PV204 Security technologies

File and disk encryption

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Data storage encryption

- Lecture
  - File and disk encryption
  - Distributed storage encryption
  - Abstraction layers, hardware acceleration
  - Cryptography basic principles
    - Confidentiality and integrity protection
    - Encryption modes
    - Key management
  - Tool examples
  - Attacks and common issues
- Lab – disk encryption attack examples

File and disk encryption

MOTIVATION & STORAGE LAYERS OVERVIEW

Motivation

Offline, "Data at Rest" protection

notebook, external drives, data in cloud, backups

Key removal = easy data disposal

Confidentiality protection

company policy to encrypt all mobile devices

prevents data leaks (stolen device)

Data integrity protection (not often yet)

Overview

(Distributed) Storage Stack

- layers accessing storage through blocks (sectors)
- near future: non-volatile byte-addressable memory
- distributed => adding network layer

Full Disk Encryption (FDE)

- self-encrypted drives
- (software) sector-level encryption

Filesystem-level encryption

- general-purpose filesystem with encryption
- cryptographic file systems

Storage stack & encryption layers

Userspace	**Application**	(Application specific)
OS kernel	**Virtual file-system** (directories, files, …)	**File-system encryption**
	Specific file-system (NTFS, ext4, XFS, …)	
	Volume Management (partitions, on-demand allocation, snapshots, deduplication, …)	**Disk encryption**
	Block layer (sectors I/O)	
	Storage transport (USB, SCSI, SAS, SATA, FC, NVME…)	**HW-based encryption** self-encrypted drives, inline (slot) encryption, chipset-based encryption, hardware security module
	Device drivers	
“Hardware”	**Hardware** (I/O controllers, disks, …)	

Clustered and distributed storage

Clustered => cooperating nodes
Distributed => storage + network

Software Defined Storage/Network (SDS, SDN)
- commodity hardware with abstracted storage/network logic
- encryption is “just” one logic function
- usually combination with classic storage (and encryption)

Distributed storage & encryption

Shared volumes (redundancy)

=> disk encryption

Clustered file-system

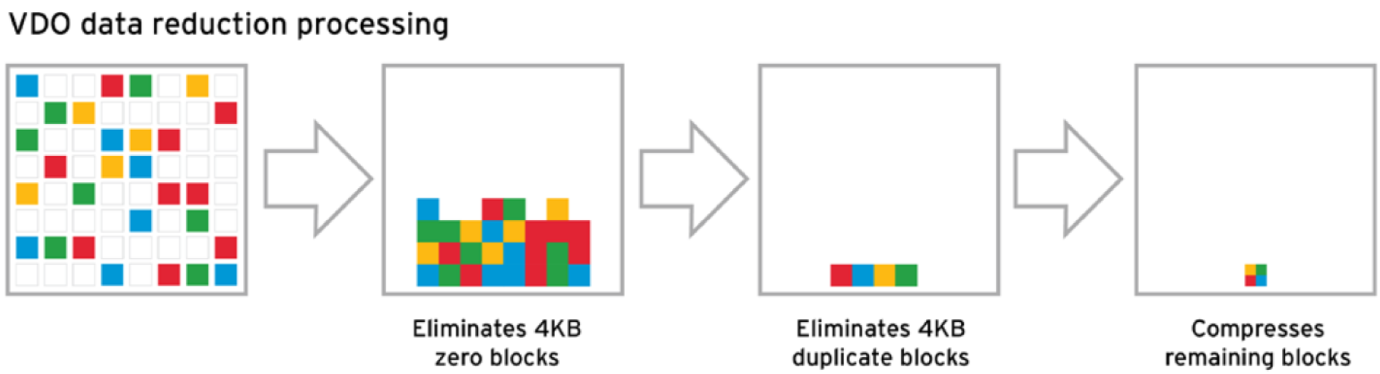
=> file-system encryption

Distributed Object Store

- direct object encryption or
- underlying storage encryption

Cloud storage – common features

Deduplication – avoid to store repeated data



Compression – generic algorithms
- special case: zeroed blocks

Data snapshots (in time)
- COW (copy on write)

Cloud storage & encryption

Encryption with storage backend and compression & deduplication & snapshots …

Encryption on client side (end-to-end)

- efficiency for deduplication/compression is lost

~ in future homomorphic encryption?

Encryption on server side

- confidentiality for clients is partially lost
- server has access to plaintext

Full Disk Encryption (FDE)

Block device – transparent disk sector level

- disk, partition, VM disk image
- ciphertext device / virtual plaintext device
- atomic unit is sector (512 bytes, 4k, 64k)
- consecutive sector numbers
- sectors encrypted independently

One key decrypts the whole device

- media (volume) key – one per device
- unlocking passphrases/keys
- usually no integrity support (only confidentiality)

Filesystem-level Encryption

File/Directory

- atomic unit is filesystem block
- blocks are encrypted independently
- **Generic filesystems with encryption**
  - some metadata can be kept in plaintext (name, size, …)
- **Cryptographic filesystems**
  - metadata encrypted
  - ~ stacked layer over generic filesystem

Multiple keys / multiple users

File vs. disk encryption

Full disk encryption

+ for notebook, external drives (offline protection)
+ transparent for filesystem
+ no user decision later what to encrypt
+ hibernation partition and swap encryption
- more users – whole disk accessible
- key disclosure – complete data leak
- usually no integrity protection

File vs. disk encryption

Filesystem based encryption

+ multiple users
+/- user can decide what to encrypt
+ copied files keeps encryption in-place
+ more effective (only really used blocks)
+ should provide integrity protection (not always!)
- more complicated sw, usually more bugs
- unusable for swap partitions

File vs. disk encryption

Combination of disk & file encryption

Distributed storage

- **must** use also network layer encryption
- difference in network and storage encryption (replay attack resistance, integrity protection, …)

File and disk encryption

CRYPTOGRAPHY

Cryptography algorithms primitives

- **Symmetric encryption**
  - block ciphers
  - cipher block mode
  - hash algorithms
- **Key management**
  - Random Number Generators (RNG)
  - Key Derivation Functions (KDF)
  - asymmetric cryptography
- **Deniable encryption / Steganography**

Data confidentiality & integrity

Confidentiality

Data are available only to authorized users.

Integrity

Data are consistent.
Data has not been modified by unauthorized user.
=> All modifications must be detected.

Note: replay attack (revert to old snapshot) detection cannot be provided without separate trusted store (TEC – Tamper Evident Counter, Merkle tree root hash, …)

Data integrity / authenticated encryption

Poor man's authentication (= no authentication)

- User is able to detect unexpected change
- Very limited, cannot prevent old content replacement

Integrity – additional overhead

- Where to store integrity data?
- Encryption + separate integrity data
- Authenticated modes (combines both)

File and disk encryption

DATA ENCRYPTION MODES

Symmetric encryption (examples)

AES, Cammelia, Adiantum,
Serpent, Twofish, (Specks, Kuznyechik, …)

Encryption-only modes

- Storage encryption mostly CBC, XTS
- Length-preserving encryption, block tweak

Authenticated modes (encryption + integrity)

- Integrity protection often on higher layer.

Storage standards like IEEE 1619 and FIPS/NIST

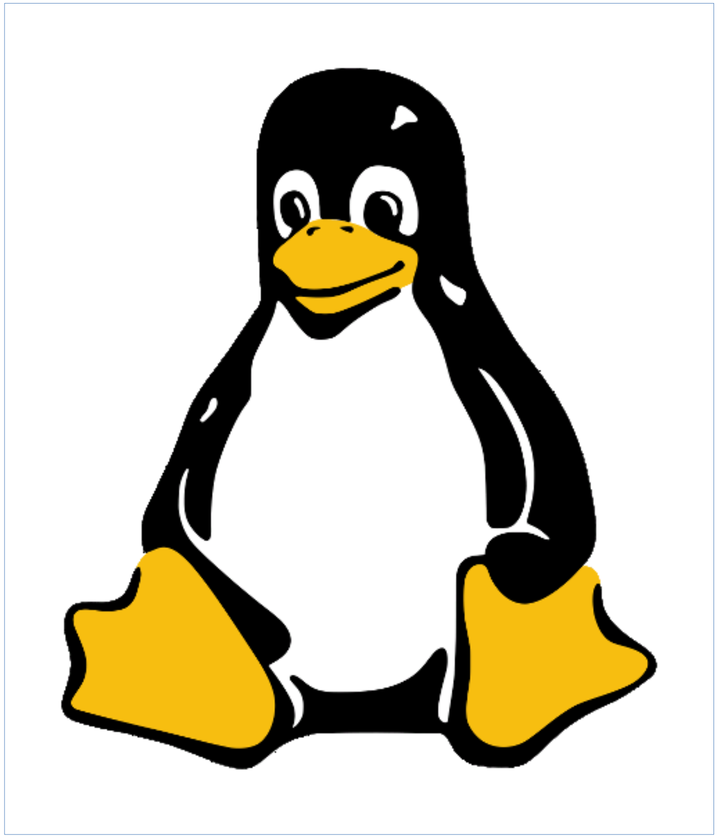
Propagation of plaintext changes

A change in the plaintext sector should transform to randomly-looking change in the whole ciphertext sector.

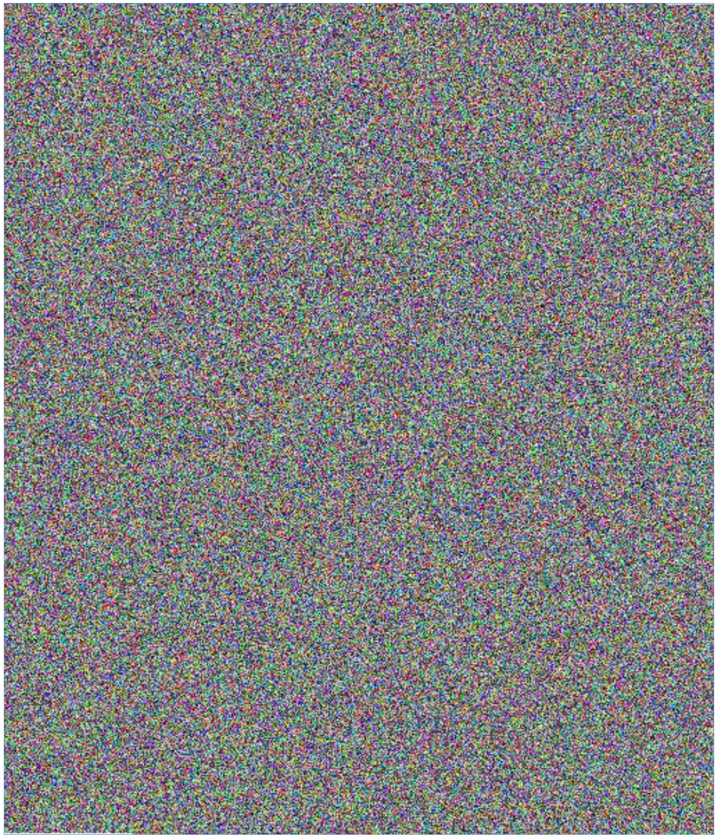
Solutions:

- Ignore it ☺ and decrease granularity of change
  => change location inside ciphertext sector
- Use wide mode (encryption block size = sector size)
  - requires at least 2x encryption loop
  - modes are patent encumbered
- Additional operations
  - Elephant diffuser in Windows Bitlocker
  - Google Adiantum (cipher composition)

Encryption example – AES-XTS

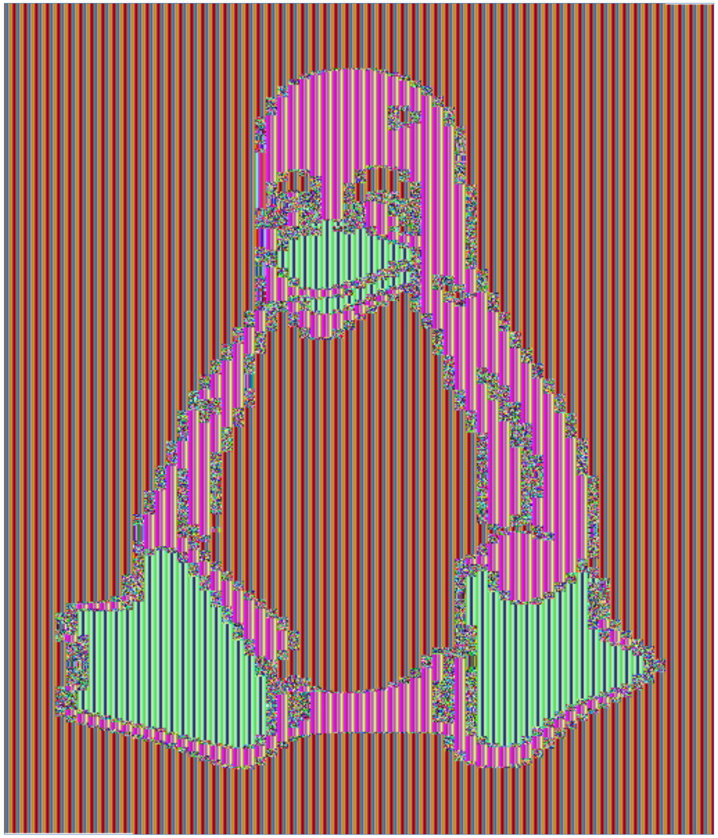


plaintext

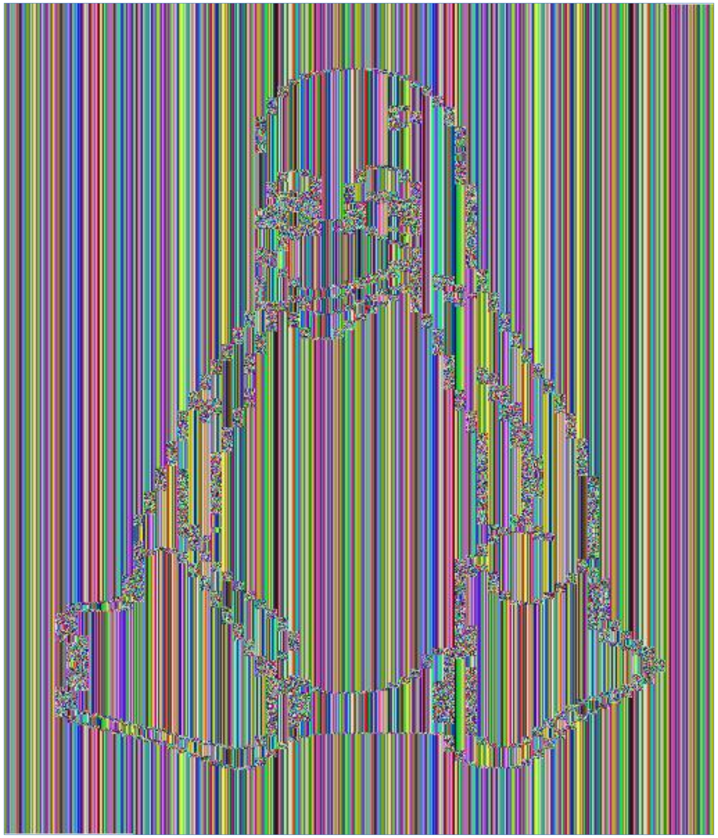


ciphertext

Wrongly used modes – ciphertext patterns



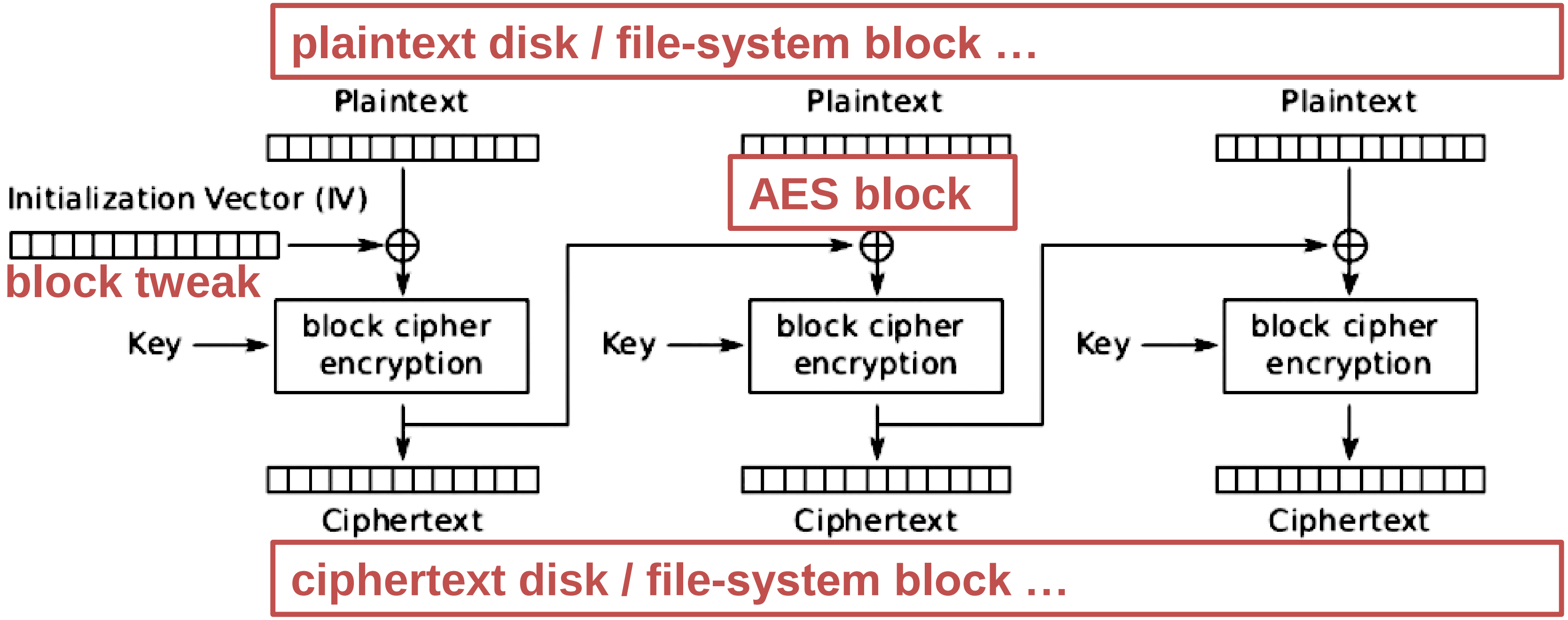
ECB mode



AES-XTS & constant IV

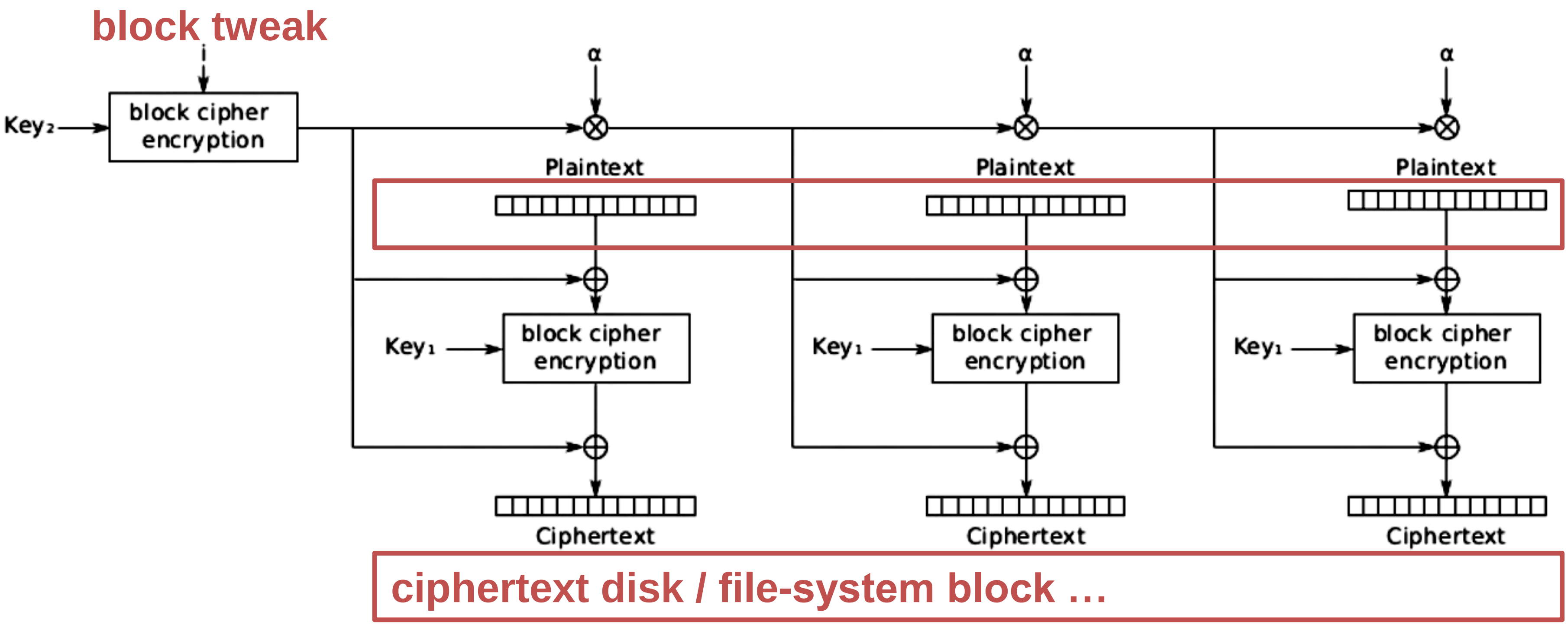
Cipher-Block-Chaining (CBC) mode

- Blocks cannot be encrypted in parallel
- Blocks can be decrypted in parallel
- Tweak must be non-predictable (watermarking!)



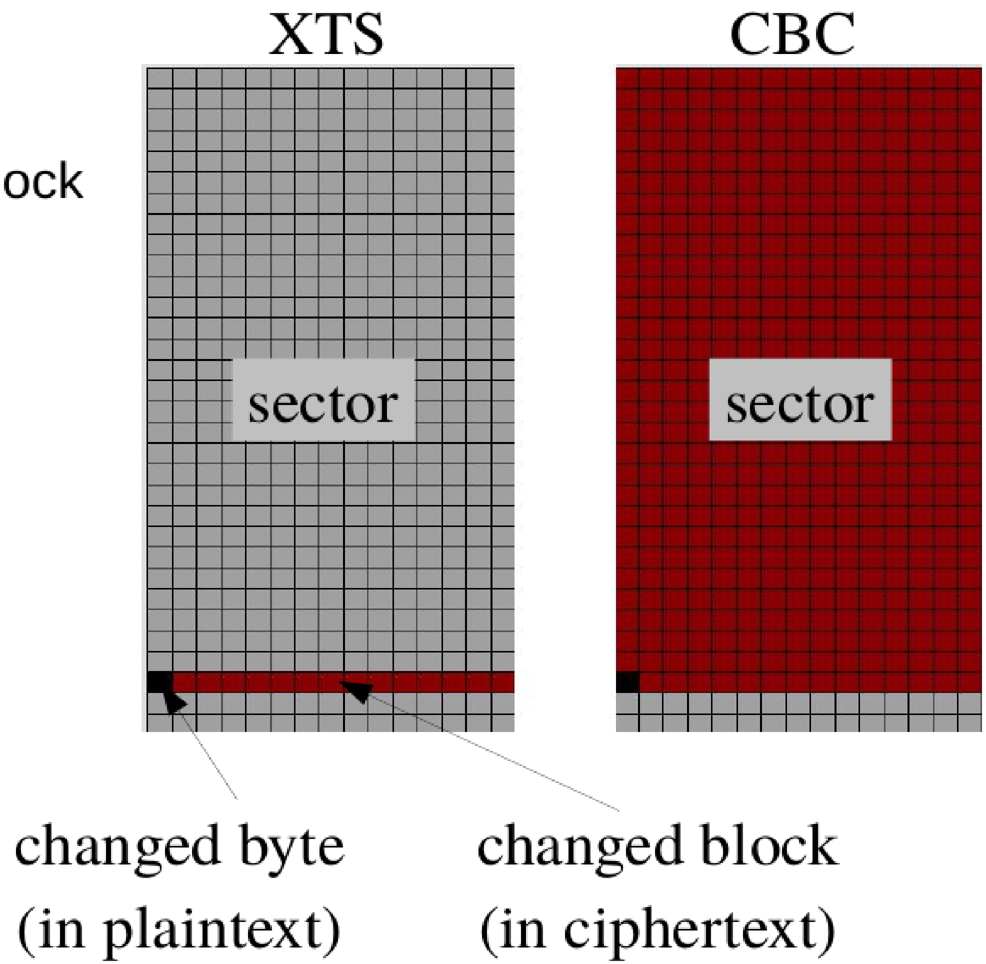
XOR-Encrypt-XOR (XEX/XTS) mode

- Encryption/decryption can be run in parallel
- Tweak can be predictable nonce – sector number (offset)



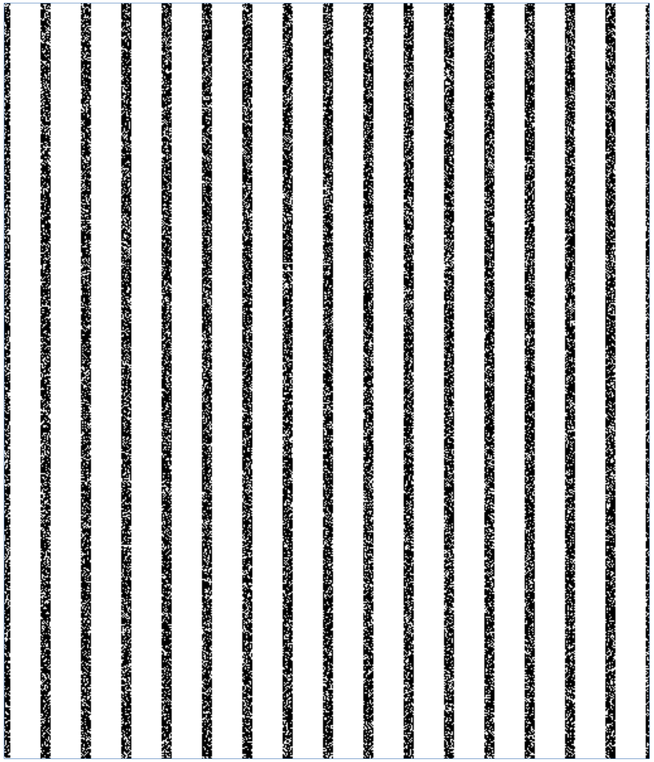
CBC and XTS change propagation

- **CBC** – cipher block chaining
  - ciphertext XOR with next block
- **XTS / XEX** (XOR encrypt XOR)
  - internally 2 keys
    - key for tweak
    - encryption key

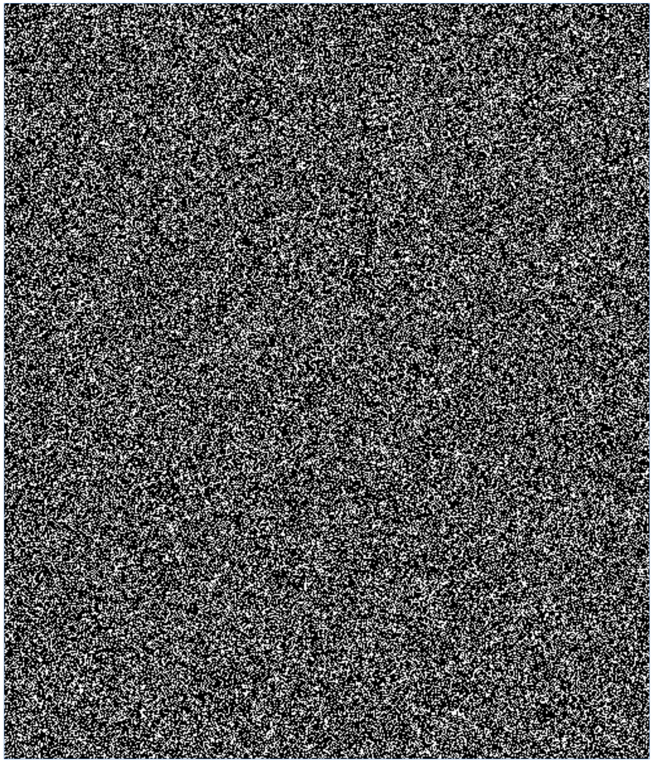


AES-XTS IV mode – sector# vs random

Every 64 byte changed (ciphertext differences)



IV is sector number



randomized IV

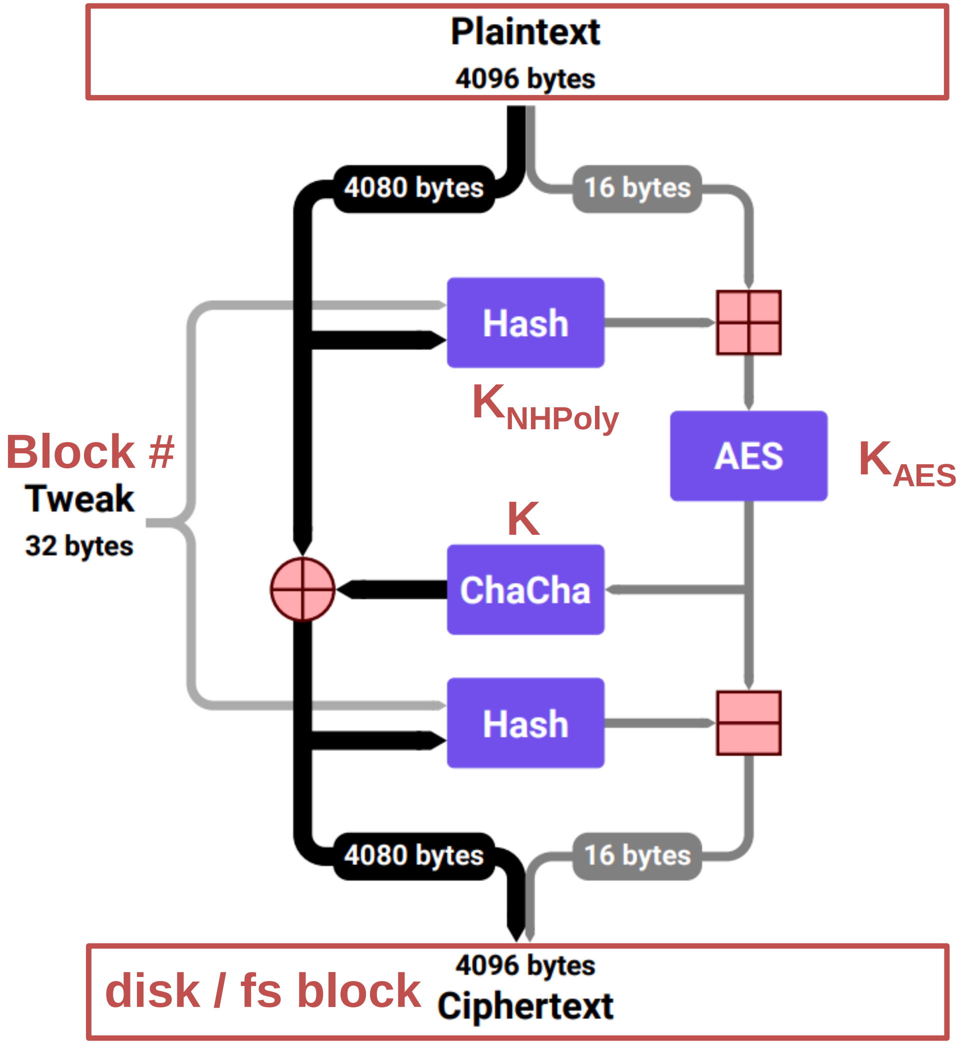
Adiantum

- Low-end mobile device disk / file encryption
- Wide "mode"

- HBSB composition:
  - Hash – NHPoly1305)
  - Block Cipher – AES
  - Stream Cipher – XChaCha12,20
  - Hash – NHPoly1305

- Key derivation

  $K_{AES} || K_{NHPoly}$ = XChaCha(K,1|0..0)



https://eprint.iacr.org/2018/720
https://security.googleblog.com/2019/02/introducing-adiantum-encryption-for.html

Steganography / deniable encryption

Plausible deniability:

existence of encrypted file/disk is deniable
if adversary cannot prove that it exists

Steganography

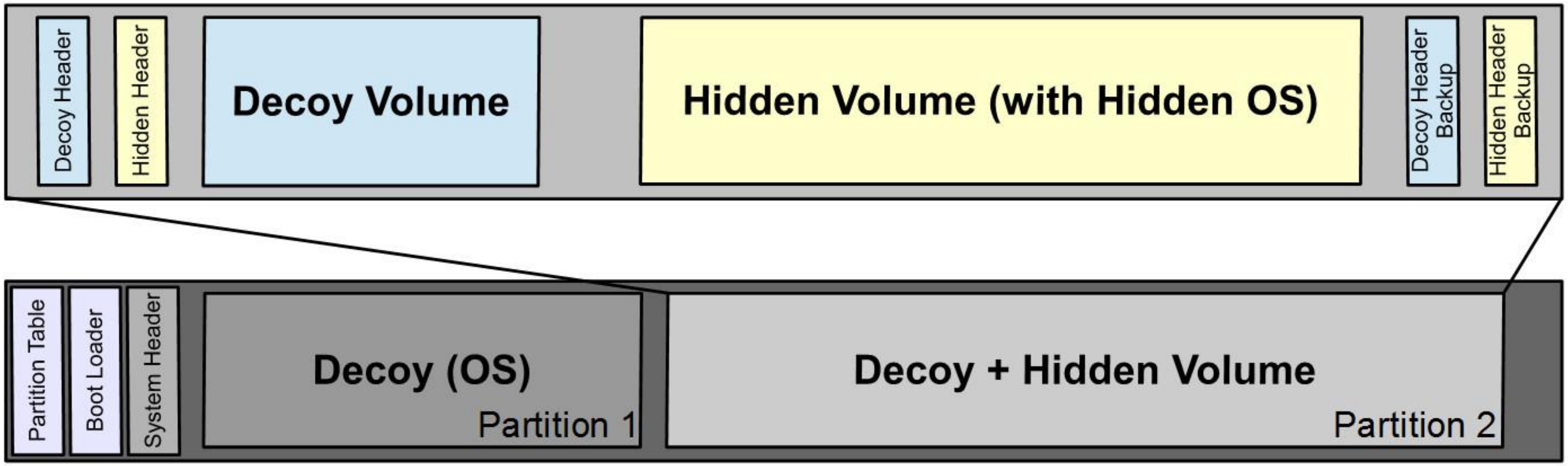
hiding data in another data object

Steganographic file-systems

Deniable disk encryption

Trivial example: VeraCrypt hidden disk

- FAT linear allocation
- Hide another disk in unallocated space



Deniable encryption problems

Side-channels

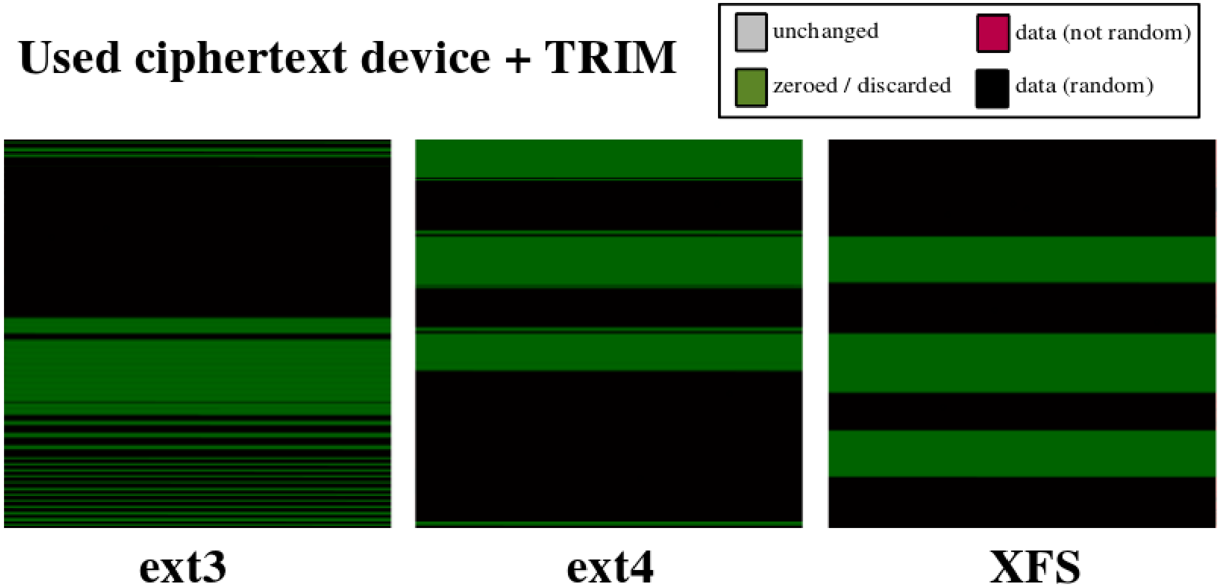
tracking activity that cannot be explained for decoy system

- Software: link to recently open documents, …
  Suspicious parameters (FAT), disabled TRIM, …
- Hardware: internal SSD block allocations
  (access to “unused” areas)

Incompatibility with new drives (TRIM)

TRIM / discard and encryption

- TRIM informs SSD drive about unused space
- Unused space is detectable
- Pattern recognition example
- Incompatible with deniable encryption



File and disk encryption

KEY MANAGEMENT

Key generation

Encryption key (~ Media Encryption Key – MEK)

- Used to encrypt device
  - change means complete reencryption
- Usually generated by a secure RNG

Unlocking key (~ Key Encryption Key – KEK)

- Independent key change (MEK remains the same)
- Can be derived from passphrase
  - PBKDF2 (Password Based Key Derivation)
  - scrypt, Argon2 (memory-hard KDFs)
- Can use key wrapping

Key storage

Outside of encrypted device / filesystem
- Another device, file, token, SmartCard, TPM, HSM
- On a key server (network)
- Protected by another key (KEK).

On the same disk (with encrypted data)
- Metadata on-disk – key slots
- Brute force and dictionary attack resistance

Integration with key management tools
- LDAP, Active Directory, ...

Combination of above

Key removal and recovery

Key removal (wipe of key) = data disposal

- intended (secure disk disposal)
- unintended (error) => complete lost of data

Key recovery

- trade-off between security and user-friendly approach
- metadata backups
- multiple metadata copies
- Key Escrow (key backup to different system)
- recovery key to regenerate encryption key

File and disk encryption

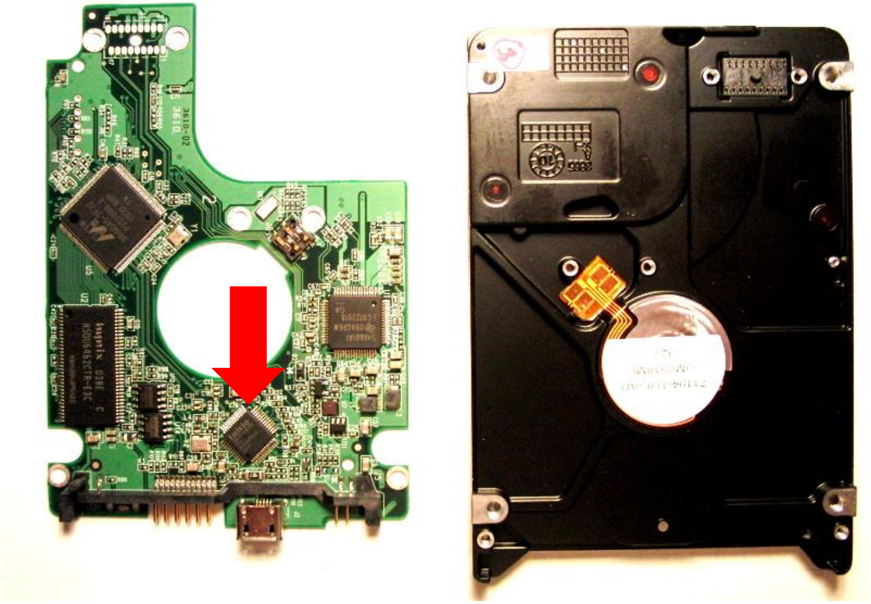
COMMON TOOLS

Examples of HW-based encryption

- **Self-encrypting drives (SED), OPAL standard**
  - Encryption on the same chip providing media access
- **Inline encryption**
  - HW Encryption, slots for keys (through OS context)
- **Chipset-based encryption**
  - Encryption on controller chip (e.g. USB bridge)
- **Hardware acceleration**
  - AES-NI, accelerators, ASICs, GPUs, …
- **Secure hardware / tokens**
  - HSM, TPM, SmartCards, ...

Examples of HW-based encryption

SATA disk
Encryption on USB-bridge



Examples of tools – filesystem encryption

Windows EFS

Linux

- **eCryptfs** – stacked encrypted file-system
- **fscrypt API** – support in ext4, F2FS, UBIFS

ZFS (legacy Solaris and Linux ports)

- supports GCM/CCM authenticated modes

Examples of tools – full disk encryption

Windows Bitlocker

- Optionally eDrive – self-encrypting drives
- Combination with secure boot and TPM

VeraCrypt

Linux LUKS / dm-crypt

MacOS FileVault

File and disk encryption

ATTACK EXAMPLES

Attacks always get better, they never get worse.

- **Against algorithm design**
  - wrongly used encryption mode
  - insufficient initialization vector
- **To implementation**
  - insufficient entropy (broken RNG)
  - weak derivation from weak passwords
  - side channels
- **Obtaining key or passphrase in open form**
  - Cold Boot
  - “Black bag analysis” - Malware, key-logger
  - social engineering
  - “Rubber-hose cryptoanalysis”

Integrity attacks

No integrity protection

- Inserted random block
  => undetected data corruption
- Inserted block from other part of disk
- Random error (RAM bit flip)
  => "silent data corruption"

Weak integrity protection

- Inserted previous content of (ciphertext) block
  => replay attack

FDE attacks – real-world examples

- Some chipsets use ECB mode
- Weak key derivation (brute-force possible)
- Trivial unlocking mode (1-bit password is ok/bad)
- Weak key-escrow (backup key in EEPROM, …)
- SED – switch power attacks
- SED – ransomware and unconfigured passphrase
- Cold boot – key in memory
- Key loggers
- Weak RNG (key is not random)

…

LAB

Laboratory – FDE attack examples

Basic understanding of some tools and hw

- VeraCrypt, LUKS, chip-based encryption

Scanning memory image for encryption key

- ColdBoot attack principle

Optional: flawed algorithm and watermarking

- Revealing TrueCrypt hidden disk existence (CBC)

HW key-logger attack