Perfectly Deniable Steganographic Disk Encryption

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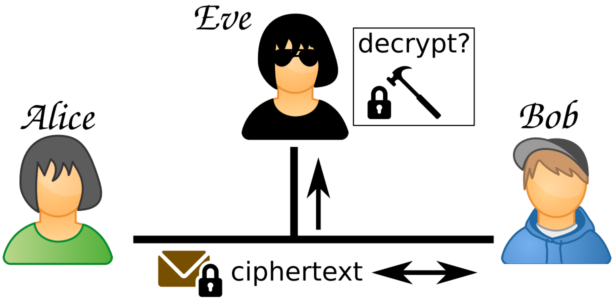
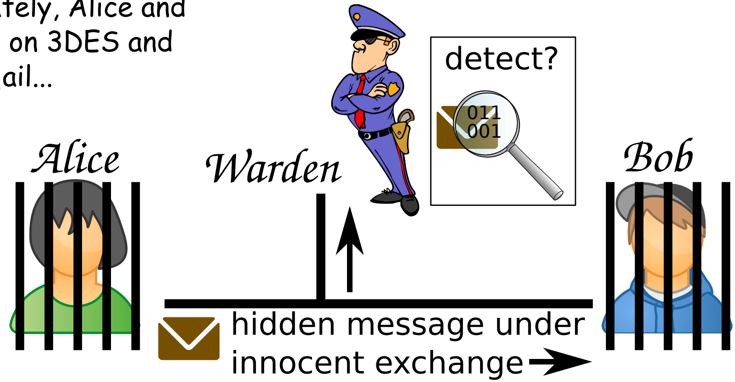
1. Overview
   - Steganography's history and modern-day importance
   - Critical appraisal of True/VeraCrypt hidden-volume/OS feature
2. Deniability Requirements
   - Essential characteristics of steganographic disk encryption
   - Technical requirements resulting from implementation
3. System Design I
   - Countering randomization & overwrites: *error correction & caching*
   - Concrete implementation of error correction and caching
4. System Design II
   - Overcoming steganography's catch 22: *a cascading bootstrap system*
   - Concrete Implementation
5. Forensic Considerations
   - Multi-snapshot imaging & FTL analysis

- ***Steganography*** or ***steg*** (literally "covered writing") dates back to antiquity. It boils down to hiding a message in an innocuous **cover**; it's a form of **covert communication**
- Cover can be a microdot (resembling a period), a JPEG image of kittens, or even human hair...
  - *Histories* (440 BC) recounts how Histiaeus had a servant's head shaved and scalp tattooed; he was sent off to deliver the secret message once his hair had regrown
  - We don't do this anymore...I think?
- Nowadays steganography is usually digital...it's faster than waiting for hair to regrow!



- Goals
  - Alice & Bob: Communicate through unbreakable ciphertext
  - Eve: Break Alice and Bob's encryption

Unfortunately, Alice and Bob relied on 3DES and landed in jail...



- New Goals
  - Alice & Bob: Exchange secret messages that cannot be detected
  - Warden: Detect the presence of secret messages in cover

- Protection of journalists and their sources
  - Some countries have real protections for the press; most don't
- Protection of human rights observers and NGO staff
  - Exfiltrating evidence of human rights abuses is risky; little chance violators observe search/seizure/self-incrimination norms
- Protection against industrial espionage at border crossings
  - Business travel often involves visits to countries that steal IP and monitor/control networks (e.g. ban VPN connections)
- Deep uncover work
  - Agents working undercover can infiltrate/exfiltrate/conceal information, even if they may be forced to surrender a password

Encryption is adequate when there's no risk of forced password disclosure.
For everything else, use steganography!

- Image/Video/Audio Steg (e.g. OpenStego, OpenPuff)
  - Hides information within e.g. lowest significant bit of pixels/samples
- 802.11 Wireless Steg (experimental)
  - Conceals data in ODFM symbols; as per 802.11 standard, some frames contain "random" data
- Disk Encryption/Filesystem Steg (e.g. StegFS, VeraCrypt)
  - Allows information to be secreted in unused disk space
- Radio-frequency Steg (e.g. spread spectrum)
  - Transmit a signal beneath the background ‘noise floor’

Note for later: these all require special software (or hardware)

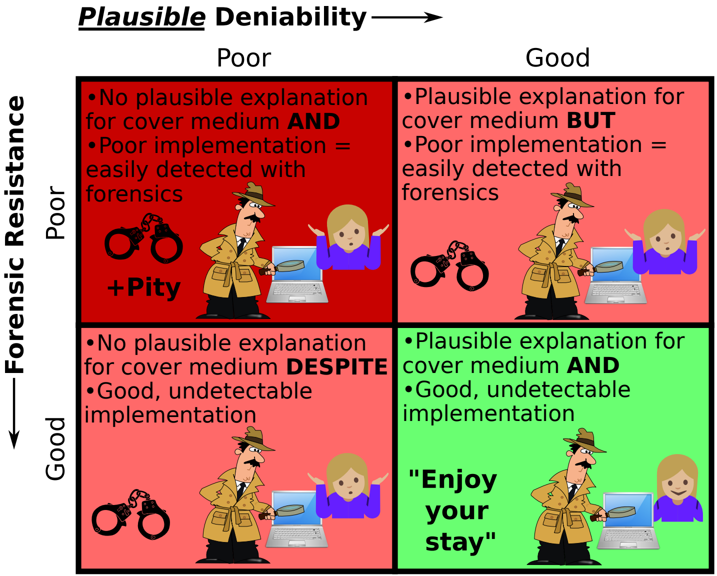
...possibly a problem?

1. Comparison of suspected file against known original
   - Using a cover file from Google images is asking for trouble...
2. Direct forensic analysis of (potential) cover media
   - Embedding hidden information into e.g. a JPEG image often disturbs the medium's statistical characteristics
   - Cat and mouse game between steganographic and steganalytic software's statistical models (more sophisticated is better)
3. Forensic analysis of a computer system suspected of being used for steganographic activities
   - Searches for indirect evidence of steganography *use*
   - Might involve examination of temporary files, log files, swap space, etc.

The first two are classified as **steganalysis**

Two Magical Ingredients

- Effective steganography depends on combining **two** magical ingredients
- Alone, neither **forensic resistance** nor **plausible deniability** offer effective protection

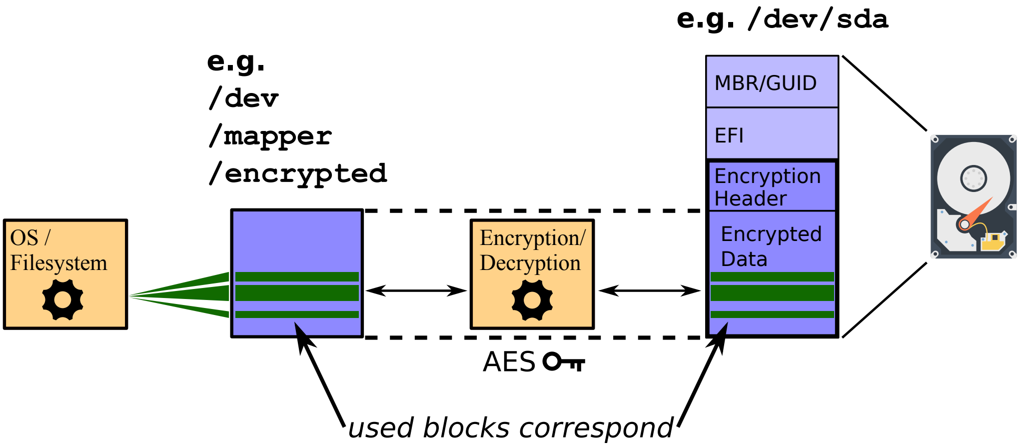


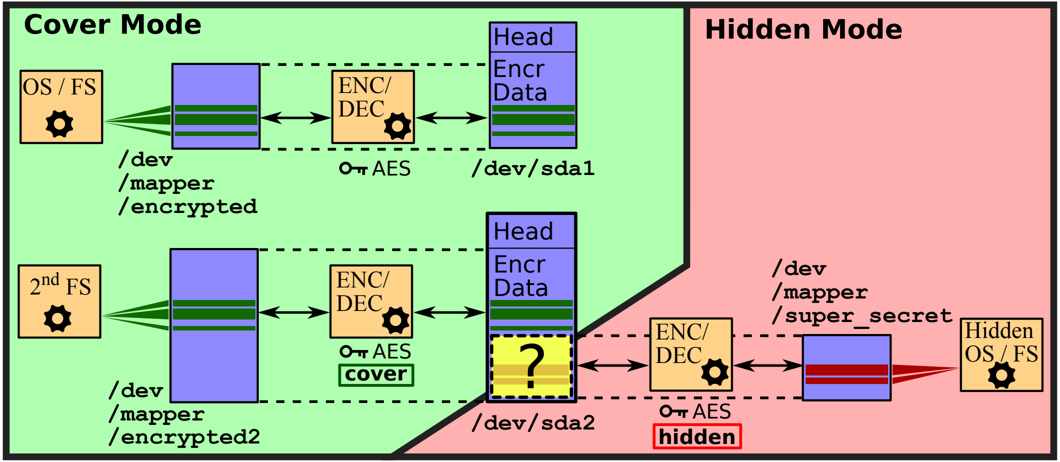
Some Colorful History...

c. 1997 → 2004 → 2013

VeraCrypt

Block-Level Encryption Overview (VeraCrypt and LUKS/dm-crypt)





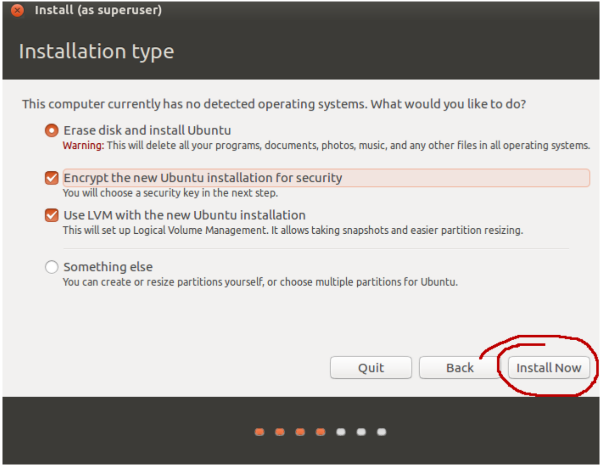
- Forensic security is high...**but**
- Is it *plausible* to have a second frozen partition...with TRIM disabled... on top of using VeraCrypt? Is "**?**" random init data or something else?

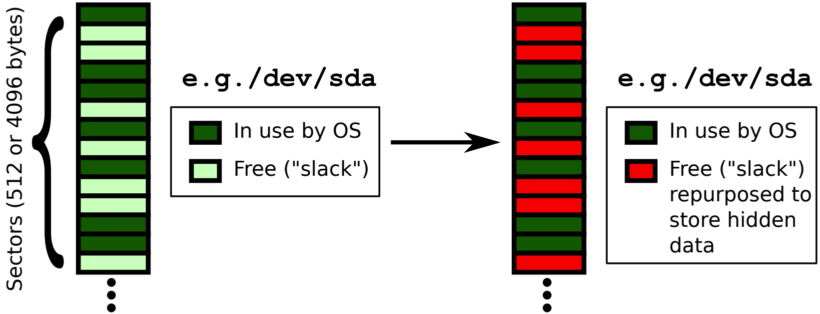
> **Possible Explanations for Existence of Two VeraCrypt Partitions on Single Drive**
> An adversary might ask why you created two VeraCrypt-encrypted partitions on a single drive...you can provide, for example, one of the following explanations:
>
> [*A number of canned explanations that are not very convincing*]

from www.veracrypt.fr/en/VeraCrypt Hidden Operating System.html

1. **Forensics:** Encrypted hidden data should masquerade as legitimate random data; hidden system should never touch cover system (e.g. swap)

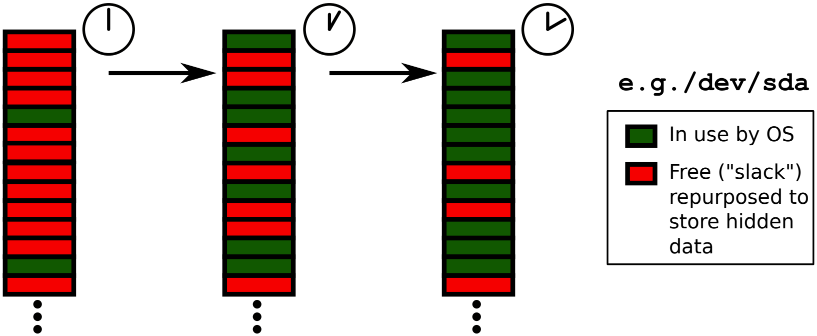
2. **Deniability:** Cover system (e.g. Ubuntu) should appear *completely normal*. **<u>There should be NO incriminating software visible</u>**. The cover system should appear, *bit-for-bit*, as if it were installed with default settings*





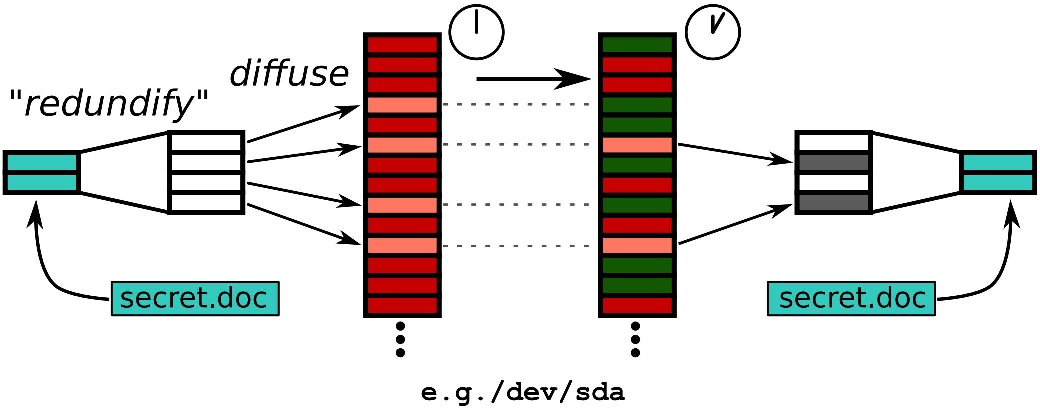
- In a system with FDE, slack space has been initialized with random data
- This random data can actually be the ciphertext of hidden data
- Similar to VC hidden partition, **but no** restrictions on cover system

Consequence 1: Concealed Data is Damaged

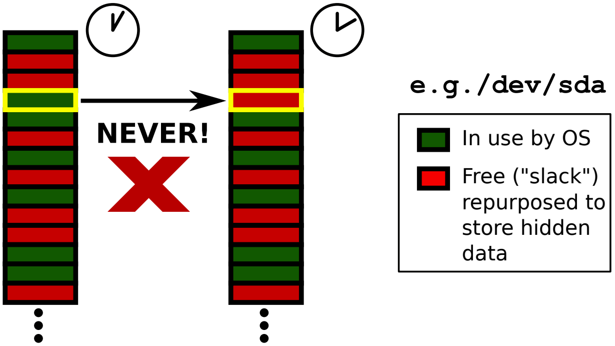


- Ongoing overwrites continually damage the underlying hidden data
- **But** for large hard drives, most slack space may never be overwritten!
- As the cover system (a default installation of Linux) acts completely normally, **there is nothing suspicious about this picture**

Consequence 1.1: Concealed Data is Stored Diffused/Redundantly



- To protect "secret.doc", add redundancy and diffuse across slack space
- To recover "secret.doc", collect intact sectors and extract original file



- Sectors in current or previous use by the cover system must never be overwritten—This would corrupt cover OS and/or suggest that something fishy is going on
- **Hidden system must reliably detect sectors used by cover OS**

Consequence 3: Kernel Module is Incriminating

Problem: Cover system overwrites hidden data

Solution: Error Correction (EC) & Randomization

Problem: Randomization & EC kill performance

Solution: Kernel module with deep cache that mitigates EC and randomization

Problem: Hidden system must respect cover-system overwrites

Solution: Sector hash checks by a kernel module

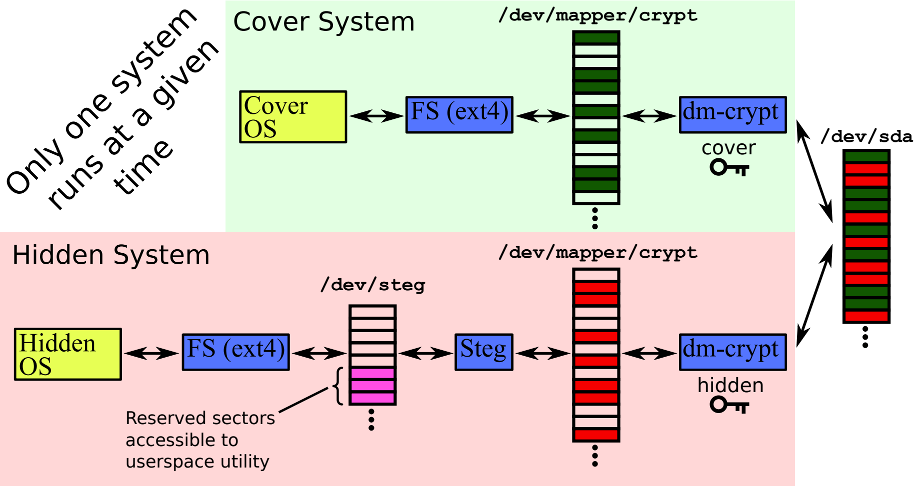
Problem: Kernel module is really incriminating!

Solution: Have the system ***hide itself***!

The problem factors into **two relatively independent sub-problems**:

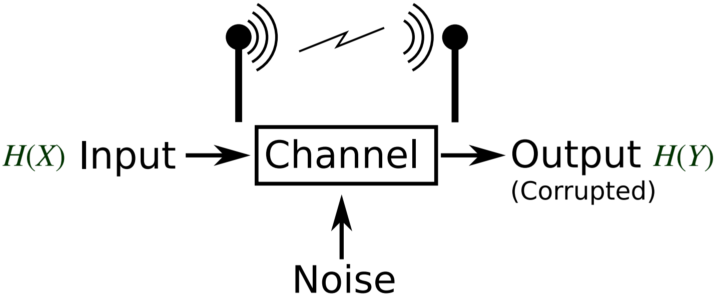
1. Develop a kernel module that does error correction, randomization, caching, and detection of cover system writes
2. Develop a set of tools that hide, extract, and load the kernel module in the most automated way possible (and without leaving a forensic trace)

- For flexibility, hidden data reads/writes should be to a **block device**



- Blue boxes = kernel space; ext4 & device names are just examples

Primer on Information Theory and Communication Channels



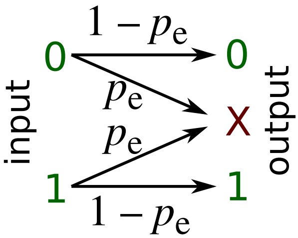
$$I(Y;X) = H(X) - H(Y|X)$$

- The **mutual information**, $I(Y;X)$, is related to the **channel capacity**
- For example, given a binary alphabet, a transmission might look like:

0	1	1	0	1	0	1	0	→	0	1	**0**	0	1	**1**	1	0

From General Channels to the Binary Erasure Channel

- Many channel models exists:
  - Input/output symbols from discrete or continuous alphabets
  - Noise can be many forms (e.g. white Gaussian, bit flips etc.)
  - Channel noise may also take the form of *erasures*
- Designating p_e as the probability of erasure, the **Binary Erasure Channel** can be modeled as $\Longrightarrow$
  - X denotes erasure
  - Mental note for later: p_e is assumed constant

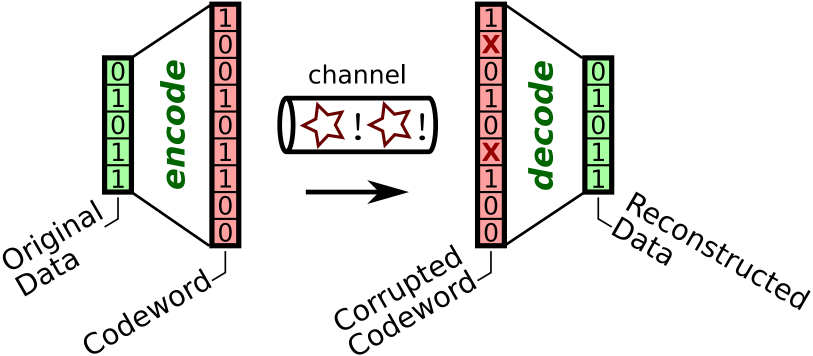


- Transmission through a binary erasure channel might look like:

0	1	1	0	1	0	1	0

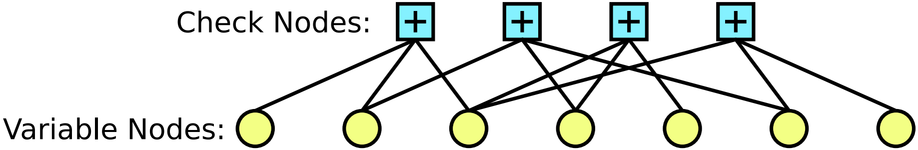
$\longrightarrow$

0	1	X	0	1	X	1	0



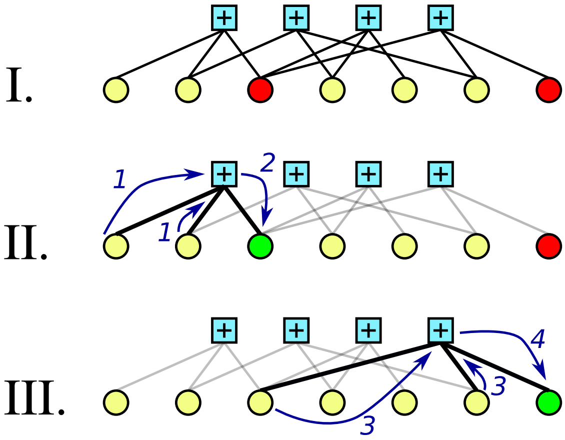
- Basic idea: Add highly interwoven redundancy to correct most errors
- **Coding rate** = size(data) / size(codeword)
- If the code is properly constructed for the channel, complete error correction should almost always be possible
- There should not be any more redundancy than is necessary

- An LDPC code can be described by its **Tanner graph**:

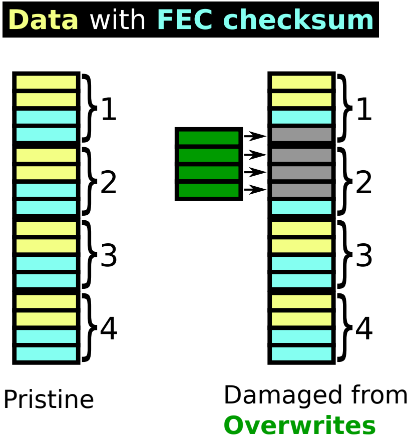


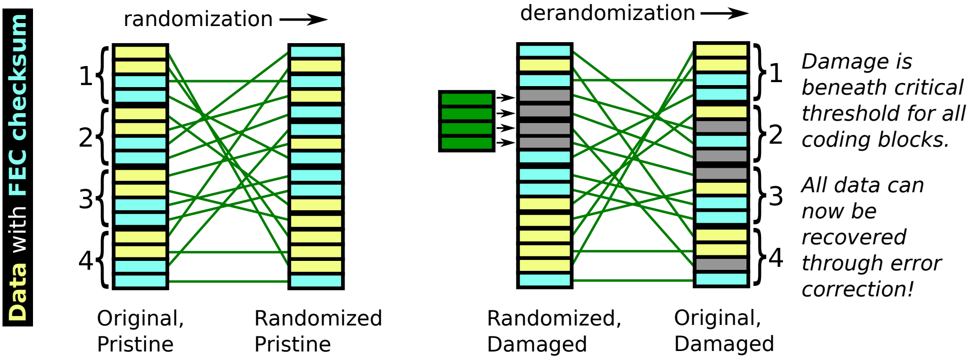
- Nodes belong to an additive group (for GF(2^n), "+" is just XOR)
- *Regular* (*Irregular*) codes have variable nodes of (non-)fixed degree
- A codeword might look like:

- Decoding employs extremely fast **Belief Propagation**
- Residual errors *may* be correctable with Gaussian elimination (albeit at much reduced dimensionality)

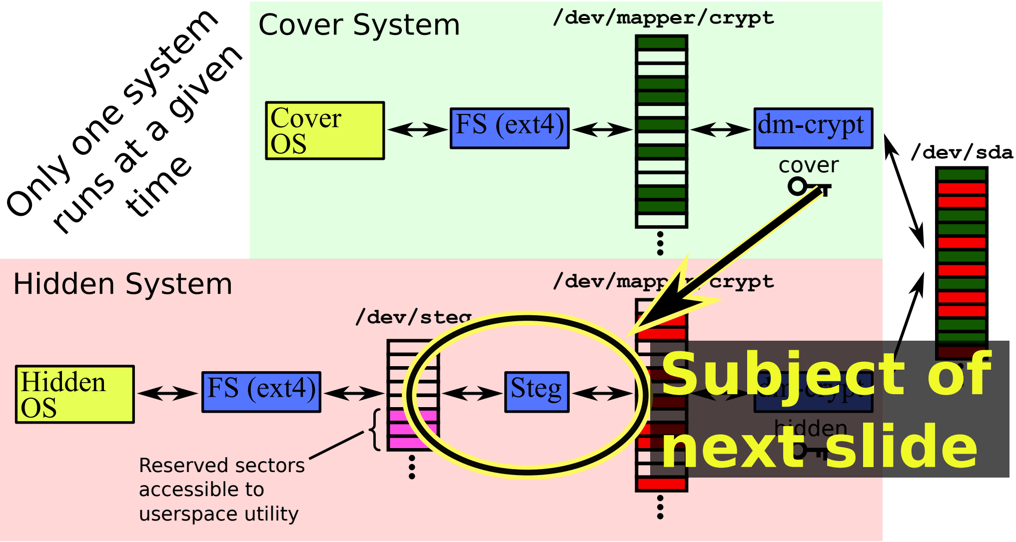


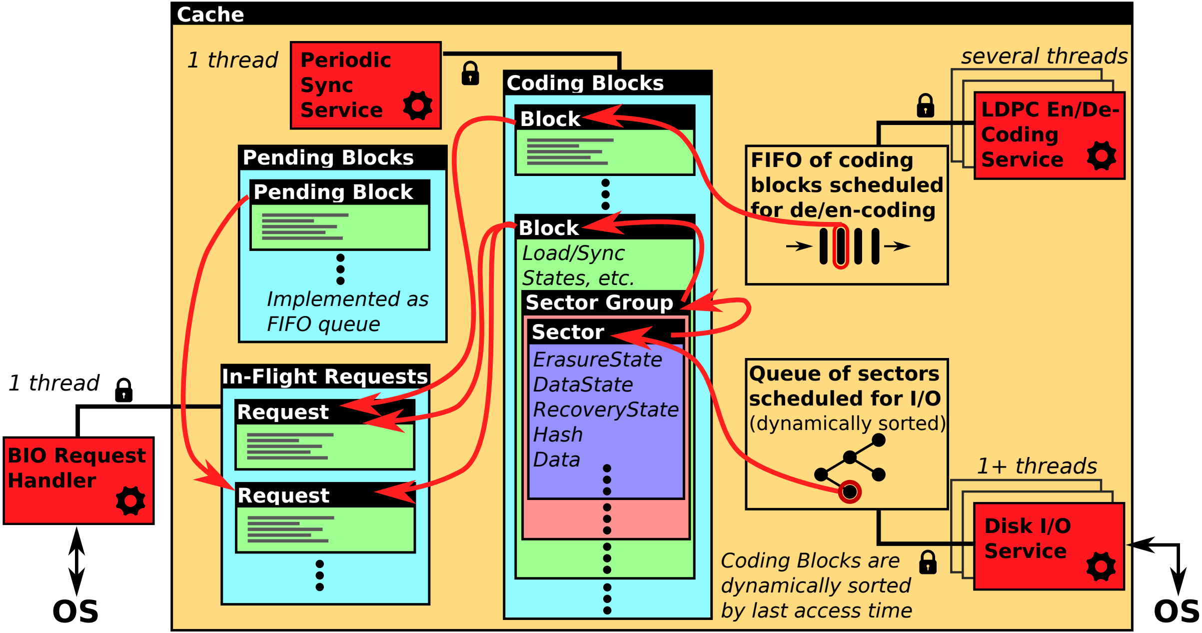
- Data is stored on the underlying device in multiple independent **coding blocks** that include redundancy for error correction
- A small number of overwrites might irrecoverably damage a coding block if its spatial arrangement is statistically similar to the overwriting process
- E.g. Coding block 1 is damaged but recoverable; coding block 2 cannot be recovered





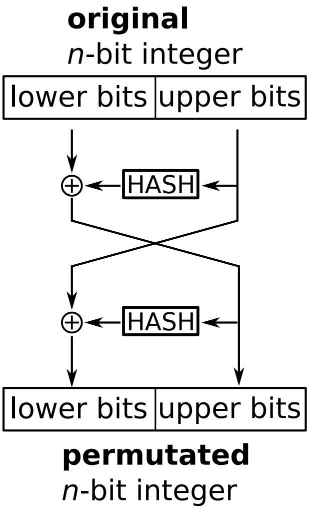
- Randomization of data **is equivalent to randomization of error**
- This means the p_e (probability of erasure of a given datum) **is constant across all data**
- <u>System is now described perfectly as a Binary Erasure Channel</u>!


Only one system runs at a given time
Cover System
/dev/mapper/crypt
Cover OS
FS (ext4)
dm-crypt
cover
/dev/sda
Hidden System
/dev/mapp
crypt
/dev/steg
Hidden OS
FS (ext4)
Steg
hidden
Reserved sectors accessible to userspace utility
Subject of next slide

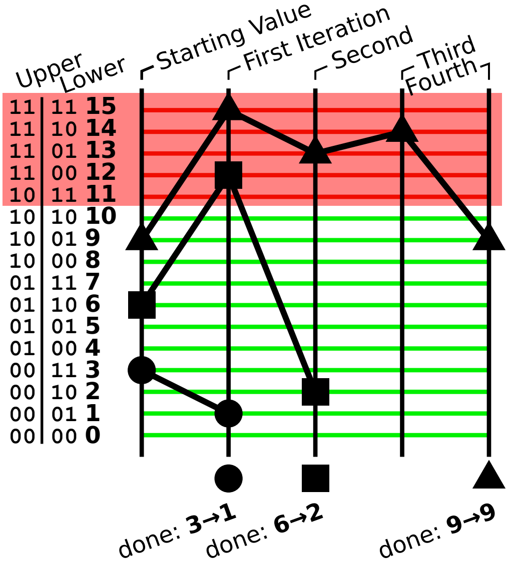


Cache
1 thread
Periodic Sync Service
Coding Blocks
Block
Pending Blocks
Pending Block
Implemented as FIFO queue
Block
Load/Sync States, etc.
Sector Group
Sector
ErasureState
DataState
RecoveryState
Hash
Data
In-Flight Requests
Request
Request
1 thread
BIO Request Handler
OS
several threads
LDPC En/De-Coding Service
FIFO of coding blocks scheduled for de/en-coding
Queue of sectors scheduled for I/O (dynamically sorted)
1+ threads
Disk I/O Service
Coding Blocks are dynamically sorted by last access time
OS

- Require an injective (1:1) function mapping each sector pseudorandomly to another
  $I : \{1, \ldots, n\} \rightarrow_{pseudorand} \{1, \ldots, n\}$
  - Can't use a hash since it's not 1:1
  - Can't use LUT (2 TB drive = 16 GB LUT!)
  - Can't use e.g. AES CTR mode, as block size is fixed at 128 bits ($n = 2^{128}$)
- Need a flexible n that is not much bigger than actual number of sectors of given hardware
- Use a **Feistel network**!
- Two rounds and a simple hash is fine; "adversary" is erasure noise, not a cryptanalyst
- However, (balanced) Feistel network is still some power of 4....if we had 1777 sectors?



- E.g. assume we require $\{0, \ldots, 10\} \rightarrow_{pseudorand} \{0, \ldots, 10\}$ (i.e. 11 sectors)
- Next largest balanced Feistel network will implement $\{0, \ldots, 15\} \rightarrow_{pseudorand} \{0, \ldots, 15\}$ (i.e. 16 instead)
- That's ok; **repeated iterations that start in $\{0, \ldots, 10\}$ will *__always__* return to $\{0, \ldots, 10\}$**
- Usually this process is very fast; *average* computational complexity is constant



HASH	DATA
32B	*480B = 3840b*

erasure = $[hash(\text{DATA}) \mathrel{!=} \text{HASH}]$

(boolean)

- Error correction are implemented as concatenation of two regular LDPC codes with 480-byte integer nodes belonging to GF(2^{3840})
- Codes found via computational search that excised 2-, 4-, and 6- cycles
- Final codes were verified with binary erasure channel simulations and were found to be reasonably close to capacity achieving
- Codes can easily be modified; concatenation has object-oriented implementation; a single coding block is $\sim$ 5 MB

Code	Regularity	#Check	#Variable	Deg Check	Rate
Outer	Regular	5,100	5,100	6	50%
Inner	Regular	100	5,000	300	98%
Combined	N/A	N/A	N/A	N/A	**49%**

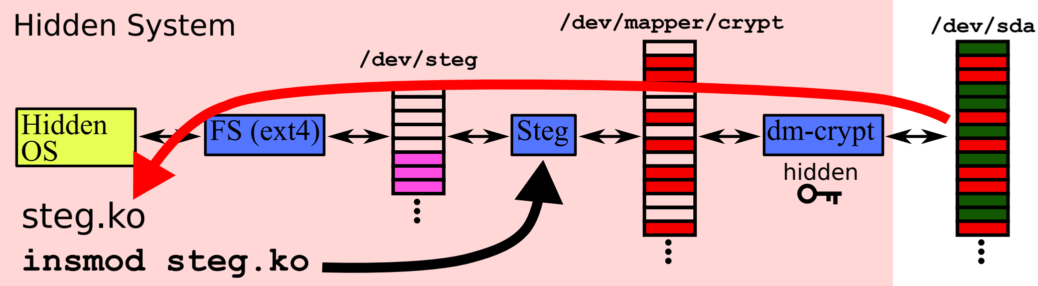
- Default cache size is 320 coding blocks
- Cache is periodically synced to disk when idle
- Encoding/Decoding done in place by multiple concurrent threads
- Coding blocks have two status variables, **`load_state`** and **`sync_state`** that form 19-state space ($\mathbb{S}_{\mathrm{CB}}$) and "dirtiness" fcns
- Complete space is $\mathbb{S}_{\mathrm{CB}}^{320} \times \mathbb{S}_{\mathrm{Q}}$, where $\mathbb{S}_{\mathrm{Q}}$ captures queued req's
- Very complex supervisory logic optimizes data access patterns and services requests as quickly as possible while minimizing accesses to base block device

- Multiple coding blocks can (un)load simultaneously; data reads /writes are interleaved via downstream elevator scheduler(s)
- Debugging multithreaded kernel-space asynchronous finite-state machine was a nightmare (what's the LD50 of caffeine again?)

Performance & SSD / HDD Variants

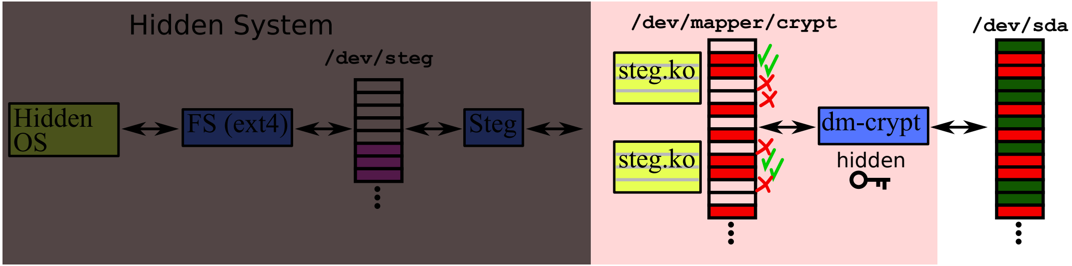
- Steg kernel module can be customized with extensive parameters that tune performance characteristics
- Some parameters, like SECTORS_PER_GROUP have many derivative parameters
- Makefile allows selection between two predefined parameter sets:
  - **SSD**: Assigns low value to SECTORS_PER_GROUP resulting in greater randomization of data and improved error correction
  - **HDD**: Assigns a higher value to SECTORS_PER_GROUP resulting in more "clumpy" data that is less randomized but generates fewer random seeks
- So what does typical performance look like?

Normal 4x PCIE NVME machine > **Steg running on 4x PCIE NVME machine** > Normal HDD machine > **Steg running on HDD machine** > Windows 95 machine needing a defrag



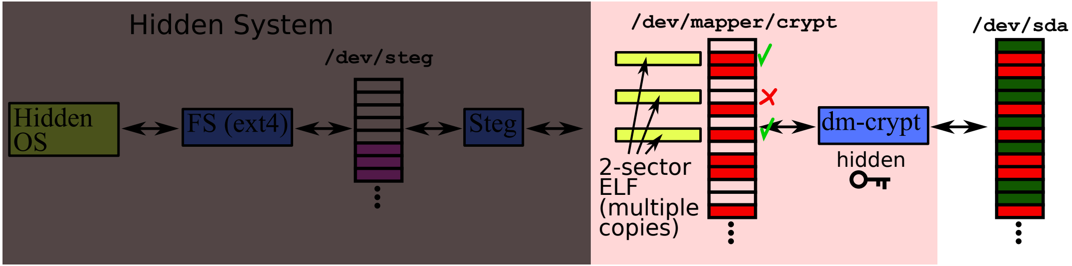
- If we had a system that was *already running*, it would be simple:
  1. Retrieve steg.ko (it's just a file on the hidden system FS)
  2. Load steg.ko into kernel with e.g. **`insmod`**
- If only things were so simple...(neverminding technicalities with FS)
- **How do we get around this catch 22?**

Leaving Aside the Steg LKM and Hidden System for a Moment...



- *Could we store steg.ko LKM directly on the mapped crypt device?*
  - Problem: It will likely be at least partly overwritten, as LKM is ∼MB
  - Especially true for big files, **as *few* large contiguous regions will exist under the cover system, even if its disk use is sparse**
- *Could we just store the steg.ko kernel multiple times?*
  - Problem: Probability of a surviving intact copy might still be small
  - Problem: Even if one exists, how do we find it? Repeatedly try running corrupted code in kernel space? (rhetorical question)

What we could do instead...(i.e. a recursive bootstrap system)



- Store multiple copies of a **very short** executable at regular intervals
  - For lightly/moderately used cover, any one copy is likely intact and will execute perfectly! *Execute in userspace* (try again if needed)
- What can you do with a 1-kB executable? ***Lots!!***
  1. Scan mapped crypt device for other shards of intact information; do rudimentary error correction to recover original shards
  2. Assemble shards into a new (much bigger) ELF and execute
  3. Repeat...each time with more sophisticated error correction

Overview of Hidden System Boot Sequence

User involvement

1. ***Cover*** Bootloader e.g. **GRUB**

   A user hits 'e' and adds 'break' to kernel command line

2. ***Cover*** Early Userspace **$**

   Using cryptsetup, a user copies over a 2-sector file to tmpfs and executes it

3. ELF **Primary Bootstrap**

   With primitive error correction, the primary bootstrap extracts and executes a larger, secondary bootstrap

4. ELF **Secondary Bootstrap**

   With sophisticated error correction, the secondary bootstrap extracts and loads, via kexec, a replacement kernel and initramfs

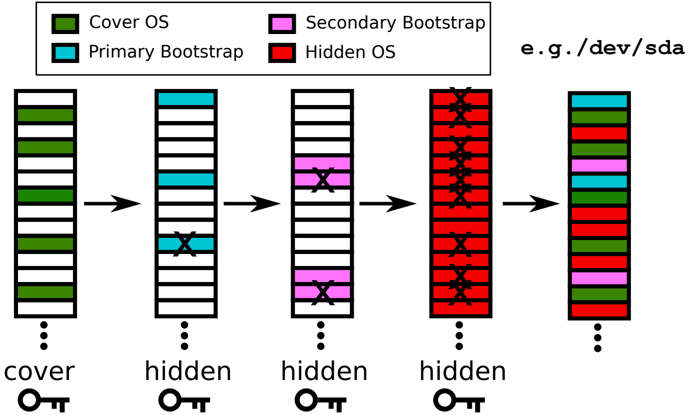
5. ***Hidden*** Early Userspace

   *The hidden system's cryptographic mapping and **steg** kernel module is loaded from a custom hook from within the hidden system's early userspace environment*

6. ***Hidden*** Final Target (e.g. Graphical)

   Completely functional system; `/etc/fstab` has `/dev/steg` entry instead of e.g. `/dev/sda1`

Just a thought...could this be automated by rolling some limited functionality into cryptsetup?

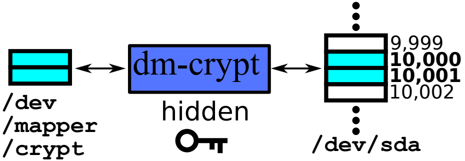


- Each of a layer's utilized blocks overwrite those to its right
- Note ascending sophistication of error correction from left to right (none, user repetition, automated repetition, LDPC)

Early Userspace Bootstrap Process: Launching Primary Bootstrap

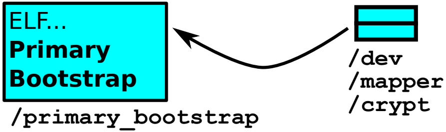
①

```
$cryptsetup open --type=plain --size=2
--skip=10000 --offset=10000 /dev/sda crypt
```



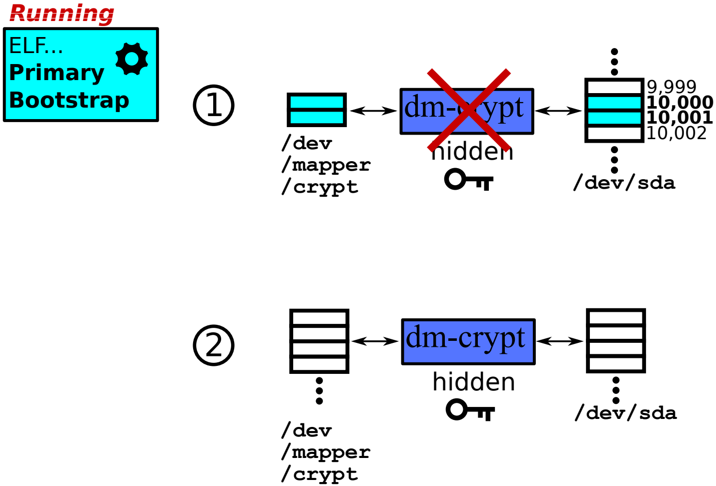
②

```
$cp /dev/mapper/crypt /steg (this is tmpfs!)
$chmod +x /steg
$/steg
```



Upon running **`/steg`**, *the user's job is done. Note* **`/steg`** *is only 1024 Bytes*

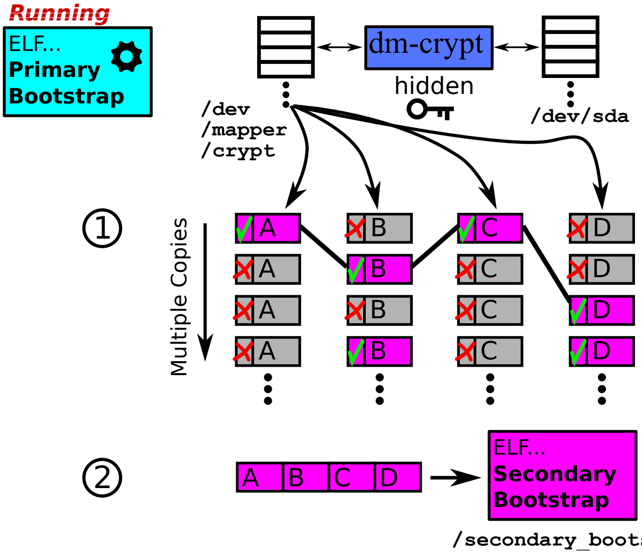
Early Userspace Bootstrap Process: Primary Bootstrap Ops (1)



1. Take down old, 2-sector crypto mapping (no longer needed)

2. Re-establish crypto mapping under same key but for **entire** sector range (i.e. no "size" parameter in cryptsetup)

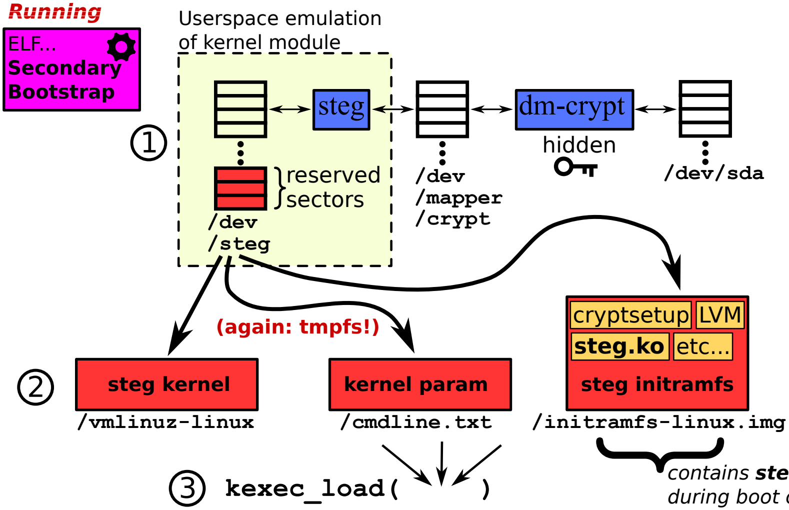
Early Userspace Bootstrap Process: Primary Bootstrap Ops (2)



1. Extract shards of a *new* ELF image. Each shard was stored multiple times at pseudo-random locations to allow the error correction done here. Compare each shard copy's header against magic number: ✓ = pass, ✗ = fail

2. Concatenate good copies of shards (using the non-header portion) to generate new ELF, which is about 350 kB. When done, **transfer control to new ELF via `execve()` system call**

Early Userspace Bootstrap Process: Secondary Bootstrap Ops



1. Establish userspace "kernel module" mapping that exposes "reserved sectors" to the secondary bootstrap program
2. Extract three files from reserved sectors and save them to tmpfs
3. Soft boot into hidden system via **kexec_load** system call parameterized with three extracted files

Kernel & initramfs are many MB—hence the need for LDPC error correction

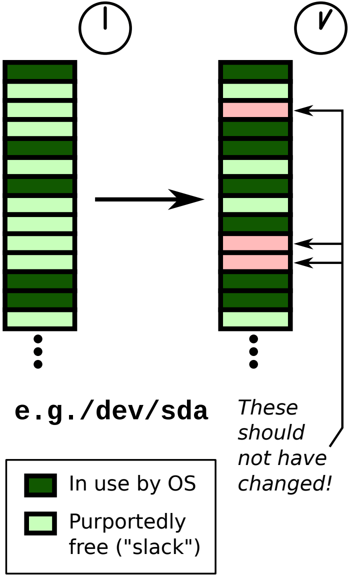
Hidden System Boot: Wrapping Up...

- Hidden system initramfs contains the steganographic kernel module
- Significant waypoints within *hidden system* early userspace boot:
  1. **Establish hidden-perspective cryptographic mapping** (e.g. `/dev/sda -> /dev/mapper/crypt`) with cryptsetup (password can be stored in hidden system initramfs)
  2. **Establish steganographic mapping** (e.g. `/dev/mapper/crypt -> /dev/steg`) by loading steganographic loadable kernel module
- Typical hidden system `/etc/fstab` will associate `/` with `/dev/steg`.
- Sundry points
  - Primary bootstrap (1024 Bytes) contains primitive EC functionality and was hand coded in assembly with *lots* of cheats/optimizations
  - Secondary bootstrap ($\sim$ 350 kB) contains heavyweight LDPC functionality and was written in C/C++ with all libraries linked in, symbols stripped out, and compressed with UPX

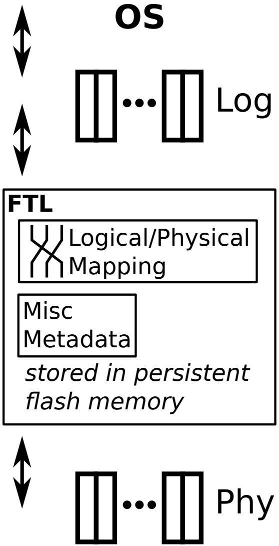
Final Points on Software Development

- Languages used: Assembly, C, C++, Make, KMake
- $\sim$ 30,000 lines of code spanning main kernel module, userspace utilities (for installation, diagnostics, etc.), and various components of bootstrap system
- $\sim$ 180 class definitions
- $\sim$ 900 functions/methods
- Extensive validation of cover system preservation by hidden system
- Seems to function well; no instability or data corruption observed
- Tested with various combinations of Arch and Ubuntu
- Confirmed that VirtualBox/Windows works very well on hidden system

- Ongoing use of the hidden system will change the data in the slack space of the cover system
- Differential analysis of slack space between temporally separated snapshots may reveal changes indicative of steganography use
- Countermeasures:
  - Cease all hidden system use after first imaging
  - Reinstall entire system if allowed by cover story



- SSDs maintain ever-changing mappings between logical/physical sectors—the FTL
- FTL also contains metadata on previous errors, read and write operations, etc.
- Statistical FTL analysis may uncover historical access patterns that implicate steganography
- Disabling TRIM is suspicious
- Countermeasures:
  - Use magnetic storage (best)
  - Put hidden OS in cover swap (default no TRIM)
  - Re-flash SSD firmware with special software from hidden system to cover tracks (expensive)
  - SSD firmware is costly and time consuming to reverse engineer—exploit this!



1. **Steganography software can recursively hide itself**
   - Need to download/possess incriminating software is obviated
   - Forensic risk can be eliminated*
2. **Russian doll steganography is made much easier**
   - Need to use an incriminating 802.11 steg communications tool? Infiltrating this tool into a hostile location is easy...
3. **Open-channel SSDs will enable physics-based steg**
   - Entire new avenues of steg are on the horizon

- **Insight into steganography use may go darker**, variously affecting journalists, NGOs, those tasked with organizational security (e.g. ISOs), law enforcement, and intelligence.
- Journalists/NGOs may gain better opsec; OTOH, organizations should consider proactive response and SSD forensics development.