Hadoop & HDFS

DSCI 551

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Hadoop

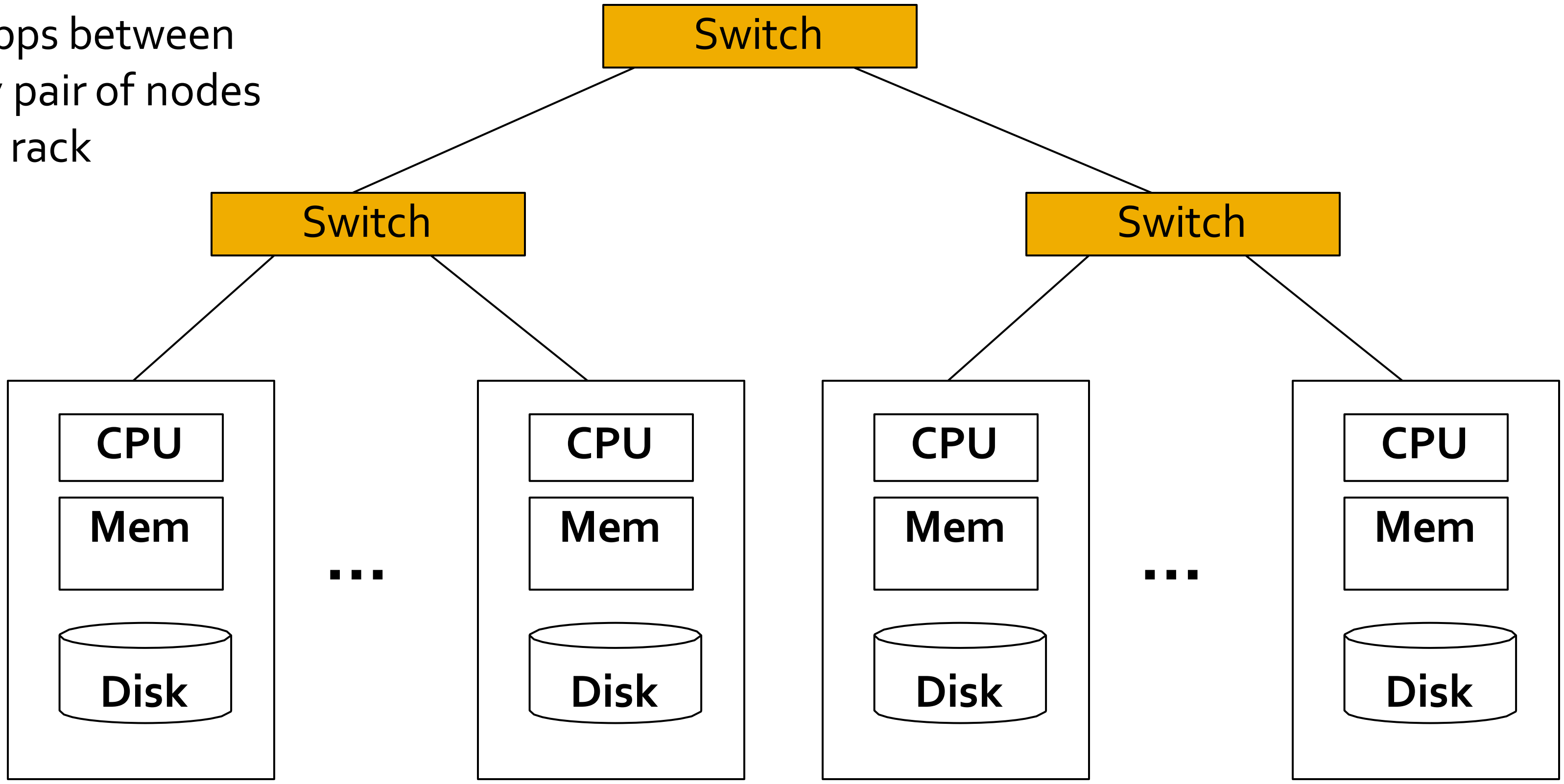
- A large-scale distributed & parallel batch-processing infrastructure

- Large-scale:
  - Handle a large amount of data and computation
- Distributed:
  - Distribute data & computation over multiple machines
- Batch processing
  - Process a series of jobs without human intervention

Cluster Architecture

2-10 Gbps backbone between racks

1 Gbps between
any pair of nodes
in a rack



Each rack contains 16-64 nodes

In 2011 it was guestimated that Google had 1M machines, http://bit.ly/Shh0RO

History

- 1st version released by Yahoo! in 2006
  - named after an elephant toy

- Originated from Google's work
  - GFS: Google File System (2003)
  - MapReduce (2004)

Roadmap

- Hadoop architecture
  - HDFS
  - MapReduce

- Installing Hadoop & HDFS

Key components

- HDFS (Hadoop distributed file system)
  - Distributed data storage with high reliability

- MapReduce
  - A parallel, distributed computational paradigm
  - With a simplified programming model

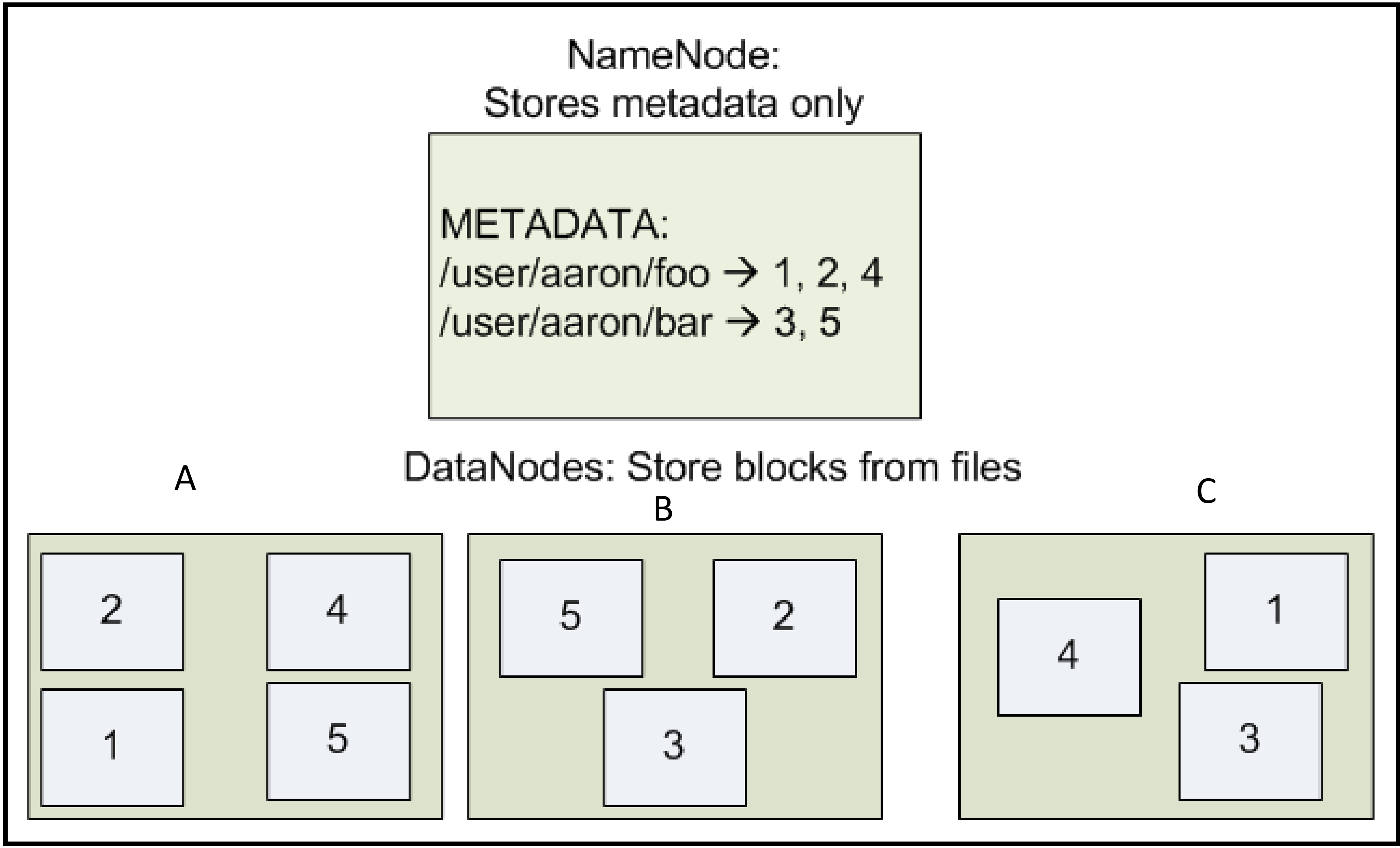
HDFS

- Data are distributed among multiple data nodes
  - Data nodes may be added on demand for more storage space

- Data are replicated to cope with node failure
  - Typically replication factor: 2 or 3

- Requests can go to any replica
  - Removing the bottleneck (as in single file server)

HDFS architecture



NameNode:
Stores metadata only

METADATA:
/user/aaron/foo → 1, 2, 4
/user/aaron/bar → 3, 5

DataNodes: Store blocks from files

/usr/john/blk_5_1.csv /usr/mary/blk_3_1.csv

HDFS has …

- A single NameNode, storing meta data:
  - A hierarchy of directories and files (name space)
  - Attributes of directories and files (in inodes), e.g., permission, access/modification times, etc.
  - Mapping of files to blocks on data nodes

- A number of DataNodes:
  - Storing contents/blocks of files

Compute nodes

- Data nodes are compute nodes too

- Advantage:
  - Allow schedule computation close to data

HDFS also has …

- A SecondaryNameNode
  - Maintaining checkpoints/images of NameNode
  - For recovery
  - not a fail over node

- In a single-machine setup
  - all nodes correspond to the same machine

Metadata in NameNode

- NameNode has an inode for each file and dir

- Record attributes of file/dir such as
  - Permission
  - Access time
  - Modification time

- Also record mapping of files to blocks

Mapping information in NameNode

- E.g., file /user/aaron/foo consists of blocks 1, 2, and 4

- Block 1 is stored on data nodes 1 and 3
- Block 2 is stored on data nodes 1 and 2
- …

Block size

- HDFS: 128 MB (version 2 & above)
  - Much larger than disk block size (4KB)
  - A: 128MB; B: 4KB
  - 128MB/4KB = 32K
  - A: 1GB/128MB = 8; B: 1GB/4KB = 2^30/2^12 = 2^18 = 2^8K = 256K
- Why larger size in HDFS?
  - Reduce metadata required per file
  - Fast streaming read of data (since larger amount of data are sequentially laid out on disk)

HDFS

- HDFS exposes the concept of blocks to client

- Reading and writing are done in two phases
  - Phase 1: client asks NameNode for block locations
    - By calling (sending request) getBlockLocations(), if reading
    - Or calling addBlock() for allocating new blocks (one at a time), if writing (need to call create()/append() first)
  - Phase 2: client talks to DataNode for data transfer
    - Reading blocks via readBlock() or writing blocks via writeBlock()

Client and Namenode communication

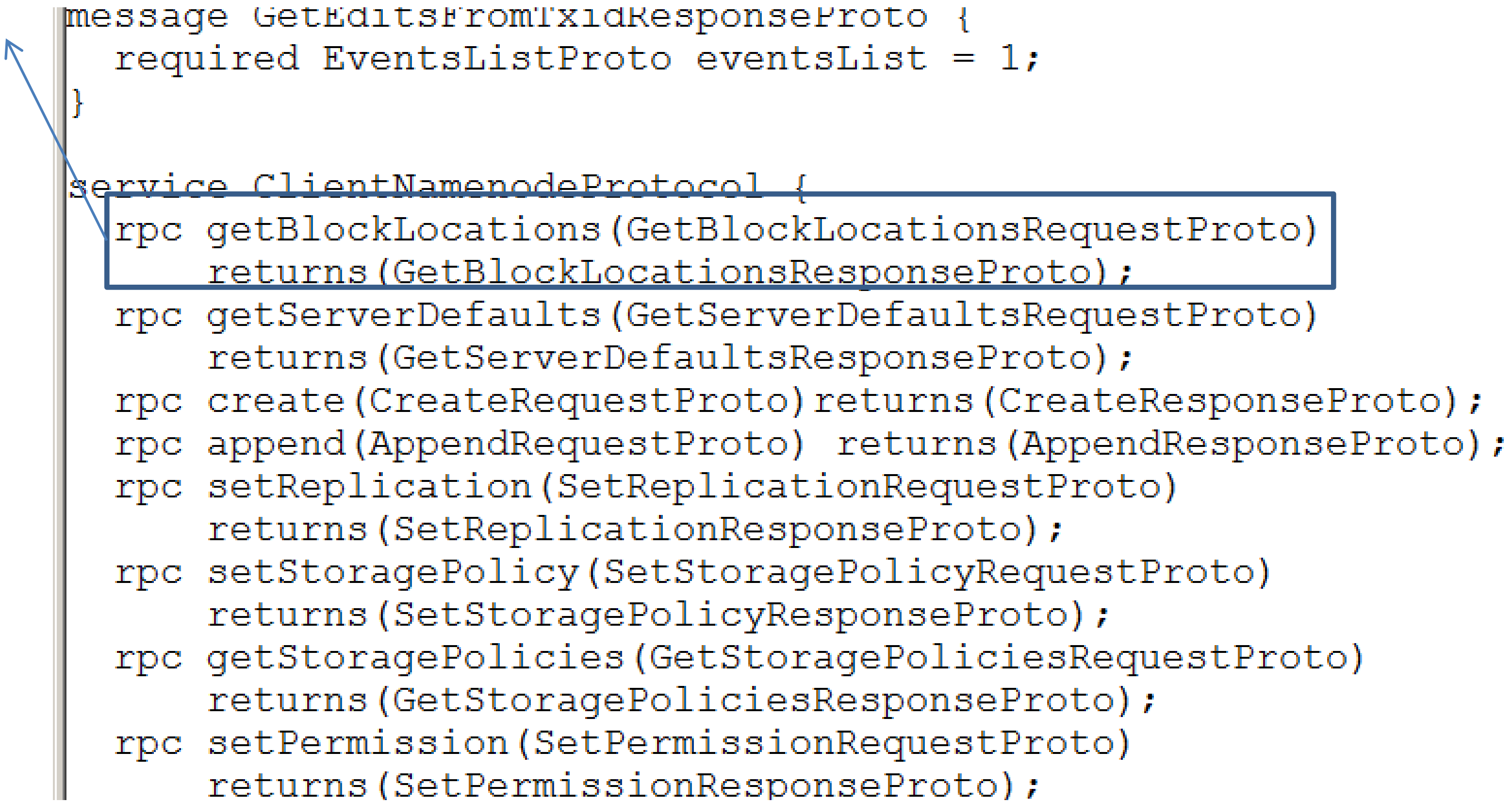
- Source code (version 2.8.1)
  - Definition of protocol
    - ClientNamenodeProtocol.proto
    - <hadoop-src-dir>\hadoop-hdfs-project\hadoop-hdfs-client\src\main\proto
  - Implementation
    - ClientProtocol.java
    - <hadoop-src-dir>\hadoop-hdfs-project\hadoop-hdfs-client\src\main\java\org\apache\hadoop\hdfs\protocol

Key operations

- Reading:
  - getBlockLocations()
- Writing
  - create()
  - append()
  - addBlock()

getBlockLocations

Before reading, client needs to first obtain locations of blocks

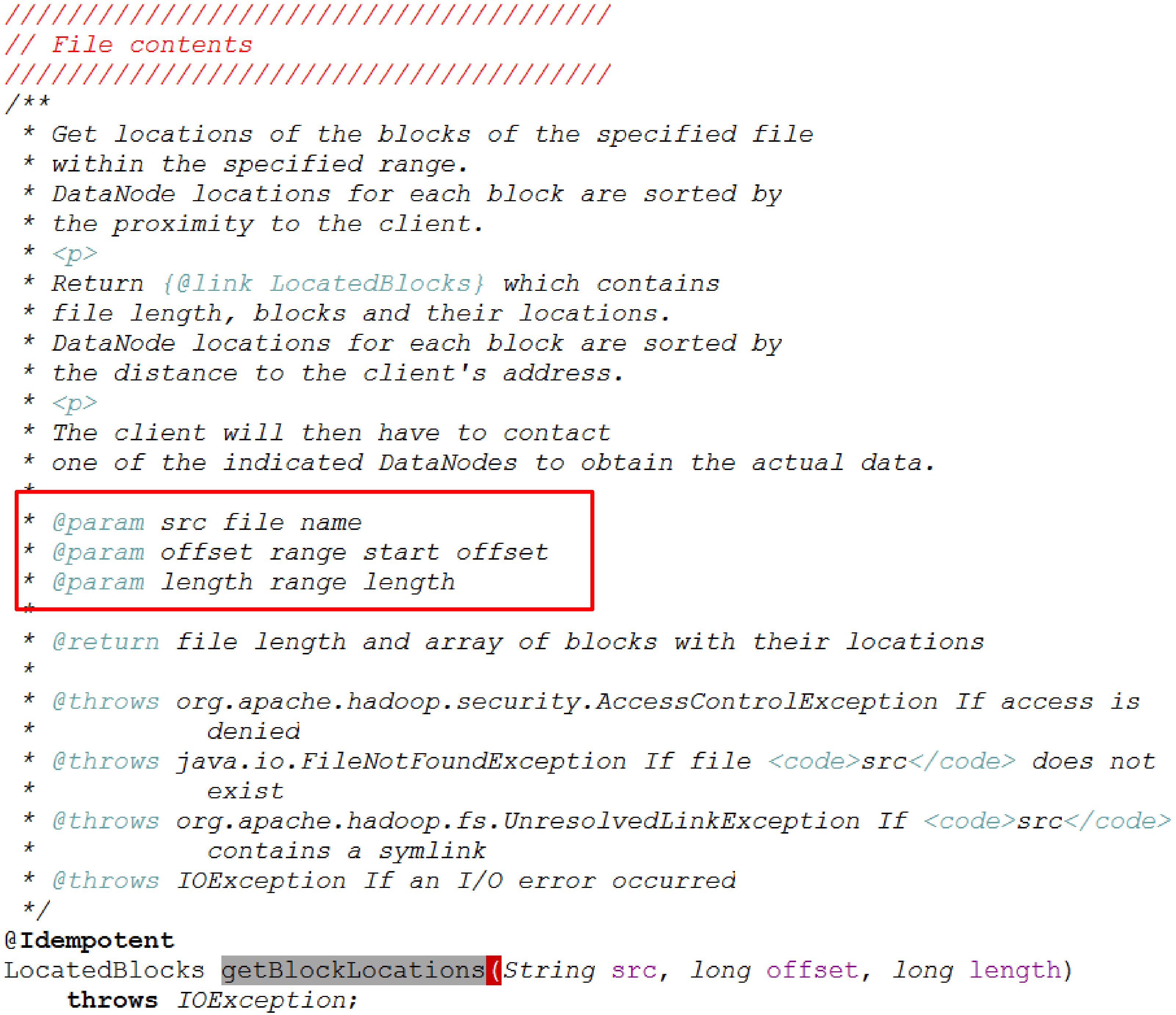


```
message GetEditsFromTxidResponseProto {
  required EventsListProto eventsList = 1;
}

service ClientNamenodeProtocol {
  rpc getBlockLocations(GetBlockLocationsRequestProto)
      returns(GetBlockLocationsResponseProto);
  rpc getServerDefaults(GetServerDefaultsRequestProto)
      returns(GetServerDefaultsResponseProto);
  rpc create(CreateRequestProto)returns(CreateResponseProto);
  rpc append(AppendRequestProto) returns(AppendResponseProto);
  rpc setReplication(SetReplicationRequestProto)
      returns(SetReplicationResponseProto);
  rpc setStoragePolicy(SetStoragePolicyRequestProto)
      returns(SetStoragePolicyResponseProto);
  rpc getStoragePolicies(GetStoragePoliciesRequestProto)
      returns(GetStoragePoliciesResponseProto);
  rpc setPermission(SetPermissionRequestProto)
      returns(SetPermissionResponseProto);
```

getBlockLocations

- Input:
  - File name
  - Offset (to start reading)
  - Length (how much data to be read)

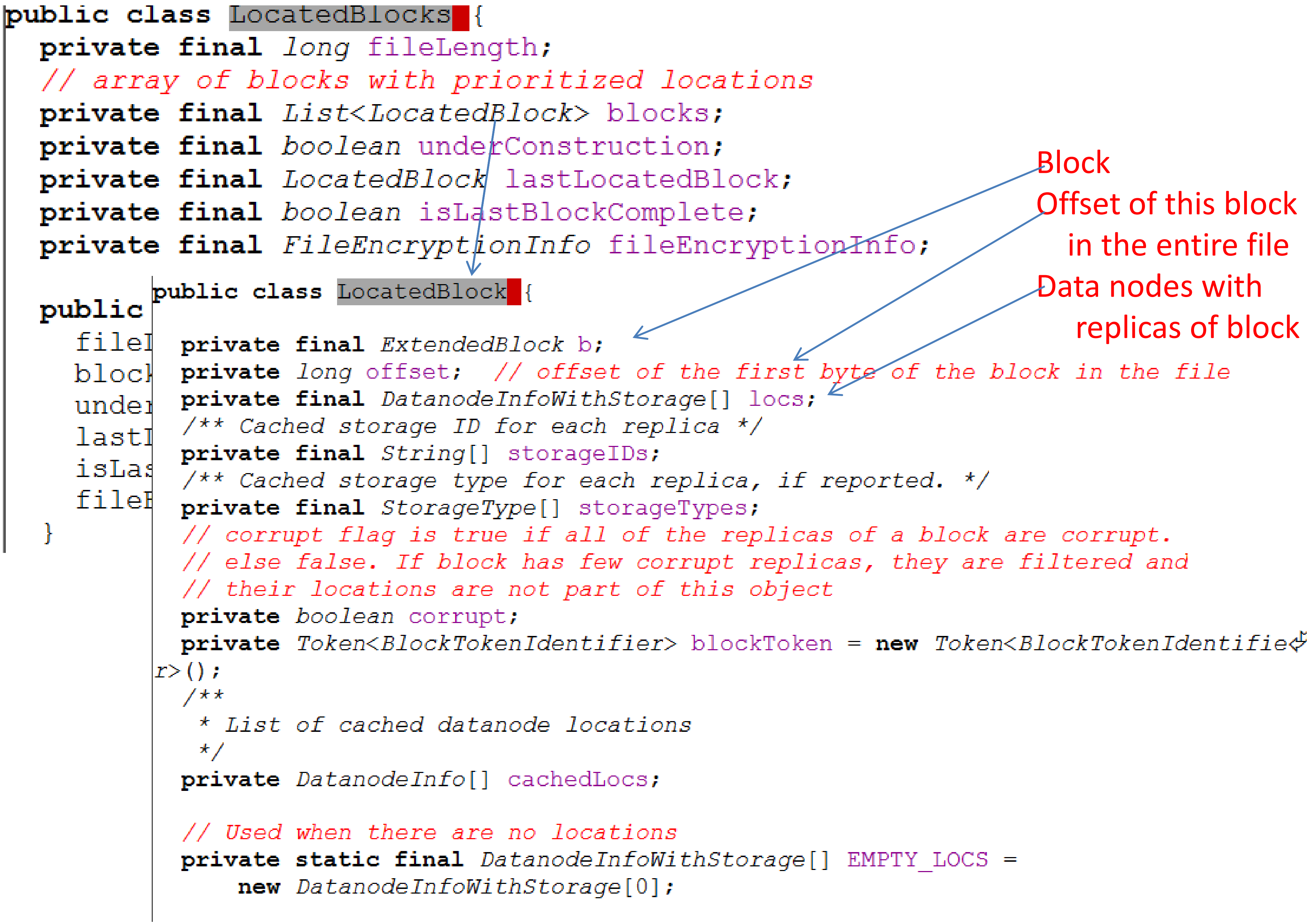
- Output:
  - Located blocks (data nodes + offsets)



```
////////////////////////////////////////
// File contents
////////////////////////////////////////
/**
 * Get locations of the blocks of the specified file
 * within the specified range.
 * DataNode locations for each block are sorted by
 * the proximity to the client.
 * <p>
 * Return {@link LocatedBlocks} which contains
 * file length, blocks and their locations.
 * DataNode locations for each block are sorted by
 * the distance to the client's address.
 * <p>
 * The client will then have to contact
 * one of the indicated DataNodes to obtain the actual data.
 *
 * @param src file name
 * @param offset range start offset
 * @param length range length
 *
 * @return file length and array of blocks with their locations
 *
 * @throws org.apache.hadoop.security.AccessControlException If access is
 *           denied
 * @throws java.io.FileNotFoundException If file <code>src</code> does not
 *           exist
 * @throws org.apache.hadoop.fs.UnresolvedLinkException If <code>src</code>
 *           contains a symlink
 * @throws IOException If an I/O error occurred
 */
@Idempotent
LocatedBlocks getBlockLocations(String src, long offset, long length)
    throws IOException;
```

s

../java/…hdfs/protocol/LocatedBlocks.java



```
public class LocatedBlocks {
  private final long fileLength;
  // array of blocks with prioritized locations
  private final List<LocatedBlock> blocks;
  private final boolean underConstruction;
  private final LocatedBlock lastLocatedBlock;
  private final boolean isLastBlockComplete;
  private final FileEncryptionInfo fileEncryptionInfo;

  public
    fileL
    block
    under
    lastL
    isLas
    fileE
  }
```

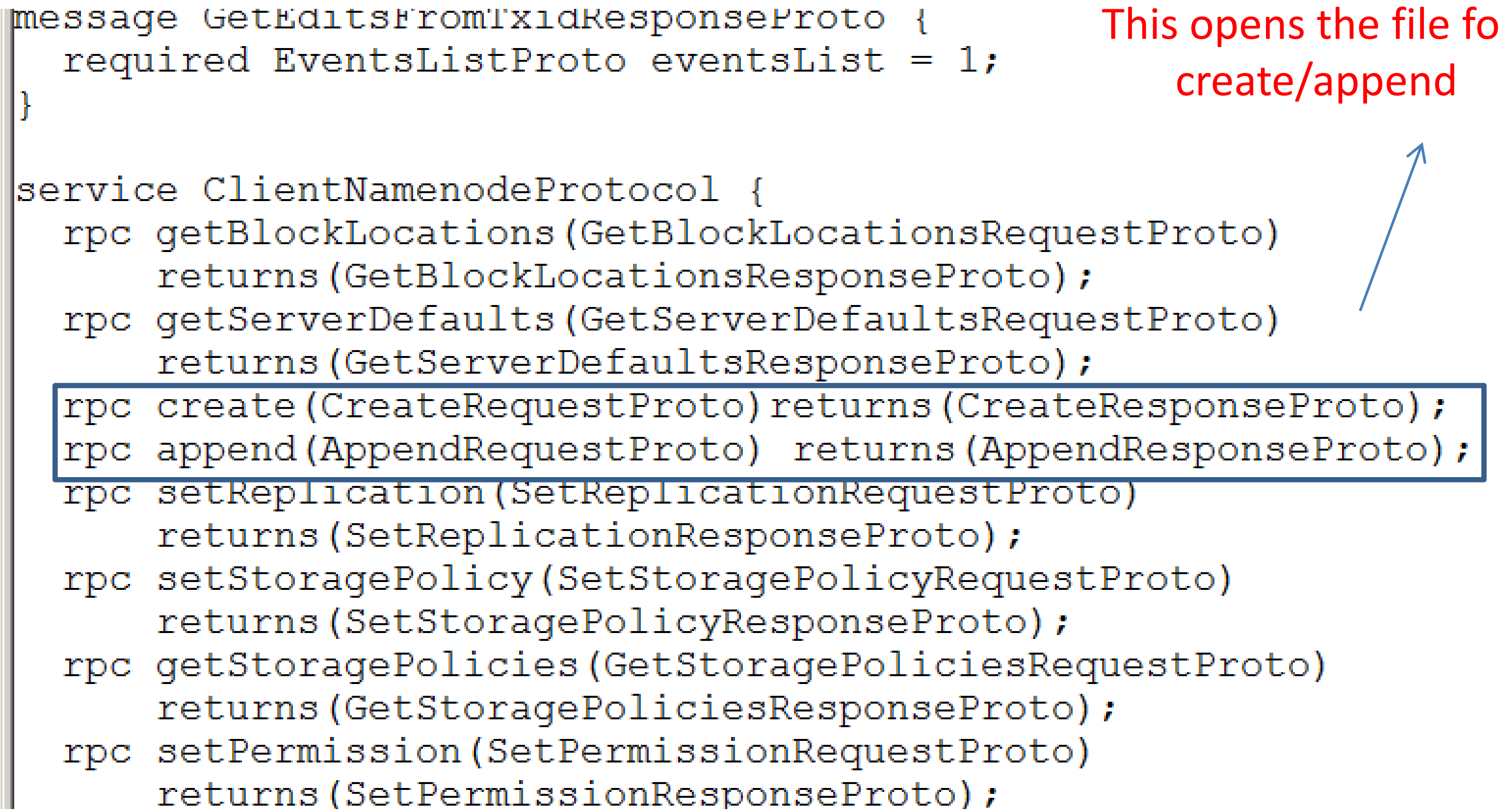
```
public class LocatedBlock {

  private final ExtendedBlock b;
  private long offset;  // offset of the first byte of the block in the file
  private final DatanodeInfoWithStorage[] locs;
  /** Cached storage ID for each replica */
  private final String[] storageIDs;
  /** Cached storage type for each replica, if reported. */
  private final StorageType[] storageTypes;
  // corrupt flag is true if all of the replicas of a block are corrupt.
  // else false. If block has few corrupt replicas, they are filtered and
  // their locations are not part of this object
  private boolean corrupt;
  private Token<BlockTokenIdentifier> blockToken = new Token<BlockTokenIdentifie
r>();
  /**
   * List of cached datanode locations
   */
  private DatanodeInfo[] cachedLocs;

  // Used when there are no locations
  private static final DatanodeInfoWithStorage[] EMPTY_LOCS =
      new DatanodeInfoWithStorage[0];
```

Block

Offset of this block
in the entire file

Data nodes with
replicas of block

Create/append a file

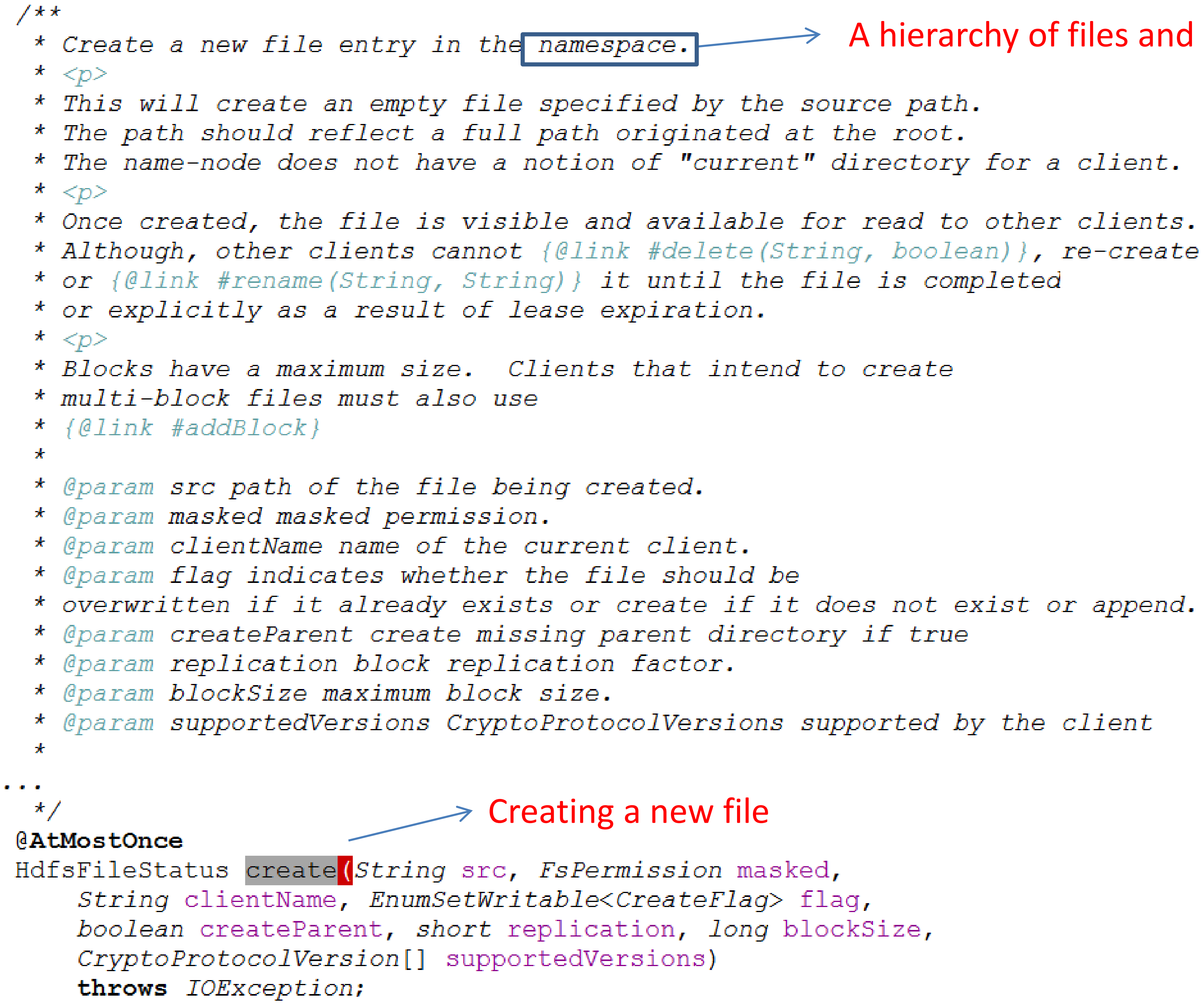


```
message GetEditsFromTxidResponseProto {
  required EventsListProto eventsList = 1;
}

service ClientNamenodeProtocol {
  rpc getBlockLocations(GetBlockLocationsRequestProto)
      returns(GetBlockLocationsResponseProto);
  rpc getServerDefaults(GetServerDefaultsRequestProto)
      returns(GetServerDefaultsResponseProto);
  rpc create(CreateRequestProto)returns(CreateResponseProto);
  rpc append(AppendRequestProto) returns(AppendResponseProto);
  rpc setReplication(SetReplicationRequestProto)
      returns(SetReplicationResponseProto);
  rpc setStoragePolicy(SetStoragePolicyRequestProto)
      returns(SetStoragePolicyResponseProto);
  rpc getStoragePolicies(GetStoragePoliciesRequestProto)
      returns(GetStoragePoliciesResponseProto);
  rpc setPermission(SetPermissionRequestProto)
      returns(SetPermissionResponseProto);
```

This opens the file for create/append

Creating a file

- Needs to specify:
  - Path to the file to be created, e.g., /foo/bar
  - Permission mask
  - Client name
  - Flag on whether to overwrite (entire file!) if already exists
  - How many replicas
  - Block size



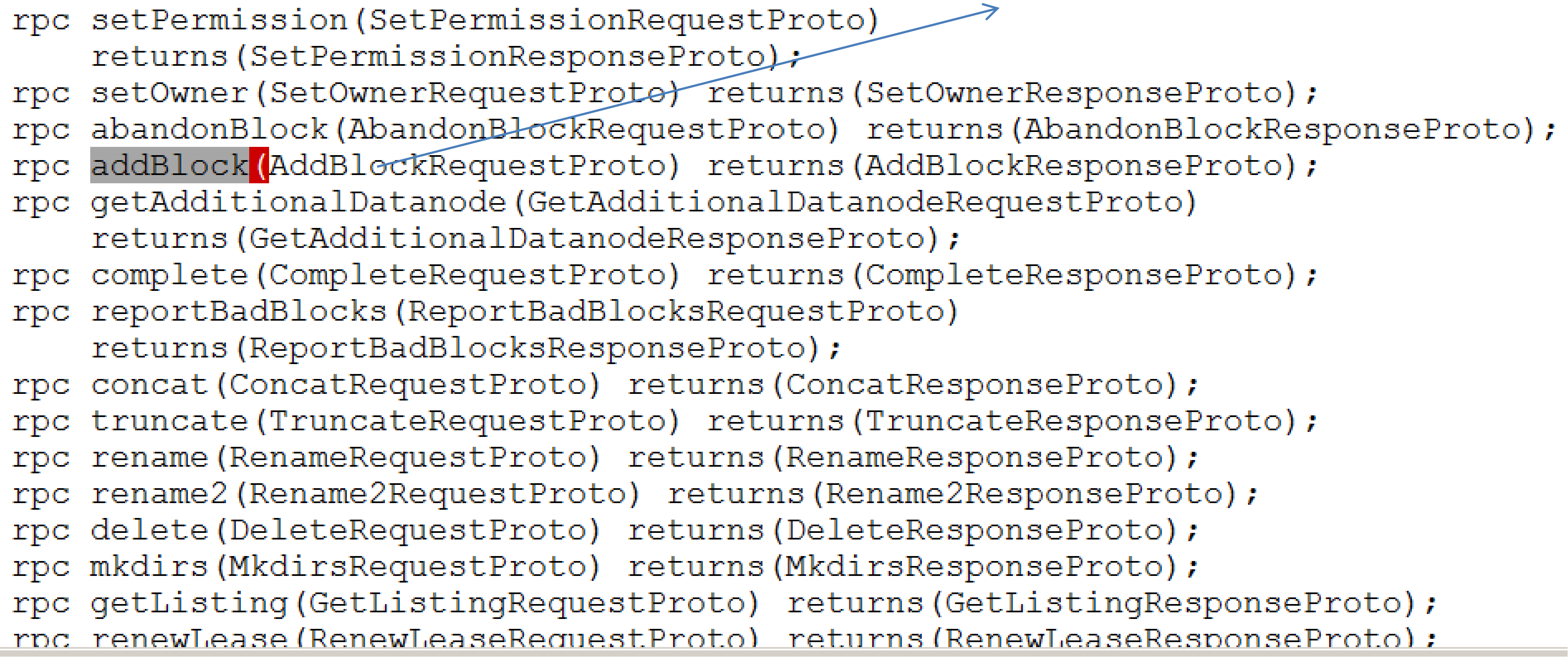
```
 /**
  * Create a new file entry in the namespace.
  * <p>
  * This will create an empty file specified by the source path.
  * The path should reflect a full path originated at the root.
  * The name-node does not have a notion of "current" directory for a client.
  * <p>
  * Once created, the file is visible and available for read to other clients.
  * Although, other clients cannot {@link #delete(String, boolean)}, re-create
  * or {@link #rename(String, String)} it until the file is completed
  * or explicitly as a result of lease expiration.
  * <p>
  * Blocks have a maximum size.  Clients that intend to create
  * multi-block files must also use
  * {@link #addBlock}
  *
  * @param src path of the file being created.
  * @param masked masked permission.
  * @param clientName name of the current client.
  * @param flag indicates whether the file should be
  * overwritten if it already exists or create if it does not exist or append.
  * @param createParent create missing parent directory if true
  * @param replication block replication factor.
  * @param blockSize maximum block size.
  * @param supportedVersions CryptoProtocolVersions supported by the client
  *
...
  */
 @AtMostOnce
 HdfsFileStatus create(String src, FsPermission masked,
     String clientName, EnumSetWritable<CreateFlag> flag,
     boolean createParent, short replication, long blockSize,
     CryptoProtocolVersion[] supportedVersions)
     throws IOException;
```

A hierarchy of files and directories

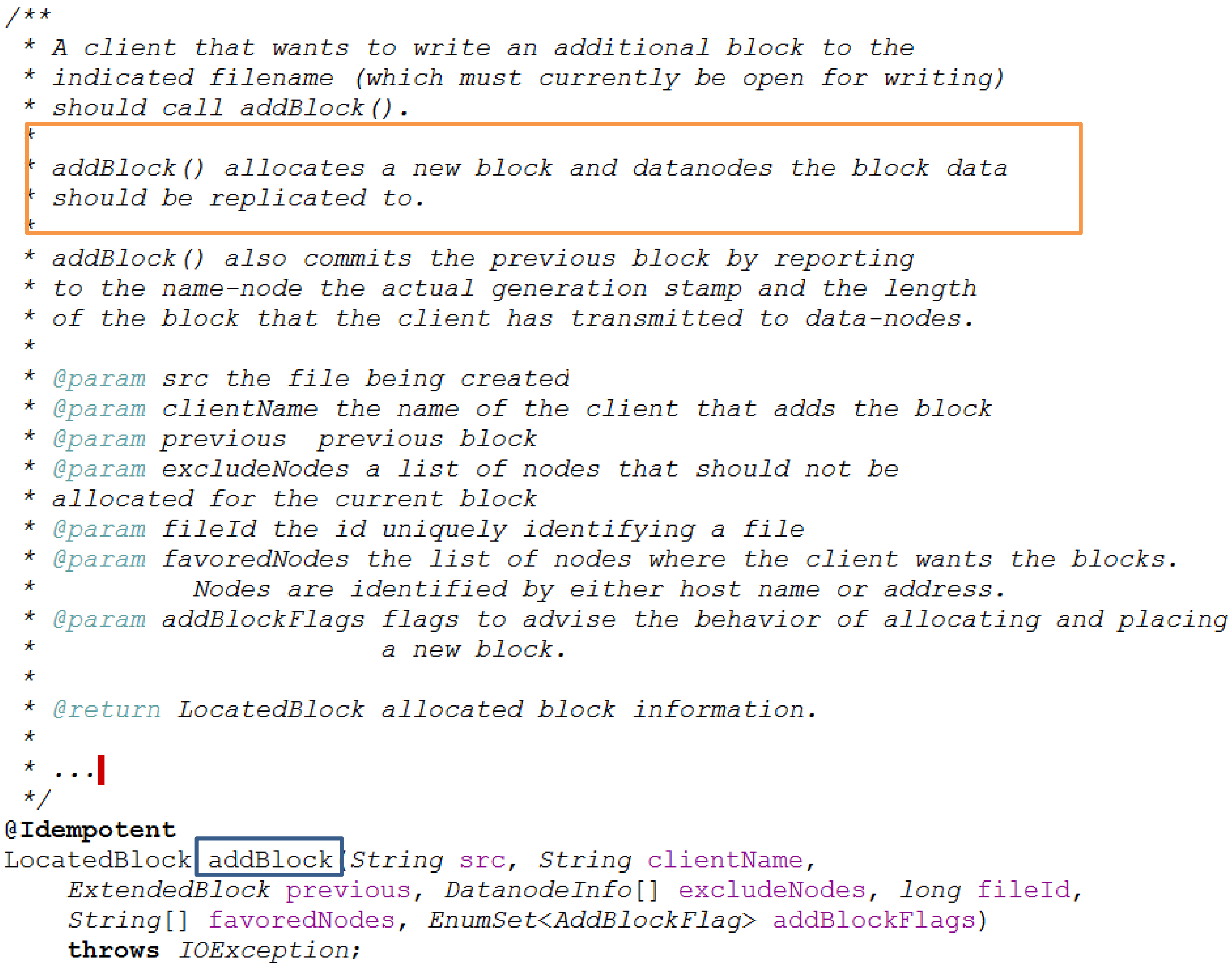
Creating a new file

Allocating new blocks for writing

Asking NameNode to allocate a new block
+ data nodes holding its replicas



```
rpc setPermission(SetPermissionRequestProto)
    returns(SetPermissionResponseProto);
rpc setOwner(SetOwnerRequestProto) returns(SetOwnerResponseProto);
rpc abandonBlock(AbandonBlockRequestProto) returns(AbandonBlockResponseProto);
rpc addBlock(AddBlockRequestProto) returns(AddBlockResponseProto);
rpc getAdditionalDatanode(GetAdditionalDatanodeRequestProto)
    returns(GetAdditionalDatanodeResponseProto);
rpc complete(CompleteRequestProto) returns(CompleteResponseProto);
rpc reportBadBlocks(ReportBadBlocksRequestProto)
    returns(ReportBadBlocksResponseProto);
rpc concat(ConcatRequestProto) returns(ConcatResponseProto);
rpc truncate(TruncateRequestProto) returns(TruncateResponseProto);
rpc rename(RenameRequestProto) returns(RenameResponseProto);
rpc rename2(Rename2RequestProto) returns(Rename2ResponseProto);
rpc delete(DeleteRequestProto) returns(DeleteResponseProto);
rpc mkdirs(MkdirsRequestProto) returns(MkdirsResponseProto);
rpc getListing(GetListingRequestProto) returns(GetListingResponseProto);
rpc renewLease(RenewLeaseRequestProto) returns(RenewLeaseResponseProto);
```



```
/**
 * A client that wants to write an additional block to the
 * indicated filename (which must currently be open for writing)
 * should call addBlock().
 *
 * addBlock() allocates a new block and datanodes the block data
 * should be replicated to.
 *
 * addBlock() also commits the previous block by reporting
 * to the name-node the actual generation stamp and the length
 * of the block that the client has transmitted to data-nodes.
 *
 * @param src the file being created
 * @param clientName the name of the client that adds the block
 * @param previous  previous block
 * @param excludeNodes a list of nodes that should not be
 * allocated for the current block
 * @param fileId the id uniquely identifying a file
 * @param favoredNodes the list of nodes where the client wants the blocks.
 *          Nodes are identified by either host name or address.
 * @param addBlockFlags flags to advise the behavior of allocating and placing
 *                     a new block.
 *
 * @return LocatedBlock allocated block information.
 *
 * ...
 */
@Idempotent
LocatedBlock addBlock(String src, String clientName,
    ExtendedBlock previous, DatanodeInfo[] excludeNodes, long fileId,
    String[] favoredNodes, EnumSet<AddBlockFlag> addBlockFlags)
    throws IOException;
```

Client and Datanode communication

- Source code (version 2.8.1)
  - Definition of protocol
    - datatransfer.proto
    - Located at: <hadoop-src-dir>\hadoop-hdfs-project\hadoop-hdfs-client\src\main\proto
  - Implementation
    - DataTransferProtocol.java
    - <hadoop-src-dir>\hadoop-hdfs-project\hadoop-hdfs-client\src\main\java\org\apache\hadoop\hdfs\protocol\datatransfer

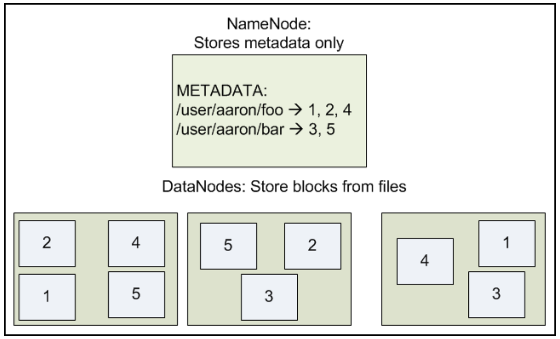
Operations

- readBlock()
- writeBlock()
- copyBlock() – for load balancing
- replaceBlock() – for load balancing
  - Move a block from one DataNode to another

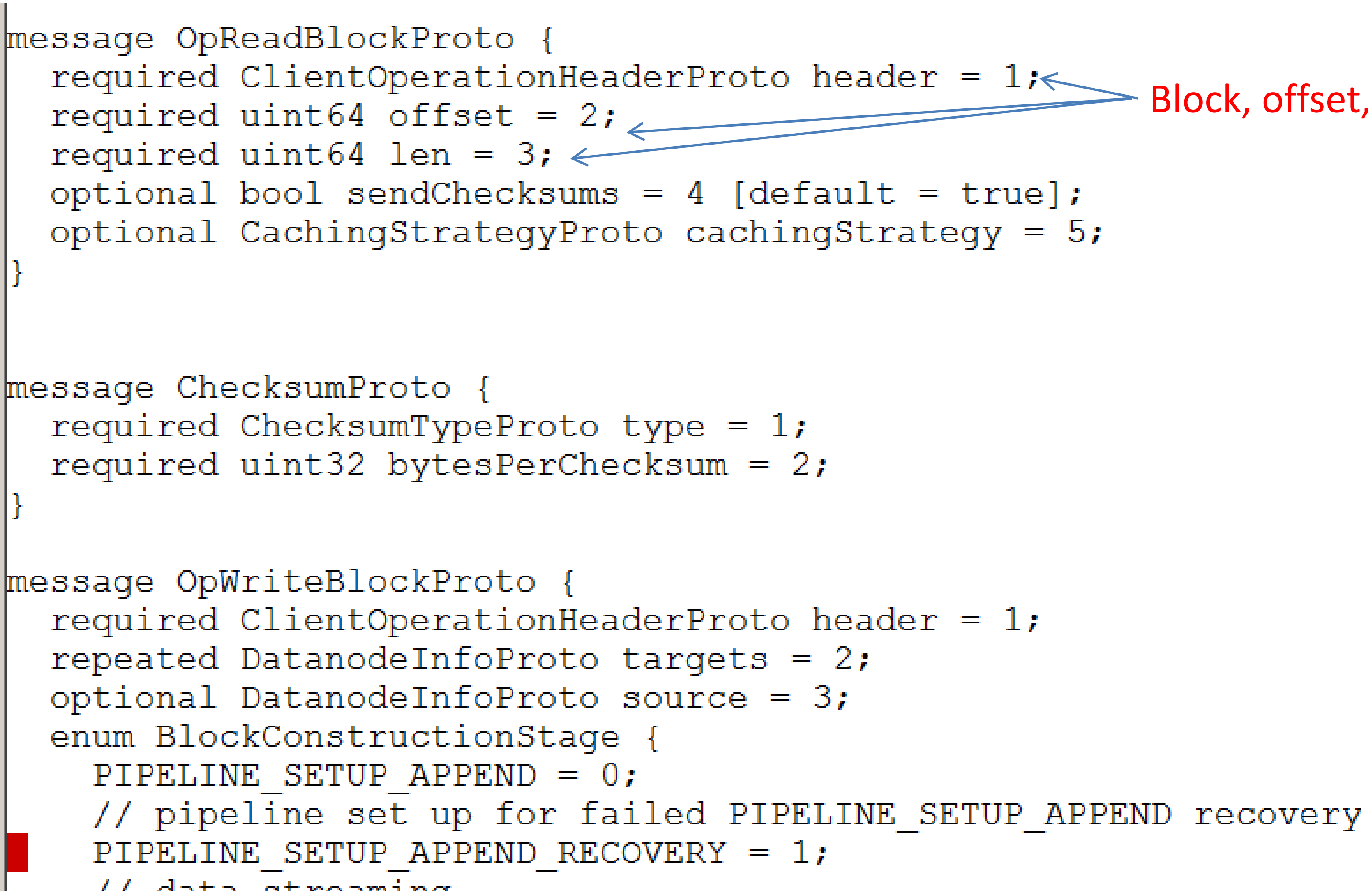
Reading a file

1. Client first contacts NameNode which informs the client of the closest DataNodes storing blocks of the file
   - This is done by making which RPC call?

2. Client contacts the DataNodes directly for reading the blocks
   - Calling readBlock()



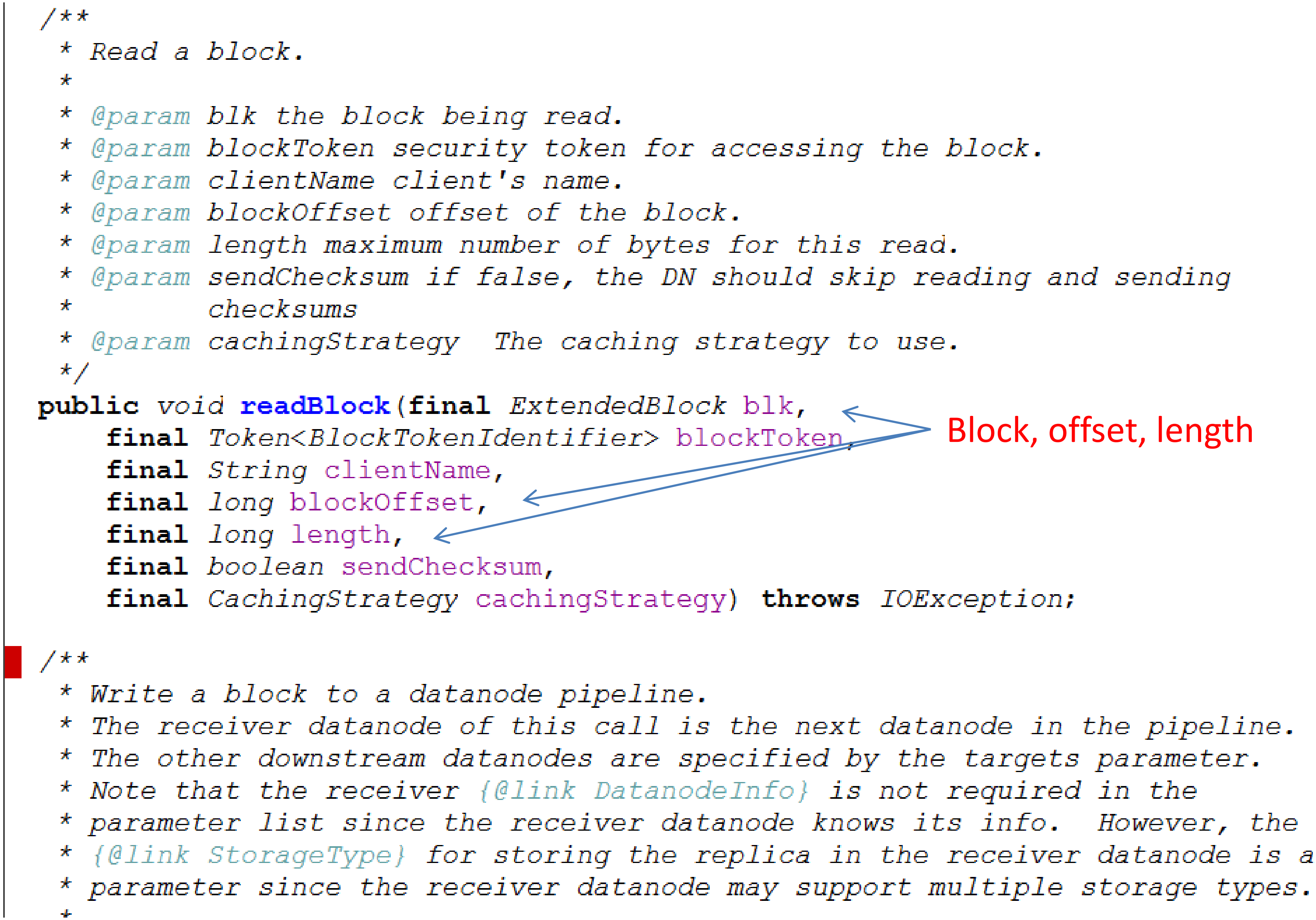
datatransfer.proto



```
message OpReadBlockProto {
  required ClientOperationHeaderProto header = 1;
  required uint64 offset = 2;
  required uint64 len = 3;
  optional bool sendChecksums = 4 [default = true];
  optional CachingStrategyProto cachingStrategy = 5;
}


message ChecksumProto {
  required ChecksumTypeProto type = 1;
  required uint32 bytesPerChecksum = 2;
}

message OpWriteBlockProto {
  required ClientOperationHeaderProto header = 1;
  repeated DatanodeInfoProto targets = 2;
  optional DatanodeInfoProto source = 3;
  enum BlockConstructionStage {
    PIPELINE_SETUP_APPEND = 0;
    // pipeline set up for failed PIPELINE_SETUP_APPEND recovery
    PIPELINE_SETUP_APPEND_RECOVERY = 1;
    // data streaming
```

Block, offset, length

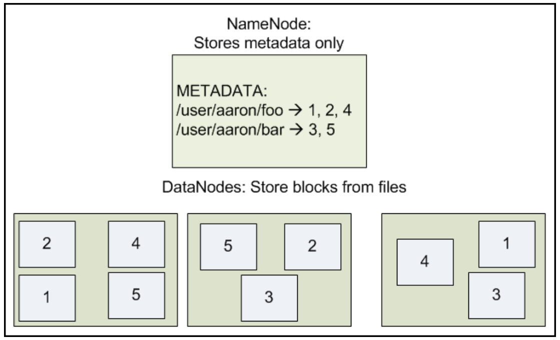
DataTransferProtocol.java



```java
/**
 * Read a block.
 *
 * @param blk the block being read.
 * @param blockToken security token for accessing the block.
 * @param clientName client's name.
 * @param blockOffset offset of the block.
 * @param length maximum number of bytes for this read.
 * @param sendChecksum if false, the DN should skip reading and sending
 *        checksums
 * @param cachingStrategy  The caching strategy to use.
 */
public void readBlock(final ExtendedBlock blk,
    final Token<BlockTokenIdentifier> blockToken,
    final String clientName,
    final long blockOffset,
    final long length,
    final boolean sendChecksum,
    final CachingStrategy cachingStrategy) throws IOException;

/**
 * Write a block to a datanode pipeline.
 * The receiver datanode of this call is the next datanode in the pipeline.
 * The other downstream datanodes are specified by the targets parameter.
 * Note that the receiver {@link DatanodeInfo} is not required in the
 * parameter list since the receiver datanode knows its info.  However, the
 * {@link StorageType} for storing the replica in the receiver datanode is a
 * parameter since the receiver datanode may support multiple storage types.
 *
```

Block, offset, length

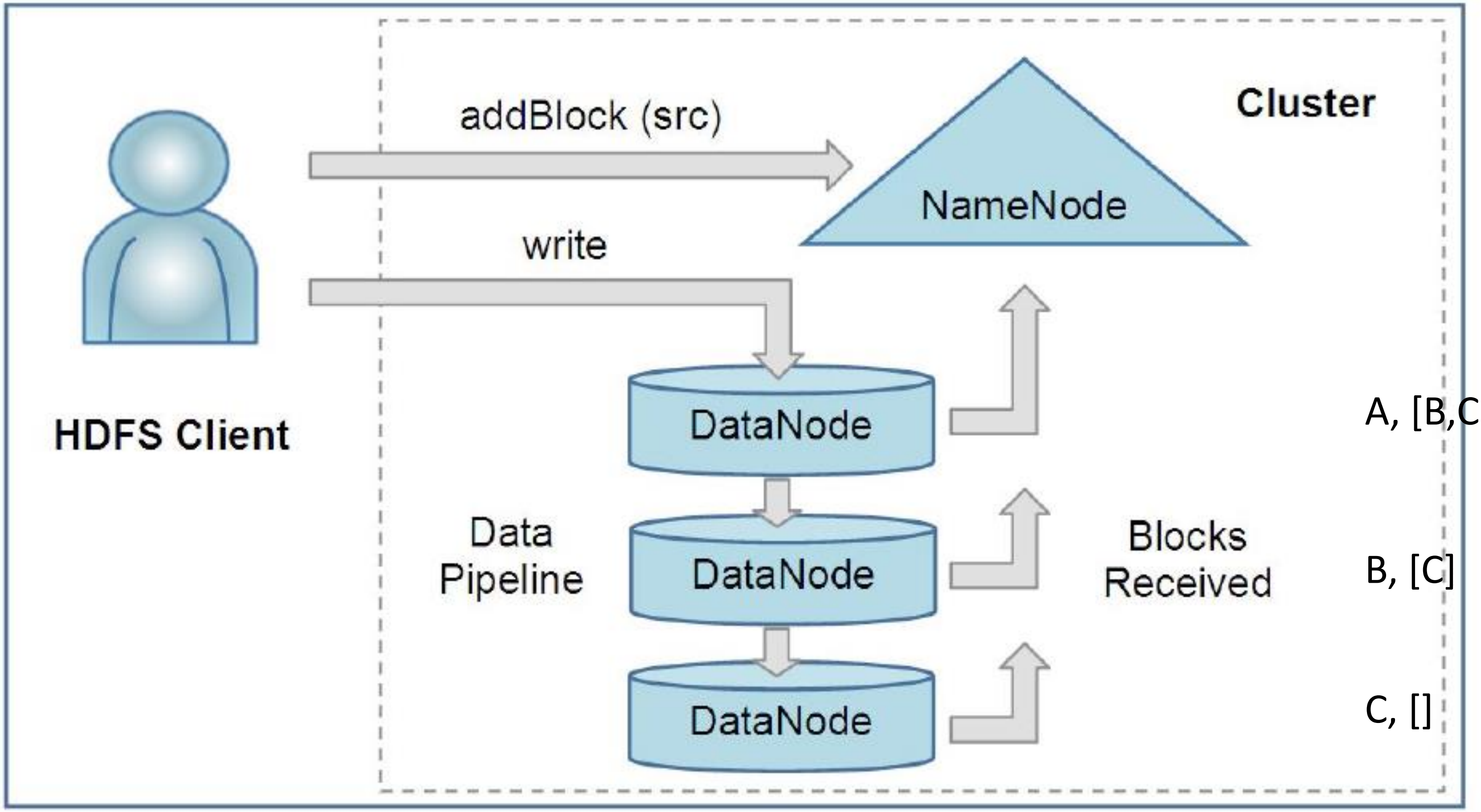
Writing a file



- Blocks are written one at a time
  - In a pipelined fashion through the data nodes

- For each block:
  - Client asks NameNode to select DataNodes for holding its replica (using which rpc call?)
    - e.g., DataNodes 1 and 3 for the first block of /user/aaron/foo
  - It then forms the pipeline to send the block

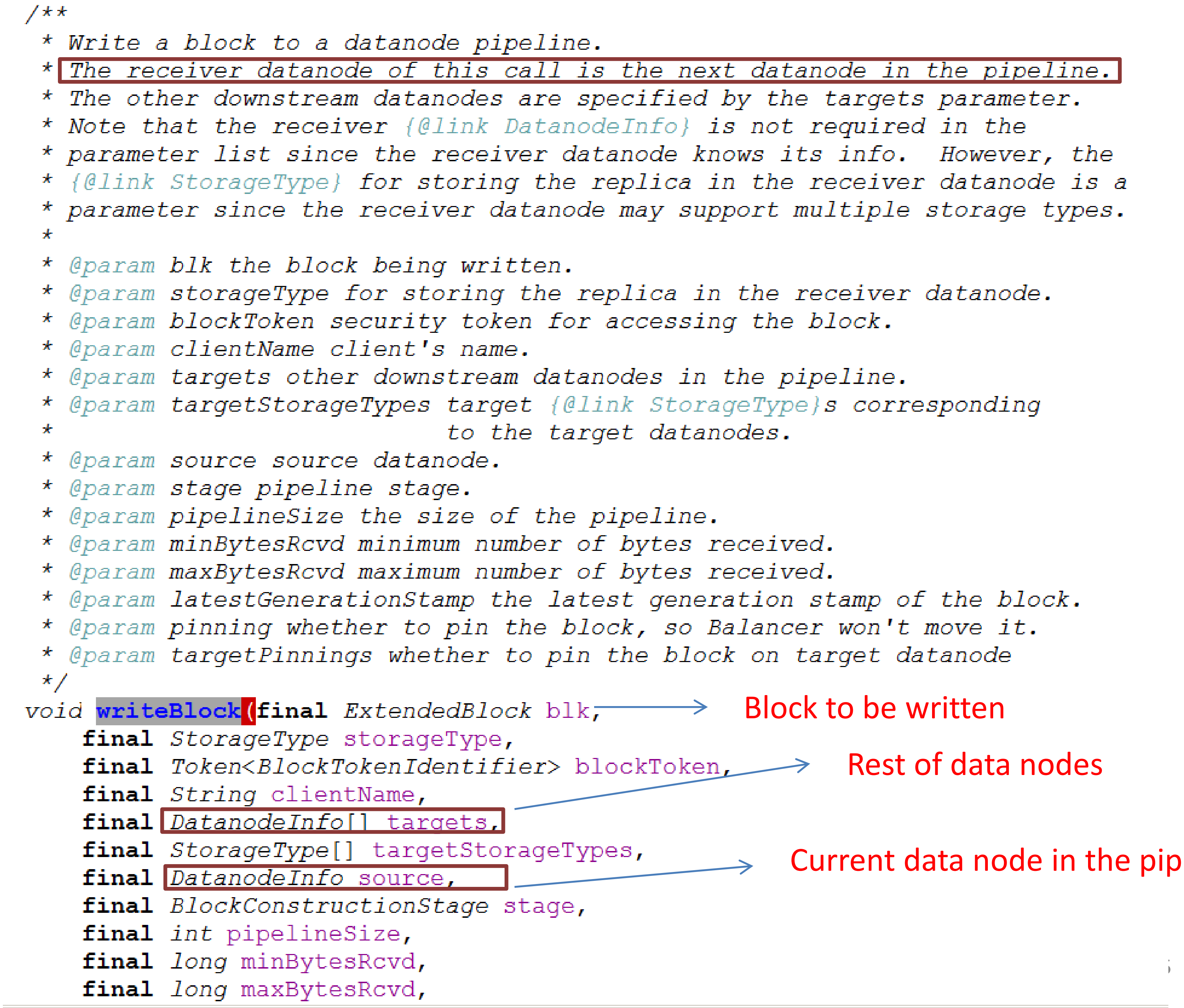
Writing a file



A, [B,C]

B, [C]

C, []



```
/**
 * Write a block to a datanode pipeline.
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 * The other downstream datanodes are specified by the targets parameter.
 * Note that the receiver {@link DatanodeInfo} is not required in the
 * parameter list since the receiver datanode knows its info.  However, the
 * {@link StorageType} for storing the replica in the receiver datanode is a
 * parameter since the receiver datanode may support multiple storage types.
 *
 * @param blk the block being written.
 * @param storageType for storing the replica in the receiver datanode.
 * @param blockToken security token for accessing the block.
 * @param clientName client's name.
 * @param targets other downstream datanodes in the pipeline.
 * @param targetStorageTypes target {@link StorageType}s corresponding
 *                           to the target datanodes.
 * @param source source datanode.
 * @param stage pipeline stage.
 * @param pipelineSize the size of the pipeline.
 * @param minBytesRcvd minimum number of bytes received.
 * @param maxBytesRcvd maximum number of bytes received.
 * @param latestGenerationStamp the latest generation stamp of the block.
 * @param pinning whether to pin the block, so Balancer won't move it.
 * @param targetPinnings whether to pin the block on target datanode
 */
void writeBlock(final ExtendedBlock blk,
    final StorageType storageType,
    final Token<BlockTokenIdentifier> blockToken,
    final String clientName,
    final DatanodeInfo[] targets,
    final StorageType[] targetStorageTypes,
    final DatanodeInfo source,
    final BlockConstructionStage stage,
    final int pipelineSize,
    final long minBytesRcvd,
    final long maxBytesRcvd,
```

Block to be written

Rest of data nodes

Current data node in the pipeline

Data pipelining

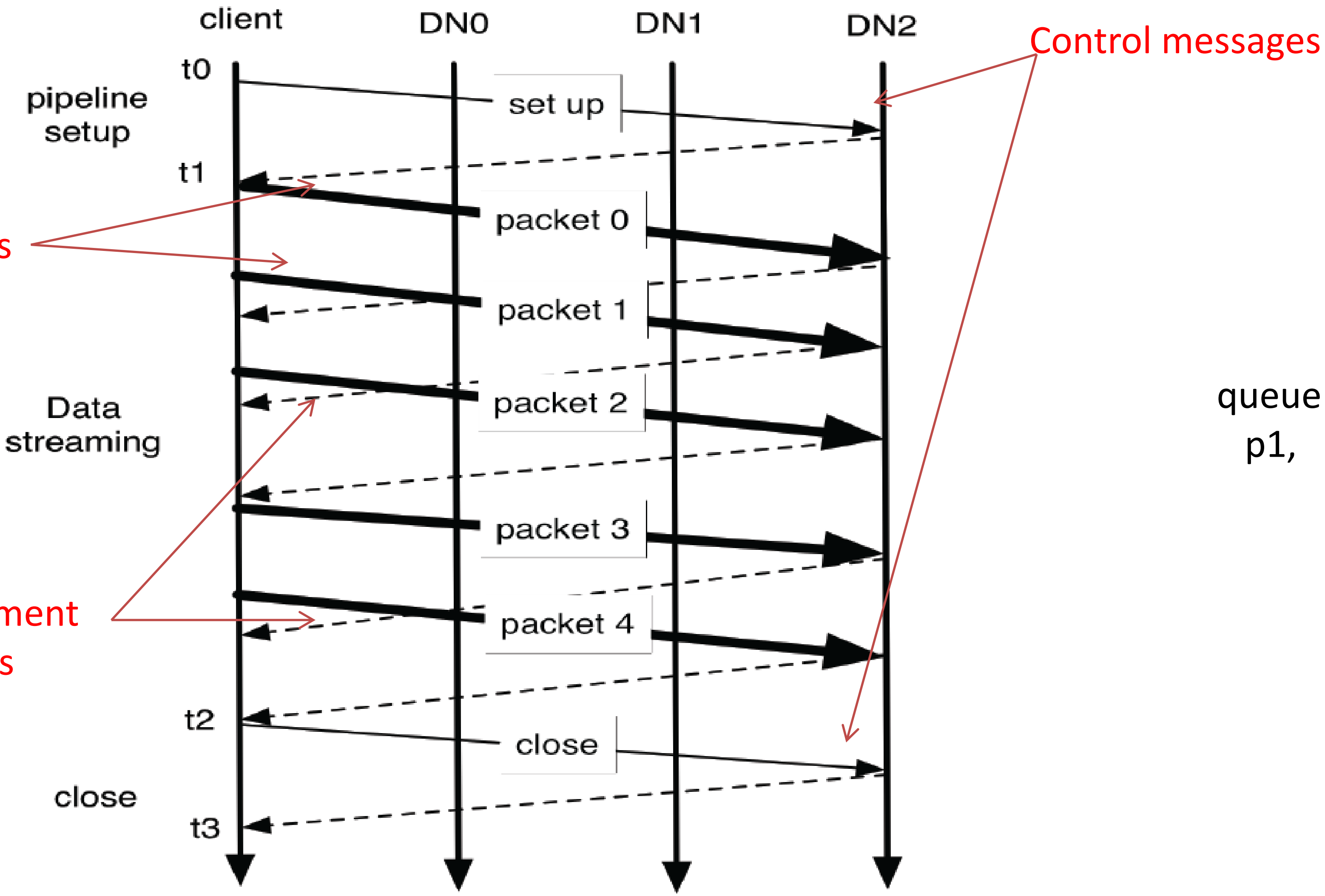
- Consider a block X to be written to DataNode A, B, and C (replication factor = 3)

1. X is broken down into packets (typically 64KB/packet)
   - 128MB/64KB = 2048
2. Client sends the packet to DataNode A
3. A sends it further to B & B further to C

Acknowledgement

- Client maintains an ack (acknowledgment) queue
- Packet removed from ack queue once received by all data nodes
- When all packets were written, client notifies NameNode
  - NameNode will update the metadata for the file
  - Reflecting that a new block has been added to the file

Data pipelining for writing blocks



queue:
p1,

Acknowledgement

- Client does not wait for the acknowledgement of previous packet before sending next one

- Is this synchronous or asynchronous?

- Advantage?

Roadmap

- Hadoop architecture
  - HDFS
  - MapReduce

- Installing Hadoop & HDFS

Hadoop & HDFS installation

- Refer to the installation note posted on course web site on how to install Hadoop and setup HDFS

Working with hdfs

- Setting up home directory in hdfs
  - hdfs dfs -mkdir /user
  - hdfs dfs -mkdir /user/ec2-user

    (ec2-user is user name of your EC2 account)

- Create a directory "input" under home
  - hdfs dfs -mkdir /user/ec2-user/input
  - Or simply:
  - hdfs dfs -mkdir input

This will automatically create the "input" directory under /user/ec2-user

Working with hdfs

- Copy data from local file system
  - hdfs dfs -put etc/hadoop/*.xml /user/ec2-user/input
  - Ignore error if you see one like this: "WARN hdfs. DataStreamer: Caught exception…"

- List the content of directory
  - hdfs dfs -ls /user/ec2-user/input

Working with hdfs

- Copy data from hdfs
  - hdfs dfs -get /user/ec2-user/input input1
  - If input1 does not exist, it will create one
  - If it does, it will create another one under it

- Examine the content of file in hdfs
  - hdfs dfs -cat /user/ec2-user/input/core-site.xml

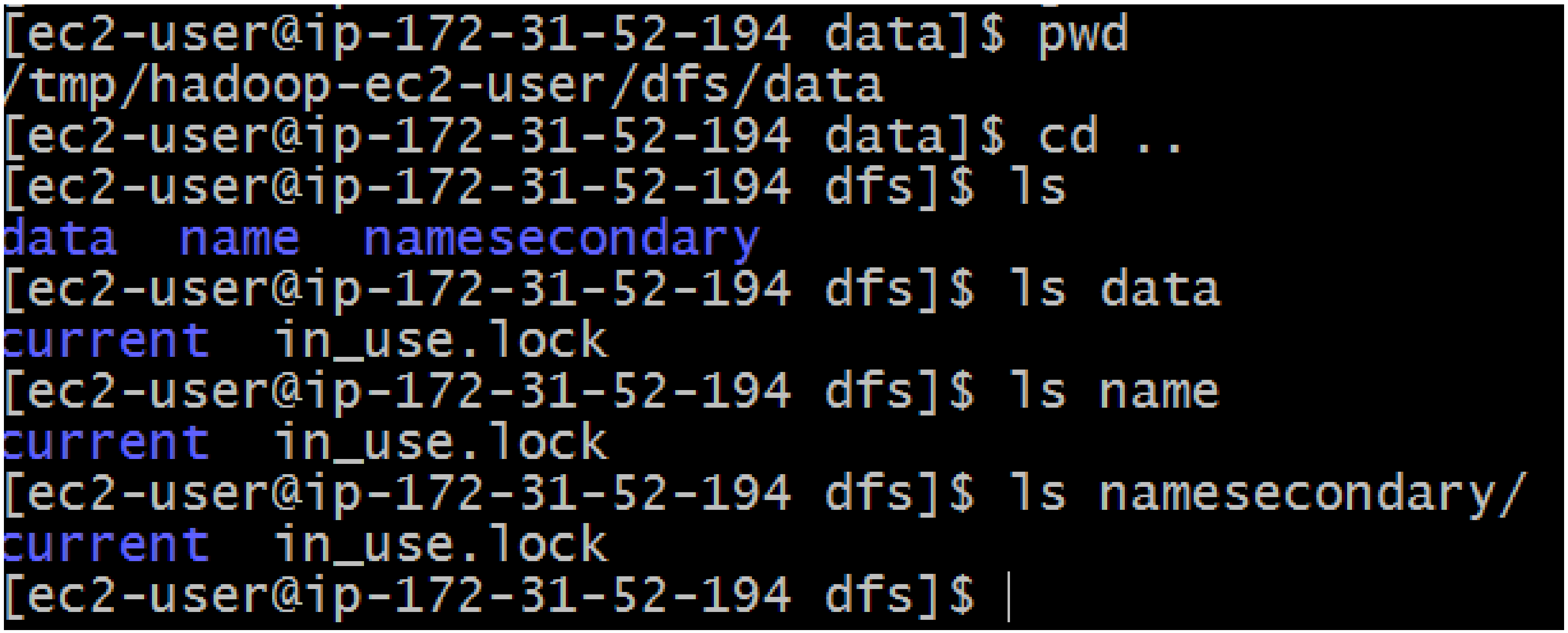
Working with hdfs

- Remove files
  - hdfs dfs -rm /user/ec2-user/input/core-site.xml
  - hdfs dfs -rm /user/ec2-user/input/*

- Remove directory
  - hdfs dfs -rmdir /user/ec2-user/input
  - Directory "input" needs to be empty first

Where is hdfs located?

- /tmp/hadoop-ec2-user/dfs/



```
[ec2-user@ip-172-31-52-194 data]$ pwd
/tmp/hadoop-ec2-user/dfs/data
[ec2-user@ip-172-31-52-194 data]$ cd ..
[ec2-user@ip-172-31-52-194 dfs]$ ls
data  name  namesecondary
[ec2-user@ip-172-31-52-194 dfs]$ ls data
current  in_use.lock
[ec2-user@ip-172-31-52-194 dfs]$ ls name
current  in_use.lock
[ec2-user@ip-172-31-52-194 dfs]$ ls namesecondary/
current  in_use.lock
[ec2-user@ip-172-31-52-194 dfs]$ |
```

References

- K. Shvachko, H. Kuang, S. Radia, and R. Chansler, "The hadoop distributed file system," in Mass Storage Systems and Technologies (MSST), 2010 IEEE 26th Symposium on, 2010, pp. 1-10.

- HDFS File System Shell Guide:
  - https://hadoop.apache.org/docs/current/hadoop-project-dist/hadoop-common/FileSystemShell.html