ECSE 427 A4 File System Design

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Block Size Selection

4KB - From the given histogram, approximately 55.6% of the files have sizes ≤ 4KB. Therefore, 4KB block size means the majority of files are in single memory blocks. A larger block size would induce internal fragmentations. A smaller block size would complicate the management of I-node and free-bit blocks.

Architecture Selection and Reasoning

Clustered I-Node

According to the instruction, the access patterns of the files are known in advance. Therefore, the files can be grouped based on the access patterns, and the files can be stored on the disk together in predetermined groups (clusters). However, if only files are grouped together without splitting the I-Node table, when accessing files in the same cluster, the I-Nodes of these files still need to be searched and cached into the memory one at a time since the I-Nodes are not separated into groups according to the file clusters. The disk head and disks would make large movements and rotations since we need to jump back and forth between the file locations and the I-Node table, which would result in huge rotational latency and seek time, and decrease the performance of the file system.

Therefore, besides grouping the files together, the I-Node table would also need to be split and distributed to each cluster to form a **clustered I-Node file system**. When a file is accessed, the entire I-Node table of the disk cluster which the accessed file belongs to will be cached into the memory. Since the files that are likely to be accessed together are stored in the same disk cluster, the I-Nodes of these files will also be in the cached I-Node table, which would not need to be searched and cached one at a time for later file accesses. In this way, the access time is reduced and the file system performs better.

Details of File System Architecture

Design Decision:

1. Each block has size of 4KB
2. Each cluster has size 32 MB
3. Each cluster has 4k I-nodes

Diagram for Secondary Storage

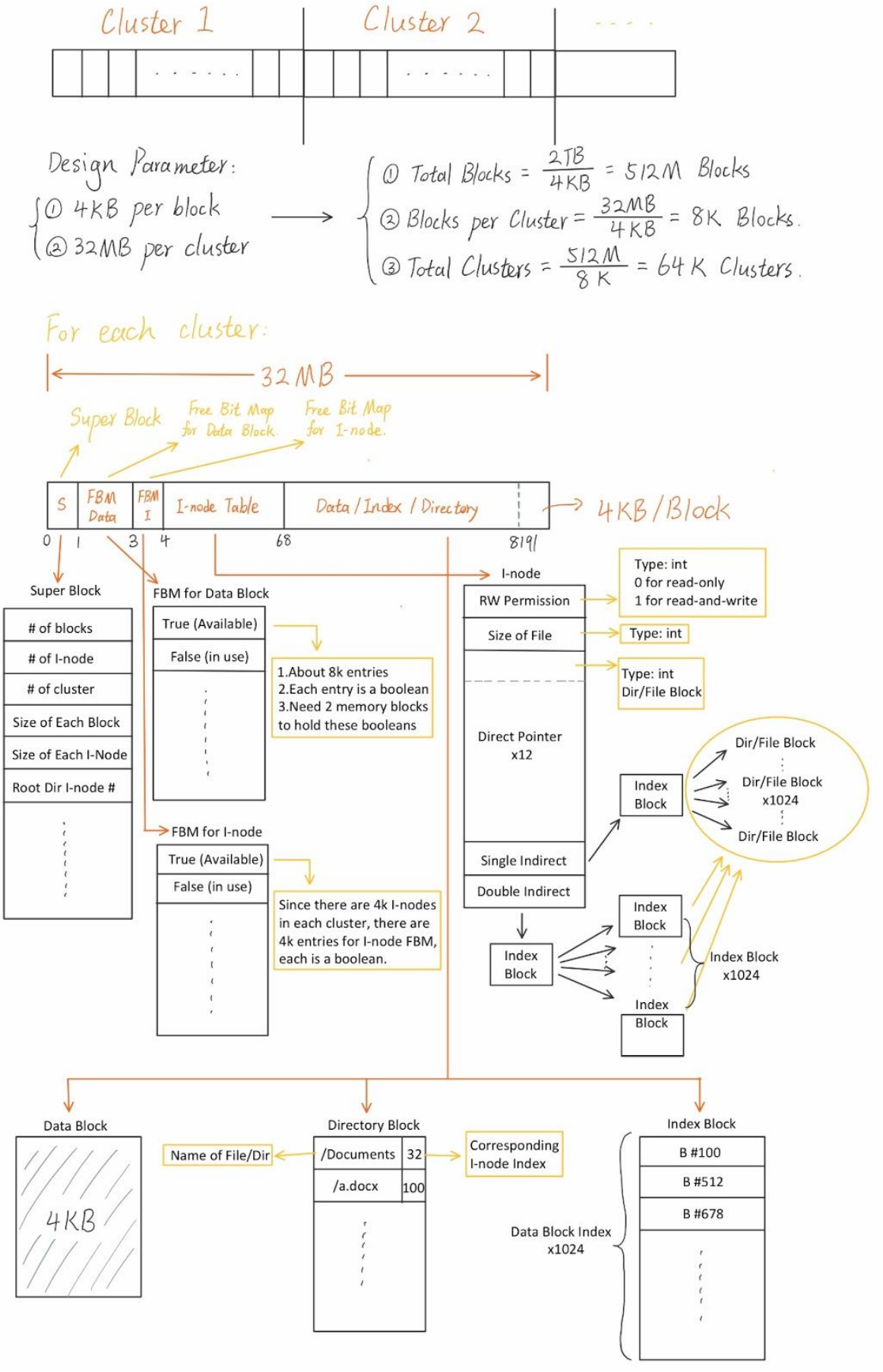
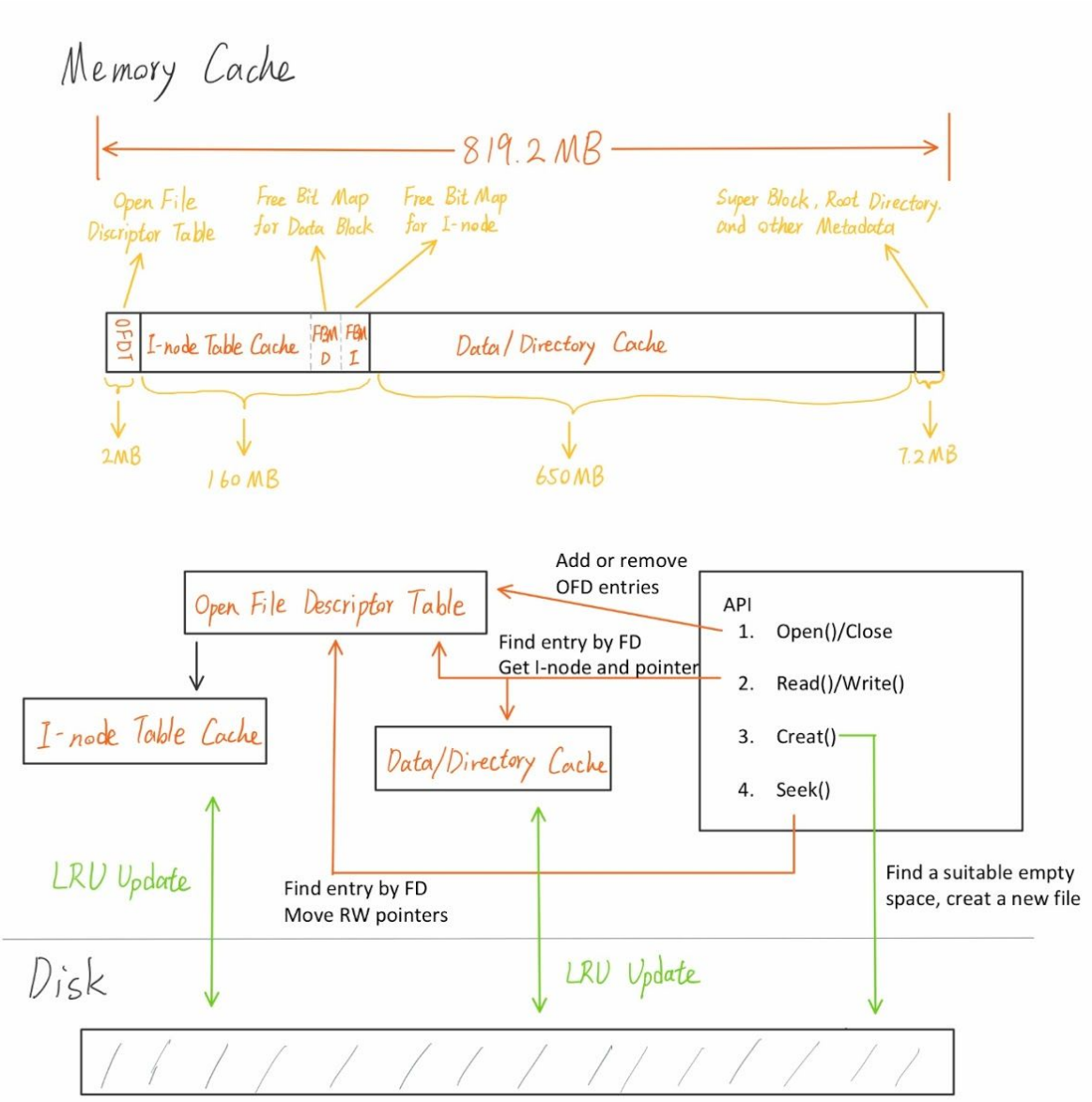


Diagram for Memory Cache



Total Cache Size = 16 GB * 5% = 819.2MB

Cache Allocation:

1. 650MB for Data/Directory
2. 160MB for I-node table and FBMs (when opening a file, the entire I-node table of the cluster will be loaded into the cache, to improve later file accesses)
   160MB/(67*4KB) = 611 clusters (611 I-node tables and corresponding FBMs)
3. 2MB for Open File Descriptor Table
   For each entry of Open File Descriptor Table, there will be 2 32-bit int for FD and I-node ID, and 2 64-bit int for RW pointers, which make each entry has size of 24 bytes.
   2MB/24 = 87381 files can be opened simultaneously.
4. Rest of the 7.2MB are used for Super Block, Root Directory and other Metadata

Pseudo code

createFile()

```
//-------------------createFile-----------------------------------------------------
int createFile(char* fileName, int permission){
    struct Block* directoryBlock = getCurrentDirectory();
    if(FileAlreadyExist(fileName)) return -1;
    struct iNode newINode = {permission, size = 0};
    if current cluster is full on data block || full on INode
        find nearest cluster with enough space (inode + one block);
        int iNodeIndex = allocateINodeInThatCluster(newINode);
        if allocate fails return -1;
    else
        int iNodeIndex = allocateINodeInCurrentCluster(newINode);
        if allocate fails return -1;
    // Do preallocation, all files will automatically have one block (4k) at creation
    allocateFirstDataBlock(iNodeIndex);
    if(isFull(directoryBlock))
        Append a newBlock after current directory blocks in its parent directory;
        newBlock.append({filename, iNodeIndex});
    else
        directoryBlock.append({filename, iNodeIndex});
    updateINodeInCache(); // Write changed directory to the disk
                // And load Inode table of this cluster in cache
    return 0;
}
```

openFile()

```
//---------------openFile-------------------------------------------------------------
int openFile(char* fileName){
    if (file is already opened)
        return getFileDescriptor(fileName);

    if fileDescriptorTable is full return -1;
    int newFD = findEmptyEntry(fileDescriptorTable);

    int iNodeIndex = findINodeIndex(fileName);
    if iNode not in cache:
        cluster = find the cluster containing the INode in Disk;
        loadINodeFromDisk(cluster);
    if not a single cluster contain this INode
        // file does not exist yet. Try create first
        if (createFile(fileName) failed) return -1;

    fileDescriptorTable[newFD].iNodeIndex = iNodeIndex;
    fileDescriptorTable[newFD].readPtr = FILE_START;
    if(peekFilePermission(iNodeIndex) == READ_ONLY)
        fileDescriptorTable[newFD].writePtr = NULL;
    else
        fileDescriptorTable[newFD].writePtr = FILE_START;
    return newFD;
}
```

read()

```
//--------------------read---------------------------------------------------------------
int read(int fdID, char* buf, int length){
    // check if file descriptor ID is valid
    if(fdID < 0 || fdID > Max_size_of_fdt){
        return -1;
    }

    int INodeID = fileDescriptorTable[fdID].INodeIndex
    int readPointer  = fileDescriptorTable[fdID].readPtr

    // unlikely to happen since the prior open() will bring INode to cache
    // But to cover extreme condition (like the file is opened but its iNode got replaced in cache)
    // we added the condition below. Same thing in write
    if (iNodeIdx exist in cache)
       curINode = get INode in cache;
   else
       curINode = find corresponding cluster and loadINodeFromDisk(cluster);

    // check if read outside of file
    if (readPointer+length > file_size){
        length = file_size - readPointer;    //if outside, change length to read to end of file
    }

    int read_end = readPointer+length;    //end position of read
    char* buf_tracker = buf     //track position in buf
    int byteAlreadyRead = 0;

    while(readPointer != read_end){
        int block_Position_In_INode = readPointer/BLOCK_SIZE;
        int bytesToRead = min(BLOCK_SIZE - readPointer % BLOCK_SIZE , length-byteAlreadyRead);
        if(isSingleIndirect(block_Position_In_INode)){
            Target_Block_toRead = single_indirect_pointer[block_Position_In_INode-12];
        }else if(isDoubleIndirect(block_Position_In_INode)){
            int first_level_indirect_location = (i-12-1024)/1024
            int second_level_indirect_location = (i-12-1024)%1024
            Target_Block_toRead = double_indirect_pointer[first_level_indirect_location][second_level_indirect_location];
        }else{
            Target_Block_toRead = direct_pointer[block_Position_In_INode];
        }

        memcpy(Target_Block_toRead + readPointer % BLOCK_SIZE, buf_tracker, bytesToRead);

        readPointer += bytesToRead;     //update pointers
        buf_tracker += bytesToRead;
        byteAlreadyRead += bytesToRead;
    }

    updateReadpointer();    //update read pinter in I-node

    return length;
}
```

writeFile()

```
//-----------------------writeFile-------------------------------------------------------------
int writeFile(int fd, const char* buf, int len){
    // Note every file "borns with one block (4k)"
    // this is to reduce the time of updating/syncing inode
    bool inodeHasChanged = false;
    char bufferForOneBlock [BLOCK_SIZE];
    memset(buffer, 0 ,BLOCK_SIZE); //intialize buffer
    int byteAlreadyWritten = 0;
    iNodeIdx = fileDescriptorTable[fd].iNodeIndex;
    if iNodeIdx is null or invalid
        return -1; // there is error in opening the file
    writePtr = fileDescriptorTable[fd].writePtr;

    if (iNodeIdx exist in cache)
        INode = get INode in cache;
    else
        find corresponding cluster holding INode and loadINodeFromDisk(cluster);
    int original_File_Size_Before_Write = INode.filesize;

    while(byteAlreadyWritten < len){
        int block_Position_In_INode = ptr/BLOCK_SIZE;
        int block_idx;
        if(is_In_12_DirectBlocks(block_Position_In_INode)){
            // One of the 12 direct node
            block_idx = directBlocksInINode[block_Position_In_INode];
            if(getBlock(block_idx) is null){
                block_idx = allocate a new data block and link to inode else break;
                inodeHasChanged = true;
            }
        }else if (is_In_Single_Indirect_Region(block_Position_In_INode)){
            // writeptr is in single indir region
            if (single indirect index block has not existed yet){
                allocate a new index block and link to INode else break;
                indexBlock_idx = get index of the index block;
                inodeHasChanged = true;
            }
            loadIndexBoxIntoBuffer(indexBlock_idx, bufferForOneBlock);
            indexBlock_SingleIndir = (int[1024])bufferForOneBlock; // now this block buffer holds 1024 entry for block
            block_idx = indexBlock_SingleIndir[block_Position_In_INode -12];
            if block_idx points to null
                // Need to allocate the target block
                block_idx = allocate a new data block else break;
                indexBlock_SingleIndir[block_Position_In_INode -12] = block_idx;
        }
        else{
            // based on block_Position_In_INode, the writePtr is targeting at the double indirect pointer
            // 1. make sure single block has exist, if not, create a single indir index block first
            if(single indirect index block has not existed yet){
                allocate a new index block and link to INode else break;
                inodeHasChanged = true;
            }
            // after making sure there are no sparse space in the single indir region in INode
            // we start touching the double indir pointer
            if(double indirect index block has not existed yet){
                // if there is no double indir block yet, allocate one
                indexBlock_idx = allocate a index block fo double indir in available cluster else break;
                inodeHasChanged = true;
            }
            loadIndexBoxIntoBuffer(indexBlock_idx, bufferForOneBlock);
            indexBlock_DoubleIndir = (int[1024])bufferForOneBlock;
            // every entry of double indir index block should be a index block (as tutorial, B-->B, not A/C)
            // the corresponding double indir index is calculated through (block_Position_In_INode - 12 - 1024)/1024
            // (block_Position_In_INode - 12 - 1024) is current block index. One entry on double indir holds 1024 blocks.
            if (indexBlock_DoubleIndir[(block_Position_In_INode - 12 - 1024)/1024] is not an index block) break;

            // targeted_index_block is what the current entry of double Indir block pointing to
            targeted_index_block = indexBlock_DoubleIndir[(block_Position_In_INode - 12 - 1024)/1024];
```

```
            if(block_idx points to null){
                block_idx = allocate a data block for write else break;
                targeted_index_block[(block_Position_In_INode - 12 - 1024)%1024] = block_idx;
            }
        }
        bufferForOneBlock = getWriteTargetBlock(block_idx);
        // determine how many bytes to write in this iteration based on the leftover space in block
        int bytesToWrite = = min(BLOCK_SIZE - writePtr % BLOCK_SIZE , len- byteAlreadyWritten);
        // Keep writing from the input buf to the disk data block buffer
        memcpy(bufferForOneBlock + writePtr % BLOCK_SIZE, buf + byteAlreadyWritten, bytesToWrite );
        byteAlreadyWritten += bytesToWrite;
        writeptr += bytesToWrite;
    }

    if(inodeHasChanged == true) updateINodeInCache();
    if updateClusterToDisk(original_File_Size_Before_Write, writeptr) == -1
        return -1; // Update to disk failed, the write is not good
    return byteAlreadyWritten;
}
```

seek()

```
//----------------seek-----------------------------------------------------------
int seek(int FDindex, int offset, char readOrWrite){
    // the seek updates the selected pointer by number specified in offset
    // if update is successful, this method return the pointer value prior to the update
    // (Analogy to sbrk())
    int pointerToChange;
    if(readOrWrite == "r")
        fileDescriptorTable[FDindex].readPtr = fileDescriptorTable[FDindex].readPtr + offset
        return pointerToChange;
    else if (readOrWrite == "w")
        fileDescriptorTable[FDindex].writePtr = fileDescriptorTable[FDindex].writePtr + offset
        return pointerToChange;
    else
        return -1;
}
```

close()

```
//---------------close-----------------------------
int CloseFile(fd){
    if(IsFileOpen(fd)){
        openFileTable[fd] = OpenFD_unused;
        return 0;
    }
    return -1;
}
```

Helper Functions

```
//-----------------Helper Method-----------------------------------------------------------------------------

// To improve performance, our implementation follows below principles syncing cache to disk:
// 1. we are using clustered INode system, thus everytime we always load complete INode table from one cluster to make use of locality
// 2. We update INode in cache only when there is a change. The changed INode is synced back to disk when it is evicted from cache
// 3. To improve performance, we keep all updating of index blocks at the end of writeFile() using helper method updateClusterToDisk()
//    please check updateClusterToDisk() for detail.
int updateClusterToDisk(original_File_Size_Before_Write, writeptr){
    // Our design choose clustered INode system
    // Principle 1 is one file must have all its data blocks in the same cluster
    // Principle 2 is that all files are dense (sparse space will be filled with data blocks of all zero,
    // also empty entries on index blocks will be filled)

    // This method first checks how many extra blocks needed to fill sparse region due to write
    // then based on the extra space, it determines whether to allocate all those blocks in current cluster
    // or to move the entire file with all data block and INode to a new cluster (since very unlikely, but current cluster is nearly full)

    dense_Block_Position_In_INode = original_File_Size_Before_Write/BLOCK_SIZE;
    end_Block_Position_In_INode = writeptr/BLOCK_SIZE;

    numberOfAdditionBlockNeeded = end_Block_Position_In_INode - dense_Block_Position_In_INode;
    if (numberOfAdditionBlockNeeded * BLOCK_SIZE > CLUSTER_SIZE - currentCluster.size){
        // current cluster is full and can not be write directly back to disk
        newCluster = find clostest cluster with enough size and bring to cache else return -1;
        copy current file I-node and data blocks there;
        fillSparseSpaceAt(newCluster, writeptr, numberOfAdditionBlockNeeded, fileInode);
    }else{
        fillSparseSpaceAt(currentCluster, writeptr, numberOfAdditionBlockNeeded,fileInode);
    }
    syncDataBlocksInCacheToDisk();
    return 0;
}

void fillSparseSpaceAt(selectedCluster, writeptr, numberOfAdditionBlockNeeded){
    newIntermediateBlocks = allocate numberOfAdditionBlockNeeded of data blocks in selectedCluster;
    if(isIn_12Direct_Block(writeptr)){
        initialize newIntermediateBlocks and link to fileInode;
    }else if(is_In_Single_Indirect_Region(writeptr)){
        initialize newIntermediateBlocks and link to fileInode and single indir index block;
    }else{
        // in second indir region
        for every single indir index block linked by the double indie index block:
            initialize newIntermediateBlocks and link to fileInode and single indir index block;
    }
}

void loadINodeFromDisk(newlyEnteringCluster){
    // according to our memory structure, the cache has enough space to hold
    // over 600 cluster's complete INode tables
    // EveryTime a new cluster is called, its inodes will be brought to cache
    // The cache replace cluster's INode table using LRU principle
    if cache is full on cluster INode table entries:
        replacedOne = find the cluster which has not been called for longest time;
        Write INode content in replaceOne back to disk;
        Evict replaceOne;
        Load newlyEnteringCluster.INodeTable in cache;
    else:
        // Cache is not full, need not to replace
        Load newlyEnteringCluster.INodeTable in cache;
}
```

Discussion of performance optimization

We choose the clustered I-Node architecture in the disk storage. We also specify the I-Node cache region and data cache region in the memory. Based on the locality in file usage, our implementation makes sure all related files' I-Node and data blocks are in the same cluster, so that the number of disk accesses is minimized.

Unlike normal I-Node architecture which scatters I-Node over a large I-Node table, we had two ways of improvement. First, for each I-Node there are 12 direct pointers, 1 single indirect pointer and 1 double indirect pointer. Thus an I-Node can hold a maximum file size of over 4000MB. This means while accessing any files, getting one I-Node is enough. Also, since we assume that the file use is in patterns, we have a cluster-based I-Node cache using LRU replacement algorithm. When accessing a file from a cluster, the entire I-Node table of this cluster will be loaded into the cache. In this way, subsequent file operations of neighbour files are cheap since very likely their I-Nodes are also in cache. Please check "loadINodeFromDisk()" in code, which is used in write(), read() and open().

Additionally, we also noticed that frequent updates of data blocks will increase the execution time. Thus, we combine all changes to data blocks in write() such as creating new index blocks and filling intermediate blocks into one writeback to the disk. Thus, every write() will only access the disk once through a comprehensive helper method "updateClusterToDisk()". This method fills in any sparse space after the written file, then checks if the changed file can still fit in the same cluster. Please check the pseudo code to see more detail.

Missing Requirements

We considered two missing requirements for file creation. The first one is what to do if the file already exists when creating a new file. In this situation, as shown in the pseudo code for createFile(), the user will be notified to have an error by returning -1 from createFile() function. Also, when creating a new file, if there is no available I-Node or enough free space in the current cluster, we decided to find the nearest cluster with available resources to place the new file.

For read and write functions, even though it rarely happens, we still considered the situation of missing I-Node in the cached I-Node table. This problem might happen if the separation time between opening and editing a file is too long, and the required I-Node has already been kicked out from the cached I-Node table by LRU algorithm. When this happens, as shown in the pseudo code for read and write functions, the file system will search for the required I-Node in the storage and reload it to the cache.

Lastly, we have conditions checking if read or write length goes beyond the file size. For reading, we automatically set the length to the end of that file. For writing, the file expansion logic is added in the pseudo code and explained in the previous section.