Encrypting Virtual Memory

Niels Provos

provos@citi.umich.edu

CITI - Center for Information Technology Integration

University of Michigan

Overview

1. Introduction
2. Related Work
3. Virtual Memory System
4. Swap Encryption
5. Performance Evaluation
6. Conclusion

Introduction

- A Cryptographic file system protects confidential data from unauthorized access.
- The proper cryptographic key is required to read its contents.
- However, the virtual memory system's **backing store** is generally **unprotected**.
- Passwords and pass phrases reside in it long after they have been typed in, even across reboots.

Introduction

- A user
  - expects that all confidential data vanishes with process termination,
  - is unaware that sensitive data may remain on backing store.
- When an attacker **compromises** the operating **system's integrity**
  - by gaining root privileges,
  - or by physical access to the machine itself

  she also **gains access** to **sensitive data** retained in backing store.

Introduction

- Our solution is to encrypt pages before they are written to secondary storage
- When the pages are brought back into physical memory, they are decrypted
- Each page has an associated encryption key.
- Encryption keys are destroyed, when they are no longer needed

Related Work

- Data protection with the "Cryptographic File System" by Blaze,
- Data hiding with the "Steganographic File System" by Anderson, Needham and Shamir.

$\Rightarrow$ data on secondary storage can reveal the **content** and **existence**.

Related Work

- Erasing the data on secondary storage could achieve the same as encryption,
- but Gutmann has shown that it is very difficult to thoroughly delete data from magnetic-media.

Virtual Memory System

- Virtual Memory increases the address space visible to application beyond the limits of physical memory.
- Data that does not fit into physical memory is saved on secondary storage.
- When a process accesses a page that has been stored on secondary storage a page fault occurs.
- The page fault causes the page to be restored from backing store.

Virtual Memory System

- Secondary storage
  - is usually slower than RAM,
  - is non-volatile, data persists over system shutdowns.
- Confidential data can survive on it beyond a user's expectations.
- At CITI we found,
  - login passwords,
  - PGP pass phrases,
  - email messages, ...

Virtual Memory System

Possible solutions:

- Avoid swapping completely: not a general solution, many applications require address space bigger than physical memory
- Use `mlock()` to prevent special memory areas to be paged out: applications need to be rewritten, reduces effectiveness of VM system, can result in worse performance

$\Rightarrow$ use **encryption** to protect confidential data.

Virtual Memory System

Encryption comes in several different flavors:

- User program installs own encrypting pager:
  - increases complexity,
  - requires applications to be modified,
  - difficult design decision about crypto.
- VM system swaps to a file in a cryptographic file system.

Virtual Memory System

In contrast to **common use of encryption**, we require

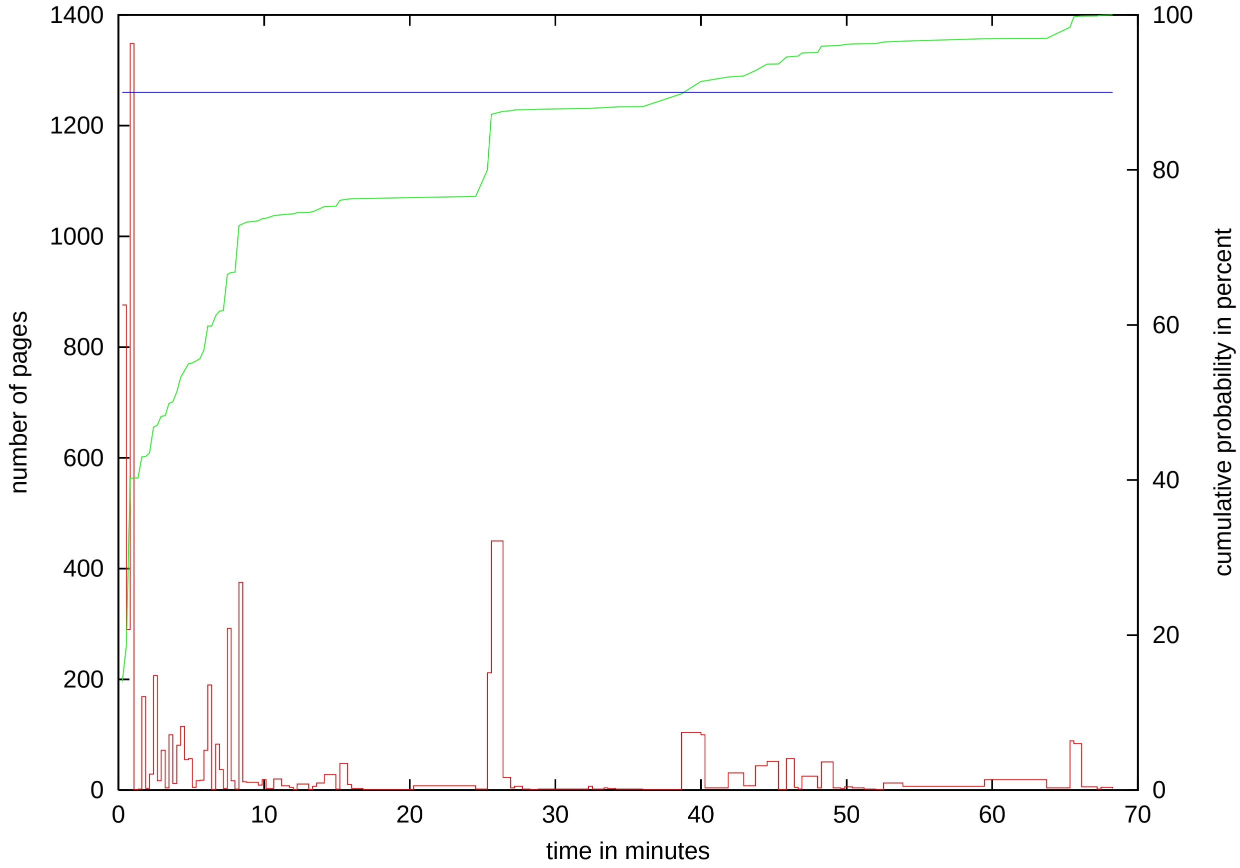
- when a page is no longer referenced, its encryption key should be destroyed after a time period (t_R) has passed,
- only the virtual memory pager should be able to decrypt pages

Best protection with $t_R = 0$, also meets user's expectation that her confidential data is deleted with process termination.

Virtual Memory System

- $t_R = 0$ too impractical, we guarantee $t_R <$ system uptime, but attempt to minimize average t_R,
- use **volatile encryption keys**
  - valid maximally for the duration of the system's uptime
  - completely independent of each other $\Rightarrow$ perfect forward secrecy
  - no complicated key management.
- $\Rightarrow$ employ encryption at pager level.

Virtual Memory System



- Most pages remain only for a few minutes, correlation: unnecessary zeroing, bad impact on system performance

Virtual Memory System

In comparison,

- deleting data by erasing incurs extra seek time and additional I/O,
- erasing a page with encryption is fast, just destroy the encryption key,
- encryption provides better protection against physical attacks, mere possession of disk is not sufficient,
- reliably erasing data from magnetic-media is difficult, does not matter for encryption.

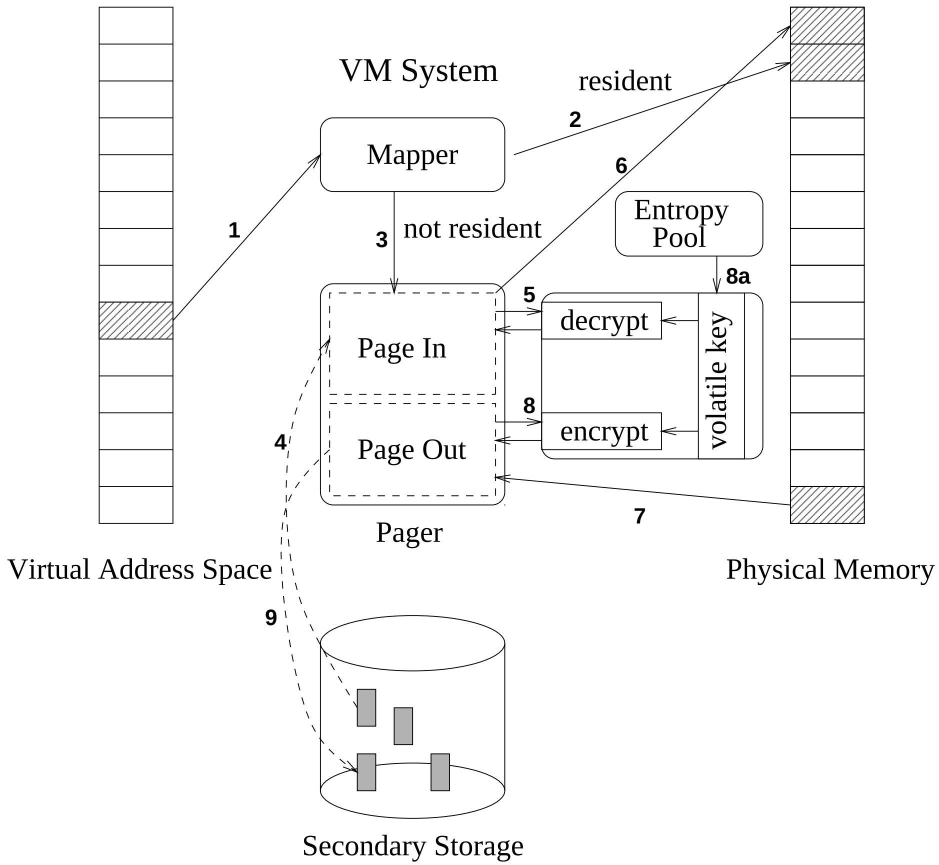
Swap Encryption

- Encryption and decryption are separated: policy decision vs. need of decryption
  - Policy: encrypt everything, only encrypt data from cfs, etc...
  - Decryption: need to remember which pages to decrypt, keep a bitmap $\Rightarrow$ allows change of encryption policy.

Swap Encryption

- Keep upper bound on t_R small by dividing the backing store into sections of 512 KByte, each section has
  - a 128-bit cryptographic key,
  - reference counter,
  - and an expiration time.
- 256 MByte backing store requires 14KB of memory for keys.
- Section's 128-bit key is created randomly on first use.
- If a section's reference counter is 0, its key is destroyed.

Swap Encryption



Overview of the swap encryption process

Swap Encryption

Cipher Selection.

For swap encryption, a cipher needs to fulfill:

- Encryption and Decryption need to be fast compare to disk I/O
- Generation of the cipher's key schedule has to be inexpensive compared to encrypting a page.
- Cipher has to support encryption and decryption on page by page basis, can not use stream cipher.

Swap Encryption

- Schneier's Blowfish encryption algorithm not suitable:
  - key schedule computation is very slow
  - key schedule requires a lot of memory
- Use **Rijndael**:
  - is finalist in advanced encryption standard (AES) competition,
  - 128-bit blocks and 128-bit keys,
  - round transformation does not have Feistel structure, instead different layers,
  - is faster in all aspects compared to Blowfish.

Swap Encryption

- Key schedule computation cost is amortized when encrypting a single 4 KByte page. (352 cycles vs. 357 cycles)
- We use the cipher in cipher-block chaining (CBC) mode.
- Encrypted block number is used as 128-bit initialization vector (IV)
  - each page is encrypted uniquely,
  - try to avoid cipher text only attacks.

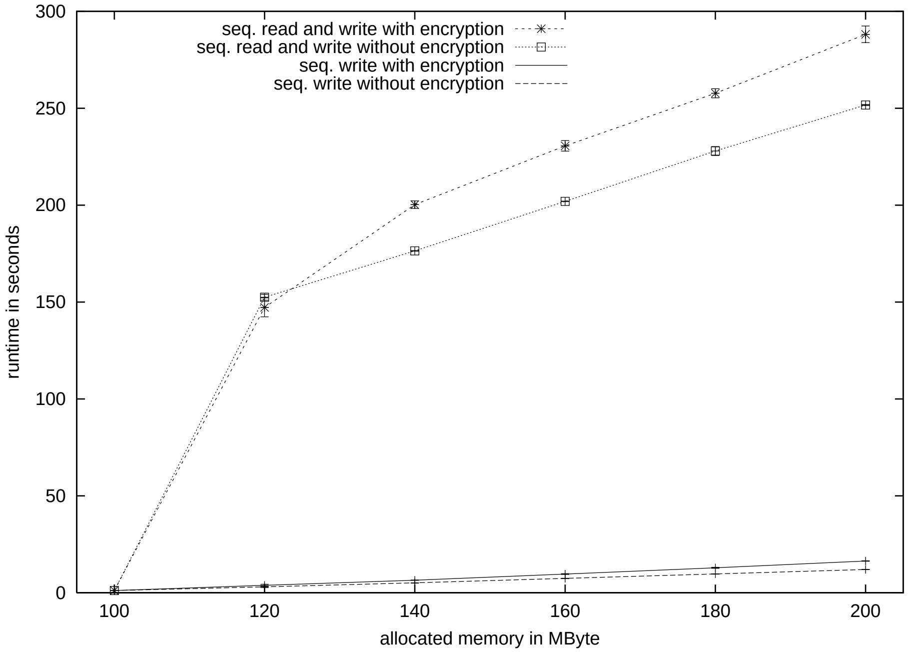
Swap Encryption

- Security relies on good encryption keys.
- Require a good source of randomness.
- **Entropy pool** collects entropy from many physical events observable by the operating system:
  - inter-keypress timing from terminals,
  - arrival time of network packets,
  - finishing time of disk requests.
- Not practical for an attacker to observe all events.

Swap Encrytion

- Use ARC4 stream cipher to extract random encryption keys.
- RC4's internal state is initialized by the entropy pool.
- Frequently reseed RC4's state to prevent none-uniform output

Performance Evaluation



- Running OpenBSD 2.6-current with UVM with 6 GByte Ultra-DMA disk, 7.5MByte/s write and 6.3 MByte/s read.
- Micro benchmark fills memory with zeros and reads it.
- Runtime increase for reads about 14%, for writes between 26%-36%

Performance Evaluation

- Macro benchmark using ImagicMagick: magnify 960×1280 image and rotate by 24^o.
- For magnification by 2.5 runtime increases nearly by 70%.
- However, we believe that the overhead is still acceptable.

Conclusion

- Confidential data can remain on backing store.
- Looked at several alternative solutions, encrypting data on backing store with volatile random keys has several advantages.
- Demonstrated acceptable performance and a viable solution.
- Software is freely available, contact the author.
- Acknowledgments:

  - Patrick McDaniel and Peter Honeyman for reviews and comments,
  - Chuck Lever for getting me interested in swap encryption,
  - Artur Grabowski for help in understanding UVM,
  - David Wagner for feedback on cipher selection.

Physical Memory

- RIO shows that physical memory can be persistent across reboots.
- However, it is common practice to erase keys before application exit, *e.g.*, OpenSSL, OpenSSH, etc...
- Encryption protects against persistent storage of data before the application can clean up.

