo_verify(
        struct xfs_buf          *bp)
{
        struct xfs_mount        *mp = bp->b_target->bt_mount;
        struct xfs_ondisk_hdr   *hdr = bp->b_addr;

        if (hdr->magic != cpu_to_be32(XFS_FOO_MAGIC))
                return false;

        if (!xfs_sb_version_hascrc(&mp->m_sb)) {
                if (!uuid_equal(&hdr->uuid, &mp->m_sb.sb_uuid))
                        return false;
                if (bp->b_bn != be64_to_cpu(hdr->blkno))
```

```
                        return false;
                if (hdr->owner == 0)
                        return false;
        }

        /* object specific verification checks here */

        return true;
}
```

If there are different magic numbers for the different formats, the verifier will look like:

```
static bool
xfs_foo_verify(
        struct xfs_buf          *bp)
{
        struct xfs_mount        *mp = bp->b_target->bt_mount;
        struct xfs_ondisk_hdr   *hdr = bp->b_addr;

        if (hdr->magic == cpu_to_be32(XFS_FOO_CRC_MAGIC)) {
                if (!uuid_equal(&hdr->uuid, &mp->m_sb.sb_uuid))
                        return false;
                if (bp->b_bn != be64_to_cpu(hdr->blkno))
                        return false;
                if (hdr->owner == 0)
                        return false;
        } else if (hdr->magic != cpu_to_be32(XFS_FOO_MAGIC))
                return false;

        /* object specific verification checks here */

        return true;
}
```

Write verifiers are very similar to the read verifiers, they just do things in the opposite order to the read verifiers. A typical write verifier:

```
static void
xfs_foo_write_verify(
        struct xfs_buf  *bp)
{
        struct xfs_mount        *mp = bp->b_target->bt_mount;
        struct xfs_buf_log_item *bip = bp->b_fspriv;

        if (!xfs_foo_verify(bp)) {
                XFS_CORRUPTION_ERROR(__func__, XFS_ERRLEVEL_LOW, mp, bp->b_addr);
                xfs_buf_ioerror(bp, EFSCORRUPTED);
                return;
        }

        if (!xfs_sb_version_hascrc(&mp->m_sb))
                return;


        if (bip) {
                struct xfs_ondisk_hdr   *hdr = bp->b_addr;
                hdr->lsn = cpu_to_be64(bip->bli_item.li_lsn);
        }
        xfs_update_cksum(bp->b_addr, BBTOB(bp->b_length), XFS_FOO_CRC_OFF);
}
```

This will verify the internal structure of the metadata before we go any further, detecting corruptions that have occurred as the metadata has been modified in memory. If the metadata verifies OK, and CRCs are enabled, we then update the LSN field (when it was last modified) and calculate the CRC on the metadata. Once this is done, we can issue the IO.

2.5 Inodes and Dquots

Inodes and dquots are special snowflakes. They have per-object CRC and self-identifiers, but they are packed so that there are multiple objects per buffer. Hence we do not use per-buffer verifiers to do the work of per-object verification and CRC calculations. The per-buffer verifiers simply perform basic identification of the buffer - that they contain inodes or dquots, and that there are magic numbers in all the expected spots. All further CRC and verification checks are done when each inode is read from or written back to the buffer.

The structure of the verifiers and the identifiers checks is very similar to the buffer code described above. The only difference is where they are called. For example, inode read verification is done in xfs_iread() when the inode is first read out of the buffer and the struct xfs_inode is instantiated. The inode is already extensively verified during writeback in xfs_iflush_int, so the only addition here is to add the LSN and CRC to the inode as it is copied back into the buffer.

Chapter 3

Delayed Logging

3.1 Introduction to Re-logging in XFS

XFS logging is a combination of logical and physical logging. Some objects, such as inodes and dquots, are logged in logical format where the details logged are made up of the changes to in-core structures rather than on-disk structures. Other objects - typically buffers - have their physical changes logged. The reason for these differences is to reduce the amount of log space required for objects that are frequently logged. Some parts of inodes are more frequently logged than others, and inodes are typically more frequently logged than any other object (except maybe the superblock buffer) so keeping the amount of metadata logged low is of prime importance.

The reason that this is such a concern is that XFS allows multiple separate modifications to a single object to be carried in the log at any given time. This allows the log to avoid needing to flush each change to disk before recording a new change to the object. XFS does this via a method called "re-logging". Conceptually, this is quite simple - all it requires is that any new change to the object is recorded with a **new copy** of all the existing changes in the new transaction that is written to the log.

That is, if we have a sequence of changes A through to F, and the object was written to disk after change D, we would see in the log the following series of transactions, their contents and the log sequence number (LSN) of the transaction:

Transaction	Contents	LSN
A	A	X
B	A+B	X+n
C	A+B+C	X+n+m
D	A+B+C+D	X+n+m+o
<object written to disk>		
E	E	Y (> X+n+m+o)
F	E+F	Y+p

In other words, each time an object is relogged, the new transaction contains the aggregation of all the previous changes currently held only in the log.

This relogging technique also allows objects to be moved forward in the log so that an object being relogged does not prevent the tail of the log from ever moving forward. This can be seen in the table above by the changing (increasing) LSN of each subsequent transaction - the LSN is effectively a direct encoding of the location in the log of the transaction.

This relogging is also used to implement long-running, multiple-commit transactions. These transaction are known as rolling transactions, and require a special log reservation known as a permanent transaction reservation. A typical example of a rolling transaction is the removal of extents from an inode which can only be done at a rate of two extents per transaction because of reservation size limitations. Hence a rolling extent removal transaction keeps relogging the inode and btree buffers as they get modified in each removal operation. This keeps them moving forward in the log as the operation progresses, ensuring that current operation never gets blocked by itself if the log wraps around.

Hence it can be seen that the relogging operation is fundamental to the correct working of the XFS journalling subsystem. From the above description, most people should be able to see why the XFS metadata operations writes so much to the log - repeated

operations to the same objects write the same changes to the log over and over again. Worse is the fact that objects tend to get dirtier as they get relogged, so each subsequent transaction is writing more metadata into the log.

Another feature of the XFS transaction subsystem is that most transactions are asynchronous. That is, they don't commit to disk until either a log buffer is filled (a log buffer can hold multiple transactions) or a synchronous operation forces the log buffers holding the transactions to disk. This means that XFS is doing aggregation of transactions in memory - batching them, if you like - to minimise the impact of the log IO on transaction throughput.

The limitation on asynchronous transaction throughput is the number and size of log buffers made available by the log manager. By default there are 8 log buffers available and the size of each is 32kB - the size can be increased up to 256kB by use of a mount option.

Effectively, this gives us the maximum bound of outstanding metadata changes that can be made to the filesystem at any point in time - if all the log buffers are full and under IO, then no more transactions can be committed until the current batch completes. It is now common for a single current CPU core to be to able to issue enough transactions to keep the log buffers full and under IO permanently. Hence the XFS journalling subsystem can be considered to be IO bound.

3.2 Delayed Logging Concepts

The key thing to note about the asynchronous logging combined with the relogging technique XFS uses is that we can be relogging changed objects multiple times before they are committed to disk in the log buffers. If we return to the previous relogging example, it is entirely possible that transactions A through D are committed to disk in the same log buffer.

That is, a single log buffer may contain multiple copies of the same object, but only one of those copies needs to be there - the last one "D", as it contains all the changes from the previous changes. In other words, we have one necessary copy in the log buffer, and three stale copies that are simply wasting space. When we are doing repeated operations on the same set of objects, these "stale objects" can be over 90% of the space used in the log buffers. It is clear that reducing the number of stale objects written to the log would greatly reduce the amount of metadata we write to the log, and this is the fundamental goal of delayed logging.

From a conceptual point of view, XFS is already doing relogging in memory (where memory == log buffer), only it is doing it extremely inefficiently. It is using logical to physical formatting to do the relogging because there is no infrastructure to keep track of logical changes in memory prior to physically formatting the changes in a transaction to the log buffer. Hence we cannot avoid accumulating stale objects in the log buffers.

Delayed logging is the name we've given to keeping and tracking transactional changes to objects in memory outside the log buffer infrastructure. Because of the relogging concept fundamental to the XFS journalling subsystem, this is actually relatively easy to do - all the changes to logged items are already tracked in the current infrastructure. The big problem is how to accumulate them and get them to the log in a consistent, recoverable manner. Describing the problems and how they have been solved is the focus of this document.

One of the key changes that delayed logging makes to the operation of the journalling subsystem is that it disassociates the amount of outstanding metadata changes from the size and number of log buffers available. In other words, instead of there only being a maximum of 2MB of transaction changes not written to the log at any point in time, there may be a much greater amount being accumulated in memory. Hence the potential for loss of metadata on a crash is much greater than for the existing logging mechanism.

It should be noted that this does not change the guarantee that log recovery will result in a consistent filesystem. What it does mean is that as far as the recovered filesystem is concerned, there may be many thousands of transactions that simply did not occur as a result of the crash. This makes it even more important that applications that care about their data use fsync() where they need to ensure application level data integrity is maintained.

It should be noted that delayed logging is not an innovative new concept that warrants rigorous proofs to determine whether it is correct or not. The method of accumulating changes in memory for some period before writing them to the log is used effectively in many filesystems including ext3 and ext4. Hence no time is spent in this document trying to convince the reader that the concept is sound. Instead it is simply considered a "solved problem" and as such implementing it in XFS is purely an exercise in software engineering.

The fundamental requirements for delayed logging in XFS are simple:

1. Reduce the amount of metadata written to the log by at least an order of magnitude.

2. Supply sufficient statistics to validate Requirement #1.
3. Supply sufficient new tracing infrastructure to be able to debug problems with the new code.
4. No on-disk format change (metadata or log format).
5. Enable and disable with a mount option.
6. No performance regressions for synchronous transaction workloads.

3.3 Delayed Logging Design

3.3.1 Storing Changes

The problem with accumulating changes at a logical level (i.e. just using the existing log item dirty region tracking) is that when it comes to writing the changes to the log buffers, we need to ensure that the object we are formatting is not changing while we do this. This requires locking the object to prevent concurrent modification. Hence flushing the logical changes to the log would require us to lock every object, format them, and then unlock them again.

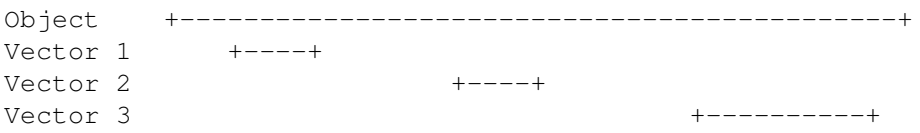
This introduces lots of scope for deadlocks with transactions that are already running. For example, a transaction has object A locked and modified, but needs the delayed logging tracking lock to commit the transaction. However, the flushing thread has the delayed logging tracking lock already held, and is trying to get the lock on object A to flush it to the log buffer. This appears to be an unsolvable deadlock condition, and it was solving this problem that was the barrier to implementing delayed logging for so long.

The solution is relatively simple - it just took a long time to recognise it. Put simply, the current logging code formats the changes to each item into an vector array that points to the changed regions in the item. The log write code simply copies the memory these vectors point to into the log buffer during transaction commit while the item is locked in the transaction. Instead of using the log buffer as the destination of the formatting code, we can use an allocated memory buffer big enough to fit the formatted vector.

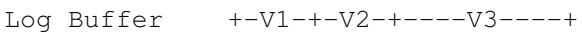
If we then copy the vector into the memory buffer and rewrite the vector to point to the memory buffer rather than the object itself, we now have a copy of the changes in a format that is compatible with the log buffer writing code. that does not require us to lock the item to access. This formatting and rewriting can all be done while the object is locked during transaction commit, resulting in a vector that is transactionally consistent and can be accessed without needing to lock the owning item.

Hence we avoid the need to lock items when we need to flush outstanding asynchronous transactions to the log. The differences between the existing formatting method and the delayed logging formatting can be seen in the diagram below.

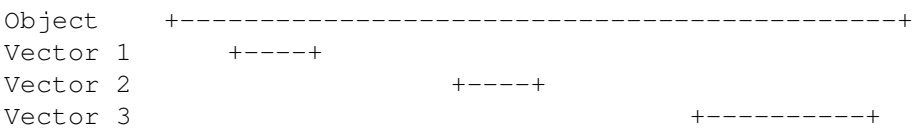
Current format log vector:



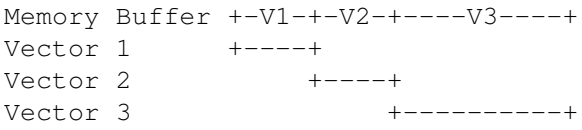
After formatting:



Delayed logging vector:



After formatting:



The memory buffer and associated vector need to be passed as a single object, but still need to be associated with the parent object so if the object is relogged we can replace the current memory buffer with a new memory buffer that contains the latest changes.

The reason for keeping the vector around after we've formatted the memory buffer is to support splitting vectors across log buffer boundaries correctly. If we don't keep the vector around, we do not know where the region boundaries are in the item, so we'd need a new encapsulation method for regions in the log buffer writing (i.e. double encapsulation). This would be an on-disk format change and as such is not desirable. It also means we'd have to write the log region headers in the formatting stage, which is problematic as there is per region state that needs to be placed into the headers during the log write.

Hence we need to keep the vector, but by attaching the memory buffer to it and rewriting the vector addresses to point at the memory buffer we end up with a self-describing object that can be passed to the log buffer write code to be handled in exactly the same manner as the existing log vectors are handled. Hence we avoid needing a new on-disk format to handle items that have been relogged in memory.

3.3.2 Tracking Changes

Now that we can record transactional changes in memory in a form that allows them to be used without limitations, we need to be able to track and accumulate them so that they can be written to the log at some later point in time. The log item is the natural place to store this vector and buffer, and also makes sense to be the object that is used to track committed objects as it will always exist once the object has been included in a transaction.

The log item is already used to track the log items that have been written to the log but not yet written to disk. Such log items are considered "active" and as such are stored in the Active Item List (AIL) which is a LSN-ordered double linked list. Items are inserted into this list during log buffer IO completion, after which they are unpinned and can be written to disk. An object that is in the AIL can be relogged, which causes the object to be pinned again and then moved forward in the AIL when the log buffer IO completes for that transaction.

Essentially, this shows that an item that is in the AIL can still be modified and relogged, so any tracking must be separate to the AIL infrastructure. As such, we cannot reuse the AIL list pointers for tracking committed items, nor can we store state in any field that is protected by the AIL lock. Hence the committed item tracking needs it's own locks, lists and state fields in the log item.

Similar to the AIL, tracking of committed items is done through a new list called the Committed Item List (CIL). The list tracks log items that have been committed and have formatted memory buffers attached to them. It tracks objects in transaction commit order, so when an object is relogged it is removed from it's place in the list and re-inserted at the tail. This is entirely arbitrary and done to make it easy for debugging - the last items in the list are the ones that are most recently modified. Ordering of the CIL is not necessary for transactional integrity (as discussed in the next section) so the ordering is done for convenience/sanity of the developers.

3.3.3 Checkpoints

When we have a log synchronisation event, commonly known as a "log force", all the items in the CIL must be written into the log via the log buffers. We need to write these items in the order that they exist in the CIL, and they need to be written as an atomic transaction. The need for all the objects to be written as an atomic transaction comes from the requirements of relogging and log replay - all the changes in all the objects in a given transaction must either be completely replayed during log recovery, or not replayed at all. If a transaction is not replayed because it is not complete in the log, then no later transactions should be replayed, either.

To fulfill this requirement, we need to write the entire CIL in a single log transaction. Fortunately, the XFS log code has no fixed limit on the size of a transaction, nor does the log replay code. The only fundamental limit is that the transaction cannot be larger than just under half the size of the log. The reason for this limit is that to find the head and tail of the log, there must be at least

one complete transaction in the log at any given time. If a transaction is larger than half the log, then there is the possibility that a crash during the write of a such a transaction could partially overwrite the only complete previous transaction in the log. This will result in a recovery failure and an inconsistent filesystem and hence we must enforce the maximum size of a checkpoint to be slightly less than a half the log.

Apart from this size requirement, a checkpoint transaction looks no different to any other transaction - it contains a transaction header, a series of formatted log items and a commit record at the tail. From a recovery perspective, the checkpoint transaction is also no different - just a lot bigger with a lot more items in it. The worst case effect of this is that we might need to tune the recovery transaction object hash size.

Because the checkpoint is just another transaction and all the changes to log items are stored as log vectors, we can use the existing log buffer writing code to write the changes into the log. To do this efficiently, we need to minimise the time we hold the CIL locked while writing the checkpoint transaction. The current log write code enables us to do this easily with the way it separates the writing of the transaction contents (the log vectors) from the transaction commit record, but tracking this requires us to have a per-checkpoint context that travels through the log write process through to checkpoint completion.

Hence a checkpoint has a context that tracks the state of the current checkpoint from initiation to checkpoint completion. A new context is initiated at the same time a checkpoint transaction is started. That is, when we remove all the current items from the CIL during a checkpoint operation, we move all those changes into the current checkpoint context. We then initialise a new context and attach that to the CIL for aggregation of new transactions.

This allows us to unlock the CIL immediately after transfer of all the committed items and effectively allow new transactions to be issued while we are formatting the checkpoint into the log. It also allows concurrent checkpoints to be written into the log buffers in the case of log force heavy workloads, just like the existing transaction commit code does. This, however, requires that we strictly order the commit records in the log so that checkpoint sequence order is maintained during log replay.

To ensure that we can be writing an item into a checkpoint transaction at the same time another transaction modifies the item and inserts the log item into the new CIL, then checkpoint transaction commit code cannot use log items to store the list of log vectors that need to be written into the transaction. Hence log vectors need to be able to be chained together to allow them to be detached from the log items. That is, when the CIL is flushed the memory buffer and log vector attached to each log item needs to be attached to the checkpoint context so that the log item can be released. In diagrammatic form, the CIL would look like this before the flush:

```
CIL Head
   |
   V
Log Item <-> log vector 1       -> memory buffer
   |                            -> vector array
   V
Log Item <-> log vector 2       -> memory buffer
   |                            -> vector array
   V
......
   |
   V
Log Item <-> log vector N-1     -> memory buffer
   |                            -> vector array
   V
Log Item <-> log vector N       -> memory buffer
                                -> vector array
```

And after the flush the CIL head is empty, and the checkpoint context log vector list would look like:

```
Checkpoint Context
   |
   V
log vector 1    -> memory buffer
   |            -> vector array
   |            -> Log Item
   V
log vector 2    -> memory buffer
   |            -> vector array
```

```
          |            -> Log Item
          V
       ......
          |
          V
       log vector N-1  -> memory buffer
          |            -> vector array
          |            -> Log Item
          V
       log vector N    -> memory buffer
                       -> vector array
                       -> Log Item
```

Once this transfer is done, the CIL can be unlocked and new transactions can start, while the checkpoint flush code works over the log vector chain to commit the checkpoint.

Once the checkpoint is written into the log buffers, the checkpoint context is attached to the log buffer that the commit record was written to along with a completion callback. Log IO completion will call that callback, which can then run transaction committed processing for the log items (i.e. insert into AIL and unpin) in the log vector chain and then free the log vector chain and checkpoint context.

Discussion Point: I am uncertain as to whether the log item is the most efficient way to track vectors, even though it seems like the natural way to do it. The fact that we walk the log items (in the CIL) just to chain the log vectors and break the link between the log item and the log vector means that we take a cache line hit for the log item list modification, then another for the log vector chaining. If we track by the log vectors, then we only need to break the link between the log item and the log vector, which means we should dirty only the log item cachelines. Normally I wouldn't be concerned about one vs two dirty cachelines except for the fact I've seen upwards of 80,000 log vectors in one checkpoint transaction. I'd guess this is a "measure and compare" situation that can be done after a working and reviewed implementation is in the dev tree....

3.3.4 Checkpoint Sequencing

One of the key aspects of the XFS transaction subsystem is that it tags committed transactions with the log sequence number of the transaction commit. This allows transactions to be issued asynchronously even though there may be future operations that cannot be completed until that transaction is fully committed to the log. In the rare case that a dependent operation occurs (e.g. re-using a freed metadata extent for a data extent), a special, optimised log force can be issued to force the dependent transaction to disk immediately.

To do this, transactions need to record the LSN of the commit record of the transaction. This LSN comes directly from the log buffer the transaction is written into. While this works just fine for the existing transaction mechanism, it does not work for delayed logging because transactions are not written directly into the log buffers. Hence some other method of sequencing transactions is required.

As discussed in the checkpoint section, delayed logging uses per-checkpoint contexts, and as such it is simple to assign a sequence number to each checkpoint. Because the switching of checkpoint contexts must be done atomically, it is simple to ensure that each new context has a monotonically increasing sequence number assigned to it without the need for an external atomic counter - we can just take the current context sequence number and add one to it for the new context.

Then, instead of assigning a log buffer LSN to the transaction commit LSN during the commit, we can assign the current checkpoint sequence. This allows operations that track transactions that have not yet completed know what checkpoint sequence needs to be committed before they can continue. As a result, the code that forces the log to a specific LSN now needs to ensure that the log forces to a specific checkpoint.

To ensure that we can do this, we need to track all the checkpoint contexts that are currently committing to the log. When we flush a checkpoint, the context gets added to a "committing" list which can be searched. When a checkpoint commit completes, it is removed from the committing list. Because the checkpoint context records the LSN of the commit record for the checkpoint, we can also wait on the log buffer that contains the commit record, thereby using the existing log force mechanisms to execute synchronous forces.

It should be noted that the synchronous forces may need to be extended with mitigation algorithms similar to the current log buffer code to allow aggregation of multiple synchronous transactions if there are already synchronous transactions being flushed. Investigation of the performance of the current design is needed before making any decisions here.

The main concern with log forces is to ensure that all the previous checkpoints are also committed to disk before the one we need to wait for. Therefore we need to check that all the prior contexts in the committing list are also complete before waiting on the one we need to complete. We do this synchronisation in the log force code so that we don't need to wait anywhere else for such serialisation - it only matters when we do a log force.

The only remaining complexity is that a log force now also has to handle the case where the forcing sequence number is the same as the current context. That is, we need to flush the CIL and potentially wait for it to complete. This is a simple addition to the existing log forcing code to check the sequence numbers and push if required. Indeed, placing the current sequence checkpoint flush in the log force code enables the current mechanism for issuing synchronous transactions to remain untouched (i.e. commit an asynchronous transaction, then force the log at the LSN of that transaction) and so the higher level code behaves the same regardless of whether delayed logging is being used or not.

3.3.5 Checkpoint Log Space Accounting

The big issue for a checkpoint transaction is the log space reservation for the transaction. We don't know how big a checkpoint transaction is going to be ahead of time, nor how many log buffers it will take to write out, nor the number of split log vector regions are going to be used. We can track the amount of log space required as we add items to the commit item list, but we still need to reserve the space in the log for the checkpoint.

A typical transaction reserves enough space in the log for the worst case space usage of the transaction. The reservation accounts for log record headers, transaction and region headers, headers for split regions, buffer tail padding, etc. as well as the actual space for all the changed metadata in the transaction. While some of this is fixed overhead, much of it is dependent on the size of the transaction and the number of regions being logged (the number of log vectors in the transaction).

An example of the differences would be logging directory changes versus logging inode changes. If you modify lots of inode cores (e.g. chmod -R g+w *), then there are lots of transactions that only contain an inode core and an inode log format structure. That is, two vectors totaling roughly 150 bytes. If we modify 10,000 inodes, we have about 1.5MB of metadata to write in 20,000 vectors. Each vector is 12 bytes, so the total to be logged is approximately 1.75MB. In comparison, if we are logging full directory buffers, they are typically 4KB each, so we in 1.5MB of directory buffers we'd have roughly 400 buffers and a buffer format structure for each buffer - roughly 800 vectors or 1.51MB total space. From this, it should be obvious that a static log space reservation is not particularly flexible and is difficult to select the "optimal value" for all workloads.

Further, if we are going to use a static reservation, which bit of the entire reservation does it cover? We account for space used by the transaction reservation by tracking the space currently used by the object in the CIL and then calculating the increase or decrease in space used as the object is relogged. This allows for a checkpoint reservation to only have to account for log buffer metadata used such as log header records.

However, even using a static reservation for just the log metadata is problematic. Typically log record headers use at least 16KB of log space per 1MB of log space consumed (512 bytes per 32k) and the reservation needs to be large enough to handle arbitrary sized checkpoint transactions. This reservation needs to be made before the checkpoint is started, and we need to be able to reserve the space without sleeping. For a 8MB checkpoint, we need a reservation of around 150KB, which is a non-trivial amount of space.

A static reservation needs to manipulate the log grant counters - we can take a permanent reservation on the space, but we still need to make sure we refresh the write reservation (the actual space available to the transaction) after every checkpoint transaction completion. Unfortunately, if this space is not available when required, then the regrant code will sleep waiting for it.

The problem with this is that it can lead to deadlocks as we may need to commit checkpoints to be able to free up log space (refer back to the description of rolling transactions for an example of this). Hence we **must** always have space available in the log if we are to use static reservations, and that is very difficult and complex to arrange. It is possible to do, but there is a simpler way.

The simpler way of doing this is tracking the entire log space used by the items in the CIL and using this to dynamically calculate the amount of log space required by the log metadata. If this log metadata space changes as a result of a transaction commit inserting a new memory buffer into the CIL, then the difference in space required is removed from the transaction that causes the change. Transactions at this level will **always** have enough space available in their reservation for this as they have already reserved the maximal amount of log metadata space they require, and such a delta reservation will always be less than or equal to the maximal amount in the reservation.

Hence we can grow the checkpoint transaction reservation dynamically as items are added to the CIL and avoid the need for reserving and regranting log space up front. This avoids deadlocks and removes a blocking point from the checkpoint flush code.

As mentioned early, transactions can't grow to more than half the size of the log. Hence as part of the reservation growing, we need to also check the size of the reservation against the maximum allowed transaction size. If we reach the maximum threshold, we need to push the CIL to the log. This is effectively a "background flush" and is done on demand. This is identical to a CIL push triggered by a log force, only that there is no waiting for the checkpoint commit to complete. This background push is checked and executed by transaction commit code.

If the transaction subsystem goes idle while we still have items in the CIL, they will be flushed by the periodic log force issued by the xfssyncd. This log force will push the CIL to disk, and if the transaction subsystem stays idle, allow the idle log to be covered (effectively marked clean) in exactly the same manner that is done for the existing logging method. A discussion point is whether this log force needs to be done more frequently than the current rate which is once every 30s.

3.3.6 Log Item Pinning

Currently log items are pinned during transaction commit while the items are still locked. This happens just after the items are formatted, though it could be done any time before the items are unlocked. The result of this mechanism is that items get pinned once for every transaction that is committed to the log buffers. Hence items that are relogged in the log buffers will have a pin count for every outstanding transaction they were dirtied in. When each of these transactions is completed, they will unpin the item once. As a result, the item only becomes unpinned when all the transactions complete and there are no pending transactions. Thus the pinning and unpinning of a log item is symmetric as there is a 1:1 relationship with transaction commit and log item completion.

For delayed logging, however, we have an asymmetric transaction commit to completion relationship. Every time an object is relogged in the CIL it goes through the commit process without a corresponding completion being registered. That is, we now have a many-to-one relationship between transaction commit and log item completion. The result of this is that pinning and unpinning of the log items becomes unbalanced if we retain the "pin on transaction commit, unpin on transaction completion" model.

To keep pin/unpin symmetry, the algorithm needs to change to a "pin on insertion into the CIL, unpin on checkpoint completion". In other words, the pinning and unpinning becomes symmetric around a checkpoint context. We have to pin the object the first time it is inserted into the CIL - if it is already in the CIL during a transaction commit, then we do not pin it again. Because there can be multiple outstanding checkpoint contexts, we can still see elevated pin counts, but as each checkpoint completes the pin count will retain the correct value according to it's context.

Just to make matters more slightly more complex, this checkpoint level context for the pin count means that the pinning of an item must take place under the CIL commit/flush lock. If we pin the object outside this lock, we cannot guarantee which context the pin count is associated with. This is because of the fact pinning the item is dependent on whether the item is present in the current CIL or not. If we don't pin the CIL first before we check and pin the object, we have a race with CIL being flushed between the check and the pin (or not pinning, as the case may be). Hence we must hold the CIL flush/commit lock to guarantee that we pin the items correctly.

3.3.7 Concurrent Scalability

A fundamental requirement for the CIL is that accesses through transaction commits must scale to many concurrent commits. The current transaction commit code does not break down even when there are transactions coming from 2048 processors at once. The current transaction code does not go any faster than if there was only one CPU using it, but it does not slow down either.

As a result, the delayed logging transaction commit code needs to be designed for concurrency from the ground up. It is obvious that there are serialisation points in the design - the three important ones are:

1. Locking out new transaction commits while flushing the CIL
2. Adding items to the CIL and updating item space accounting
3. Checkpoint commit ordering

Looking at the transaction commit and CIL flushing interactions, it is clear that we have a many-to-one interaction here. That is, the only restriction on the number of concurrent transactions that can be trying to commit at once is the amount of space available

in the log for their reservations. The practical limit here is in the order of several hundred concurrent transactions for a 128MB log, which means that it is generally one per CPU in a machine.

The amount of time a transaction commit needs to hold out a flush is a relatively long period of time - the pinning of log items needs to be done while we are holding out a CIL flush, so at the moment that means it is held across the formatting of the objects into memory buffers (i.e. while memcpy()s are in progress). Ultimately a two pass algorithm where the formatting is done separately to the pinning of objects could be used to reduce the hold time of the transaction commit side.

Because of the number of potential transaction commit side holders, the lock really needs to be a sleeping lock - if the CIL flush takes the lock, we do not want every other CPU in the machine spinning on the CIL lock. Given that flushing the CIL could involve walking a list of tens of thousands of log items, it will get held for a significant time and so spin contention is a significant concern. Preventing lots of CPUs spinning doing nothing is the main reason for choosing a sleeping lock even though nothing in either the transaction commit or CIL flush side sleeps with the lock held.

It should also be noted that CIL flushing is also a relatively rare operation compared to transaction commit for asynchronous transaction workloads - only time will tell if using a read-write semaphore for exclusion will limit transaction commit concurrency due to cache line bouncing of the lock on the read side.

The second serialisation point is on the transaction commit side where items are inserted into the CIL. Because transactions can enter this code concurrently, the CIL needs to be protected separately from the above commit/flush exclusion. It also needs to be an exclusive lock but it is only held for a very short time and so a spin lock is appropriate here. It is possible that this lock will become a contention point, but given the short hold time once per transaction I think that contention is unlikely.

The final serialisation point is the checkpoint commit record ordering code that is run as part of the checkpoint commit and log force sequencing. The code path that triggers a CIL flush (i.e. whatever triggers the log force) will enter an ordering loop after writing all the log vectors into the log buffers but before writing the commit record. This loop walks the list of committing checkpoints and needs to block waiting for checkpoints to complete their commit record write. As a result it needs a lock and a wait variable. Log force sequencing also requires the same lock, list walk, and blocking mechanism to ensure completion of checkpoints.

These two sequencing operations can use the mechanism even though the events they are waiting for are different. The checkpoint commit record sequencing needs to wait until checkpoint contexts contain a commit LSN (obtained through completion of a commit record write) while log force sequencing needs to wait until previous checkpoint contexts are removed from the committing list (i.e. they've completed). A simple wait variable and broadcast wakeups (thundering herds) has been used to implement these two serialisation queues. They use the same lock as the CIL, too. If we see too much contention on the CIL lock, or too many context switches as a result of the broadcast wakeups these operations can be put under a new spinlock and given separate wait lists to reduce lock contention and the number of processes woken by the wrong event.

3.3.8 Lifecycle Changes

The existing log item life cycle is as follows:

```
1. Transaction allocate
2. Transaction reserve
3. Lock item
4. Join item to transaction
        If not already attached,
                Allocate log item
                Attach log item to owner item
        Attach log item to transaction
5. Modify item
        Record modifications in log item
6. Transaction commit
        Pin item in memory
        Format item into log buffer
        Write commit LSN into transaction
        Unlock item
        Attach transaction to log buffer

<log buffer IO dispatched>
<log buffer IO completes>
```

```
7. Transaction completion
        Mark log item committed
        Insert log item into AIL
                Write commit LSN into log item
        Unpin log item
8. AIL traversal
        Lock item
        Mark log item clean
        Flush item to disk

<item IO completion>

9. Log item removed from AIL
        Moves log tail
        Item unlocked
```

Essentially, steps 1-6 operate independently from step 7, which is also independent of steps 8-9. An item can be locked in steps 1-6 or steps 8-9 at the same time step 7 is occurring, but only steps 1-6 or 8-9 can occur at the same time. If the log item is in the AIL or between steps 6 and 7 and steps 1-6 are re-entered, then the item is relogged. Only when steps 8-9 are entered and completed is the object considered clean.

With delayed logging, there are new steps inserted into the life cycle:

```
1. Transaction allocate
2. Transaction reserve
3. Lock item
4. Join item to transaction
        If not already attached,
                Allocate log item
                Attach log item to owner item
        Attach log item to transaction
5. Modify item
        Record modifications in log item
6. Transaction commit
        Pin item in memory if not pinned in CIL
        Format item into log vector + buffer
        Attach log vector and buffer to log item
        Insert log item into CIL
        Write CIL context sequence into transaction
        Unlock item

<next log force>

7. CIL push
        lock CIL flush
        Chain log vectors and buffers together
        Remove items from CIL
        unlock CIL flush
        write log vectors into log
        sequence commit records
        attach checkpoint context to log buffer

<log buffer IO dispatched>
<log buffer IO completes>

8. Checkpoint completion
        Mark log item committed
        Insert item into AIL
                Write commit LSN into log item
        Unpin log item
9. AIL traversal
```

```
                Lock item
                Mark log item clean
                Flush item to disk
        <item IO completion>
        10. Log item removed from AIL
                Moves log tail
                Item unlocked
```

From this, it can be seen that the only life cycle differences between the two logging methods are in the middle of the life cycle - they still have the same beginning and end and execution constraints. The only differences are in the committing of the log items to the log itself and the completion processing. Hence delayed logging should not introduce any constraints on log item behaviour, allocation or freeing that don't already exist.

As a result of this zero-impact "insertion" of delayed logging infrastructure and the design of the internal structures to avoid on disk format changes, we can basically switch between delayed logging and the existing mechanism with a mount option. Fundamentally, there is no reason why the log manager would not be able to swap methods automatically and transparently depending on load characteristics, but this should not be necessary if delayed logging works as designed.

EOF.

Chapter 4

Sharing Data Blocks

On a traditional filesystem, there is a 1:1 mapping between a logical block offset in a file and a physical block on disk, which is to say that physical blocks are not shared. However, there exist various use cases for being able to share blocks between files — deduplicating files saves space on archival systems; creating space-efficient clones of disk images for virtual machines and containers facilitates efficient datacenters; and deferring the payment of the allocation cost of a file system tree copy as long as possible makes regular work faster. In all of these cases, a write to one of the shared copies **must** not affect the other shared copies, which means that writes to shared blocks must employ a copy-on-write strategy. Sharing blocks in this manner is commonly referred to as "reflinking".

XFS implements block sharing in a fairly straightforward manner. All existing data fork structures remain unchanged, save for the addition of a per-allocation group reference count B+tree Section 13.8. This data structure tracks reference counts for all shared physical blocks, with a few rules to maintain compatibility with existing code: If a block is free, it will be tracked in the free space B+trees. If a block is owned by a single file, it appears in neither the free space nor the reference count B+trees. If a block is shared, it will appear in the reference count B+tree with a reference count >= 2. The first two cases are established precedent in XFS, so the third case is the only behavioral change.

When a filesystem block is shared, the block mapping in the destination file is updated to point to that filesystem block and the reference count B+tree records are updated to reflect the increased refcount. If a shared block is written, a new block will be allocated, the dirty data written to this new block, and the file's block mapping updated to point to the new block. If a shared block is unmapped, the reference count records are updated to reflect the decreased refcount and the block is also freed if its reference count becomes zero. This enables users to create space efficient clones of disk images and to copy filesystem subtrees quickly, using the standard Linux coreutils packages.

Deduplication employs the same mechanism to share blocks and copy them at write time. However, the kernel confirms that the contents of both files are identical before updating the destination file's mapping. This enables XFS to be used by userspace deduplication programs such as `duperemove`.

Chapter 5

Metadata Reconstruction

Note
This is a theoretical discussion of how reconstruction could work; none of this is implemented as of 2015.

A simple UNIX filesystem can be thought of in terms of a directed acyclic graph. To a first approximation, there exists a root directory node, which points to other nodes. Those other nodes can themselves be directories or they can be files. Each file, in turn, points to data blocks.

XFS adds a few more details to this picture:

- The real root(s) of an XFS filesystem are the allocation group headers (superblock, AGF, AGI, AGFL).
- Each allocation group's headers point to various per-AG B+trees (free space, inode, free inodes, free list, etc.)
- The free space B+trees point to unused extents;
- The inode B+trees point to blocks containing inode chunks;
- All superblocks point to the root directory and the log;
- Hardlinks mean that multiple directories can point to a single file node;
- File data block pointers are indexed by file offset;
- Files and directories can have a second collection of pointers to data blocks which contain extended attributes;
- Large directories require multiple data blocks to store all the subpointers;
- Still larger directories use high-offset data blocks to store a B+tree of hashes to directory entries;
- Large extended attribute forks similarly use high-offset data blocks to store a B+tree of hashes to attribute keys; and
- Symbolic links can point to data blocks.

The beauty of this massive graph structure is that under normal circumstances, everything known to the filesystem is discoverable (access controls notwithstanding) from the root. The major weakness of this structure of course is that breaking a edge in the graph can render entire subtrees inaccessible. `xfs_repair` "recovers" from broken directories by scanning for unlinked inodes and connecting them to `/lost+found`, but this isn't sufficiently general to recover from breaks in other parts of the graph structure. Wouldn't it be useful to have back pointers as a secondary data structure? The current repair strategy is to reconstruct whatever can be rebuilt, but to scrap anything that doesn't check out.

The reverse-mapping B+tree Section 13.7 fills in part of the puzzle. Since it contains copies of every entry in each inode's data and attribute forks, we can fix a corrupted block map with these records. Furthermore, if the inode B+trees become corrupt, it is possible to visit all inode chunks using the reverse-mapping data. Should XFS ever gain the ability to store parent directory information in each inode, it also becomes possible to resurrect damaged directory trees, which should reduce the complaints about inodes ending up in `/lost+found`. Everything else in the per-AG primary metadata can already be reconstructed via `xfs_repair`. Hopefully, reconstruction will not turn out to be a fool's errand.

Chapter 6

Common XFS Types

All the following XFS types can be found in xfs_types.h. NULL values are always -1 on disk (ie. all bits for the value set to one).

xfs_ino_t
Unsigned 64 bit absolute inode number Section 13.3.1.

xfs_off_t
Signed 64 bit file offset.

xfs_daddr_t
Signed 64 bit disk address (sectors).

xfs_agnumber_t
Unsigned 32 bit AG number Chapter 13.

xfs_agblock_t
Unsigned 32 bit AG relative block number.

xfs_extlen_t
Unsigned 32 bit extent Chapter 17 length in blocks.

xfs_extnum_t
Signed 32 bit number of extents in a data fork.

xfs_aextnum_t
Signed 16 bit number of extents in an attribute fork.

xfs_dablk_t
Unsigned 32 bit block number for directories Chapter 18 and extended attributes Chapter 19.

xfs_dahash_t
Unsigned 32 bit hash of a directory file name or extended attribute name.

xfs_fsblock_t
Unsigned 64 bit filesystem block number combining AG number Chapter 13 and block offset into the AG.

xfs_rfsblock_t
Unsigned 64 bit raw filesystem block number.

xfs_rtblock_t
Unsigned 64 bit extent number in the real-time Section 13.6 sub-volume.

xfs_fileoff_t
Unsigned 64 bit block offset into a file.

xfs_filblks_t
Unsigned 64 bit block count for a file.

uuid_t
16-byte universally unique identifier (UUID).

xfs_fsize_t
Signed 64 bit byte size of a file.

Chapter 7

Magic Numbers

These are the magic numbers that are known to XFS, along with links to the relevant chapters. Magic numbers tend to have consistent locations:

- 32-bit magic numbers are always at offset zero in the block.
- 16-bit magic numbers for the directory and attribute B+tree are at offset eight.
- The quota magic number is at offset zero.
- The inode magic is at the beginning of each inode.

Flag	Hexadecimal	ASCII	Data structure
XFS_SB_MAGIC	0x58465342	XFSB	Superblock Section 13.1
XFS_AGF_MAGIC	0x58414746	XAGF	Free Space Section 13.2.1
XFS_AGI_MAGIC	0x58414749	XAGI	Inode Information Section 13.3.2
XFS_AGFL_MAGIC	0x5841464c	XAFL	Free Space List Section 13.2.3, v5 only
XFS_DINODE_MAGIC	0x494e	IN	Inodes Section 16.1
XFS_DQUOT_MAGIC	0x4451	DQ	Quota Inodes Section 15.1
XFS_SYMLINK_MAGIC	0x58534c4d	XSLM	Symbolic Links Section 20.2
XFS_ABTB_MAGIC	0x41425442	ABTB	Free Space by Block B+tree Section 13.2.2
XFS_ABTB_CRC_MAGIC	0x41423342	AB3B	Free Space by Block B+tree Section 13.2.2, v5 only
XFS_ABTC_MAGIC	0x41425443	ABTC	Free Space by Size B+tree Section 13.2.2
XFS_ABTC_CRC_MAGIC	0x41423343	AB3C	Free Space by Size B+tree Section 13.2.2, v5 only
XFS_IBT_MAGIC	0x49414254	IABT	Inode B+tree Section 13.4
XFS_IBT_CRC_MAGIC	0x49414233	IAB3	Inode B+tree Section 13.4, v5 only
XFS_FIBT_MAGIC	0x46494254	FIBT	Free Inode B+tree Section 13.4
XFS_FIBT_CRC_MAGIC	0x46494233	FIB3	Free Inode B+tree Section 13.4, v5 only
XFS_BMAP_MAGIC	0x424d4150	BMAP	B+Tree Extent List Section 17.2
XFS_BMAP_CRC_MAGIC	0x424d4133	BMA3	B+Tree Extent List Section 17.2, v5 only

Flag	Hexadecimal	ASCII	Data structure
XLOG_HEADER_MAGIC_NUM	0xfeedbabe		Log Records Section 14.1
XFS_DA_NODE_MAGIC	0xfebe		Directory/Attribute Node Section 11.2
XFS_DA3_NODE_MAGIC	0x3ebe		Directory/Attribute Node Section 11.2, v5 only
XFS_DIR2_BLOCK_MAGIC	0x58443242	XD2B	Block Directory Data Section 18.2
XFS_DIR3_BLOCK_MAGIC	0x58444233	XDB3	Block Directory Data Section 18.2, v5 only
XFS_DIR2_DATA_MAGIC	0x58443244	XD2D	Leaf Directory Data Section 18.3
XFS_DIR3_DATA_MAGIC	0x58444433	XDD3	Leaf Directory Data Section 18.3, v5 only
XFS_DIR2_LEAF1_MAGIC	0xd2f1		Leaf Directory Section 18.3
XFS_DIR3_LEAF1_MAGIC	0x3df1		Leaf Directory Section 18.3, v5 only
XFS_DIR2_LEAFN_MAGIC	0xd2ff		Node Directory Section 18.4
XFS_DIR3_LEAFN_MAGIC	0x3dff		Node Directory Section 18.4, v5 only
XFS_DIR2_FREE_MAGIC	0x58443246	XD2F	Node Directory Free Space Section 18.4
XFS_DIR3_FREE_MAGIC	0x58444633	XDF3	Node Directory Free Space Section 18.4, v5 only
XFS_ATTR_LEAF_MAGIC	0xfbee		Leaf Attribute Section 19.2
XFS_ATTR3_LEAF_MAGIC	0x3bee		Leaf Attribute Section 19.2, v5 only
XFS_ATTR3_RMT_MAGIC	0x5841524d	XARM	Remote Attribute Value Section 19.5, v5 only
XFS_RMAP_CRC_MAGIC	0x524d4233	RMB3	Reverse Mapping B+tree Section 13.7, v5 only
XFS_RTRMAP_CRC_MAGIC	0x4d415052	MAPR	Real-Time Reverse Mapping B+tree Section 15.2.3, v5 only
XFS_REFC_CRC_MAGIC	0x52334643	R3FC	Reference Count B+tree Section 13.8, v5 only
XFS_MD_MAGIC	0x5846534d	XFSM	Metadata Dumps Chapter 21

The magic numbers for log items are at offset zero in each log item, but items are not aligned to blocks.

Flag	Hexadecimal	ASCII	Data structure
XFS_TRANS_HEADER_MAGIC	0x5452414e	TRAN	Log Transactions Section 14.3.1
XFS_LI_EFI	0x1236		Extent Freeing Intent Log Item Section 14.3.2
XFS_LI_EFD	0x1237		Extent Freeing Done Log Item Section 14.3.3
XFS_LI_IUNLINK	0x1238		Unknown?
XFS_LI_INODE	0x123b		Inode Updates Log Item Section 14.3.10
XFS_LI_BUF	0x123c		Buffer Writes Log Item Section 14.3.12

Flag	Hexadecimal	ASCII	Data structure
XFS_LI_DQUOT	0x123d		Update Quota Log Item Section 14.3.14
XFS_LI_QUOTAOFF	0x123e		Quota Off Log Item Section 14.3.16
XFS_LI_ICREATE	0x123f		Inode Creation Log Item Section 14.3.17
XFS_LI_RUI	0x1240		Reverse Mapping Update Intent Section 14.3.4
XFS_LI_RUD	0x1241		Reverse Mapping Update Done Section 14.3.5
XFS_LI_CUI	0x1242		Reference Count Update Intent Section 14.3.6
XFS_LI_CUD	0x1243		Reference Count Update Done Section 14.3.7
XFS_LI_BUI	0x1244		File Block Mapping Update Intent Section 14.3.8
XFS_LI_BUD	0x1245		File Block Mapping Update Done Section 14.3.9

Chapter 8

Theoretical Limits

XFS can create really big filesystems!

Item	1KiB blocks	4KiB blocks	64KiB blocks
Blocks	2^{52}	2^{52}	2^{52}
Inodes	2^{63}	2^{63}	2^{64}
Allocation Groups	2^{32}	2^{32}	2^{32}
File System Size	8EiB	8EiB	8EiB
Blocks per AG	2^{31}	2^{31}	2^{31}
Inodes per AG	2^{32}	2^{32}	2^{32}
Max AG Size	2TiB	8TiB	128TiB
Blocks Per File	2^{54}	2^{54}	2^{54}
File Size	8EiB	8EiB	8EiB
Max Dir Size	32GiB	32GiB	32GiB

Linux doesn't support files or devices larger than 8EiB, so the block limitations are largely ignorable.

Chapter 9

Testing Filesystem Changes

People put a lot of trust in filesystems to preserve their data in a reliable fashion. To that end, it is very important that users and developers have access to a suite of regression tests that can be used to prove correct operation of any given filesystem code, or to analyze failures to fix problems found in the code. The XFS regression test suite, `xfstests`, is hosted at `git://git.kernel.org/pub/scm/fs/xfs/xfstests-dev.git`. Most tests apply to filesystems in general, but the suite also contains tests for features specific to each filesystem.

When fixing bugs, it is important to provide a testcase exposing the bug so that the developers can avoid a future re-occurrence of the regression. Furthermore, if you're developing a new user-visible feature for XFS, please help the rest of the development community to sustain and maintain the whole codebase by providing generous test coverage to check its behavior.

When altering, adding, or removing an on-disk data structure, please remember to update both the in-kernel structure size checks in `xfs_ondisk.h` and to ensure that your changes are reflected in xfstest xfs/122. These regression tests enable us to detect compiler bugs, alignment problems, and anything else that might result in the creation of incompatible filesystem images.

Part II

Global Structures

Chapter 10

Fixed Length Record B+trees

XFS uses b+trees to index all metadata records. This well known data structure is used to provide efficient random and sequential access to metadata records while minimizing seek times. There are two btree formats: a short format for records pertaining to a single allocation group, since all block pointers in an AG are 32-bits in size; and a long format for records pertaining to a file, since file data can have 64-bit block offsets. Each b+tree block is either a leaf node containing records, or an internal node containing keys and pointers to other b+tree blocks. The tree consists of a root block which may point to some number of other blocks; blocks in the bottom level of the b+tree contains only records.

Leaf blocks of both types of b+trees have the same general format: a header describing the data in the block, and an array of records. The specific header formats are given in the next two sections, and the record format is provided by the b+tree client itself. The generic b+tree code does not have any specific knowledge of the record format.

```
+--------+------------+-------------+
| header |   record   | records... |
+--------+------------+-------------+
```

Internal node blocks of both types of b+trees also have the same general format: a header describing the data in the block, an array of keys, and an array of pointers. Each pointer may be associated with one or two keys. The first key uniquely identifies the first record accessible via the leftmost path down the branch of the tree.

If the records in a b+tree are indexed by an interval, then a range of keys can uniquely identify a single record. For example, if a record covers blocks 12-16, then any one of the keys 12, 13, 14, 15, or 16 return the same record. In this case, the key for the record describing "12-16" is 12. If none of the records overlap, we only need to store one key.

This is the format of a standard b+tree node:

```
+--------+---------+---------+---------+---------+
| header |   key   | keys... |   ptr   | ptrs... |
+--------+---------+---------+---------+---------+
```

If the b+tree records do not overlap, performing a b+tree lookup is simple. Start with the root. If it is a leaf block, perform a binary search of the records until we find the record with a lower key than our search key. If the block is a node block, perform a binary search of the keys until we find a key lower than our search key, then follow the pointer to the next block. Repeat until we find a record.

However, if b+tree records contain intervals and are allowed to overlap, the internal nodes of the b+tree become larger:

```
+--------+---------+----------+---------+-------------+---------+----------+
| header | low key | high key | low key | high key... |   ptr   | ptrs... |
+--------+---------+----------+---------+-------------+---------+----------+
```

The low keys are exactly the same as the keys in the non-overlapping b+tree. High keys, however, are a little different. Recall that a record with a key consisting of an interval can be referenced by a number of keys. Since the low key of a record indexes the low end of that key range, the high key indexes the high end of the key range. Returning to the example above, the high key for the record describing "12-16" is 16. The high key recorded in a b+tree node is the largest of the high keys of all records

accessible under the subtree rooted by the pointer. For a level 1 node, this is the largest high key in the pointed-to leaf node; for any other node, this is the largest of the high keys in the pointed-to node.

Nodes and leaves use the same magic numbers.

10.1 Short Format B+trees

Each allocation group uses a "short format" B+tree to index various information about the allocation group. The structure is called short format because all block pointers are AG block numbers. The trees use the following header:

```
struct xfs_btree_sblock {
     __be32                  bb_magic;
     __be16                  bb_level;
     __be16                  bb_numrecs;
     __be32                  bb_leftsib;
     __be32                  bb_rightsib;

     /* version 5 filesystem fields start here */
     __be64                  bb_blkno;
     __be64                  bb_lsn;
     uuid_t                  bb_uuid;
     __be32                  bb_owner;
     __le32                  bb_crc;
};
```

bb_magic
Specifies the magic number for the per-AG B+tree block.

bb_level
The level of the tree in which this block is found. If this value is 0, this is a leaf block and contains records; otherwise, it is a node block and contains keys and pointers. Level values increase towards the root.

bb_numrecs
Number of records in this block.

bb_leftsib
AG block number of the left sibling of this B+tree node.

bb_rightsib
AG block number of the right sibling of this B+tree node.

bb_blkno
FS block number of this B+tree block.

bb_lsn
Log sequence number of the last write to this block.

bb_uuid
The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

bb_owner
The AG number that this B+tree block ought to be in.

bb_crc
Checksum of the B+tree block.

10.2 Long Format B+trees

Long format B+trees are similar to short format B+trees, except that their block pointers are 64-bit filesystem block numbers instead of 32-bit AG block numbers. Because of this, long format b+trees can be (and usually are) rooted in an inode's data or attribute fork. The nodes and leaves of this B+tree use the `xfs_btree_lblock` declaration:

```
struct xfs_btree_lblock {
     __be32                  bb_magic;
     __be16                  bb_level;
     __be16                  bb_numrecs;
     __be64                  bb_leftsib;
     __be64                  bb_rightsib;

     /* version 5 filesystem fields start here */
     __be64                  bb_blkno;
     __be64                  bb_lsn;
     uuid_t                  bb_uuid;
     __be64                  bb_owner;
     __le32                  bb_crc;
     __be32                  bb_pad;
};
```

bb_magic
Specifies the magic number for the btree block.

bb_level
The level of the tree in which this block is found. If this value is 0, this is a leaf block and contains records; otherwise, it is a node block and contains keys and pointers.

bb_numrecs
Number of records in this block.

bb_leftsib
FS block number of the left sibling of this B+tree node.

bb_rightsib
FS block number of the right sibling of this B+tree node.

bb_blkno
FS block number of this B+tree block.

bb_lsn
Log sequence number of the last write to this block.

bb_uuid
The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

bb_owner
The AG number that this B+tree block ought to be in.

bb_crc
Checksum of the B+tree block.

bb_pad
Pads the structure to 64 bytes.

Chapter 11

Variable Length Record B+trees

Directories and extended attributes are implemented as a simple key-value record store inside the blocks pointed to by the data or attribute fork of a file. Blocks referenced by either data structure are block offsets of an inode fork, not physical blocks.

Directory and attribute data are stored as a linear array of variable-length records in the low blocks of a fork. Both data types share the property that record keys and record values are both arbitrary and unique sequences of bytes. See the respective sections about directories Chapter 18 or attributes Chapter 19 for more information about the exact record formats.

The dir/attr b+tree (or "dabtree"), if present, computes a hash of the record key to produce the b+tree key, and b+tree keys are used to index the fork block in which the record may be found. Unlike the fixed-length b+trees, the variable length b+trees can index the same key multiple times. B+tree keypointers and records both take this format:

```
+---------+--------------+
| hashval | before_block |
+---------+--------------+
```

The "before block" is the block offset in the inode fork of the block in which we can find the record whose hashed key is "hashval". The hash function is as follows:

```
#define rol32(x,y)              (((x) << (y)) | ((x) >> (32 - (y))))

xfs_dahash_t
xfs_da_hashname(const uint8_t *name, int namelen)
{
        xfs_dahash_t hash;

        /*
         * Do four characters at a time as long as we can.
         */
        for (hash = 0; namelen >= 4; namelen -= 4, name += 4)
                hash = (name[0] << 21) ^ (name[1] << 14) ^ (name[2] << 7) ^
                       (name[3] << 0) ^ rol32(hash, 7 * 4);

        /*
         * Now do the rest of the characters.
         */
        switch (namelen) {
        case 3:
                return (name[0] << 14) ^ (name[1] << 7) ^ (name[2] << 0) ^
                       rol32(hash, 7 * 3);
        case 2:
                return (name[0] << 7) ^ (name[1] << 0) ^ rol32(hash, 7 * 2);
        case 1:
                return (name[0] << 0) ^ rol32(hash, 7 * 1);
        default: /* case 0: */
                return hash;
```

```
        }
}
```

11.1 Block Headers

- Tree nodes, leaf and node directories Chapter 18, and leaf and node extended attributes Chapter 19 use the `xfs_da_blkinfo_t` filesystem block header. The structure appears as follows:

```
typedef struct xfs_da_blkinfo {
     __be32                  forw;
     __be32                  back;
     __be16                  magic;
     __be16                  pad;
} xfs_da_blkinfo_t;
```

forw
Logical block offset of the previous B+tree block at this level.

back
Logical block offset of the next B+tree block at this level.

magic
Magic number for this directory/attribute block.

pad
Padding to maintain alignment.

- On a v5 filesystem, the leaves use the `struct xfs_da3_blkinfo_t` filesystem block header. This header is used in the same place as `xfs_da_blkinfo_t`:

```
struct xfs_da3_blkinfo {
     /* these values are inside xfs_da_blkinfo */
     __be32                  forw;
     __be32                  back;
     __be16                  magic;
     __be16                  pad;

     __be32                  crc;
     __be64                  blkno;
     __be64                  lsn;
     uuid_t                  uuid;
     __be64                  owner;
};
```

forw
Logical block offset of the previous B+tree block at this level.

back
Logical block offset of the next B+tree block at this level.

magic
Magic number for this directory/attribute block.

pad
Padding to maintain alignment.

crc
Checksum of the directory/attribute block.

blkno
Block number of this directory/attribute block.

lsn
Log sequence number of the last write to this block.

uuid
The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

owner
The inode number that this directory/attribute block belongs to.

11.2 Internal Nodes

The nodes of a dabtree have the following format:

```
typedef struct xfs_da_intnode {
     struct xfs_da_node_hdr {
           xfs_da_blkinfo_t     info;
           __uint16_t           count;
           __uint16_t           level;
     } hdr;
     struct xfs_da_node_entry {
           xfs_dahash_t         hashval;
           xfs_dablk_t          before;
     } btree[1];
} xfs_da_intnode_t;
```

info
Directory/attribute block info. The magic number is `XFS_DA_NODE_MAGIC` (0xfebe).

count
Number of node entries in this block.

level
The level of this block in the B+tree. Levels start at 1 for blocks that point to directory or attribute data blocks and increase towards the root.

hashval
The hash value of a particular record.

before
The directory/attribute logical block containing all entries up to the corresponding hash value.

- On a v5 filesystem, the directory/attribute node blocks have the following structure:

```
struct xfs_da3_intnode {
     struct xfs_da3_node_hdr {
           struct xfs_da3_blkinfo    info;
           __uint16_t                count;
           __uint16_t                level;
           __uint32_t                pad32;
     } hdr;
     struct xfs_da_node_entry {
           xfs_dahash_t              hashval;
           xfs_dablk_t               before;
     } btree[1];
};
```

info
Directory/attribute block info. The magic number is `XFS_DA3_NODE_MAGIC` (0x3ebe).

count
Number of node entries in this block.

level
The level of this block in the B+tree. Levels start at 1 for blocks that point to directory or attribute data blocks, and increase towards the root.

pad32
Padding to maintain alignment.

hashval
The hash value of a particular record.

before
The directory/attribute logical block containing all entries up to the corresponding hash value.

Chapter 12

Timestamps

XFS needs to be able to persist the concept of a point in time. This chapter discusses how timestamps are represented on disk.

12.1 Inode Timestamps

The filesystem preserves up to four different timestamps for each file stored in the filesystem. These quantities are: the time when the file was created (`di_crtime`), the last time the file metadata were changed (`di_ctime`), the last time the file contents were changed (`di_mtime`), and the last time the file contents were accessed (`di_atime`). The filesystem epoch is aligned with the Unix epoch, which is to say that a value of all zeroes represents 00:00:00 UTC on January 1st, 1970.

Prior to the introduction of the bigtime feature, inode timestamps were laid out as as segmented counter of seconds and nanoseconds:

```
struct xfs_legacy_timestamp {
     __int32_t                  t_sec;
     __int32_t                  t_nsec;
};
```

The smallest date this format can represent is 20:45:52 UTC on December 31st, 1901, and the largest date supported is 03:14:07 UTC on January 19, 2038.

With the introduction of the bigtime feature, the format is changed to interpret the timestamp as a 64-bit count of nanoseconds since the smallest date supported by the old encoding. This means that the smallest date supported is still 20:45:52 UTC on December 31st, 1901; but now the largest date supported is 20:20:24 UTC on July 2nd, 2486.

12.2 Quota Grace Period Expiration Timers

XFS' quota control allows administrators to set a soft limit on each type of resource that a regular user can consume: inodes, blocks, and realtime blocks. The administrator can establish a grace period after which the soft limit becomes a hard limit for the user. Therefore, XFS needs to be able to store the exact time when a grace period expires.

Prior to the introduction of the bigtime feature, quota grace period expirations were unsigned 32-bit seconds counters, with the magic value zero meaning that the soft limit has not been exceeded. Therefore, the smallest expiration date that can be expressed is 00:00:01 UTC on January 1st, 1970; and the largest is 06:28:15 on February 7th, 2106.

With the introduction of the bigtime feature, the ondisk field now encodes the upper 32 bits of an unsigned 34-bit seconds counter. Zero is still a magic value that means the soft limit has not been exceeded. The smallest quota expiration date is now 00:00:04 UTC on January 1st, 1970; and the largest is 20:20:24 UTC on July 2nd, 2486. The format can encode slightly larger expiration dates, but it was decided to end support for both timers at exactly the same point.

The default grace periods are stored in the timer fields of the quota record for id zero. Since this quantity is an interval, these fields are always interpreted as an unsigned 32 bit quantity. Therefore, the longest possible grace period is approximately 136 years, 29 weeks, 3 days, 6 hours, 28 minutes and 15 seconds.

Chapter 13

Allocation Groups

As mentioned earlier, XFS filesystems are divided into a number of equally sized chunks called Allocation Groups. Each AG can almost be thought of as an individual filesystem that maintains its own space usage. Each AG can be up to one terabyte in size (512 bytes $\times$ 2^{31}), regardless of the underlying device's sector size.

Each AG has the following characteristics:

- A super block describing overall filesystem info
- Free space management
- Inode allocation and tracking
- Reverse block-mapping index (optional)
- Data block reference count index (optional)

Having multiple AGs allows XFS to handle most operations in parallel without degrading performance as the number of concurrent accesses increases.

The only global information maintained by the first AG (primary) is free space across the filesystem and total inode counts. If the `XFS_SB_VERSION2_LAZYSBCOUNTBIT` flag is set in the superblock, these are only updated on-disk when the filesystem is cleanly unmounted (umount or shutdown).

Immediately after a `mkfs.xfs`, the primary AG has the following disk layout; the subsequent AGs do not have any inodes allocated:

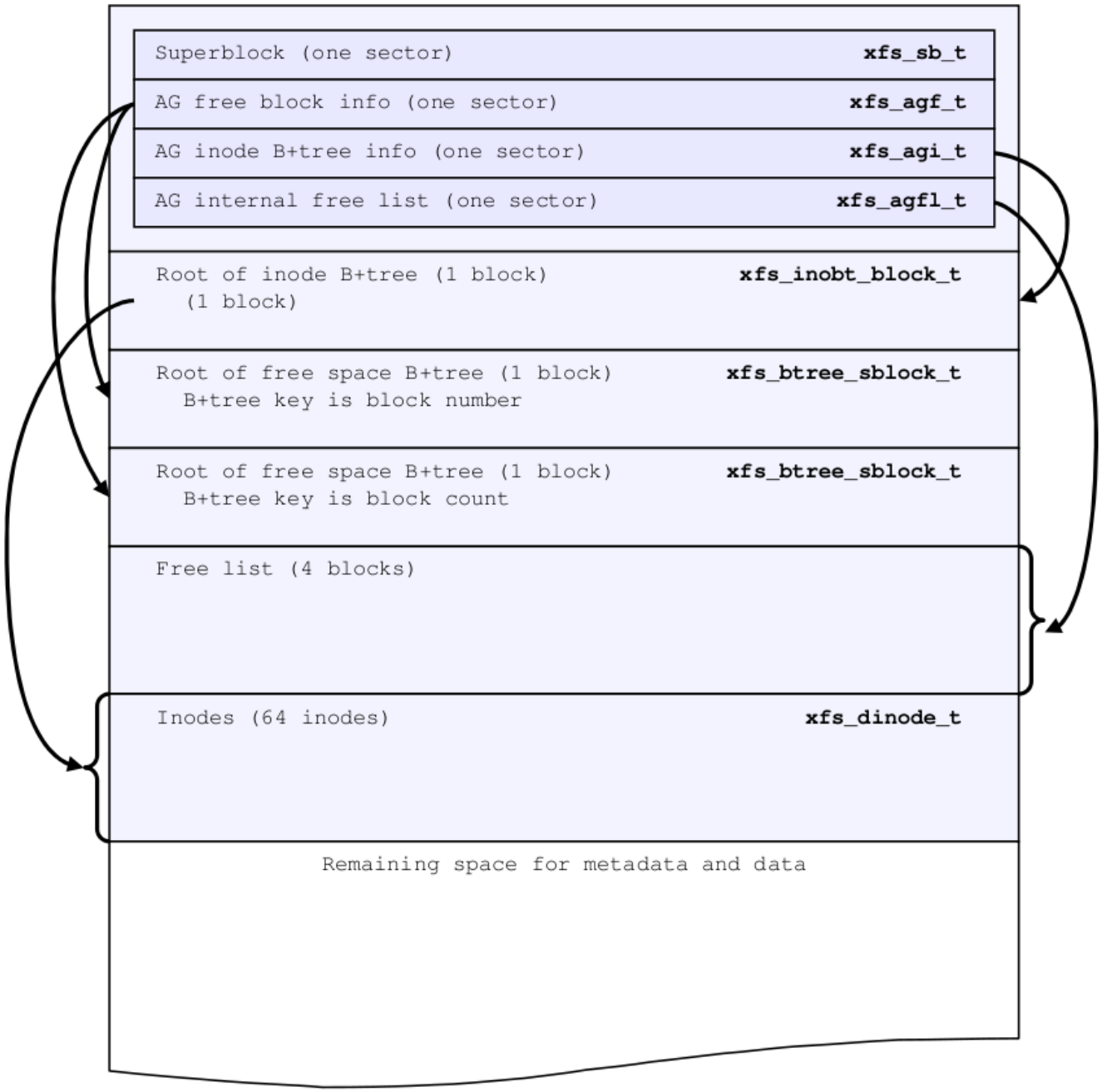


Figure 13.1: Allocation group layout

Each of these structures are expanded upon in the following sections.

13.1 Superblocks

Each AG starts with a superblock. The first one, in AG 0, is the primary superblock which stores aggregate AG information. Secondary superblocks are only used by xfs_repair when the primary superblock has been corrupted. A superblock is one sector in length.

The superblock is defined by the following structure. The description of each field follows.

```
struct xfs_sb
{
        __uint32_t              sb_magicnum;
        __uint32_t              sb_blocksize;
        xfs_rfsblock_t          sb_dblocks;
        xfs_rfsblock_t          sb_rblocks;
        xfs_rtblock_t           sb_rextents;
        uuid_t                  sb_uuid;
        xfs_fsblock_t           sb_logstart;
        xfs_ino_t               sb_rootino;
        xfs_ino_t               sb_rbmino;
        xfs_ino_t               sb_rsumino;
        xfs_agblock_t           sb_rextsize;
        xfs_agblock_t           sb_agblocks;
        xfs_agnumber_t          sb_agcount;
        xfs_extlen_t            sb_rbmblocks;
        xfs_extlen_t            sb_logblocks;
        __uint16_t              sb_versionnum;
        __uint16_t              sb_sectsize;
        __uint16_t              sb_inodesize;
        __uint16_t              sb_inopblock;
        char                    sb_fname[12];
        __uint8_t               sb_blocklog;
        __uint8_t               sb_sectlog;
        __uint8_t               sb_inodelog;
        __uint8_t               sb_inopblog;
        __uint8_t               sb_agblklog;
        __uint8_t               sb_rextslog;
        __uint8_t               sb_inprogress;
        __uint8_t               sb_imax_pct;
        __uint64_t              sb_icount;
        __uint64_t              sb_ifree;
        __uint64_t              sb_fdblocks;
        __uint64_t              sb_frextents;
        xfs_ino_t               sb_uquotino;
        xfs_ino_t               sb_gquotino;
        __uint16_t              sb_qflags;
        __uint8_t               sb_flags;
        __uint8_t               sb_shared_vn;
        xfs_extlen_t            sb_inoalignmt;
        __uint32_t              sb_unit;
        __uint32_t              sb_width;
        __uint8_t               sb_dirblklog;
        __uint8_t               sb_logsectlog;
        __uint16_t              sb_logsectsize;
        __uint32_t              sb_logsunit;
        __uint32_t              sb_features2;
        __uint32_t              sb_bad_features2;

        /* version 5 superblock fields start here */
        __uint32_t              sb_features_compat;
        __uint32_t              sb_features_ro_compat;
        __uint32_t              sb_features_incompat;
        __uint32_t              sb_features_log_incompat;

        __uint32_t              sb_crc;
        xfs_extlen_t            sb_spino_align;

        xfs_ino_t               sb_pquotino;
        xfs_lsn_t               sb_lsn;
        uuid_t                  sb_meta_uuid;
```

```
        xfs_ino_t               sb_rrmapino;
};
```

sb_magicnum
Identifies the filesystem. Its value is `XFS_SB_MAGIC` "XFSB" (0x58465342).

sb_blocksize
The size of a basic unit of space allocation in bytes. Typically, this is 4096 (4KB) but can range from 512 to 65536 bytes.

sb_dblocks
Total number of blocks available for data and metadata on the filesystem.

sb_rblocks
Number blocks in the real-time disk device. Refer to real-time sub-volumes Section 13.6 for more information.

sb_rextents
Number of extents on the real-time device.

sb_uuid
UUID (Universally Unique ID) for the filesystem. Filesystems can be mounted by the UUID instead of device name.

sb_logstart
First block number for the journaling log if the log is internal (ie. not on a separate disk device). For an external log device, this will be zero (the log will also start on the first block on the log device). The identity of the log devices is not recorded in the filesystem, but the UUIDs of the filesystem and the log device are compared to prevent corruption.

sb_rootino
Root inode number for the filesystem. Normally, the root inode is at the start of the first possible inode chunk in AG 0. This is 128 when using a 4KB block size.

sb_rbmino
Bitmap inode for real-time extents.

sb_rsumino
Summary inode for real-time bitmap.

sb_rextsize
Realtime extent size in blocks.

sb_agblocks
Size of each AG in blocks. For the actual size of the last AG, refer to the free space Section 13.2 `agf_length` value.

sb_agcount
Number of AGs in the filesystem.

sb_rbmblocks
Number of real-time bitmap blocks.

sb_logblocks
Number of blocks for the journaling log.

sb_versionnum
Filesystem version number. This is a bitmask specifying the features enabled when creating the filesystem. Any disk checking tools or drivers that do not recognize any set bits must not operate upon the filesystem. Most of the flags indicate features introduced over time. If the value of the lower nibble is >= 4, the higher bits indicate feature flags as follows:

Table 13.1: Version 4 Superblock version flags

Flag	Description
XFS_SB_VERSION_ATTRBIT	Set if any inode have extended attributes. If this bit is set; the XFS_SB_VERSION2_ATTR2BIT is not set; and the attr2 mount flag is not specified, the di_forkoff inode field will not be dynamically adjusted. See the section about extended attribute versions Section 16.4.1 for more information.
XFS_SB_VERSION_NLINKBIT	Set if any inodes use 32-bit di_nlink values.
XFS_SB_VERSION_QUOTABIT	Quotas are enabled on the filesystem. This also brings in the various quota fields in the superblock.
XFS_SB_VERSION_ALIGNBIT	Set if sb_inoalignmt is used.
XFS_SB_VERSION_DALIGNBIT	Set if sb_unit and sb_width are used.
XFS_SB_VERSION_SHAREDBIT	Set if sb_shared_vn is used.
XFS_SB_VERSION_LOGV2BIT	Version 2 journaling logs are used.
XFS_SB_VERSION_SECTORBIT	Set if sb_sectsize is not 512.
XFS_SB_VERSION_EXTFLGBIT	Unwritten extents are used. This is always set.
XFS_SB_VERSION_DIRV2BIT	Version 2 directories are used. This is always set.
XFS_SB_VERSION_MOREBITSBIT	Set if the sb_features2 field in the superblock contains more flags.

If the lower nibble of this value is 5, then this is a v5 filesystem; the XFS_SB_VERSION2_CRCBIT feature must be set in sb_features2.

sb_sectsize
Specifies the underlying disk sector size in bytes. Typically this is 512 or 4096 bytes. This determines the minimum I/O alignment, especially for direct I/O.

sb_inodesize
Size of the inode in bytes. The default is 256 (2 inodes per standard sector) but can be made as large as 2048 bytes when creating the filesystem. On a v5 filesystem, the default and minimum inode size are both 512 bytes.

sb_inopblock
Number of inodes per block. This is equivalent to sb_blocksize /sb_inodesize.

sb_fname[12]
Name for the filesystem. This value can be used in the mount command.

sb_blocklog
$\log_2$ value of sb_blocksize. In other terms, $\texttt{sb\_blocksize} = 2^{\texttt{sb\_blocklog}}$.

sb_sectlog
$\log_2$ value of sb_sectsize.

sb_inodelog
$\log_2$ value of sb_inodesize.

sb_inopblog
$\log_2$ value of sb_inopblock.

sb_agblklog
$\log_2$ value of sb_agblocks (rounded up). This value is used to generate inode numbers and absolute block numbers defined in extent maps.

sb_rextslog
$\log_2$ value of sb_rextents.

sb_inprogress
Flag specifying that the filesystem is being created.

sb_imax_pct
Maximum percentage of filesystem space that can be used for inodes. The default value is 5%.

sb_icount
Global count for number inodes allocated on the filesystem. This is only maintained in the first superblock.

sb_ifree
Global count of free inodes on the filesystem. This is only maintained in the first superblock.

sb_fdblocks
Global count of free data blocks on the filesystem. This is only maintained in the first superblock.

sb_frextents
Global count of free real-time extents on the filesystem. This is only maintained in the first superblock.

sb_uquotino
Inode for user quotas. This and the following two quota fields only apply if `XFS_SB_VERSION_QUOTABIT` flag is set in `sb_versionnum`. Refer to quota inodes Section 15.1 for more information

sb_gquotino
Inode for group or project quotas. Group and Project quotas cannot be used at the same time.

sb_qflags
Quota flags. It can be a combination of the following flags:

Table 13.2: Superblock quota flags

Flag	Description
XFS_UQUOTA_ACCT	User quota accounting is enabled.
XFS_UQUOTA_ENFD	User quotas are enforced.
XFS_UQUOTA_CHKD	User quotas have been checked.
XFS_PQUOTA_ACCT	Project quota accounting is enabled.
XFS_OQUOTA_ENFD	Other (group/project) quotas are enforced.
XFS_OQUOTA_CHKD	Other (group/project) quotas have been checked.
XFS_GQUOTA_ACCT	Group quota accounting is enabled.
XFS_GQUOTA_ENFD	Group quotas are enforced.
XFS_GQUOTA_CHKD	Group quotas have been checked.
XFS_PQUOTA_ENFD	Project quotas are enforced.
XFS_PQUOTA_CHKD	Project quotas have been checked.

sb_flags
Miscellaneous flags.

Table 13.3: Superblock flags

Flag	Description
XFS_SBF_READONLY	Only read-only mounts allowed.

sb_shared_vn
Reserved and must be zero ("vn" stands for version number).

sb_inoalignmt
Inode chunk alignment in fsblocks. Prior to v5, the default value provided for inode chunks to have an 8KiB alignment. Starting with v5, the default value scales with the multiple of the inode size over 256 bytes. Concretely, this means an alignment of 16KiB for 512-byte inodes, 32KiB for 1024-byte inodes, etc. If sparse inodes are enabled, the `ir_startino` field of each inode B+tree record must be aligned to this block granularity, even if the inode given by `ir_startino` itself is sparse.

sb_unit
Underlying stripe or raid unit in blocks.

sb_width
Underlying stripe or raid width in blocks.

sb_dirblklog
$\log_2$ multiplier that determines the granularity of directory block allocations in fsblocks.

sb_logsectlog
$\log_2$ value of the log subvolume's sector size. This is only used if the journaling log is on a separate disk device (i.e. not internal).

sb_logsectsize
The log's sector size in bytes if the filesystem uses an external log device.

sb_logsunit
The log device's stripe or raid unit size. This only applies to version 2 logs `XFS_SB_VERSION_LOGV2BIT` is set in `sb_versionnum`.

sb_features2
Additional version flags if `XFS_SB_VERSION_MOREBITSBIT` is set in `sb_versionnum`. The currently defined additional features include:

Table 13.4: Extended Version 4 Superblock flags

Flag	Description
`XFS_SB_VERSION2_LAZYSBCOUNTBIT`	Lazy global counters. Making a filesystem with this bit set can improve performance. The global free space and inode counts are only updated in the primary superblock when the filesystem is cleanly unmounted.
`XFS_SB_VERSION2_ATTR2BIT`	Extended attributes version 2. Making a filesystem with this optimises the inode layout of extended attributes. If this bit is set and the `noattr2` mount flag is not specified, the `di_forkoff` inode field will be dynamically adjusted. See the section about extended attribute versions Section 16.4.1 for more information.
`XFS_SB_VERSION2_PARENTBIT`	Parent pointers. All inodes must have an extended attribute that points back to its parent inode. The primary purpose for this information is in backup systems.
`XFS_SB_VERSION2_PROJID32BIT`	32-bit Project ID. Inodes can be associated with a project ID number, which can be used to enforce disk space usage quotas for a particular group of directories. This flag indicates that project IDs can be 32 bits in size.
`XFS_SB_VERSION2_CRCBIT`	Metadata checksumming. All metadata blocks have an extended header containing the block checksum, a copy of the metadata UUID, the log sequence number of the last update to prevent stale replays, and a back pointer to the owner of the block. This feature must be and can only be set if the lowest nibble of `sb_versionnum` is set to 5.

Table 13.4: (continued)

Flag	Description
XFS_SB_VERSION2_FTYPE	Directory file type. Each directory entry records the type of the inode to which the entry points. This speeds up directory iteration by removing the need to load every inode into memory.

sb_bad_features2
This field mirrors sb_features2, due to past 64-bit alignment errors.

sb_features_compat
Read-write compatible feature flags. The kernel can still read and write this FS even if it doesn't understand the flag. Currently, there are no valid flags.

sb_features_ro_compat
Read-only compatible feature flags. The kernel can still read this FS even if it doesn't understand the flag.

Table 13.5: Extended Version 5 Superblock Read-Only compatibility flags

Flag	Description
XFS_SB_FEAT_RO_COMPAT_FINOBT	Free inode B+tree. Each allocation group contains a B+tree to track inode chunks containing free inodes. This is a performance optimization to reduce the time required to allocate inodes.
XFS_SB_FEAT_RO_COMPAT_RMAPBT	Reverse mapping B+tree. Each allocation group contains a B+tree containing records mapping AG blocks to their owners. See the section about reconstruction Chapter 5 for more details.
XFS_SB_FEAT_RO_COMPAT_REFLINK	Reference count B+tree. Each allocation group contains a B+tree to track the reference counts of AG blocks. This enables files to share data blocks safely. See the section about reflink and deduplication Chapter 4 for more details.
XFS_SB_FEAT_RO_COMPAT_INOBTCNT	Inode B+tree block counters. Each allocation group's inode (AGI) header tracks the number of blocks in each of the inode B+trees. This allows us to have a slightly higher level of redundancy over the shape of the inode btrees, and decreases the amount of time to compute the metadata B+tree preallocations at mount time.

sb_features_incompat
Read-write incompatible feature flags. The kernel cannot read or write this FS if it doesn't understand the flag.

Table 13.6: Extended Version 5 Superblock Read-Write incompatibility flags

Flag	Description
XFS_SB_FEAT_INCOMPAT_FTYPE	Directory file type. Each directory entry tracks the type of the inode to which the entry points. This is a performance optimization to remove the need to load every inode into memory to iterate a directory.
XFS_SB_FEAT_INCOMPAT_SPINODES	Sparse inodes. This feature relaxes the requirement to allocate inodes in chunks of 64. When the free space is heavily fragmented, there might exist plenty of free space but not enough contiguous free space to allocate a new inode chunk. With this feature, the user can continue to create files until all free space is exhausted. Unused space in the inode B+tree records are used to track which parts of the inode chunk are not inodes. See the chapter on Sparse Inodes Section 13.5 for more information.
XFS_SB_FEAT_INCOMPAT_META_UUID	Metadata UUID. The UUID stamped into each metadata block must match the value in sb_meta_uuid. This enables the administrator to change sb_uuid at will without having to rewrite the entire filesystem.
XFS_SB_FEAT_INCOMPAT_BIGTIME	Large timestamps. Inode timestamps and quota expiration timers are extended to support times through the year 2486. See the section on timestamps Chapter 12 for more information.
XFS_SB_FEAT_INCOMPAT_NEEDSREPAIR	The filesystem is not in operable condition, and must be run through xfs_repair before it can be mounted.

sb_features_log_incompat
Read-write incompatible feature flags for the log. The kernel cannot read or write this FS log if it doesn't understand the flag. Currently, no flags are defined.

sb_crc
Superblock checksum.

sb_spino_align
Sparse inode alignment, in fsblocks. Each chunk of inodes referenced by a sparse inode B+tree record must be aligned to this block granularity.

sb_pquotino
Project quota inode.

sb_lsn
Log sequence number of the last superblock update.

sb_meta_uuid
If the XFS_SB_FEAT_INCOMPAT_META_UUID feature is set, then the UUID field in all metadata blocks must match this UUID. If not, the block header UUID field must match sb_uuid.

sb_rrmapino
If the XFS_SB_FEAT_RO_COMPAT_RMAPBT feature is set and a real-time device is present (sb_rblocks > 0), this field points to an inode that contains the root to the Real-Time Reverse Mapping B+tree Section 15.2.3. This field is zero otherwise.

13.1.1 xfs_db Superblock Example

A filesystem is made on a single disk with the following command:

```
# mkfs.xfs -i attr=2 -n size=16384 -f /dev/sda7
meta-data=/dev/sda7              isize=256    agcount=16, agsize=3923122 blks
         =                       sectsz=512   attr=2
data     =                       bsize=4096   blocks=62769952, imaxpct=25
         =                       sunit=0      swidth=0 blks, unwritten=1
naming   =version 2              bsize=16384
log      =internal log           bsize=4096   blocks=30649, version=1
         =                       sectsz=512   sunit=0 blks
realtime =none                   extsz=65536  blocks=0, rtextents=0
```

And in xfs_db, inspecting the superblock:

```
xfs_db> sb
xfs_db> p
magicnum = 0x58465342
blocksize = 4096
dblocks = 62769952
rblocks = 0
rextents = 0
uuid = 32b24036-6931-45b4-b68c-cd5e7d9a1ca5
logstart = 33554436
rootino = 128
rbmino = 129
rsumino = 130
rextsize = 16
agblocks = 3923122
agcount = 16
rbmblocks = 0
logblocks = 30649
versionnum = 0xb084
sectsize = 512
inodesize = 256
inopblock = 16
fname = "\000\000\000\000\000\000\000\000\000\000\000\000"
blocklog = 12
sectlog = 9
inodelog = 8
inopblog = 4
agblklog = 22
rextslog = 0
inprogress = 0
imax_pct = 25
icount = 64
ifree = 61
fdblocks = 62739235
frextents = 0
uquotino = 0
gquotino = 0
qflags = 0
flags = 0
shared_vn = 0
inoalignmt = 2
unit = 0
width = 0
dirblklog = 2
logsectlog = 0
logsectsize = 0
logsunit = 0
```

```
features2 = 8
```

13.2 AG Free Space Management

The XFS filesystem tracks free space in an allocation group using two B+trees. One B+tree tracks space by block number, the second by the size of the free space block. This scheme allows XFS to find quickly free space near a given block or of a given size.

All block numbers, indexes, and counts are AG relative.

13.2.1 AG Free Space Block

The second sector in an AG contains the information about the two free space B+trees and associated free space information for the AG. The "AG Free Space Block" also knows as the `AGF`, uses the following structure:

```
struct xfs_agf {
     __be32              agf_magicnum;
     __be32              agf_versionnum;
     __be32              agf_seqno;
     __be32              agf_length;
     __be32              agf_roots[XFS_BTNUM_AGF];
     __be32              agf_levels[XFS_BTNUM_AGF];
     __be32              agf_flfirst;
     __be32              agf_fllast;
     __be32              agf_flcount;
     __be32              agf_freeblks;
     __be32              agf_longest;
     __be32              agf_btreeblks;

     /* version 5 filesystem fields start here */
     uuid_t              agf_uuid;
     __be32              agf_rmap_blocks;
     __be32              agf_refcount_blocks;
     __be32              agf_refcount_root;
     __be32              agf_refcount_level;
     __be64              agf_spare64[14];

     /* unlogged fields, written during buffer writeback. */
     __be64              agf_lsn;
     __be32              agf_crc;
     __be32              agf_spare2;
};
```

The rest of the bytes in the sector are zeroed. `XFS_BTNUM_AGF` is set to 3: index 0 for the free space B+tree indexed by block number; index 1 for the free space B+tree indexed by extent size; and index 2 for the reverse-mapping B+tree.

agf_magicnum
: Specifies the magic number for the AGF sector: "XAGF" (0x58414746).

agf_versionnum
: Set to `XFS_AGF_VERSION` which is currently 1.

agf_seqno
: Specifies the AG number for the sector.

agf_length
: Specifies the size of the AG in filesystem blocks. For all AGs except the last, this must be equal to the superblock's `sb_agblocks` value. For the last AG, this could be less than the `sb_agblocks` value. It is this value that should be used to determine the size of the AG.

agf_roots
Specifies the block number for the root of the two free space B+trees and the reverse-mapping B+tree, if enabled.

agf_levels
Specifies the level or depth of the two free space B+trees and the reverse-mapping B+tree, if enabled. For a fresh AG, this value will be one, and the "roots" will point to a single leaf of level 0.

agf_flfirst
Specifies the index of the first "free list" block. Free lists are covered in more detail later on.

agf_fllast
Specifies the index of the last "free list" block.

agf_flcount
Specifies the number of blocks in the "free list".

agf_freeblks
Specifies the current number of free blocks in the AG.

agf_longest
Specifies the number of blocks of longest contiguous free space in the AG.

agf_btreeblks
Specifies the number of blocks used for the free space B+trees. This is only used if the `XFS_SB_VERSION2_LAZYSBCOUNTBIT` bit is set in `sb_features2`.

agf_uuid
The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

agf_rmap_blocks
The size of the reverse mapping B+tree in this allocation group, in blocks.

agf_refcount_blocks
The size of the reference count B+tree in this allocation group, in blocks.

agf_refcount_root
Block number for the root of the reference count B+tree, if enabled.

agf_refcount_level
Depth of the reference count B+tree, if enabled.

agf_spare64
Empty space in the logged part of the AGF sector, for use for future features.

agf_lsn
Log sequence number of the last AGF write.

agf_crc
Checksum of the AGF sector.

agf_spare2
Empty space in the unlogged part of the AGF sector.

13.2.2 AG Free Space B+trees

The two Free Space B+trees store a sorted array of block offset and block counts in the leaves of the B+tree. The first B+tree is sorted by the offset, the second by the count or size.

Leaf nodes contain a sorted array of offset/count pairs which are also used for node keys:

```
struct xfs_alloc_rec {
     __be32                  ar_startblock;
     __be32                  ar_blockcount;
};
```

ar_startblock
AG block number of the start of the free space.

ar_blockcount
Length of the free space.

Node pointers are an AG relative block pointer:

```
typedef __be32 xfs_alloc_ptr_t;
```

- As the free space tracking is AG relative, all the block numbers are only 32-bits.
- The `bb_magic` value depends on the B+tree: "ABTB" (0x41425442) for the block offset B+tree, "ABTC" (0x41425443) for the block count B+tree. On a v5 filesystem, these are "AB3B" (0x41423342) and "AB3C" (0x41423343), respectively.
- The `xfs_btree_sblock_t` header is used for intermediate B+tree node as well as the leaves.
- For a typical 4KB filesystem block size, the offset for the `xfs_alloc_ptr_t` array would be `0xab0` (2736 decimal).
- There are a series of macros in `xfs_btree.h` for deriving the offsets, counts, maximums, etc for the B+trees used in XFS.

The following diagram shows a single level B+tree which consists of one leaf:

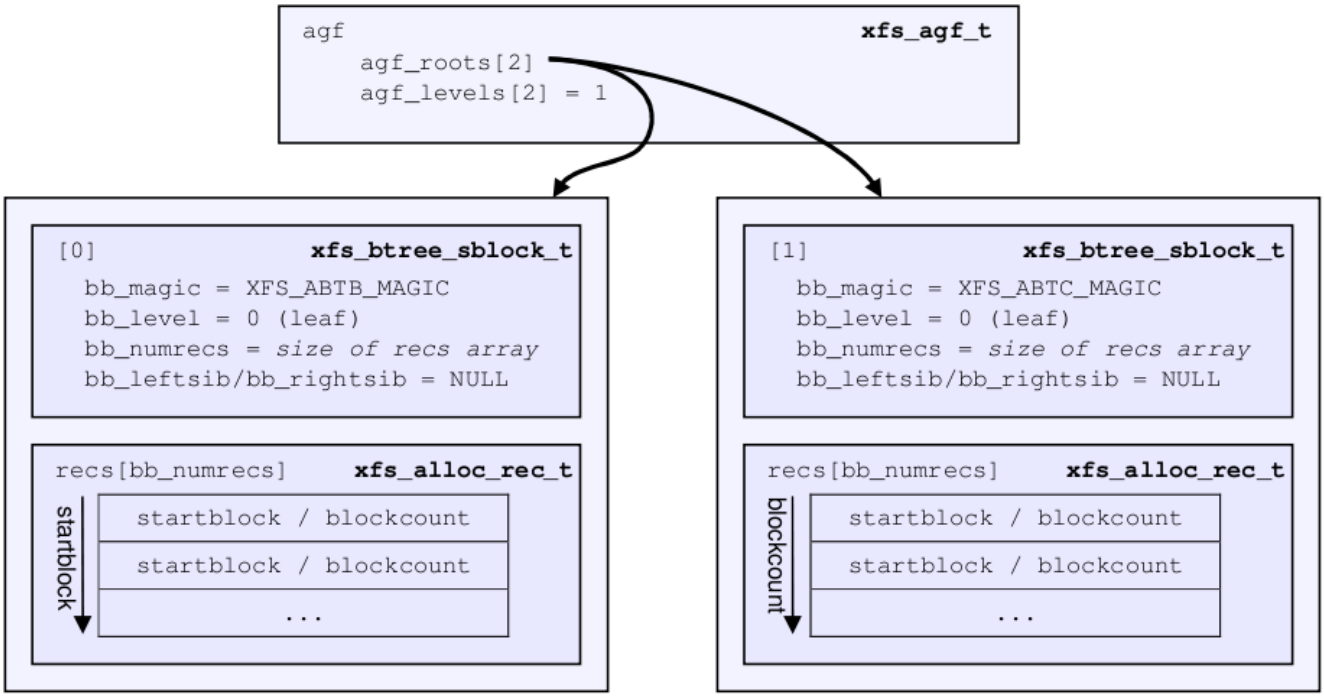


Figure 13.2: Freespace B+tree with one leaf.

With the intermediate nodes, the associated leaf pointers are stored in a separate array about two thirds into the block. The following diagram illustrates a 2-level B+tree for a free space B+tree:

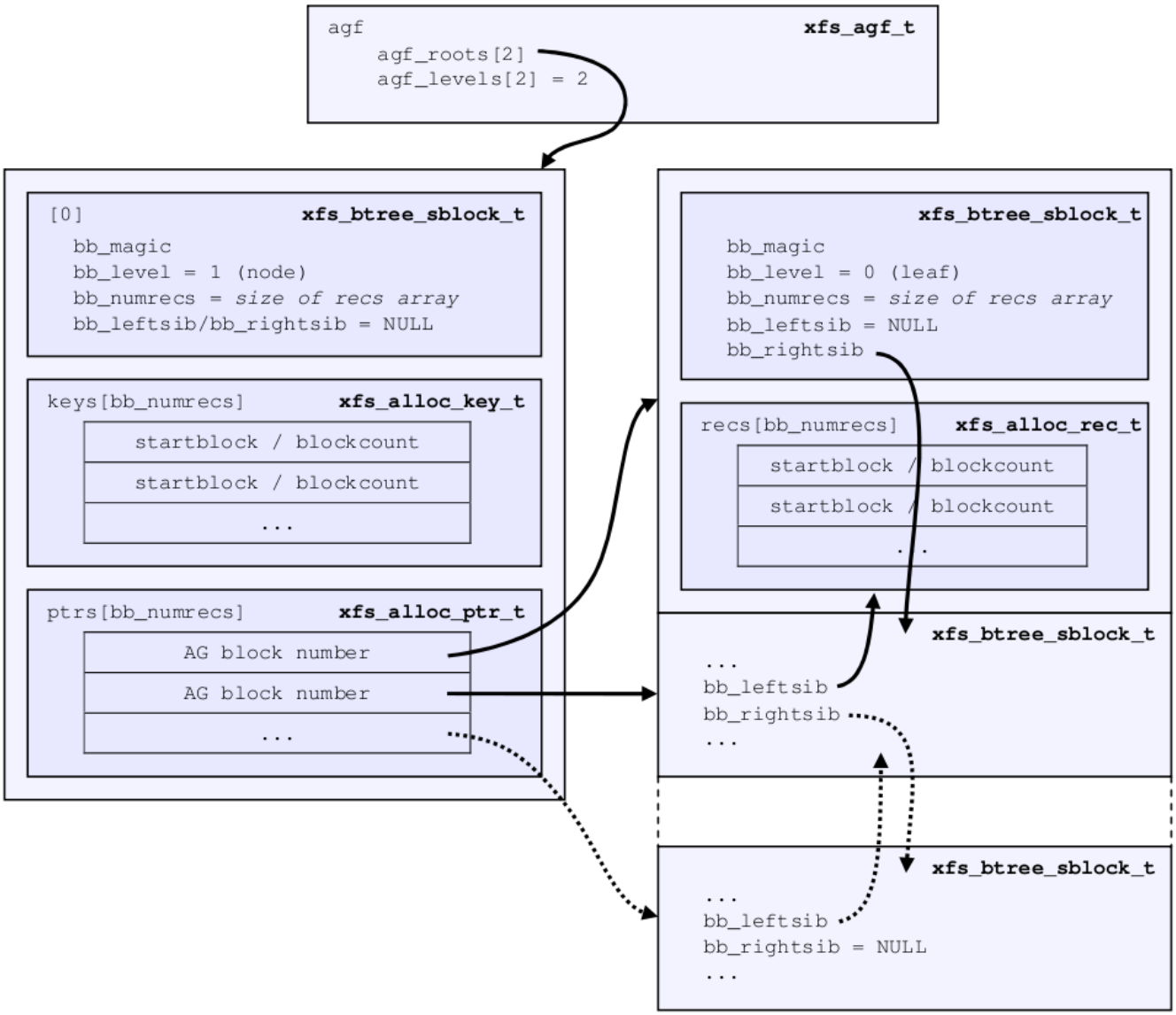


Figure 13.3: Multi-level freespace B+tree.

13.2.3 AG Free List

The AG Free List is located in the 4th sector of each AG and is known as the AGFL. It is an array of AG relative block pointers for reserved space for growing the free space B+trees. This space cannot be used for general user data including inodes, data, directories and extended attributes.

With a freshly made filesystem, 4 blocks are reserved immediately after the free space B+tree root blocks (blocks 4 to 7). As they are used up as the free space fragments, additional blocks will be reserved from the AG and added to the free list array. This size may increase as features are added.

As the free list array is located within a single sector, a typical device will have space for 128 elements in the array (512 bytes per sector, 4 bytes per AG relative block pointer). The actual size can be determined by using the `XFS_AGFL_SIZE` macro.

Active elements in the array are specified by the AGF's Section 13.2.1 `agf_flfirst`, `agf_fllast` and `agf_flcount` values. The array is managed as a circular list.

On a v5 filesystem, the following header precedes the free list entries:

```
struct xfs_agfl {
     __be32              agfl_magicnum;
     __be32              agfl_seqno;
     uuid_t              agfl_uuid;
     __be64              agfl_lsn;
     __be32              agfl_crc;
};
```

agfl_magicnum
Specifies the magic number for the AGFL sector: "XAFL" (0x5841464c).

agfl_seqno
Specifies the AG number for the sector.

agfl_uuid
The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

agfl_lsn
Log sequence number of the last AGFL write.

agfl_crc
Checksum of the AGFL sector.

On a v4 filesystem there is no header; the array of free block numbers begins at the beginning of the sector.

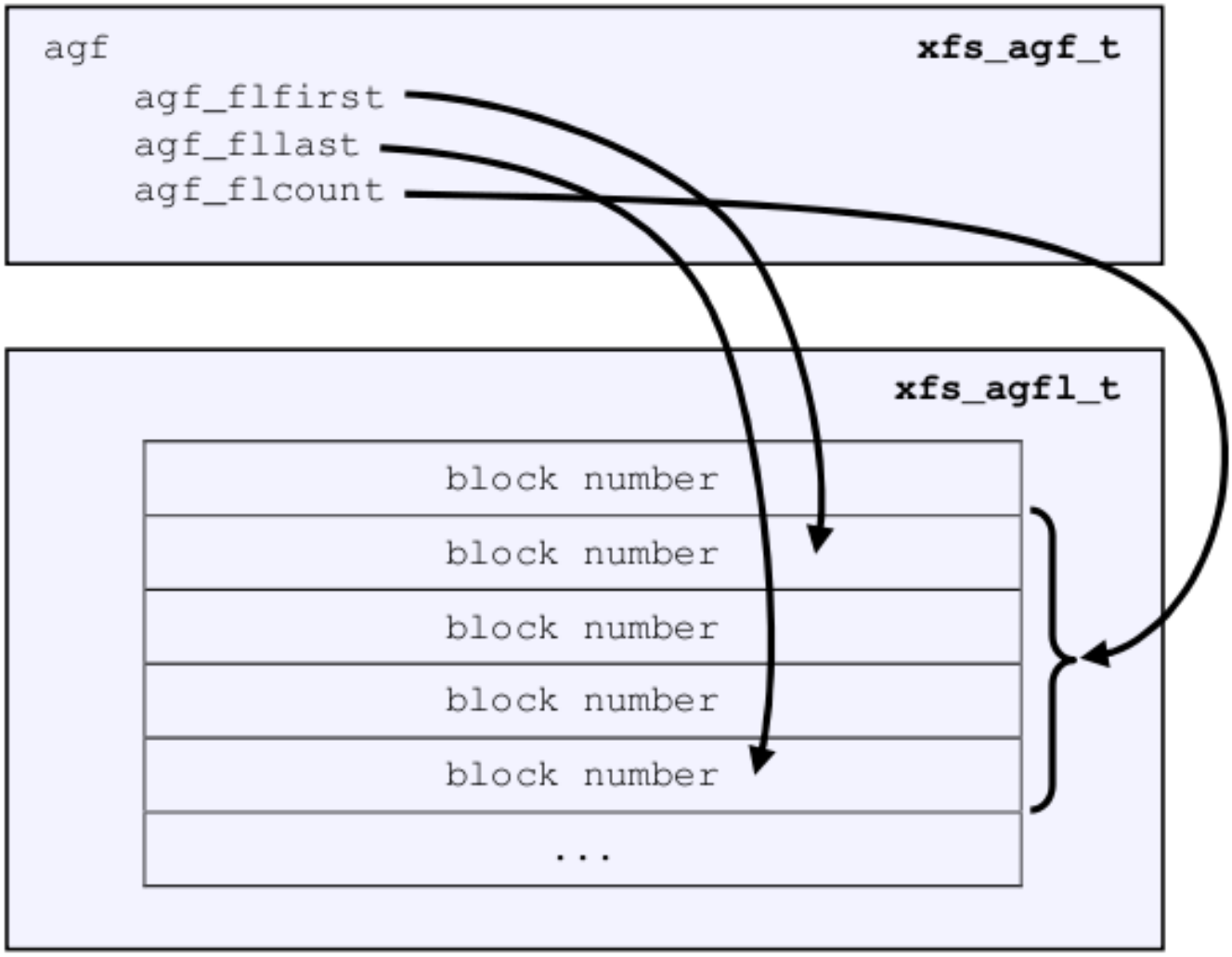


Figure 13.4: AG Free List layout

The presence of these reserved blocks guarantees that the free space B+trees can be updated if any blocks are freed by extent changes in a full AG.

13.2.3.1 xfs_db AGF Example

These examples are derived from an AG that has been deliberately fragmented. The AGF:

```
xfs_db> agf 0
xfs_db> p
magicnum = 0x58414746
versionnum = 1
seqno = 0
length = 3923122
bnoroot = 7
cntroot = 83343
bnolevel = 2
cntlevel = 2
flfirst = 22
fllast = 27
flcount = 6
```

```
freeblks = 3654234
longest = 3384327
btreeblks = 0
```

In the AGFL, the active elements are from 22 to 27 inclusive which are obtained from the `flfirst` and `fllast` values from the `agf` in the previous example:

```
xfs_db> agfl 0
xfs_db> p
bno[0-127] = 0:4 1:5 2:6 3:7 4:83342 5:83343 6:83344 7:83345 8:83346 9:83347
             10:4 11:5 12:80205 13:80780 14:81496 15:81766 16:83346 17:4 18:5
             19:80205 20:82449 21:81496 22:81766 23:82455 24:80780 25:5
             26:80205 27:83344
```

The root block of the free space B+tree sorted by block offset is found in the AGF's `bnoroot` value:

```
xfs_db> fsblock 7
xfs_db> type bnobt
xfs_db> p
magic = 0x41425442
level = 1
numrecs = 4
leftsib = null
rightsib = null
keys[1-4] = [startblock,blockcount]
           1:[12,16] 2:[184586,3] 3:[225579,1] 4:[511629,1]
ptrs[1-4] = 1:2 2:83347 3:6 4:4
```

Blocks 2, 83347, 6 and 4 contain the leaves for the free space B+tree by starting block. Block 2 would contain offsets 12 up to but not including 184586 while block 4 would have all offsets from 511629 to the end of the AG.

The root block of the free space B+tree sorted by block count is found in the AGF's `cntroot` value:

```
xfs_db> fsblock 83343
xfs_db> type cntbt
xfs_db> p
magic = 0x41425443
level = 1
numrecs = 4
leftsib = null
rightsib = null
keys[1-4] = [blockcount,startblock]
           1:[1,81496] 2:[1,511729] 3:[3,191875] 4:[6,184595]
ptrs[1-4] = 1:3 2:83345 3:83342 4:83346
```

The leaf in block 3, in this example, would only contain single block counts. The offsets are sorted in ascending order if the block count is the same.

Inspecting the leaf in block 83346, we can see the largest block at the end:

```
xfs_db> fsblock 83346
xfs_db> type cntbt
xfs_db> p
magic = 0x41425443
level = 0
numrecs = 344
leftsib = 83342
rightsib = null
recs[1-344] = [startblock,blockcount]
           1:[184595,6] 2:[187573,6] 3:[187776,6]
           ...
           342:[513712,755] 343:[230317,258229] 344:[538795,3384327]
```

The longest block count (3384327) must be the same as the AGF's `longest` value.

13.3 AG Inode Management

13.3.1 Inode Numbers

Inode numbers in XFS come in two forms: AG relative and absolute.

AG relative inode numbers always fit within 32 bits. The number of bits actually used is determined by the sum of the superblock's Section 13.1 `sb_inoplog` and `sb_agblklog` values. Relative inode numbers are found within the AG's inode structures.

Absolute inode numbers include the AG number in the high bits, above the bits used for the AG relative inode number. Absolute inode numbers are found in directory Chapter 18 entries and the superblock.

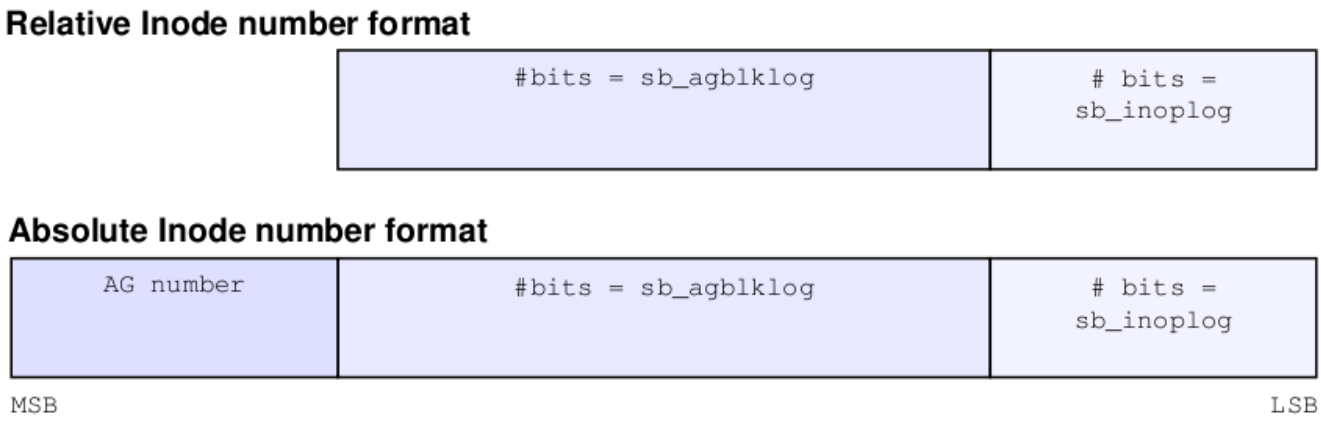


Figure 13.5: Inode number formats

13.3.2 Inode Information

Each AG manages its own inodes. The third sector in the AG contains information about the AG's inodes and is known as the AGI.

The AGI uses the following structure:

```
struct xfs_agi {
     __be32              agi_magicnum;
     __be32              agi_versionnum;
     __be32              agi_seqno
     __be32              agi_length;
     __be32              agi_count;
     __be32              agi_root;
     __be32              agi_level;
     __be32              agi_freecount;
     __be32              agi_newino;
     __be32              agi_dirino;
     __be32              agi_unlinked[64];

     /*
      * v5 filesystem fields start here; this marks the end of logging region 1
      * and start of logging region 2.
      */
     uuid_t              agi_uuid;
     __be32              agi_crc;
     __be32              agi_pad32;
     __be64              agi_lsn;
```

```
        __be32              agi_free_root;
        __be32              agi_free_level;

        __be32              agi_iblocks;
        __be32              agi_fblocks;

}
```

agi_magicnum
Specifies the magic number for the AGI sector: "XAGI" (0x58414749).

agi_versionnum
Set to `XFS_AGI_VERSION` which is currently 1.

agi_seqno
Specifies the AG number for the sector.

agi_length
Specifies the size of the AG in filesystem blocks.

agi_count
Specifies the number of inodes allocated for the AG.

agi_root
Specifies the block number in the AG containing the root of the inode B+tree.

agi_level
Specifies the number of levels in the inode B+tree.

agi_freecount
Specifies the number of free inodes in the AG.

agi_newino
Specifies AG-relative inode number of the most recently allocated chunk.

agi_dirino
Deprecated and not used, this is always set to NULL (-1).

agi_unlinked[64]
Hash table of unlinked (deleted) inodes that are still being referenced. Refer to unlinked list pointers Section 16.2 for more information.

agi_uuid
The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

agi_crc
Checksum of the AGI sector.

agi_pad32
Padding field, otherwise unused.

agi_lsn
Log sequence number of the last write to this block.

agi_free_root
Specifies the block number in the AG containing the root of the free inode B+tree.

agi_free_level
Specifies the number of levels in the free inode B+tree.

agi_iblocks
The number of blocks in the inode B+tree, including the root. This field is zero if the XFS_SB_FEAT_RO_COMPAT_INOBTCNT feature is not enabled.

agi_fblocks
The number of blocks in the free inode B+tree, including the root. This field is zero if the XFS_SB_FEAT_RO_COMPAT_INOBTCNT feature is not enabled.

13.4 Inode B+trees

Inodes are traditionally allocated in chunks of 64, and a B+tree is used to track these chunks of inodes as they are allocated and freed. The block containing root of the B+tree is defined by the AGI's agi_root value. If the XFS_SB_FEAT_RO_COMPAT_FINOBT feature is enabled, a second B+tree is used to track the chunks containing free inodes; this is an optimization to speed up inode allocation.

The B+tree header for the nodes and leaves use the xfs_btree_sblock structure which is the same as the header used in the AGF B+trees Section 13.2.2.

The magic number of the inode B+tree is "IABT" (0x49414254). On a v5 filesystem, the magic number is "IAB3" (0x49414233).

The magic number of the free inode B+tree is "FIBT" (0x46494254). On a v5 filesystem, the magic number is "FIB3" (0x46494254).

Leaves contain an array of the following structure:

```
struct xfs_inobt_rec {
     __be32                    ir_startino;
     __be32                    ir_freecount;
     __be64                    ir_free;
};
```

ir_startino
The lowest-numbered inode in this chunk.

ir_freecount
Number of free inodes in this chunk.

ir_free
A 64 element bitmap showing which inodes in this chunk are free.

Nodes contain key/pointer pairs using the following types:

```
struct xfs_inobt_key {
     __be32                     ir_startino;
};
typedef __be32 xfs_inobt_ptr_t;
```

The following diagram illustrates a single level inode B+tree:

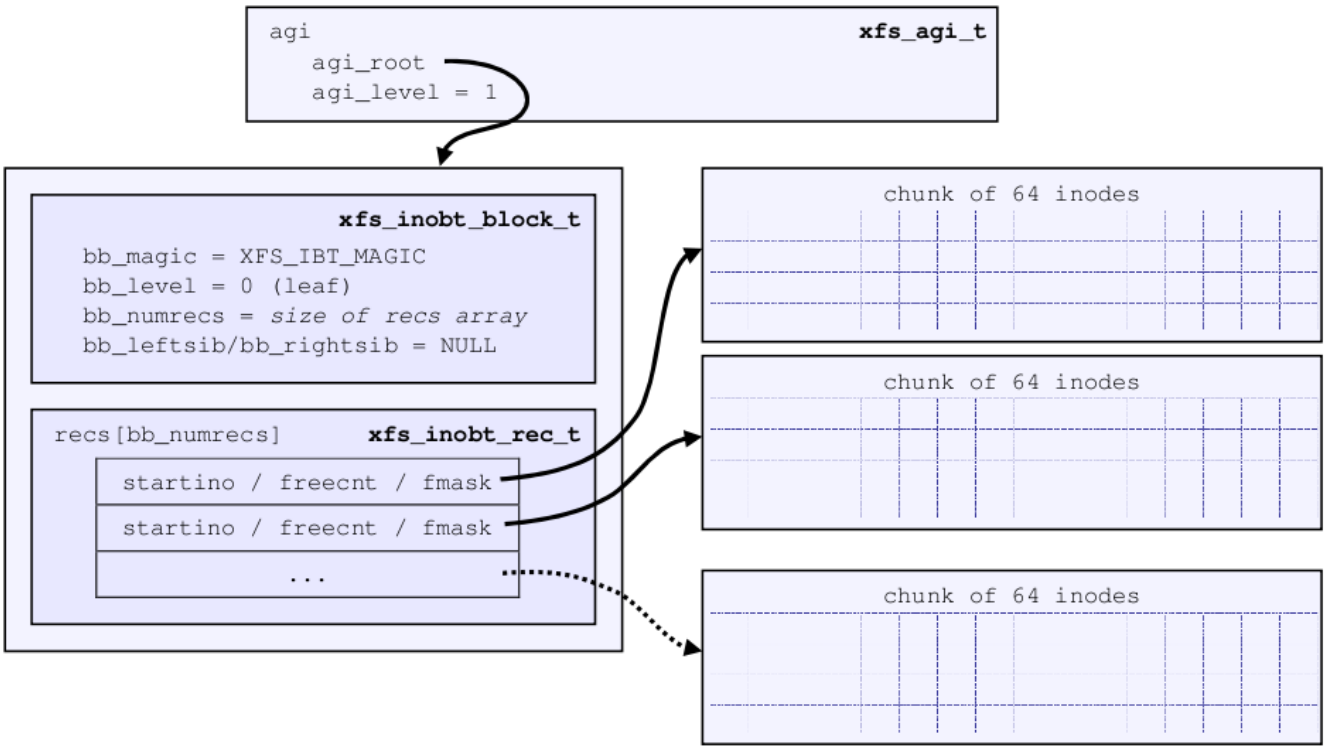


Figure 13.6: Single Level inode B+tree

And a 2-level inode B+tree:

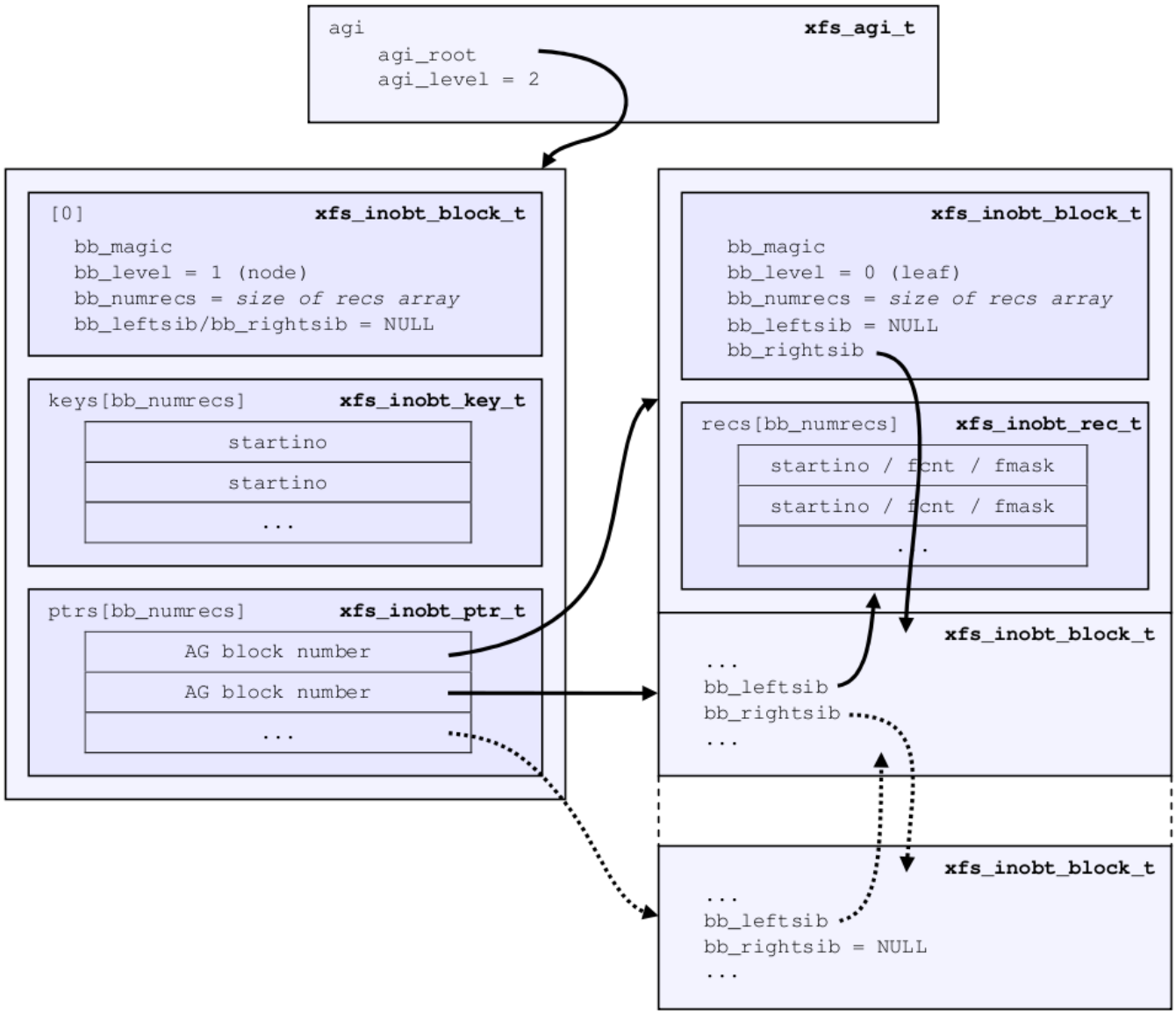


Figure 13.7: Multi-Level inode B+tree

13.4.1 xfs_db AGI Example

This is an AGI of a freshly populated filesystem:

```
xfs_db> agi 0
xfs_db> p
magicnum = 0x58414749
versionnum = 1
seqno = 0
length = 825457
count = 5440
root = 3
level = 1
freecount = 9
newino = 5792
dirino = null
unlinked[0-63] =
```

```
uuid = 3dfa1e5c-5a5f-4ca2-829a-000e453600fe
lsn = 0x1000032c2
crc = 0x14cb7e5c (correct)
free_root = 4
free_level = 1
```

From this example, we see that the inode B+tree is rooted at AG block 3 and that the free inode B+tree is rooted at AG block 4. Let's look at the inode B+tree:

```
xfs_db> addr root
xfs_db> p
magic = 0x49414233
level = 0
numrecs = 85
leftsib = null
rightsib = null
bno = 24
lsn = 0x1000032c2
uuid = 3dfa1e5c-5a5f-4ca2-829a-000e453600fe
owner = 0
crc = 0x768f9592 (correct)
recs[1-85] = [startino,freecount,free]
        1:[96,0,0] 2:[160,0,0] 3:[224,0,0] 4:[288,0,0]
        5:[352,0,0] 6:[416,0,0] 7:[480,0,0] 8:[544,0,0]
        9:[608,0,0] 10:[672,0,0] 11:[736,0,0] 12:[800,0,0]
        ...
        85:[5792,9,0xff80000000000000]
```

Most of the inode chunks on this filesystem are totally full, since the `free` value is zero. This means that we ought to expect inode 160 to be linked somewhere in the directory structure. However, notice that 0xff80000000000000 in record 85 — this means that we would expect inode 5847 to be free. Moving on to the free inode B+tree, we see that this is indeed the case:

```
xfs_db> addr free_root
xfs_db> p
magic = 0x46494233
level = 0
numrecs = 1
leftsib = null
rightsib = null
bno = 32
lsn = 0x1000032c2
uuid = 3dfa1e5c-5a5f-4ca2-829a-000e453600fe
owner = 0
crc = 0x338af88a (correct)
recs[1] = [startino,freecount,free] 1:[5792,9,0xff80000000000000]
```

Observe also that the AGI's `agi_newino` points to this chunk, which has never been fully allocated.

13.5 Sparse Inodes

As mentioned in the previous section, XFS allocates inodes in chunks of 64. If there are no free extents large enough to hold a full chunk of 64 inodes, the inode allocation fails and XFS claims to have run out of space. On a filesystem with highly fragmented free space, this can lead to out of space errors long before the filesystem runs out of free blocks.

The sparse inode feature tracks inode chunks in the inode B+tree as if they were full chunks but uses some previously unused bits in the freecount field to track which parts of the inode chunk are not allocated for use as inodes. This allows XFS to allocate inodes one block at a time if absolutely necessary.

The inode and free inode B+trees operate in the same manner as they do without the sparse inode feature; the B+tree header for the nodes and leaves use the `xfs_btree_sblock` structure which is the same as the header used in the AGF B+trees Section 13.2.2.

It is theoretically possible for a sparse inode B+tree record to reference multiple non-contiguous inode chunks.

Leaves contain an array of the following structure:

```
struct xfs_inobt_rec {
     __be32                  ir_startino;
     __be16                  ir_holemask;
     __u8                    ir_count;
     __u8                    ir_freecount;
     __be64                  ir_free;
};
```

ir_startino
The lowest-numbered inode in this chunk, rounded down to the nearest multiple of 64, even if the start of this chunk is sparse.

ir_holemask
A 16 element bitmap showing which parts of the chunk are not allocated to inodes. Each bit represents four inodes; if a bit is marked here, the corresponding bits in ir_free must also be marked.

ir_count
Number of inodes allocated to this chunk.

ir_freecount
Number of free inodes in this chunk.

ir_free
A 64 element bitmap showing which inodes in this chunk are not available for allocation.

13.5.1 xfs_db Sparse Inode AGI Example

This example derives from an AG that has been deliberately fragmented. The inode B+tree:

```
xfs_db> agi 0
xfs_db> p
magicnum = 0x58414749
versionnum = 1
seqno = 0
length = 6400
count = 10432
root = 2381
level = 2
freecount = 0
newino = 14912
dirino = null
unlinked[0-63] =
uuid = b9b4623b-f678-4d48-8ce7-ce08950e3cd6
lsn = 0x600000ac4
crc = 0xef550dbc (correct)
free_root = 4
free_level = 1
```

This AGI was formatted on a v5 filesystem; notice the extra v5 fields. So far everything else looks much the same as always.

```
xfs_db> addr root
magic = 0x49414233
level = 1
numrecs = 2
leftsib = null
rightsib = null
bno = 19048
```

```
lsn = 0x50000192b
uuid = b9b4623b-f678-4d48-8ce7-ce08950e3cd6
owner = 0
crc = 0xd98cd2ca (correct)
keys[1-2] = [startino] 1:[128] 2:[35136]
ptrs[1-2] = 1:3 2:2380
xfs_db> addr ptrs[1]
xfs_db> p
magic = 0x49414233
level = 0
numrecs = 159
leftsib = null
rightsib = 2380
bno = 24
lsn = 0x600000ac4
uuid = b9b4623b-f678-4d48-8ce7-ce08950e3cd6
owner = 0
crc = 0x836768a6 (correct)
recs[1-159] = [startino,holemask,count,freecount,free]
        1:[128,0,64,0,0]
        2:[14912,0xff,32,0,0xffffffff]
        3:[15040,0,64,0,0]
        4:[15168,0xff00,32,0,0xffffffff00000000]
        5:[15296,0,64,0,0]
        6:[15424,0xff,32,0,0xffffffff]
        7:[15552,0,64,0,0]
        8:[15680,0xff00,32,0,0xffffffff00000000]
        9:[15808,0,64,0,0]
        10:[15936,0xff,32,0,0xffffffff]
```

Here we see the difference in the inode B+tree records. For example, in record 2, we see that the holemask has a value of 0xff. This means that the first sixteen inodes in this chunk record do not actually map to inode blocks; the first inode in this chunk is actually inode 14944:

```
xfs_db> inode 14912
Metadata corruption detected at block 0x3a40/0x2000
...
Metadata CRC error detected for ino 14912
xfs_db> p core.magic
core.magic = 0
xfs_db> inode 14944
xfs_db> p core.magic
core.magic = 0x494e
```

The chunk record also indicates that this chunk has 32 inodes, and that the missing inodes are also “free”.

13.6 Real-time Devices

The performance of the standard XFS allocator varies depending on the internal state of the various metadata indices enabled on the filesystem. For applications which need to minimize the jitter of allocation latency, XFS supports the notion of a “real-time device”. This is a special device separate from the regular filesystem where extent allocations are tracked with a bitmap and free space is indexed with a two-dimensional array. If an inode is flagged with `XFS_DIFLAG_REALTIME`, its data will live on the real time device. The metadata for real time devices is discussed in the section about real time inodes Section 15.2.

By placing the real time device (and the journal) on separate high-performance storage devices, it is possible to reduce most of the unpredictability in I/O response times that come from metadata operations.

None of the XFS per-AG B+trees are involved with real time files. It is not possible for real time files to share data blocks.

13.7 Reverse-Mapping B+tree

Note
This data structure is under construction! Details may change.

If the feature is enabled, each allocation group has its own reverse block-mapping B+tree, which grows in the free space like the free space B+trees. As mentioned in the chapter about reconstruction Chapter 5, this data structure is another piece of the puzzle necessary to reconstruct the data or attribute fork of a file from reverse-mapping records; we can also use it to double-check allocations to ensure that we are not accidentally cross-linking blocks, which can cause severe damage to the filesystem.

This B+tree is only present if the `XFS_SB_FEAT_RO_COMPAT_RMAPBT` feature is enabled. The feature requires a version 5 filesystem.

Each record in the reverse-mapping B+tree has the following structure:

```
struct xfs_rmap_rec {
     __be32                     rm_startblock;
     __be32                     rm_blockcount;
     __be64                     rm_owner;
     __be64                     rm_fork:1;
     __be64                     rm_bmbt:1;
     __be64                     rm_unwritten:1;
     __be64                     rm_unused:7;
     __be64                     rm_offset:54;
};
```

rm_startblock
AG block number of this record.

rm_blockcount
The length of this extent.

rm_owner
A 64-bit number describing the owner of this extent. This is typically the absolute inode number, but can also correspond to one of the following:

Table 13.7: Special owner values

Value	Description
`XFS_RMAP_OWN_NULL`	No owner. This should never appear on disk.
`XFS_RMAP_OWN_UNKNOWN`	Unknown owner; for EFI recovery. This should never appear on disk.
`XFS_RMAP_OWN_FS`	Allocation group headers
`XFS_RMAP_OWN_LOG`	XFS log blocks
`XFS_RMAP_OWN_AG`	Per-allocation group B+tree blocks. This means free space B+tree blocks, blocks on the freelist, and reverse-mapping B+tree blocks.
`XFS_RMAP_OWN_INOBT`	Per-allocation group inode B+tree blocks. This includes free inode B+tree blocks.
`XFS_RMAP_OWN_INODES`	Inode chunks
`XFS_RMAP_OWN_REFC`	Per-allocation group refcount B+tree blocks. This will be used for reflink support.
`XFS_RMAP_OWN_COW`	Blocks that have been reserved for a copy-on-write operation that has not completed.

rm_fork
If `rm_owner` describes an inode, this can be 1 if this record is for an attribute fork.

rm_bmbt
If `rm_owner` describes an inode, this can be 1 to signify that this record is for a block map B+tree block. In this case, `rm_offset` has no meaning.

rm_unwritten
A flag indicating that the extent is unwritten. This corresponds to the flag in the extent record Chapter 17 format which means `XFS_EXT_UNWRITTEN`.

rm_offset
The 54-bit logical file block offset, if `rm_owner` describes an inode. Meaningless otherwise.

Note
The single-bit flag values `rm_unwritten`, `rm_fork`, and `rm_bmbt` are packed into the larger fields in the C structure definition.

The key has the following structure:

```
struct xfs_rmap_key {
     __be32                     rm_startblock;
     __be64                     rm_owner;
     __be64                     rm_fork:1;
     __be64                     rm_bmbt:1;
     __be64                     rm_reserved:1;
     __be64                     rm_unused:7;
     __be64                     rm_offset:54;
};
```

For the reverse-mapping B+tree on a filesystem that supports sharing of file data blocks, the key definition is larger than the usual AG block number. On a classic XFS filesystem, each block has only one owner, which means that `rm_startblock` is sufficient to uniquely identify each record. However, shared block support (reflink) on XFS breaks that assumption; now filesystem blocks can be linked to any logical block offset of any file inode. Therefore, the key must include the owner and offset information to preserve the 1 to 1 relation between key and record.

- As the reference counting is AG relative, all the block numbers are only 32-bits.
- The `bb_magic` value is "RMB3" (0x524d4233).
- The `xfs_btree_sblock_t` header is used for intermediate B+tree node as well as the leaves.
- Each pointer is associated with two keys. The first of these is the "low key", which is the key of the smallest record accessible through the pointer. This low key has the same meaning as the key in all other btrees. The second key is the high key, which is the maximum of the largest key that can be used to access a given record underneath the pointer. Recall that each record in the reverse mapping b+tree describes an interval of physical blocks mapped to an interval of logical file block offsets; therefore, it makes sense that a range of keys can be used to find to a record.

13.7.1 xfs_db rmapbt Example

This example shows a reverse-mapping B+tree from a freshly populated root filesystem:

```
xfs_db> agf 0
xfs_db> addr rmaproot
xfs_db> p
magic = 0x524d4233
level = 1
numrecs = 43
leftsib = null
rightsib = null
bno = 56
lsn = 0x3000004c8
uuid = 1977221d-8345-464e-b1f4-aa2ea36895f4
owner = 0
crc = 0x7cf8be6f (correct)
keys[1-43] = [startblock,owner,offset]
keys[1-43] = [startblock,owner,offset,attrfork,bmbtblock,startblock_hi,owner_hi,
              offset_hi,attrfork_hi,bmbtblock_hi]
        1:[0,-3,0,0,0,351,4418,66,0,0]
        2:[417,285,0,0,0,827,4419,2,0,0]
        3:[829,499,0,0,0,2352,573,55,0,0]
        4:[1292,710,0,0,0,32168,262923,47,0,0]
        5:[32215,-5,0,0,0,34655,2365,3411,0,0]
        6:[34083,1161,0,0,0,34895,265220,1,0,1]
        7:[34896,256191,0,0,0,36522,-9,0,0,0]
        ...
        41:[50998,326734,0,0,0,51430,-5,0,0,0]
        42:[51431,327010,0,0,0,51600,325722,11,0,0]
        43:[51611,327112,0,0,0,94063,23522,28375272,0,0]
ptrs[1-43] = 1:5 2:6 3:8 4:9 5:10 6:11 7:418 ... 41:46377 42:48784 43:49522
```

We arbitrarily pick pointer 17 to traverse downwards:

```
xfs_db> addr ptrs[17]
xfs_db> p
magic = 0x524d4233
level = 0
numrecs = 168
leftsib = 36284
rightsib = 37617
bno = 294760
lsn = 0x200002761
uuid = 1977221d-8345-464e-b1f4-aa2ea36895f4
owner = 0
crc = 0x2dad3fbe (correct)
recs[1-168] = [startblock,blockcount,owner,offset,extentflag,attrfork,bmbtblock]
        1:[40326,1,259615,0,0,0,0] 2:[40327,1,-5,0,0,0,0]
        3:[40328,2,259618,0,0,0,0] 4:[40330,1,259619,0,0,0,0]
        ...
        127:[40540,1,324266,0,0,0,0] 128:[40541,1,324266,8388608,0,0,0]
        129:[40542,2,324266,1,0,0,0] 130:[40544,32,-7,0,0,0,0]
```

Several interesting things pop out here. The first record shows that inode 259,615 has mapped AG block 40,326 at offset 0. We confirm this by looking at the block map for that inode:

```
xfs_db> inode 259615
xfs_db> bmap
data offset 0 startblock 40326 (0/40326) count 1 flag 0
```

Next, notice records 127 and 128, which describe neighboring AG blocks that are mapped to non-contiguous logical blocks in inode 324,266. Given the logical offset of 8,388,608 we surmise that this is a leaf directory, but let us confirm:

```
xfs_db> inode 324266
```

```
xfs_db> p core.mode
core.mode = 040755
xfs_db> bmap
data offset 0 startblock 40540 (0/40540) count 1 flag 0
data offset 1 startblock 40542 (0/40542) count 2 flag 0
data offset 3 startblock 40576 (0/40576) count 1 flag 0
data offset 8388608 startblock 40541 (0/40541) count 1 flag 0
xfs_db> p core.mode
core.mode = 0100644
xfs_db> dblock 0
xfs_db> p dhdr.hdr.magic
dhdr.hdr.magic = 0x58444433
xfs_db> dblock 8388608
xfs_db> p lhdr.info.hdr.magic
lhdr.info.hdr.magic = 0x3df1
```

Indeed, this inode 324,266 appears to be a leaf directory, as it has regular directory data blocks at low offsets, and a single leaf block.

Notice further the two reverse-mapping records with negative owners. An owner of -7 corresponds to `XFS_RMAP_OWN_INODES`, which is an inode chunk, and an owner code of -5 corresponds to `XFS_RMAP_OWN_AG`, which covers free space B+trees and free space. Let's see if block 40,544 is part of an inode chunk:

```
xfs_db> blockget
xfs_db> fsblock 40544
xfs_db> blockuse
block 40544 (0/40544) type inode
xfs_db> stack
1:
        byte offset 166068224, length 4096
        buffer block 324352 (fsbno 40544), 8 bbs
        inode 324266, dir inode 324266, type data
xfs_db> type inode
xfs_db> p
core.magic = 0x494e
```

Our suspicions are confirmed. Let's also see if 40,327 is part of a free space tree:

```
xfs_db> fsblock 40327
xfs_db> blockuse
block 40327 (0/40327) type btrmap
xfs_db> type rmapbt
xfs_db> p
magic = 0x524d4233
```

As you can see, the reverse block-mapping B+tree is an important secondary metadata structure, which can be used to reconstruct damaged primary metadata. Now let's look at an extend rmap btree:

```
xfs_db> agf 0
xfs_db> addr rmaproot
xfs_db> p
magic = 0x34524d42
level = 1
numrecs = 5
leftsib = null
rightsib = null
bno = 6368
lsn = 0x100000d1b
uuid = 400f0928-6b88-4c37-af1e-cef1f8911f3f
owner = 0
crc = 0x8d4ace05 (correct)
```

```
keys[1-5] = [startblock,owner,offset,attrfork,bmbtblock,startblock_hi,owner_hi,offset_hi, ↩
    attrfork_hi,bmbtblock_hi]
1:[0,-3,0,0,0,705,132,681,0,0]
2:[24,5761,0,0,0,548,5761,524,0,0]
3:[24,5929,0,0,0,380,5929,356,0,0]
4:[24,6097,0,0,0,212,6097,188,0,0]
5:[24,6277,0,0,0,807,-7,0,0,0]
ptrs[1-5] = 1:5 2:771 3:9 4:10 5:11
```

The second pointer stores both the low key [24,5761,0,0,0] and the high key [548,5761,524,0,0], which means that we can expect block 771 to contain records starting at physical block 24, inode 5761, offset zero; and that one of the records can be used to find a reverse mapping for physical block 548, inode 5761, and offset 524:

```
xfs_db> addr ptrs[2]
xfs_db> p
magic = 0x34524d42
level = 0
numrecs = 168
leftsib = 5
rightsib = 9
bno = 6168
lsn = 0x100000d1b
uuid = 400f0928-6b88-4c37-af1e-cef1f8911f3f
owner = 0
crc = 0xd58eff0e (correct)
recs[1-168] = [startblock,blockcount,owner,offset,extentflag,attrfork,bmbtblock]
1:[24,525,5761,0,0,0,0]
2:[24,524,5762,0,0,0,0]
3:[24,523,5763,0,0,0,0]
...
166:[24,360,5926,0,0,0,0]
167:[24,359,5927,0,0,0,0]
168:[24,358,5928,0,0,0,0]
```

Observe that the first record in the block starts at physical block 24, inode 5761, offset zero, just as we expected. Note that this first record is also indexed by the highest key as provided in the node block; physical block 548, inode 5761, offset 524 is the very last block mapped by this record. Furthermore, note that record 168, despite being the last record in this block, has a lower maximum key (physical block 382, inode 5928, offset 23) than the first record.

13.8 Reference Count B+tree

Note
This data structure is under construction! Details may change.

To support the sharing of file data blocks (reflink), each allocation group has its own reference count B+tree, which grows in the allocated space like the inode B+trees. This data could be collected by performing an interval query of the reverse-mapping B+tree, but doing so would come at a huge performance penalty. Therefore, this data structure is a cache of computable information.

This B+tree is only present if the `XFS_SB_FEAT_RO_COMPAT_REFLINK` feature is enabled. The feature requires a version 5 filesystem.

Each record in the reference count B+tree has the following structure:

```
struct xfs_refcount_rec {
     __be32                     rc_startblock;
     __be32                     rc_blockcount;
     __be32                     rc_refcount;
};
```

rc_startblock
AG block number of this record. The high bit is set for all records referring to an extent that is being used to stage a copy on write operation. This reduces recovery time during mount operations. The reference count of these staging events must only be 1.

rc_blockcount
The length of this extent.

rc_refcount
Number of mappings of this filesystem extent.

Node pointers are an AG relative block pointer:

```
struct xfs_refcount_key {
     __be32                     rc_startblock;
};
```

- As the reference counting is AG relative, all the block numbers are only 32-bits.
- The `bb_magic` value is "R3FC" (0x52334643).
- The `xfs_btree_sblock_t` header is used for intermediate B+tree node as well as the leaves.

13.8.1 xfs_db refcntbt Example

For this example, an XFS filesystem was populated with a root filesystem and a deduplication program was run to create shared blocks:

```
xfs_db> agf 0
xfs_db> addr refcntroot
xfs_db> p
magic = 0x52334643
level = 1
numrecs = 6
leftsib = null
rightsib = null
bno = 36892
lsn = 0x200004ec2
uuid = f1f89746-e00b-49c9-96b3-ecef0f2f14ae
owner = 0
crc = 0x75f35128 (correct)
keys[1-6] = [startblock] 1:[14] 2:[65633] 3:[65780] 4:[94571] 5:[117201] 6:[152442]
ptrs[1-6] = 1:7 2:25836 3:25835 4:18447 5:18445 6:18449
xfs_db> addr ptrs[3]
xfs_db> p
magic = 0x52334643
level = 0
numrecs = 80
leftsib = 25836
rightsib = 18447
bno = 51670
lsn = 0x200004ec2
uuid = f1f89746-e00b-49c9-96b3-ecef0f2f14ae
owner = 0
crc = 0xc3962813 (correct)
recs[1-80] = [startblock,blockcount,refcount,cowflag]
        1:[65780,1,2,0] 2:[65781,1,3,0] 3:[65785,2,2,0] 4:[66640,1,2,0]
        5:[69602,4,2,0] 6:[72256,16,2,0] 7:[72871,4,2,0] 8:[72879,20,2,0]
        9:[73395,4,2,0] 10:[75063,4,2,0] 11:[79093,4,2,0] 12:[86344,16,2,0]
        ...
        80:[35235,10,1,1]
```

Notice record 80. The copy on write flag is set and the reference count is 1, which indicates that the extent 35,235 - 35,244 are being used to stage a copy on write activity. The "cowflag" field is the high bit of rc_startblock.

Record 6 in the reference count B+tree for AG 0 indicates that the AG extent starting at block 72,256 and running for 16 blocks has a reference count of 2. This means that there are two files sharing the block:

```
xfs_db> blockget -n
xfs_db> fsblock 72256
xfs_db> blockuse
block 72256 (0/72256) type rldata inode 25169197
```

The blockuse type changes to “rldata” to indicate that the block is shared data. Unfortunately, blockuse only tells us about one block owner. If we happen to have enabled the reverse-mapping B+tree, we can use it to find all inodes that own this block:

```
xfs_db> agf 0
xfs_db> addr rmaproot
...
xfs_db> addr ptrs[3]
...
xfs_db> addr ptrs[7]
xfs_db> p
magic = 0x524d4233
level = 0
numrecs = 22
leftsib = 65057
rightsib = 65058
bno = 291478
lsn = 0x200004ec2
uuid = f1f89746-e00b-49c9-96b3-ecef0f2f14ae
owner = 0
crc = 0xed7da3f7 (correct)
recs[1-22] = [startblock,blockcount,owner,offset,extentflag,attrfork,bmbtblock]
        1:[68957,8,3201,0,0,0,0] 2:[68965,4,25260953,0,0,0,0]
        ...
        18:[72232,58,3227,0,0,0,0] 19:[72256,16,25169197,24,0,0,0]
        20:[72290,75,3228,0,0,0,0] 21:[72365,46,3229,0,0,0,0]
```

Records 18 and 19 intersect the block 72,256; they tell us that inodes 3,227 and 25,169,197 both claim ownership. Let us confirm this:

```
xfs_db> inode 25169197
xfs_db> bmap
data offset 0 startblock 12632259 (3/49347) count 24 flag 0
data offset 24 startblock 72256 (0/72256) count 16 flag 0
data offset 40 startblock 12632299 (3/49387) count 18 flag 0
xfs_db> inode 3227
xfs_db> bmap
data offset 0 startblock 72232 (0/72232) count 58 flag 0
```

Inodes 25,169,197 and 3,227 both contain mappings to block 0/72,256.

Chapter 14

Journaling Log

Note
Only v2 log format is covered here.

The XFS journal exists on disk as a reserved extent of blocks within the filesystem, or as a separate journal device. The journal itself can be thought of as a series of log records; each log record contains a part of or a whole transaction. A transaction consists of a series of log operation headers ("log items"), formatting structures, and raw data. The first operation in a transaction establishes the transaction ID and the last operation is a commit record. The operations recorded between the start and commit operations represent the metadata changes made by the transaction. If the commit operation is missing, the transaction is incomplete and cannot be recovered.

14.1 Log Records

The XFS log is split into a series of log records. Log records seem to correspond to an in-core log buffer, which can be up to 256KiB in size. Each record has a log sequence number, which is the same LSN recorded in the v5 metadata integrity fields.

Log sequence numbers are a 64-bit quantity consisting of two 32-bit quantities. The upper 32 bits are the "cycle number", which increments every time XFS cycles through the log. The lower 32 bits are the "block number", which is assigned when a transaction is committed, and should correspond to the block offset within the log.

A log record begins with the following header, which occupies 512 bytes on disk:

```
typedef struct xlog_rec_header {
     __be32                    h_magicno;
     __be32                    h_cycle;
     __be32                    h_version;
     __be32                    h_len;
     __be64                    h_lsn;
     __be64                    h_tail_lsn;
     __le32                    h_crc;
     __be32                    h_prev_block;
     __be32                    h_num_logops;
     __be32                    h_cycle_data[XLOG_HEADER_CYCLE_SIZE / BBSIZE];
     /* new fields */
     __be32                    h_fmt;
     uuid_t                    h_fs_uuid;
     __be32                    h_size;
} xlog_rec_header_t;
```

h_magicno
The magic number of log records, 0xfeedbabe.

h_cycle
Cycle number of this log record.

h_version
Log record version, currently 2.

h_len
Length of the log record, in bytes. Must be aligned to a 64-bit boundary.

h_lsn
Log sequence number of this record.

h_tail_lsn
Log sequence number of the first log record with uncommitted buffers.

h_crc
Checksum of the log record header, the cycle data, and the log records themselves.

h_prev_block
Block number of the previous log record.

h_num_logops
The number of log operations in this record.

h_cycle_data
The first u32 of each log sector must contain the cycle number. Since log item buffers are formatted without regard to this requirement, the original contents of the first four bytes of each sector in the log are copied into the corresponding element of this array. After that, the first four bytes of those sectors are stamped with the cycle number. This process is reversed at recovery time. If there are more sectors in this log record than there are slots in this array, the cycle data continues for as many sectors are needed; each sector is formatted as type `xlog_rec_ext_header`.

h_fmt
Format of the log record. This is one of the following values:

Table 14.1: Log record formats

Format value	Log format
XLOG_FMT_UNKNOWN	Unknown. Perhaps this log is corrupt.
XLOG_FMT_LINUX_LE	Little-endian Linux.
XLOG_FMT_LINUX_BE	Big-endian Linux.
XLOG_FMT_IRIX_BE	Big-endian Irix.

h_fs_uuid
Filesystem UUID.

h_size
In-core log record size. This is somewhere between 16 and 256KiB, with 32KiB being the default.

As mentioned earlier, if this log record is longer than 256 sectors, the cycle data overflows into the next sector(s) in the log. Each of those sectors is formatted as follows:

```
typedef struct xlog_rec_ext_header {
    __be32                  xh_cycle;
    __be32                  xh_cycle_data[XLOG_HEADER_CYCLE_SIZE / BBSIZE];
} xlog_rec_ext_header_t;
```

xh_cycle
Cycle number of this log record. Should match `h_cycle`.

xh_cycle_data
Overflow cycle data.

14.2 Log Operations

Within a log record, log operations are recorded as a series consisting of an operation header immediately followed by a data region. The operation header has the following format:

```
typedef struct xlog_op_header {
     __be32                   oh_tid;
     __be32                   oh_len;
     __u8                     oh_clientid;
     __u8                     oh_flags;
     __u16                    oh_res2;
} xlog_op_header_t;
```

oh_tid
Transaction ID of this operation.

oh_len
Number of bytes in the data region.

oh_clientid
The originator of this operation. This can be one of the following:

Table 14.2: Log Operation Client ID

Client ID	Originator
XFS_TRANSACTION	Operation came from a transaction.
XFS_VOLUME	???
XFS_LOG	???

oh_flags
Specifies flags associated with this operation. This can be a combination of the following values (though most likely only one will be set at a time):

Table 14.3: Log Operation Flags

Flag	Description
XLOG_START_TRANS	Start a new transaction. The next operation header should describe a transaction header.
XLOG_COMMIT_TRANS	Commit this transaction.
XLOG_CONTINUE_TRANS	Continue this trans into new log record.
XLOG_WAS_CONT_TRANS	This transaction started in a previous log record.
XLOG_END_TRANS	End of a continued transaction.
XLOG_UNMOUNT_TRANS	Transaction to unmount a filesystem.

oh_res2
Padding.

The data region follows immediately after the operation header and is exactly `oh_len` bytes long. These payloads are in host-endian order, which means that one cannot replay the log from an unclean XFS filesystem on a system with a different byte order.

14.3 Log Items

Following are the types of log item payloads that can follow an `xlog_op_header`. Except for buffer data and inode cores, all log items have a magic number to distinguish themselves. Buffer data items only appear after `xfs_buf_log_format` items; and inode core items only appear after `xfs_inode_log_format` items.

Table 14.4: Log Operation Magic Numbers

Magic	Hexadecimal	Operation Type
XFS_TRANS_HEADER_MAGIC	0x5452414e	Log Transaction Header Section 14.3.1
XFS_LI_EFI	0x1236	Extent Freeing Intent Section 14.3.2
XFS_LI_EFD	0x1237	Extent Freeing Done Section 14.3.3
XFS_LI_IUNLINK	0x1238	Unknown?
XFS_LI_INODE	0x123b	Inode Updates Section 14.3.10
XFS_LI_BUF	0x123c	Buffer Writes Section 14.3.12
XFS_LI_DQUOT	0x123d	Update Quota Section 14.3.14
XFS_LI_QUOTAOFF	0x123e	Quota Off Section 14.3.16
XFS_LI_ICREATE	0x123f	Inode Creation Section 14.3.17
XFS_LI_RUI	0x1240	Reverse Mapping Update Intent Section 14.3.4
XFS_LI_RUD	0x1241	Reverse Mapping Update Done Section 14.3.5
XFS_LI_CUI	0x1242	Reference Count Update Intent Section 14.3.6
XFS_LI_CUD	0x1243	Reference Count Update Done Section 14.3.7
XFS_LI_BUI	0x1244	File Block Mapping Update Intent Section 14.3.8
XFS_LI_BUD	0x1245	File Block Mapping Update Done Section 14.3.9

Note that all log items (except for transaction headers) MUST start with the following header structure. The type and size fields are baked into each log item header, but there is not a separately defined header.

```
struct xfs_log_item {
     __uint16_t                magic;
     __uint16_t                size;
};
```

14.3.1 Transaction Headers

A transaction header is an operation payload that starts a transaction.

```
typedef struct xfs_trans_header {
     uint                    th_magic;
     uint                    th_type;
     __int32_t               th_tid;
     uint                    th_num_items;
} xfs_trans_header_t;
```

th_magic
The signature of a transaction header, "TRAN" (0x5452414e). Note that this value is in host-endian order, not big-endian like the rest of XFS.

th_type
Transaction type. This is one of the following values:

Type	Description
XFS_TRANS_SETATTR_NOT_SIZE	Set an inode attribute that isn't the inode's size.
XFS_TRANS_SETATTR_SIZE	Setting the size attribute of an inode.
XFS_TRANS_INACTIVE	Freeing blocks from an unlinked inode.
XFS_TRANS_CREATE	Create a file.
XFS_TRANS_CREATE_TRUNC	Unused?
XFS_TRANS_TRUNCATE_FILE	Truncate a quota file.
XFS_TRANS_REMOVE	Remove a file.
XFS_TRANS_LINK	Link an inode into a directory.
XFS_TRANS_RENAME	Rename a path.
XFS_TRANS_MKDIR	Create a directory.
XFS_TRANS_RMDIR	Remove a directory.
XFS_TRANS_SYMLINK	Create a symbolic link.
XFS_TRANS_SET_DMATTRS	Set the DMAPI attributes of an inode.
XFS_TRANS_GROWFS	Expand the filesystem.
XFS_TRANS_STRAT_WRITE	Convert an unwritten extent or delayed-allocate some blocks to handle a write.
XFS_TRANS_DIOSTRAT	Allocate some blocks to handle a direct I/O write.
XFS_TRANS_WRITEID	Update an inode's preallocation flag.
XFS_TRANS_ADDAFORK	Add an attribute fork to an inode.
XFS_TRANS_ATTRINVAL	Erase the attribute fork of an inode.
XFS_TRANS_ATRUNCATE	Unused?
XFS_TRANS_ATTR_SET	Set an extended attribute.
XFS_TRANS_ATTR_RM	Remove an extended attribute.
XFS_TRANS_ATTR_FLAG	Unused?
XFS_TRANS_CLEAR_AGI_BUCKET	Clear a bad inode pointer in the AGI unlinked inode hash bucket.
XFS_TRANS_SB_CHANGE	Write the superblock to disk.
XFS_TRANS_QM_QUOTAOFF	Start disabling quotas.
XFS_TRANS_QM_DQALLOC	Allocate a disk quota structure.
XFS_TRANS_QM_SETQLIM	Adjust quota limits.
XFS_TRANS_QM_DQCLUSTER	Unused?
XFS_TRANS_QM_QINOCREATE	Create a (quota) inode with reference taken.
XFS_TRANS_QM_QUOTAOFF_END	Finish disabling quotas.
XFS_TRANS_FSYNC_TS	Update only inode timestamps.
XFS_TRANS_GROWFSRT_ALLOC	Grow the realtime bitmap and summary data for growfs.
XFS_TRANS_GROWFSRT_ZERO	Zero space in the realtime bitmap and summary data.
XFS_TRANS_GROWFSRT_FREE	Free space in the realtime bitmap and summary data.
XFS_TRANS_SWAPEXT	Swap data fork of two inodes.
XFS_TRANS_CHECKPOINT	Checkpoint the log.
XFS_TRANS_ICREATE	Unknown?
XFS_TRANS_CREATE_TMPFILE	Create a temporary file.

th_tid
Transaction ID.

th_num_items
The number of operations appearing after this operation, not including the commit operation. In effect, this tracks the number of metadata change operations in this transaction.

14.3.2 Intent to Free an Extent

The next two operation types work together to handle the freeing of filesystem blocks. Naturally, the ranges of blocks to be freed can be expressed in terms of extents:

```
typedef struct xfs_extent_32 {
     __uint64_t                ext_start;
     __uint32_t                ext_len;
} __attribute__((packed)) xfs_extent_32_t;

typedef struct xfs_extent_64 {
     __uint64_t                ext_start;
     __uint32_t                ext_len;
     __uint32_t                ext_pad;
} xfs_extent_64_t;
```

ext_start
Start block of this extent.

ext_len
Length of this extent.

The "extent freeing intent" operation comes first; it tells the log that XFS wants to free some extents. This record is crucial for correct log recovery because it prevents the log from replaying blocks that are subsequently freed. If the log lacks a corresponding "extent freeing done" operation, the recovery process will free the extents.

```
typedef struct xfs_efi_log_format {
     __uint16_t                efi_type;
     __uint16_t                efi_size;
     __uint32_t                efi_nextents;
     __uint64_t                efi_id;
     xfs_extent_t              efi_extents[1];
} xfs_efi_log_format_t;
```

efi_type
The signature of an EFI operation, 0x1236. This value is in host-endian order, not big-endian like the rest of XFS.

efi_size
Size of this log item. Should be 1.

efi_nextents
Number of extents to free.

efi_id
A 64-bit number that binds the corresponding EFD log item to this EFI log item.

efi_extents
Variable-length array of extents to be freed. The array length is given by `efi_nextents`. The record type will be either `xfs_extent_64_t` or `xfs_extent_32_t`; this can be determined from the log item size (`oh_len`) and the number of extents (`efi_nextents`).

14.3.3 Completion of Intent to Free an Extent

The "extent freeing done" operation complements the "extent freeing intent" operation. This second operation indicates that the block freeing actually happened, so that log recovery needn't try to free the blocks. Typically, the operations to update the free space B+trees follow immediately after the EFD.

```
typedef struct xfs_efd_log_format {
     __uint16_t                efd_type;
     __uint16_t                efd_size;
     __uint32_t                efd_nextents;
     __uint64_t                efd_efi_id;
     xfs_extent_t              efd_extents[1];
} xfs_efd_log_format_t;
```

efd_type
The signature of an EFD operation, 0x1237. This value is in host-endian order, not big-endian like the rest of XFS.

efd_size
Size of this log item. Should be 1.

efd_nextents
Number of extents to free.

efd_id
A 64-bit number that binds the corresponding EFI log item to this EFD log item.

efd_extents
Variable-length array of extents to be freed. The array length is given by `efd_nextents`. The record type will be either `xfs_extent_64_t` or `xfs_extent_32_t`; this can be determined from the log item size (`oh_len`) and the number of extents (`efd_nextents`).

14.3.4 Reverse Mapping Updates Intent

The next two operation types work together to handle deferred reverse mapping updates. Naturally, the mappings to be updated can be expressed in terms of mapping extents:

```
struct xfs_map_extent {
     __uint64_t                me_owner;
     __uint64_t                me_startblock;
     __uint64_t                me_startoff;
     __uint32_t                me_len;
     __uint32_t                me_flags;
};
```

me_owner
Owner of this reverse mapping. See the values in the section about reverse mapping Section 13.7 for more information.

me_startblock
Filesystem block of this mapping.

me_startoff
Logical block offset of this mapping.

me_len
The length of this mapping.

me_flags
The lower byte of this field is a type code indicating what sort of reverse mapping operation we want. The upper three bytes are flag bits.

Table 14.5: Reverse mapping update log intent types

Value	Description
XFS_RMAP_EXTENT_MAP	Add a reverse mapping for file data.
XFS_RMAP_EXTENT_MAP_SHARED	Add a reverse mapping for file data for a file with shared blocks.
XFS_RMAP_EXTENT_UNMAP	Remove a reverse mapping for file data.
XFS_RMAP_EXTENT_UNMAP_SHARED	Remove a reverse mapping for file data for a file with shared blocks.
XFS_RMAP_EXTENT_CONVERT	Convert a reverse mapping for file data between unwritten and normal.
XFS_RMAP_EXTENT_CONVERT_SHARED	Convert a reverse mapping for file data between unwritten and normal for a file with shared blocks.
XFS_RMAP_EXTENT_ALLOC	Add a reverse mapping for non-file data.
XFS_RMAP_EXTENT_FREE	Remove a reverse mapping for non-file data.

Table 14.6: Reverse mapping update log intent flags

Value	Description
XFS_RMAP_EXTENT_ATTR_FORK	Extent is for the attribute fork.
XFS_RMAP_EXTENT_BMBT_BLOCK	Extent is for a block mapping btree block.
XFS_RMAP_EXTENT_UNWRITTEN	Extent is unwritten.

The "rmap update intent" operation comes first; it tells the log that XFS wants to update some reverse mappings. This record is crucial for correct log recovery because it enables us to spread a complex metadata update across multiple transactions while ensuring that a crash midway through the complex update will be replayed fully during log recovery.

```
struct xfs_rui_log_format {
     __uint16_t                rui_type;
     __uint16_t                rui_size;
     __uint32_t                rui_nextents;
     __uint64_t                rui_id;
     struct xfs_map_extent     rui_extents[1];
};
```

rui_type
The signature of an RUI operation, 0x1240. This value is in host-endian order, not big-endian like the rest of XFS.

rui_size
Size of this log item. Should be 1.

rui_nextents
Number of reverse mappings.

rui_id
A 64-bit number that binds the corresponding RUD log item to this RUI log item.

rui_extents
Variable-length array of reverse mappings to update.

14.3.5 Completion of Reverse Mapping Updates

The "reverse mapping update done" operation complements the "reverse mapping update intent" operation. This second operation indicates that the update actually happened, so that log recovery needn't replay the update. The RUD and the actual updates are typically found in a new transaction following the transaction in which the RUI was logged.

```
struct xfs_rud_log_format {
      __uint16_t               rud_type;
      __uint16_t               rud_size;
      __uint32_t               __pad;
      __uint64_t               rud_rui_id;
};
```

rud_type
The signature of an RUD operation, 0x1241. This value is in host-endian order, not big-endian like the rest of XFS.

rud_size
Size of this log item. Should be 1.

rud_rui_id
A 64-bit number that binds the corresponding RUI log item to this RUD log item.

14.3.6 Reference Count Updates Intent

The next two operation types work together to handle reference count updates. Naturally, the ranges of extents having reference count updates can be expressed in terms of physical extents:

```
struct xfs_phys_extent {
     __uint64_t               pe_startblock;
     __uint32_t               pe_len;
     __uint32_t               pe_flags;
};
```

pe_startblock
Filesystem block of this extent.

pe_len
The length of this extent.

pe_flags
The lower byte of this field is a type code indicating what sort of reverse mapping operation we want. The upper three bytes are flag bits.

Table 14.7: Reference count update log intent types

Value	Description
XFS_REFCOUNT_EXTENT_INCREASE	Increase the reference count for this extent.
XFS_REFCOUNT_EXTENT_DECREASE	Decrease the reference count for this extent.
XFS_REFCOUNT_EXTENT_ALLOC_COW	Reserve an extent for staging copy on write.
XFS_REFCOUNT_EXTENT_FREE_COW	Unreserve an extent for staging copy on write.

The "reference count update intent" operation comes first; it tells the log that XFS wants to update some reference counts. This record is crucial for correct log recovery because it enables us to spread a complex metadata update across multiple transactions while ensuring that a crash midway through the complex update will be replayed fully during log recovery.

```
struct xfs_cui_log_format {
     __uint16_t                cui_type;
     __uint16_t                cui_size;
     __uint32_t                cui_nextents;
     __uint64_t                cui_id;
     struct xfs_map_extent     cui_extents[1];
};
```

cui_type
The signature of an CUI operation, 0x1242. This value is in host-endian order, not big-endian like the rest of XFS.

cui_size
Size of this log item. Should be 1.

cui_nextents
Number of reference count updates.

cui_id
A 64-bit number that binds the corresponding RUD log item to this RUI log item.

cui_extents
Variable-length array of reference count update information.

14.3.7 Completion of Reference Count Updates

The "reference count update done" operation complements the "reference count update intent" operation. This second operation indicates that the update actually happened, so that log recovery needn't replay the update. The CUD and the actual updates are typically found in a new transaction following the transaction in which the CUI was logged.

```
struct xfs_cud_log_format {
      __uint16_t                cud_type;
      __uint16_t                cud_size;
      __uint32_t                __pad;
      __uint64_t                cud_cui_id;
};
```

cud_type
The signature of an RUD operation, 0x1243. This value is in host-endian order, not big-endian like the rest of XFS.

cud_size
Size of this log item. Should be 1.

cud_cui_id
A 64-bit number that binds the corresponding CUI log item to this CUD log item.

14.3.8 File Block Mapping Intent

The next two operation types work together to handle deferred file block mapping updates. The extents to be mapped are expressed via the `xfs_map_extent` structure discussed in the section about reverse mapping intents Section 14.3.4.

The lower byte of the `me_flags` field is a type code indicating what sort of file block mapping operation we want. The upper three bytes are flag bits.

Table 14.8: File block mapping update log intent types

Value	Description
XFS_BMAP_EXTENT_MAP	Add a mapping for file data.
XFS_BMAP_EXTENT_UNMAP	Remove a mapping for file data.

Table 14.9: File block mapping update log intent flags

Value	Description
XFS_BMAP_EXTENT_ATTR_FORK	Extent is for the attribute fork.
XFS_BMAP_EXTENT_UNWRITTEN	Extent is unwritten.

The "file block mapping update intent" operation comes first; it tells the log that XFS wants to map or unmap some extents in a file. This record is crucial for correct log recovery because it enables us to spread a complex metadata update across multiple transactions while ensuring that a crash midway through the complex update will be replayed fully during log recovery.

```
struct xfs_bui_log_format {
     __uint16_t                bui_type;
     __uint16_t                bui_size;
     __uint32_t                bui_nextents;
     __uint64_t                bui_id;
     struct xfs_map_extent     bui_extents[1];
};
```

bui_type
The signature of an BUI operation, 0x1244. This value is in host-endian order, not big-endian like the rest of XFS.

bui_size
Size of this log item. Should be 1.

bui_nextents
Number of file mappings. Should be 1.

bui_id
A 64-bit number that binds the corresponding BUD log item to this BUI log item.

bui_extents
Variable-length array of file block mappings to update. There should only be one mapping present.

14.3.9 Completion of File Block Mapping Updates

The "file block mapping update done" operation complements the "file block mapping update intent" operation. This second operation indicates that the update actually happened, so that log recovery needn't replay the update. The BUD and the actual updates are typically found in a new transaction following the transaction in which the BUI was logged.

```
struct xfs_bud_log_format {
      __uint16_t                bud_type;
      __uint16_t                bud_size;
      __uint32_t                __pad;
      __uint64_t                bud_bui_id;
};
```

bud_type
The signature of an BUD operation, 0x1245. This value is in host-endian order, not big-endian like the rest of XFS.

bud_size
Size of this log item. Should be 1.

bud_bui_id
A 64-bit number that binds the corresponding BUI log item to this BUD log item.

14.3.10 Inode Updates

This operation records changes to an inode record. There are several types of inode updates, each corresponding to different parts of the inode record. Allowing updates to proceed at a sub-inode granularity reduces contention for the inode, since different parts of the inode can be updated simultaneously.

The actual buffer data are stored in subsequent log items.

The inode log format header is as follows:

```
typedef struct xfs_inode_log_format_64 {
     __uint16_t                 ilf_type;
     __uint16_t                 ilf_size;
     __uint32_t                 ilf_fields;
     __uint16_t                 ilf_asize;
     __uint16_t                 ilf_dsize;
     __uint32_t                 ilf_pad;
     __uint64_t                 ilf_ino;
     union {
          __uint32_t            ilfu_rdev;
          uuid_t                ilfu_uuid;
     } ilf_u;
     __int64_t                  ilf_blkno;
     __int32_t                  ilf_len;
     __int32_t                  ilf_boffset;
} xfs_inode_log_format_64_t;
```

ilf_type
The signature of an inode update operation, 0x123b. This value is in host-endian order, not big-endian like the rest of XFS.

ilf_size
Number of operations involved in this update, including this format operation.

ilf_fields
Specifies which parts of the inode are being updated. This can be certain combinations of the following:

Flag	Inode changes to log include:
XFS_ILOG_CORE	The standard inode fields.
XFS_ILOG_DDATA	Data fork's local data.
XFS_ILOG_DEXT	Data fork's extent list.
XFS_ILOG_DBROOT	Data fork's B+tree root.
XFS_ILOG_DEV	Data fork's device number.
XFS_ILOG_UUID	Data fork's UUID contents.
XFS_ILOG_ADATA	Attribute fork's local data.
XFS_ILOG_AEXT	Attribute fork's extent list.
XFS_ILOG_ABROOT	Attribute fork's B+tree root.
XFS_ILOG_DOWNER	Change the data fork owner on replay.
XFS_ILOG_AOWNER	Change the attr fork owner on replay.
XFS_ILOG_TIMESTAMP	Timestamps are dirty, but not necessarily anything else. Should never appear on disk.

Flag	Inode changes to log include:
XFS_ILOG_NONCORE	(XFS_ILOG_DDATA | XFS_ILOG_DEXT | XFS_ILOG_DBROOT | XFS_ILOG_DEV | XFS_ILOG_UUID | XFS_ILOG_ADATA | XFS_ILOG_AEXT | XFS_ILOG_ABROOT | XFS_ILOG_DOWNER | XFS_ILOG_AOWNER)
XFS_ILOG_DFORK	(XFS_ILOG_DDATA | XFS_ILOG_DEXT | XFS_ILOG_DBROOT)
XFS_ILOG_AFORK	(XFS_ILOG_ADATA | XFS_ILOG_AEXT | XFS_ILOG_ABROOT)
XFS_ILOG_ALL	(XFS_ILOG_CORE | XFS_ILOG_DDATA | XFS_ILOG_DEXT | XFS_ILOG_DBROOT | XFS_ILOG_DEV | XFS_ILOG_UUID | XFS_ILOG_ADATA | XFS_ILOG_AEXT | XFS_ILOG_ABROOT | XFS_ILOG_TIMESTAMP | XFS_ILOG_DOWNER | XFS_ILOG_AOWNER)

ilf_asize
Size of the attribute fork, in bytes.

ilf_dsize
Size of the data fork, in bytes.

ilf_ino
Absolute node number.

ilfu_rdev
Device number information, for a device file update.

ilfu_uuid
UUID, for a UUID update?

ilf_blkno
Block number of the inode buffer, in sectors.

ilf_len
Length of inode buffer, in sectors.

ilf_boffset
Byte offset of the inode in the buffer.

Be aware that there is a nearly identical `xfs_inode_log_format_32` which may appear on disk. It is the same as `xfs_inode_log_format_64`, except that it is missing the `ilf_pad` field and is 52 bytes long as opposed to 56 bytes.

14.3.11 Inode Data Log Item

This region contains the new contents of a part of an inode, as described in the previous section Section 14.3.10. There are no magic numbers.

If `XFS_ILOG_CORE` is set in `ilf_fields`, the corresponding data buffer must be in the format `struct xfs_icdinode`, which has the same format as the first 96 bytes of an inode Chapter 16, but is recorded in host byte order.

14.3.12 Buffer Log Item

This operation writes parts of a buffer to disk. The regions to write are tracked in the data map; the actual buffer data are stored in subsequent log items.

```
typedef struct xfs_buf_log_format {
     unsigned short            blf_type;
     unsigned short            blf_size;
     ushort                    blf_flags;
     ushort                    blf_len;
     __int64_t                 blf_blkno;
     unsigned int              blf_map_size;
     unsigned int              blf_data_map[XFS_BLF_DATAMAP_SIZE];
} xfs_buf_log_format_t;
```

blf_type
Magic number to specify a buffer log item, 0x123c.

blf_size
Number of buffer data items following this item.

blf_flags
Specifies flags associated with the buffer item. This can be any of the following:

Flag	Description
XFS_BLF_INODE_BUF	Inode buffer. These must be recovered before replaying items that change this buffer.
XFS_BLF_CANCEL	Don't recover this buffer, blocks are being freed.
XFS_BLF_UDQUOT_BUF	User quota buffer, don't recover if there's a subsequent quotaoff.
XFS_BLF_PDQUOT_BUF	Project quota buffer, don't recover if there's a subsequent quotaoff.
XFS_BLF_GDQUOT_BUF	Group quota buffer, don't recover if there's a subsequent quotaoff.

blf_len
Number of sectors affected by this buffer.

blf_blkno
Block number to write, in sectors.

blf_map_size
The size of `blf_data_map`, in 32-bit words.

blf_data_map
This variable-sized array acts as a dirty bitmap for the logged buffer. Each 1 bit represents a dirty region in the buffer, and each run of 1 bits corresponds to a subsequent log item containing the new contents of the buffer area. Each bit represents `(blf_len * 512) /(blf_map_size * NBBY)` bytes.

14.3.13 Buffer Data Log Item

This region contains the new contents of a part of a buffer, as described in the previous section Section 14.3.12. There are no magic numbers.

14.3.14 Update Quota File

This updates a block in a quota file. The buffer data must be in the next log item.

```
typedef struct xfs_dq_logformat {
     __uint16_t               qlf_type;
     __uint16_t               qlf_size;
     xfs_dqid_t               qlf_id;
     __int64_t                qlf_blkno;
     __int32_t                qlf_len;
     __uint32_t               qlf_boffset;
} xfs_dq_logformat_t;
```

qlf_type
The signature of an inode create operation, 0x123e. This value is in host-endian order, not big-endian like the rest of XFS.

qlf_size
Size of this log item. Should be 2.

qlf_id
The user/group/project ID to alter.

qlf_blkno
Block number of the quota buffer, in sectors.

qlf_len
Length of the quota buffer, in sectors.

qlf_boffset
Buffer offset of the quota data to update, in bytes.

14.3.15 Quota Update Data Log Item

This region contains the new contents of a part of a buffer, as described in the previous section Section 14.3.14. There are no magic numbers.

14.3.16 Disable Quota Log Item

A request to disable quota controls has the following format:

```
typedef struct xfs_qoff_logformat {
     unsigned short           qf_type;
     unsigned short           qf_size;
     unsigned int             qf_flags;
     char                     qf_pad[12];
} xfs_qoff_logformat_t;
```

qf_type
The signature of an inode create operation, 0x123d. This value is in host-endian order, not big-endian like the rest of XFS.

qf_size
Size of this log item. Should be 1.

qf_flags
Specifies which quotas are being turned off. Can be a combination of the following:

Flag	Quota type to disable
XFS_UQUOTA_ACCT	User quotas.
XFS_PQUOTA_ACCT	Project quotas.
XFS_GQUOTA_ACCT	Group quotas.

14.3.17 Inode Creation Log Item

This log item is created when inodes are allocated in-core. When replaying this item, the specified inode records will be zeroed and some of the inode fields populated with default values.

```
struct xfs_icreate_log {
     __uint16_t                icl_type;
     __uint16_t                icl_size;
     __be32                    icl_ag;
     __be32                    icl_agbno;
     __be32                    icl_count;
     __be32                    icl_isize;
     __be32                    icl_length;
     __be32                    icl_gen;
};
```

icl_type
The signature of an inode create operation, 0x123f. This value is in host-endian order, not big-endian like the rest of XFS.

icl_size
Size of this log item. Should be 1.

icl_ag
AG number of the inode chunk to create.

icl_agbno
AG block number of the inode chunk.

icl_count
Number of inodes to initialize.

icl_isize
Size of each inode, in bytes.

icl_length
Length of the extent being initialized, in blocks.

icl_gen
Inode generation number to write into the new inodes.

14.4 xfs_logprint Example

Here's an example of dumping the XFS log contents with `xfs_logprint`:

```
# xfs_logprint /dev/sda
xfs_logprint: /dev/sda contains a mounted and writable filesystem
xfs_logprint:
    data device: 0xfc03
    log device: 0xfc03 daddr: 900931640 length: 879816

cycle: 48       version: 2              lsn: 48,0       tail_lsn: 47,879760
length of Log Record: 19968     prev offset: 879808             num ops: 53
uuid: 24afeec2-f418-46a2-a573-10091f5e200e   format: little endian linux
h_size: 32768
```

This is the log record header.

```
Oper (0): tid: 30483aec  len: 0  clientid: TRANS  flags: START
```

This operation indicates that we're starting a transaction, so the next operation should record the transaction header.

```
Oper (1): tid: 30483aec  len: 16  clientid: TRANS  flags: none
TRAN:    type: CHECKPOINT       tid: 30483aec       num_items: 50
```

This operation records a transaction header. There should be fifty operations in this transaction and the transaction ID is 0x30483aec.

```
Oper (2): tid: 30483aec  len: 24  clientid: TRANS  flags: none
BUF:  #regs: 2   start blkno: 145400496 (0x8aaa2b0)  len: 8  bmap size: 1  flags: 0x2000
Oper (3): tid: 30483aec  len: 3712  clientid: TRANS  flags: none
BUF DATA
...
Oper (4): tid: 30483aec  len: 24  clientid: TRANS  flags: none
BUF:  #regs: 3   start blkno: 59116912 (0x3860d70)  len: 8  bmap size: 1  flags: 0x2000
Oper (5): tid: 30483aec  len: 128  clientid: TRANS  flags: none
BUF DATA
 0 43544241 49010000 fa347000 2c357000 3a40b200 13000000 2343c200 13000000
 8 3296d700 13000000 375deb00 13000000 8a551501 13000000 56be1601 13000000
10 af081901 13000000 ec741c01 13000000 9e911c01 13000000 69073501 13000000
18 4e539501 13000000  6549501 13000000 5d0e7f00 14000000 c6908200 14000000

Oper (6): tid: 30483aec  len: 640  clientid: TRANS  flags: none
BUF DATA
 0 7f47c800 21000000 23c0e400 21000000 2d0dfe00 21000000 e7060c01 21000000
 8 34b91801 21000000 9cca9100 22000000 26e69800 22000000 4c969900 22000000
...
90 1cf69900 27000000 42f79c00 27000000  6a99e00 27000000  6a99e00 27000000
98  6a99e00 27000000  6a99e00 27000000  6a99e00 27000000  6a99e00 27000000
```

Operations 4-6 describe two updates to a single dirty buffer at disk address 59,116,912. The first chunk of dirty data is 128 bytes long. Notice how the first four bytes of the first chunk is 0x43544241? Remembering that log items are in host byte order, reverse that to 0x41425443, which is the magic number for the free space B+tree ordered by size.

The second chunk is 640 bytes. There are more buffer changes, so we'll skip ahead a few operations:

```
Oper (19): tid: 30483aec  len: 56  clientid: TRANS  flags: none
INODE: #regs: 2   ino: 0x63a73b4e  flags: 0x1   dsize: 40
        blkno: 1412688704  len: 16  boff: 7168
Oper (20): tid: 30483aec  len: 96  clientid: TRANS  flags: none
INODE CORE
magic 0x494e mode 0100600 version 2 format 3
nlink 1 uid 1000 gid 1000
atime 0x5633d58d mtime 0x563a391b ctime 0x563a391b
size 0x109dc8 nblocks 0x111 extsize 0x0 nextents 0x1b
naextents 0x0 forkoff 0 dmevmask 0x0 dmstate 0x0
flags 0x0 gen 0x389071be
```

This is an update to the core of inode 0x63a73b4e. There were similar inode core updates after this, so we'll skip ahead a bit:

```
Oper (32): tid: 30483aec  len: 56  clientid: TRANS  flags: none
INODE: #regs: 3   ino: 0x4bde428  flags: 0x5   dsize: 16
        blkno: 79553568  len: 16  boff: 4096
Oper (33): tid: 30483aec  len: 96  clientid: TRANS  flags: none
INODE CORE
magic 0x494e mode 0100644 version 2 format 2
nlink 1 uid 1000 gid 1000
atime 0x563a3924 mtime 0x563a3931 ctime 0x563a3931
size 0x1210 nblocks 0x2 extsize 0x0 nextents 0x1
naextents 0x0 forkoff 0 dmevmask 0x0 dmstate 0x0
flags 0x0 gen 0x2829c6f9
Oper (34): tid: 30483aec  len: 16  clientid: TRANS  flags: none
EXTENTS inode data
```

This inode update changes both the core and also the data fork. Since we're changing the block map, it's unsurprising that one of the subsequent operations is an EFI:

```
Oper (37): tid: 30483aec  len: 32  clientid: TRANS  flags: none
EFI:  #regs: 1    num_extents: 1  id: 0xffff8801147b5c20
(s: 0x720daf, l: 1)
\--------------------------------------------------------------------------
Oper (38): tid: 30483aec  len: 32  clientid: TRANS  flags: none
EFD:  #regs: 1    num_extents: 1  id: 0xffff8801147b5c20
\--------------------------------------------------------------------------
Oper (39): tid: 30483aec  len: 24  clientid: TRANS  flags: none
BUF:  #regs: 2   start blkno: 8 (0x8)  len: 8  bmap size: 1  flags: 0x2800
Oper (40): tid: 30483aec  len: 128  clientid: TRANS  flags: none
AGF Buffer: XAGF
ver: 1  seq#: 0  len: 56308224
root BNO: 18174905  CNT: 18175030
level BNO: 2  CNT: 2
1st: 41  last: 46  cnt: 6  freeblks: 35790503  longest: 19343245
\--------------------------------------------------------------------------
Oper (41): tid: 30483aec  len: 24  clientid: TRANS  flags: none
BUF:  #regs: 3   start blkno: 145398760 (0x8aa9be8)  len: 8  bmap size: 1  flags: 0x2000
Oper (42): tid: 30483aec  len: 128  clientid: TRANS  flags: none
BUF DATA
Oper (43): tid: 30483aec  len: 128  clientid: TRANS  flags: none
BUF DATA
\--------------------------------------------------------------------------
Oper (44): tid: 30483aec  len: 24  clientid: TRANS  flags: none
BUF:  #regs: 3   start blkno: 145400224 (0x8aaa1a0)  len: 8  bmap size: 1  flags: 0x2000
Oper (45): tid: 30483aec  len: 128  clientid: TRANS  flags: none
BUF DATA
Oper (46): tid: 30483aec  len: 3584  clientid: TRANS  flags: none
BUF DATA
\--------------------------------------------------------------------------
Oper (47): tid: 30483aec  len: 24  clientid: TRANS  flags: none
BUF:  #regs: 3   start blkno: 59066216 (0x3854768)  len: 8  bmap size: 1  flags: 0x2000
Oper (48): tid: 30483aec  len: 128  clientid: TRANS  flags: none
BUF DATA
Oper (49): tid: 30483aec  len: 768  clientid: TRANS  flags: none
BUF DATA
```

Here we see an EFI, followed by an EFD, followed by updates to the AGF and the free space B+trees. Most probably, we just unmapped a few blocks from a file.

```
Oper (50): tid: 30483aec  len: 56  clientid: TRANS  flags: none
INODE: #regs: 2   ino: 0x3906f20  flags: 0x1   dsize: 16
        blkno: 59797280  len: 16  boff: 0
Oper (51): tid: 30483aec  len: 96  clientid: TRANS  flags: none
INODE CORE
magic 0x494e mode 0100644 version 2 format 2
nlink 1 uid 1000 gid 1000
atime 0x563a3938 mtime 0x563a3938 ctime 0x563a3938
size 0x0 nblocks 0x0 extsize 0x0 nextents 0x0
naextents 0x0 forkoff 0 dmevmask 0x0 dmstate 0x0
flags 0x0 gen 0x35ed661
\--------------------------------------------------------------------------
Oper (52): tid: 30483aec  len: 0  clientid: TRANS  flags: COMMIT
```

One more inode core update and this transaction commits.

Chapter 15

Internal Inodes

XFS allocates several inodes when a filesystem is created. These are internal and not accessible from the standard directory structure. These inodes are only accessible from the superblock.

15.1 Quota Inodes

Prior to version 5 filesystems, two inodes can be allocated for quota management. The first inode will be used for user quotas. The second inode will be used for group quotas or project quotas, depending on mount options. Group and project quotas are mutually exclusive features in these environments.

In version 5 or later filesystems, each quota type is allocated its own inode, making it possible to use group and project quota management simultaneously.

- Project quota's primary purpose is to track and monitor disk usage for directories. For this to occur, the directory inode must have the `XFS_DIFLAG_PROJINHERIT` flag set so all inodes created underneath the directory inherit the project ID.
- Inodes and blocks owned by ID zero do not have enforced quotas, but only quota accounting.
- Extended attributes do not contribute towards the ID's quota.
- To access each ID's quota information in the file, seek to the ID offset multiplied by the size of `xfs_dqblk_t` (136 bytes).

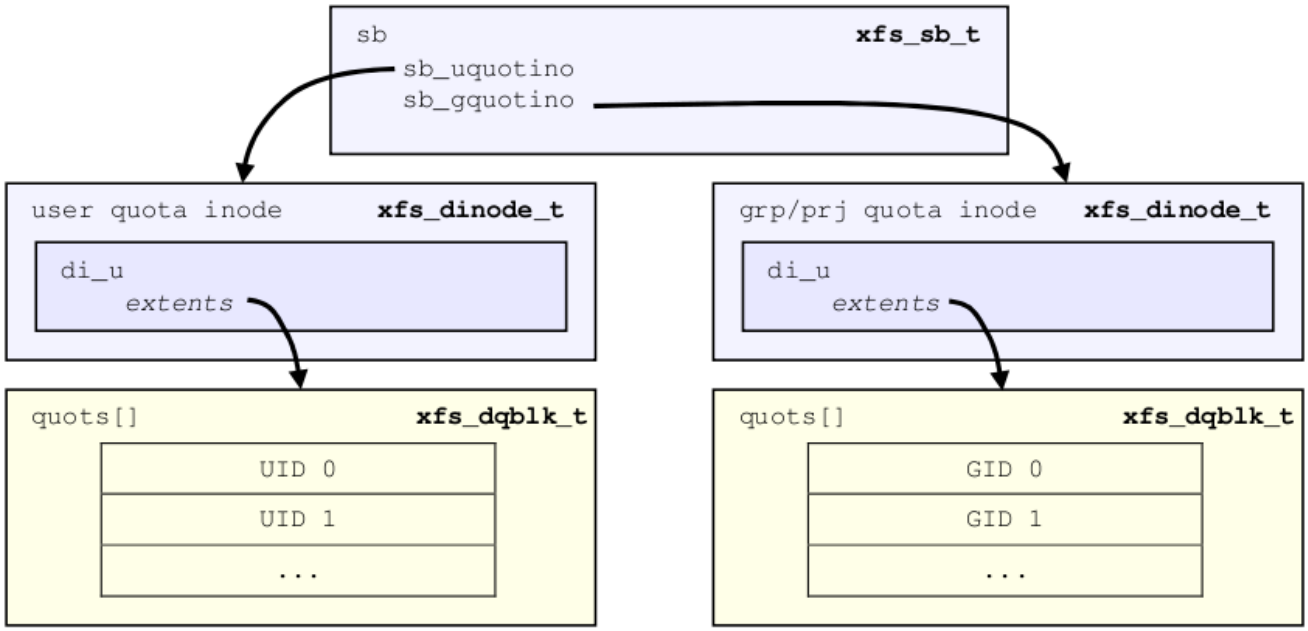


Figure 15.1: Quota inode layout

Quota information is stored in the data extents of the reserved quota inodes as an array of the `xfs_dqblk` structures, where there is one array element for each ID in the system:

```
struct xfs_disk_dquot {
     __be16                  d_magic;
     __u8                    d_version;
     __u8                    d_flags;
     __be32                  d_id;
     __be64                  d_blk_hardlimit;
     __be64                  d_blk_softlimit;
     __be64                  d_ino_hardlimit;
     __be64                  d_ino_softlimit;
     __be64                  d_bcount;
     __be64                  d_icount;
     __be32                  d_itimer;
     __be32                  d_btimer;
     __be16                  d_iwarns;
     __be16                  d_bwarns;
     __be32                  d_pad0;
     __be64                  d_rtb_hardlimit;
     __be64                  d_rtb_softlimit;
     __be64                  d_rtbcount;
     __be32                  d_rtbtimer;
     __be16                  d_rtbwarns;
     __be16                  d_pad;
};
struct xfs_dqblk {
     struct xfs_disk_dquot dd_diskdq;
     char                    dd_fill[4];

     /* version 5 filesystem fields begin here */
     __be32                  dd_crc;
     __be64                  dd_lsn;
     uuid_t                  dd_uuid;
};
```

d_magic
Specifies the signature where these two bytes are 0x4451 (`XFS_DQUOT_MAGIC`), or "DQ" in ASCII.

d_version
The structure version, currently this is 1 (`XFS_DQUOT_VERSION`).

d_flags
Specifies which type of ID the structure applies to:

```
#define XFS_DQ_USER  0x0001
#define XFS_DQ_PROJ  0x0002
#define XFS_DQ_GROUP 0x0004
```

d_id
The ID for the quota structure. This will be a uid, gid or projid based on the value of `d_flags`.

d_blk_hardlimit
The hard limit for the number of filesystem blocks the ID can own. The ID will not be able to use more space than this limit. If it is attempted, `ENOSPC` will be returned.

d_blk_softlimit
The soft limit for the number of filesystem blocks the ID can own. The ID can temporarily use more space than by `d_blk_softlimit` up to `d_blk_hardlimit`. If the space is not freed by the time limit specified by ID zero's `d_btimer` value, the ID will be denied more space until the total blocks owned goes below `d_blk_softlimit`.

d_ino_hardlimit
The hard limit for the number of inodes the ID can own. The ID will not be able to create or own any more inodes if `d_icount` reaches this value.

d_ino_softlimit
The soft limit for the number of inodes the ID can own. The ID can temporarily create or own more inodes than specified by `d_ino_softlimit` up to `d_ino_hardlimit`. If the inode count is not reduced by the time limit specified by ID zero's `d_itimer` value, the ID will be denied from creating or owning more inodes until the count goes below `d_ino_softlimit`.

d_bcount
How many filesystem blocks are actually owned by the ID.

d_icount
How many inodes are actually owned by the ID.

d_itimer
Specifies the time when the ID's `d_icount` exceeded `d_ino_softlimit`. The soft limit will turn into a hard limit after the elapsed time exceeds ID zero's `d_itimer` value. When d_icount goes back below `d_ino_softlimit`, `d_itimer` is reset back to zero.

If the `XFS_SB_FEAT_INCOMPAT_BIGTIME` feature is enabled, the 32 bits used by the timestamp field are interpreted as the upper 32 bits of an 34-bit unsigned seconds counter. See the section about quota expiration timers Section 12.2 for more details.

d_btimer
Specifies the time when the ID's `d_bcount` exceeded `d_blk_softlimit`. The soft limit will turn into a hard limit after the elapsed time exceeds ID zero's `d_btimer` value. When d_bcount goes back below `d_blk_softlimit`, `d_btimer` is reset back to zero.

d_iwarns , d_bwarns , d_rtbwarns
Specifies how many times a warning has been issued. Currently not used.

d_rtb_hardlimit
The hard limit for the number of real-time blocks the ID can own. The ID cannot own more space on the real-time subvolume beyond this limit.

d_rtb_softlimit
The soft limit for the number of real-time blocks the ID can own. The ID can temporarily own more space than specified by `d_rtb_softlimit` up to `d_rtb_hardlimit`. If `d_rtbcount` is not reduced by the time limit specified by ID zero's `d_rtbtimer value`, the ID will be denied from owning more space until the count goes below `d_rtb_soft limit`.

d_rtbcount
How many real-time blocks are currently owned by the ID.

d_rtbtimer
Specifies the time when the ID's `d_rtbcount` exceeded `d_rtb_softlimit`. The soft limit will turn into a hard limit after the elapsed time exceeds ID zero's `d_rtbtimer` value. When `d_rtbcount` goes back below `d_rtb_softli mit`, `d_rtbtimer` is reset back to zero.

dd_uuid
The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

dd_lsn
Log sequence number of the last DQ block write.

dd_crc
Checksum of the DQ block.

15.2 Real-time Inodes

There are two inodes allocated to managing the real-time device's space, the Bitmap Inode and the Summary Inode.

15.2.1 Real-Time Bitmap Inode

The real time bitmap inode, `sb_rbmino`, tracks the used/free space in the real-time device using an old-style bitmap. One bit is allocated per real-time extent. The size of an extent is specified by the superblock's `sb_rextsize` value.

The number of blocks used by the bitmap inode is equal to the number of real-time extents (`sb_rextents`) divided by the block size (`sb_blocksize`) and bits per byte. This value is stored in `sb_rbmblocks`. The nblocks and extent array for the inode should match this. Each real time block gets its own bit in the bitmap.

15.2.2 Real-Time Summary Inode

The real time summary inode, `sb_rsumino`, tracks the used and free space accounting information for the real-time device. This file indexes the approximate location of each free extent on the real-time device first by log2(extent size) and then by the real-time bitmap block number. The size of the summary inode file is equal to `sb_rbmblocks` × log2(realtime device size) × sizeof(`xfs_suminfo_t`). The entry for a given log2(extent size) and rtbitmap block number is 0 if there is no free extents of that size at that rtbitmap location, and positive if there are any.

This data structure is not particularly space efficient, however it is a very fast way to provide the same data as the two free space B+trees for regular files since the space is preallocated and metadata maintenance is minimal.

15.2.3 Real-Time Reverse-Mapping B+tree

Note
This data structure is under construction! Details may change.

If the reverse-mapping B+tree and real-time storage device features are enabled, the real-time device has its own reverse block-mapping B+tree.

As mentioned in the chapter about reconstruction Chapter 5, this data structure is another piece of the puzzle necessary to reconstruct the data or attribute fork of a file from reverse-mapping records; we can also use it to double-check allocations to ensure that we are not accidentally cross-linking blocks, which can cause severe damage to the filesystem.

This B+tree is only present if the XFS_SB_FEAT_RO_COMPAT_RMAPBT feature is enabled and a real time device is present. The feature requires a version 5 filesystem.

The real-time reverse mapping B+tree is rooted in an inode's data fork; the inode number is given by the sb_rrmapino field in the superblock. The B+tree blocks themselves are stored in the regular filesystem. The structures used for an inode's B+tree root are:

```
struct xfs_rtrmap_root {
     __be16                     bb_level;
     __be16                     bb_numrecs;
};
```

- On disk, the B+tree node starts with the xfs_rtrmap_root header followed by an array of xfs_rtrmap_key values and then an array of xfs_rtrmap_ptr_t values. The size of both arrays is specified by the header's bb_numrecs value.
- The root node in the inode can only contain up to 10 key/pointer pairs for a standard 512 byte inode before a new level of nodes is added between the root and the leaves. di_forkoff should always be zero, because there are no extended attributes.

Each record in the real-time reverse-mapping B+tree has the following structure:

```
struct xfs_rtrmap_rec {
     __be64                     rm_startblock;
     __be64                     rm_blockcount;
     __be64                     rm_owner;
     __be64                     rm_fork:1;
     __be64                     rm_bmbt:1;
     __be64                     rm_unwritten:1;
     __be64                     rm_unused:7;
     __be64                     rm_offset:54;
};
```

rm_startblock
Real-time device block number of this record.

rm_blockcount
The length of this extent, in real-time blocks.

rm_owner
A 64-bit number describing the owner of this extent. This must be an inode number, because the real-time device is for file data only.

rm_fork
If rm_owner describes an inode, this can be 1 if this record is for an attribute fork. This value will always be zero for real-time extents.

rm_bmbt
If rm_owner describes an inode, this can be 1 to signify that this record is for a block map B+tree block. In this case, rm_offset has no meaning. This value will always be zero for real-time extents.

rm_unwritten
A flag indicating that the extent is unwritten. This corresponds to the flag in the extent record Chapter 17 format which means XFS_EXT_UNWRITTEN.

rm_offset
The 54-bit logical file block offset, if `rm_owner` describes an inode.

Note
The single-bit flag values `rm_unwritten`, `rm_fork`, and `rm_bmbt` are packed into the larger fields in the C structure definition.

The key has the following structure:

```
struct xfs_rtrmap_key {
     __be64                     rm_startblock;
     __be64                     rm_owner;
     __be64                     rm_fork:1;
     __be64                     rm_bmbt:1;
     __be64                     rm_reserved:1;
     __be64                     rm_unused:7;
     __be64                     rm_offset:54;
};
```

- All block numbers are 64-bit real-time device block numbers.
- The `bb_magic` value is “MAPR” (0x4d415052).
- The `xfs_btree_lblock_t` header is used for intermediate B+tree node as well as the leaves.
- Each pointer is associated with two keys. The first of these is the "low key", which is the key of the smallest record accessible through the pointer. This low key has the same meaning as the key in all other btrees. The second key is the high key, which is the maximum of the largest key that can be used to access a given record underneath the pointer. Recall that each record in the real-time reverse mapping b+tree describes an interval of physical blocks mapped to an interval of logical file block offsets; therefore, it makes sense that a range of keys can be used to find to a record.

15.2.3.1 xfs_db rtrmapbt Example

This example shows a real-time reverse-mapping B+tree from a freshly populated root filesystem:

```
xfs_db> sb 0
xfs_db> addr rrmapino
xfs_db> p
core.magic = 0x494e
core.mode = 0100000
core.version = 3
core.format = 5 (rtrmapbt)
...
u3.rtrmapbt.level = 3
u3.rtrmapbt.numrecs = 1
u3.rtrmapbt.keys[1] = [startblock,owner,offset,attrfork,bmbtblock,startblock_hi,
                       owner_hi,offset_hi,attrfork_hi,bmbtblock_hi]
        1:[1,132,1,0,0,1705337,133,54431,0,0]
u3.rtrmapbt.ptrs[1] = 1:671
xfs_db> addr u3.rtrmapbt.ptrs[1]
xfs_db> p
magic = 0x4d415052
level = 2
numrecs = 8
leftsib = null
rightsib = null
bno = 5368
lsn = 0x400000000
```

```
uuid = 98bbde42-67e7-46a5-a73e-d64a76b1b5ce
owner = 131
crc = 0x2560d199 (correct)
keys[1-8] = [startblock,owner,offset,attrfork,bmbtblock,startblock_hi,owner_hi,
             offset_hi,attrfork_hi,bmbtblock_hi]
        1:[1,132,1,0,0,17749,132,17749,0,0]
        2:[17751,132,17751,0,0,35499,132,35499,0,0]
        3:[35501,132,35501,0,0,53249,132,53249,0,0]
        4:[53251,132,53251,0,0,1658473,133,7567,0,0]
        5:[1658475,133,7569,0,0,1667473,133,16567,0,0]
        6:[1667475,133,16569,0,0,1685223,133,34317,0,0]
        7:[1685225,133,34319,0,0,1694223,133,43317,0,0]
        8:[1694225,133,43319,0,0,1705337,133,54431,0,0]
ptrs[1-8] = 1:134 2:238 3:345 4:453 5:795 6:563 7:670 8:780
```

We arbitrarily pick pointer 7 (twice) to traverse downwards:

```
xfs_db> addr ptrs[7]
xfs_db> p
magic = 0x4d415052
level = 1
numrecs = 36
leftsib = 563
rightsib = 780
bno = 5360
lsn = 0
uuid = 98bbde42-67e7-46a5-a73e-d64a76b1b5ce
owner = 131
crc = 0x6807761d (correct)
keys[1-36] = [startblock,owner,offset,attrfork,bmbtblock,startblock_hi,owner_hi,
              offset_hi,attrfork_hi,bmbtblock_hi]
        1:[1685225,133,34319,0,0,1685473,133,34567,0,0]
        2:[1685475,133,34569,0,0,1685723,133,34817,0,0]
        3:[1685725,133,34819,0,0,1685973,133,35067,0,0]
        ...
        34:[1693475,133,42569,0,0,1693723,133,42817,0,0]
        35:[1693725,133,42819,0,0,1693973,133,43067,0,0]
        36:[1693975,133,43069,0,0,1694223,133,43317,0,0]
ptrs[1-36] = 1:669 2:672 3:674...34:722 35:723 36:725
xfs_db> addr ptrs[7]
xfs_db> p
magic = 0x4d415052
level = 0
numrecs = 125
leftsib = 678
rightsib = 681
bno = 5440
lsn = 0
uuid = 98bbde42-67e7-46a5-a73e-d64a76b1b5ce
owner = 131
crc = 0xefce34d4 (correct)
recs[1-125] = [startblock,blockcount,owner,offset,extentflag,attrfork,bmbtblock]
        1:[1686725,1,133,35819,0,0,0]
        2:[1686727,1,133,35821,0,0,0]
        3:[1686729,1,133,35823,0,0,0]
        ...
        123:[1686969,1,133,36063,0,0,0]
        124:[1686971,1,133,36065,0,0,0]
        125:[1686973,1,133,36067,0,0,0]
```

Several interesting things pop out here. The first record shows that inode 133 has mapped real-time block 1,686,725 at offset 35,819. We confirm this by looking at the block map for that inode:

```
xfs_db> inode 133
xfs_db> p core.realtime
core.realtime = 1
xfs_db> bmap
data offset 35817 startblock 1686723 (1/638147) count 1 flag 0
data offset 35819 startblock 1686725 (1/638149) count 1 flag 0
data offset 35821 startblock 1686727 (1/638151) count 1 flag 0
```

Notice that inode 133 has the real-time flag set, which means that its data blocks are all allocated from the real-time device.

Part III

Dynamically Allocated Structures

Chapter 16

On-disk Inode

All files, directories, and links are stored on disk with inodes and descend from the root inode with its number defined in the superblock Section 13.1. The previous section on AG Inode Management Section 13.3 describes the allocation and management of inodes on disk. This section describes the contents of inodes themselves.

An inode is divided into 3 parts:

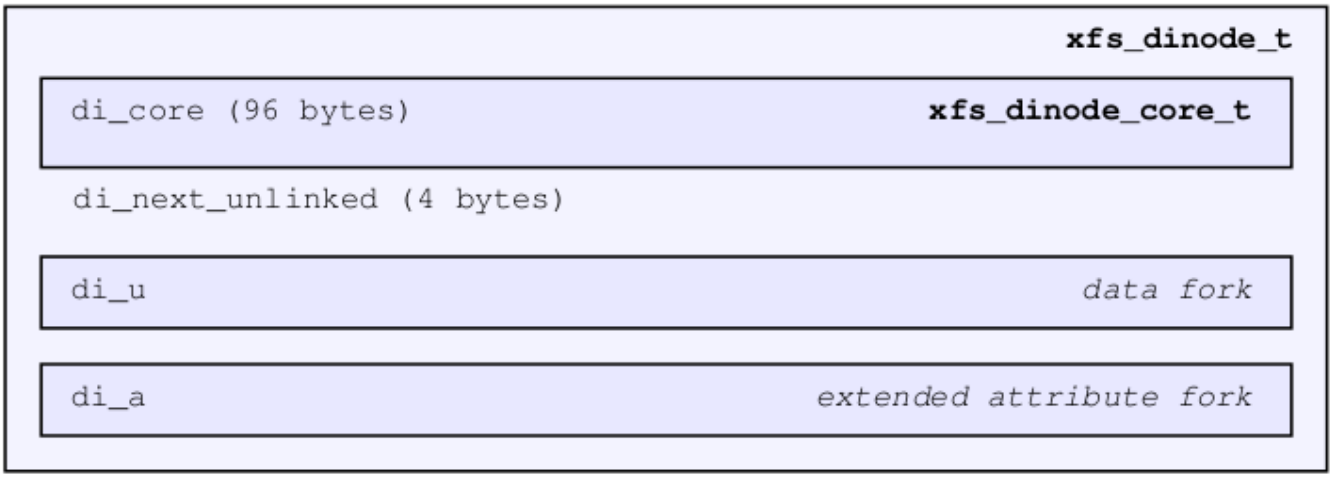


Figure 16.1: On-disk inode sections

- The core contains what the inode represents, stat data, and information describing the data and attribute forks.
- The `di_u` "data fork" contains normal data related to the inode. Its contents depends on the file type specified by `di_core.di_mode` (eg. regular file, directory, link, etc) and how much information is contained in the file which determined by `di_core.di_format`. The following union to represent this data is declared as follows:

```
union {
     xfs_bmdr_block_t di_bmbt;
     xfs_bmbt_rec_t   di_bmx[1];
     xfs_dir2_sf_t    di_dir2sf;
     char             di_c[1];
     xfs_dev_t        di_dev;
     uuid_t           di_muuid;
     char             di_symlink[1];
} di_u;
```

- The `di_a` "attribute fork" contains extended attributes. Its layout is determined by the `di_core.di_aformat` value. Its representation is declared as follows:

```
union {
     xfs_bmdr_block_t      di_abmbt;
     xfs_bmbt_rec_t        di_abmx[1];
     xfs_attr_shortform_t  di_attrsf;
} di_a;
```

Note
The above two unions are rarely used in the XFS code, but the structures within the union are directly cast depending on the `di_mode/di_format` and `di_aformat` values. They are referenced in this document to make it easier to explain the various structures in use within the inode.

The remaining space in the inode after `di_next_unlinked` where the two forks are located is called the inode's "literal area". This starts at offset 100 (0x64) in a version 1 or 2 inode, and offset 176 (0xb0) in a version 3 inode.

The space for each of the two forks in the literal area is determined by the inode size, and `di_core.di_forkoff`. The data fork is located between the start of the literal area and `di_forkoff`. The attribute fork is located between `di_forkoff` and the end of the inode.

16.1 Inode Core

The inode's core is 96 bytes on a V4 filesystem and 176 bytes on a V5 filesystem. It contains information about the file itself including most stat data information about data and attribute forks after the core within the inode. It uses the following structure:

```
struct xfs_dinode_core {
     __uint16_t               di_magic;
     __uint16_t               di_mode;
     __int8_t                 di_version;
     __int8_t                 di_format;
     __uint16_t               di_onlink;
     __uint32_t               di_uid;
     __uint32_t               di_gid;
     __uint32_t               di_nlink;
     __uint16_t               di_projid;
     __uint16_t               di_projid_hi;
     __uint8_t                di_pad[6];
     __uint16_t               di_flushiter;
     xfs_timestamp_t          di_atime;
     xfs_timestamp_t          di_mtime;
     xfs_timestamp_t          di_ctime;
     xfs_fsize_t              di_size;
     xfs_rfsblock_t           di_nblocks;
     xfs_extlen_t             di_extsize;
     xfs_extnum_t             di_nextents;
     xfs_aextnum_t            di_anextents;
     __uint8_t                di_forkoff;
     __int8_t                 di_aformat;
     __uint32_t               di_dmevmask;
     __uint16_t               di_dmstate;
     __uint16_t               di_flags;
     __uint32_t               di_gen;

     /* di_next_unlinked is the only non-core field in the old dinode */
     __be32                   di_next_unlinked;
```

```
     /* version 5 filesystem (inode version 3) fields start here */
     __le32                  di_crc;
     __be64                  di_changecount;
     __be64                  di_lsn;
     __be64                  di_flags2;
     __be32                  di_cowextsize;
     __u8                    di_pad2[12];
     xfs_timestamp_t         di_crtime;
     __be64                  di_ino;
     uuid_t                  di_uuid;

};
```

di_magic
The inode signature; these two bytes are "IN" (0x494e).

di_mode
Specifies the mode access bits and type of file using the standard S_Ixxx values defined in stat.h.

di_version
Specifies the inode version which currently can only be 1, 2, or 3. The inode version specifies the usage of the `di_onlink`, `di_nlink` and `di_projid` values in the inode core. Initially, inodes are created as v1 but can be converted on the fly to v2 when required. v3 inodes are created only for v5 filesystems.

di_format
Specifies the format of the data fork in conjunction with the `di_mode` type. This can be one of several values. For directories and links, it can be "local" where all metadata associated with the file is within the inode; "extents" where the inode contains an array of extents to other filesystem blocks which contain the associated metadata or data; or "btree" where the inode contains a B+tree root node which points to filesystem blocks containing the metadata or data. Migration between the formats depends on the amount of metadata associated with the inode. "dev" is used for character and block devices while "uuid" is currently not used. "rmap" indicates that a reverse-mapping B+tree is rooted in the fork.

```
typedef enum xfs_dinode_fmt {
     XFS_DINODE_FMT_DEV,
     XFS_DINODE_FMT_LOCAL,
     XFS_DINODE_FMT_EXTENTS,
     XFS_DINODE_FMT_BTREE,
     XFS_DINODE_FMT_UUID,
     XFS_DINODE_FMT_RMAP,
} xfs_dinode_fmt_t;
```

di_onlink
In v1 inodes, this specifies the number of links to the inode from directories. When the number exceeds 65535, the inode is converted to v2 and the link count is stored in `di_nlink`.

di_uid
Specifies the owner's UID of the inode.

di_gid
Specifies the owner's GID of the inode.

di_nlink
Specifies the number of links to the inode from directories. This is maintained for both inode versions for current versions of XFS. Prior to v2 inodes, this field was part of `di_pad`.

di_projid
Specifies the owner's project ID in v2 inodes. An inode is converted to v2 if the project ID is set. This value must be zero for v1 inodes.

di_projid_hi
Specifies the high 16 bits of the owner's project ID in v2 inodes, if the XFS_SB_VERSION2_PROJID32BIT feature is set; and zero otherwise.

di_pad[6]
Reserved, must be zero.

di_flushiter
Incremented on flush.

di_atime
Specifies the last access time of the files using UNIX time conventions the following structure. This value may be undefined if the filesystem is mounted with the "noatime" option. XFS supports timestamps with nanosecond resolution:

```
struct xfs_timestamp {
     __int32_t                  t_sec;
     __int32_t                  t_nsec;
};
```

If the XFS_SB_FEAT_INCOMPAT_BIGTIME feature is enabled, the 64 bits used by the timestamp field are interpreted as a flat 64-bit nanosecond counter. See the section about inode timestamps Section 12.1 for more details.

di_mtime
Specifies the last time the file was modified.

di_ctime
Specifies when the inode's status was last changed.

di_size
Specifies the EOF of the inode in bytes. This can be larger or smaller than the extent space (therefore actual disk space) used for the inode. For regular files, this is the filesize in bytes, directories, the space taken by directory entries and for links, the length of the symlink.

di_nblocks
Specifies the number of filesystem blocks used to store the inode's data including relevant metadata like B+trees. This does not include blocks used for extended attributes.

di_extsize
Specifies the extent size for filesystems with real-time devices or an extent size hint for standard filesystems. For normal filesystems, and with directories, the XFS_DIFLAG_EXTSZINHERIT flag must be set in di_flags if this field is used. Inodes created in these directories will inherit the di_extsize value and have XFS_DIFLAG_EXTSIZE set in their di_flags. When a file is written to beyond allocated space, XFS will attempt to allocate additional disk space based on this value.

di_nextents
Specifies the number of data extents associated with this inode.

di_anextents
Specifies the number of extended attribute extents associated with this inode.

di_forkoff
Specifies the offset into the inode's literal area where the extended attribute fork starts. This is an 8-bit value that is multiplied by 8 to determine the actual offset in bytes (ie. attribute data is 64-bit aligned). This also limits the maximum size of the inode to 2048 bytes. This value is initially zero until an extended attribute is created. When in attribute is added, the nature of di_forkoff depends on the XFS_SB_VERSION2_ATTR2BIT flag in the superblock. Refer to Extended Attribute Versions Section 16.4.1 for more details.

di_aformat
Specifies the format of the attribute fork. This uses the same values as di_format, but restricted to "local", "extents" and "btree" formats for extended attribute data.

di_dmevmask
DMAPI event mask.

di_dmstate
DMAPI state.

di_flags
Specifies flags associated with the inode. This can be a combination of the following values:

Table 16.1: Version 2 Inode flags

Flag	Description
XFS_DIFLAG_REALTIME	The inode's data is located on the real-time device.
XFS_DIFLAG_PREALLOC	The inode's extents have been preallocated.
XFS_DIFLAG_NEWRTBM	Specifies the sb_rbmino uses the new real-time bitmap format
XFS_DIFLAG_IMMUTABLE	Specifies the inode cannot be modified.
XFS_DIFLAG_APPEND	The inode is in append only mode.
XFS_DIFLAG_SYNC	The inode is written synchronously.
XFS_DIFLAG_NOATIME	The inode's di_atime is not updated.
XFS_DIFLAG_NODUMP	Specifies the inode is to be ignored by xfsdump.
XFS_DIFLAG_RTINHERIT	For directory inodes, new inodes inherit the XFS_DIFLAG_REALTIME bit.
XFS_DIFLAG_PROJINHERIT	For directory inodes, new inodes inherit the di_projid value.
XFS_DIFLAG_NOSYMLINKS	For directory inodes, symlinks cannot be created.
XFS_DIFLAG_EXTSIZE	Specifies the extent size for real-time files or an extent size hint for regular files.
XFS_DIFLAG_EXTSZINHERIT	For directory inodes, new inodes inherit the di_extsize value.
XFS_DIFLAG_NODEFRAG	Specifies the inode is to be ignored when defragmenting the filesystem.
XFS_DIFLAG_FILESTREAMS	Use the filestream allocator. The filestreams allocator allows a directory to reserve an entire allocation group for exclusive use by files created in that directory. Files in other directories cannot use AGs reserved by other directories.

di_gen
A generation number used for inode identification. This is used by tools that do inode scanning such as backup tools and xfsdump. An inode's generation number can change by unlinking and creating a new file that reuses the inode.

di_next_unlinked
See the section on unlinked inode pointers Section 16.2 for more information.

di_crc
Checksum of the inode.

di_changecount
Counts the number of changes made to the attributes in this inode.

di_lsn
Log sequence number of the last inode write.

di_flags2
Specifies extended flags associated with a v3 inode.

Table 16.2: Version 3 Inode flags

Flag	Description
XFS_DIFLAG2_DAX	For a file, enable DAX to increase performance on persistent-memory storage. If set on a directory, files created in the directory will inherit this flag.
XFS_DIFLAG2_REFLINK	This inode shares (or has shared) data blocks with another inode.
XFS_DIFLAG2_COWEXTSIZE	For files, this is the extent size hint for copy on write operations; see di_cowextsize for details. For directories, the value in di_cowextsize will be copied to all newly created files and directories.

di_cowextsize
Specifies the extent size hint for copy on write operations. When allocating extents for a copy on write operation, the allocator will be asked to align its allocations to either di_cowextsize blocks or di_extsize blocks, whichever is greater. The XFS_DIFLAG2_COWEXTSIZE flag must be set if this field is used. If this field and its flag are set on a directory file, the value will be copied into any files or directories created within this directory. During a block sharing operation, this value will be copied from the source file to the destination file if the sharing operation completely overwrites the destination file's contents and the destination file does not already have di_cowextsize set.

di_pad2
Padding for future expansion of the inode.

di_crtime
Specifies the time when this inode was created.

di_ino
The full inode number of this inode.

di_uuid
The UUID of this inode, which must match either sb_uuid or sb_meta_uuid depending on which features are set.

16.2 Unlinked Pointer

The di_next_unlinked value in the inode is used to track inodes that have been unlinked (deleted) but are still open by a program. When an inode is in this state, the inode is added to one of the AGI's Section 13.3 agi_unlinked hash buckets. The AGI unlinked bucket points to an inode and the di_next_unlinked value points to the next inode in the chain. The last inode in the chain has di_next_unlinked set to NULL (-1).

Once the last reference is released, the inode is removed from the unlinked hash chain and di_next_unlinked is set to NULL. In the case of a system crash, XFS recovery will complete the unlink process for any inodes found in these lists.

The only time the unlinked fields can be seen to be used on disk is either on an active filesystem or a crashed system. A cleanly unmounted or recovered filesystem will not have any inodes in these unlink hash chains.

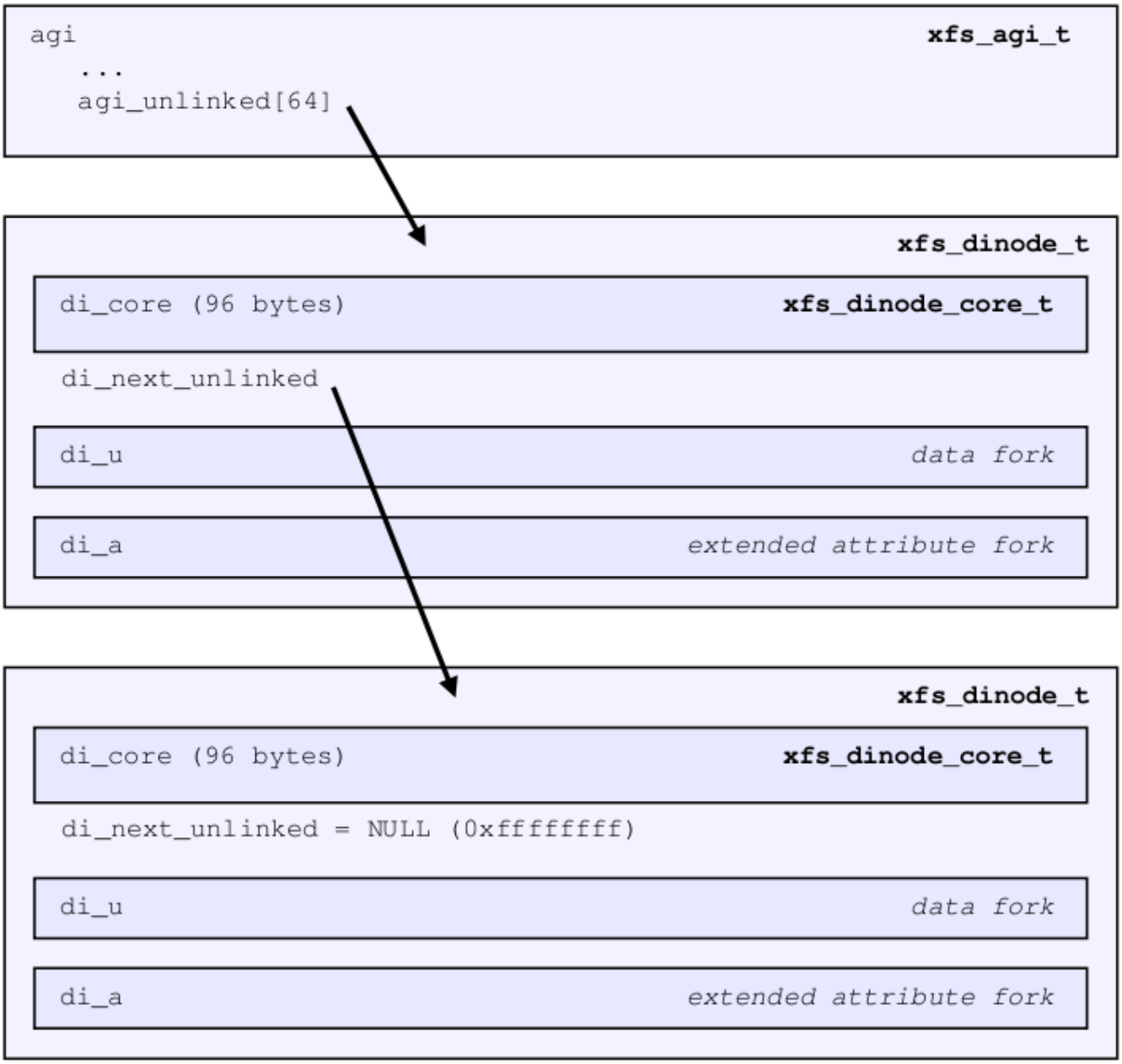


Figure 16.2: Unlinked inode pointer

16.3 Data Fork

The structure of the inode's data fork based is on the inode's type and `di_format`. The data fork begins at the start of the inode's "literal area". This area starts at offset 100 (0x64), or offset 176 (0xb0) in a v3 inode. The size of the data fork is determined by the type and format. The maximum size is determined by the inode size and `di_forkoff`. In code, use the `XFS_DFORK_PTR` macro specifying `XFS_DATA_FORK` for the "which" parameter. Alternatively, the `XFS_DFORK_DPTR` macro can be used.

Each of the following sub-sections summarises the contents of the data fork based on the inode type.

16.3.1 Regular Files (S_IFREG)

The data fork specifies the file's data extents. The extents specify where the file's actual data is located within the filesystem. Extents can have 2 formats which is defined by the di_format value:

- `XFS_DINODE_FMT_EXTENTS`: The extent data is fully contained within the inode which contains an array of extents to the filesystem blocks for the file's data. To access the extents, cast the return value from `XFS_DFORK_DPTR` to `xfs_bmbt_rec_t*`.
- `XFS_DINODE_FMT_BTREE`: The extent data is contained in the leaves of a B+tree. The inode contains the root node of the tree and is accessed by casting the return value from `XFS_DFORK_DPTR` to `xfs_bmdr_block_t*`.

Details for each of these data extent formats are covered in the Data Extents Chapter 17 later on.

16.3.2 Directories (S_IFDIR)

The data fork contains the directory's entries and associated data. The format of the entries is also determined by the `di_format` value and can be one of 3 formats:

- `XFS_DINODE_FMT_LOCAL`: The directory entries are fully contained within the inode. This is accessed by casting the value from `XFS_DFORK_DPTR` to `xfs_dir2_sf_t*`.
- `XFS_DINODE_FMT_EXTENTS`: The actual directory entries are located in another filesystem block, the inode contains an array of extents to these filesystem blocks (`xfs_bmbt_rec_t*`).
- `XFS_DINODE_FMT_BTREE`: The directory entries are contained in the leaves of a B+tree. The inode contains the root node (`xfs_bmdr_block_t*`).

Details for each of these directory formats are covered in the Directories Chapter 18 later on.

16.3.3 Symbolic Links (S_IFLNK)

The data fork contains the contents of the symbolic link. The format of the link is determined by the `di_format` value and can be one of 2 formats:

- `XFS_DINODE_FMT_LOCAL`: The symbolic link is fully contained within the inode. This is accessed by casting the return value from `XFS_DFORK_DPTR` to `char*`.
- `XFS_DINODE_FMT_EXTENTS`: The actual symlink is located in another filesystem block, the inode contains the extents to these filesystem blocks (`xfs_bmbt_rec_t*`).

Details for symbolic links is covered in the section about Symbolic Links Chapter 20.

16.3.4 Other File Types

For character and block devices (`S_IFCHR` and `S_IFBLK`), cast the value from `XFS_DFORK_DPTR` to `xfs_dev_t*`.

16.4 Attribute Fork

The attribute fork in the inode always contains the location of the extended attributes associated with the inode.

The location of the attribute fork in the inode's literal area is specified by the `di_forkoff` value in the inode's core. If this value is zero, the inode does not contain any extended attributes. If non-zero, the attribute fork's byte offset into the literal area can be computed from `di_forkoff` × 8. Attributes must be allocated on a 64-bit boundary on the disk. To access the extended attributes in code, use the `XFS_DFORK_PTR` macro specifying `XFS_ATTR_FORK` for the "which" parameter. Alternatively, the `XFS_DFORK_APTR` macro can be used.

The structure of the attribute fork depends on the `di_aformat` value in the inode. It can be one of the following values:

- XFS_DINODE_FMT_LOCAL: The extended attributes are contained entirely within the inode. This is accessed by casting the value from XFS_DFORK_APTR to xfs_attr_shortform_t*.
- XFS_DINODE_FMT_EXTENTS: The attributes are located in another filesystem block, the inode contains an array of pointers to these filesystem blocks. They are accessed by casting the value from XFS_DFORK_APTR to xfs_bmbt_rec_t*.
- XFS_DINODE_FMT_BTREE: The extents for the attributes are contained in the leaves of a B+tree. The inode contains the root node of the tree and is accessed by casting the value from XFS_DFORK_APTR to xfs_bmdr_block_t*.

Detailed information on the layouts of extended attributes are covered in the Extended Attributes Chapter 19 in this document.

16.4.1 Extended Attribute Versions

Extended attributes come in two versions: “attr1” or “attr2”. The attribute version is specified by the XFS_SB_VERSION2_ATTR2BIT flag in the sb_features2 field in the superblock. It determines how the inode’s extra space is split between di_u and di_a forks which also determines how the di_forkoff value is maintained in the inode’s core.

With “attr1” attributes, the di_forkoff is set to somewhere in the middle of the space between the core and end of the inode and never changes (which has the effect of artificially limiting the space for data information). As the data fork grows, when it gets to di_forkoff, it will move the data to the next format level (ie. local < extent < btree). If very little space is used for either attributes or data, then a good portion of the available inode space is wasted with this version.

“attr2” was introduced to maximum the utilisation of the inode’s literal area. The di_forkoff starts at the end of the inode and works its way to the data fork as attributes are added. Attr2 is highly recommended if extended attributes are used.

The following diagram compares the two versions:

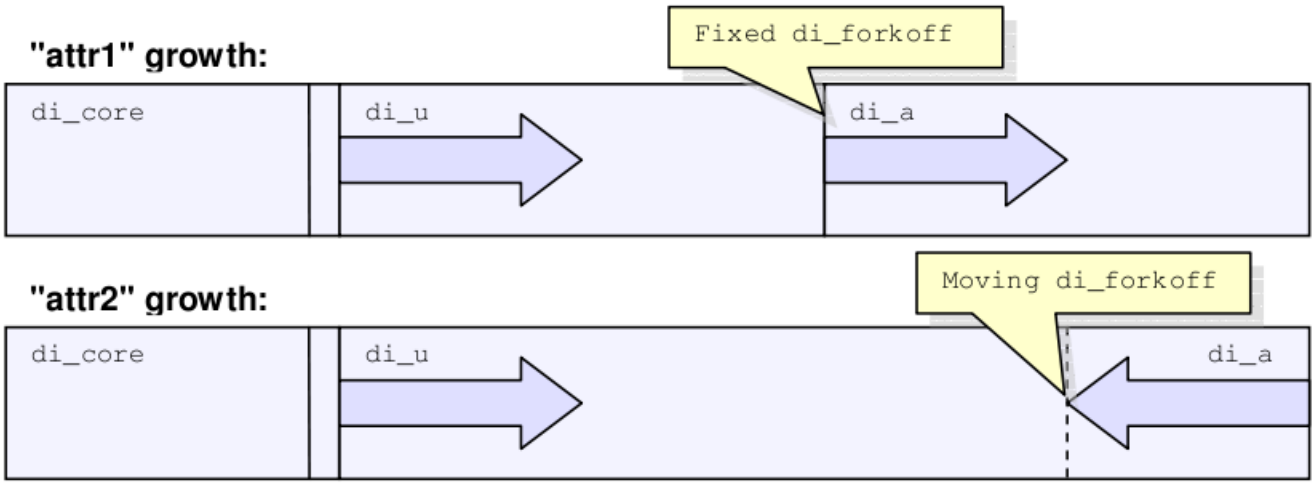


Figure 16.3: Extended attribute layouts

Note that because di_forkoff is an 8-bit value measuring units of 8 bytes, the maximum size of an inode is $2^8 \times 2^3 = 2^{11} =$ 2048 bytes.

Chapter 17

Data Extents

XFS manages space using extents, which are defined as a starting location and length. A fork in an XFS inode maps a logical offset to a space extent. This enables a file's extent map to support sparse files (i.e. "holes" in the file). A flag is also used to specify if the extent has been preallocated but has not yet been written (unwritten extent).

A file can have more than one extent if one chunk of contiguous disk space is not available for the file. As a file grows, the XFS space allocator will attempt to keep space contiguous and to merge extents. If more than one file is being allocated space in the same AG at the same time, multiple extents for the files will occur as the extent allocations interleave. The effect of this can vary depending on the extent allocator used in the XFS driver.

An extent is 128 bits in size and uses the following packed layout:

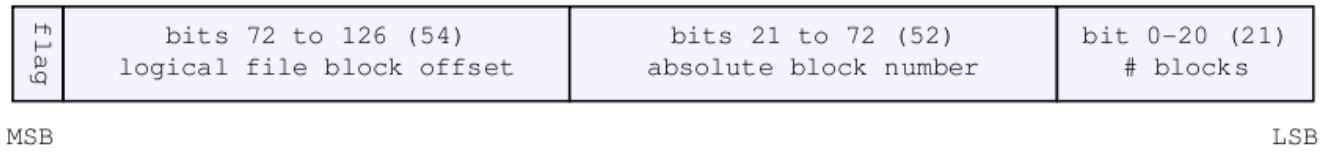


Figure 17.1: Extent record format

The extent is represented by the `xfs_bmbt_rec` structure which uses a big endian format on-disk. In-core management of extents use the `xfs_bmbt_irec` structure which is the unpacked version of `xfs_bmbt_rec`:

```
struct xfs_bmbt_irec {
     xfs_fileoff_t              br_startoff;
     xfs_fsblock_t              br_startblock;
     xfs_filblks_t              br_blockcount;
     xfs_exntst_t               br_state;
};
```

br_startoff
Logical block offset of this mapping.

br_startblock
Filesystem block of this mapping.

br_blockcount
The length of this mapping.

br_state
The extent `br_state` field uses the following enum declaration:

```
typedef enum {
     XFS_EXT_NORM,
     XFS_EXT_UNWRITTEN,
     XFS_EXT_INVALID
} xfs_exntst_t;
```

Some other points about extents:

- The `xfs_bmbt_rec_32_t` and `xfs_bmbt_rec_64_t` structures were effectively the same as `xfs_bmbt_rec_t`, just different representations of the same 128 bits in on-disk big endian format. `xfs_bmbt_rec_32_t` was removed and `xfs_bmbt_rec_64_t` renamed to `xfs_bmbt_rec_t` some time ago.
- When a file is created and written to, XFS will endeavour to keep the extents within the same AG as the inode. It may use a different AG if the AG is busy or there is no space left in it.
- If a file is zero bytes long, it will have no extents and `di_nblocks` and `di_nexents` will be zero. Any file with data will have at least one extent, and each extent can use from 1 to over 2 million blocks (2^{21}) on the filesystem. For a default 4KB block size filesystem, a single extent can be up to 8GB in length.

The following two subsections cover the two methods of storing extent information for a file. The first is the fastest and simplest where the inode completely contains an extent array to the file's data. The second is slower and more complex B+tree which can handle thousands to millions of extents efficiently.

17.1 Extent List

If the entire extent list is short enough to fit within the inode's fork region, we say that the fork is in "extent list" format. This is the most optimal in terms of speed and resource consumption. The trade-off is the file can only have a few extents before the inode runs out of space.

The data fork of the inode contains an array of extents; the size of the array is determined by the inode's `di_nextents` value.

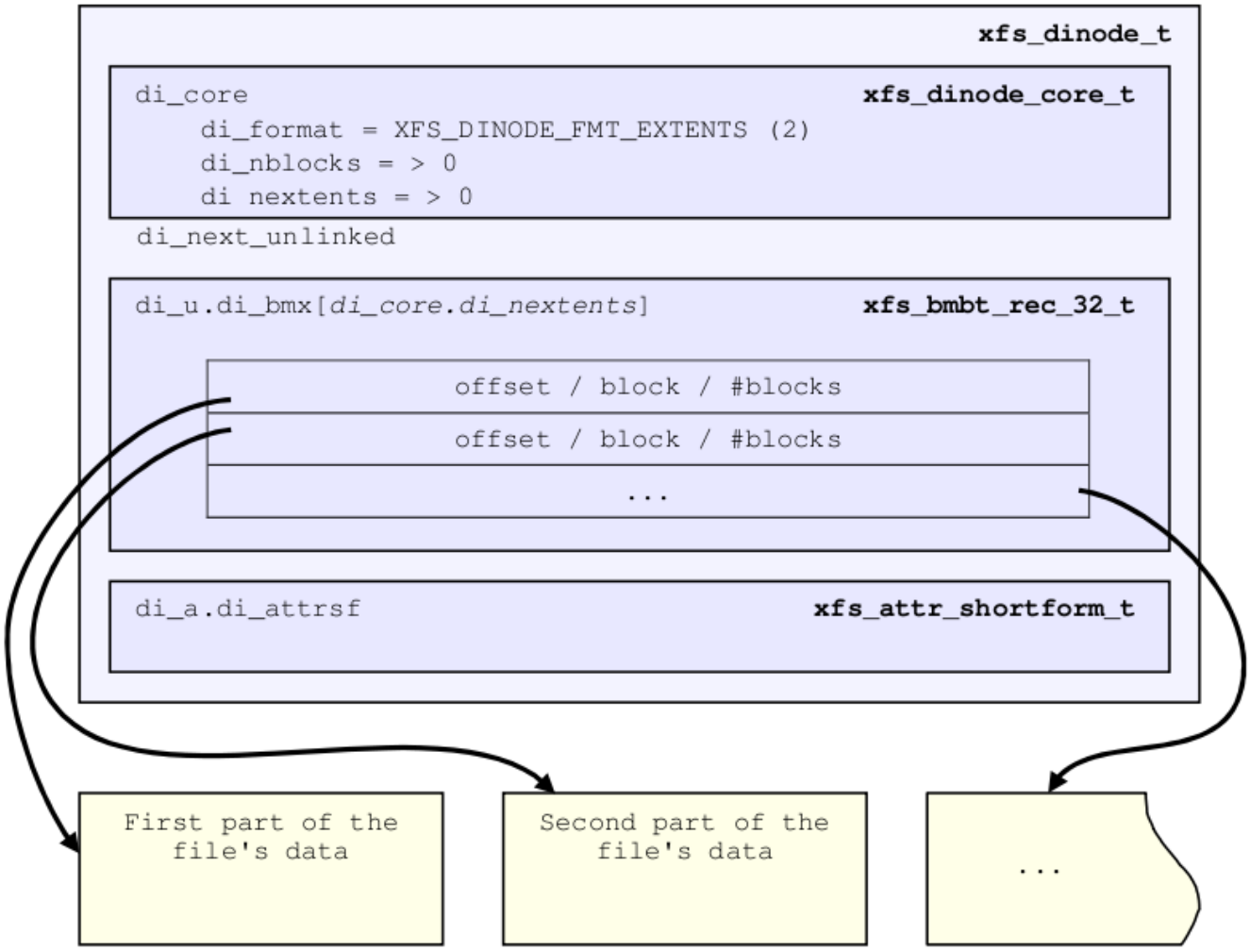


Figure 17.2: Inode data fork extent layout

The number of extents that can fit in the inode depends on the inode size and `di_forkoff`. For a default 256 byte inode with no extended attributes, a file can have up to 9 extents with this format. On a default v5 filesystem with 512 byte inodes, a file can have up to 21 extents with this format. Beyond that, extents have to use the B+tree format.

17.1.1 xfs_db Inode Data Fork Extents Example

An 8MB file with one extent:

```
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 0100644
core.version = 1
core.format = 2 (extents)
...
core.size = 8294400
core.nblocks = 2025
core.extsize = 0
core.nextents = 1
core.naextents = 0
```

```
core.forkoff = 0
...
u.bmx[0] = [startoff,startblock,blockcount,extentflag]
        0:[0,25356,2025,0]
```

A 24MB file with three extents:

```
xfs_db> inode <inode#>
xfs_db> p
...
core.format = 2 (extents)
...
core.size = 24883200
core.nblocks = 6075
core.nextents = 3
...
u.bmx[0-2] = [startoff,startblock,blockcount,extentflag]
        0:[0,27381,2025,0]
        1:[2025,31431,2025,0]
        2:[4050,35481,2025,0]
```

Raw disk version of the inode with the third extent highlighted (`di_u` starts at offset 0x64):

```
xfs_db> type text
xfs_db> p
00: 49 4e 81 a4 01 02 00 01 00 00 00 00 00 00 00 00 IN..............
10: 00 00 00 01 00 00 00 00 00 00 00 00 00 00 00 01 ................
20: 44 b6 88 dd 2f 8a ed d0 44 b6 88 f7 10 8c 5b de D.......D.......
30: 44 b6 88 f7 10 8c 5b d0 00 00 00 00 01 7b b0 00 D.............
40: 00 00 00 00 00 00 17 bb 00 00 00 00 00 00 00 03 ................
50: 00 00 00 02 00 00 00 00 00 00 00 00 00 00 00 00 ................
60: ff ff ff ff 00 00 00 00 00 00 00 00 00 00 00 0d ................
70: 5e a0 07 e9 00 00 00 00 00 0f d2 00 00 00 00 0f ................
80: 58 e0 07 e9 00 00 00 00 00 1f a4 00 00 00 00 11 X...............
90: 53 20 07 e9 00 00 00 00 00 00 00 00 00 00 00 00 S...............
a0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
be: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
co: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
do: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
e0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
fo: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
```

We can expand the highlighted section into the following bit array from MSB to LSB with the file offset and the block count highlighted:

```
127-96:  0000 0000 0000 0000  0000 0000 0000 0000
 95-64:  0000 0000 0001 1111  1010 0100 0000 0000
 63-32:  0000 0000 0000 0000  0000 0000 0000 1111
 31-0 :  0101 1000 1110 0000  0000 0111 1110 1001

Grouping by highlights we get:
   file offset = 0x0fd2 (4050)
   start block = 0x7ac7 (31431)
   block count = 0x07e9 (2025)
```

A 4MB file with two extents and a hole in the middle, the first extent containing 64KB of data, the second about 4MB in containing 32KB (`write` 64KB, `lseek` 4MB, `write` 32KB operations):

```
xfs_db> inode <inode#>
xfs_db> p
...
core.format = 2 (extents)
```

```
...
core.size = 4063232
core.nblocks = 24
core.nextents = 2
...
u.bmx[0-1] = [startoff,startblock,blockcount,extentflag]
        0:[0,37506,16,0]
        1:[984,37522,8,0]
```

17.2 B+tree Extent List

To manage extent maps that cannot fit in the inode fork area, XFS uses long format B+trees Section 10.2. The root node of the B+tree is stored in the inode's data fork. All block pointers for extent B+trees are 64-bit filesystem block numbers.

For a single level B+tree, the root node points to the B+tree's leaves. Each leaf occupies one filesystem block and contains a header and an array of extents sorted by the file's offset. Each leaf has left and right (or backward and forward) block pointers to adjacent leaves. For a standard 4KB filesystem block, a leaf can contain up to 254 extents before a B+tree rebalance is triggered.

For a multi-level B+tree, the root node points to other B+tree nodes which eventually point to the extent leaves. B+tree keys are based on the file's offset and have pointers to the next level down. Nodes at each level in the B+tree also have pointers to the adjacent nodes.

The base B+tree node is used for extents, directories and extended attributes. The structures used for an inode's B+tree root are:

```
struct xfs_bmdr_block {
     __be16                  bb_level;
     __be16                  bb_numrecs;
};
struct xfs_bmbt_key {
     xfs_fileoff_t           br_startoff;
};
typedef xfs_fsblock_t xfs_bmbt_ptr_t, xfs_bmdr_ptr_t;
```

- On disk, the B+tree node starts with the `xfs_bmdr_block_t` header followed by an array of `xfs_bmbt_key_t` values and then an array of `xfs_bmbt_ptr_t` values. The size of both arrays is specified by the header's `bb_numrecs` value.
- The root node in the inode can only contain up to 9 key/pointer pairs for a standard 256 byte inode before a new level of nodes is added between the root and the leaves. This will be less if `di_forkoff` is not zero (i.e. attributes are in use on the inode).
- The magic number for a BMBT block is "BMAP" (0x424d4150). On a v5 filesystem, this is "BMA3" (0x424d4133).
- For intermediate nodes, the data following `xfs_btree_lblock` is the same as the root node: array of `xfs_bmbt_key` value followed by an array of `xfs_bmbt_ptr_t` values that starts halfway through the block (offset 0x808 for a 4096 byte filesystem block).
- For leaves, an array of `xfs_bmbt_rec` extents follow the `xfs_btree_lblock` header.
- Nodes and leaves use the same value for `bb_magic`.
- The `bb_level` value determines if the node is an intermediate node or a leaf. Leaves have a `bb_level` of zero, nodes are one or greater.
- Intermediate nodes, like leaves, can contain up to 254 pointers to leaf blocks for a standard 4KB filesystem block size as both the keys and pointers are 64 bits in size.

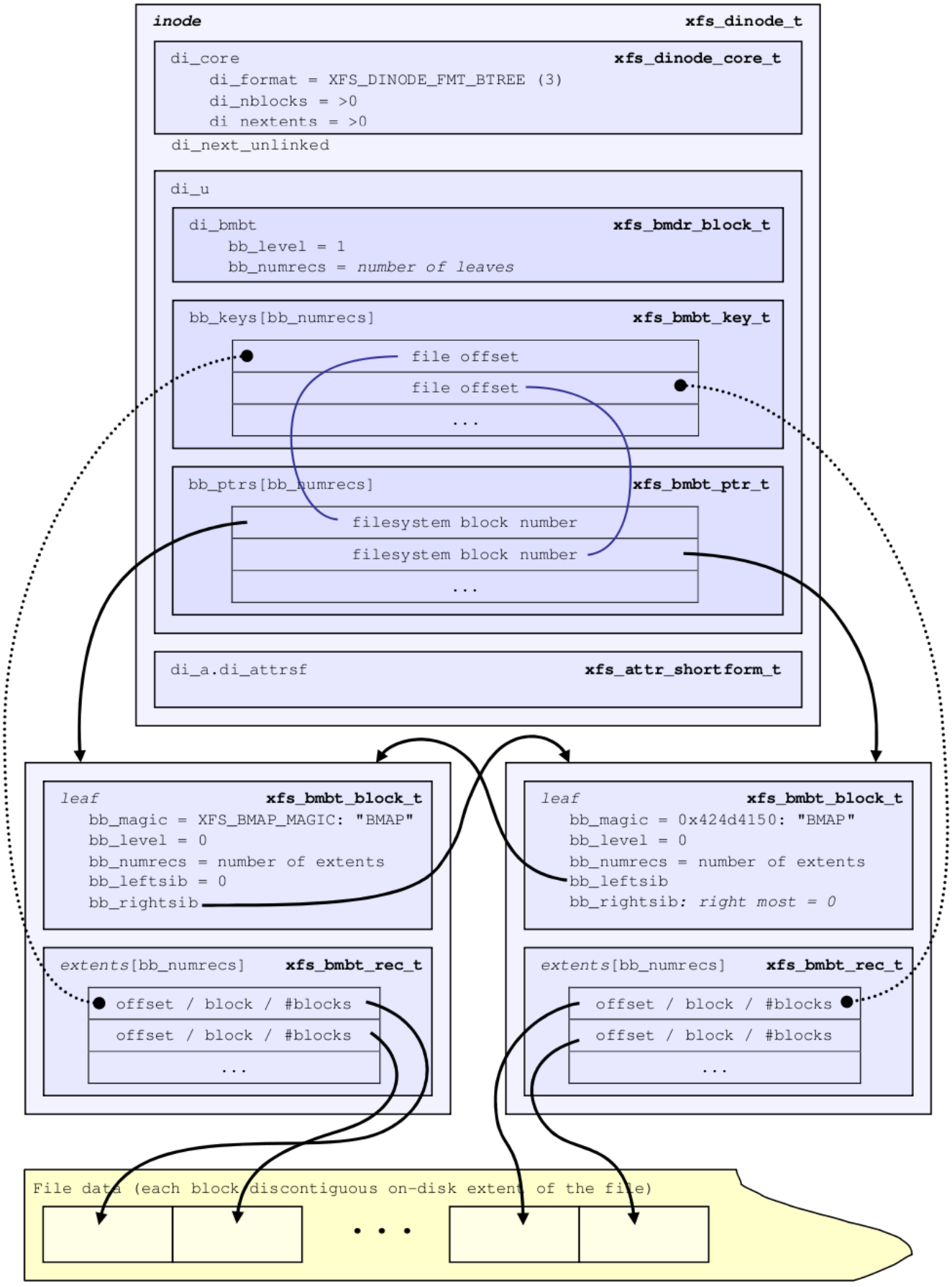


Figure 17.3: Single level extent B+tree

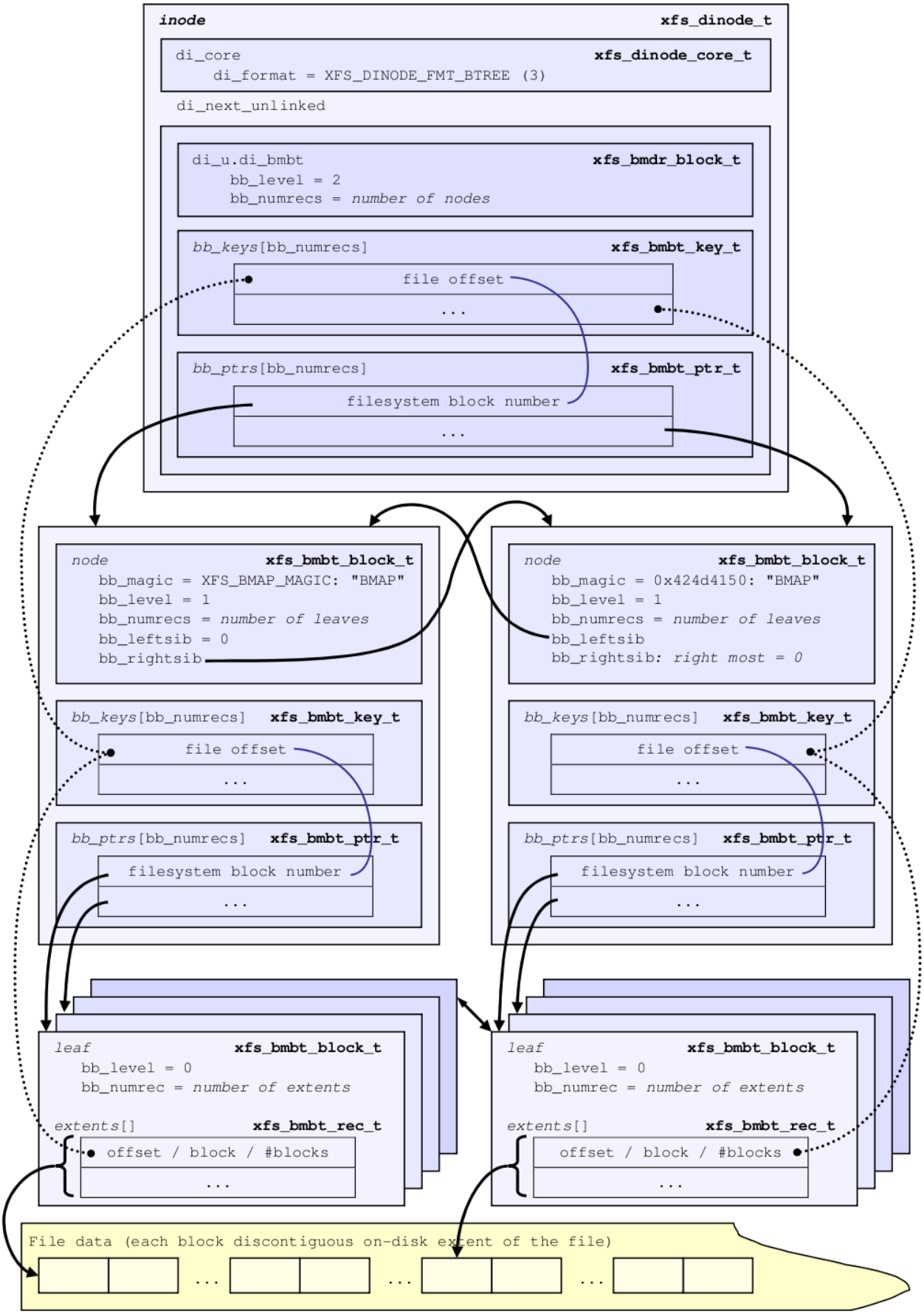


Figure 17.4: Multiple level extent B+tree

17.2.1 xfs_db bmbt Example

In this example, we dissect the data fork of a VM image that is sufficiently sparse and interleaved to have become a B+tree.

```
xfs_db> inode 132
xfs_db> p
core.magic = 0x494e
core.mode = 0100600
core.version = 3
core.format = 3 (btree)
...
u3.bmbt.level = 1
u3.bmbt.numrecs = 3
u3.bmbt.keys[1-3] = [startoff] 1:[0] 2:[9072] 3:[13136]
u3.bmbt.ptrs[1-3] = 1:8568 2:8569 3:8570
```

As you can see, the block map B+tree is rooted in the inode. This tree has two levels, so let's go down a level to look at the records:

```
xfs_db> addr u3.bmbt.ptrs[1]
xfs_db> p
magic = 0x424d4133
level = 0
numrecs = 251
leftsib = null
rightsib = 8569
bno = 68544
lsn = 0x100000006
uuid = 9579903c-333f-4673-a7d4-3254c05816ea
owner = 132
crc = 0xc61513dc (correct)
recs[1-251] = [startoff,startblock,blockcount,extentflag]
        1:[0,8520,48,0] 2:[48,4421,16,0] 3:[80,9136,16,0] 4:[96,8569,16,0]
        5:[144,8601,32,0] 6:[192,8637,16,0] 7:[240,8680,16,0] 8:[288,9870,16,0]
        9:[320,9920,16,0] 10:[336,9950,16,0] 11:[384,4004,32,0]
        12:[432,6771,16,0] 13:[480,2702,16,0] 14:[528,8420,16,0]
        ...
```

Chapter 18

Directories

Note
Only v2 directories covered here. v1 directories are obsolete.

Note
The term "block" in this section will refer to directory blocks, not filesystem blocks unless otherwise specified.

The size of a "directory block" is defined by the superblock's Section 13.1 `sb_dirblklog` value. The size in bytes = `sb_blocksize` × $2^{\texttt{sb\_dirblklog}}$. For example, if `sb_blocksize` = 4096 and `sb_dirblklog` = 2, the directory block size is 16384 bytes. Directory blocks are always allocated in multiples based on `sb_dirblklog`. Directory blocks cannot be more that 65536 bytes in size.

All directory entries contain the following "data":

- The entry's name (counted string consisting of a single byte `namelen` followed by `name` consisting of an array of 8-bit chars without a NULL terminator).
- The entry's absolute inode number Section 13.3.1, which are always 64 bits (8 bytes) in size except a special case for shortform directories.
- An `offset` or `tag` used for iterative readdir calls.
- If the `XFS_SB_FEAT_INCOMPAT_FTYPE` feature flag is set, each directory entry contains an `ftype` field that caches the inode's type to avoid having to perform an inode lookup.

Table 18.1: ftype values

Flag	Description
`XFS_DIR3_FT_UNKNOWN`	Entry points to an unknown inode type. This should never appear on disk.
`XFS_DIR3_FT_REG_FILE`	Entry points to a file.
`XFS_DIR3_FT_DIR`	Entry points to another directory.
`XFS_DIR3_FT_CHRDEV`	Entry points to a character device.
`XFS_DIR3_FT_BLKDEV`	Entry points to a block device.
`XFS_DIR3_FT_FIFO`	Entry points to a FIFO.
`XFS_DIR3_FT_SOCK`	Entry points to a socket.
`XFS_DIR3_FT_SYMLINK`	Entry points to a symbolic link.
`XFS_DIR3_FT_WHT`	Entry points to an overlayfs whiteout file. This (as far as the author knows) has never appeared on disk.

All non-shortform directories also contain two additional structures: “leaves” and “freespace indexes”.

- Leaves contain the sorted hashed name value (`xfs_da_hashname()` in xfs_da_btree.c) and associated “address” which points to the effective offset into the directory’s data structures. Leaves are used to optimise lookup operations.
- Freespace indexes contain free space/empty entry tracking for quickly finding an appropriately sized location for new entries. They maintain the largest free space for each “data” block.

A few common types are used for the directory structures:

```
typedef __uint16_t xfs_dir2_data_off_t;
typedef __uint32_t xfs_dir2_dataptr_t;
```

18.1 Short Form Directories

- Directory entries are stored within the inode.
- The only data stored is the name, inode number, and offset. No “leaf” or “freespace index” information is required as an inode can only store a few entries.
- “.” is not stored (as it’s in the inode itself), and “..” is a dedicated `parent` field in the header.
- The number of directories that can be stored in an inode depends on the inode Chapter 16 size, the number of entries, the length of the entry names, and extended attribute data.
- Once the number of entries exceeds the space available in the inode, the format is converted to a block directory Section 18.2.
- Shortform directory data is packed as tightly as possible on the disk with the remaining space zeroed:

```
typedef struct xfs_dir2_sf {
     xfs_dir2_sf_hdr_t         hdr;
     xfs_dir2_sf_entry_t       list[1];
} xfs_dir2_sf_t;
```

hdr
: Short form directory header.

list
: An array of variable-length directory entry records.

```
typedef struct xfs_dir2_sf_hdr {
     __uint8_t                 count;
     __uint8_t                 i8count;
     xfs_dir2_inou_t           parent;
} xfs_dir2_sf_hdr_t;
```

count
: Number of directory entries.

i8count
: Number of directory entries requiring 64-bit entries, if any inode numbers require 64-bits. Zero otherwise.

parent
: The absolute inode number of this directory’s parent.

```
typedef struct xfs_dir2_sf_entry {
     __uint8_t                  namelen;
     xfs_dir2_sf_off_t          offset;
     __uint8_t                  name[1];
     __uint8_t                  ftype;
     xfs_dir2_inou_t            inumber;
} xfs_dir2_sf_entry_t;
```

namelen
Length of the name, in bytes.

offset
Offset tag used to assist with directory iteration.

name
The name of the directory entry. The entry is not NULL-terminated.

ftype
The type of the inode. This is used to avoid reading the inode while iterating a directory. The `XFS_SB_VERSION2_FTYPE` feature must be set, or this field will not be present.

inumber
The inode number that this entry points to. The length is either 32 or 64 bits, depending on whether `icount` or `i8count`, respectively, are set in the header.

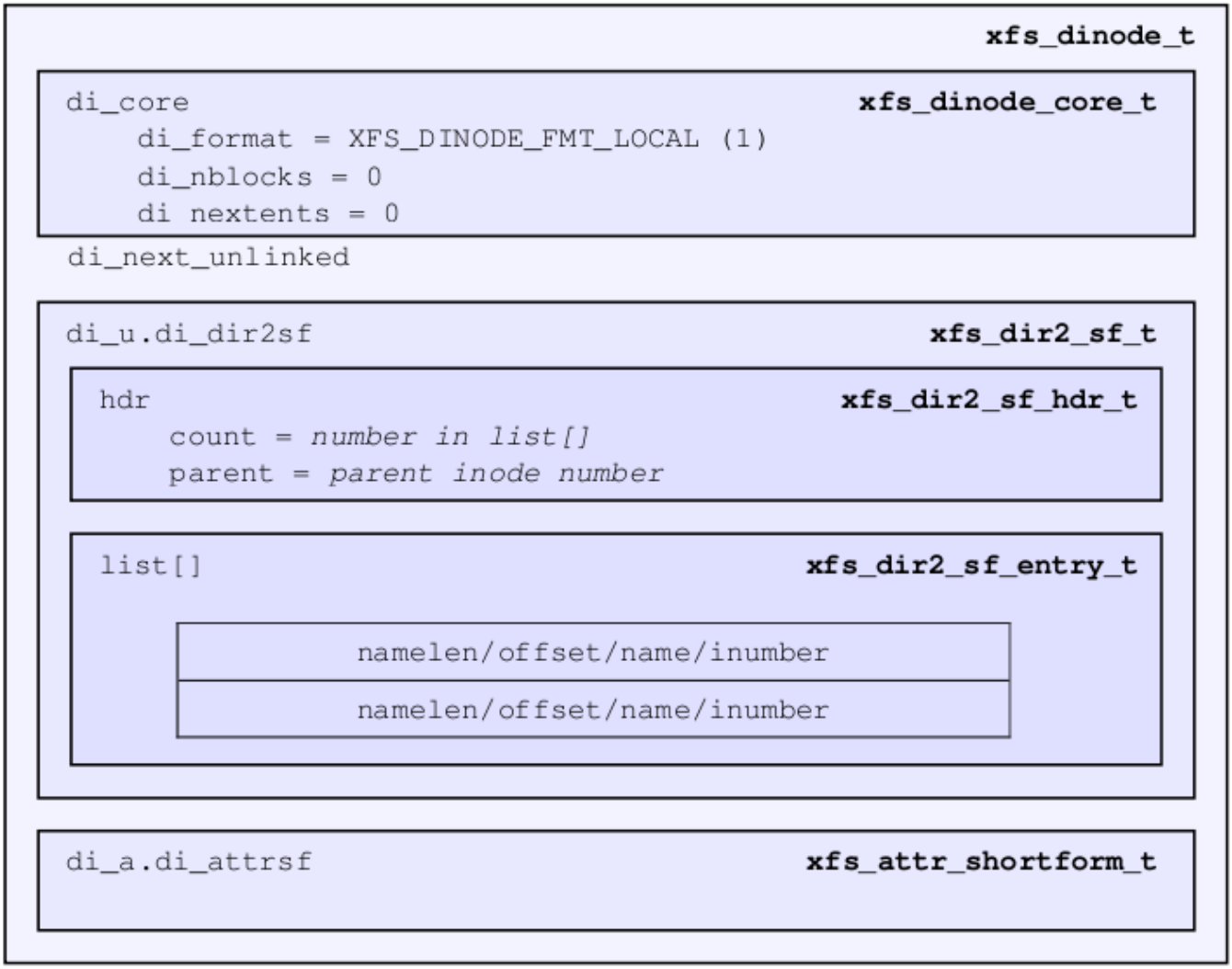


Figure 18.1: Short form directory layout

- Inode numbers are stored using 4 or 8 bytes depending on whether all the inode numbers for the directory fit in 4 bytes (32 bits) or not. If all inode numbers fit in 4 bytes, the header's `count` value specifies the number of entries in the directory and `i8count` will be zero. If any inode number exceeds 4 bytes, all inode numbers will be 8 bytes in size and the header's `i8count` value specifies the number of entries requiring larger inodes. `i4count` is still the number of entries. The following union covers the shortform inode number structure:

```
typedef struct { __uint8_t i[8]; } xfs_dir2_ino8_t;
typedef struct { __uint8_t i[4]; } xfs_dir2_ino4_t;
typedef union {
     xfs_dir2_ino8_t           i8;
     xfs_dir2_ino4_t           i4;
} xfs_dir2_inou_t;
```

18.1.1 xfs_db Short Form Directory Example

A directory is created with 4 files, all inode numbers fitting within 4 bytes:

```
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 040755
core.version = 1
core.format = 1 (local)
core.nlinkv1 = 2
...
core.size = 94
core.nblocks = 0
core.extsize = 0
core.nextents = 0
...
u.sfdir2.hdr.count = 4
u.sfdir2.hdr.i8count = 0
u.sfdir2.hdr.parent.i4 = 128              /* parent = root inode */
u.sfdir2.list[0].namelen = 15
u.sfdir2.list[0].offset = 0x30
u.sfdir2.list[0].name = "frame000000.tst"
u.sfdir2.list[0].inumber.i4 = 25165953
u.sfdir2.list[1].namelen = 15
u.sfdir2.list[1].offset = 0x50
u.sfdir2.list[1].name = "frame000001.tst"
u.sfdir2.list[1].inumber.i4 = 25165954
u.sfdir2.list[2].namelen = 15
u.sfdir2.list[2].offset = 0x70
u.sfdir2.list[2].name = "frame000002.tst"
u.sfdir2.list[2].inumber.i4 = 25165955
u.sfdir2.list[3].namelen = 15
u.sfdir2.list[3].offset = 0x90
u.sfdir2.list[3].name = "frame000003.tst"
u.sfdir2.list[3].inumber.i4 = 25165956
```

The raw data on disk with the first entry highlighted. The six byte header precedes the first entry:

```
xfs_db> type text
xfs_db> p
00: 49 4e 41 ed 01 01 00 02 00 00 00 00 00 00 00 00 INA.............
10: 00 00 00 02 00 00 00 00 00 00 00 00 00 00 00 02 ................
20: 44 ad 3a 83 1d a9 4a d0 44 ad 3a ab 0b c7 a7 d0 D.....J.D.......
30: 44 ad 3a ab 0b c7 a7 d0 00 00 00 00 00 00 00 5e D...............
40: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
50: 00 00 00 02 00 00 00 00 00 00 00 00 00 00 00 00 ................
60: ff ff ff ff 04 00 00 00 00 80 0f 00 30 66 72 61 ............0fra
70: 6d 65 30 30 30 30 30 30 2e 74 73 74 01 80 00 81 me000000.tst....
80: 0f 00 50 66 72 61 6d 65 30 30 30 30 30 31 2e 74 ..Pframe000001.t
90: 73 74 01 80 00 82 0f 00 70 66 72 61 6d 65 30 30 st......pframe00
a0: 30 30 30 32 2e 74 73 74 01 80 00 83 0f 00 90 66 0002.tst........
b0: 72 61 6d 65 30 30 30 30 30 33 2e 74 73 74 01 80 rame000003.tst..
cO: 00 84 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
```

Next, an entry is deleted (frame000001.tst), and any entries after the deleted entry are moved or compacted to “cover” the hole:

```
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 040755
core.version = 1
core.format = 1 (local)
core.nlinkv1 = 2
...
```

```
core.size = 72
core.nblocks = 0
core.extsize = 0
core.nextents = 0
...
u.sfdir2.hdr.count = 3
u.sfdir2.hdr.i8count = 0
u.sfdir2.hdr.parent.i4 = 128
u.sfdir2.list[0].namelen = 15
u.sfdir2.list[0].offset = 0x30
u.sfdir2.list[0].name = "frame000000.tst"
u.sfdir2.list[0].inumber.i4 = 25165953
u.sfdir2.list[1].namelen = 15
u.sfdir2.list[1].offset = 0x70
u.sfdir2.list[1].name = "frame000002.tst"
u.sfdir2.list[1].inumber.i4 = 25165955
u.sfdir2.list[2].namelen = 15
u.sfdir2.list[2].offset = 0x90
u.sfdir2.list[2].name = "frame000003.tst"
u.sfdir2.list[2].inumber.i4 = 25165956
```

Raw disk data, the space beyond the shortform entries is invalid and could be non-zero:

```
xfs_db> type text
xfs_db> p
00: 49  4e 41 ed 01 01 00 02 00 00 00 00 00 00 00 00 INA.............
10: 00  00 00 02 00 00 00 00 00 00 00 00 00 00 00 03 ................
20: 44  b2 45 a2 09 fd e4 50 44 b2 45 a3 12 ee b5 d0 D.E....PD.E.....
30: 44  b2 45 a3 12 ee b5 d0 00 00 00 00 00 00 00 48 D.E............H
40: 00  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
50: 00  00 00 02 00 00 00 00 00 00 00 00 00 00 00 00 ................
60: ff  ff ff ff 03 00 00 00 00 80 0f 00 30 66 72 61 ............0fra
70: 6d  65 30 30 30 30 30 30 2e 74 73 74 01 80 00 81 me000000.tst....
80: 0f  00 70 66 72 61 6d 65 30 30 30 30 30 32 2e 74 ..pframe000002.t
90: 73  74 01 80 00 83 0f 00 90 66 72 61 6d 65 30 30 st.......frame00
a0: 30  30 30 33 2e 74 73 74 01 80 00 84 0f 00 90 66 0003.tst.......f
b0: 72  61 6d 65 30 30 30 30 30 33 2e 74 73 74 01 80 rame000003.tst..
c0: 00  84 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
```

This is an example of mixed 4-byte and 8-byte inodes in a directory:

```
xfs_db> inode 1024
xfs_db> p
core.magic = 0x494e
core.mode = 040755
core.version = 3
core.format = 1 (local)
core.nlinkv2 = 9
...
core.size = 125
core.nblocks = 0
core.extsize = 0
core.nextents = 0
...
u3.sfdir3.hdr.count = 7
u3.sfdir3.hdr.i8count = 4
u3.sfdir3.hdr.parent.i8 = 1024
u3.sfdir3.list[0].namelen = 3
u3.sfdir3.list[0].offset = 0x60
u3.sfdir3.list[0].name = "git"
u3.sfdir3.list[0].inumber.i8 = 1027
u3.sfdir3.list[0].filetype = 2
```

```
u3.sfdir3.list[1].namelen = 4
u3.sfdir3.list[1].offset = 0x70
u3.sfdir3.list[1].name = "home"
u3.sfdir3.list[1].inumber.i8 = 13422826546
u3.sfdir3.list[1].filetype = 2
u3.sfdir3.list[2].namelen = 10
u3.sfdir3.list[2].offset = 0x80
u3.sfdir3.list[2].name = "mike"
u3.sfdir3.list[2].inumber.i8 = 4299308032
u3.sfdir3.list[2].filetype = 2
u3.sfdir3.list[3].namelen = 3
u3.sfdir3.list[3].offset = 0x98
u3.sfdir3.list[3].name = "mtr"
u3.sfdir3.list[3].inumber.i8 = 13433252916
u3.sfdir3.list[3].filetype = 2
u3.sfdir3.list[4].namelen = 3
u3.sfdir3.list[4].offset = 0xa8
u3.sfdir3.list[4].name = "vms"
u3.sfdir3.list[4].inumber.i8 = 16647516355
u3.sfdir3.list[4].filetype = 2
u3.sfdir3.list[5].namelen = 5
u3.sfdir3.list[5].offset = 0xb8
u3.sfdir3.list[5].name = "rsync"
u3.sfdir3.list[5].inumber.i8 = 3494912
u3.sfdir3.list[5].filetype = 2
u3.sfdir3.list[6].namelen = 3
u3.sfdir3.list[6].offset = 0xd0
u3.sfdir3.list[6].name = "tmp"
u3.sfdir3.list[6].inumber.i8 = 1593379
u3.sfdir3.list[6].filetype = 2
```

18.2 Block Directories

When the shortform directory space exceeds the space in an inode, the directory data is moved into a new single directory block outside the inode. The inode's format is changed from "local" to "extent" Following is a list of points about block directories.

- All directory data is stored within the one directory block, including "." and ".." entries which are mandatory.
- The block also contains "leaf" and "freespace index" information.
- The location of the block is defined by the inode's in-core extent list Section 17.1: the `di_u.u_bmx[0]` value. The file offset in the extent must always be zero and the `length` = (directory block size / filesystem block size). The block number points to the filesystem block containing the directory data.
- Block directory data is stored in the following structures:

```
#define XFS_DIR2_DATA_FD_COUNT 3
typedef struct xfs_dir2_block {
     xfs_dir2_data_hdr_t        hdr;
     xfs_dir2_data_union_t      u[1];
     xfs_dir2_leaf_entry_t      leaf[1];
     xfs_dir2_block_tail_t      tail;
} xfs_dir2_block_t;
```

hdr
: Directory block header. On a v5 filesystem this is `xfs_dir3_data_hdr_t`.

u
: Union of directory and unused entries.

leaf
: Hash values of the entries in this block.

tail
: Bookkeeping for the leaf entries.

```
typedef struct xfs_dir2_data_hdr {
     __uint32_t                 magic;
     xfs_dir2_data_free_t       bestfree[XFS_DIR2_DATA_FD_COUNT];
} xfs_dir2_data_hdr_t;
```

magic
: Magic number for this directory block.

bestfree
: An array pointing to free regions in the directory block.

On a v5 filesystem, directory and attribute blocks are formatted with v3 headers, which contain extra data:

```
struct xfs_dir3_blk_hdr {
     __be32                     magic;
     __be32                     crc;
     __be64                     blkno;
     __be64                     lsn;
     uuid_t                     uuid;
     __be64                     owner;
};
```

magic
: Magic number for this directory block.

crc
: Checksum of the directory block.

blkno
: Block number of this directory block.

lsn
: Log sequence number of the last write to this block.

uuid
: The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

owner
: The inode number that this directory block belongs to.

```
struct xfs_dir3_data_hdr {
     struct xfs_dir3_blk_hdr    hdr;
     xfs_dir2_data_free_t       best_free[XFS_DIR2_DATA_FD_COUNT];
     __be32                     pad;
};
```

hdr
: The v5 directory/attribute block header.

best_free
An array pointing to free regions in the directory block.

pad
Padding to maintain a 64-bit alignment.

Within the block, data structures are as follows:

```
typedef struct xfs_dir2_data_free {
     xfs_dir2_data_off_t        offset;
     xfs_dir2_data_off_t        length;
} xfs_dir2_data_free_t;
```

offset
Block offset of a free block, in bytes.

length
Length of the free block, in bytes.

Space inside the directory block can be used for directory entries or unused entries. This is signified via a union of the two types:

```
typedef union {
     xfs_dir2_data_entry_t      entry;
     xfs_dir2_data_unused_t     unused;
} xfs_dir2_data_union_t;
```

entry
A directory entry.

unused
An unused entry.

```
typedef struct xfs_dir2_data_entry {
     xfs_ino_t                  inumber;
     __uint8_t                  namelen;
     __uint8_t                  name[1];
     __uint8_t                  ftype;
     xfs_dir2_data_off_t        tag;
} xfs_dir2_data_entry_t;
```

inumber
The inode number that this entry points to.

namelen
Length of the name, in bytes.

name
The name associated with this entry.

ftype
The type of the inode. This is used to avoid reading the inode while iterating a directory. The `XFS_SB_VERSION2_FTYPE` feature must be set, or this field will not be present.

tag
Starting offset of the entry, in bytes. This is used for directory iteration.

```
typedef struct xfs_dir2_data_unused {
     __uint16_t                 freetag;  /* 0xffff */
     xfs_dir2_data_off_t        length;
     xfs_dir2_data_off_t        tag;
} xfs_dir2_data_unused_t;
```

freetag
Magic number signifying that this is an unused entry. Must be 0xFFFF.

length
Length of this unused entry, in bytes.

tag
Starting offset of the entry, in bytes.

```
typedef struct xfs_dir2_leaf_entry {
     xfs_dahash_t               hashval;
     xfs_dir2_dataptr_t         address;
} xfs_dir2_leaf_entry_t;
```

hashval
Hash value of the name of the directory entry. This is used to speed up entry lookups.

address
Block offset of the entry, in eight byte units.

```
typedef struct xfs_dir2_block_tail {
     __uint32_t                 count;
     __uint32_t                 stale;
} xfs_dir2_block_tail_t;
```

count
Number of leaf entries.

stale
Number of free leaf entries.

Following is a diagram of how these pieces fit together for a block directory.

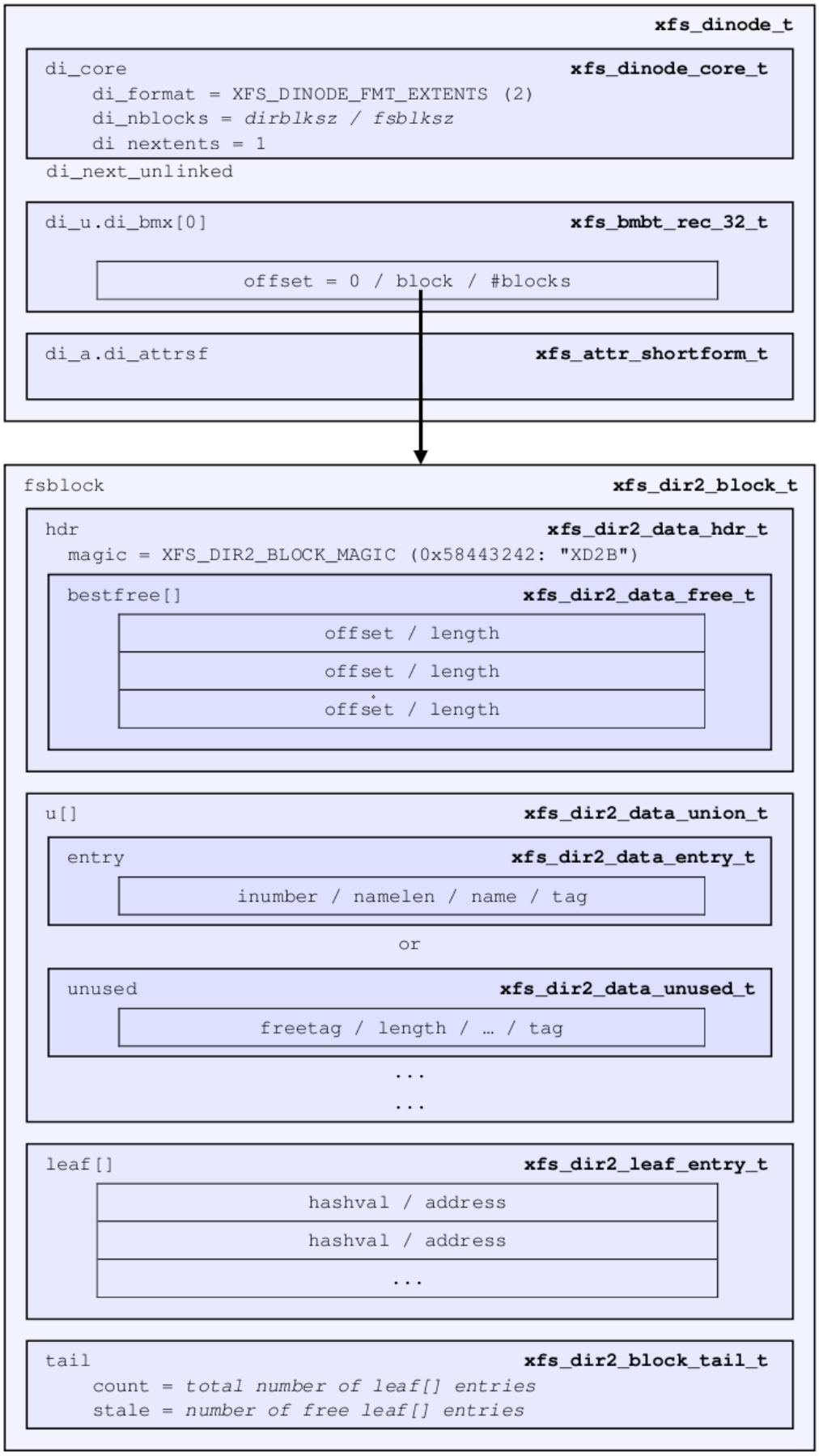


Figure 18.2: Block directory layout

- The magic number in the header is "XD2B" (0x58443242), or "XDB3" (0x58444233) on a v5 filesystem.
- The `tag` in the `xfs_dir2_data_entry_t` structure stores its offset from the start of the block.
- The start of a free space region is marked with the `xfs_dir2_data_unused_t` structure where the `freetag` is `0xffff`. The `freetag` and `length` overwrites the `inumber` for an entry. The `tag` is located at `length -sizeof(tag)` from the start of the `unused` entry on-disk.
- The `bestfree` array in the header points to as many as three of the largest spaces of free space within the block for storing new entries sorted by largest to third largest. If there are less than 3 empty regions, the remaining `bestfree` elements are zeroed. The `offset` specifies the offset from the start of the block in bytes, and the `length` specifies the size of the free space in bytes. The location each points to must contain the above `xfs_dir2_data_unused_t` structure. As a block cannot exceed 64KB in size, each is a 16-bit value. `bestfree` is used to optimise the time required to locate space to create an entry. It saves scanning through the block to find a location suitable for every entry created.
- The `tail` structure specifies the number of elements in the `leaf` array and the number of `stale` entries in the array. The `tail` is always located at the end of the block. The `leaf` data immediately precedes the `tail` structure.
- The `leaf` array, which grows from the end of the block just before the `tail` structure, contains an array of hash/address pairs for quickly looking up a name by a hash value. Hash values are covered by the introduction to directories. The `address` on-disk is the offset into the block divided by 8 (`XFS_DIR2_DATA_ALIGN`). Hash/address pairs are stored on disk to optimise lookup speed for large directories. If they were not stored, the hashes would have to be calculated for all entries each time a lookup occurs in a directory.

18.2.1 xfs_db Block Directory Example

A directory is created with 8 entries, directory block size = filesystem block size:

```
xfs_db> sb 0
xfs_db> p
magicnum = 0x58465342
blocksize = 4096
...
dirblklog = 0
...
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 040755
core.version = 1
core.format = 2 (extents)
core.nlinkv1 = 2
...
core.size = 4096
core.nblocks = 1
core.extsize = 0
core.nextents = 1
...
u.bmx[0] = [startoff,startblock,blockcount,extentflag] 0:[0,2097164,1,0]
```

Go to the "startblock" and show the raw disk data:

```
xfs_db> dblock 0
xfs_db> type text
xfs_db> p
000: 58 44 32 42  01 30 0e 78 00 00 00 00 00 00 00 00 XD2B.0.x........
010: 00 00 00 00  02 00 00 80 01 2e 00 00 00 00 00 10 ................
020: 00 00 00 00  00 00 00 80 02 2e 2e 00 00 00 00 20 ................
030: 00 00 00 00  02 00 00 81 0f 66 72 61 6d 65 30 30 .........frame00
040: 30 30 30 30  2e 74 73 74 80 8e 59 00 00 00 00 30 0000.tst..Y....0
050: 00 00 00 00  02 00 00 82 0f 66 72 61 6d 65 30 30 .........frame00
```

```
060: 30 30 30 31  2e 74 73 74 d0 ca 5c 00 00 00 00 50 0001.tst.......P
070: 00 00 00 00  02 00 00 83 0f 66 72 61 6d 65 30 30 .........frame00
080: 30 30 30 32  2e 74 73 74 00 00 00 00 00 00 00 70 0002.tst.......p
090: 00 00 00 00  02 00 00 84 0f 66 72 61 6d 65 30 30 .........frame00
0a0: 30 30 30 33  2e 74 73 74 00 00 00 00 00 00 00 90 0003.tst........
0b0: 00 00 00 00  02 00 00 85 0f 66 72 61 6d 65 30 30 .........frame00
0c0: 30 30 30 34 2e 74 73 74 00 00 00 00 00 00 00 b0 0004.tst........
0d0: 00 00 00 00 02 00 00 86 0f 66 72 61 6d 65 30 30 .........frame00
0e0: 30 30 30 35 2e 74 73 74 00 00 00 00 00 00 00 d0 0005.tst........
0f0: 00 00 00 00 02 00 00 87 0f 66 72 61 6d 65 30 30 .........frame00
100: 30 30 30 36 2e 74 73 74 00 00 00 00 00 00 00 f0 0006.tst........
110: 00 00 00 00 02 00 00 88 0f 66 72 61 6d 65 30 30 .........frame00
120: 30 30 30 37 2e 74 73 74 00 00 00 00 00 00 01 10 0007.tst........
130: ff ff 0e 78 00 00 00 00 00 00 00 00 00 00 00 00 ...x............
```

The “leaf” and “tail” structures are stored at the end of the block, so as the directory grows, the middle is filled in:

```
fa0: 00 00 00 00 00 00 01 30 00 00 00 2e 00 00 00 02 .......0........
fb0: 00 00 17 2e 00 00 00 04 83 a0 40 b4 00 00 00 0e ..............
fc0: 93 a0 40 b4 00 00 00 12 a3 a0 40 b4 00 00 00 06 ..............
fd0: b3 a0 40 b4 00 00 00 0a c3 a0 40 b4 00 00 00 1e ..............
fe0: d3 a0 40 b4 00 00 00 22 e3 a0 40 b4 00 00 00 16 ..............
ff0: f3 a0 40 b4 00 00 00 1a 00 00 00 0a 00 00 00 00 ..............
```

In a readable format:

```
xfs_db> type dir2
xfs_db> p
bhdr.magic = 0x58443242
bhdr.bestfree[0].offset = 0x130
bhdr.bestfree[0].length = 0xe78
bhdr.bestfree[1].offset = 0
bhdr.bestfree[1].length = 0
bhdr.bestfree[2].offset = 0
bhdr.bestfree[2].length = 0
bu[0].inumber = 33554560
bu[0].namelen = 1
bu[0].name = "."
bu[0].tag = 0x10
bu[1].inumber = 128
bu[1].namelen = 2
bu[1].name = ".."
bu[1].tag = 0x20
bu[2].inumber = 33554561
bu[2].namelen = 15
bu[2].name = "frame000000.tst"
bu[2].tag = 0x30
bu[3].inumber = 33554562
bu[3].namelen = 15
bu[3].name = "frame000001.tst"
bu[3].tag = 0x50
...
bu[8].inumber = 33554567
bu[8].namelen = 15
bu[8].name = "frame000006.tst"
bu[8].tag = 0xf0
bu[9].inumber = 33554568
bu[9].namelen = 15
bu[9].name = "frame000007.tst"
bu[9].tag = 0x110
bu[10].freetag = 0xffff
bu[10].length = 0xe78
```

```
bu[10].tag = 0x130
bleaf[0].hashval = 0x2e
bleaf[0].address = 0x2
bleaf[1].hashval = 0x172e
bleaf[1].address = 0x4
bleaf[2].hashval = 0x83a040b4
bleaf[2].address = 0xe
...
bleaf[8].hashval = 0xe3a040b4
bleaf[8].address = 0x16
bleaf[9].hashval = 0xf3a040b4
bleaf[9].address = 0x1a
btail.count = 10
btail.stale = 0
```

Note
For block directories, all xfs_db fields are preceded with “b”.

For a simple lookup example, the hash of frame000000.tst is 0xb3a040b4. Looking up that value, we get an address of 0x6. Multiply that by 8, it becomes offset 0x30 and the inode at that point is 33554561.

When we remove an entry from the middle (frame000004.tst), we can see how the freespace details are adjusted:

```
bhdr.magic = 0x58443242
bhdr.bestfree[0].offset = 0x130
bhdr.bestfree[0].length = 0xe78
bhdr.bestfree[1].offset = 0xb0
bhdr.bestfree[1].length = 0x20
bhdr.bestfree[2].offset = 0
bhdr.bestfree[2].length = 0
...
bu[5].inumber = 33554564
bu[5].namelen = 15
bu[5].name = "frame000003.tst"
bu[5].tag = 0x90
bu[6].freetag = 0xffff
bu[6].length = 0x20
bu[6].tag = 0xb0
bu[7].inumber = 33554566
bu[7].namelen = 15
bu[7].name = "frame000005.tst"
bu[7].tag = 0xd0
...
bleaf[7].hashval = 0xd3a040b4
bleaf[7].address = 0x22
bleaf[8].hashval = 0xe3a040b4
bleaf[8].address = 0
bleaf[9].hashval = 0xf3a040b4
bleaf[9].address = 0x1a
btail.count = 10
btail.stale = 1
```

A new “bestfree” value is added for the entry, the start of the entry is marked as unused with 0xffff (which overwrites the inode number for an actual entry), and the length of the space. The tag remains intact at the `offset+length -sizeof(tag)`. The address for the hash is also cleared. The affected areas are highlighted below:

```
090: 00 00 00 00 02 00 00 84 0f 66 72 61 6d 65 30 30 .........frame00
0a0: 30 30 30 33 2e 74 73 74 00 00 00 00 00 00 00 90 0003.tst........
0b0: ff ff 00 20 02 00 00 85 0f 66 72 61 6d 65 30 30 .........frame00
```

```
0c0: 30 30 30 34 2e 74 73 74 00 00 00 00 00 00 00 b0 0004.tst.........
0d0: 00 00 00 00 02 00 00 86 0f 66 72 61 6d 65 30 30 .........frame00
0e0: 30 30 30 35 2e 74 73 74 00 00 00 00 00 00 00 0d 0005.tst.........
...
fb0: 00 00 17 2e 00 00 00 04 83 a0 40 b4 00 00 00 0e ..............
fc0: 93 a0 40 b4 00 00 00 12 a3 a0 40 b4 00 00 00 06 ..............
fd0: b3 a0 40 b4 00 00 00 0a c3 a0 40 b4 00 00 00 1e ..............
fe0: d3 a0 40 b4 00 00 00 22 e3 a0 40 b4 00 00 00 00 ..............
ff0: f3 a0 40 b4 00 00 00 1a 00 00 00 0a 00 00 00 01 ..............
```

18.3 Leaf Directories

Once a Block Directory has filled the block, the directory data is changed into a new format. It still uses extents Chapter 17 and the same basic structures, but the "data" and "leaf" are split up into their own extents. The "leaf" information only occupies one extent. As "leaf" information is more compact than "data" information, more than one "data" extent is common.

- Block to Leaf conversions retain the existing block for the data entries and allocate a new block for the leaf and freespace index information.
- As with all directories, data blocks must start at logical offset zero.
- The "leaf" block has a special offset defined by `XFS_DIR2_LEAF_OFFSET`. Currently, this is 32GB and in the extent view, a block offset of 32GB / `sb_blocksize`. On a 4KB block filesystem, this is 0x800000 (8388608 decimal).
- Blocks with directory entries ("data" extents) have the magic number "X2D2" (0x58443244), or "XDD3" (0x58444433) on a v5 filesystem.
- The "data" extents have a new header (no "leaf" data):

```
typedef struct xfs_dir2_data {
     xfs_dir2_data_hdr_t       hdr;
     xfs_dir2_data_union_t     u[1];
} xfs_dir2_data_t;
```

hdr
: Data block header. On a v5 filesystem, this field is `struct xfs_dir3_data_hdr`.

u
: Union of directory and unused entries, exactly the same as in a block directory.

- The "leaf" extent uses the following structures:

```
typedef struct xfs_dir2_leaf {
     xfs_dir2_leaf_hdr_t       hdr;
     xfs_dir2_leaf_entry_t     ents[1];
     xfs_dir2_data_off_t       bests[1];
     xfs_dir2_leaf_tail_t      tail;
} xfs_dir2_leaf_t;
```

hdr
: Directory leaf header. On a v5 filesystem this is `struct xfs_dir3_leaf_hdr_t`.

ents
: Hash values of the entries in this block.

bests
An array pointing to free regions in the directory block.

tail
Bookkeeping for the leaf entries.

```
typedef struct xfs_dir2_leaf_hdr {
     xfs_da_blkinfo_t          info;
     __uint16_t                count;
     __uint16_t                stale;
} xfs_dir2_leaf_hdr_t;
```

info
Leaf btree block header.

count
Number of leaf entries.

stale
Number of stale/zeroed leaf entries.

```
struct xfs_dir3_leaf_hdr {
     struct xfs_da3_blkinfo    info;
     __uint16_t                count;
     __uint16_t                stale;
     __be32                    pad;
};
```

info
Leaf B+tree block header.

count
Number of leaf entries.

stale
Number of stale/zeroed leaf entries.

pad
Padding to maintain alignment rules.

```
typedef struct xfs_dir2_leaf_tail {
     __uint32_t                bestcount;
} xfs_dir2_leaf_tail_t;
```

bestcount
Number of best free entries.

- The magic number of the leaf block is `XFS_DIR2_LEAF1_MAGIC` (0xd2f1); on a v5 filesystem it is `XFS_DIR3_LEAF1_MAGIC` (0x3df1).
- The size of the `ents` array is specified by `hdr.count`.
- The size of the `bests` array is specified by the `tail.bestcount`, which is also the number of "data" blocks for the directory. The bests array maintains each data block's `bestfree[0].length` value.

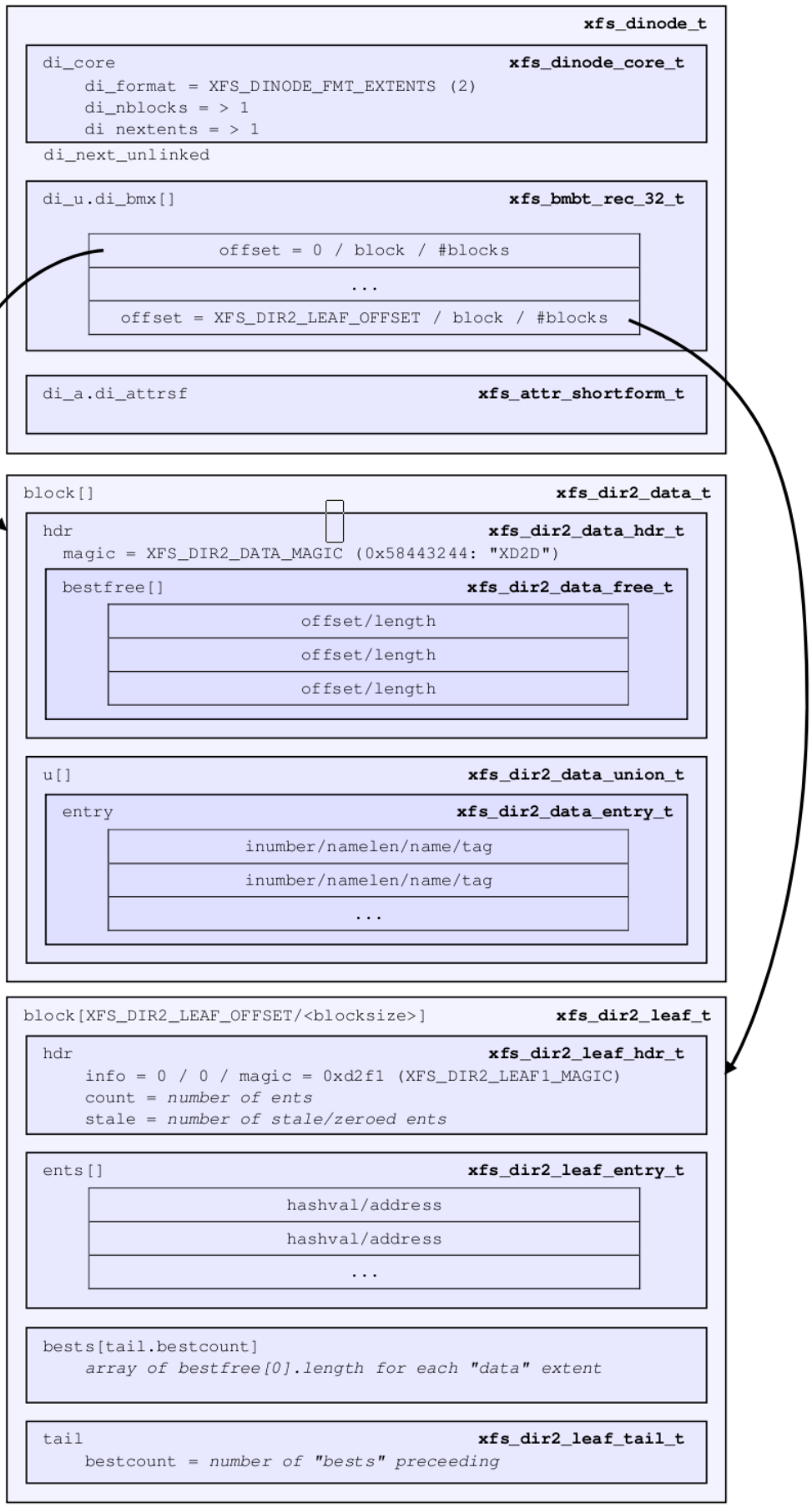


Figure 18.3: Leaf directory free entry detail

18.3.1 xfs_db Leaf Directory Example

For this example, a directory was created with 256 entries (frame000000.tst to frame000255.tst). Some files were deleted (frame00005*, frame00018* and frame000240.tst) to show free list characteristics.

```
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 040755
core.version = 1
core.format = 2 (extents)
core.nlinkv1 = 2
...
core.size = 12288
core.nblocks = 4
core.extsize = 0
core.nextents = 3
...
u.bmx[0-2] = [startoff,startblock,blockcount,extentflag]
          0:[0,4718604,1,0]
          1:[1,4718610,2,0]
          2:[8388608,4718605,1,0]
```

As can be seen in this example, three blocks are used for “data” in two extents, and the “leaf” extent has a logical offset of 8388608 blocks (32GB).

Examining the first block:

```
xfs_db> dblock 0
xfs_db> type dir2
xfs_db> p
dhdr.magic = 0x58443244
dhdr.bestfree[0].offset = 0x670
dhdr.bestfree[0].length = 0x140
dhdr.bestfree[1].offset = 0xff0
dhdr.bestfree[1].length = 0x10
dhdr.bestfree[2].offset = 0
dhdr.bestfree[2].length = 0
du[0].inumber = 75497600
du[0].namelen = 1
du[0].name = "."
du[0].tag = 0x10
du[1].inumber = 128
du[1].namelen = 2
du[1].name = ".."
du[1].tag = 0x20
du[2].inumber = 75497601
du[2].namelen = 15
du[2].name = "frame000000.tst"
du[2].tag = 0x30
du[3].inumber = 75497602
du[3].namelen = 15
du[3].name = "frame000001.tst"
du[3].tag = 0x50
...
du[51].inumber = 75497650
du[51].namelen = 15
du[51].name = "frame000049.tst"
du[51].tag = 0x650
du[52].freetag = 0xffff
du[52].length = 0x140
du[52].tag = 0x670
```

```
du[53].inumber = 75497661
du[53].namelen = 15
du[53].name = "frame000060.tst"
du[53].tag = 0x7b0
...
du[118].inumber = 75497758
du[118].namelen = 15
du[118].name = "frame000125.tst"
du[118].tag = 0xfd0
du[119].freetag = 0xffff
du[119].length = 0x10
du[119].tag = 0xff0
```

Note
The xfs_db field output is preceded by a “d” for “data”.

The next “data” block:

```
xfs_db> dblock 1
xfs_db> type dir2
xfs_db> p
dhdr.magic = 0x58443244
dhdr.bestfree[0].offset = 0x6d0
dhdr.bestfree[0].length = 0x140
dhdr.bestfree[1].offset = 0xe50
dhdr.bestfree[1].length = 0x20
dhdr.bestfree[2].offset = 0xff0
dhdr.bestfree[2].length = 0x10
du[0].inumber = 75497759
du[0].namelen = 15
du[0].name = "frame000126.tst"
du[0].tag = 0x10
...
du[53].inumber = 75497844
du[53].namelen = 15
du[53].name = "frame000179.tst"
du[53].tag = 0x6b0
du[54].freetag = 0xffff
du[54].length = 0x140
du[54].tag = 0x6d0
du[55].inumber = 75497855
du[55].namelen = 15
du[55].name = "frame000190.tst"
du[55].tag = 0x810
...
du[104].inumber = 75497904
du[104].namelen = 15
du[104].name = "frame000239.tst"
du[104].tag = 0xe30
du[105].freetag = 0xffff
du[105].length = 0x20
du[105].tag = 0xe50
du[106].inumber = 75497906
du[106].namelen = 15
du[106].name = "frame000241.tst"
du[106].tag = 0xe70
...
du[117].inumber = 75497917
du[117].namelen = 15
```

```
du[117].name = "frame000252.tst"
du[117].tag = 0xfd0
du[118].freetag = 0xffff
du[118].length = 0x10
du[118].tag = 0xff0
```

And the last data block:

```
xfs_db> dblock 2
xfs_db> type dir2
xfs_db> p
dhdr.magic = 0x58443244
dhdr.bestfree[0].offset = 0x70
dhdr.bestfree[0].length = 0xf90
dhdr.bestfree[1].offset = 0
dhdr.bestfree[1].length = 0
dhdr.bestfree[2].offset = 0
dhdr.bestfree[2].length = 0
du[0].inumber = 75497918
du[0].namelen = 15
du[0].name = "frame000253.tst"
du[0].tag = 0x10
du[1].inumber = 75497919
du[1].namelen = 15
du[1].name = "frame000254.tst"
du[1].tag = 0x30
du[2].inumber = 75497920
du[2].namelen = 15
du[2].name = "frame000255.tst"
du[2].tag = 0x50
du[3].freetag = 0xffff
du[3].length = 0xf90
du[3].tag = 0x70
```

Examining the “leaf” block (with the fields preceded by an “l” for “leaf”):

```
xfs_db> dblock 8388608
xfs_db> type dir2
xfs_db> p
lhdr.info.forw = 0
lhdr.info.back = 0
lhdr.info.magic = 0xd2f1
lhdr.count = 258
lhdr.stale = 0
lbests[0-2] = 0:0x10 1:0x10 2:0xf90
lents[0].hashval = 0x2e
lents[0].address = 0x2
lents[1].hashval = 0x172e
lents[1].address = 0x4
lents[2].hashval = 0x23a04084
lents[2].address = 0x116
...
lents[257].hashval = 0xf3a048bc
lents[257].address = 0x366
ltail.bestcount = 3
```

Note how the `lbests` array correspond with the `bestfree[0].length` values in the “data” blocks:

```
xfs_db> dblock 0
xfs_db> type dir2
xfs_db> p
dhdr.magic = 0x58443244
```

```
dhdr.bestfree[0].offset = 0xff0
dhdr.bestfree[0].length = 0x10
...
xfs_db> dblock 1
xfs_db> type dir2
xfs_db> p
dhdr.magic = 0x58443244
dhdr.bestfree[0].offset = 0xff0
dhdr.bestfree[0].length = 0x10
...
xfs_db> dblock 2
xfs_db> type dir2
xfs_db> p
dhdr.magic = 0x58443244
dhdr.bestfree[0].offset = 0x70
dhdr.bestfree[0].length = 0xf90
```

Now after the entries have been deleted:

```
xfs_db> dblock 8388608
xfs_db> type dir2
xfs_db> p
lhdr.info.forw = 0
lhdr.info.back = 0
lhdr.info.magic = 0xd2f1
lhdr.count = 258
lhdr.stale = 21
lbests[0-2] = 0:0x140 1:0x140 2:0xf90
lents[0].hashval = 0x2e
lents[0].address = 0x2
lents[1].hashval = 0x172e
lents[1].address = 0x4
lents[2].hashval = 0x23a04084
lents[2].address = 0x116
...
```

As can be seen, the `lbests` values have been update to contain each `hdr.bestfree[0].length` values. The leaf's `hdr.stale` value has also been updated to specify the number of stale entries in the array. The stale entries have an address of zero.

TODO: Need an example for where new entries get inserted with several large free spaces.

18.4 Node Directories

When the "leaf" information fills a block, the extents undergo another separation. All "freeindex" information moves into its own extent. Like Leaf Directories, the "leaf" block maintained the best free space information for each "data" block. This is not possible with more than one leaf.

- The "data" blocks stay the same as leaf directories.
- After the "freeindex" data moves to its own block, it is possible for the leaf data to fit within a single leaf block. This single leaf block has a magic number of `XFS_DIR2_LEAFN_MAGIC` (0xd2ff) or on a v5 filesystem, `XFS_DIR3_LEAFN_MAGIC` (0x3dff).
- The "leaf" blocks eventually change into a B+tree with the generic B+tree header pointing to directory "leaves" as described in Leaf Directories Section 18.3. Blocks with leaf data still have the `LEAFN_MAGIC` magic number as outlined above. The top-level tree blocks are called "nodes" and have a magic number of `XFS_DA_NODE_MAGIC` (0xfebe), or on a v5 filesystem, `XFS_DA3_NODE_MAGIC` (0x3ebe).
- Distinguishing between a combined leaf/freeindex block (`LEAF1_MAGIC`), a leaf-only block (`LEAFN_MAGIC`), and a btree node block (`NODE_MAGIC`) can only be done by examining the magic number.

- The new “freeindex” block(s) only contains the bests for each data block.
- The freeindex block uses the following structures:

```
typedef struct xfs_dir2_free_hdr {
     __uint32_t                magic;
     __int32_t                 firstdb;
     __int32_t                 nvalid;
     __int32_t                 nused;
} xfs_dir2_free_hdr_t;
```

magic
The magic number of the free block, “XD2F” (0x0x58443246).

firstdb
The starting directory block number for the bests array.

nvalid
Number of valid elements in the bests array. This number must correspond with the number of directory blocks can fit under the inode `di_size`.

nused
Number of used elements in the bests array. This number must correspond with the number of directory blocks actually mapped under the inode `di_size`.

```
typedef struct xfs_dir2_free {
     xfs_dir2_free_hdr_t       hdr;
     xfs_dir2_data_off_t       bests[1];
} xfs_dir2_free_t;
```

hdr
Free block header.

bests
An array specifying the best free counts in each directory data block.

- On a v5 filesystem, the freeindex block uses the following structures:

```
struct xfs_dir3_free_hdr {
     struct xfs_dir3_blk_hdr   hdr;
     __int32_t                 firstdb;
     __int32_t                 nvalid;
     __int32_t                 nused;
     __int32_t                 pad;
};
```

hdr
v3 directory block header. The magic number is "XDF3" (0x0x58444633).

firstdb
The starting directory block number for the bests array.

nvalid
Number of valid elements in the bests array. This number must correspond with the number of directory blocks can fit under the inode `di_size`.

nused
Number of used elements in the bests array. This number must correspond with the number of directory blocks actually mapped under the inode `di_size`.

pad
Padding to maintain alignment.

```
struct xfs_dir3_free {
     xfs_dir3_free_hdr_t       hdr;
     __be16                    bests[1];
};
```

hdr
Free block header.

bests
An array specifying the best free counts in each directory data block.

- The location of the leaf blocks can be in any order, the only way to determine the appropriate is by the node block hash/before values. Given a hash to look up, you read the node's `btree` array and first `hashval` in the array that exceeds the given hash and it can then be found in the block pointed to by the `before` value.

- The freeindex's `bests` array starts from the end of the block and grows to the start of the block.
- When an data block becomes unused (ie. all entries in it have been deleted), the block is freed, the data extents contain a hole, and the freeindex's `hdr.nused` value is decremented and the associated `bests[]` entry is set to 0xffff.
- As the first data block always contains "." and "..", it's invalid for the directory to have a hole at the start.
- The freeindex's `hdr.nused` should always be the same as the number of allocated data directory blocks containing name/inode data and will always be less than or equal to `hdr.nvalid`. The value of `hdr.nvalid` should be the same as the index of the last data directory block plus one (i.e. when the last data block is freed, `nused` and `nvalid` are decremented).

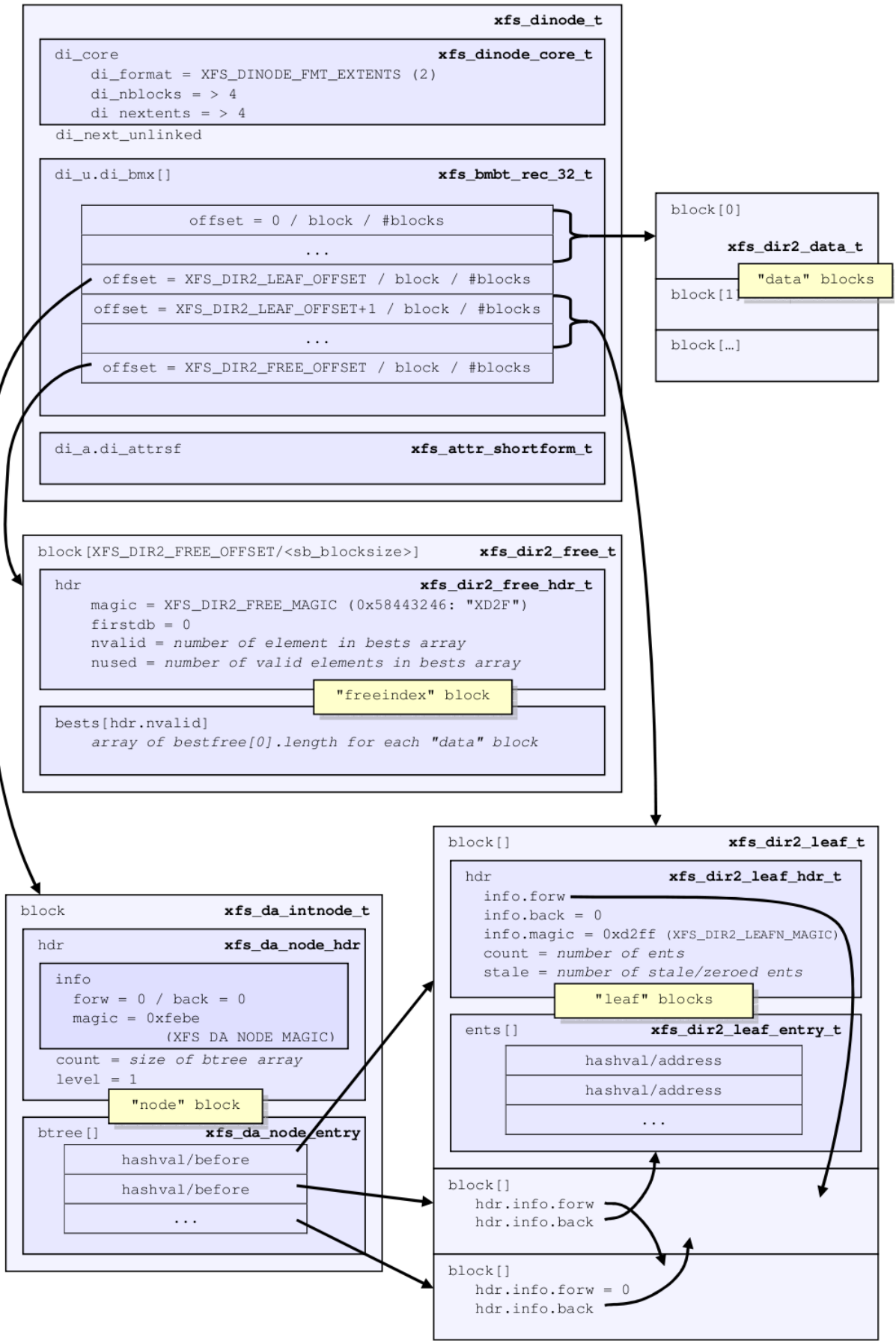


Figure 18.4: Node directory layout

18.4.1 xfs_db Node Directory Example

With the node directory examples, we are using a filesystems with 4KB block size, and a 16KB directory size. The directory has over 2000 entries:

```
xfs_db> sb 0
xfs_db> p
magicnum = 0x58465342
blocksize = 4096
...
dirblklog = 2
...
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 040755
core.version = 1
core.format = 2 (extents)
...
core.size = 81920
core.nblocks = 36
core.extsize = 0
core.nextents = 8
...
u.bmx[0-7] = [startoff,startblock,blockcount,extentflag] 0:[0,7368,4,0]
1:[4,7408,4,0] 2:[8,7444,4,0] 3:[12,7480,4,0] 4:[16,7520,4,0]
5:[8388608,7396,4,0] 6:[8388612,7524,8,0] 7:[16777216,7516,4,0]
```

As can already be observed, all extents are allocated is multiples of 4 blocks.

Blocks 0 to 19 (16+4-1) are used for directory data blocks. Looking at blocks 16-19, we can seen that it's the same as the single-leaf format, except the `length` values are a lot larger to accommodate the increased directory block size:

```
xfs_db> dblock 16
xfs_db> type dir2
xfs_db> p
dhdr.magic = 0x58443244
dhdr.bestfree[0].offset = 0xb0
dhdr.bestfree[0].length = 0x3f50
dhdr.bestfree[1].offset = 0
dhdr.bestfree[1].length = 0
dhdr.bestfree[2].offset = 0
dhdr.bestfree[2].length = 0
du[0].inumber = 120224
du[0].namelen = 15
du[0].name = "frame002043.tst"
du[0].tag = 0x10
du[1].inumber = 120225
du[1].namelen = 15
du[1].name = "frame002044.tst"
du[1].tag = 0x30
du[2].inumber = 120226
du[2].namelen = 15
du[2].name = "frame002045.tst"
du[2].tag = 0x50
du[3].inumber = 120227
du[3].namelen = 15
du[3].name = "frame002046.tst"
du[3].tag = 0x70
du[4].inumber = 120228
du[4].namelen = 15
du[4].name = "frame002047.tst"
```

```
du[4].tag = 0x90
du[5].freetag = 0xffff
du[5].length = 0x3f50
du[5].tag = 0
```

Next, the "node" block, the fields are preceded with *n* for node blocks:

```
xfs_db> dblock 8388608
xfs_db> type dir2
xfs_db> p
nhdr.info.forw = 0
nhdr.info.back = 0
nhdr.info.magic = 0xfebe
nhdr.count = 2
nhdr.level = 1
nbtree[0-1] = [hashval,before] 0:[0xa3a440ac,8388616] 1:[0xf3a440bc,8388612]
```

The two following leaf blocks were allocated as part of the directory's conversion to node format. All hashes less than 0xa3a440ac are located at directory offset 8,388,616, and hashes less than 0xf3a440bc are located at directory offset 8,388,612. Hashes greater or equal to 0xf3a440bc don't exist in this directory.

```
xfs_db> dblock 8388616
xfs_db> type dir2
xfs_db> p
lhdr.info.forw = 8388612
lhdr.info.back = 0
lhdr.info.magic = 0xd2ff
lhdr.count = 1023
lhdr.stale = 0
lents[0].hashval = 0x2e
lents[0].address = 0x2
lents[1].hashval = 0x172e
lents[1].address = 0x4
lents[2].hashval = 0x23a04084
lents[2].address = 0x116
...
lents[1021].hashval = 0xa3a440a4
lents[1021].address = 0x1fa2
lents[1022].hashval = 0xa3a440ac
lents[1022].address = 0x1fca
xfs_db> dblock 8388612
xfs_db> type dir2
xfs_db> p
lhdr.info.forw = 0
lhdr.info.back = 8388616
lhdr.info.magic = 0xd2ff
lhdr.count = 1027
lhdr.stale = 0
lents[0].hashval = 0xa3a440b4
lents[0].address = 0x1f52
lents[1].hashval = 0xa3a440bc
lents[1].address = 0x1f7a
...
lents[1025].hashval = 0xf3a440b4
lents[1025].address = 0x1f66
lents[1026].hashval = 0xf3a440bc
lents[1026].address = 0x1f8e
```

An example lookup using xfs_db:

```
xfs_db> hash frame001845.tst
0xf3a26094
```

Doing a binary search through the array, we get address 0x1ce6, which is offset 0xe730. Each fsblock is 4KB in size (0x1000), so it will be offset 0x730 into directory offset 14. From the extent map, this will be fsblock 7482:

```
xfs_db> fsblock 7482
xfs_db> type text
xfs_db> p
...
730: 00 00 00 00 00 01 d4 da 0f 66 72 61 6d 65 30 30 .........frame00
740: 31 38 34 35 2e 74 73 74 00 00 00 00 00 00 27 30 1845.tst.......0
```

Looking at the freeindex information (fields with an *f* tag):

```
xfs_db> fsblock 7516
xfs_db> type dir2
xfs_db> p
fhdr.magic = 0x58443246
fhdr.firstdb = 0
fhdr.nvalid = 5
fhdr.nused = 5
fbests[0-4] = 0:0x10 1:0x10 2:0x10 3:0x10 4:0x3f50
```

Like the Leaf Directory, each of the `fbests` values correspond to each data block's `bestfree[0].length` value.

The `fbests` array is highlighted in a raw block dump:

```
xfs_db> type text
xfs_db> p
000: 58 44 32 46 00 00 00 00 00 00 00 05 00 00 00 05 XD2F............
010: 00 10 00 10 00 10 00 10 3f 50 00 00 1f 01 ff ff .........P......
```

TODO: Example with a hole in the middle

18.5 B+tree Directories

When the extent map in an inode grows beyond the inode's space, the inode format is changed to a "btree". The inode contains a filesystem block point to the B+tree extent map for the directory's blocks. The B+tree extents contain the extent map for the "data", "node", "leaf", and "freeindex" information as described in Node Directories.

Refer to the previous section on B+tree Data Extents Section 17.2 for more information on XFS B+tree extents.

The following properties apply to both node and B+tree directories:

- The node/leaf trees can be more than one level deep.
- More than one freeindex block may exist, but this will be quite rare. It would required hundreds of thousand files with quite long file names (or millions with shorter names) to get a second freeindex block.

18.5.1 xfs_db B+tree Directory Example

A directory has been created with 200,000 entries with each entry being 100 characters long. The filesystem block size and directory block size are 4KB:

```
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 040755
core.version = 1
core.format = 3 (btree)
...
```

```
core.size = 22757376
core.nblocks = 6145
core.extsize = 0
core.nextents = 234
core.naextents = 0
core.forkoff = 0
...
u.bmbt.level = 1
u.bmbt.numrecs = 1
u.bmbt.keys[1] = [startoff] 1:[0]
u.bmbt.ptrs[1] = 1:89
xfs_db> fsblock 89
xfs_db> type bmapbtd
xfs_db> p
magic = 0x424d4150
level = 0
numrecs = 234
leftsib = null
rightsib = null
recs[1-234] = [startoff,startblock,blockcount,extentflag]
   1:[0,53,1,0] 2:[1,55,13,0] 3:[14,69,1,0] 4:[15,72,13,0]
   5:[28,86,2,0] 6:[30,90,21,0] 7:[51,112,1,0] 8:[52,114,11,0]
   ...
   125:[5177,902,15,0] 126:[5192,918,6,0] 127:[5198,524786,358,0]
   128:[8388608,54,1,0] 129:[8388609,70,2,0] 130:[8388611,85,1,0]
   ...
   229:[8389164,917,1,0] 230:[8389165,924,19,0] 231:[8389184,944,9,0]
   232:[16777216,68,1,0] 233:[16777217,7340114,1,0] 234:[16777218,5767362,1,0]
```

We have 128 extents and a total of 5555 blocks being used to store name/inode pairs. With only about 2000 values that can be stored in the freeindex block, 3 blocks have been allocated for this information. The `firstdb` field specifies the starting directory block number for each array:

```
xfs_db> dblock 16777216
xfs_db> type dir2
xfs_db> p
fhdr.magic = 0x58443246
fhdr.firstdb = 0
fhdr.nvalid = 2040
fhdr.nused = 2040
fbests[0-2039] = ...
xfs_db> dblock 16777217
xfs_db> type dir2
xfs_db> p
fhdr.magic = 0x58443246
fhdr.firstdb = 2040
fhdr.nvalid = 2040
fhdr.nused = 2040
fbests[0-2039] = ...
xfs_db> dblock 16777218
xfs_db> type dir2
xfs_db> p
fhdr.magic = 0x58443246
fhdr.firstdb = 4080
fhdr.nvalid = 1476
fhdr.nused = 1476
fbests[0-1475] = ...
```

Looking at the root node in the node block, it's a pretty deep tree:

```
xfs_db> dblock 8388608
xfs_db> type dir2
```

```
xfs_db> p
nhdr.info.forw = 0
nhdr.info.back = 0
nhdr.info.magic = 0xfebe
nhdr.count = 2
nhdr.level = 2
nbtree[0-1] = [hashval,before] 0:[0x6bbf6f39,8389121] 1:[0xfbbf7f79,8389120]
xfs_db> dblock 8389121
xfs_db> type dir2
xfs_db> p
nhdr.info.forw = 8389120
nhdr.info.back = 0
nhdr.info.magic = 0xfebe
nhdr.count = 263
nhdr.level = 1
nbtree[0-262] = ... 262:[0x6bbf6f39,8388928]
xfs_db> dblock 8389120
xfs_db> type dir2
xfs_db> p
nhdr.info.forw = 0
nhdr.info.back = 8389121
nhdr.info.magic = 0xfebe
nhdr.count = 319
nhdr.level = 1
nbtree[0-318] = [hashval,before] 0:[0x70b14711,8388919] ...
```

The leaves at each the end of a node always point to the end leaves in adjacent nodes. Directory block 8388928 has a forward pointer to block 8388919 and block 8388919 has a previous pointer to block 8388928, as highlighted in the following example:

```
xfs_db> dblock 8388928
xfs_db> type dir2
xfs_db> p
lhdr.info.forw = 8388919
lhdr.info.back = 8388937
lhdr.info.magic = 0xd2ff
...

xfs_db> dblock 8388919
xfs_db> type dir2
xfs_db> p
lhdr.info.forw = 8388706
lhdr.info.back = 8388928
lhdr.info.magic = 0xd2ff
...
```

Chapter 19

Extended Attributes

Extended attributes enable users and administrators to attach (name: value) pairs to inodes within the XFS filesystem. They could be used to store meta-information about the file.

Attribute names can be up to 256 bytes in length, terminated by the first 0 byte. The intent is that they be printable ASCII (or other character set) names for the attribute. The values can contain up to 64KB of arbitrary binary data. Some XFS internal attributes (eg. parent pointers) use non-printable names for the attribute.

Access Control Lists (ACLs) and Data Migration Facility (DMF) use extended attributes to store their associated metadata with an inode.

XFS uses two disjoint attribute name spaces associated with every inode. These are the root and user address spaces. The root address space is accessible only to the superuser, and then only by specifying a flag argument to the function call. Other users will not see or be able to modify attributes in the root address space. The user address space is protected by the normal file permissions mechanism, so the owner of the file can decide who is able to see and/or modify the value of attributes on any particular file.

To view extended attributes from the command line, use the `getfattr` command. To set or delete extended attributes, use the `setfattr` command. ACLs control should use the `getfacl` and `setfacl` commands.

XFS attributes supports three namespaces: “user”, “trusted” (or “root” using IRIX terminology), and “secure”.

See the section about extended attributes Section 16.4.1 in the inode for instructions on how to calculate the location of the attributes.

The following four sections describe each of the on-disk formats.

19.1 Short Form Attributes

When the all extended attributes can fit within the inode’s attribute fork, the inode’s `di_aformat` is set to “local” and the attributes are stored in the inode’s literal area starting at offset `di_forkoff` × 8.

Shortform attributes use the following structures:

```
typedef struct xfs_attr_shortform {
     struct xfs_attr_sf_hdr {
          __be16               totsize;
          __u8                 count;
     } hdr;
     struct xfs_attr_sf_entry {
          __uint8_t            namelen;
          __uint8_t            valuelen;
          __uint8_t            flags;
          __uint8_t            nameval[1];
     } list[1];
```

```
} xfs_attr_shortform_t;
typedef struct xfs_attr_sf_hdr xfs_attr_sf_hdr_t;
typedef struct xfs_attr_sf_entry xfs_attr_sf_entry_t;
```

totsize
Total size of the attribute structure in bytes.

count
The number of entries that can be found in this structure.

namelen and valuelen
These values specify the size of the two byte arrays containing the name and value pairs. `valuelen` is zero for extended attributes with no value.

nameval[]
A single array whose size is the sum of `namelen` and `valuelen`. The names and values are not null terminated on-disk. The value immediately follows the name in the array.

flags
A combination of the following:

Table 19.1: Attribute Namespaces

Flag	Description
0	The attribute's namespace is "user".
XFS_ATTR_ROOT	The attribute's namespace is "trusted".
XFS_ATTR_SECURE	The attribute's namespace is "secure".
XFS_ATTR_INCOMPLETE	This attribute is being modified.
XFS_ATTR_LOCAL	The attribute value is contained within this block.

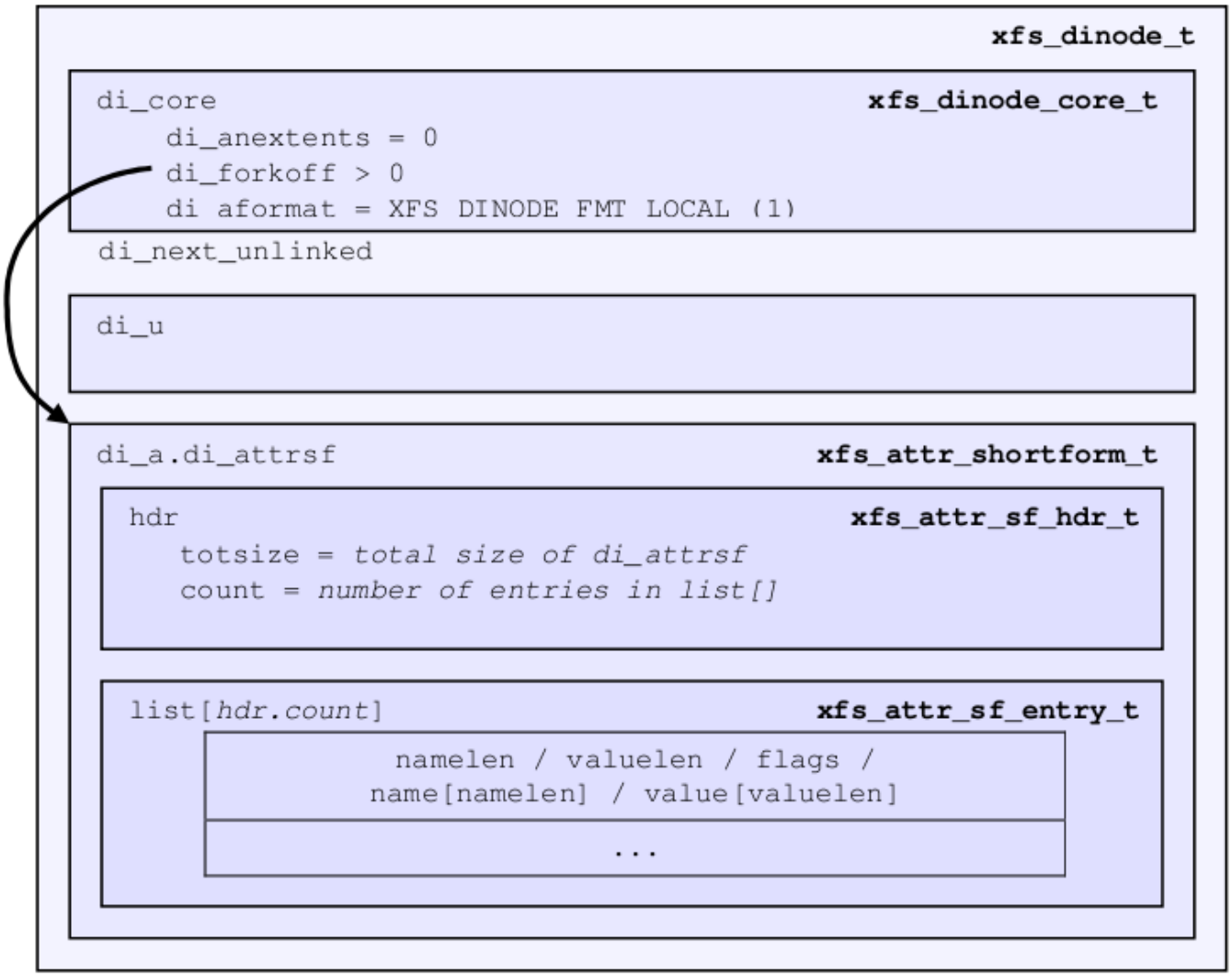


Figure 19.1: Short form attribute layout

19.1.1 xfs_db Short Form Attribute Example

A file is created and two attributes are set:

```
# setfattr -n user.empty few_attr
# setfattr -n trusted.trust -v val1 few_attr
```

Using xfs_db, we dump the inode:

```
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 0100644
...
core.naextents = 0
core.forkoff = 15
core.aformat = 1 (local)
...
a.sfattr.hdr.totsize = 24
```

```
a.sfattr.hdr.count = 2
a.sfattr.list[0].namelen = 5
a.sfattr.list[0].valuelen = 0
a.sfattr.list[0].root = 0
a.sfattr.list[0].secure = 0
a.sfattr.list[0].name = "empty"
a.sfattr.list[1].namelen = 5
a.sfattr.list[1].valuelen = 4
a.sfattr.list[1].root = 1
a.sfattr.list[1].secure = 0
a.sfattr.list[1].name = "trust"
a.sfattr.list[1].value = "val1"
```

We can determine the actual inode offset to be 220 (15 x 8 + 100) or `0xdc`. Examining the raw dump, the second attribute is highlighted:

```
xfs_db> type text
xfs_db> p
09: 49 4e 81 a4 01 02 00 01 00 00 00 00 00 00 00 00 IN..............
10: 00 00 00 01 00 00 00 00 00 00 00 00 00 00 00 02 ................
20: 44 be 19 be 38 d1 26 98 44 be 1a be 38 d1 26 98 D...8...D...8...
30: 44 be 1a e1 3a 9a ea 18 00 00 00 00 00 00 00 04 D...............
40: 00 00 00 00 00 00 00 01 00 00 00 00 00 00 00 01 ................
50: 00 00 0f 01 00 00 00 00 00 00 00 00 00 00 00 00 ................
60: ff ff ff ff 00 00 00 00 00 00 00 00 00 00 00 12 ................
70: 53 a0 00 01 00 00 00 00 00 00 00 00 00 00 00 00 ................
80: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
90: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
a0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
b0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
c0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
d0: 00 00 00 00 00 00 00 00 00 00 00 00 00 18 02 00 ..............   <-- hdr.totsize = 0 ↩
    x18
e0: 05 00 00 65 6d 70 74 79 05 04 02 74 72 75 73 74 ...empty...trust
f0: 76 61 6c 31 00 00 00 00 00 00 00 00 00 00 00 00 val1............
```

Adding another attribute with attr1, the format is converted to extents and `di_forkoff` remains unchanged (and all those zeros in the dump above remain unused):

```
xfs_db> inode <inode#>
xfs_db> p
...
core.naextents = 1
core.forkoff = 15
core.aformat = 2 (extents)
...
a.bmx[0] = [startoff,startblock,blockcount,extentflag] 0:[0,37534,1,0]
```

Performing the same steps with attr2, adding one attribute at a time, you can see `di_forkoff` change as attributes are added:

```
xfs_db> inode <inode#>
xfs_db> p
...
core.naextents = 0
core.forkoff = 15
core.aformat = 1 (local)
...
a.sfattr.hdr.totsize = 17
a.sfattr.hdr.count = 1
a.sfattr.list[0].namelen = 10
a.sfattr.list[0].valuelen = 0
a.sfattr.list[0].root = 0
```

```
a.sfattr.list[0].secure = 0
a.sfattr.list[0].name = "empty_attr"
```

Attribute added:

```
xfs_db> p
...
core.naextents = 0
core.forkoff = 15
core.aformat = 1 (local)
...
a.sfattr.hdr.totsize = 31
a.sfattr.hdr.count = 2
a.sfattr.list[0].namelen = 10
a.sfattr.list[0].valuelen = 0
a.sfattr.list[0].root = 0
a.sfattr.list[0].secure = 0
a.sfattr.list[0].name = "empty_attr"
a.sfattr.list[1].namelen = 7
a.sfattr.list[1].valuelen = 4
a.sfattr.list[1].root = 1
a.sfattr.list[1].secure = 0
a.sfattr.list[1].name = "trust_a"
a.sfattr.list[1].value = "val1"
```

Another attribute is added:

```
xfs_db> p
...
core.naextents = 0
core.forkoff = 13
core.aformat = 1 (local)
...
a.sfattr.hdr.totsize = 52
a.sfattr.hdr.count = 3
a.sfattr.list[0].namelen = 10
a.sfattr.list[0].valuelen = 0
a.sfattr.list[0].root = 0
a.sfattr.list[0].secure = 0
a.sfattr.list[0].name = "empty_attr"
a.sfattr.list[1].namelen = 7
a.sfattr.list[1].valuelen = 4
a.sfattr.list[1].root = 1
a.sfattr.list[1].secure = 0
a.sfattr.list[1].name = "trust_a"
a.sfattr.list[1].value = "val1"
a.sfattr.list[2].namelen = 6
a.sfattr.list[2].valuelen = 12
a.sfattr.list[2].root = 0
a.sfattr.list[2].secure = 0
a.sfattr.list[2].name = "second"
a.sfattr.list[2].value = "second_value"
```

One more is added:

```
xfs_db> p
core.naextents = 0
core.forkoff = 10
core.aformat = 1 (local)
...
a.sfattr.hdr.totsize = 69
a.sfattr.hdr.count = 4
```

```
a.sfattr.list[0].namelen = 10
a.sfattr.list[0].valuelen = 0
a.sfattr.list[0].root = 0
a.sfattr.list[0].secure = 0
a.sfattr.list[0].name = "empty_attr"
a.sfattr.list[1].namelen = 7
a.sfattr.list[1].valuelen = 4
a.sfattr.list[1].root = 1
a.sfattr.list[1].secure = 0
a.sfattr.list[1].name = "trust_a"
a.sfattr.list[1].value = "val1"
a.sfattr.list[2].namelen = 6
a.sfattr.list[2].valuelen = 12
a.sfattr.list[2].root = 0
a.sfattr.list[2].secure = 0
a.sfattr.list[2].name = "second"
a.sfattr.list[2].value = "second_value"
a.sfattr.list[3].namelen = 6
a.sfattr.list[3].valuelen = 8
a.sfattr.list[3].root = 0
a.sfattr.list[3].secure = 1
a.sfattr.list[3].name = "policy"
a.sfattr.list[3].value = "contents"
```

A raw dump is shown to compare with the attr1 dump on a prior page, the header is highlighted:

```
xfs_db> type text
xfs_db> p
00: 49 4e 81 a4 01 02 00 01 00 00 00 00 00 00 00 00 IN..............
10: 00 00 00 01 00 00 00 00 00 00 00 00 00 00 00 05 ................
20: 44 be 24 cd 0f b0 96 18 44 be 24 cd 0f b0 96 18 D.......D.......
30: 44 be 2d f5 01 62 7a 18 00 00 00 00 00 00 00 04 D....bz.........
40: 00 00 00 00 00 00 00 01 00 00 00 00 00 00 00 01 ................
50: 00 00 0a 01 00 00 00 00 00 00 00 00 00 00 00 00 ................
60: ff ff ff ff 00 00 00 00 00 00 00 00 00 00 00 01 ................
70: 41 c0 00 01 00 00 00 00 00 00 00 00 00 00 00 00 A...............
80: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
90: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
a0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
b0: 00 00 00 00 00 45 04 00 0a 00 00 65 6d 70 74 79 .....E.....empty
c0: 5f 61 74 74 72 07 04 02 74 72 75 73 74 5f 61 76 .attr...trust.av
d0: 61 6c 31 06 0c 00 73 65 63 6f 6e 64 73 65 63 6f all...secondseco
e0: 6e 64 5f 76 61 6c 75 65 06 08 04 70 6f 6c 69 63 nd.value...polic
f0: 79 63 6f 6e 74 65 6e 74 73 64 5f 76 61 6c 75 65 ycontentsd.value
```

It can be clearly seen that attr2 allows many more attributes to be stored in an inode before they are moved to another filesystem block.

19.2 Leaf Attributes

When an inode's attribute fork space is used up with shortform attributes and more are added, the attribute format is migrated to "extents".

Extent based attributes use hash/index pairs to speed up an attribute lookup. The first part of the "leaf" contains an array of fixed size hash/index pairs with the flags stored as well. The remaining part of the leaf block contains the array name/value pairs, where each element varies in length.

Each leaf is based on the `xfs_da_blkinfo_t` block header declared in the section about directories Section 11.1. On a v5 filesystem, the block header is `xfs_da3_blkinfo_t`. The structure encapsulating all other structures in the attribute block is `xfs_attr_leafblock_t`.

The structures involved are:

```
typedef struct xfs_attr_leaf_map {
     __be16                    base;
     __be16                    size;
} xfs_attr_leaf_map_t;
```

base
Block offset of the free area, in bytes.

size
Size of the free area, in bytes.

```
typedef struct xfs_attr_leaf_hdr {
     xfs_da_blkinfo_t          info;
     __be16                    count;
     __be16                    usedbytes;
     __be16                    firstused;
     __u8                      holes;
     __u8                      pad1;
     xfs_attr_leaf_map_t       freemap[3];
} xfs_attr_leaf_hdr_t;
```

info
Directory/attribute block header.

count
Number of entries.

usedbytes
Number of bytes used in the leaf block.

firstused
Block offset of the first entry in use, in bytes.

holes
Set to 1 if block compaction is necessary.

pad1
Padding to maintain alignment to 64-bit boundaries.

```
typedef struct xfs_attr_leaf_entry {
     __be32                    hashval;
     __be16                    nameidx;
     __u8                      flags;
     __u8                      pad2;
} xfs_attr_leaf_entry_t;
```

hashval
Hash value of the attribute name.

nameidx
Block offset of the name entry, in bytes.

flags
Attribute flags, as specified above Table 19.1.

pad2
Pads the structure to 64-bit boundaries.

```
typedef struct xfs_attr_leaf_name_local {
     __be16                     valuelen;
     __u8                       namelen;
     __u8                       nameval[1];
} xfs_attr_leaf_name_local_t;
```

valuelen
Length of the value, in bytes.

namelen
Length of the name, in bytes.

nameval
The name and the value. String values are not zero-terminated.

```
typedef struct xfs_attr_leaf_name_remote {
     __be32                     valueblk;
     __be32                     valuelen;
     __u8                       namelen;
     __u8                       name[1];
} xfs_attr_leaf_name_remote_t;
```

valueblk
The logical block in the attribute map where the value is located.

valuelen
Length of the value, in bytes.

namelen
Length of the name, in bytes.

nameval
The name. String values are not zero-terminated.

```
typedef struct xfs_attr_leafblock  {
     xfs_attr_leaf_hdr_t           hdr;
     xfs_attr_leaf_entry_t         entries[1];
     xfs_attr_leaf_name_local_t    namelist;
     xfs_attr_leaf_name_remote_t   valuelist;
} xfs_attr_leafblock_t;
```

hdr
Attribute block header.

entries
A variable-length array of attribute entries.

namelist
A variable-length array of descriptors of local attributes. The location and size of these entries is determined dynamically.

valuelist
A variable-length array of descriptors of remote attributes. The location and size of these entries is determined dynamically.

On a v5 filesystem, the header becomes `xfs_da3_blkinfo_t` to accommodate the extra metadata integrity fields:

```
typedef struct xfs_attr3_leaf_hdr {
     xfs_da3_blkinfo_t          info;
     __be16                     count;
     __be16                     usedbytes;
     __be16                     firstused;
     __u8                       holes;
     __u8                       pad1;
     xfs_attr_leaf_map_t        freemap[3];
     __be32                     pad2;
} xfs_attr3_leaf_hdr_t;


typedef struct xfs_attr3_leafblock  {
     xfs_attr3_leaf_hdr_t          hdr;
     xfs_attr_leaf_entry_t         entries[1];
     xfs_attr_leaf_name_local_t    namelist;
     xfs_attr_leaf_name_remote_t   valuelist;
} xfs_attr3_leafblock_t;
```

Each leaf header uses the magic number `XFS_ATTR_LEAF_MAGIC` (0xfbee). On a v5 filesystem, the magic number is `XFS_ATTR3_LEAF_MAGIC` (0x3bee).

The hash/index elements in the `entries[]` array are packed from the top of the block. Name/values grow from the bottom but are not packed. The freemap contains run-length-encoded entries for the free bytes after the `entries[]` array, but only the three largest runs are stored (smaller runs are dropped). When the `freemap` doesn't show enough space for an allocation, the name/value area is compacted and allocation is tried again. If there still isn't enough space, then the block is split. The name/value structures (both local and remote versions) must be 32-bit aligned.

For attributes with small values (ie. the value can be stored within the leaf), the `XFS_ATTR_LOCAL` flag is set for the attribute. The entry details are stored using the `xfs_attr_leaf_name_local_t` structure. For large attribute values that cannot be stored within the leaf, separate filesystem blocks are allocated to store the value. They use the `xfs_attr_leaf_name_remote_t` structure. See Remote Values Section 19.5 for more information.

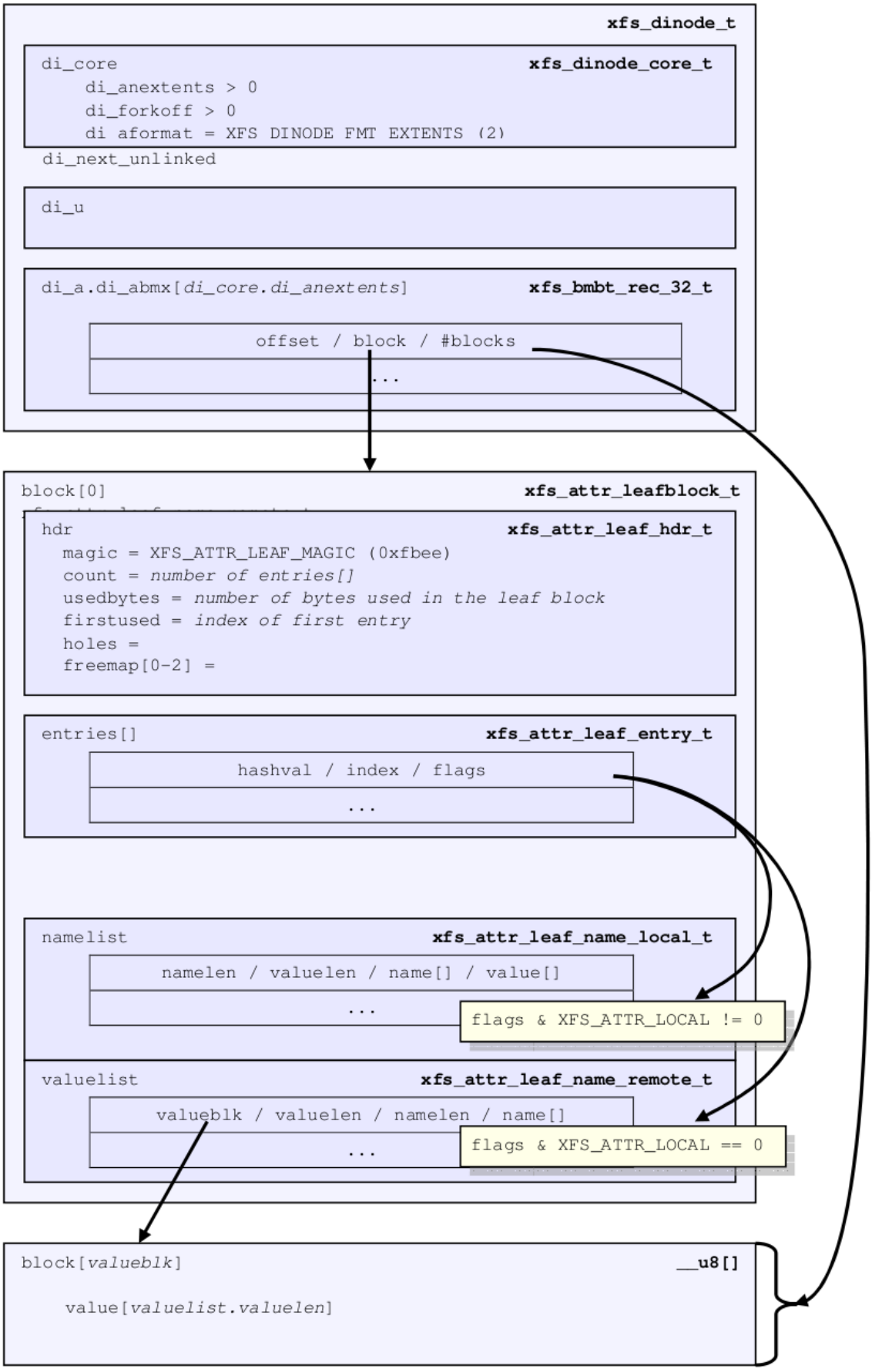


Figure 19.2: Leaf attribute layout

Both local and remote entries can be interleaved as they are only addressed by the hash/index entries. The flag is stored with the hash/index pairs so the appropriate structure can be used.

Since duplicate hash keys are possible, for each hash that matches during a lookup, the actual name string must be compared.

An “incomplete” bit is also used for attribute flags. It shows that an attribute is in the middle of being created and should not be shown to the user if we crash during the time that the bit is set. The bit is cleared when attribute has finished being set up. This is done because some large attributes cannot be created inside a single transaction.

19.2.1 xfs_db Leaf Attribute Example

A single 30KB extended attribute is added to an inode:

```
xfs_db> inode <inode#>
xfs_db> p
...
core.nblocks = 9
core.nextents = 0
core.naextents = 1
core.forkoff = 15
core.aformat = 2 (extents)
...
a.bmx[0] = [startoff,startblock,blockcount,extentflag]
          0:[0,37535,9,0]
xfs_db> ablock 0
xfs_db> p
hdr.info.forw = 0
hdr.info.back = 0
hdr.info.magic = 0xfbee
hdr.count = 1
hdr.usedbytes = 20
hdr.firstused = 4076
hdr.holes = 0
hdr.freemap[0-2] = [base,size] 0:[40,4036] 1:[0,0] 2:[0,0]
entries[0] = [hashval,nameidx,incomplete,root,secure,local]
          0:[0xfcf89d4f,4076,0,0,0,0]
nvlist[0].valueblk = 0x1
nvlist[0].valuelen = 30692
nvlist[0].namelen = 8
nvlist[0].name = "big_attr"
```

Attribute blocks 1 to 8 (filesystem blocks 37536 to 37543) contain the raw binary value data for the attribute.

Index 4076 (0xfec) is the offset into the block where the name/value information is. As can be seen by the value, it’s at the end of the block:

```
xfs_db> type text
xfs_db> p

000: 00 00 00 00  00 00 00 00 fb ee 00 00 00 01 00 14 ................
010: 0f ec 00 00  00 28 0f c4 00 00 00 00 00 00 00 00 ................
020: fc f8 9d 4f  0f ec 00 00 00 00 00 00 00 00 00 00 ...O............
030: 00 00 00 00  00 00 00 00 00 00 00 00 00 00 00 00 ................
...
fe0: 00 00 00 00  00 00 00 00 00 00 00 00 00 00 00 01 ................
ff0: 00 00 77 e4  08 62 69 67 5f 61 74 74 72 00 00 00 ..w..big.attr...
```

A 30KB attribute and a couple of small attributes are added to a file:

```
xfs_db> inode <inode#>
xfs_db> p
...
```

```
core.nblocks = 10
core.extsize = 0
core.nextents = 1
core.naextents = 2
core.forkoff = 15
core.aformat = 2 (extents)
...
u.bmx[0] = [startoff,startblock,blockcount,extentflag]
          0:[0,81857,1,0]
a.bmx[0-1] = [startoff,startblock,blockcount,extentflag]
          0:[0,81858,1,0]
          1:[1,182398,8,0]
xfs_db> ablock 0
xfs_db> p
hdr.info.forw = 0
hdr.info.back = 0
hdr.info.magic = 0xfbee
hdr.count = 3
hdr.usedbytes = 52
hdr.firstused = 4044
hdr.holes = 0
hdr.freemap[0-2] = [base,size] 0:[56,3988] 1:[0,0] 2:[0,0]
entries[0-2] = [hashval,nameidx,incomplete,root,secure,local]
          0:[0x1e9d3934,4044,0,0,0,1]
          1:[0x1e9d3937,4060,0,0,0,1]
          2:[0xfcf89d4f,4076,0,0,0,0]
nvlist[0].valuelen = 6
nvlist[0].namelen = 5
nvlist[0].name = "attr2"
nvlist[0].value = "value2"
nvlist[1].valuelen = 6
nvlist[1].namelen = 5
nvlist[1].name = "attr1"
nvlist[1].value = "value1"
nvlist[2].valueblk = 0x1
nvlist[2].valuelen = 30692
nvlist[2].namelen = 8
nvlist[2].name = "big_attr"
```

As can be seen in the entries array, the two small attributes have the local flag set and the values are printed.

A raw disk dump shows the attributes. The last attribute added is highlighted (offset 4044 or 0xfcc):

```
000: 00 00 00 00 00 00 00 00 fb ee 00 00 00 03 00 34 ...............4
010: 0f cc 00 00 00 38 0f 94 00 00 00 00 00 00 00 00 .....8..........
020: 1e 9d 39 34 0f cc 01 00 1e 9d 39 37 0f dc 01 00 ..94......97....
030: fc f8 9d 4f 0f ec 00 00 00 00 00 00 00 00 00 00 ...0............
040: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00................
...
fc0: 00 00 00 00 00 00 00 00 00 00 00 00 00 06 05 61 ...............a
fd0: 74 74 72 32 76 61 6c 75 65 32 00 00 00 06 05 61 ttr2value2.....a
fe0: 74 74 72 31 76 61 6c 75 65 31 00 00 00 00 00 01 ttr1value1......
ff0: 00 00 77 e4 08 62 69 67 5f 61 74 74 72 00 00 00 ..w..big.attr...
```

19.3 Node Attributes

When the number of attributes exceeds the space that can fit in one filesystem block (ie. hash, flag, name and local values), the first attribute block becomes the root of a B+tree where the leaves contain the hash/name/value information that was stored in a single leaf block. The inode's attribute format itself remains extent based. The nodes use the `xfs_da_intnode_t` or `xfs_da3_intnode_t` structures introduced in the section about directories Section 11.2.

The location of the attribute leaf blocks can be in any order. The only way to find an attribute is by walking the node block hash/before values. Given a hash to look up, search the node's btree array for the first `hashval` in the array that exceeds the given hash. The entry is in the block pointed to by the `before` value.

Each attribute node block has a magic number of `XFS_DA_NODE_MAGIC` (0xfebe). On a v5 filesystem this is `XFS_DA3_NODE_MAGIC` (0x3ebe).

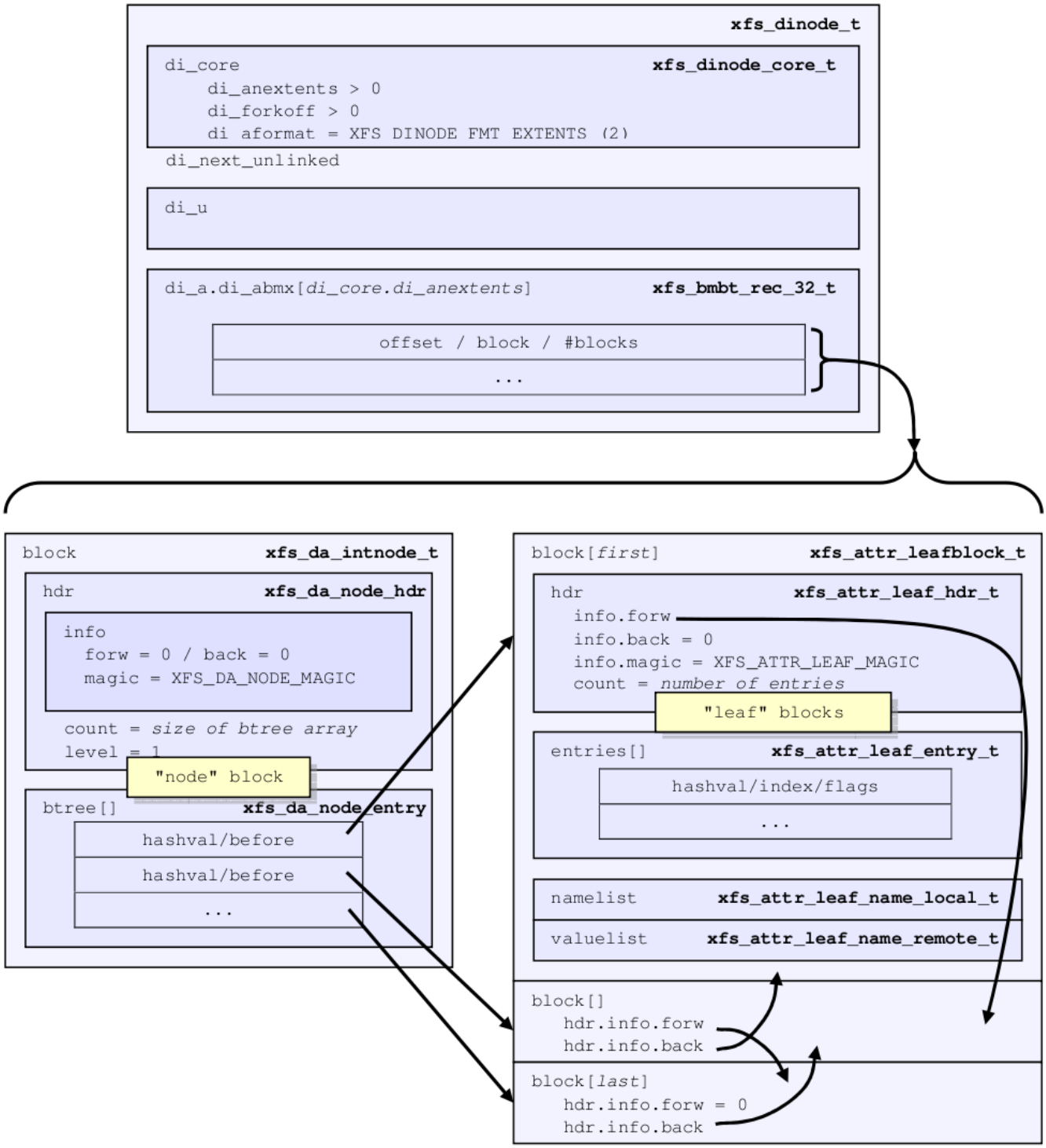


Figure 19.3: Node attribute layout

19.3.1 xfs_db Node Attribute Example

An inode with 1000 small attributes with the naming “attribute_n” where *n* is a number:

```
xfs_db> inode <inode#>
xfs_db> p
...
core.nblocks = 15
core.nextents = 0
core.naextents = 1
core.forkoff = 15
core.aformat = 2 (extents)
...
a.bmx[0] = [startoff,startblock,blockcount,extentflag] 0:[0,525144,15,0]
xfs_db> ablock 0
xfs_db> p
hdr.info.forw = 0
hdr.info.back = 0
hdr.info.magic = 0xfebe
hdr.count = 14
hdr.level = 1
btree[0-13] = [hashval,before]
          0:[0x3435122d,1]
          1:[0x343550a9,14]
          2:[0x343553a6,13]
          3:[0x3436122d,12]
          4:[0x343650a9,8]
          5:[0x343653a6,7]
          6:[0x343691af,6]
          7:[0x3436d0ab,11]
          8:[0x3436d3a7,10]
          9:[0x3437122d,9]
          10:[0x3437922e,3]
          11:[0x3437d22a,5]
          12:[0x3e686c25,4]
          13:[0x3e686fad,2]
```

The hashes are in ascending order in the btree array, and if the hash for the attribute we are looking up is before the entry, we go to the addressed attribute block.

For example, to lookup attribute “attribute_267”:

```
xfs_db> hash attribute_267
0x3437d1a8
```

In the root btree node, this falls between `0x3437922e` and `0x3437d22a`, therefore leaf 11 or attribute block 5 will contain the entry.

```
xfs_db> ablock 5
xfs_db> p
hdr.info.forw = 4
hdr.info.back = 3
hdr.info.magic = 0xfbee
hdr.count = 96
hdr.usedbytes = 2688
hdr.firstused = 1408
hdr.holes = 0
hdr.freemap[0-2] = [base,size] 0:[800,608] 1:[0,0] 2:[0,0]
entries[0.95] = [hashval,nameidx,incomplete,root,secure,local]
          0:[0x3437922f,4068,0,0,0,1]
          1:[0x343792a6,4040,0,0,0,1]
          2:[0x343792a7,4012,0,0,0,1]
```

```
          3:[0x343792a8,3984,0,0,0,1]
          ...
          82:[0x3437d1a7,2892,0,0,0,1]
          83:[0x3437d1a8,2864,0,0,0,1]
          84:[0x3437d1a9,2836,0,0,0,1]
          ...
          95:[0x3437d22a,2528,0,0,0,1]
nvlist[0].valuelen = 10
nvlist[0].namelen = 13
nvlist[0].name = "attribute_310"
nvlist[0].value = "value_316\d"
nvlist[1].valuelen = 16
nvlist[1].namelen = 13
nvlist[1].name = "attribute_309"
nvlist[1].value = "value_309\d"
nvlist[2].valuelen = 10
nvlist[2].namelen = 13
nvlist[2].name = "attribute_308"
nvlist[2].value = "value_308\d"
nvlist[3].valuelen = 10
nvlist[3].namelen = 13
nvlist[3].name = "attribute_307"
nvlist[3].value = "value_307\d"
...
nvlist[82].valuelen = 10
nvlist[82].namelen = 13
nvlist[82].name = "attribute_268"
nvlist[82].value = "value_268\d"
nvlist[83].valuelen = 10
nvlist[83].namelen = 13
nvlist[83].name = "attribute_267"
nvlist[83].value = "value_267\d"
nvlist[84].valuelen = 10
nvlist[84].namelen = 13
nvlist[84].name = "attribute_266"
nvlist[84].value = "value_266\d"
...
```

Each of the hash entries has `XFS_ATTR_LOCAL` flag set (1), which means the attribute's value follows immediately after the name. Raw disk of the name/value pair at offset 2864 (0xb30), highlighted with "value_267" following immediately after the name:

```
b00: 62 75 74 65 5f 32 36 35 76 61 6c 75 65 5f 32 36 bute.265value.26
b10: 35 0a 00 00 00 0a 0d 61 74 74 72 69 62 75 74 65 5......attribute
b20: 51 32 36 36 76 61 6c 75 65 5f 32 36 36 0a 00 00 .266value.266...
b30: 00 0a 0d 61 74 74 72 69 62 75 74 65 5f 32 36 37 ...attribute.267
b40: 76 61 6c 75 65 5f 32 36 37 0a 00 00 00 0a 0d 61 value.267......a
b50: 74 74 72 69 62 75 74 65 5f 32 36 38 76 61 6c 75 ttribute.268valu
b60: 65 5f 32 36 38 0a 00 00 00 0a 0d 61 74 74 72 69 e.268......attri
b70: 62 75 74 65 5f 32 36 39 76 61 6c 75 65 5f 32 36 bute.269value.26
```

Each entry starts on a 32-bit (4 byte) boundary, therefore the highlighted entry has 2 unused bytes after it.

19.4 B+tree Attributes

When the attribute's extent map in an inode grows beyond the available space, the inode's attribute format is changed to a "btree". The inode contains root node of the extent B+tree which then address the leaves that contains the extent arrays for the attribute data. The attribute data itself in the allocated filesystem blocks use the same layout and structures as described in Node Attributes Section 19.3.

Refer to the previous section on B+tree Data Extents Section 17.2 for more information on XFS B+tree extents.

19.4.1 xfs_db B+tree Attribute Example

Added 2000 attributes with 729 byte values to a file:

```
xfs_db> inode <inode#>
xfs_db> p
...
core.nblocks = 640
core.extsize = 0
core.nextents = 1
core.naextents = 274
core.forkoff = 15
core.aformat = 3 (btree)
...
a.bmbt.level = 1
a.bmbt.numrecs = 2
a.bmbt.keys[1-2] = [startoff] 1:[0] 2:[219]
a.bmbt.ptrs[1-2] = 1:83162 2:109968
xfs_db> fsblock 83162
xfs_db> type bmapbtd
xfs_db> p
magic = 0x424d4150
level = 0
numrecs = 127
leftsib = null
rightsib = 109968
recs[1-127] = [startoff,startblock,blockcount,extentflag]
          1:[0,81870,1,0]
          ...
xfs_db> fsblock 109968
xfs_db> type bmapbtd
xfs_db> p
magic = 0x424d4150
level = 0
numrecs = 147
leftsib = 83162
rightsib = null
recs[1-147] = [startoff,startblock,blockcount,extentflag]
          ...
                              (which is fsblock 81870)
xfs_db> ablock 0
xfs_db> p
hdr.info.forw = 0
hdr.info.back = 0
hdr.info.magic = 0xfebe
hdr.count = 2
hdr.level = 2
btree[0-1] = [hashval,before] 0:[0x343612a6,513] 1:[0x3e686fad,512]
```

The extent B+tree has two leaves that specify the 274 extents used for the attributes. Looking at the first block, it can be seen that the attribute B+tree is two levels deep. The two blocks at offset 513 and 512 (ie. access using the `ablock` command) are intermediate `xfs_da_intnode_t` nodes that index all the attribute leaves.

19.5 Remote Attribute Values

On a v5 filesystem, all remote value blocks start with this header:

```
struct xfs_attr3_rmt_hdr {
        __be32  rm_magic;
        __be32  rm_offset;
        __be32  rm_bytes;
        __be32  rm_crc;
        uuid_t  rm_uuid;
        __be64  rm_owner;
        __be64  rm_blkno;
        __be64  rm_lsn;
};
```

rm_magic
Specifies the magic number for the remote value block: "XARM" (0x5841524d).

rm_offset
Offset of the remote value data, in bytes.

rm_bytes
Number of bytes used to contain the remote value data.

rm_crc
Checksum of the remote value block.

rm_uuid
The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

rm_owner
The inode number that this remote value block belongs to.

rm_blkno
Disk block number of this remote value block.

rm_lsn
Log sequence number of the last write to this block.

Filesystems formatted prior to v5 do not have this header in the remote block. Value data begins immediately at offset zero.

19.6 Key Differences Between Directories and Extended Attributes

Directories and extended attributes share the function of mapping names to information, but the differences in the functionality requirements applied to each type of structure influence their respective internal formats. Directories map variable length names to iterable directory entry records (dirent records), whereas extended attributes map variable length names to non-iterable attribute records. Both structures can take advantage of variable length record btree structures (i.e the dabtree) to map name hashes, but there are major differences in the way each type of structure integrate the dabtree index within the information being stored. The directory dabtree leaf nodes contain mappings between a name hash and the location of a dirent record inside the directory entry segment. Extended attributes, on the other hand, store attribute records directly in the leaf nodes of the dabtree.

When XFS adds or removes an attribute record in any dabtree, it splits or merges leaf nodes of the tree based on where the name hash index determines a record needs to be inserted into or removed. In the attribute dabtree, XFS splits or merges sparse leaf nodes of the dabtree as a side effect of inserting or removing attribute records.

Directories, however, are subject to stricter constraints. The userspace readdir/seekdir/telldir directory cookie API places a requirement on the directory structure that dirent record cookie cannot change for the life of the dirent record. XFS uses the dirent record's logical offset into the directory data segment as the cookie, and hence the dirent record cannot change location. Therefore, XFS cannot store dirent records in the leaf nodes of the dabtree because the offset into the tree would change as other entries are inserted and removed.

Dirent records are therefore stored within directory data blocks, all of which are mapped in the first directory segment. The directory dabtree is mapped into the second directory segment. Therefore, directory blocks require external free space tracking

because they are not part of the dabtree itself. Because the dabtree only stores pointers to dirent records in the first data segment, there is no need to leave holes in the dabtree itself. The dabtree splits or merges leaf nodes as required as pointers to the directory data segment are added or removed, and needs no free space tracking.

When XFS adds a dirent record, it needs to find the best-fitting free space in the directory data segment to turn into the new record. This requires a free space index for the directory data segment. The free space index is held in the third directory segment. Once XFS has used the free space index to find the block with that best free space, it modifies the directory data block and updates the dabtree to point the name hash at the new record. When XFS removes dirent records, it leaves hole in the data segment so that the rest of the entries do not move, and removes the corresponding dabtree name hash mapping.

Note that for small directories, XFS collapses the name hash mappings and the free space information into the directory data blocks to save space.

In summary, the requirement for a free space map in the directory structure results from storing the dirent records externally to the dabtree. Attribute records are stored directly in the dabtree leaf nodes of the dabtree (except for remote attribute values which can be anywhere in the attr fork address space) and do not need external free space tracking to determine where to best insert them. As a result, extended attributes exhibit nearly perfect scaling until the computer runs out of memory.

Chapter 20

Symbolic Links

Symbolic links to a file can be stored in one of two formats: “local” and “extents”. The length of the symlink contents is always specified by the inode’s `di_size` value.

20.1 Short Form Symbolic Links

Symbolic links are stored with the “local” `di_format` if the symbolic link can fit within the inode’s data fork. The link data is an array of characters (`di_symlink` array in the data fork union).

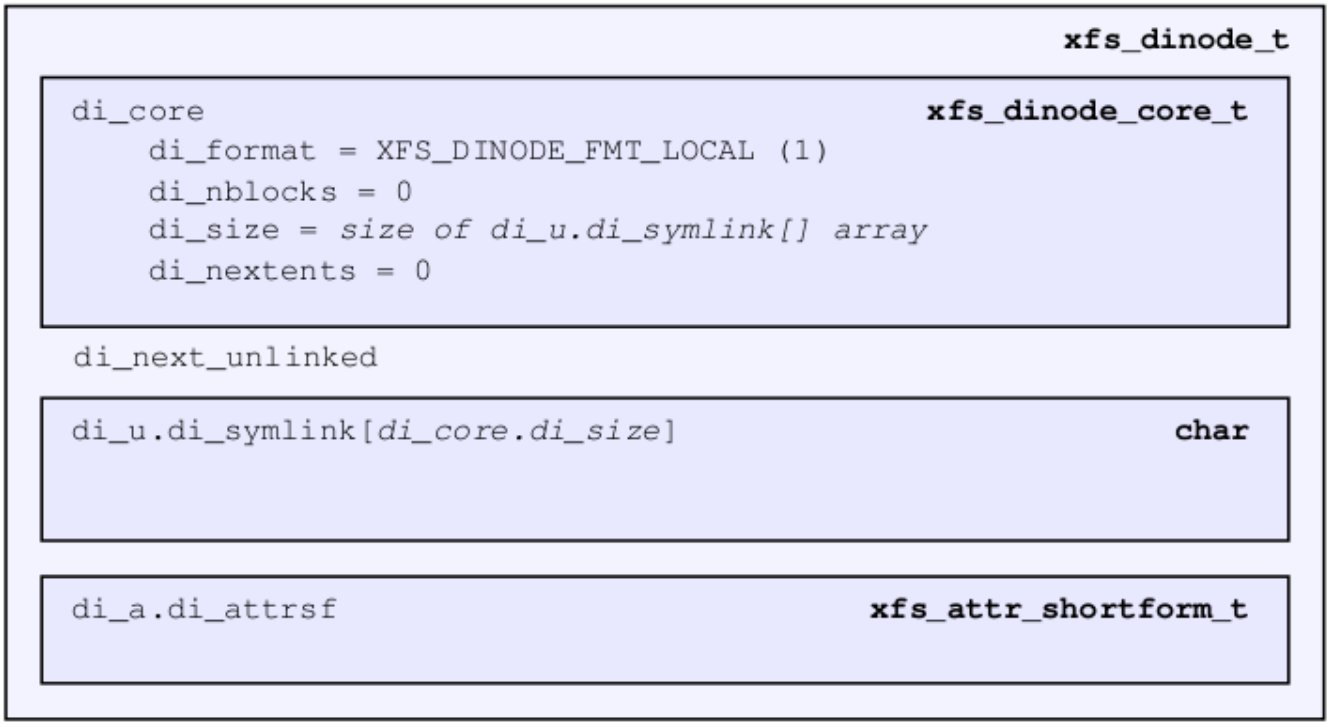


Figure 20.1: Symbolic link short form layout

20.1.1 xfs_db Short Form Symbolic Link Example

A short symbolic link to a file is created:

```
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 0120777
core.version = 1
core.format = 1 (local)
...
core.size = 12
core.nblocks = 0
core.extsize = 0
core.nextents = 0
...
u.symlink = "small_target"
```

Raw on-disk data with the link contents highlighted:

```
xfs_db> type text
xfs_db> p
00: 49 4e a1 ff 01 01 00 01 00 00 00 00 00 00 00 00 IN..............
10: 00 00 00 01 00 00 00 00 00 00 00 00 00 00 00 01 ................
20: 44 be e1 c7 03 c4 d4 18 44 be el c7 03 c4 d4 18 D.......D.......
30: 44 be e1 c7 03 c4 d4 18 00 00 00 00 00 00 00 Oc D...............
40: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
50: 00 00 00 02 00 00 00 00 00 00 00 00 00 00 00 00 ................
60: ff ff ff ff 73 6d 61 6c 6c 5f 74 61 72 67 65 74 ....small.target
70: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ................
```

20.2 Extent Symbolic Links

If the length of the symbolic link exceeds the space available in the inode's data fork, the link is moved to a new filesystem block and the inode's `di_format` is changed to "extents". The location of the block(s) is specified by the data fork's `di_bmx[]` array. In the significant majority of cases, this will be in one filesystem block as a symlink cannot be longer than 1024 characters.

On a v5 filesystem, the first block of each extent starts with the following header structure:

```
struct xfs_dsymlink_hdr {
     __be32                  sl_magic;
     __be32                  sl_offset;
     __be32                  sl_bytes;
     __be32                  sl_crc;
     uuid_t                  sl_uuid;
     __be64                  sl_owner;
     __be64                  sl_blkno;
     __be64                  sl_lsn;
};
```

sl_magic
: Specifies the magic number for the symlink block: "XSLM" (0x58534c4d).

sl_offset
: Offset of the symbolic link target data, in bytes.

sl_bytes
: Number of bytes used to contain the link target data.

sl_crc
: Checksum of the symlink block.

sl_uuid
The UUID of this block, which must match either `sb_uuid` or `sb_meta_uuid` depending on which features are set.

sl_owner
The inode number that this symlink block belongs to.

sl_blkno
Disk block number of this symlink.

sl_lsn
Log sequence number of the last write to this block.

Filesystems formatted prior to v5 do not have this header in the remote block. Symlink data begins immediately at offset zero.

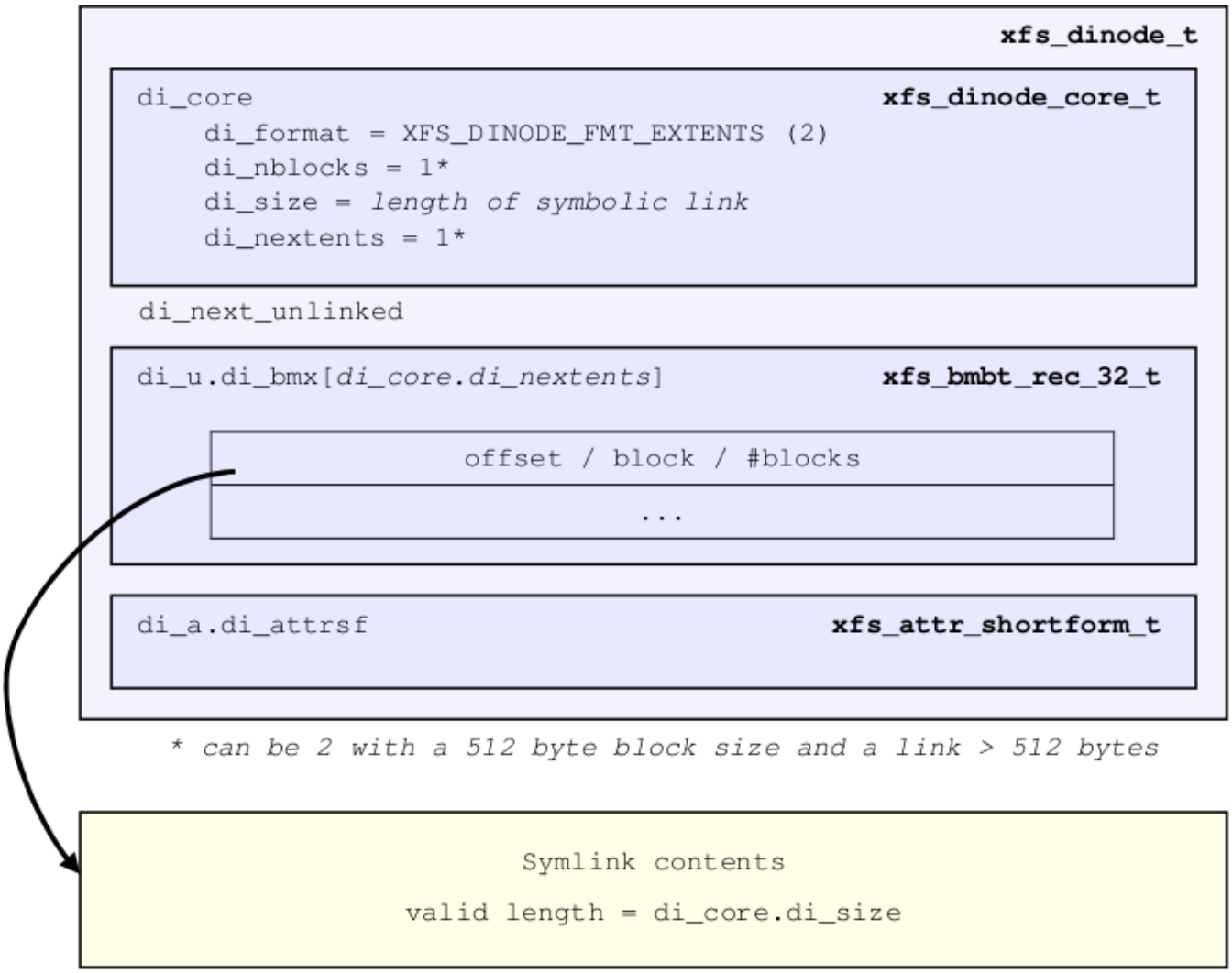


Figure 20.2: Symbolic link extent layout

20.2.1 xfs_db Symbolic Link Extent Example

A longer link is created (greater than 156 bytes):

```
xfs_db> inode <inode#>
xfs_db> p
core.magic = 0x494e
core.mode = 0120777
core.version = 1
core.format = 2 (extents)
...
core.size = 182
core.nblocks = 1
core.extsize = 0
core.nextents = 1
...
u.bmx[0] = [startoff,startblock,blockcount,extentflag] 0:[0,37530,1,0]
xfs_db> dblock 0
xfs_db> type symlink
xfs_db> p
"symlink contents..."
```

Part IV

Auxiliary Data Structures

Chapter 21

Metadata Dumps

The `xfs_metadump` and `xfs_mdrestore` tools are used to create a sparse snapshot of a live file system and to restore that snapshot onto a block device for debugging purposes. Only the metadata are captured in the snapshot, and the metadata blocks may be obscured for privacy reasons.

A metadump file starts with a `xfs_metablock` that records the addresses of the blocks that follow. Following that are the metadata blocks captured from the filesystem. The first block following the first superblock must be the superblock from AG 0. If the metadump has more blocks than can be pointed to by the `xfs_metablock.mb_daddr` area, the sequence of `xfs_metablock` followed by metadata blocks is repeated.

Metadata Dump Format

```
struct xfs_metablock {
        __be32          mb_magic;
        __be16          mb_count;
        uint8_t         mb_blocklog;
        uint8_t         mb_reserved;
        __be64          mb_daddr[];
};
```

mb_magic
The magic number, "XFSM" (0x5846534d).

mb_count
Number of blocks indexed by this record. This value must not exceed `(1 << mb_blocklog) -sizeof(struct xfs_metablock)`.

mb_blocklog
The log size of a metadump block. This size of a metadump block 512 bytes, so this value should be 9.

mb_reserved
Reserved. Should be zero.

mb_daddr
An array of disk addresses. Each of the `mb_count` blocks (of size `(1 << mb_blocklog)`) following the `xfs_metablock` should be written back to the address pointed to by the corresponding `mb_daddr` entry.

21.1 Dump Obfuscation

Unless explicitly disabled, the `xfs_metadump` tool obfuscates empty block space and naming information to avoid leaking sensitive information into the metadump file. `xfs_metadump` does not copy user data blocks.

The obfuscation policy is as follows:

- File and extended attribute names are both considered "names".
- Names longer than 8 characters are totally rewritten with a name that matches the hash of the old name.
- Names between 5 and 8 characters are partially rewritten to match the hash of the old name.
- Names shorter than 5 characters are not obscured at all.
- Names that cross a block boundary are not obscured at all.
- Extended attribute values are zeroed.
- Empty parts of metadata blocks are zeroed.