Zurich Research Laboratory

Cryptographic Protection for Networked Storage Systems

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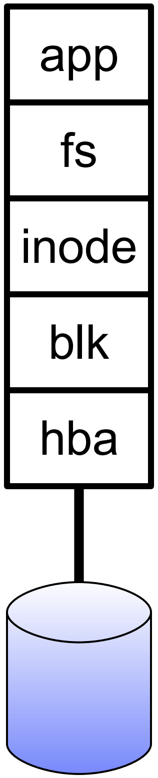
Overview

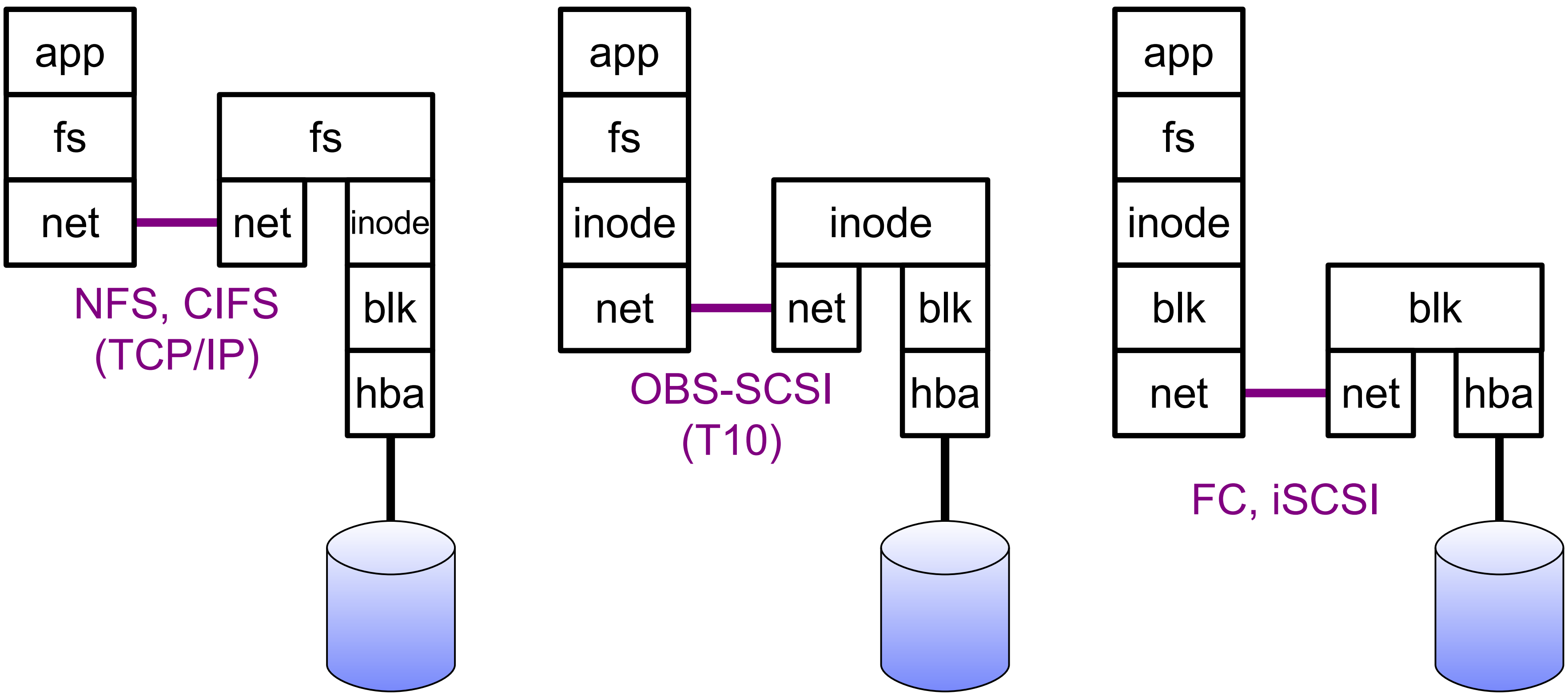
- Networked storage systems
  - → NAS, SAN, OBS
- Design options for security
  - → Data in flight & data at rest
- Block layer
  - → Tweakable encryption modes
  - → Integrity protection using tweakable encryption
- Object layer
  - → Capabilities in Object Store
- Filesystem
  - → Designs for key management
  - → Encryption using lazy revocation and key updating
  - → Integrity protection using hash trees
- Example: a cryptographic SAN file system

Traditional Storage Systems



Direct-attached Storage

Networked Storage Systems: NAS, OBS, SAN

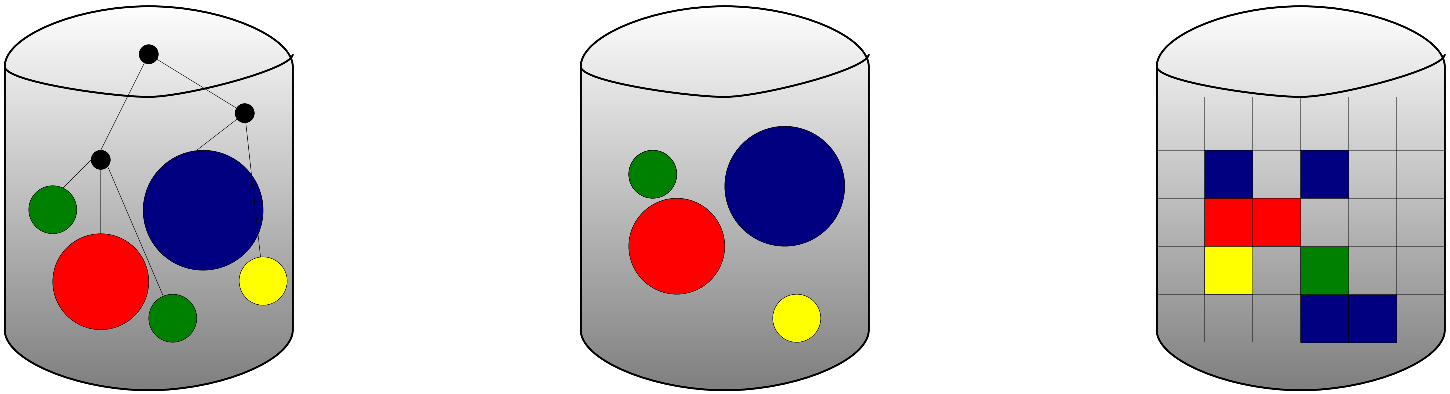


NAS
(Network-attached Storage)

OBS
(Object Storage)

SAN
(Storage-area Network)

Network-based Storage Devices



File server
- read & write data in file
- create & destroy file
- directory operations
- file/dir-based access control
- space allocation
- backup ops

Object storage dev.
- read & write bytes in object
- create & destroy object

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- object-level access control
- space allocation
- backup ops

Block device
- read & write blocks

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- device-level access control

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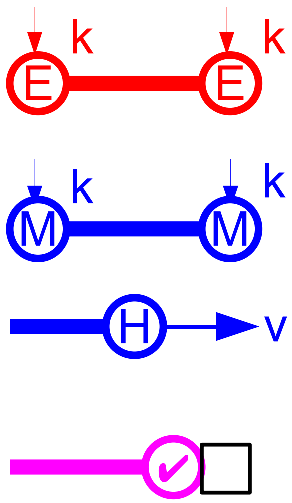
Security in Networked Storage Systems

- Existing technology offers little protection
  - → Server room only
  - → Trusted storage providers, networks, and clients
  - → Coarse-grained access control
- Security is needed
  - → Storage as a commodity
  - → Networked storage to desktop (iSCSI)
- Threats
  - - physical access to disks
  - - access to network
  - - authorized machines
  - - unauthorized machines
  - ...

Design Options for Security

Security Toolbox

- Goals
  - Confidentiality (no unauthorized access)
  - Integrity (no unauthorized modification)
  - Availability
- Security mechanisms
  - Encryption
  - → Confidentiality based on shared key k
  - Message-authentication code (MAC)
  - → Integrity based on shared key k
  - Hashing and digital signatures
  - → Integrity, w.r.t. reference value v
  - Access control
  - → Confidentiality, integrity, availability



- Any mechanism may be applied on any layer

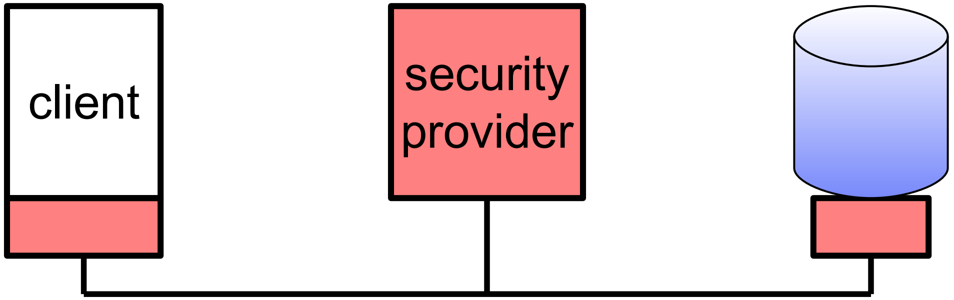
Any Security Mechanism May Be Applied on Any Layer

- Storage systems have these layers for good reason
  - → Not all security mechanisms are useful and efficient on all layers
- Challenge is to select the “right” combination
- Talk outline:

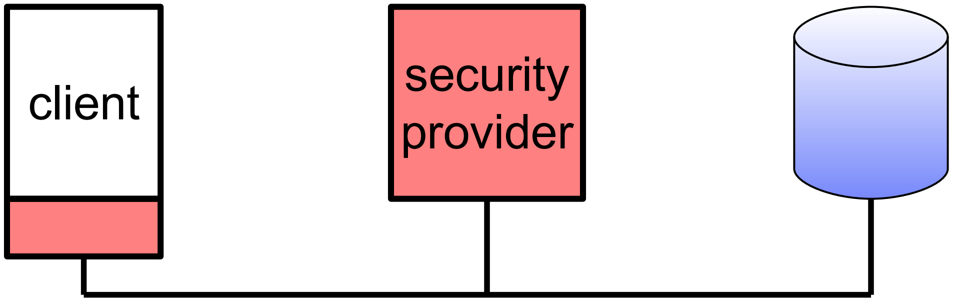
	Ⓔ	Ⓜ	✔
file	key mgmt. & lazy revocation	hash trees	
object			OBS security protocol
block	tweakable block encryption	hybrid block-integrity protection	

Generic Model of a Secure Storage System

- Option 1: Protect data in flight
  - → Trusted client, trusted storage (untrusted network)



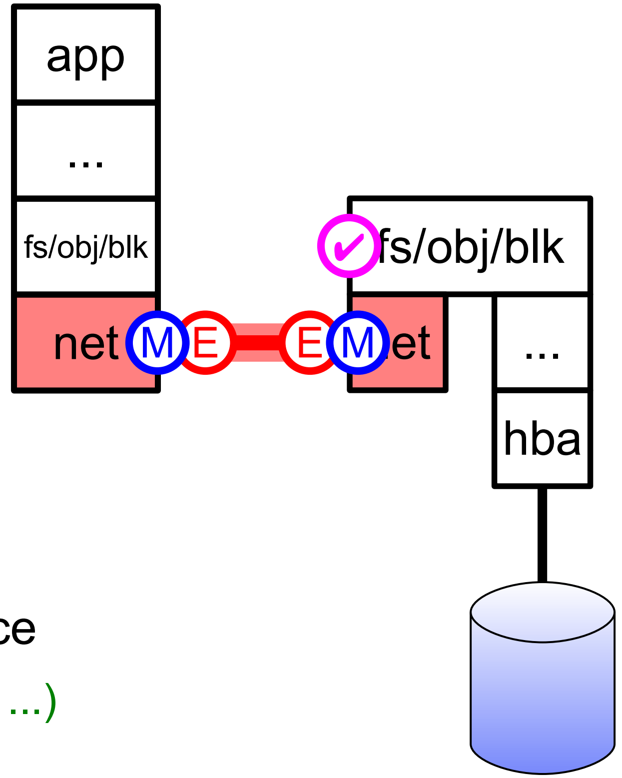
- Option 2: Protect data at rest
  - → Trusted client (untrusted storage and untrusted network)
  - → Allows DoS attack, data may be lost



Security for Networked Storage Systems (1)

Option 1: Protect the data in flight

- ✔ Access control
- M Integrity protection
- E Encryption

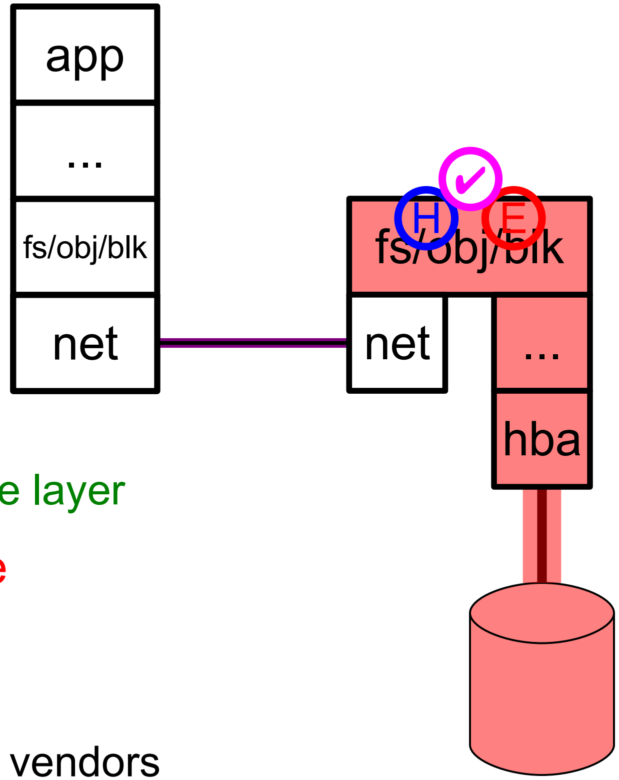


- Encrypt the communication
  - → Session, transport or packet layer
  - → Secure RPC, SSL, IPsec, FC-SP ...
- Layer-specific access control on storage device
  - → NAS at filesystem layer (exists in AFS, NFSv4 ...)
  - → ObjectStore at object layer (in standard)
  - → SAN at block layer (proposed)

Security for Networked Storage Systems (2)

Option 2: Protect the data at rest

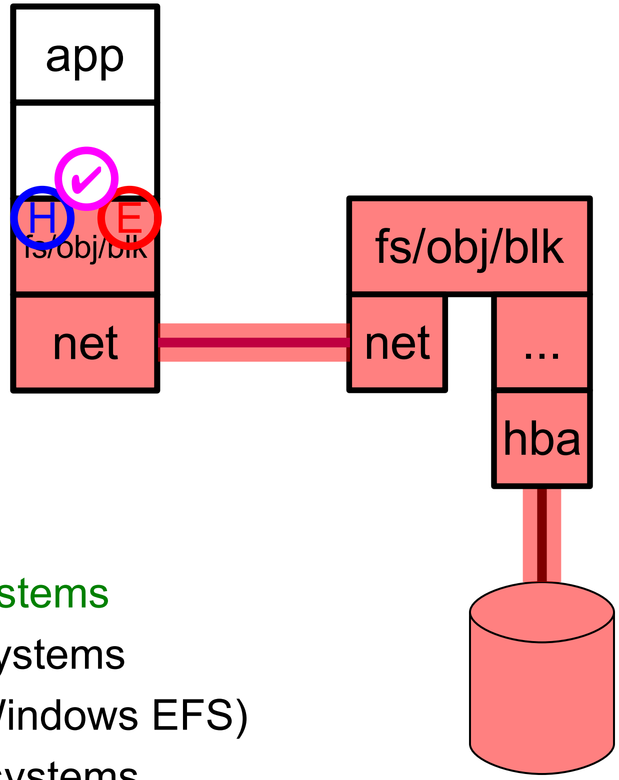
✔ Access control
H Integrity protection
E Encryption



- Encrypt the storage space
  - → Encryption and integrity protection for a storage layer
- Layer-specific cryptography on storage device
  - → Typically on low layers: block encryption
    - - Upcoming disk storage systems
    - - Available today as security appliance from vendors Decru/NetApp or NeoScale

Security for Networked Storage Systems (3)

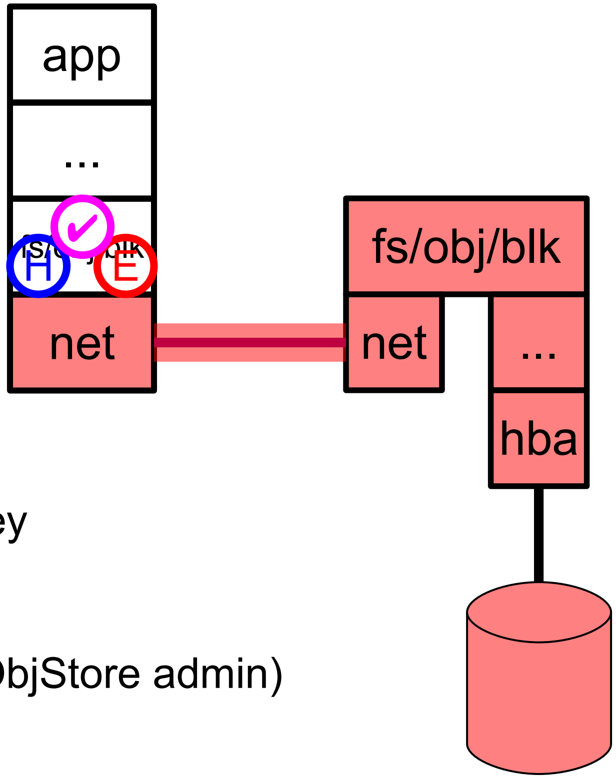
Combining Options 1 & 2: Protecting data in flight & at rest



- Encrypt the storage space
  - → But don't trust the network and don't trust the storage device
- Layer-specific cryptography on client
  - → Typically on higher layers: cryptographic filesystems
    - - Available today in local cryptographic filesystems (CFS, SFS, Linux loopback encryption, Windows EFS)
    - - Not yet widely available for distributed filesystems

Design Dimensions

- Encryption: keys?
  - Separate security admin server
  - Encrypted with user/group public key
  - Held by hardware module
- Integrity verification: reference values?
  - Integrated in directory
  - Inode tree is hash tree
  - Digital signatures under user/group public-key
- Access control: credentials?
  - Separate security admin server (Kerberos, ObjStore admin)



Talk Outline

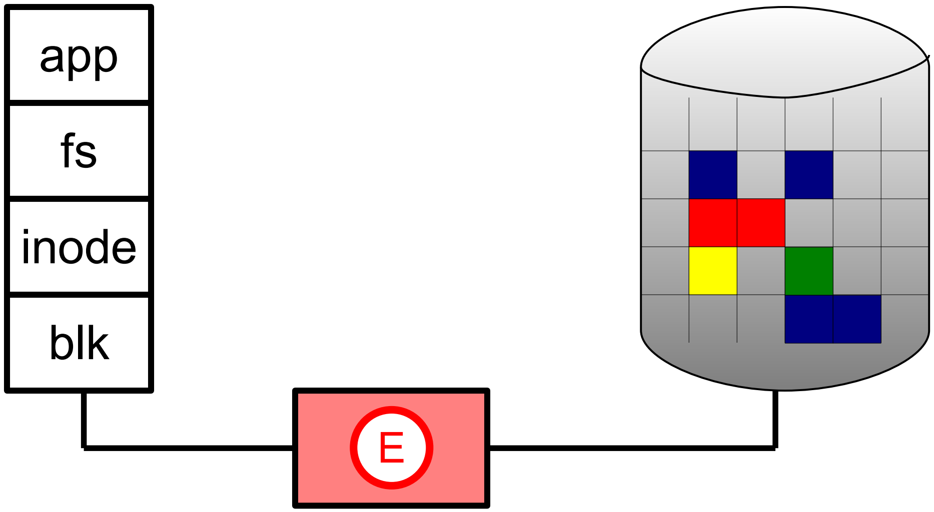
- Storage systems have these layers for good reason
  - → Not all security mechanisms are useful and efficient on all layers
- Challenge is to select the "right" combination

	Ⓔ	Ⓜ	✔
file	key mgmt. & lazy revocation	hash trees	
object			OBS security protocol
block	tweakable block encryption	hybrid block-integrity protection	

Block Layer

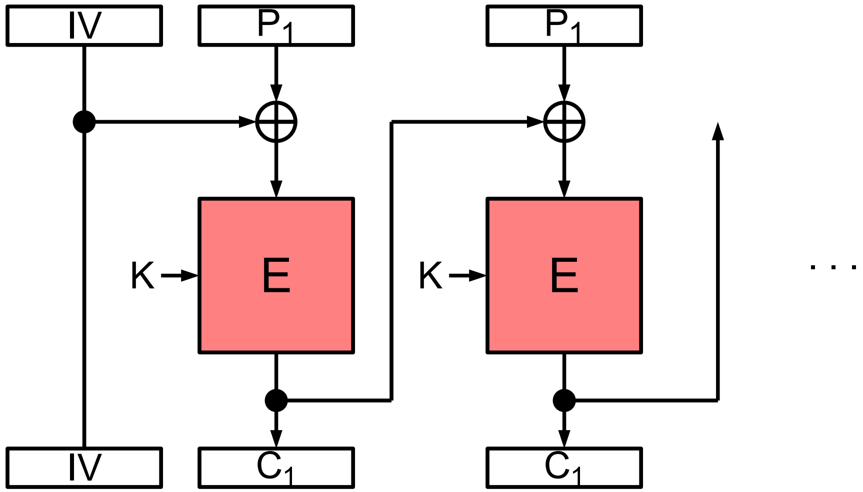
Encryption at the Block Layer

- “Sector” encryption, 512-byte blocks
- Transparent to storage system → no extra space available



- IEEE SISW standardization effort: P1619, P1619.1, ...

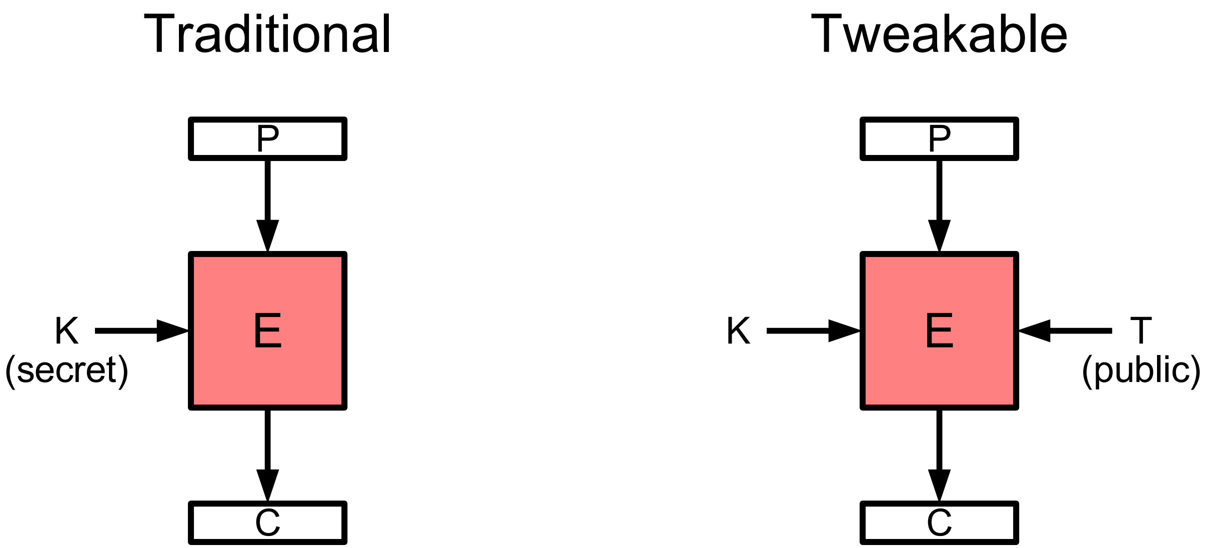
Using CBC Mode



- IV chosen at random → must be stored, doesn't work
- Derive IV from offset of sector on disk

  IV = E_K(sector offset | disk LUN)

Tweakable Block Encryption [LRW02]



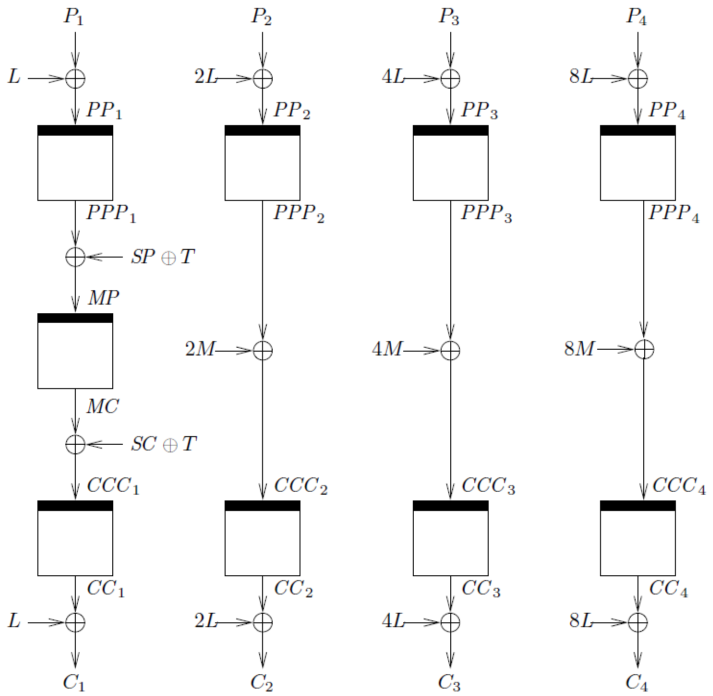
E_K() is PRP

$E_{K,T}$() is a PRP for every T

- E_K() is a deterministic permutation (after picking K)
- Tweakable $E_{K,T}$() is a family of independent such permutations
  - → T = LUN | offset of sector on LUN
- Change of even one bit → decrypted P' completely independent of C

Using Tweakable Encryption Mode

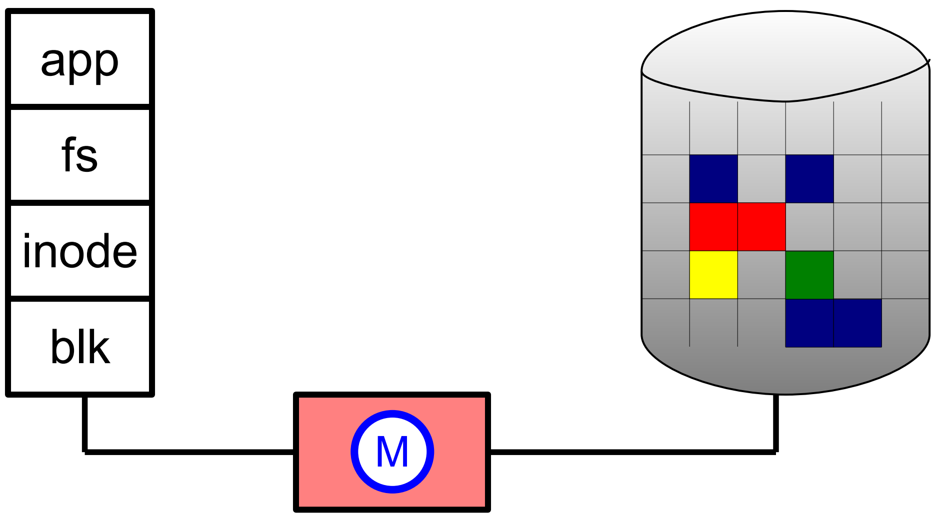
- Turns an ordinary narrow-block cipher E (16-byte blocks) into a tweakable, wide-block cipher (512-byte blocks).
- EME [HR04], calls to E are parallelizable:



- EME requires ≈2 block cipher calls per plaintext block (better is ≈1)
- Mode by [LRW02] is more efficient, but less secure

Integrity Protection at the Block Layer

- No extra space available → really problematic for integrity
- All integrity protection and data authentication methods require extra space for a tag or a hash value



- If there was space, use a MAC or a hash tree ...

Hybrid Integrity Protection at the Block Layer [ORY05]

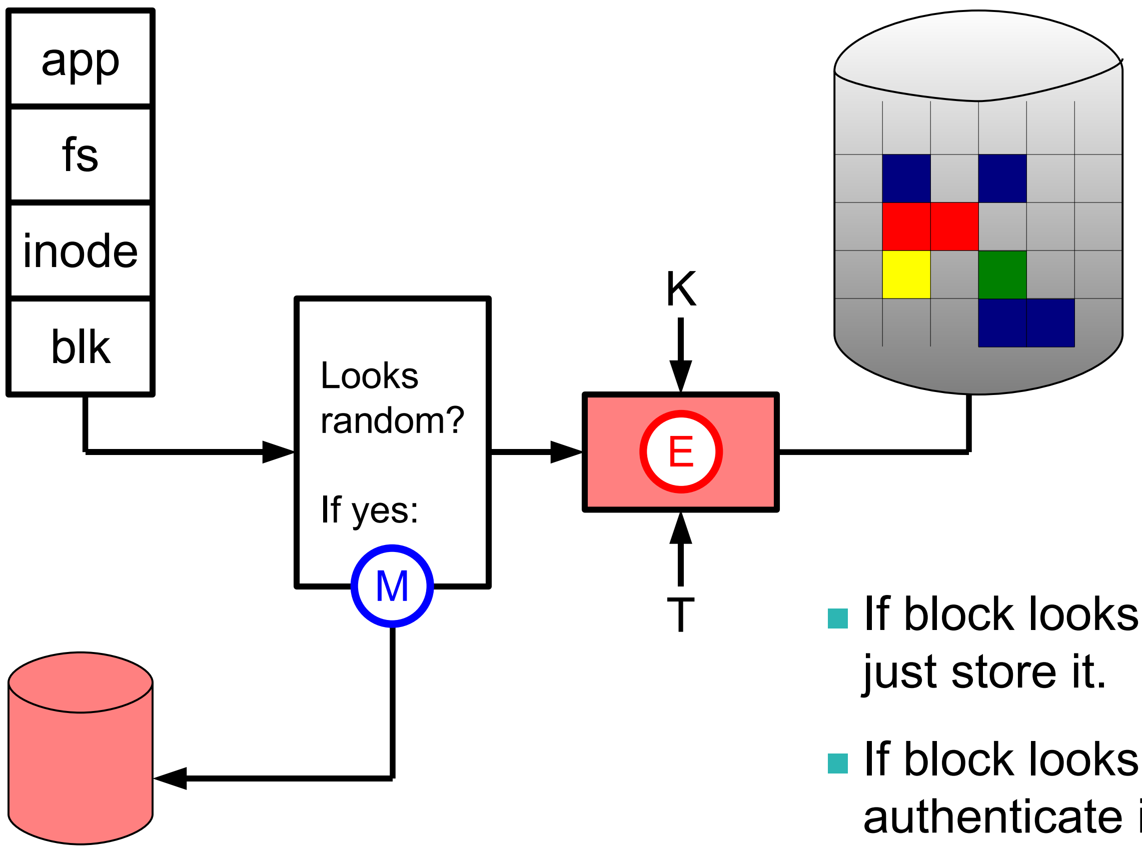
- Data is encrypted
- Use tweakable encryption mode on wide block (sector size, 512B)
- Idea

  If data contains redundancy, then any modification of ciphertext is detectable because decrypted plaintext will look random.

  → "Redundant" blocks are not extra protected for modification detection
  → "Random" blocks are protected in traditional way

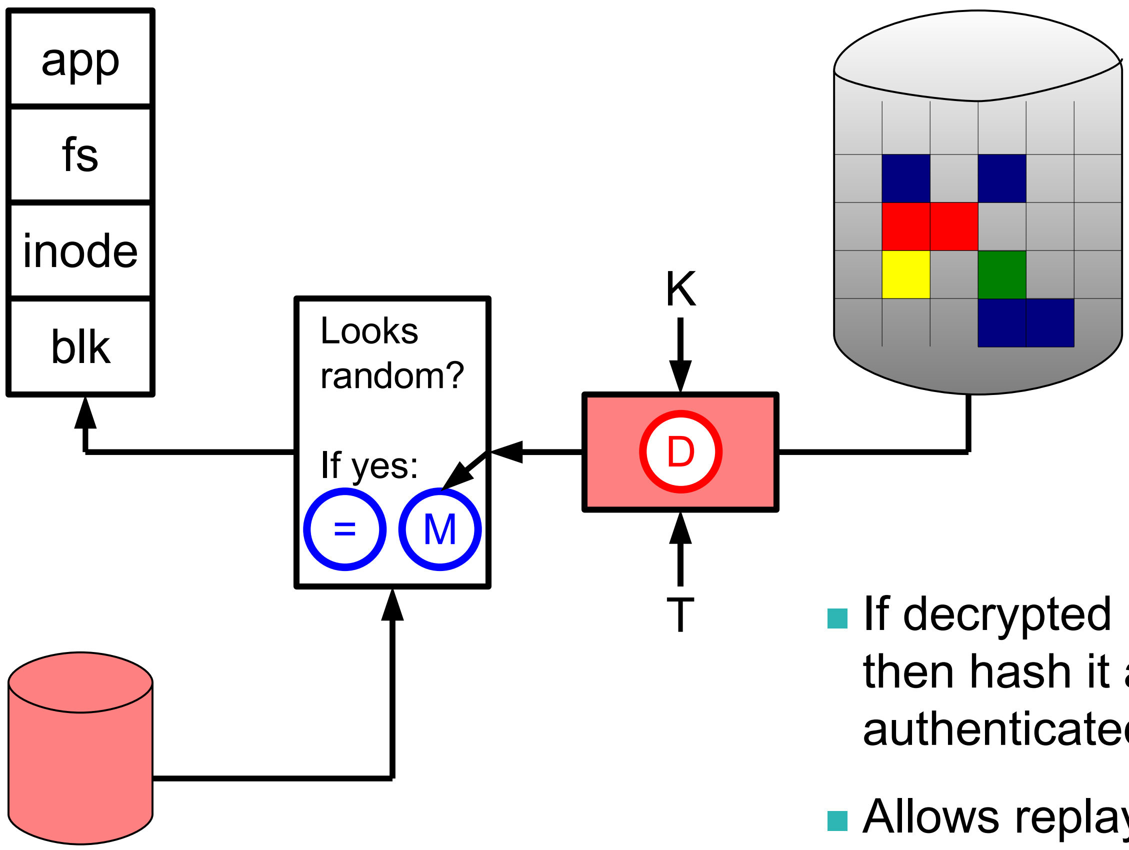
- Needs a heuristic test for "redundancy"

Writing Data



- If block looks redundant, just store it.
- If block looks random, authenticate it using extra trusted storage.

Reading Data



- If decrypted block looks random, then hash it and compare it with authenticated value.
- Allows replay attack with previous content of sector.

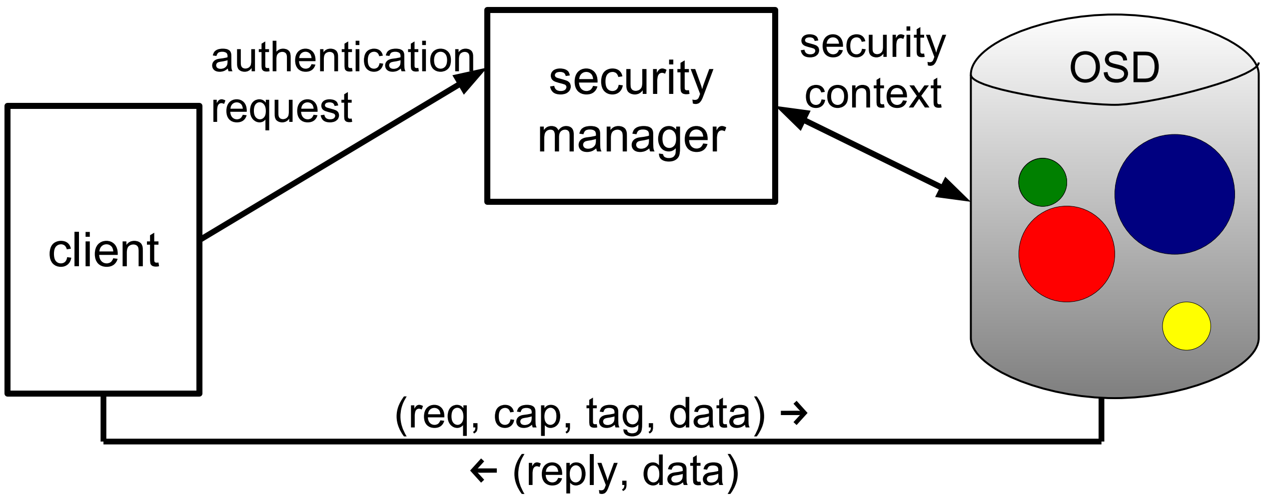
Discussion of Hybrid Scheme

- Performance depends on payload data
- Suffers from replay attacks
- Depends on estimator for redundancy
  → Simple 1-st order entropy test on 8-bit blocks in 1024-byte sector
    - Threshold set to 7.7 bits
    - 98% of blocks from file system trace have observed entropy < 7.7

  → Saves 98% storage space compared to hashing every block
  (Or: protects integrity of 98% of observed data.)
- Cannot achieve ideal security for arbitrary payload

Object Layer

Object Store Security Protocol [ACF+02]



- Capability-based protocol to authenticate requests and traffic between client and object-storage device (OSD)
- Key establishment protocol between OSD and security mgr.
- Protocol between client and security mgr. specific to file system

Protocol Features

- Security methods

  NONE: --

  CAPKEY: authenticate requests at OSD level, no transport security

  → tag computed only over cap

  CMDRSP: above plus transport integrity for request and reply

  → tag computed over capability and request

  ALLDATA: above plus transport integrity for payload data

  → tag computed over capability, request, and data

- May replace IPsec for iSCSI or FC-SEC for Fibre Channel (also duplicates some of their functionality)

OSD Data Types

- Object hierarchy

  OBS → Partition → Object

- Key hierarchy

  Master key: to initialize OSD and create root key

  Root key: to manage partitions and their keys

  Partition key: only to create per-partition working key

  Working key: per partition, changed frequently, useful for revocation (among other uses), protects all objects in partition

OBS Security Protocol Details (CAPKEY)

- PRF F
- Capabilities

  (obj, exptime, permissions, nonce)
- Client requests credential from security manager and receives

  cred = (cap, Kcap)

  where Kcap = F_K(cap) under appropriate partition working key K
- Client sends

  (req, cap, tag)

  to OSD, where

  tag = F_{Kcap}(cap | client | OSD)
- OSD verifies that

  1. req is allowed by cap in partition

  2. validates tag from its own id, using key K' = F_K(cap) with working key K of current partition

File Layer

Key Management in Cryptographic File Systems

- Two approaches

  On-line and centralized

  - Only symmetric-key crypto
  - Simple and efficient
  - Limited scope and scalability
  - Ex. Cryptographic SAN.FS [PC06]

  Off-line and de-centralized

  - Requires public-key crypto
  - Complex, computationally expensive
  - Scalable
  - Ex. SFS [FKM02], Windows EFS, Plutus [KRS+03], Sirius [GSMB03] ...

De-centralized Key Management

- Users have SK/PK pair
- Groups have SK/PK pair; every member of group knows SK
- Files encrypted using FEK with block cipher
- Confidentiality: Store FEK encrypted in meta-data

  → Encrypted under every PK of every user/group that has access

  Example: File X, encrypted with FEK_X

  ```
  owner: A, rwx, E_PKA(FEK_X),
  group: G, r-w, E_PKG( FEK_X),
  world:    ---
  ```

- Integrity: Add FSK_X / FVK_X, key pair for digital signatures, to X

  → Store FSK like this in every encrypted file

- Drawback: key revocation is tedious

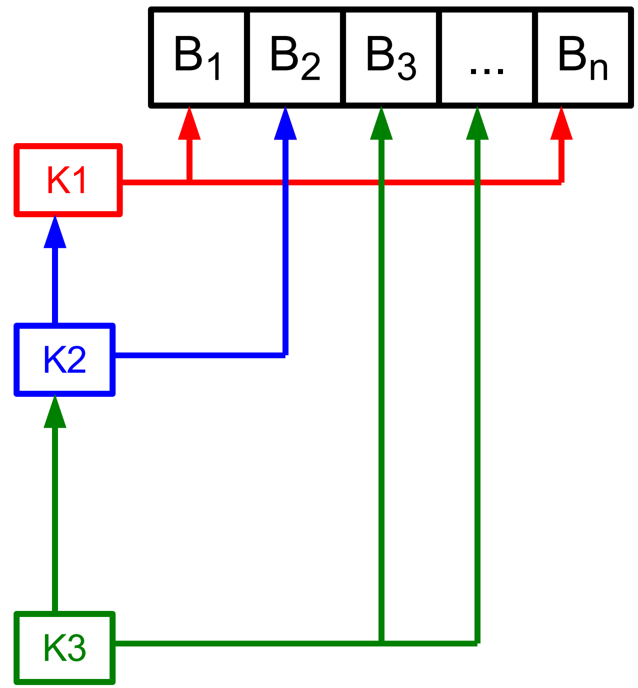
Key Revocation

- User revoked → change all keys that were known to user
  - → Re-encrypt all data with fresh keys
- Very expensive and disruptive operation
- Idea: Lazy Revocation [F99]
  - → Re-encrypt data only when it changes after revocation, keep old keys around.
- All versions of a key must remain accessible.

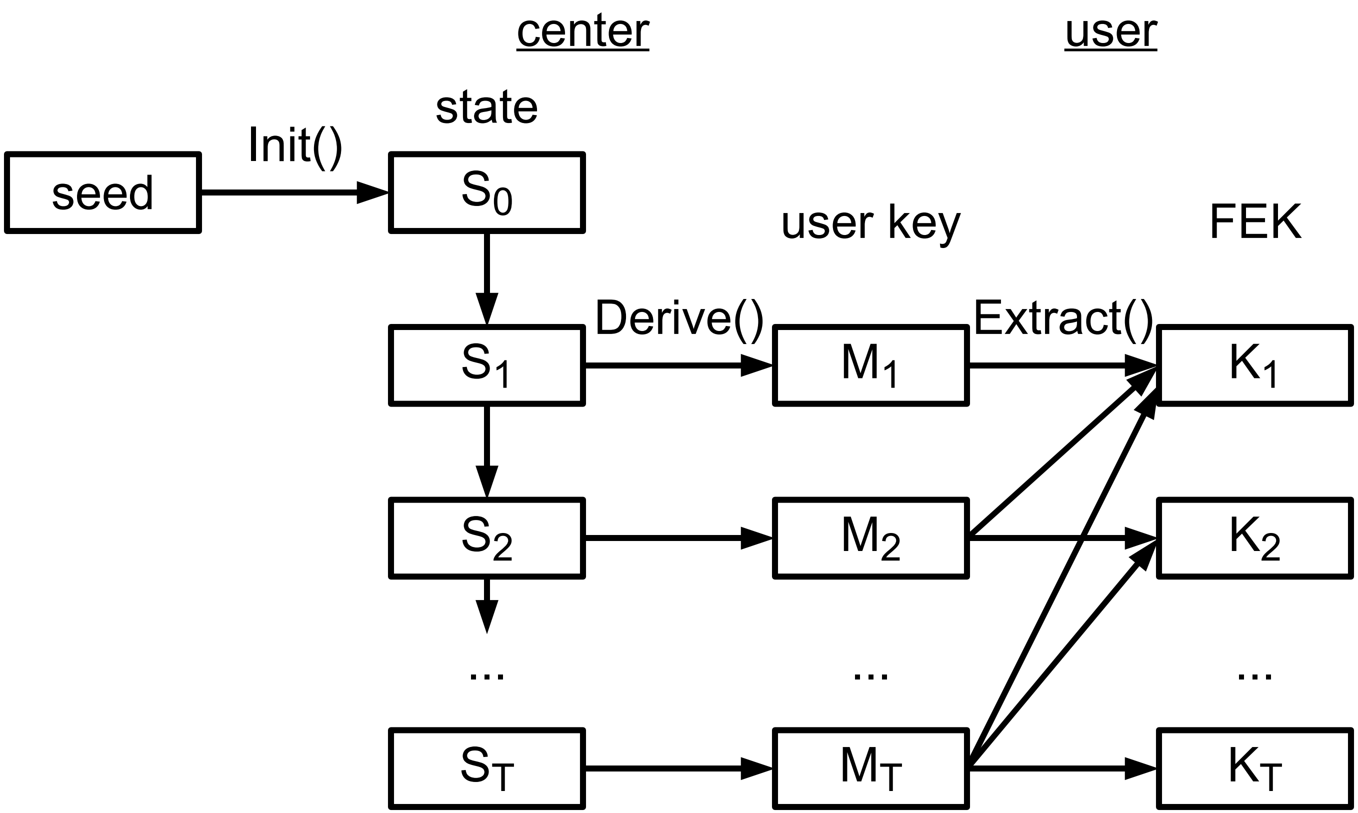
Lazy Revocation [KRS+03]

time	center	users: u	u'	u''
	S1(K1)	K1	K1	K1
u' is revoked				
	S1(K1,K2)	K2	--	K2
u'' writes B_2				
u'' is revoked				
	S1(K1,K2,K3)	K3	--	--
u writes B_3 ...				

storage



Key Updating Schemes for Lazy Revocation



- Requirements
  - → User can obtain K_1 ... K_t from M_t
  - → Adversary with M_t cannot distinguish K_{t+1} from uniformly random string

Formalization [BCO05, BCO06, FKK06]

- Key updating scheme for T periods

  KU_T = (Init, Update, Derive, Extract)

- Metrics of interest
  - → Time of Update(), Derive(), and Extract()
  - → Size of center state S_t
  - → Size of user key M_t

Composition of Key Updating Schemes [BCO06]

- Addition

  $KU^1_{T1} \oplus KU^2_{T2} \;=\; KU^{\oplus}_{T1+T2}$

  Construction

  → First T1 intervals use KU^1

  → Subsequent T2 intervals use KU^2 and include M_{T1} in user key

- Multiplication

  $KU^1_{T1} \otimes KU^1_{T2} \;=\; KU^{\otimes}_{T1 \cdot T2}$

  Construction

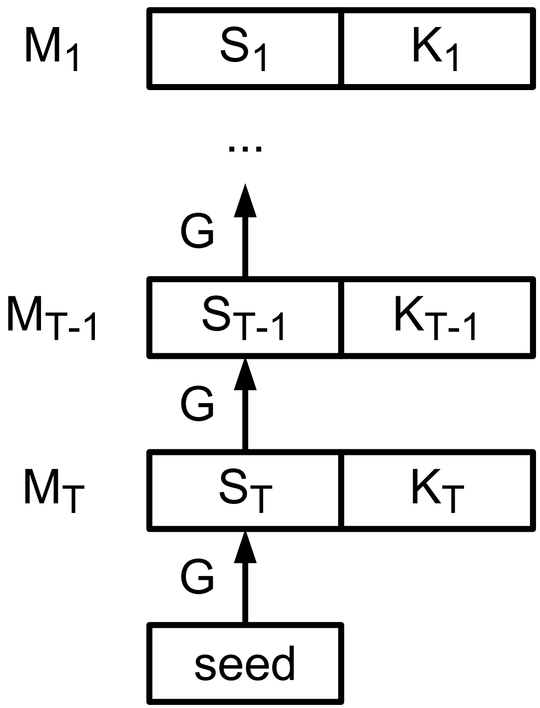
  → Every key generated with KU^1 is used to seed an instance of KU^2

Constructions

- Chaining construction
- Trapdoor permutation-based
- Tree construction

Chaining Construction ("Hash Chain")

- Using pseudo-random generator G

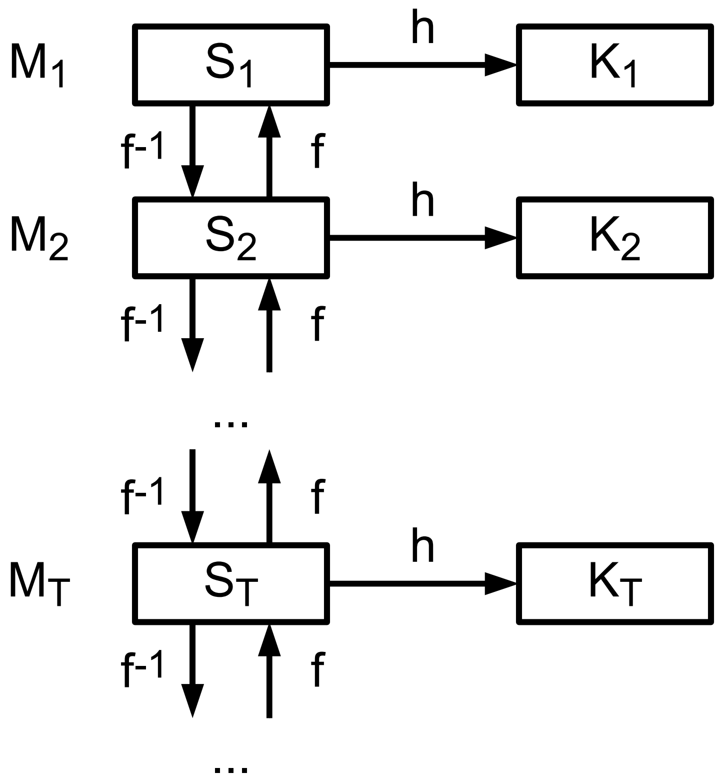


State	Update	Derive	Extract
seed	0	O(T) PRG	O(T) PRG

- Drawback: Fixed T

Trapdoor Permutation Construction [KRS+03]

- Using trap-door permutation TDP (f, f^{-1}), where f is easy and f^{-1} is hard without secret key, hash function h() in ROM

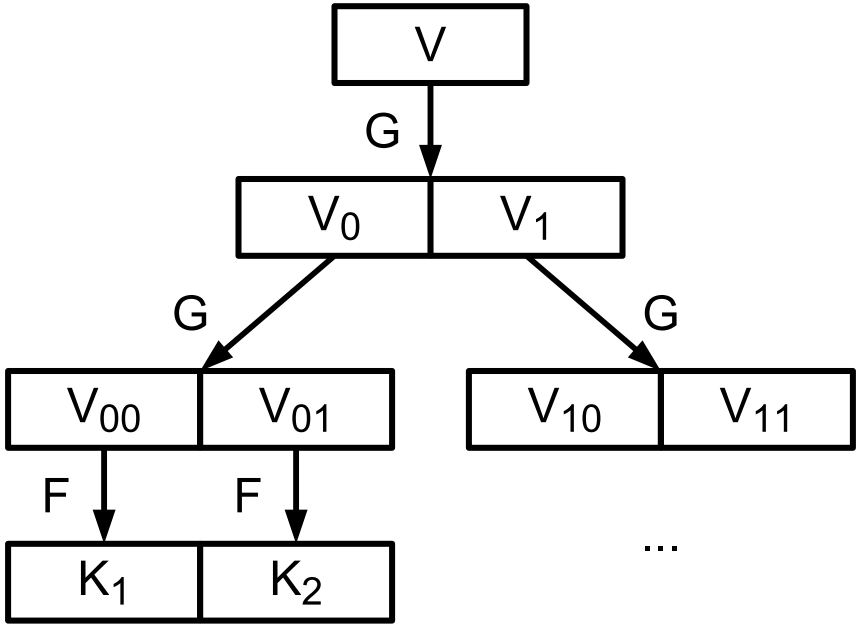


State	Update	Derive	Extract
seed	TDP	const.	O(T) TDP

Advantage: Flxible T

Tree Construction [BCO06]

- Using PRG G and PRF F



State	Update	Derive	Extract
O(log T)	O(log T) PRG	0	O(log T) PRG

- User key M_t is smallest set of nodes needed to derive K_1 ... K_t
- Fixed T, but state parameters only logarithmic in T

Comparison of Key Updating Schemes

- Trapdoor scheme using RSA-1024
- PRF/PRG using AES-128
- Average times [ms] measured on Intel 2.4 GHz Xeon

Scheme	T	Derive + Update	Extract
Chaining	1024	1.28	1.24
Trapdoor	1024	15.4	15.2
Tree	1024	0.015	0.006
Tree	2^{16}	0.015	0.008
Tree	2^{25}	0.015	0.01

Integrity Protection

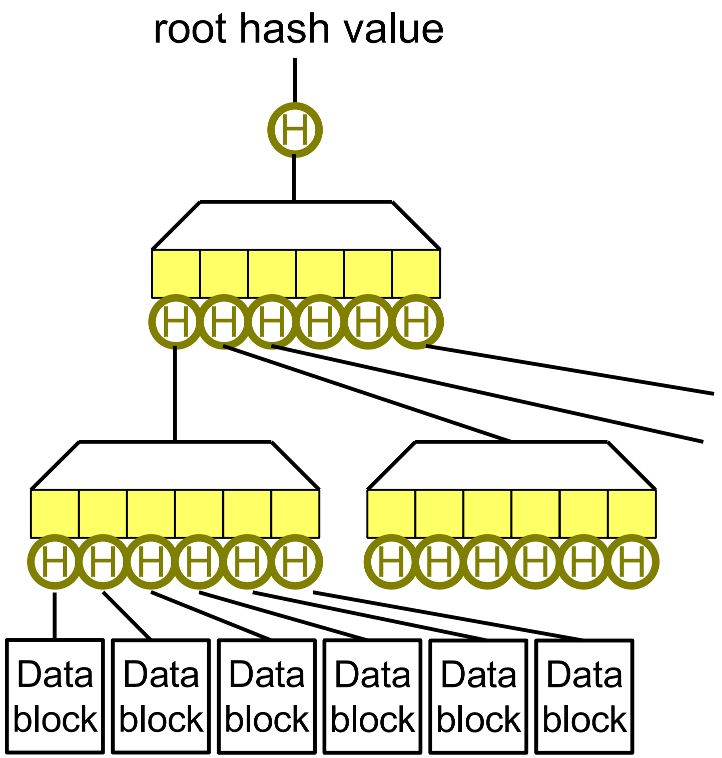
- Storage server not trusted
- Associate short reference value v with long file
  - → Store v on trusted server, with file meta-data
  - → Sign v with digital signature
- Hash function?

  v = H(file)

  - → Infeasible for long files
  - → No random access
- Solution:
  - → Hash tree [Merkle]

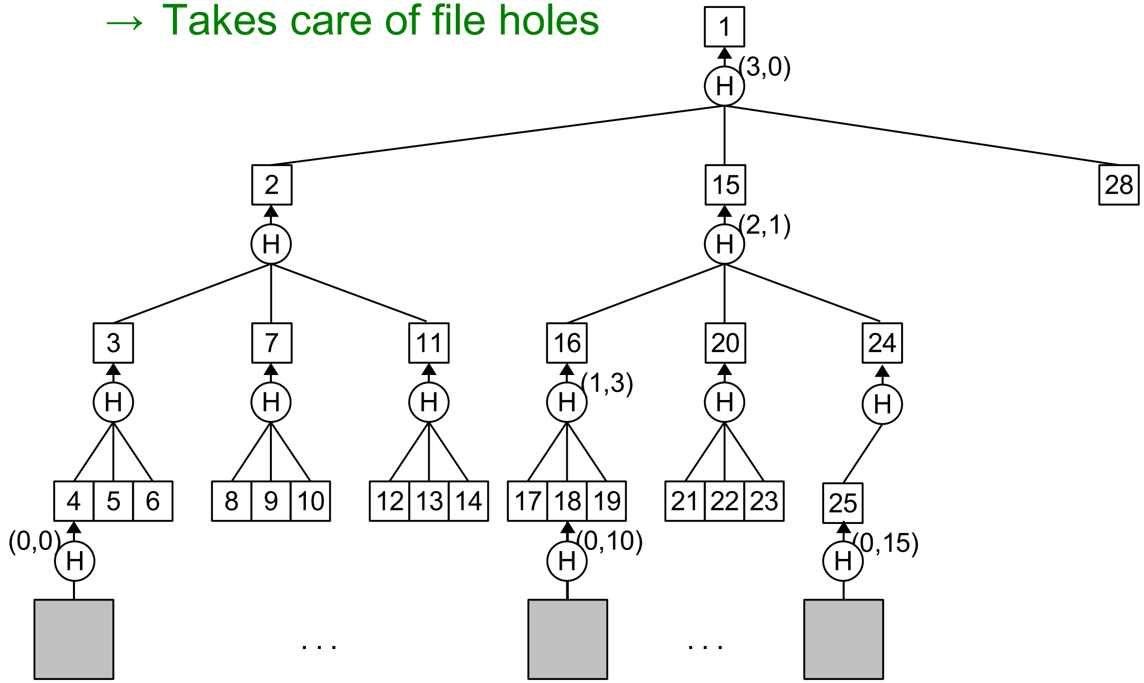
Integrity Protection Using Hash Trees

- Merkle hash trees
  - → Root hash value represents all data blocks of the file
  - → Root hash value in trusted storage
  - → Tree stored on untrusted storage
- Reads and updates take O(log n) extra operations
- With local buffering, sequential read or update of all blocks has constant overhead



Implementing Hash Trees

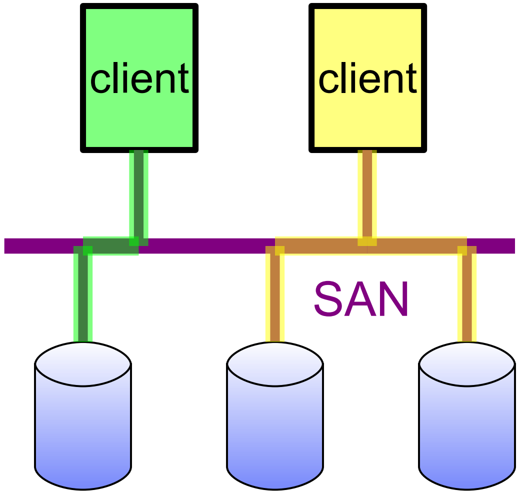
- Much more complex than encryption in file system
  - → Dual and mutually dependent data paths
- Degree may vary (2 ... 128), determine experimentally (≈16)
- Serialize nodes using pre-order enumeration
  - → Sparse allocation of maximum-size tree
  - → Takes care of file holes



Example: A Cryptographic SAN File System [PC06]

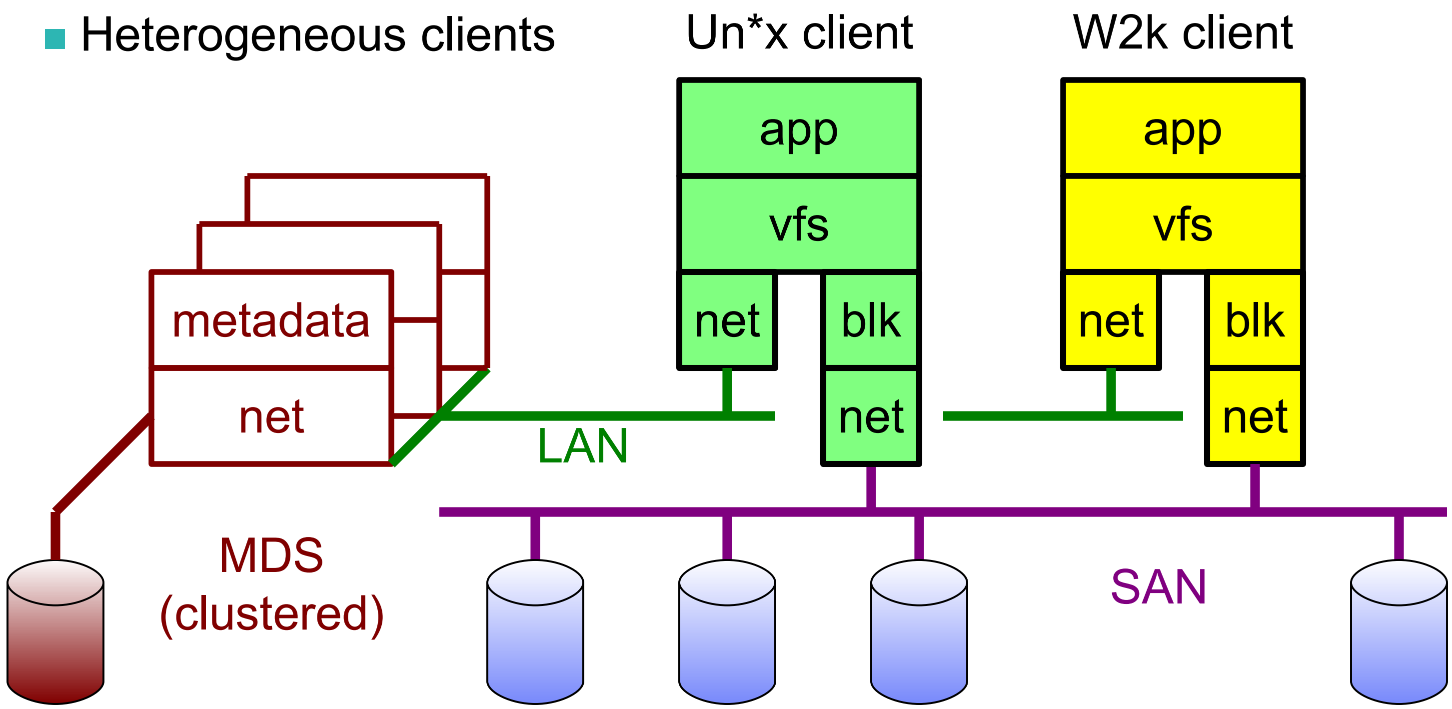
SANs and SAN File Systems

- SAN today:
  - Clients access block storage devices directly
  - → Fibre Channel (SCSI)
  - Static configuration
  - → OS sees a local block storage device
  - Static access control
  - → zoning & fencing in FC switch
  - Inside server room only



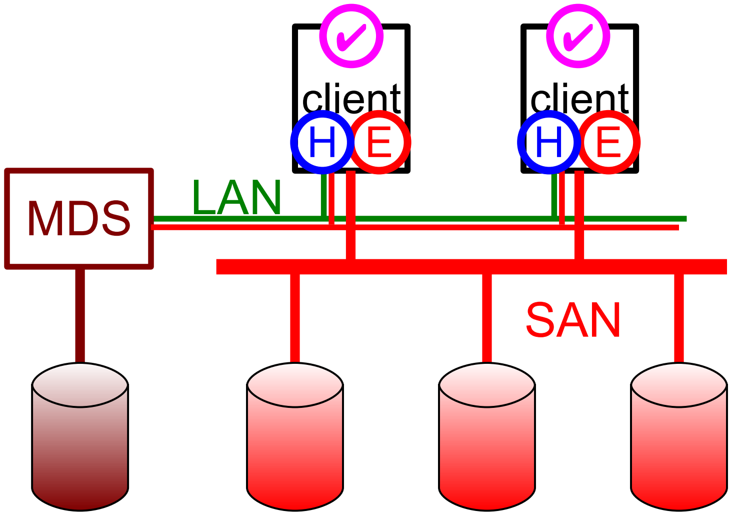
SAN Filesystems (e.g. IBM's StorageTank)

- Virtualized block storage space
- Block access managed by metadata server (MDS)
- Single filesystem name space
- Heterogeneous clients



Design of a Cryptographic SAN Filesystem

- Integrity verification & encryption in client
  - → Scalable
  - → End-to-end security
- MDS is trusted, provides encryption keys & reference data
  - → Integrate key management with metadata
  - → No modification of storage interface
- Needs
  - secure LAN connection (IPsec)
  - trusted client kernels

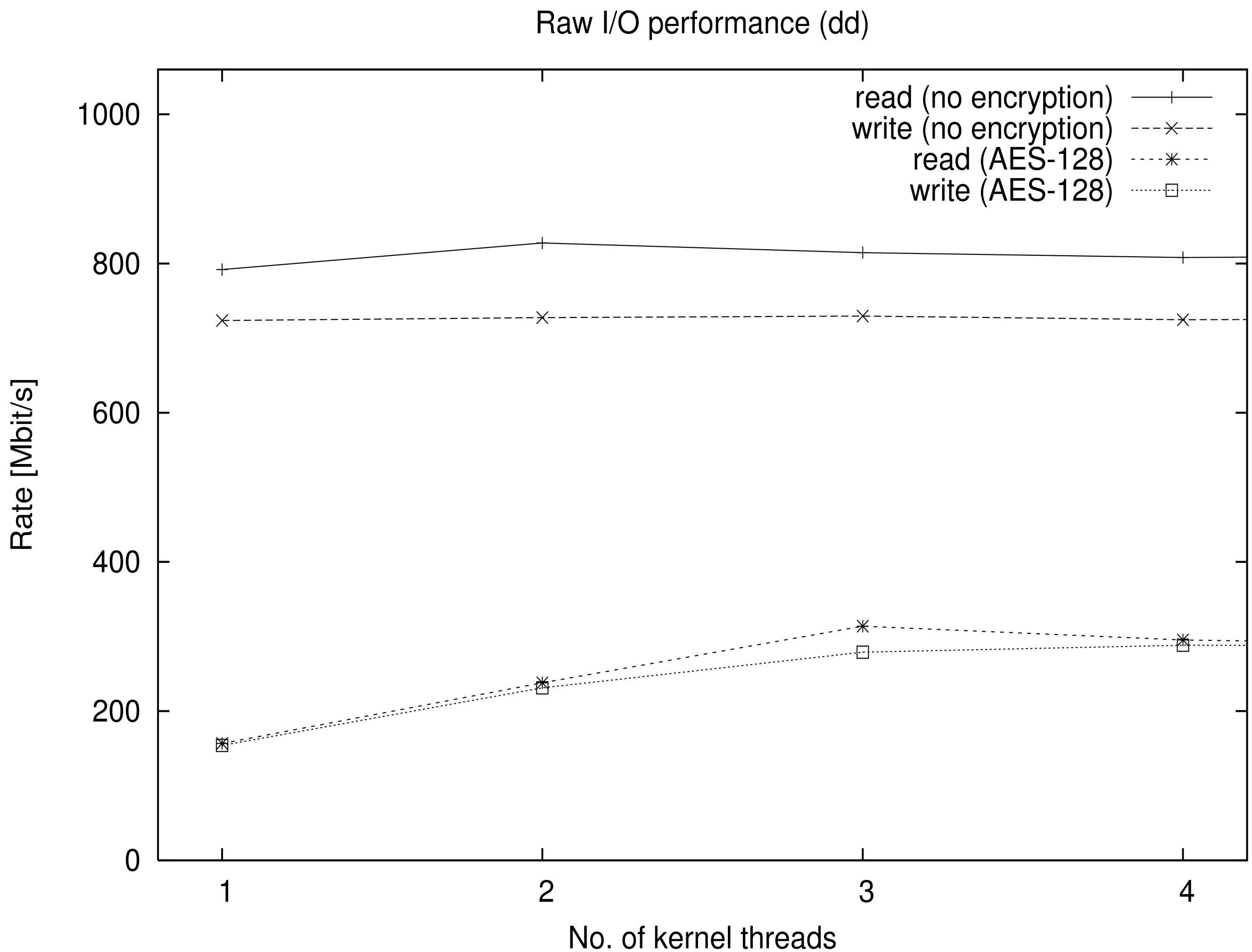


✓ Access control

H Integrity protection

E Encryption

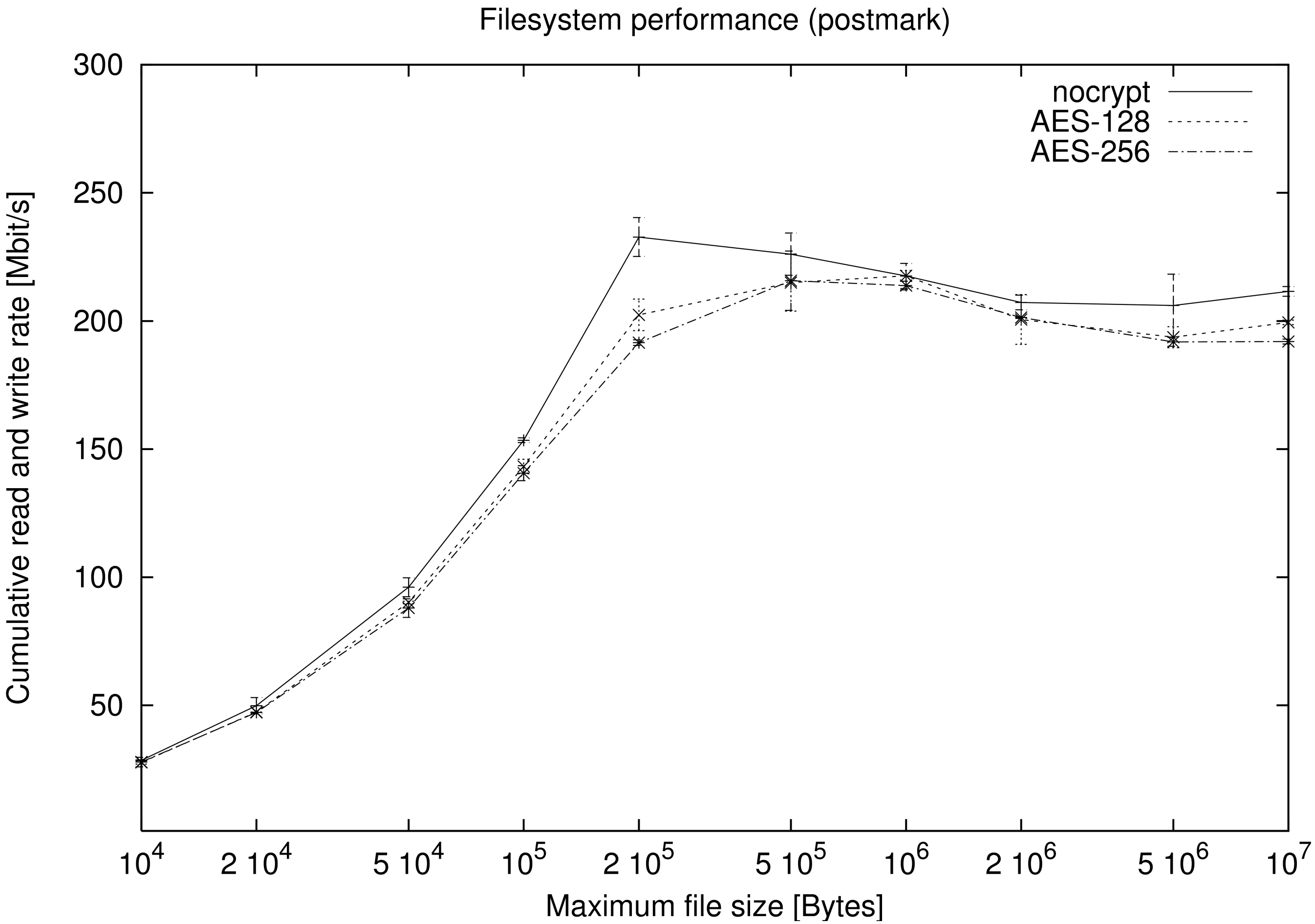
Raw Peak Performance with Encryption (dd)



- SAN.FS client 8.9 on
  - IBM x336
  - dual Xeon 3.2GHz (4 CPUs in Linux)
  - 3 GB RAM
  - Linux 2.6.6
- iSCSI 4.0.1.7 over
  - 1Gbit/s Ethernet
- Storage target on
  - IBM x346
  - dual Xeon 3.6GHz

Kernel threads used by STFS pager

Application Performance with Encryption (postmark)



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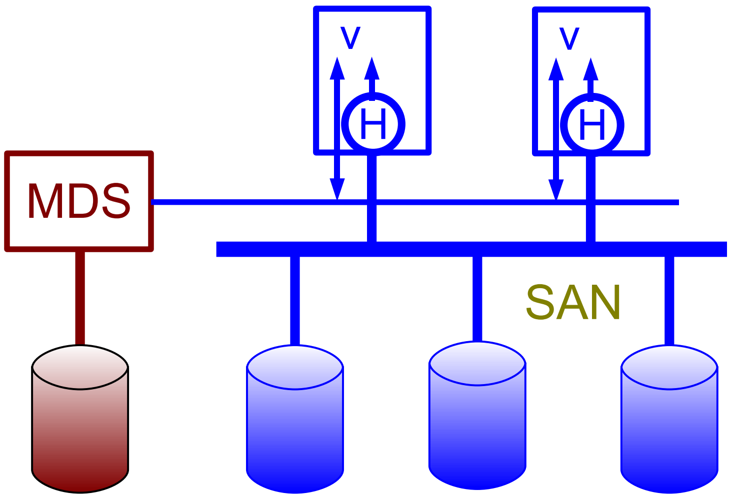
postmark performed 5000 transactions on 2000 randomly sized files between 1k and max. file size

Integrity Protection

- Data is hashed on client to digest values
  - → Digest values stored at MDS
  - → Secure transfer of digests
  - → Integrity protected in flight *and* at rest, modifications are detected
- Storage interface unmodified
  - → Impossible to prevent overwrites, but violations are detected
- SHA-1, SHA-256 or others
  - → NIST standards, fast & secure
  - → ~ 260 MByte/s in software (Xeon 3GHz)
- Using hash tree



Summary

- Any security mechanism can be applied on all layers
- Challenge is to select the “right” combination

	E	M	✓
file	key mgmt. & lazy revocation	hash trees	
object			OBS security protocol
block	tweakable block encryption	hybrid block-integrity protection	

Thank you!

- More information?

  http://www.zurich.ibm.com/~cca

  <cca@zurich.ibm.com>

References (1)

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