Proving Confidentiality in a File System Using DiskSec

Atalay Mert İleri, Tej Chajed,
Adam Chlipala, Frans Kaashoek, Nickolai Zeldovich
MIT CSAIL

Storage Systems Contain Confidential Data

Users rely on the storage system to maintain their confidentiality.

- A file system will be used as a case study in this talk.

Confidentiality in a File System

- Alice and Bob share a file-system on the same machine

- Bob tries to learn the content of Alice’s files

Threat model: Bob can call the file-system interface and cannot bypass it.

  - can’t steal the disk
  - can’t read or write directly to the disk etc.

Bugs May Leak Confidential Data

File-systems are also subject to confidentiality bugs.

Examples

● Crash can expose deleted data	(ext4 - 2017)
● Anyone can change POSIX ACLs	(NFS - 2016)
● Truncated data can be accessed	(btrfs - 2015)
● Crash can expose data	(ext4 - 2014)
● Anyone can change POSIX ACLs	(btrfs, gfs2 - 2010)
● ...	

Approach: Formal Verification

- Write a specification that captures the desired behavior of the system.
- Prove that implementation satisfies the specification.
- As long as specification accurately captures the desired behavior, implementation details are irrelevant.
- We have verified file systems with correctness specifications (e.g. DFSCQ [SOSP'17]).

Functional Specifications Do Not Ensure Confidentiality

Functional specifications ensure many security properties.
(e.g. no memory corruption, no disk corruption etc.)

Example: Specification for readdir

`readdir` can return entries in any order.

```
/dir_a        readdir(...) ⇒ dir_a, dir_b ✓
/dir_b                       dir_b, dir_a ✓
```

Functional Specifications Do Not Ensure Confidentiality

```
def readdir(...)
    dirs = get_dirlist(...)
    if (alice.txt file contains ‘a’)
        return sort(dirs)
    else
        return reverse_sort(dirs)
```

- Meets specification
- Leaks confidential data

Nondeterministic functional specifications allow breach of confidentiality.

Confidentiality requires better specifications.

State of the Art in Verifying Confidentiality

Existing Systems

- seL4 [SSP'13]
- Ironclad [OSDI'14]
- CertiKOS [PLDI'16]
- Komodo [SOSP'17]
- Nickel [OSDI'18]

Above systems use non-interference for their confidentiality specifications.

Non-interference does not allow **any** data exposure from Alice to Bob.

Non-interference is Not Suitable for File System Confidentiality.

- File systems have discretionary access control
- File systems intentionally expose metadata.

Contributions

DiskSec

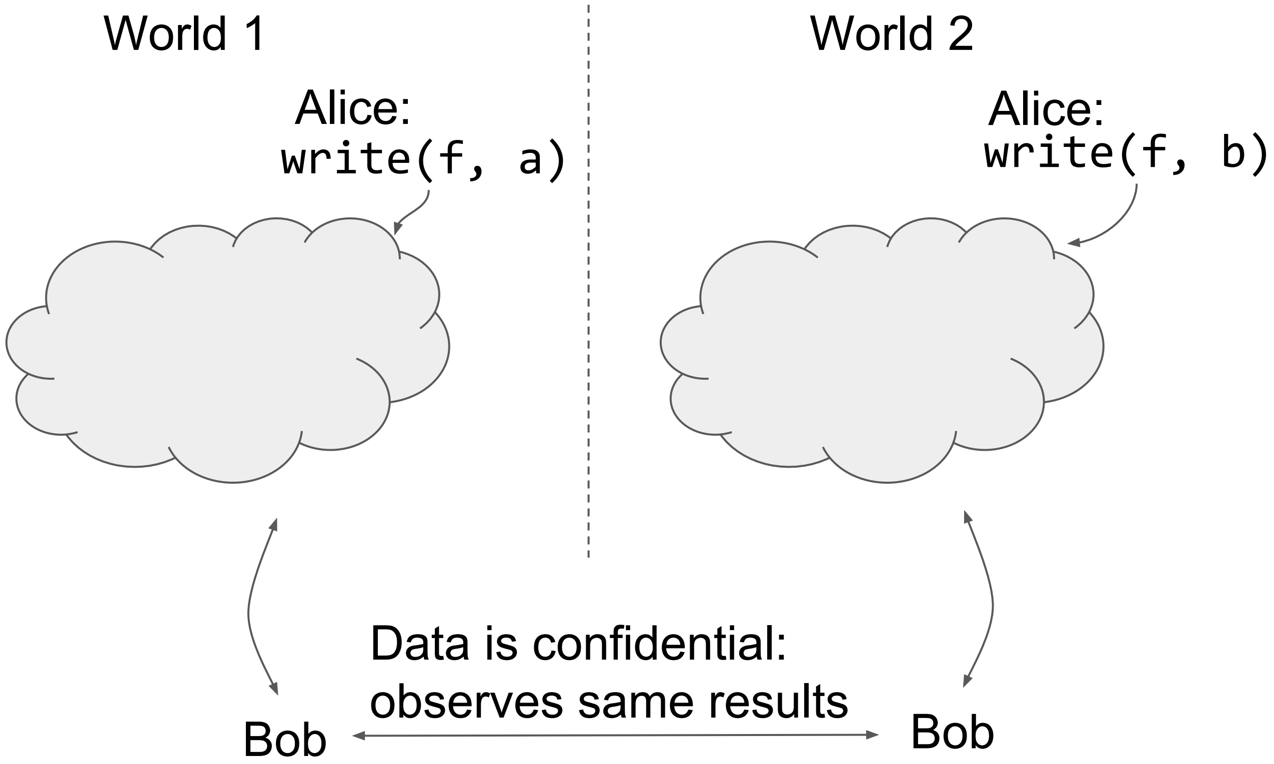
Framework for proving confidentiality of storage systems.

- File-system confidentiality specification.
- Proof technique to track ownership of the data.
- DiskSec implemented and proven in Coq Proof Assistant.

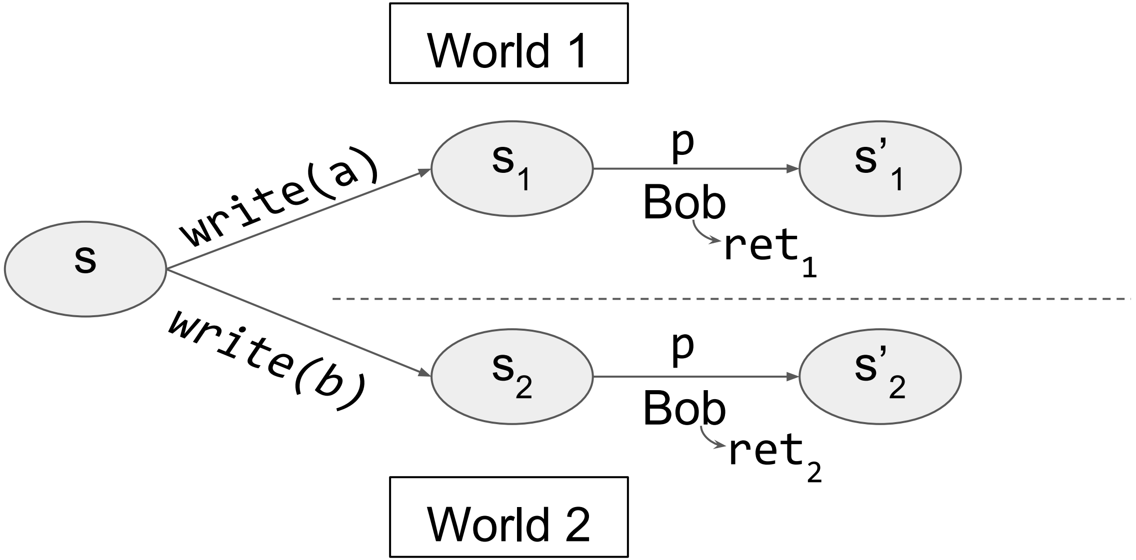
Evaluation

- SFSCQ file system: extension of DFSCQ with confidentiality theorem
- Confidentiality for simple app on top of SFSCQ

Bob Cannot Infer Alice's Confidential Data



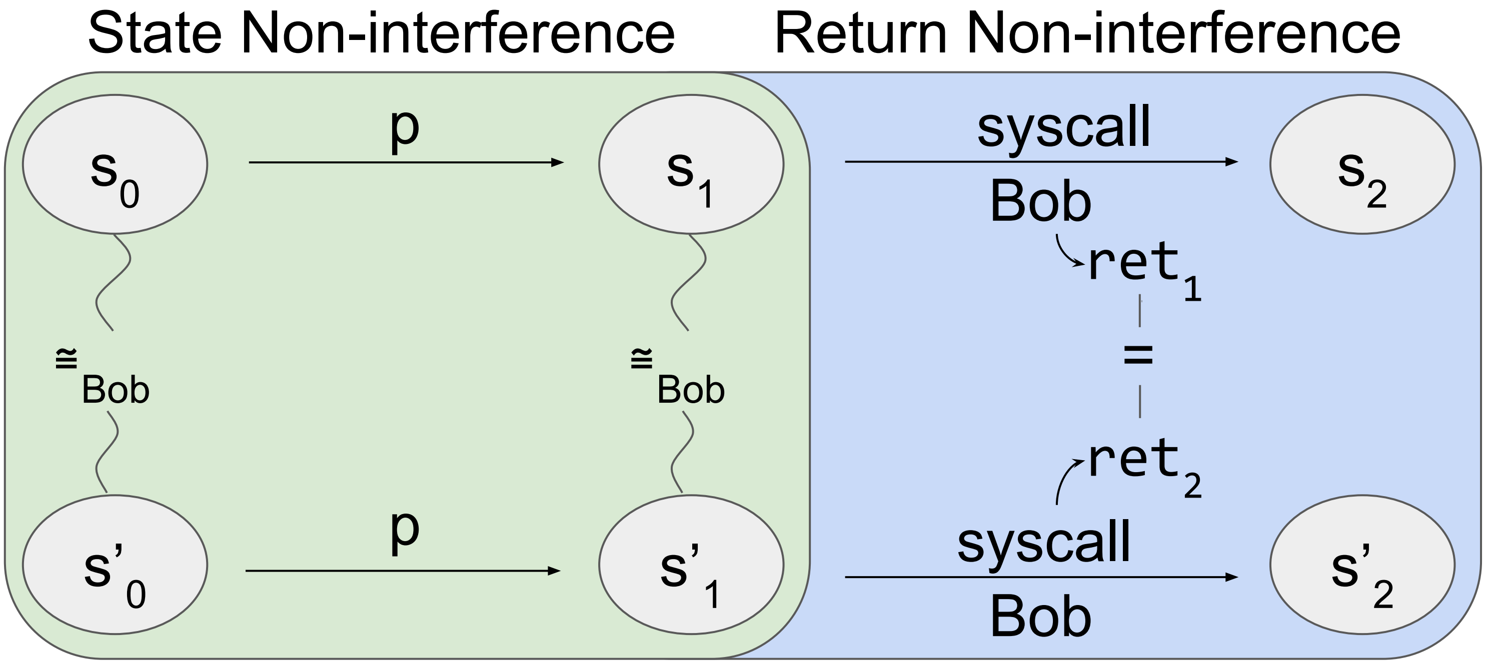
Confidentiality Means Other Users See Same Thing Regardless of Your Data



Confidentiality requires that $ret_1 = ret_2$

Two states are equivalent with respect to a user ($\cong_{user}$), if all the data **visible to that user** is the same in both states.

Our Confidentiality Specification: Data Non-interference



Data Non-interference is a Good Confidentiality Specification for File Systems

Data non-interference

- allows discretionary access control,
- allows exposing of metadata,
- forbids exposing of user data
  - even indirectly (e.g. readdir)

How can We Prove Data Non-interference?

Data non-interference require more complicated proofs than functional correctness.

- Require reasoning about behavior of two executions.

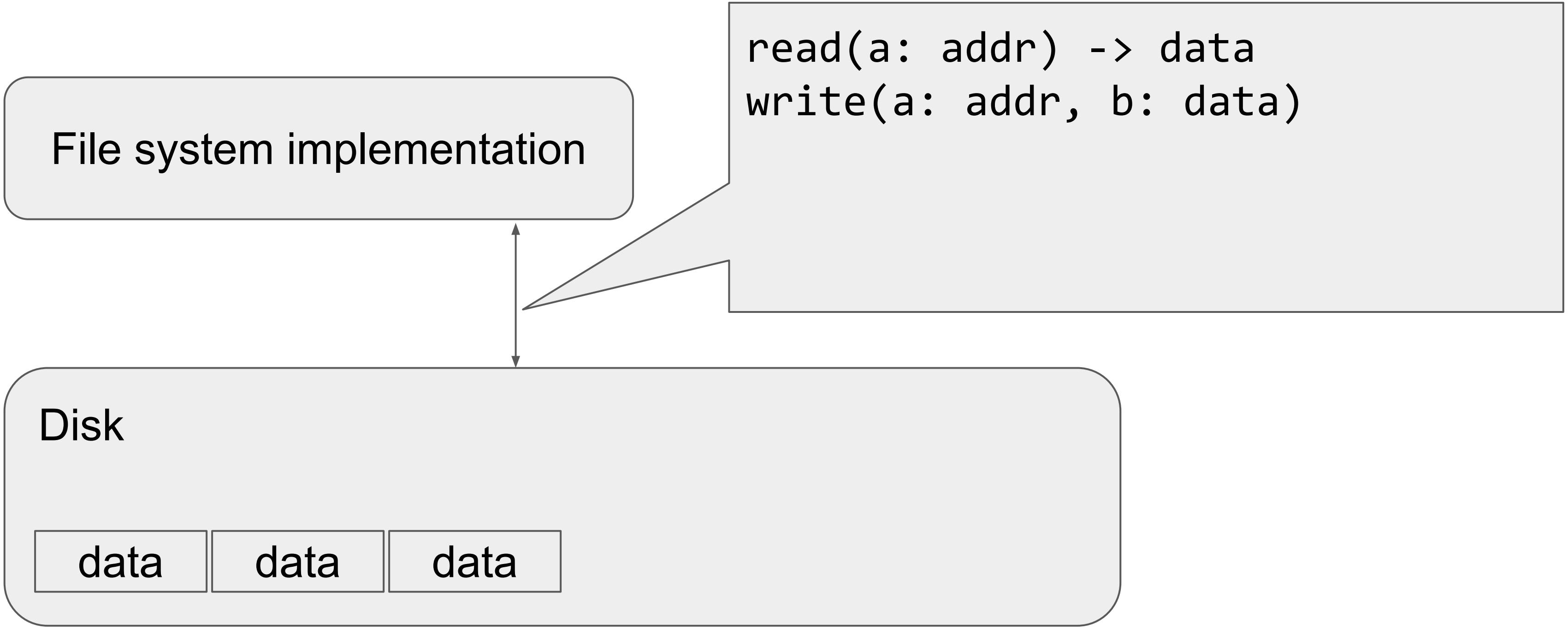
Insight: File systems mostly does not inspect user data.

- Suffices to reason about where user data is accessed in one execution.

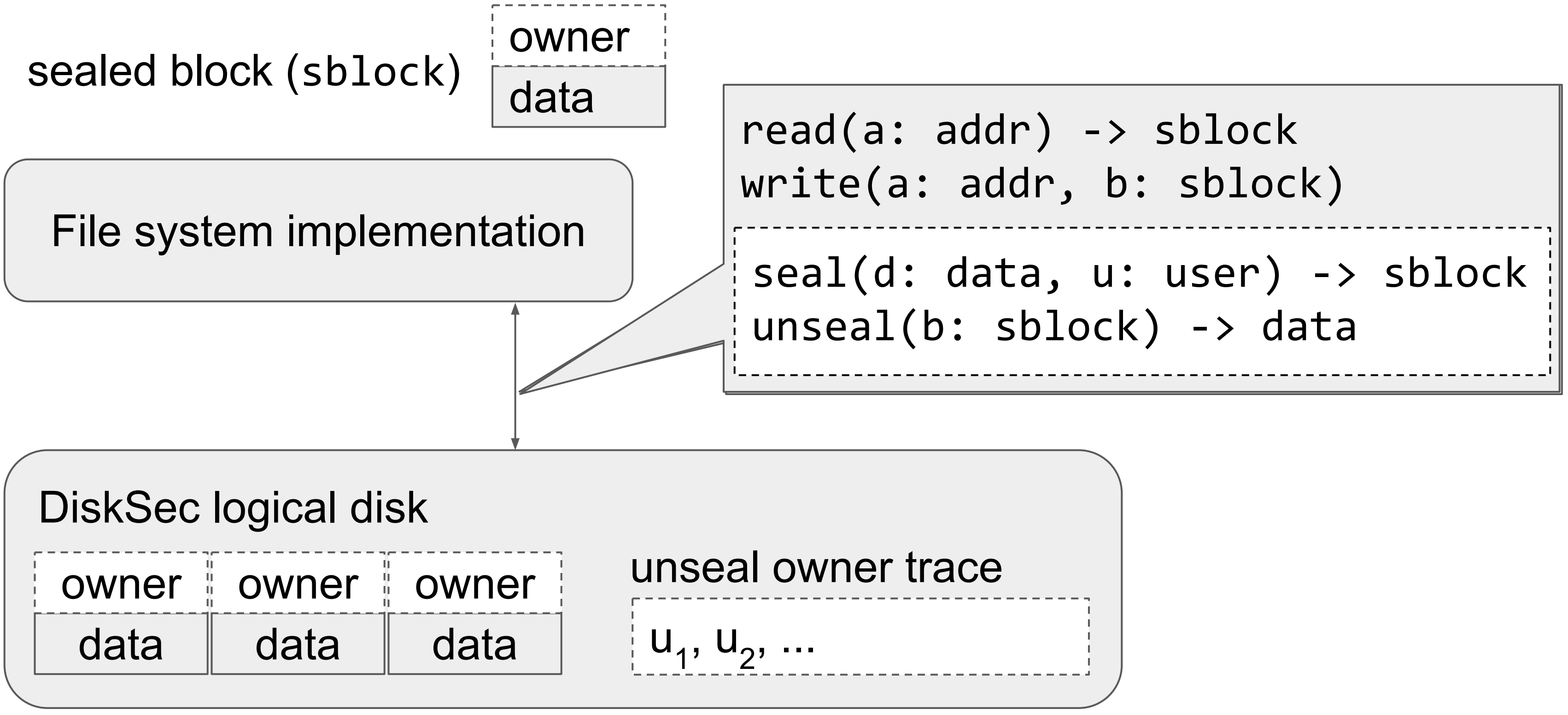
Our Approach: Sealed Blocks

- **Pretend** that all disk blocks are **logically** sealed.
- Function needs to request an **unseal** to access the data content.
- Functions can be analyzed to prove that they do not unseal user data.

Standard Disk Infrastructure



DiskSec Infrastructure



How to Use DiskSec?

1. Developer instruments his code with seals, unseals and access control checks.

Standard Implementation

```
def read(f,...)
  data = read_disk(f,...)
  return data
```

DiskSec Implementation

```
def read (f,...)
  if (can_access(f))
    sealed_data = read_disk(f,...)
    data = unseal(sealed_data)
    return data
  else
    return error
```

2. Developer proves that a certain property holds for the unseal trace of the implementation.

Sealed Blocks Simplify Confidentiality Proofs

Unseal Public

Function only unseals data accessible to **every user**.

Unseal Public ➝ Data Non-interference

Unseal Secure

Function only unseals data accessible to the **current user**

Unseal Secure ➝ Return Non-interference

In this case, state non-interference needs to be proven separately.

DiskSec Summary

- Provides infrastructure for access control in storage systems.
- Formalizes data non-interference as a confidentiality specification.
- Simplifies proof effort by reducing data non-interference proofs to unseal trace proofs.

Applying DiskSec: SFSCQ Overview

- Based on DFSCQ [SOSP'17]
- Supports multiple users
- Simplified permission model
  - All metadata, including file names, are public.
  - File contents may be public or private.
  - File owner is set upon creation.
- Fully implemented and verified in Coq Proof Assistant

Evaluation

- Did we prove DFSCQ satisfies data non-interference?
  - Not completely.
  - Needed to remove an advanced feature.
- Is performance the same as DFSCQ?
  - SFSCQ code = DFSCQ code + access control checks
- How much effort did it require?
  - Took one author ~3 months

Conclusions

- Correctness specifications are not enough for confidentiality.
- Data non-interference is a suitable confidentiality specification for file systems.
- We designed and implemented DiskSec, a framework for confidentiality proofs for storage systems.
- We implemented SFSCQ, the first file system with machine-checkable confidentiality proofs, using DiskSec.

https://github.com/mit-pdos/fscq/tree/security