

Horus: Fine-Grained Encryption-Based Security for High Performance Petascale Storage

Ranjana Rajendran • Ethan L. Miller • Darrell D. E. Long
Storage Systems Research Center
University of California, Santa Cruz

Problem

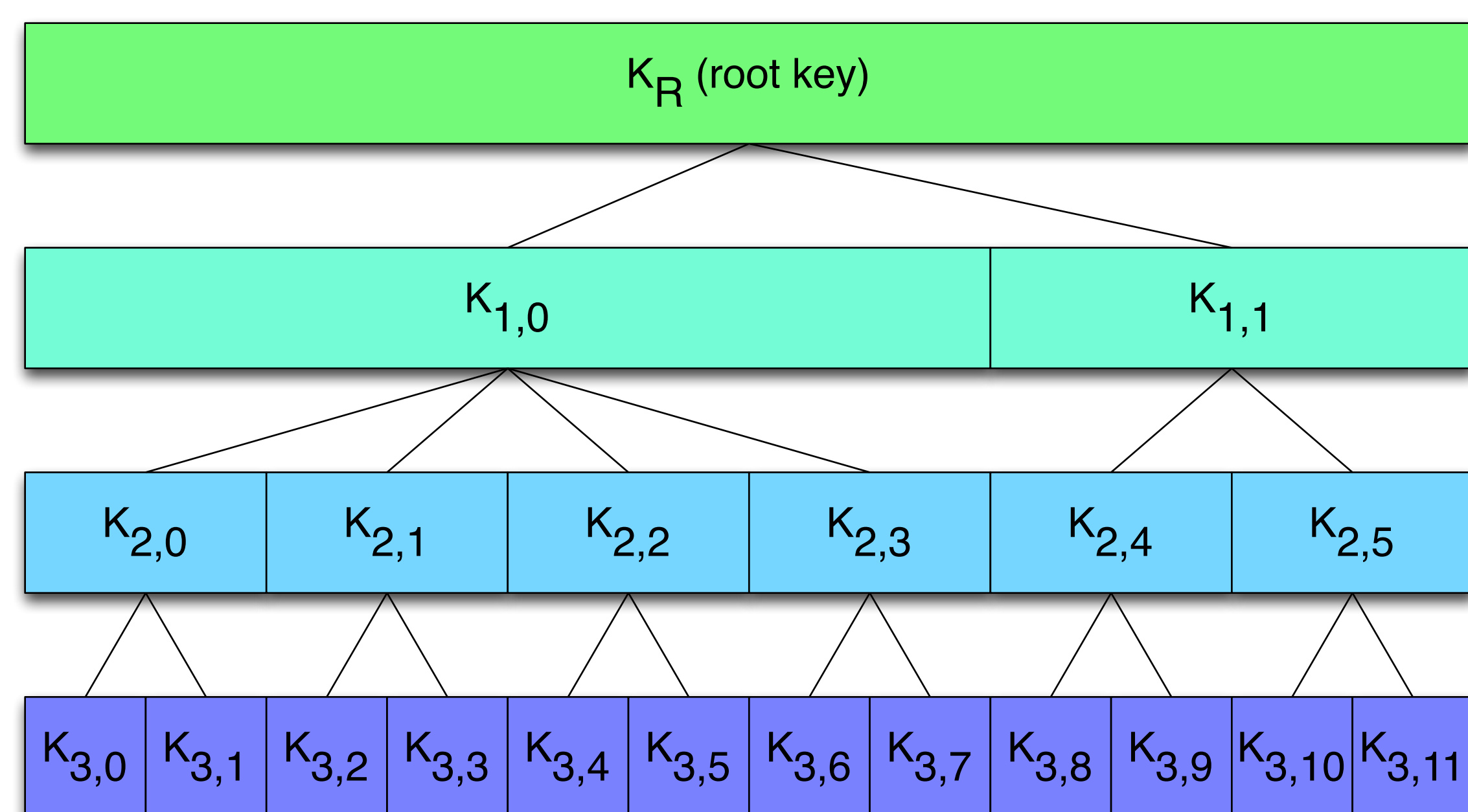
- Large files contain potentially sensitive data
- File data can be leaked by many HPC elements (disk, client, metadata server)
- Ensure data confidentiality in the face of physical and software attacks

Design Principles

- Prevent compromise by metadata server and storage nodes
 - Encrypt / decrypt all data at the client
- Restrict client leaks to only parts of the file to which the client has access
 - Most clients don't need access to the whole file
- Provide a small, stateless trusted computing base
 - Less vulnerable to compromise
 - Easier to erase between computations
- Work as a "filter" layer
 - Implement natively in the operating system
 - Implement as a client-level layer above existing file system calls

Hierarchical Keyed Hash Tree

- Single file root key can encrypt / decrypt the entire file
- Successively lower keys in the tree are based on a keyed hash depending on
 - Parent key
 - Level in the tree
 - Position in the level
- Deriving keys lower in the tree is fast and simple
- Deriving keys higher in the key or at the same level is "difficult"



Block key calculation

Require: $0 \leq \text{start} < \text{end} < d$
for $x = \text{start} + 1$ **to** end **do**
 $k \leftarrow \text{keyed_hash}(k, x \parallel b/B_x)$
end for
return k

$$x \parallel b/B_x = 3 \parallel 9$$

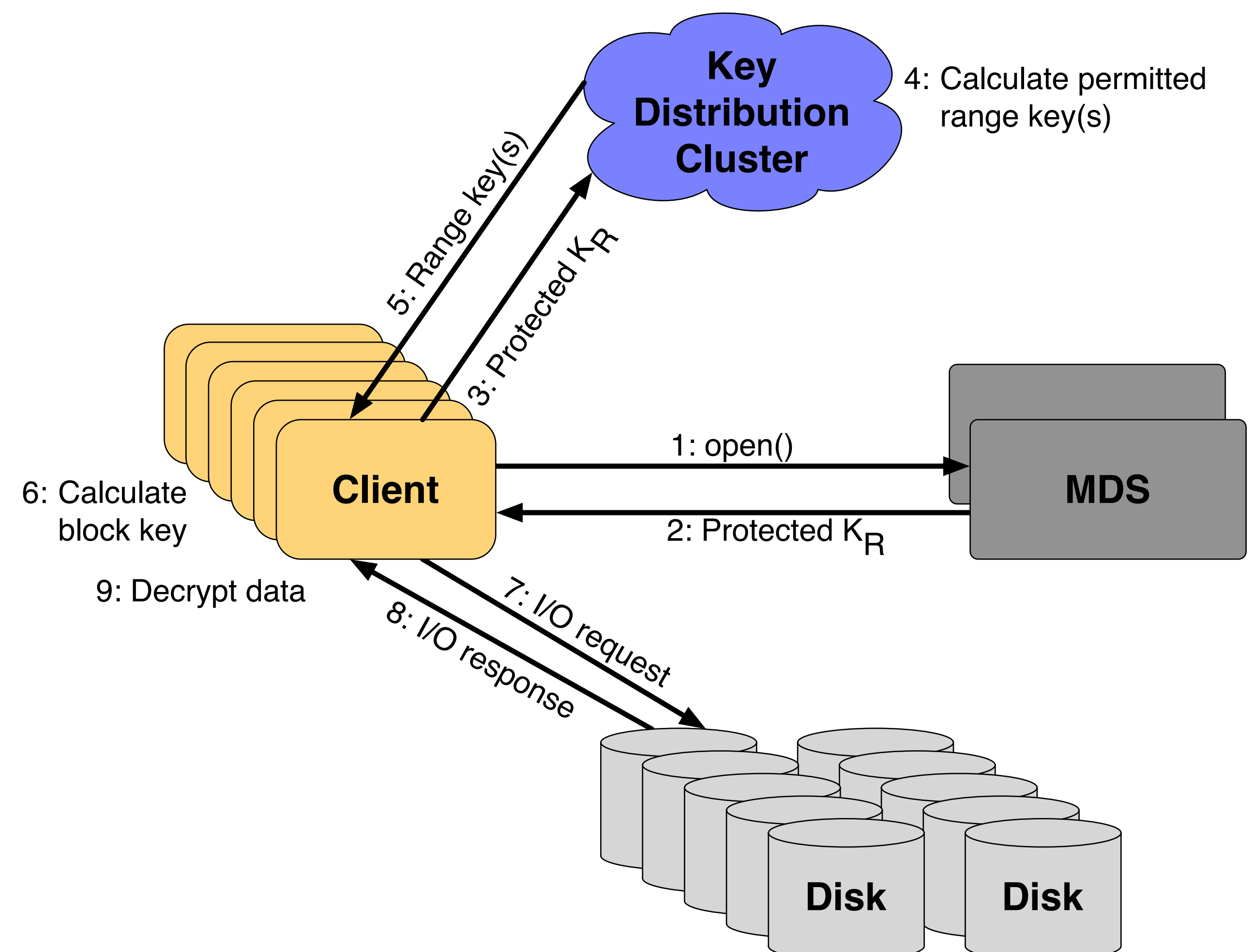
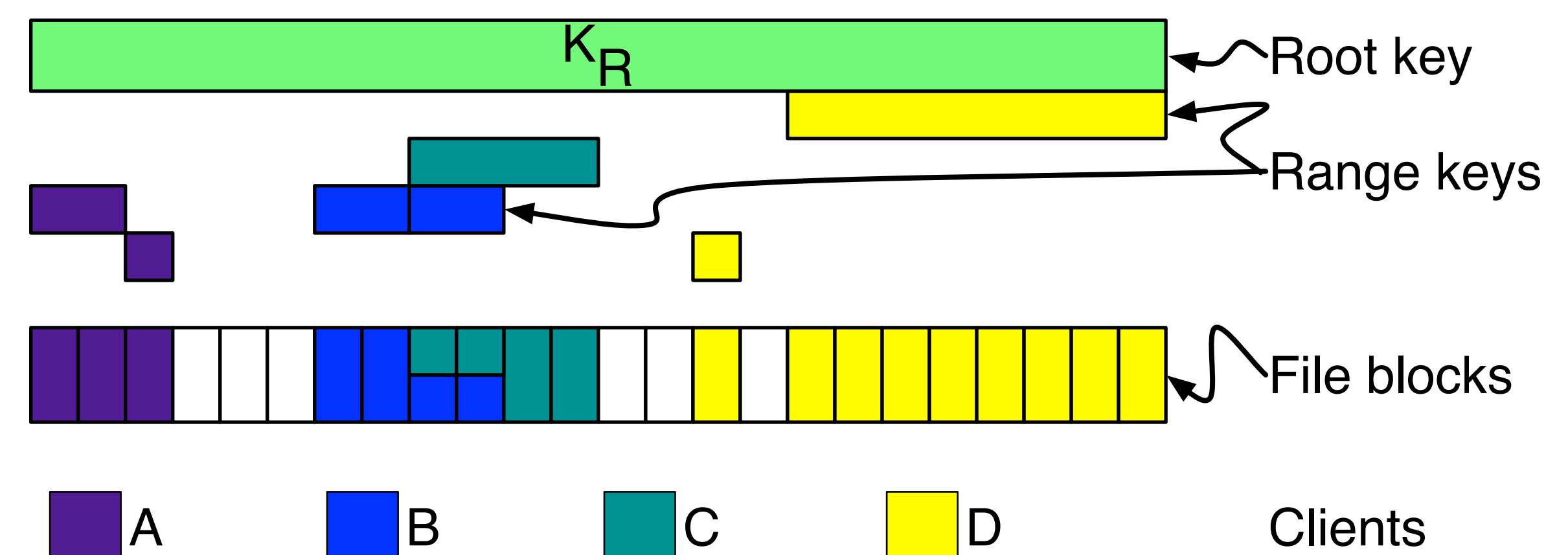
$$d = 4$$

Storing the key on the metadata server

- Encrypt file root key with user's public key
- Store result on the MDS
 - Separate key file
 - Extended attribute
 - In-file metadata (e. g., HDF5)

Key Distribution

- Client only receives range keys for blocks it's allowed to access
 - Client can derive a block key from any range key "above" it in the tree
- Different clients can receive the same (or different) keys for a given block
- Key distribution cluster can be run on MDS, on one or more clients, or separately
 - Can leverage application work distribution program logic to decide which clients access which ranges



Security Analysis

- Data only exists in the clear on a client and keys only in the clear on client and KDC
 - Compromise of a disk cannot reveal data
 - Compromise of a metadata server cannot reveal data
- Clients only receive range keys for blocks they need for the computation
 - Thousands of clients, each of which only needs to access a small fraction of the file
 - Individual compromised client can only reveal a small fraction of the file
- Range keys cannot be used to access data outside the range
 - Keyed hash is "one-way": cannot derive parent key from the child

Risks

- Fabricated data: encrypt cryptographic checksum along with data
- Access control for writing: use Maat
- Key revocation: use Plutus-like approach
- Access control for reading: no need (client can't read without key)

Ongoing Work

- Implementation of a user-level client library interposed above system calls
- Development of the protocol between the KDC and clients
- Performance testing
- Integration into Ceph?

Conclusions

- Security is an increasingly important problem for large-scale HPC storage
- Data can be protected against disclosure by disks and metadata servers
- A small number of compromised clients can only leak a small amount of data
- Horus can be implemented natively or as a client library
- Horus is ideally suited to provide confidentiality for HPC data