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SMA CYBER Sector

Practical Cryptographic Key Recovery

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Outline

- **Introduction**
- **Targets**
- **Current Methods**
- **Tool Marks**
- **Example - BitLocker**
- **Conclusion**

Targets

- Documented Open Source
  - TrueCrypt
- Undocumented Open Source
  - PGP Whole Disk Encryption
  - http://www.pgp.com/downloads/sourcecode/
- Documented Closed Source
  - BitLocker Drive Encryption*
- Undocumented Closed Source
  - PointSec
  - Previously unseen tools

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Current Methods

- **Brute Force**
  - **Try every block of bytes as possible key**
  - **"Last resort of the incompetent"**
  - **See "Linear Scan" paper by Hargreaves and Chivers**
  - **Doesn't work for split keys**

Current Methods

- **Key Schedule Search**
  - **Better brute force**
  - **Really identifying data that is not *a key schedule***
  - ***See "Cold Boot" paper by Halderman et al.***

Current Methods

- **Source code analysis**
  - **Requires elbow grease**
  - **Can't be automated**
  - **Works great**
  - **May have to update for each version**
  - **See "Volatools" paper by Walters and Petroni, BlackHat Federal 2007**

Tool Marks

Image courtesy Flickr user grendelkhan, http://flickr.com/photos/grendelkhan/118876699/

- **Marks specific to individual tools**
- **Associated with physical forensics**

Tool Marks

- **Were the screwdrivers found in the suspect's house used on the screws found on the bank vault?**

Image courtesy Flickr user Uwe Hermann, http://flickr.com/photos/uwehermann/92145964/sizes/m/

Computer Forensics Tool Marks

- **Anything detectable that software stores in RAM or on disk that identifies the tool in question**
  - **Most Recently Used lists**
  - **Header and footer carving**
  - **Registry keys left after program removed**
  - **Preferences files in user directories**
  - **Wiping programs leave traces behind**

Cryptographic Tool Marks

- **Hard to detect the keys themselves**
  - **Should be random**
- **Can detect the cryptographic tool itself**
  - **Programs**
  - **Drivers**
  - **Mounted volumes**
- **Can detect the structure surrounding the keys**

BitLocker Drive Encryption

- Full Volume Encryption bundled with Windows Vista Ultimate
- Uses 128 bit AES-CBC + Elephant diffuser
  - Can configure for 256 bit and/or without diffuser
- Crypto developed by Niels Ferguson
  - also wrote Twofish, Helix, Fortuna RNG, CCM mode
  - Uses AES-CCM for key management
- Actual encryption work is done with 512 bit Full Volume Encryption Key (FVEK)
  - Key is 512 bits regardless of mode being used

BitLocker Drive Encryption

- **I am not aware of any backdoors in BitLocker Drive Encryption**
- **You cannot access a protected volume without the FVEK**

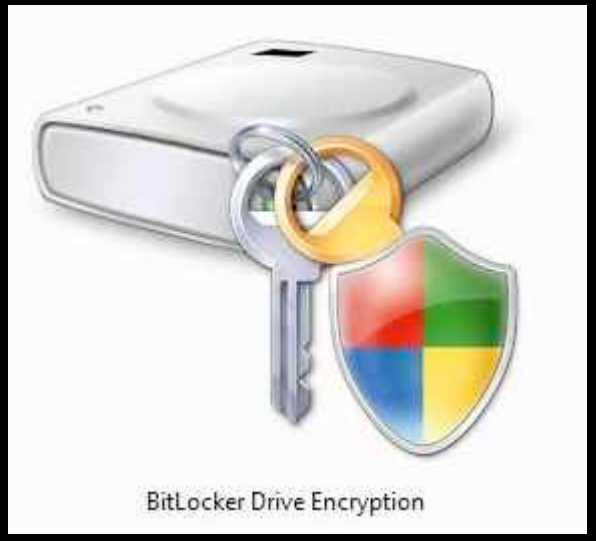

Image courtesy of the Microsoft Corporation.

BitLocker Drive Encryption is a registered trademark of the Microsoft Corporation.

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BitLocker Drive Encryption

- Good documentation, but not complete
  - Key management systems not described
  - No implementation of elephant provided
- Reverse engineered by Kumar and Kumar
  - Published paper, linux driver to mount protected volumes
  - http://www.nvlabs.in/node/9

BitLocker Drive Encryption

- **Brute Force works**
  - **FVEK is in RAM**
- **Key schedule search works**
  - **Finds several schedules**
  - **Two of the keys make up the FVEK**
    - **Some assembly required**
- **Source code analysis**
  - **Not an option for most of us**

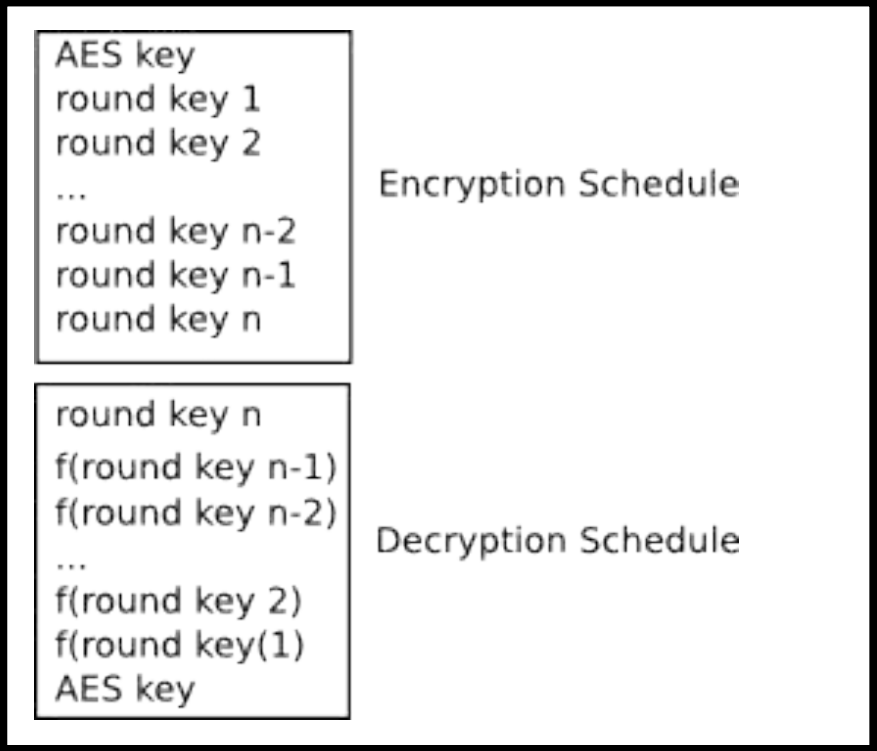
BitLocker Tool Marks

- **BitLocker AES key schedules**
  - **Several schedules in memory at any given time**
  - **Some bits of FVEK used to generate sector keys**
  - **Other bits of FVEK used to encrypt/decrypt data**
  - **In default mode, some bits unused**

Offset	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
00000000	3F	26	C8	B5	FF	87	47	B1	D5	26	12	43	EC	CD	78	C6
00000010	D5	09	AF	19	D1	5A	10	03	B5	4D	1B	73	0E	EC	0A	93
00000020	7A	16	05	EB	54	9F	39	1C	2E	5D	6A	DB	BC	67	C2	36
00000030	1C	3D	F3	60	AF	A1	EB	6F	E4	47	B2	E3	A5	B5	38	D9

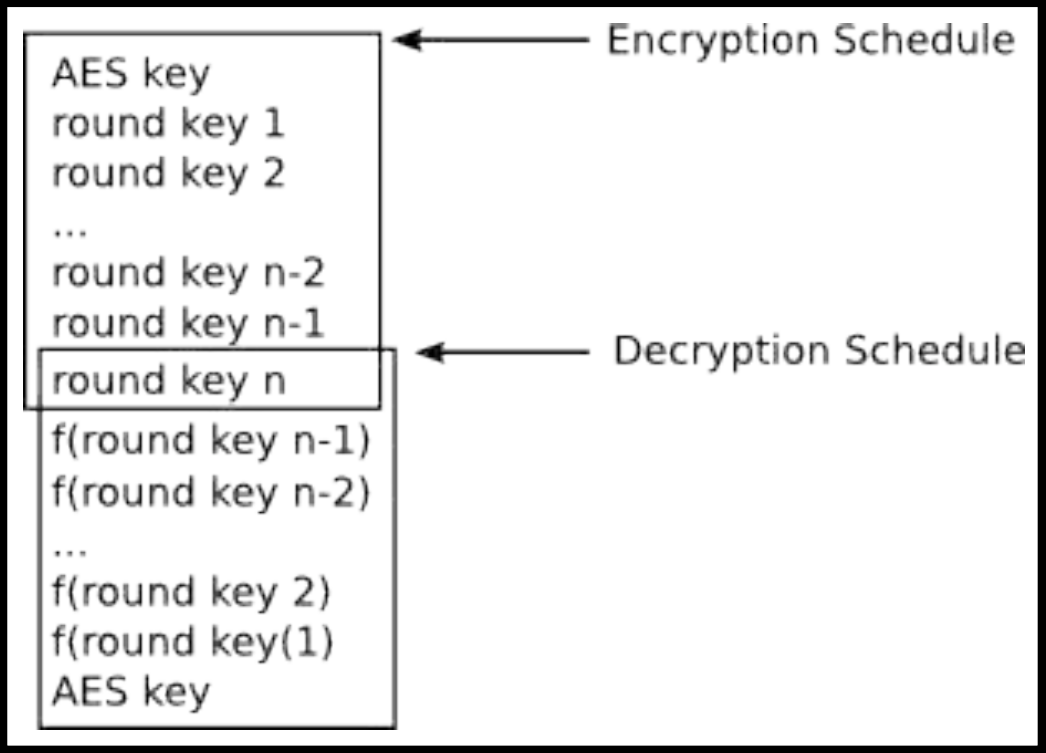
BitLocker Tool Marks

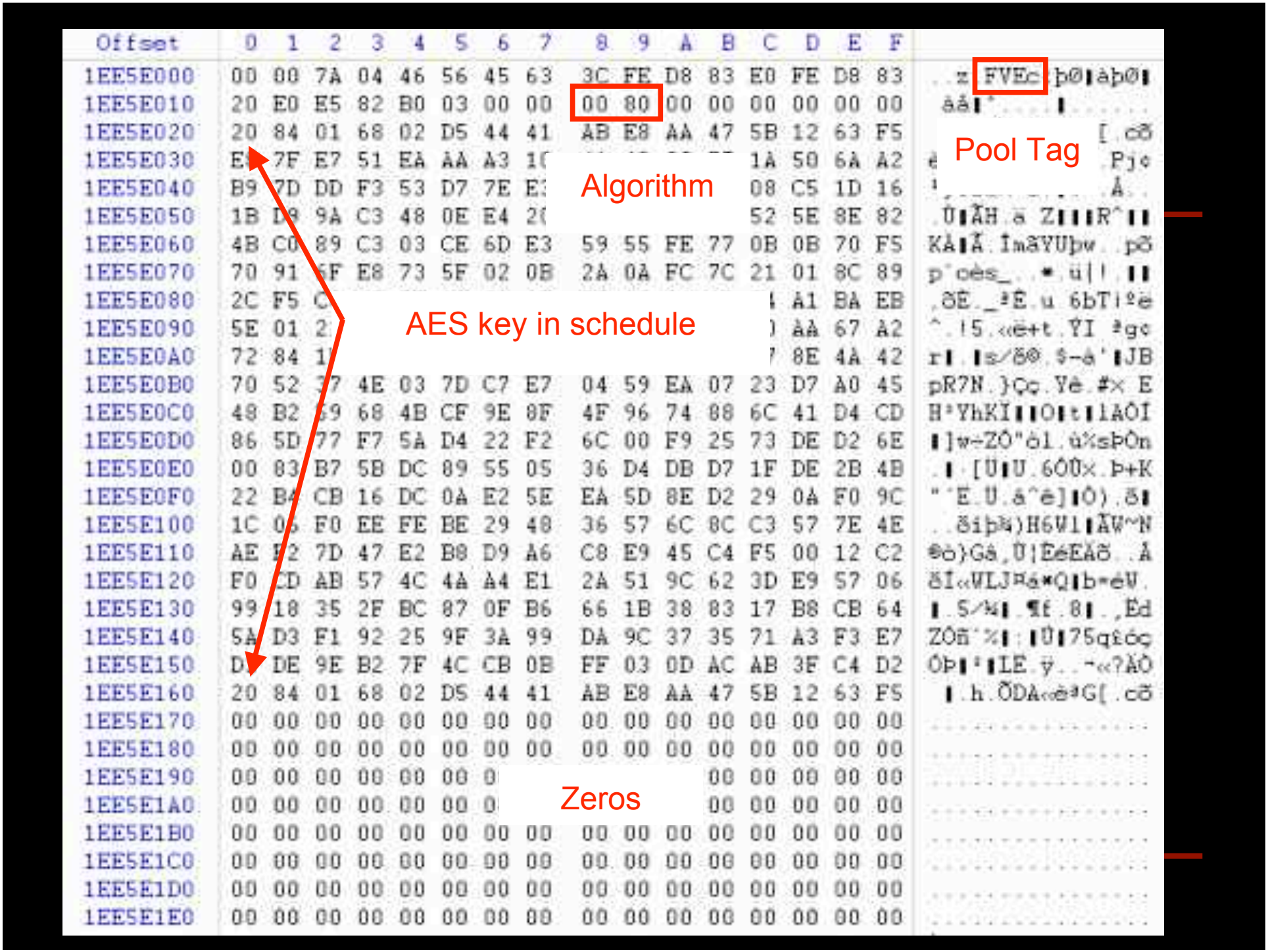
- **AES key schedules**
  - **Encryption and Decryption schedules**



BitLocker Tool Marks

- **Searching for BitLocker *AES key schedules in RAM***
  - ***Overlapped slightly***




Offset 0 1 2 3 4 5 6 7 8 9 A B C D E F
1EE5E000 00 00 7A 04 46 56 45 63 3C FE D8 83 E0 FE D8 83
1EE5E010 20 E0 E5 82 B0 03 00 00 00 80 00 00 00 00 00 00
1EE5E020 20 84 01 68 02 D5 44 41 AB E8 AA 47 5B 12 63 F5
1EE5E030 1A 50 6A A2
1EE5E040 08 C5 1D 16
1EE5E050 52 5E 8E 82
1EE5E060 4B C0 89 C3 03 CE 6D E3 59 55 FE 77 0B 0B 70 F5
1EE5E070 70 91 2C F5
1EE5E080 A1 BA EB
1EE5E090 AA 67 A2
1EE5E0A0 8E 4A 42
1EE5E0B0 70 52 37 4E 03 7D C7 E7 04 59 EA 07 23 D7 A0 45
1EE5E0C0 48 B2 69 68 4B CF 9E 8F 4F 96 74 88 6C 41 D4 CD
1EE5E0D0 86 5D 77 F7 5A D4 22 F2 6C 00 F9 25 73 DE D2 6E
1EE5E0E0 00 83 B7 5B DC 89 55 05 36 D4 DB D7 1F DE 2B 4B
1EE5E0F0 22 B4 CB 16 DC 0A E2 5E EA 5D 8E D2 29 0A F0 9C
1EE5E100 1C 06 F0 EE FE BE 29 48 36 57 6C 8C C3 57 7E 4E
1EE5E110 AE B2 7D 47 E2 B8 D9 A6 C8 E9 45 C4 F5 00 12 C2
1EE5E120 F0 CD AB 57 4C 4A A4 E1 2A 51 9C 62 3D E9 57 06
1EE5E130 99 18 35 2F BC 87 0F B6 66 1B 38 83 17 B8 CB 64
1EE5E140 5A D3 F1 92 25 9F 3A 99 DA 9C 37 35 71 A3 F3 E7
1EE5E150 DA DE 9E B2 7F 4C CB 0B FF 03 0D AC AB 3F C4 D2
1EE5E160 20 84 01 68 02 D5 44 41 AB E8 AA 47 5B 12 63 F5
1EE5E170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1EE5E180 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1EE5E190 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1EE5E1A0 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1EE5E1B0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1EE5E1C0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1EE5E1D0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1EE5E1E0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
Pool Tag
Algorithm
AES key in schedule
Zeros

BitLocker Tool Marks

- 0x0 FVEc pool tag
- 0x14 Algorithm ID, must be 0x8000-0x8003
- 0x1C Start of first BitLocker AES schedule
  - AES key must be at start and end of schedule
    - bytes 0x1C-0x2C and 0x15C-0x16C for 128-bit
  - Zeros at end of schedule if 128-bit mode
- 0x1EC Start of second BitLocker AES schedule
  - Same rules as above

BitLocker Tool Marks

- **Not perfect, but good enough**
- **Original**

Offset	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
00000000	3F	26	C8	B5	FF	87	47	B1	D5	26	12	43	EC	CD	78	C6
00000010	D5	09	AF	19	D1	5A	10	03	B5	4D	1B	73	0E	EC	0A	93
00000020	7A	16	05	EB	54	9F	39	1C	2E	5D	6A	DB	BC	67	C2	36
00000030	1C	3D	F3	60	AF	A1	EB	6F	E4	47	B2	E3	A5	B5	38	D9

- **Recovered**

Offset	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
00000000	3F	26	C8	B5	FF	87	47	B1	D5	26	12	43	EC	CD	78	C6
00000010	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00
00000020	7A	16	05	EB	54	9F	39	1C	2E	5D	6A	DB	BC	67	C2	36
00000030	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00

Finding Tool Marks

- How did we do this?
  - RTFM
    - FIPS certifications are great!
    - Ask developers for help
  - WinHex
  - IDA Pro
  - Checked builds
  - Debugging symbols
- Always trying to answer:
  - How does <u>it</u> know where to look?

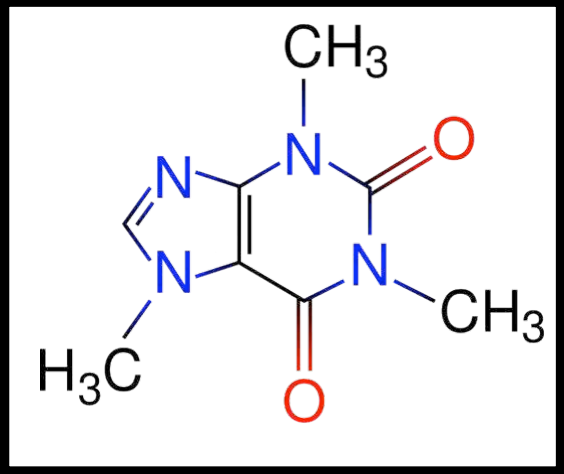


Image courtesy of User:Icey on Wikipedia and is public domain

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Performance

- **Brute Force**
  - **O(nm)**
- **Key Schedule Search**
  - **O(nm)**
- **Source Code**
  - **X* + O(n), where X* may be infinite**
- **Toolmarks**
  - **X + O(n)**

Forensics Tool Marks

- Requires as much elbow grease as source code analysis
  - Often more
  - Doesn't require the source code
- May require updating for each version
  - TrueCrypt
- May be your only option for previously unseen tools

Questions?

- **Introduction**
- **Targets**
- **Current Methods**
- **Tool Marks**
- **Example - BitLocker**
- **Conclusion**

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Thank you

Image courtesy of the Microsoft Corporation.

- **Microsoft Corporation for keeping me employed**
- **Kumar and Kumar for their reverse engineering work**
- **AAron Walters for organizing**
- **ManTech International Corporation for letting me geek out**
- **You for staying!**

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References

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- Brute Force Searches
  - C. Hargeaves and H. Chivers, "Recovery of Encryption Keys from Memory Using a Linear Scan", http://ieeexplore.ieee.org/Xplore/login.jsp?url=/iel5/4529302/4529303/04529504.pdf

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  - **Cold Boot paper, http://citp.princeton.edu/memory/**
- **Source Code Analysis**
  - **AAron Walters and Nick Petroni, Volatools, Volatools: Integrating Volatile Memory Forensics into the Digital Investigation Process, http://4tphi.net/fatkit/**