TrueErase: Full-storage-data-path Per-file Secure Deletion

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Overview

- Problem
  - Per-file secure-deletion is difficult to achieve
    - Important for expired data, statute of limitations, etc.
- Existing solutions tend to be
  - Limited to a segment of legacy storage data path
  - File-system- or storage-medium-specific
- TrueErase
  - Storage-data-path-wide solution
  - Works with common file systems & storage media

The Problem

- Most users believe that files are deleted once
  - Files are no longer visible
  - The trash can is emptied
  - The partition is formatted
- In reality
  - Actual data remains

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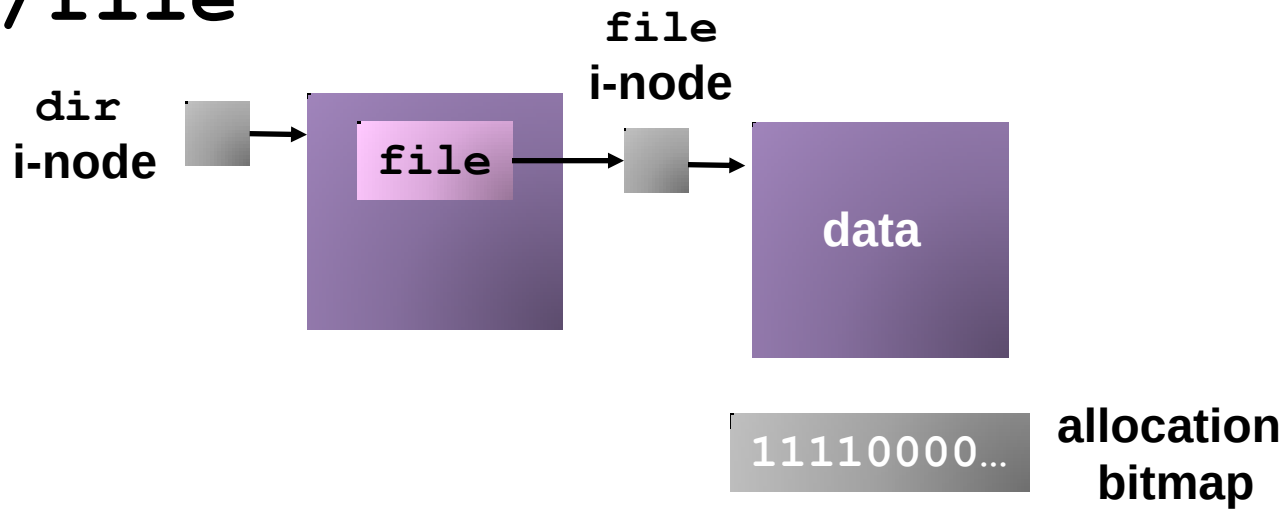
What is *secure deletion*?

- Rendering a file's deleted content and metadata (e.g., name) irrecoverable
- **`/dir/file`**



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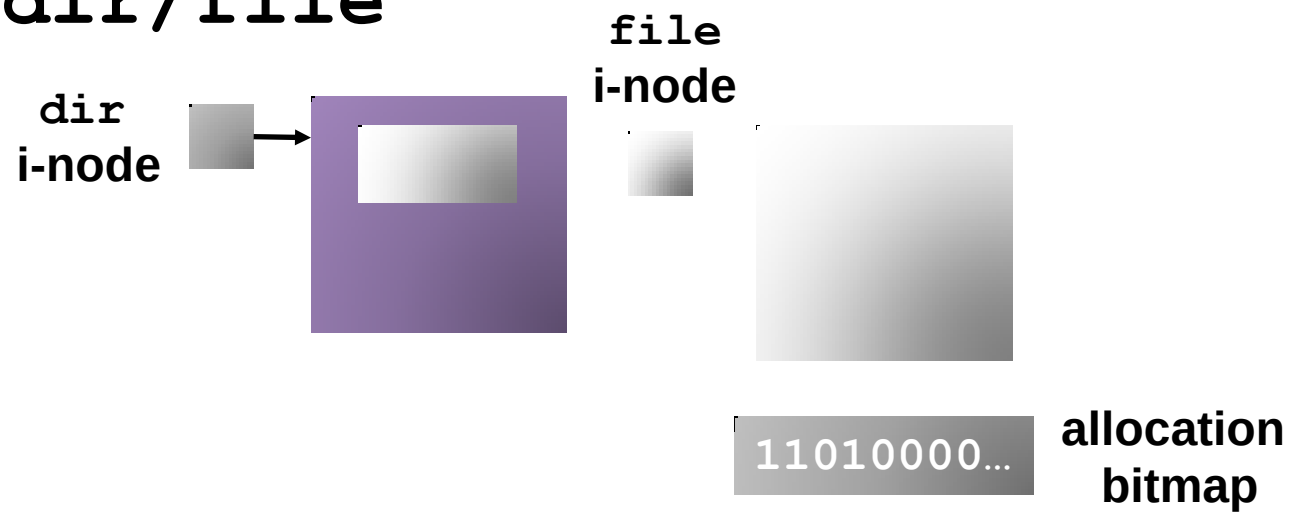
- **`rm /dir/file`**



How hard can this be?

- Diverse threat models
  - Attacks on backups, live systems, cold boot attacks, covert channels, policy violations, etc.
- Our focus
  - Dead forensic attacks on local storage
    - Occur after the computer has been shut down properly

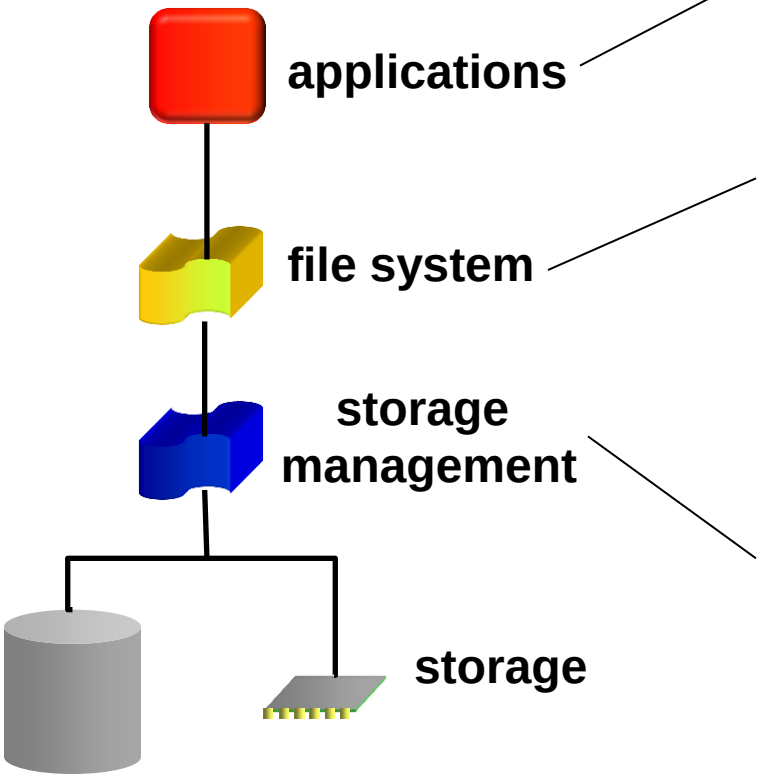
Basic Research Question

- Under the most benign environments
- What can we design and build to ensure that the secure deletion of a file is honored?
  - Throughout the legacy storage data path

TrueErase: A Storage-data-path-wide Framework

- Irrevocably deletes data and metadata
- Offers a unique combination of properties
  - Compatible with legacy apps, file systems, and storage media
  - Per-file deletion granularity
  - Solution covers the entire data path
  - Can survive common system failures
  - Core logic systemically verified

Legacy Storage Data Path



- Limited control over metadata
- Not aware of storage medium; limited control over storage locations
- No access to a block's type, file ownership, in-use status

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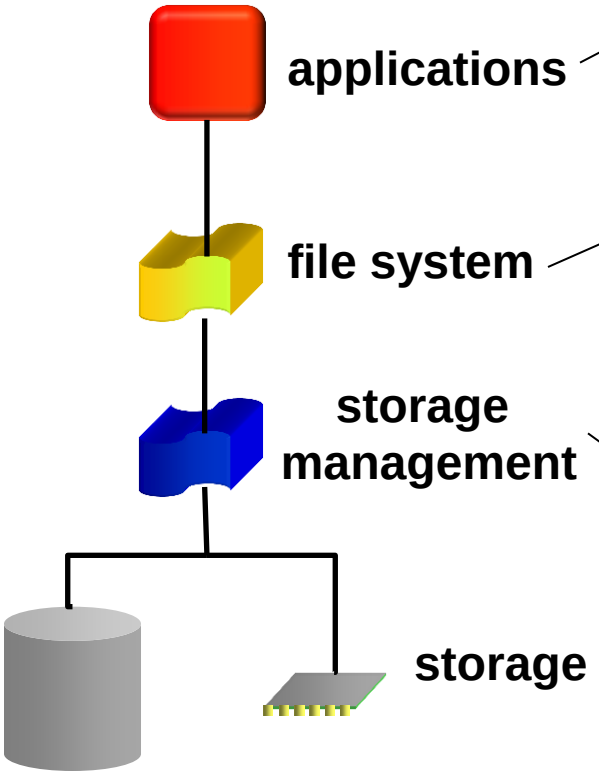

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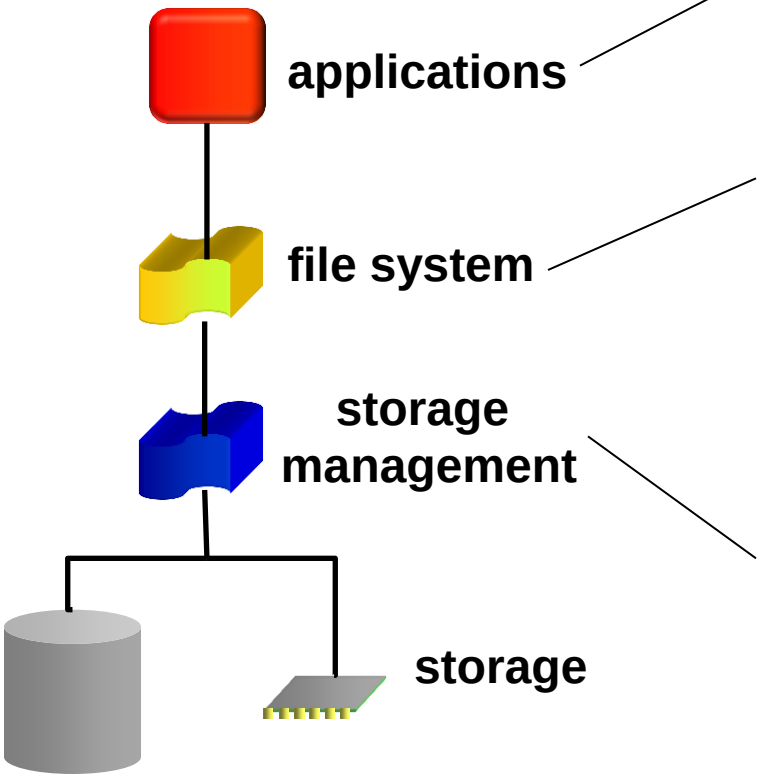

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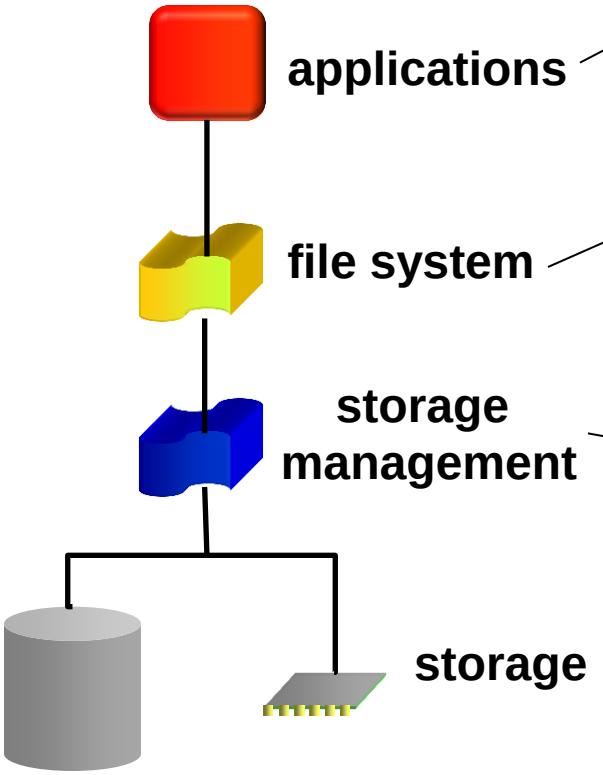
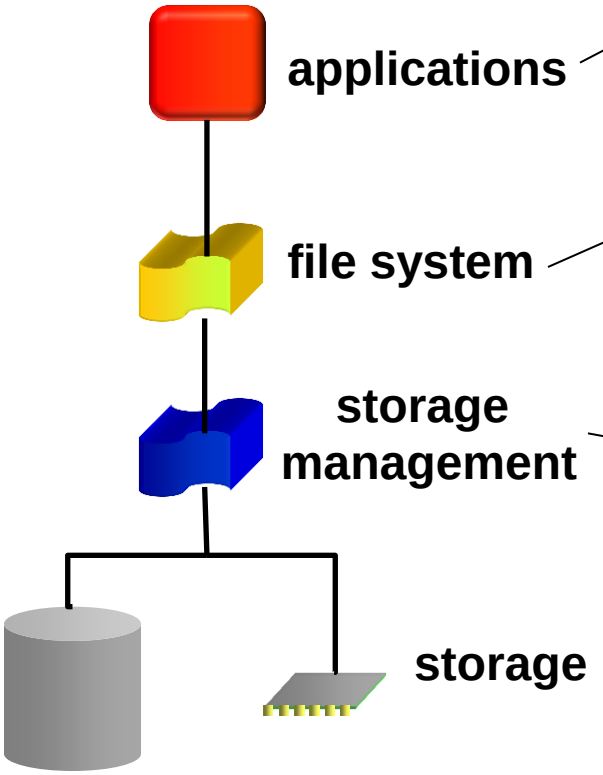
Existing Secure-deletion Solutions



- May leak metadata information
- Cannot ensure ***in-place*** updates
  - Encryption will not help
- Hard to provide per-file solutions
- Cross-layer solutions tend to be file-system- and medium-specific

Existing Secure-deletion Solutions



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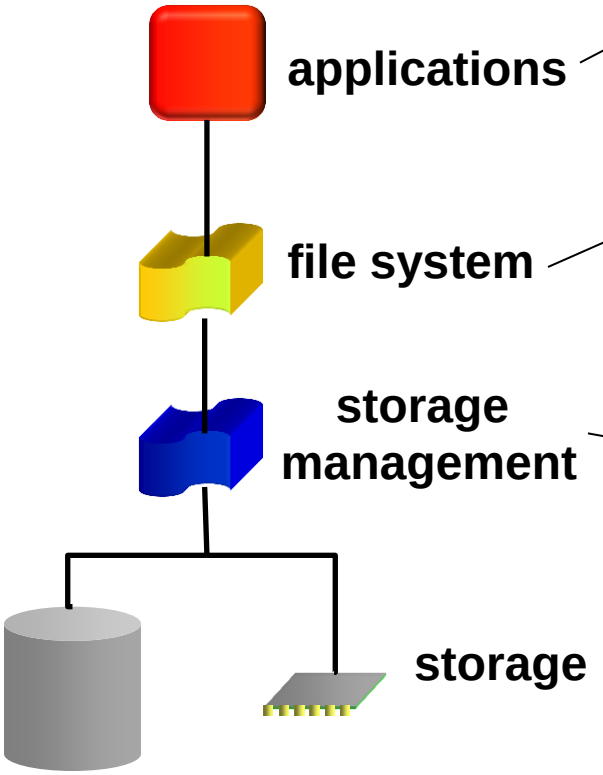

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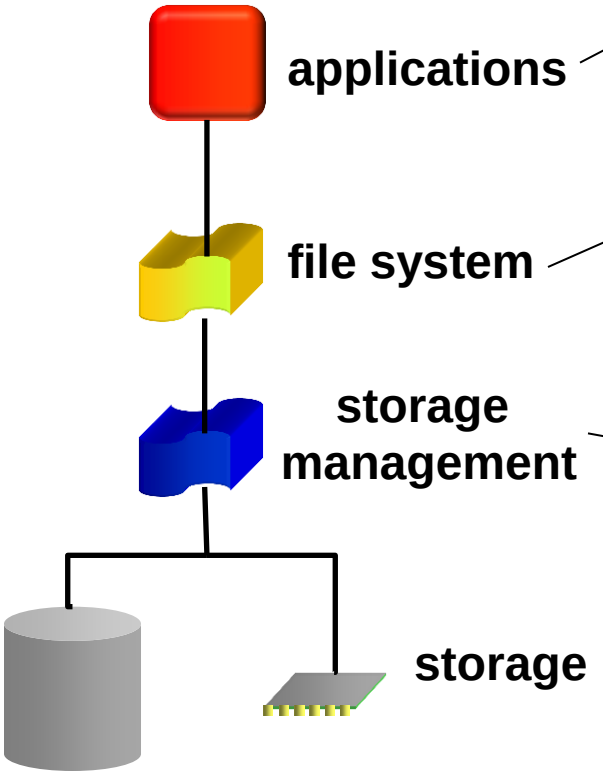

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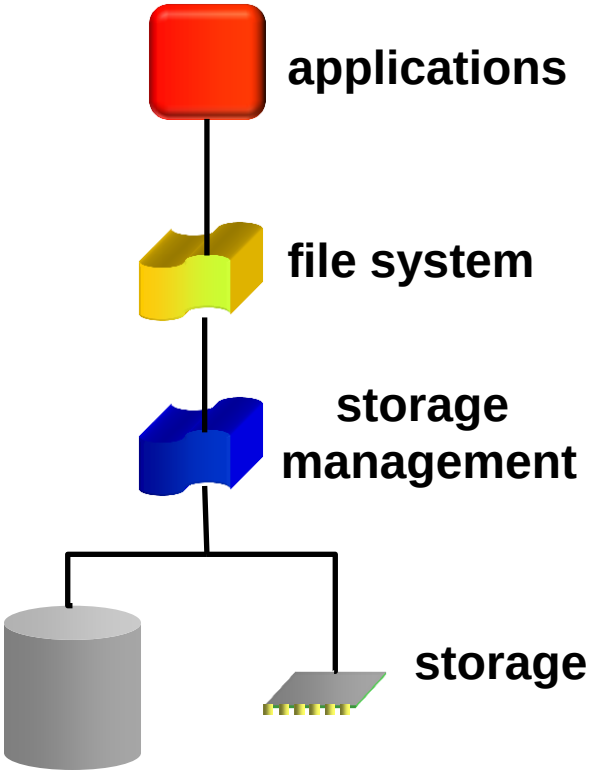
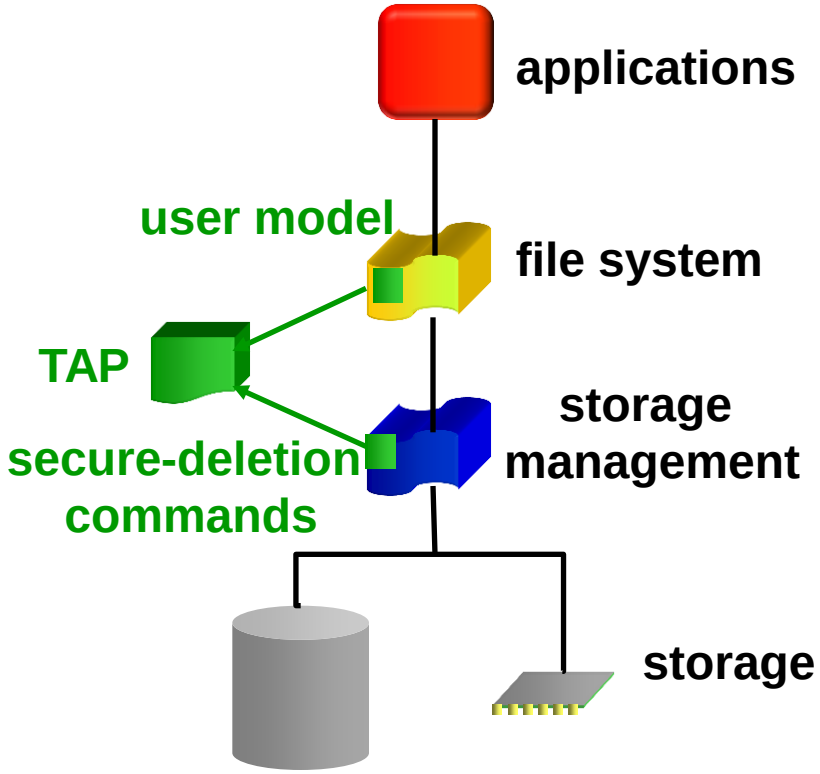
Other Secure-deletion Challenges



- No legacy requests to delete data blocks
  - For performance
- Legacy optimizations
  - Requests can be split, reordered, cancelled, consolidated, buffered, with versions in transit
- Lack of global IDs
- Crashes/verification

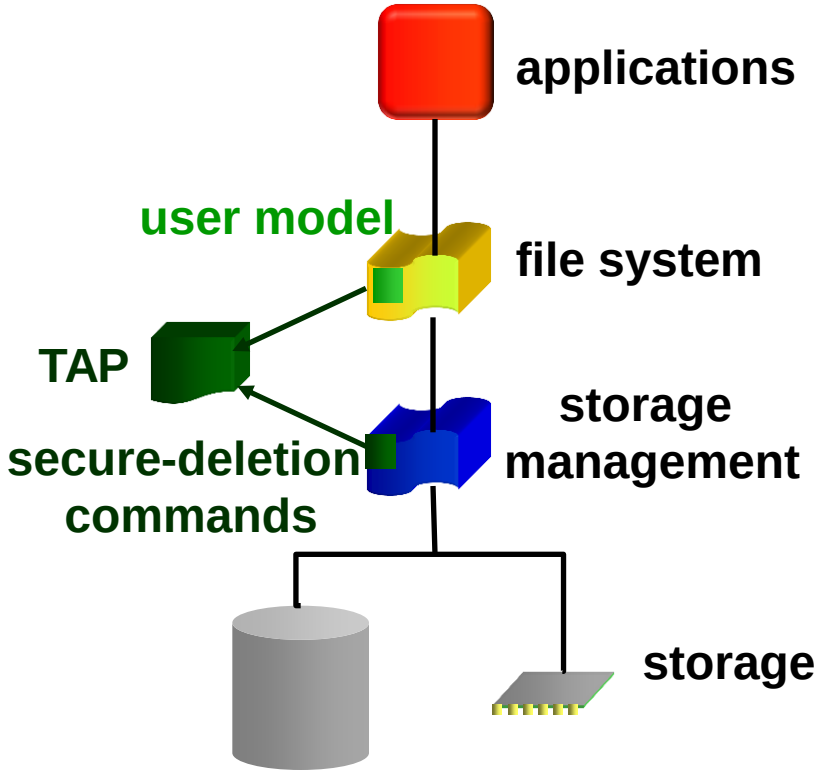
TrueErase Overview

- A centralized, per-file secure-deletion framework



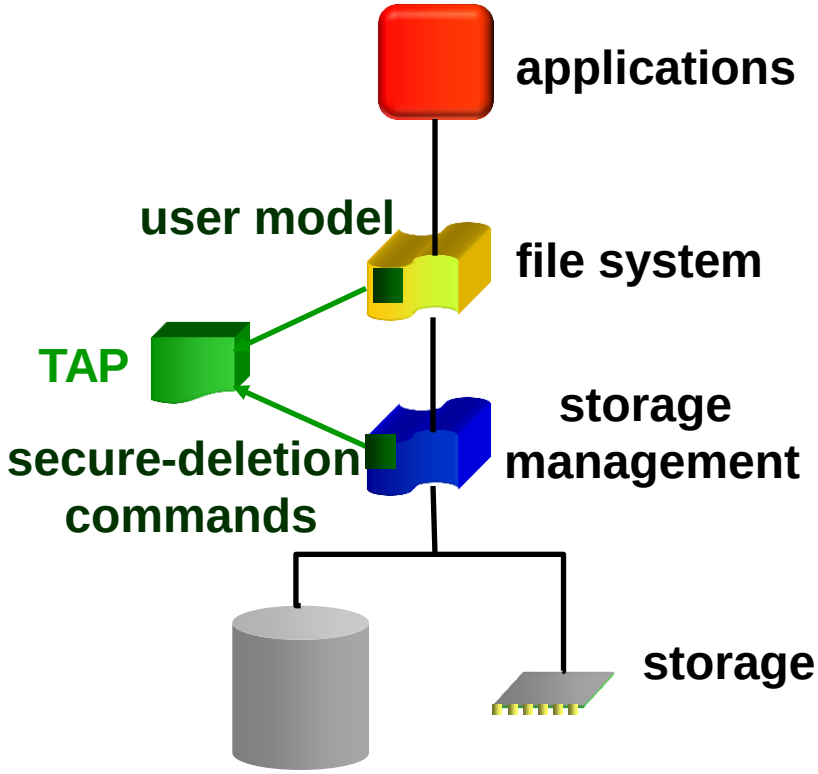
TrueErase Overview

- User model
  - Use extended attributes to specify files/dirs for secure deletion
  - Compatible to legacy applications



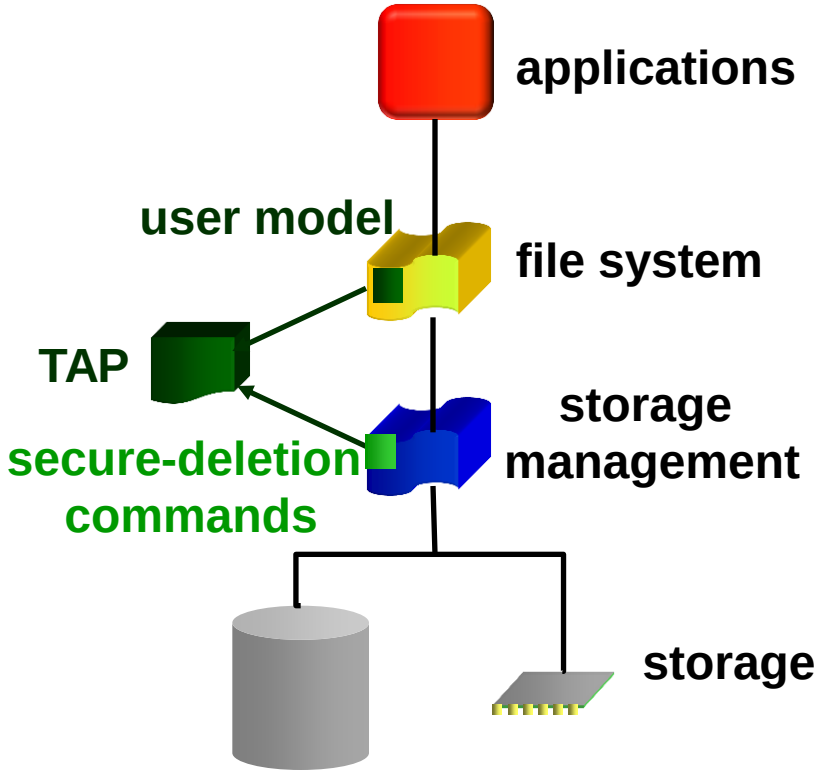
TrueErase Overview

- Type/attribute propagation module (***TAP***)
  - File system reports pending updates
    - Uses global unique IDs to track versions
  - Tracks only soft states
    - No need for mechanisms to recover states



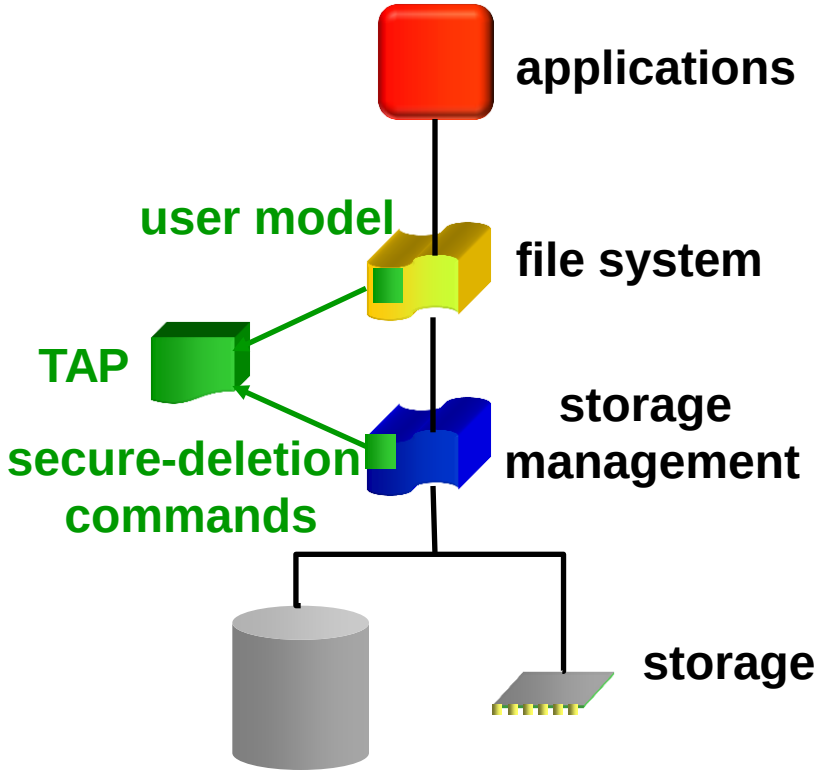
TrueErase Overview

- Enhanced storage-management layer
  - Can inquire about file-system-level info
  - Added secure-deletion commands for various storage media
  - Disabled some optimizations (e.g., storage-built-in cache)



TrueErase Overview

- After a crash
  - All replayed and reissued deletions are done securely
  - All data/metadata in the storage data path from prior session will be securely deleted



TrueErase Assumptions

- Benign personal computing environment
  - Uncompromised, single-user, single-file-system, non-RAID, non-distributed system
- Dead forensics attacks
- Full control of storage data path
- Journaling file systems that adhere to the consistency properties specified in [SIVA05]
- All updates are reported
- Does not handle user copies (no tainting)

TrueErase Design

- User model
- TAP
- Enhanced storage-management layer

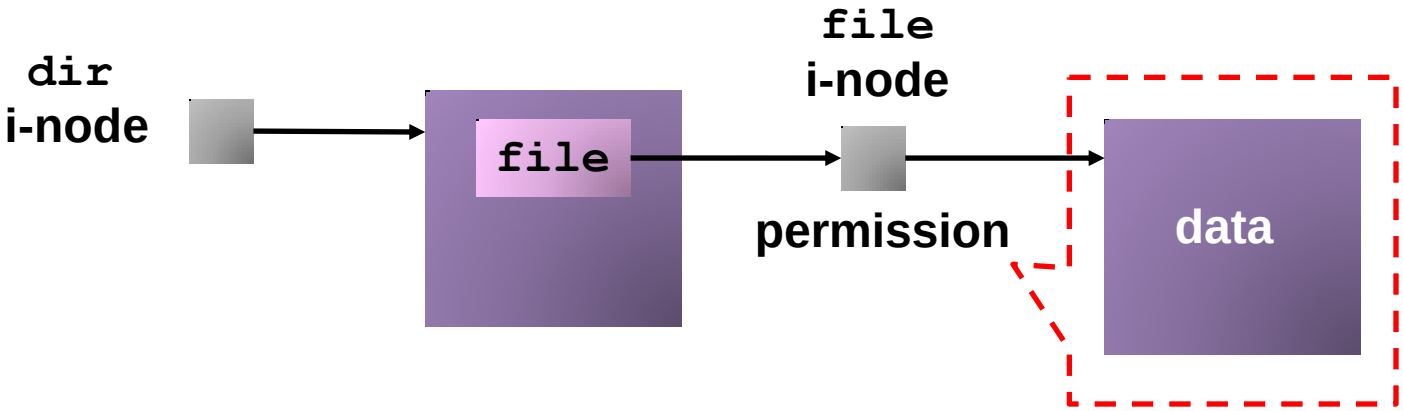
- Exploiting file-system-consistency properties to identify and handle corner cases

User Model

- Ideally, use traditional file-system permission semantics
  - Use extended-attribute-setting tools to mark files/dirs ***sensitive***
    - Which will be securely deleted from the entire storage data path
  - Legacy apps just operate on specified files/dirs

Name Handling

- Legacy file-permission semantics



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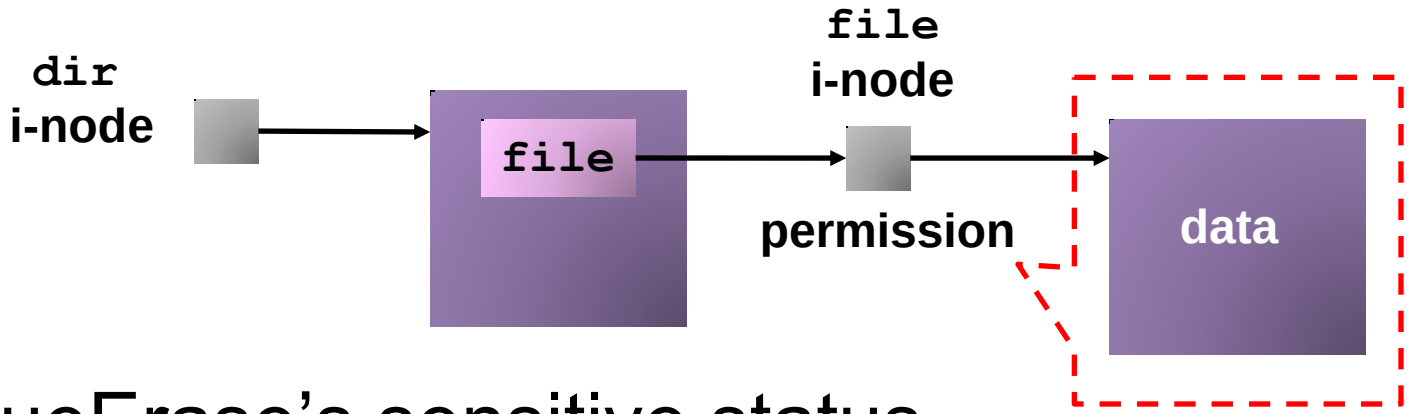
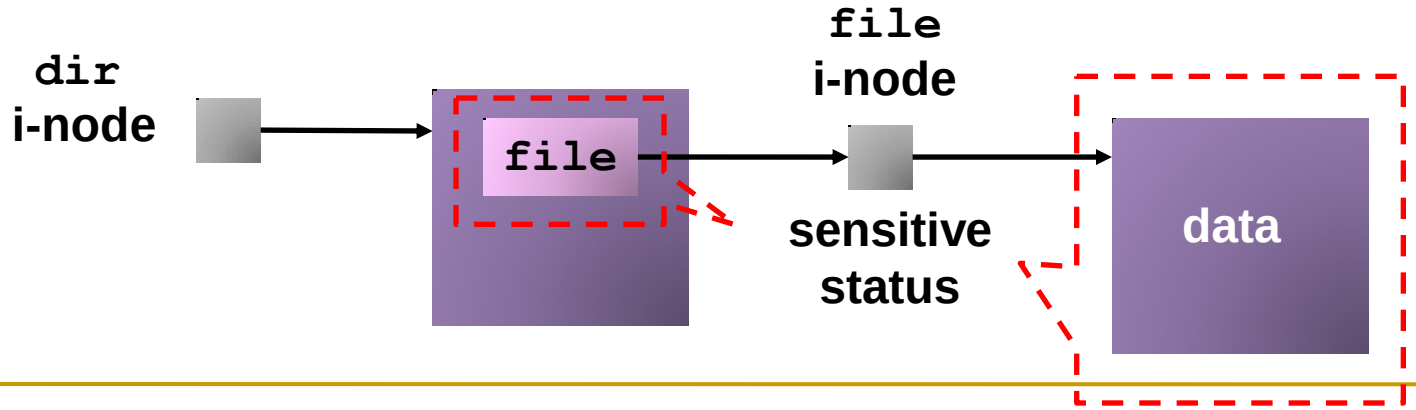


- TrueErase's sensitive status



Toggling of the Sensitive Status

- Implications
  - Tracking update versions for all files at all times
  - Or, removing old versions for all files at all times
- TrueErase
  - Enforces secure deletions for files/dirs that have stayed sensitive since their creation

Name Handling

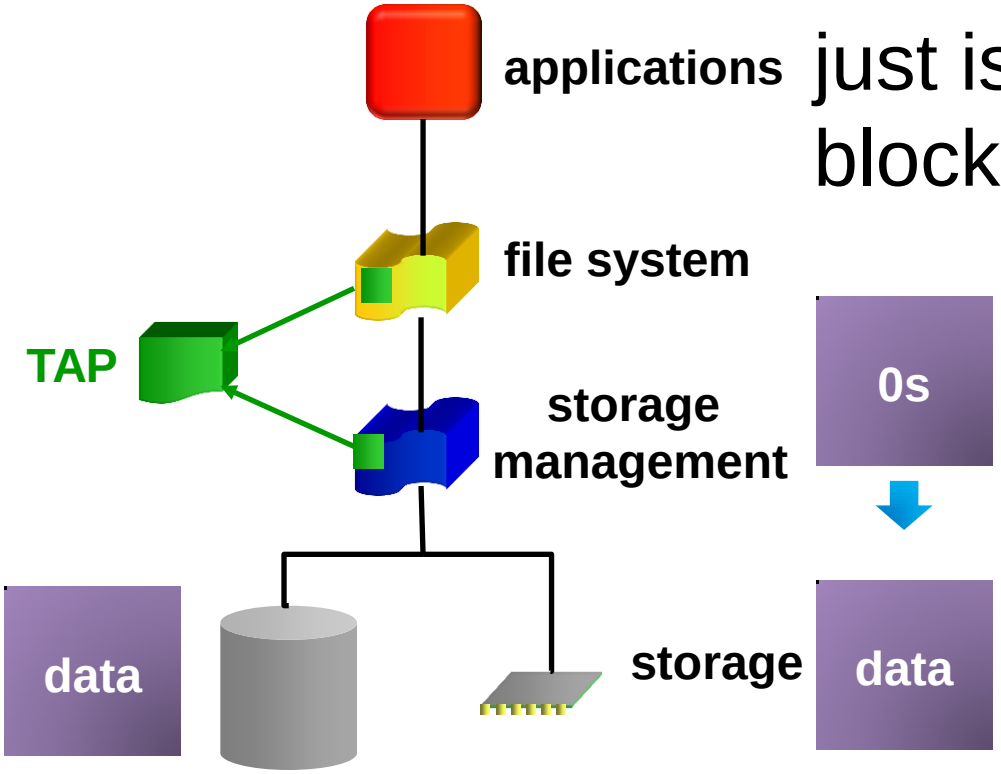
- By the time one can set attributes of a file
  - File name may already be stored non-sensitively
- Some remedies
  - Inherit the sensitive status
    - Creating a file under a sensitive directory
  - smkdir wrapper script
    - Creates a temporary name, marks it sensitive, and renames it to the sensitive name

TAP Module

- Tracks and propagates info from file-system layer to storage-management layer
- Challenges
  - Where to instantiate the deletion requests to file content?
  - What and how to track?
  - How to interact with TAP?

Where to instantiate deletion requests to file content?

- Can a file system just issue zeroed blocks?



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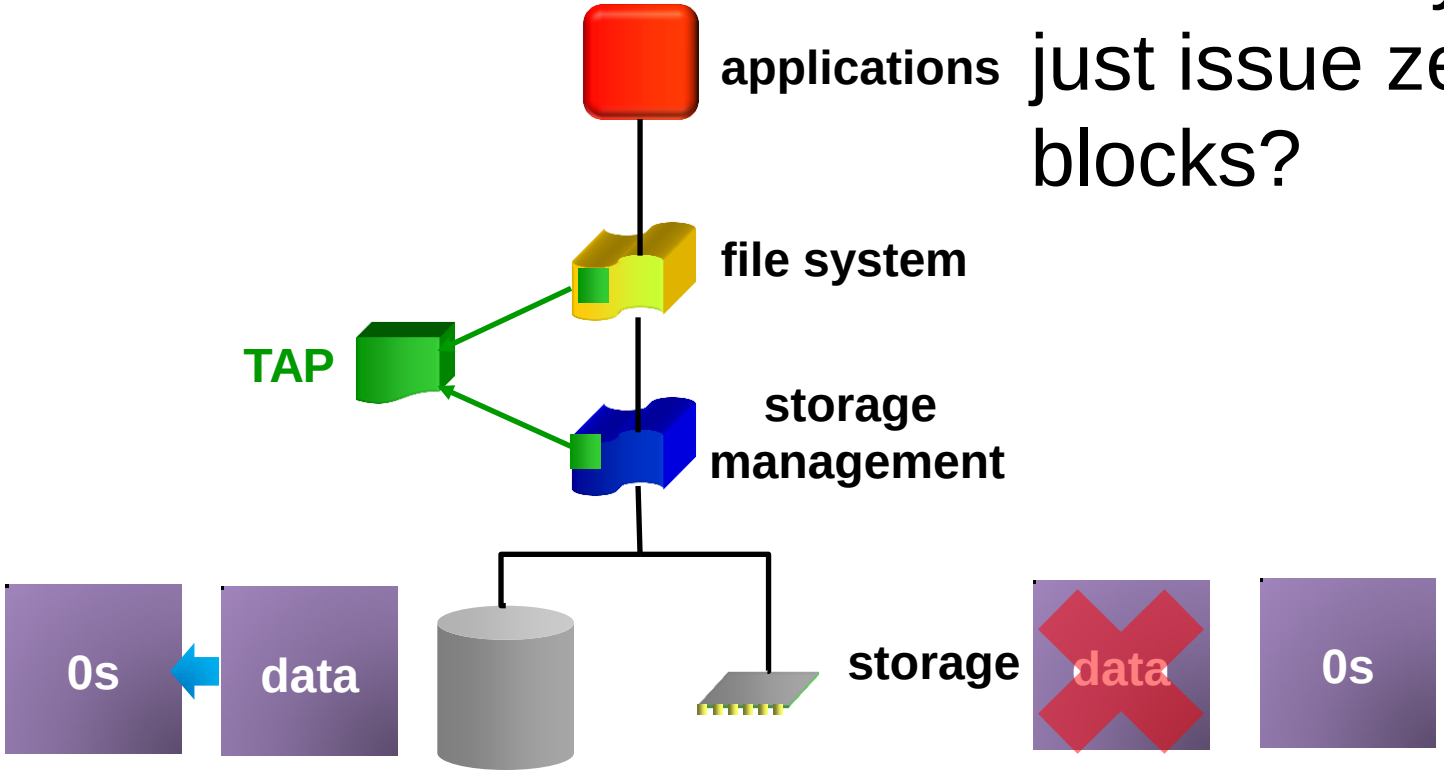

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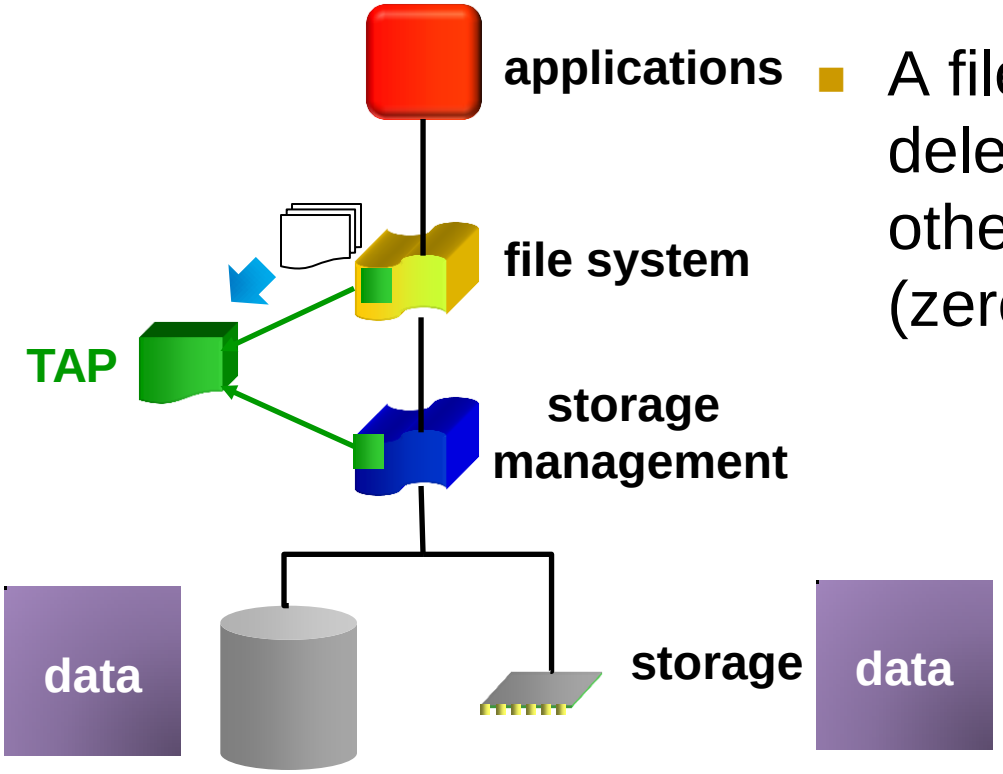
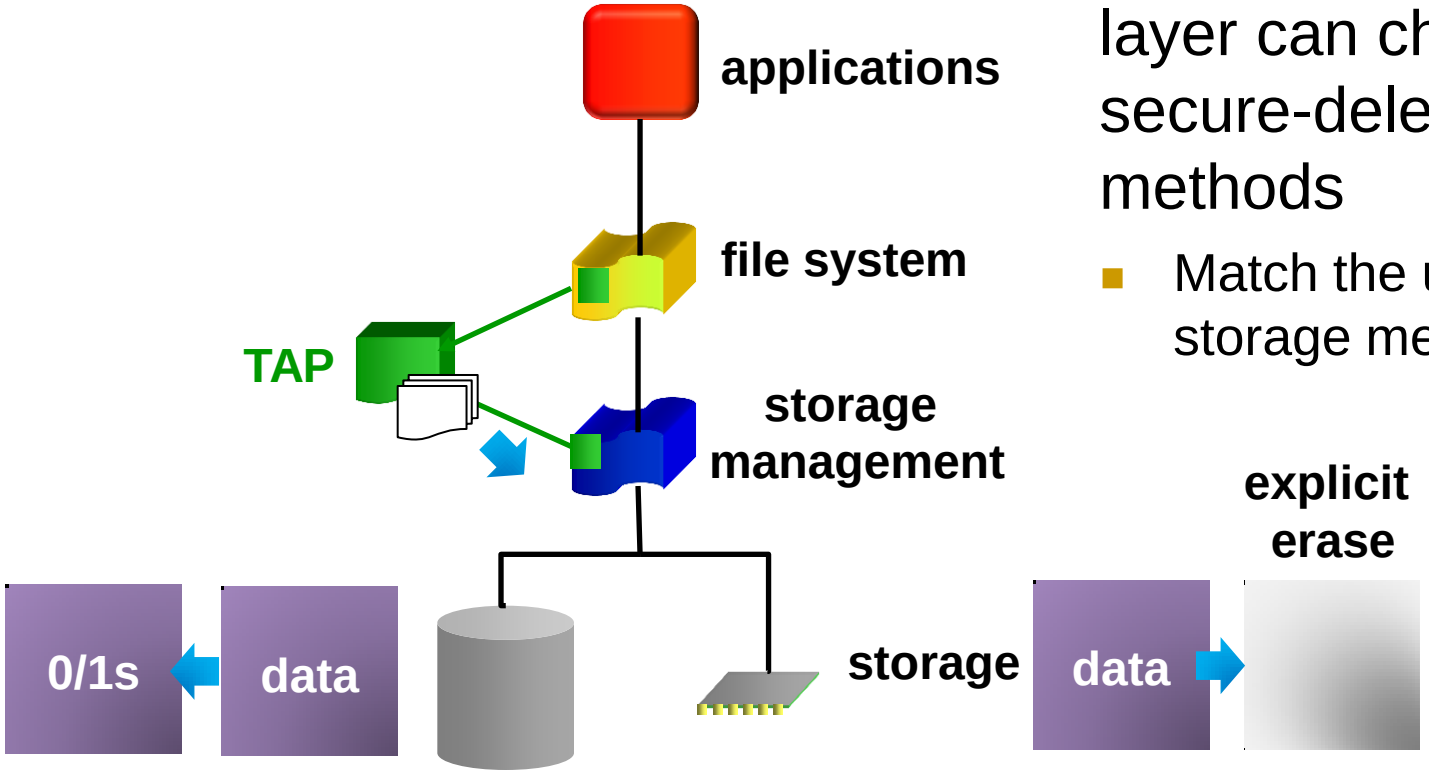


- Instead
  - A file system attaches deletion reminders to other deletion requests (zeroing allocation bits)

Where to instantiate deletion requests to file content?



- Storage-management layer can choose secure-deletion methods
  - Match the underlying storage medium

What to track?

- Tracking deletion is not enough
  - At the secure-deletion time
    - Versions of a file's blocks may have been stored
    - Metadata may not reference to old versions
      - Need additional persistent states to track old versions
- TrueErase deletes old versions along the way
  - Overwriting a sensitive data

    = Secure deletion + update (***secure write***)
  - Tracks all in-transit sensitive updates

What to track?

- Tracking sensitive updates is still not enough
  - Metadata items are small
  - A metadata block can be shared by files with mixed sensitive status
    - A non-sensitive request can make sensitive metadata appear in the storage data path
- TrueErase tracks all in-transit updates
  - For simplicity and verification

How to track?

- Challenges
  - Reuse of name space (i-node number), data structures, memory addresses
  - Versions of requests in transit
- TrueErase
  - Global unique page ID per memory page

Tracking Granularity

- TrueErase tracks physical sector numbers (e.g., 512B)
  - Smallest update unit
  - GUID: global unique page ID + sector number

How to interact with TAP?

- Report_write() creates a per-sector tracking entry
- Report_delete() attaches deletion reminders to a tracking entry
- Report_copy() clones a tracking entry and transfers reminders
- Cleanup_write() deletes a tracking entry
- Check_info() retrieves the sensitive status of a sector and its reminders

Enhanced Storage-management Layer

- Decide which secure-deletion method to use
  - Based on the underlying storage medium
  - We used NAND flash for this demonstration

NAND Flash Basics

- Writing is slower than reading
  - Erasure can be much slower
- NAND reads/writes in ***flash pages***
  - Deletes in ***flash blocks***
    - Consisting of contiguous pages

NAND Flash Basics

- In-place updates are not allowed
  - Flash block containing the page needs to be erased before being written again
    - In-use pages are migrated elsewhere
- Each location can be erased 10K -1M times

Flash Translation Layer (FTL)

- To optimize performance
  - ***FTL*** remaps an overwrite request to an erased empty page
- To prolong the lifespan
  - ***Wear leveling*** evenly spreads the number of erasures across storage locations

Added NAND Secure-deletion Commands

- Secure_delete(pages)
  - Copies other in-use pages from the current flash block to elsewhere
  - Issue erase command on the current block
- Secure_write(page)
  - Write the new page
  - Call Secure_delete() on the old (if applicable)

Crash Handling

- A crash may occur during a secure operation
  - Page migration may not complete
- Since copies are done first
  - No data loss; but potential duplicates
  - Journal recovery mechanisms will reissue the request, and secure operations will continue

Wear Leveling

- When flash runs low on space
  - Wear leveling compacts in-use pages into fewer flash blocks
- Problem: internal storage reorganization
  - No respect for file boundaries, sensitive status

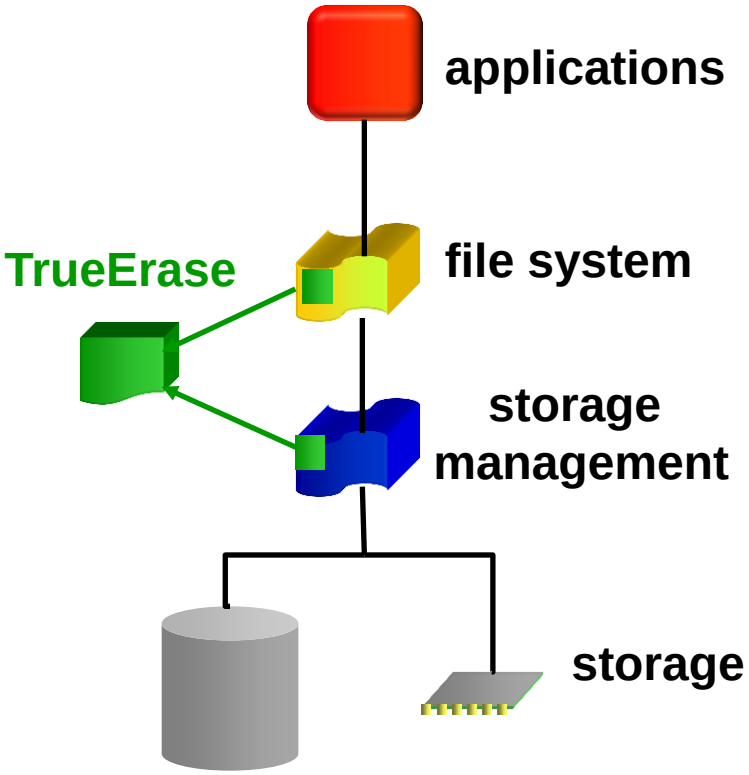
Wear Leveling

- TrueErase
  - Stores a sensitive-status bit in per-page control areas
    - Used to enforce secure-deletion semantics
  - May not always be in sync with the file-system-level sensitive status
    - E.g., short-lived files
    - When the bit disagrees with file system's secure status, mark the bit sensitive and treat it as such

File-system-consistency Properties and Secure Deletion

- File-system-consistency properties
  - A file's metadata reference the right data and metadata versions throughout the data path
- For non-journaling file systems
  - ***Reuse-ordering*** & ***pointer-ordering properties***
  - Without both (e.g., ext2), a file may end up with blocks from another file
- For journaling file systems
  - ***Non-rollback property***

Without Pointer-ordering Property



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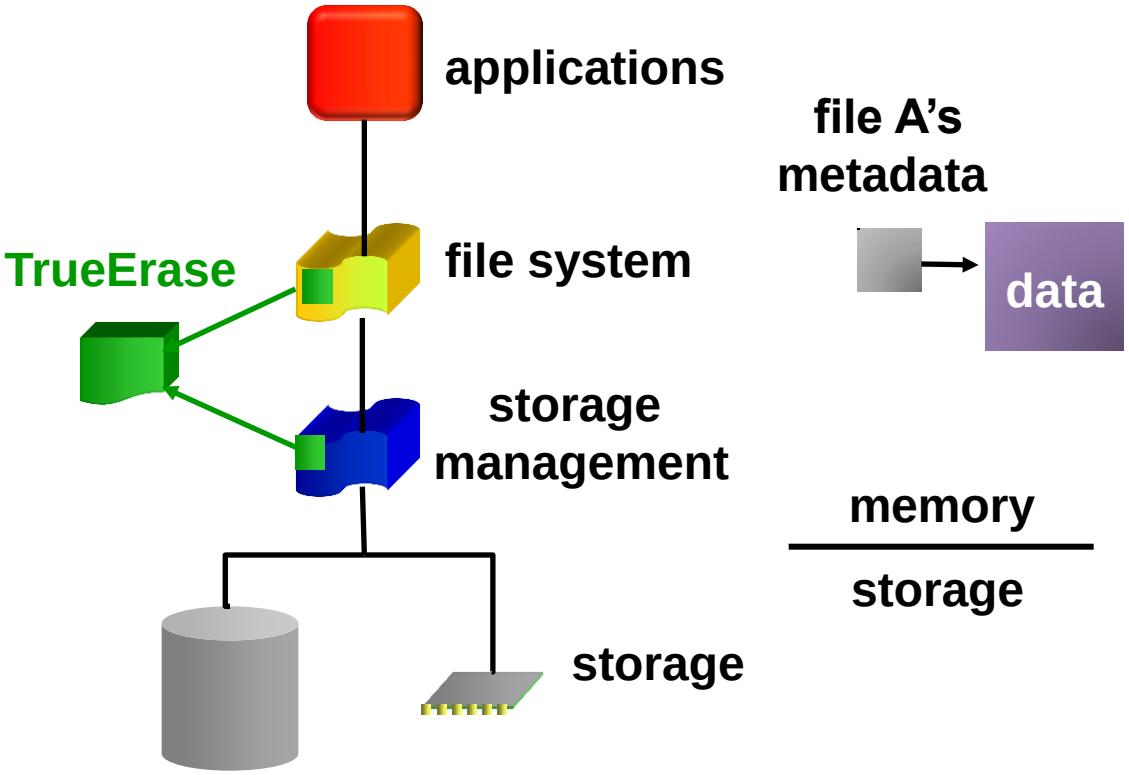

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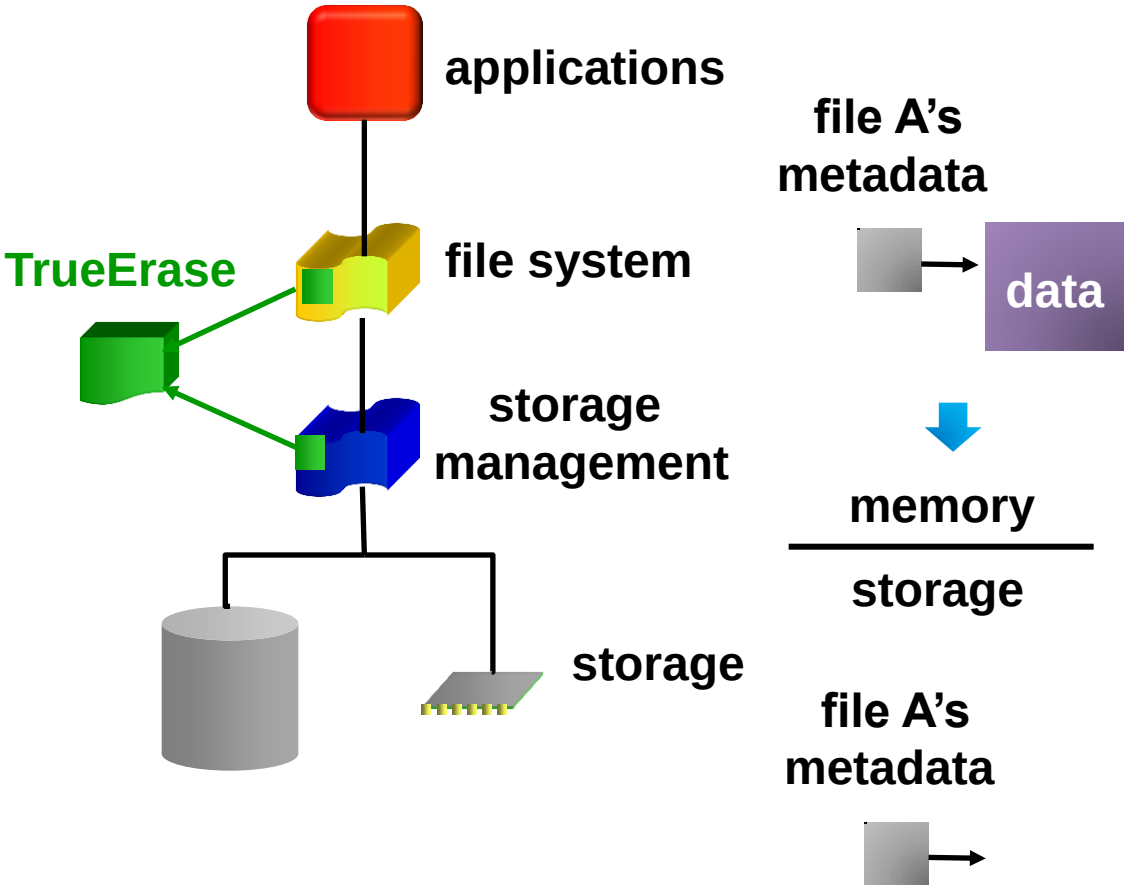

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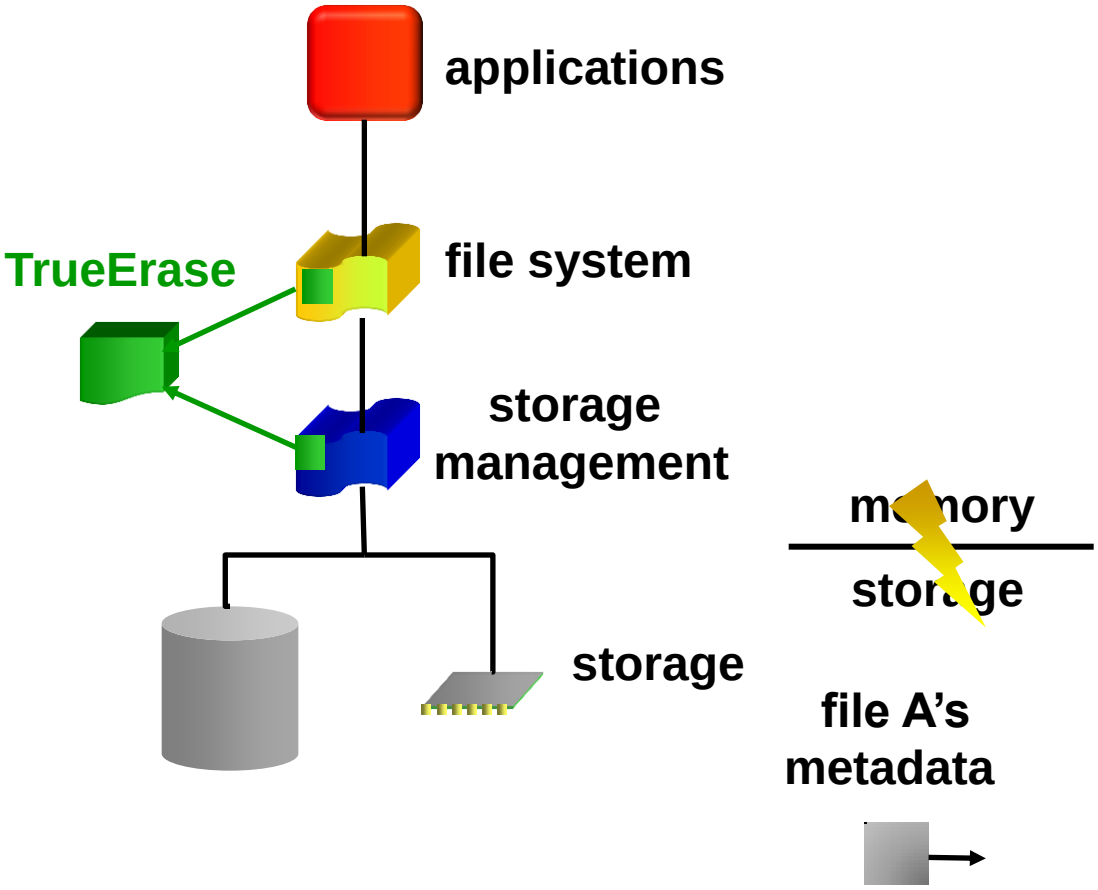

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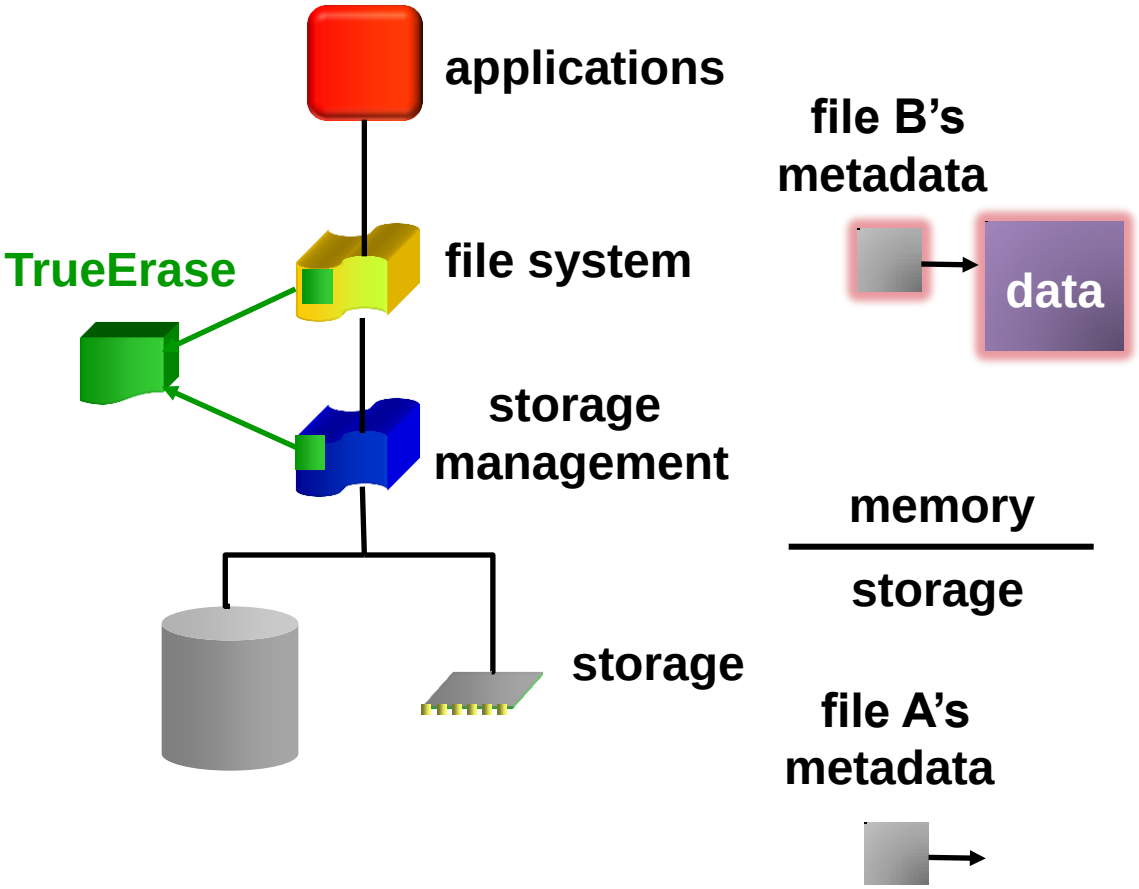

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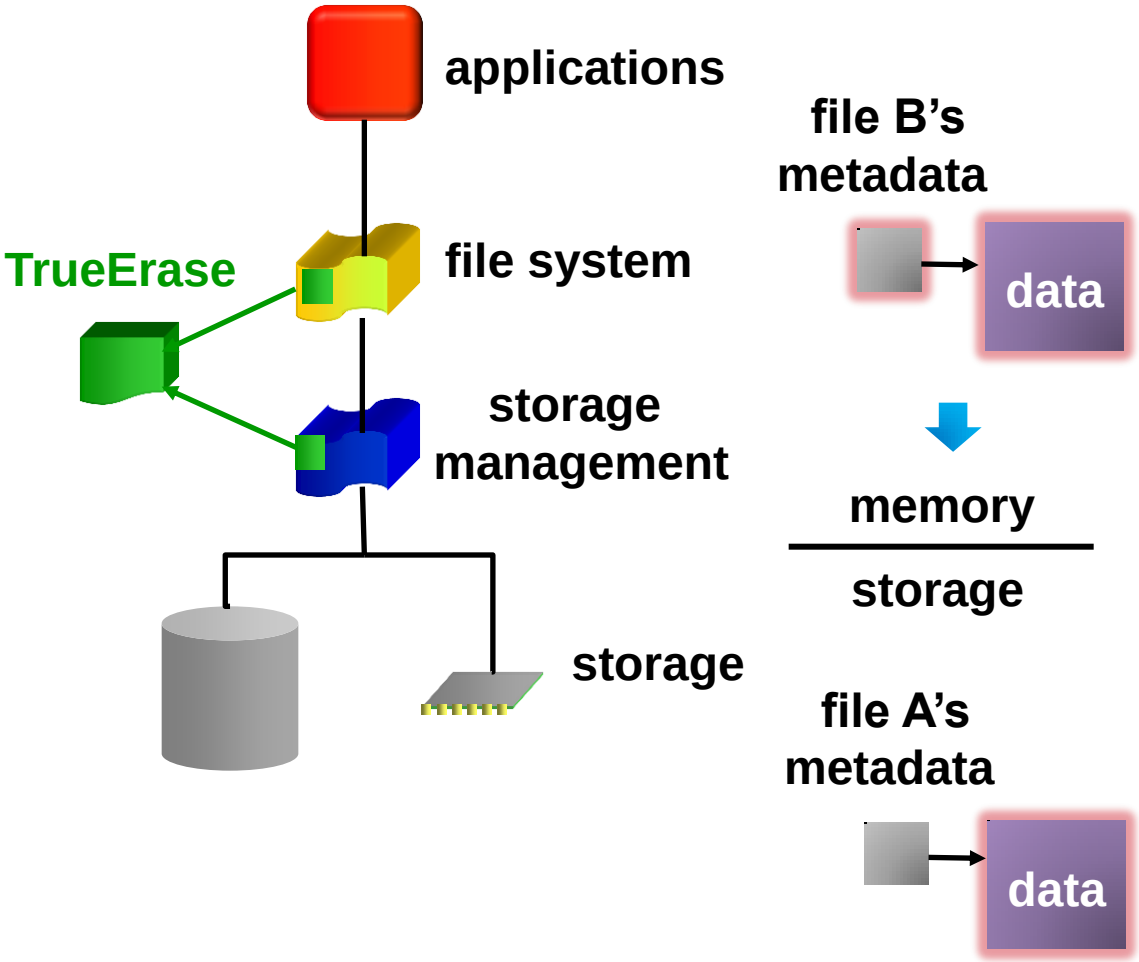
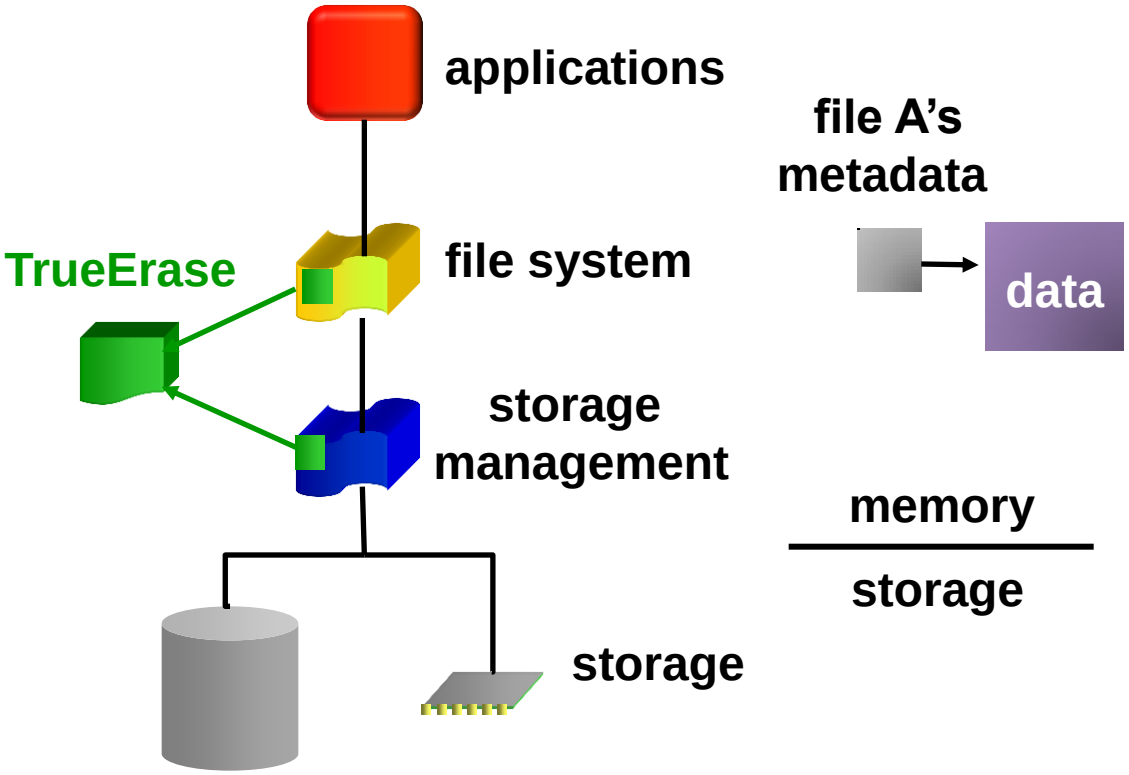


- Secure deletion of A can end up deleting B's block

Pointer-ordering Property



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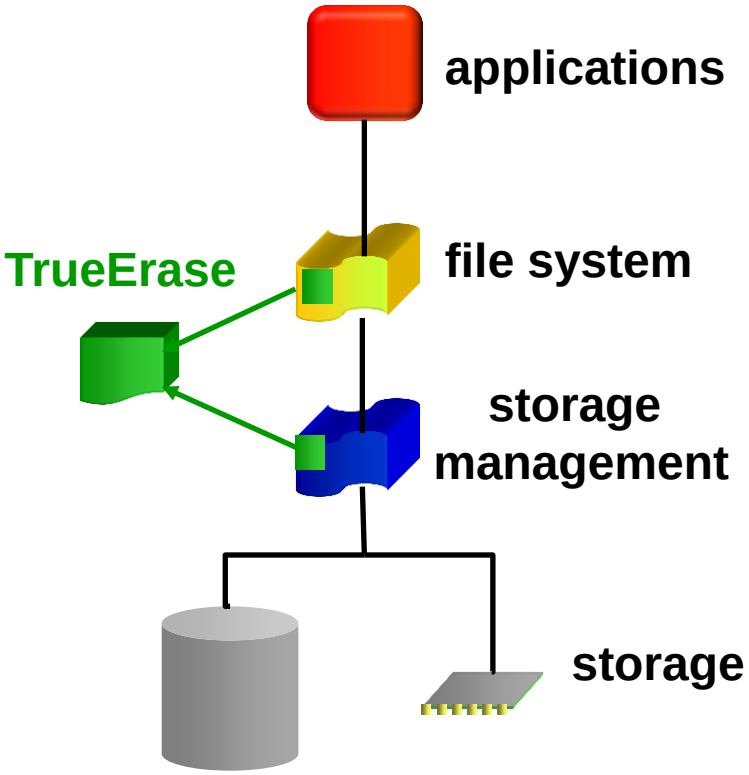
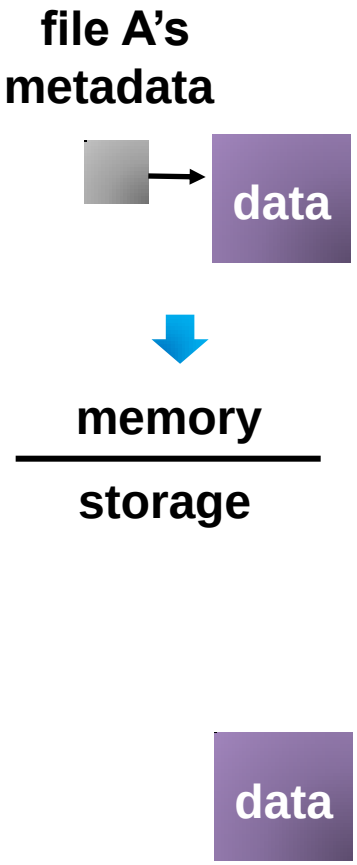
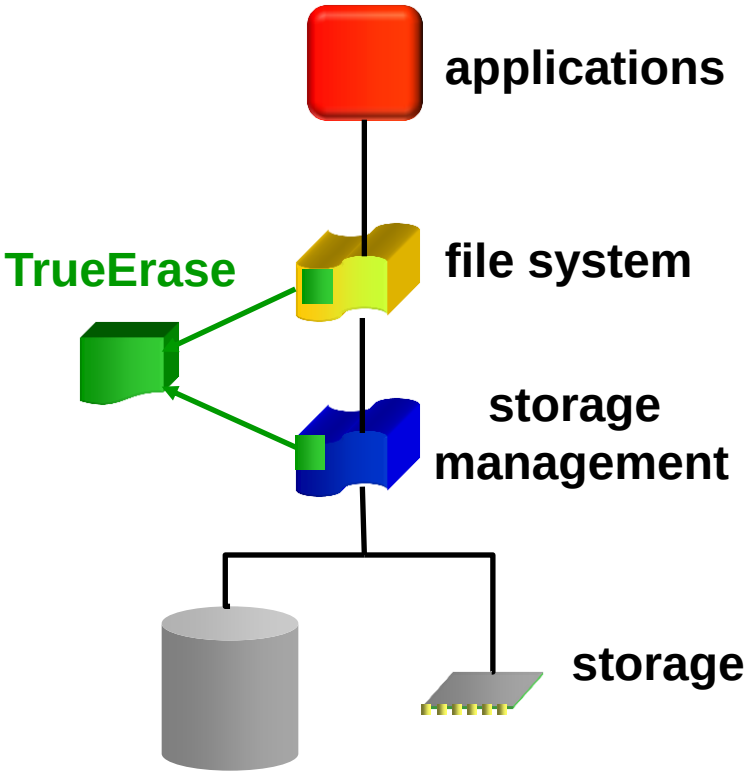
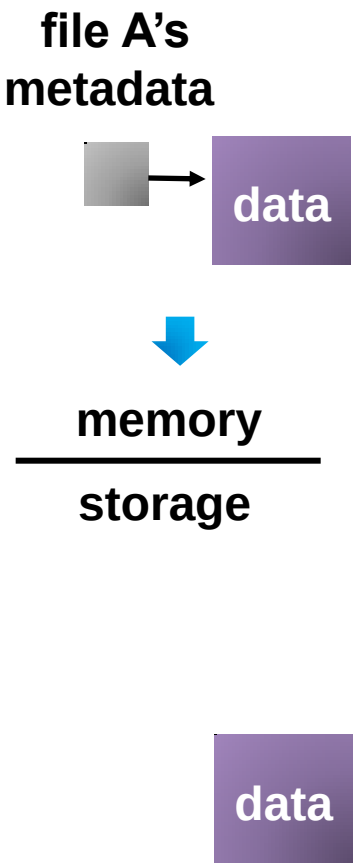




- Data blocks are propagated first

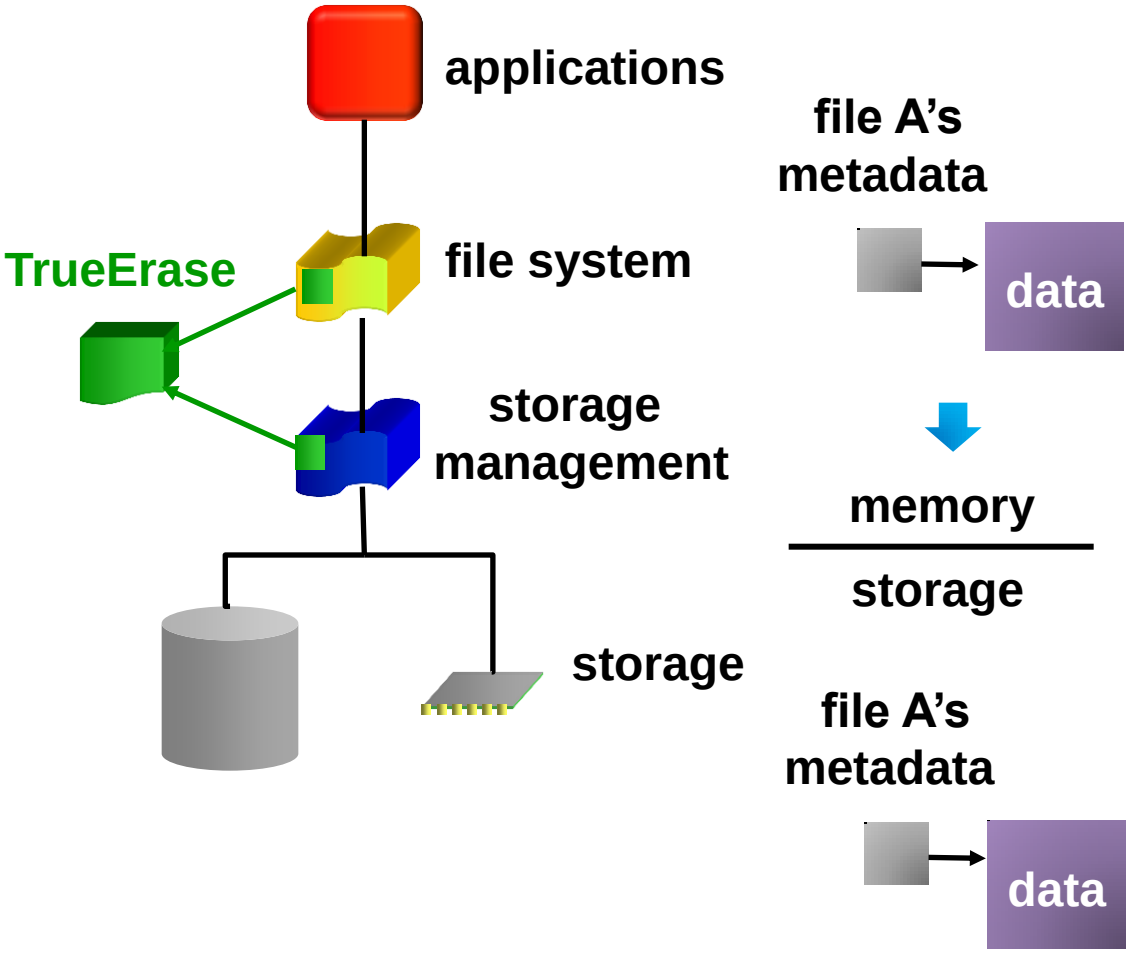
Pointer-ordering Property



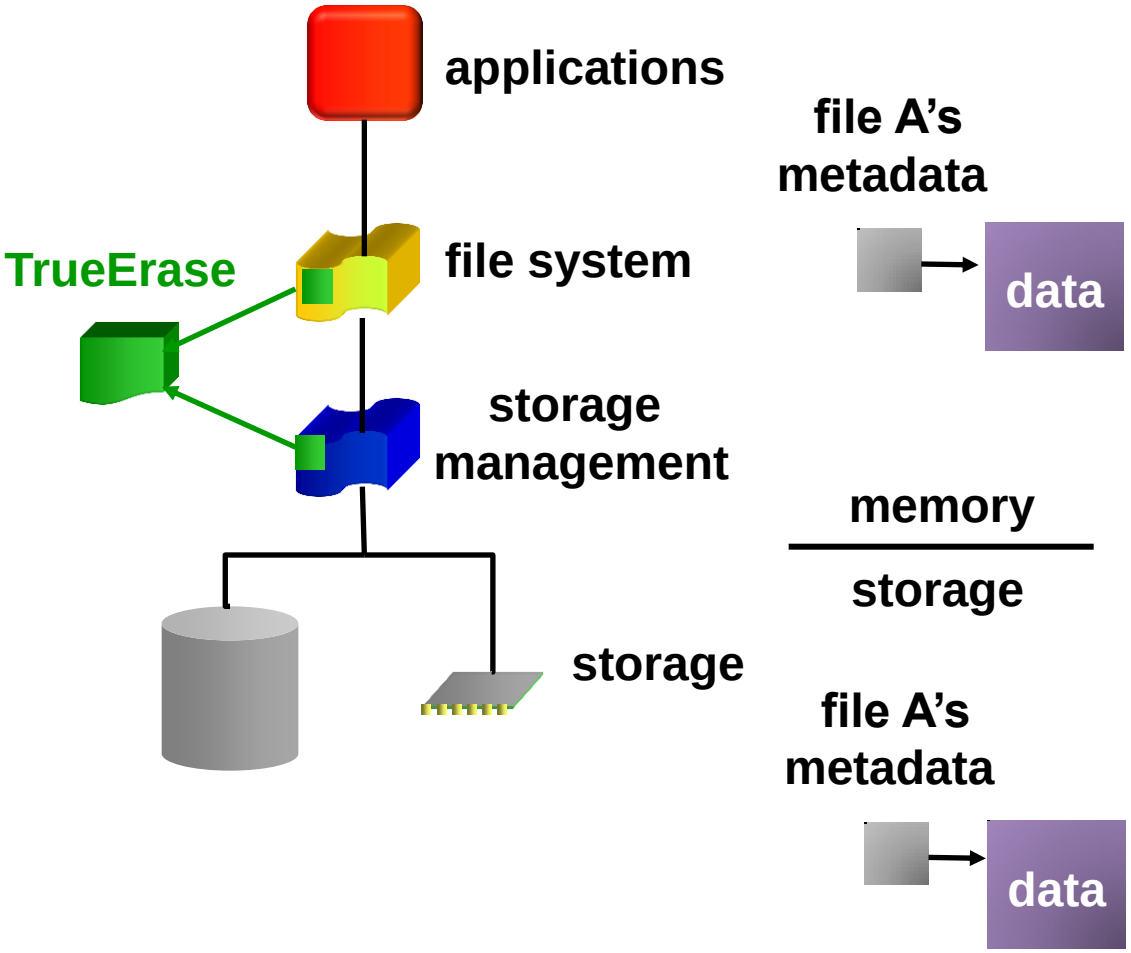


- May need to perform secure write
- Need to handle crash at this point (remove unreferenced sensitive blocks at recovery time)
- Need to ensure persistence (e.g., disabling storage-built-in caches)

Pointer-ordering Property



Without Reuse-ordering Property



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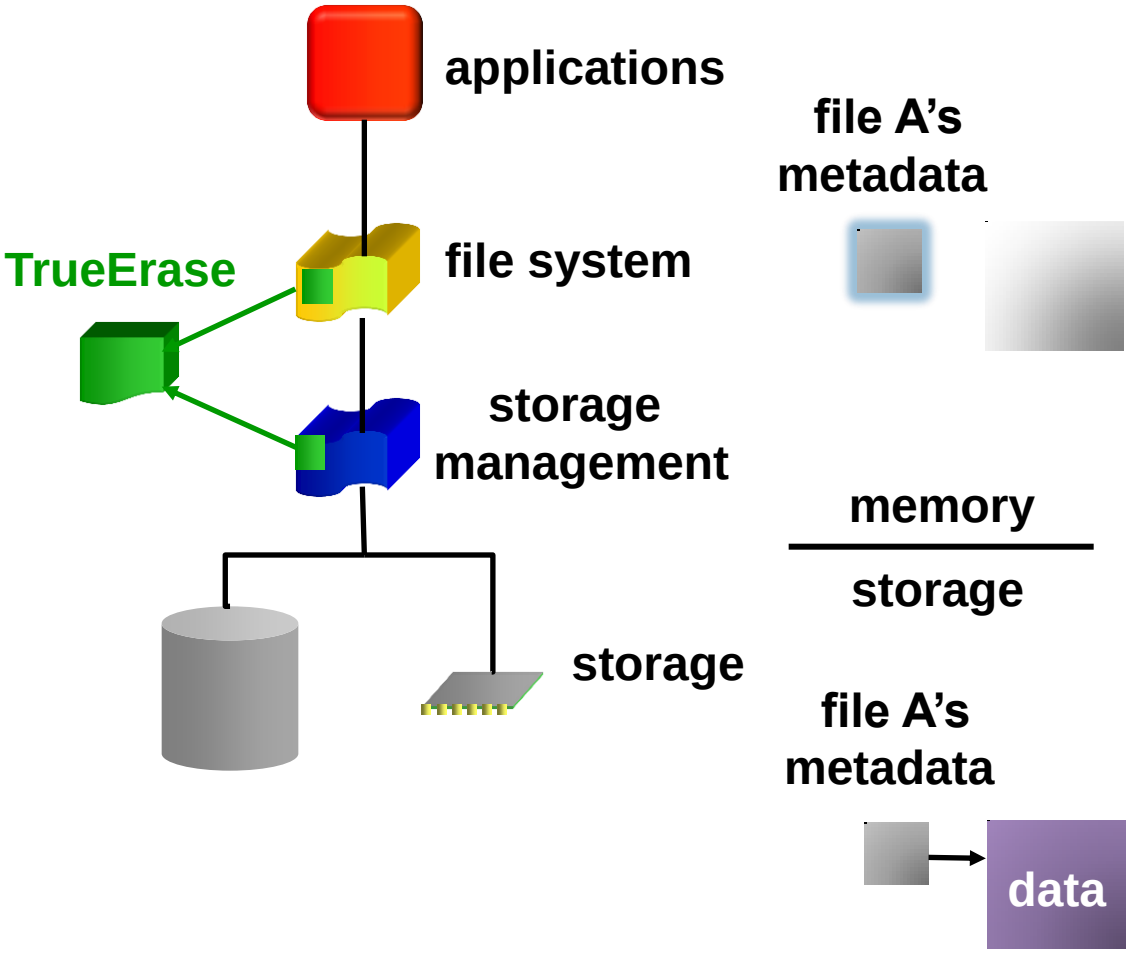

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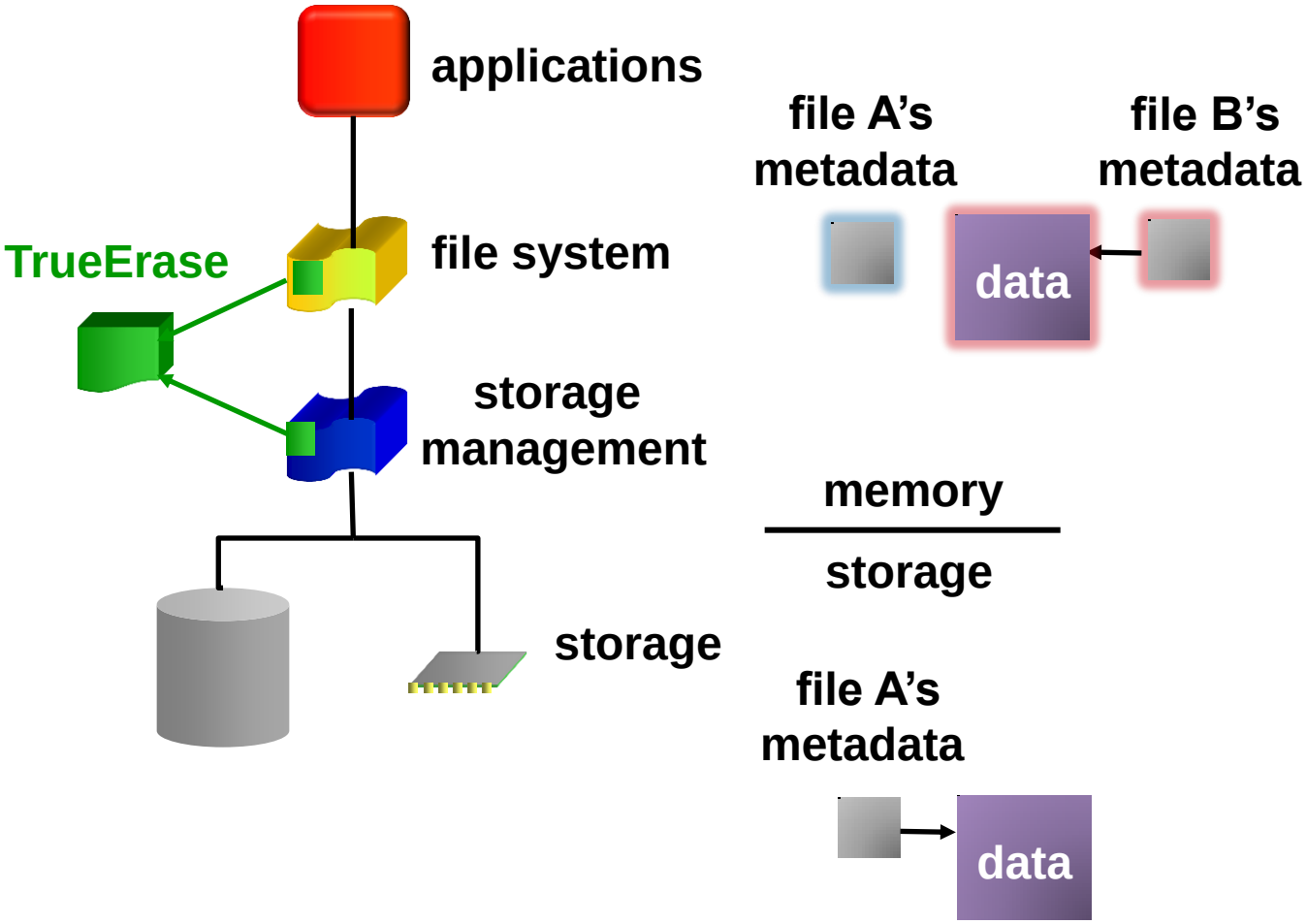
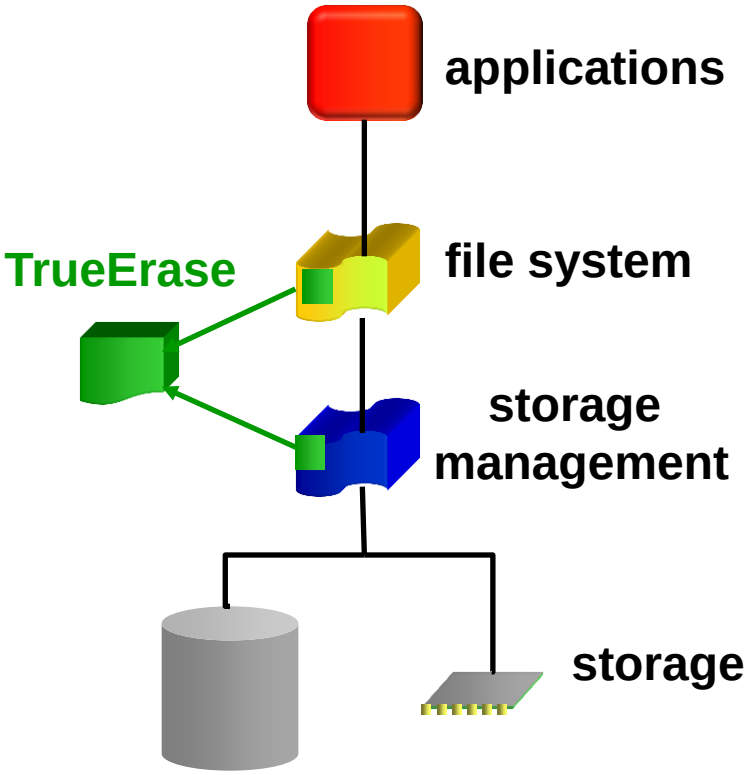
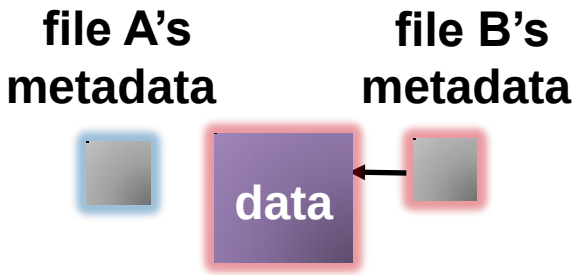


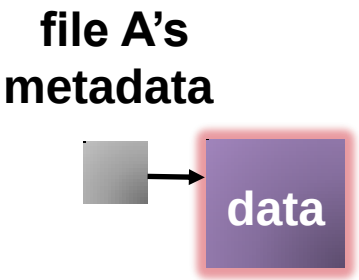
Without Reuse-ordering Property





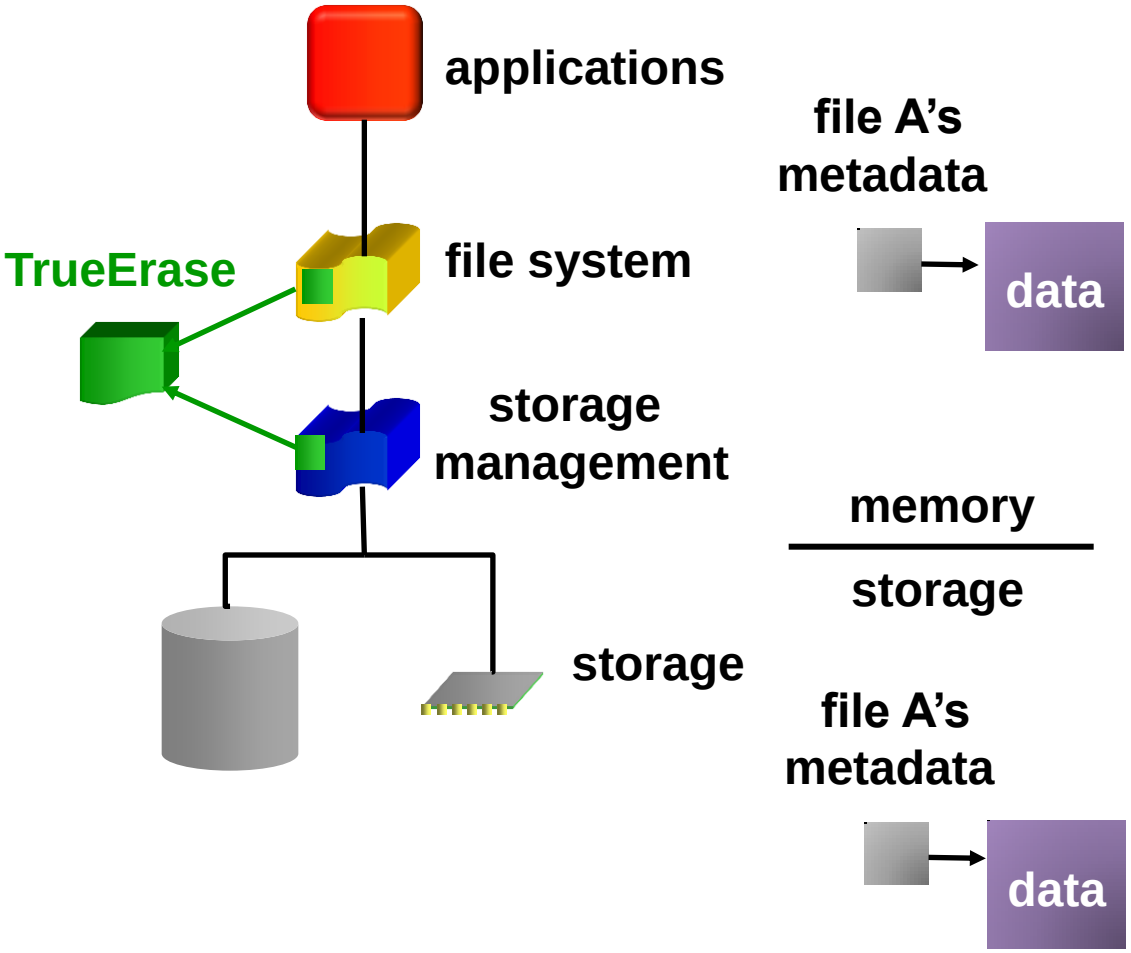
memory

storage

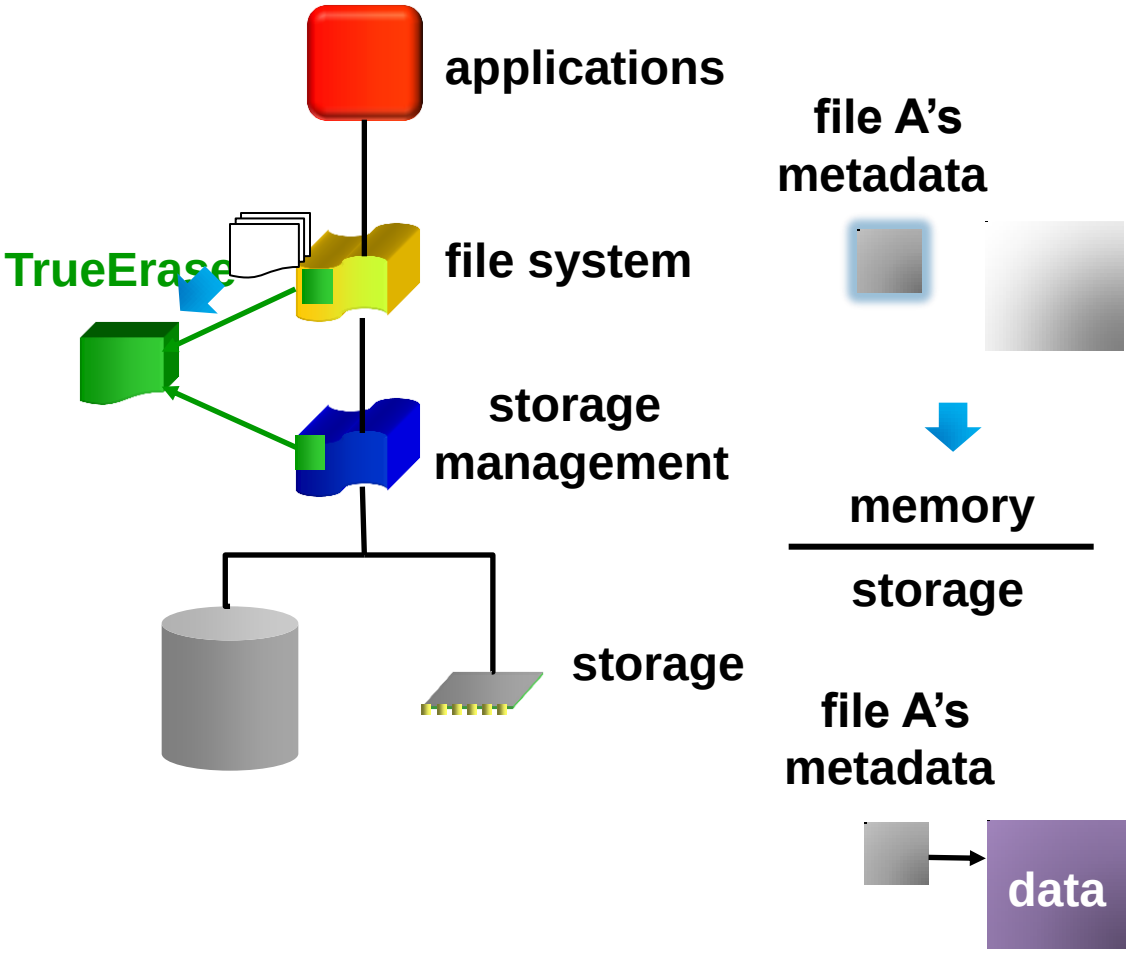


- Secure deletion of A can end up deleting B's block

Reuse-ordering Property

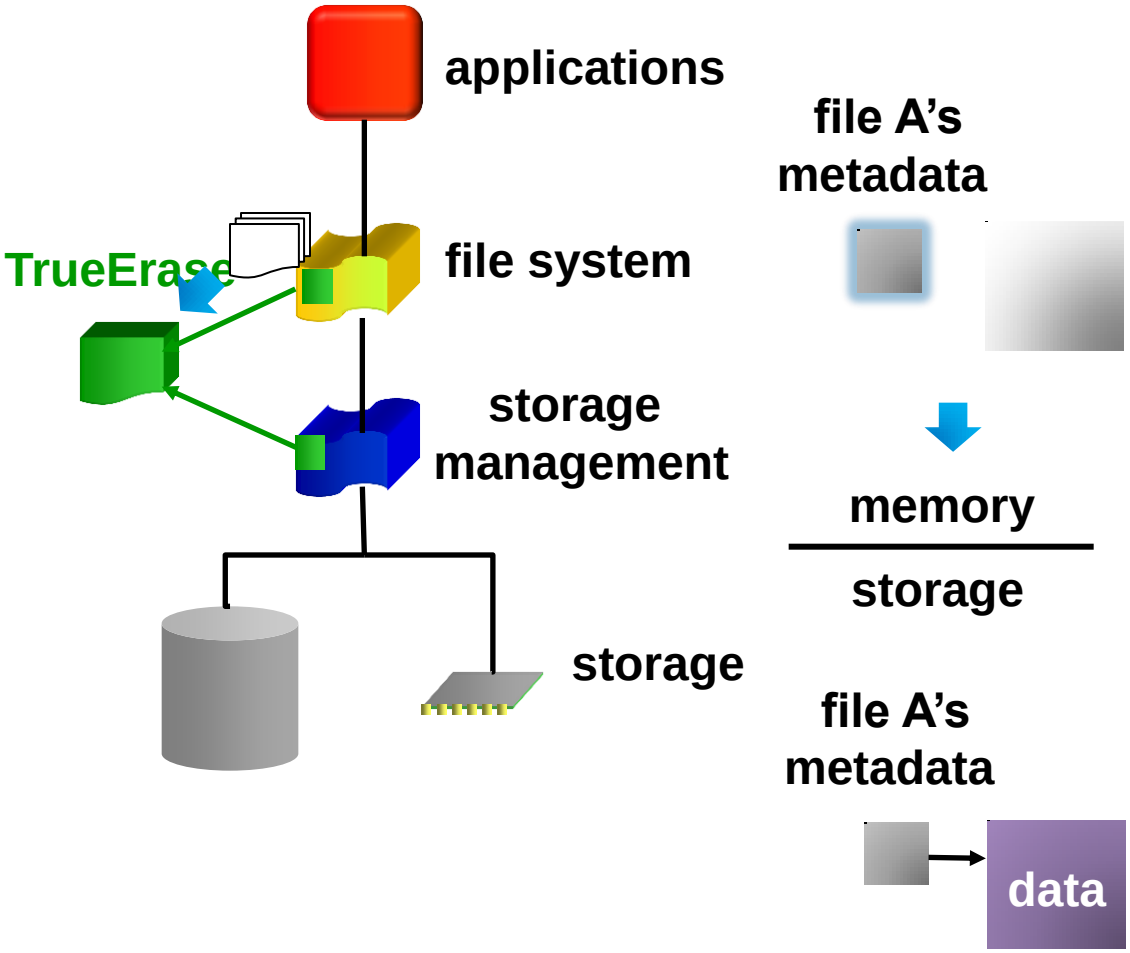


Reuse-ordering Property



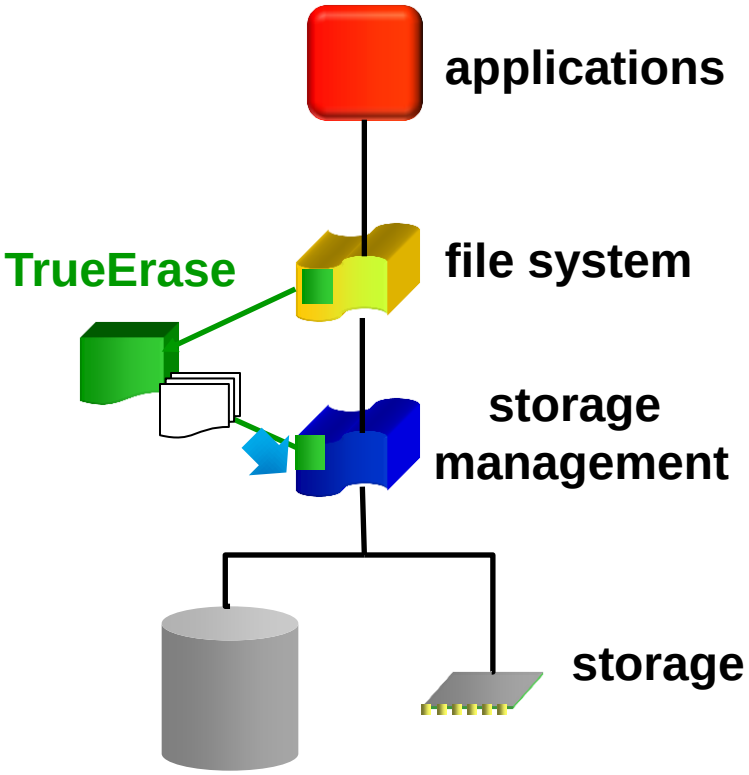
- A block cannot be reused until its free status is persistent

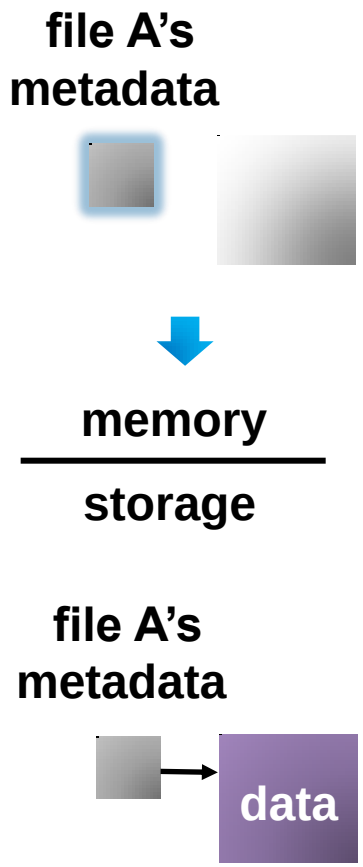
Reuse-ordering Property



- Pending updates to the unreferenced data block should not be written
- Unreferenced in-memory data blocks need to be wiped

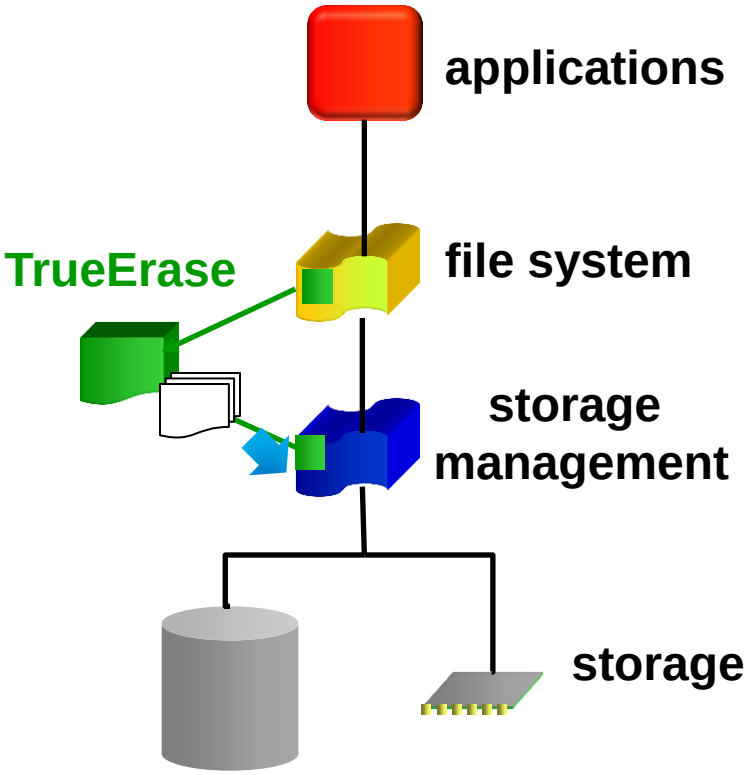
Reuse-ordering Property

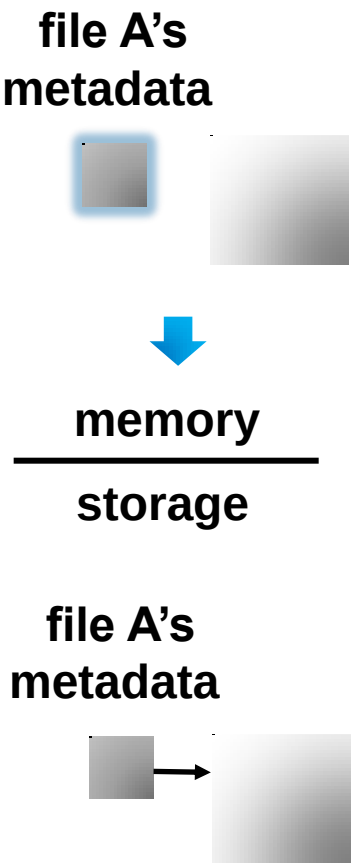




- By pointer ordering, all prior data updates are flushed
- Secure delete the data block before making its free status persistent

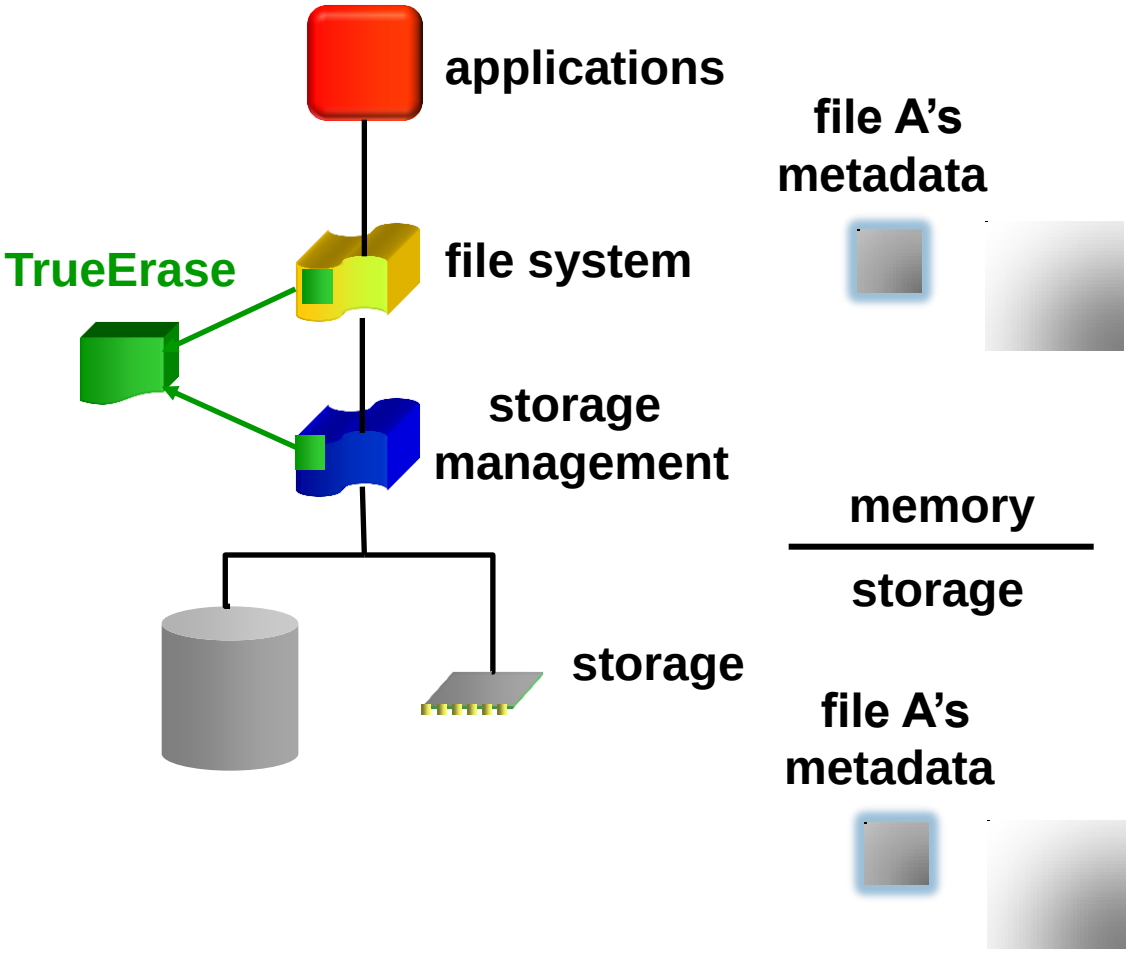
Reuse-ordering Property





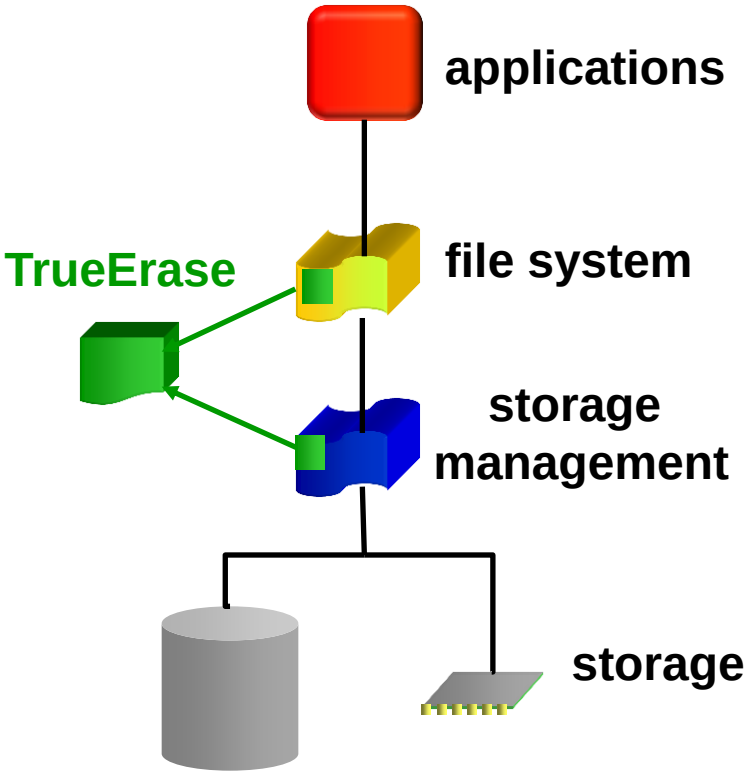
- A crash will show secure deletion in progress
- Recovery mechanism will reissue file deletion

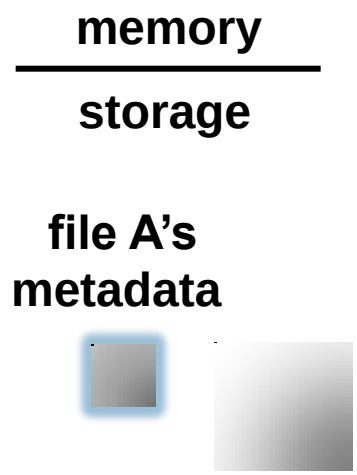
Reuse-ordering Property



- Need to ensure persistence (e.g., disabling storage-built-in caches)

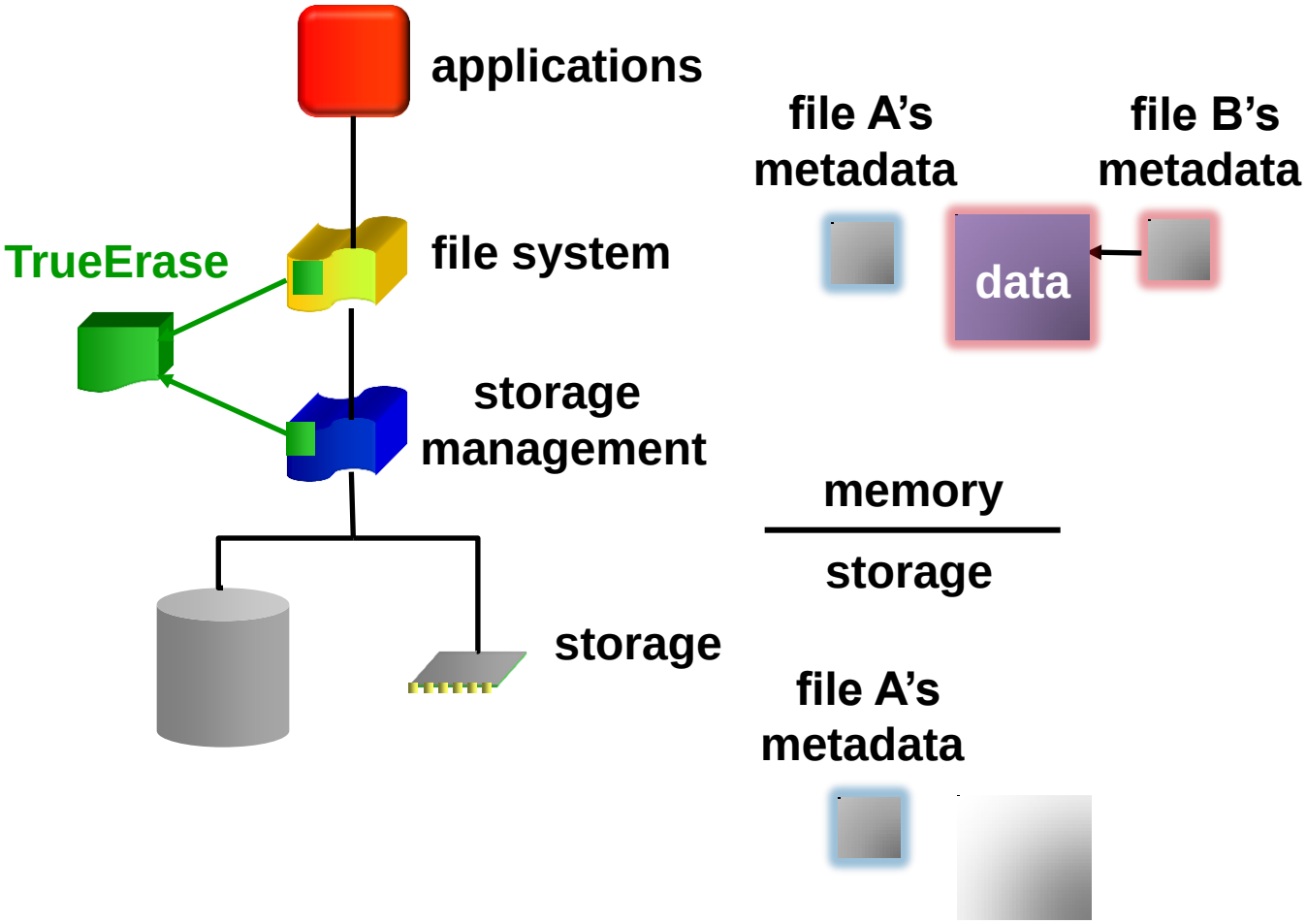
Reuse-ordering Property





- Static file types and ownerships for in-transit blocks
- Still need GUIDs to track versions
- Need to handle dynamic sensitive mode changes (once marked sensitive, always sensitive)

Reuse-ordering Property



Non-rollback Property

- Older versions of updates will not overwrite newer versions persistently
- Implications
  - An update followed by a secure deletion will be applied in the right order
  - Need to disable some optimizations at the storage-management layer (e.g., built-in cache)
  - Merging/splitting requests okay (we track sectors)
  - A consolidated update is sensitive, if one is sensitive

Structure of Corner Cases

- Ensuring that a secure deletion occurs before a block is persistently declared free
- Hunting down the persistent sensitive blocks left behind after a crash
- Making sure that secure deletion is not applied to the wrong file
- Making sure that a securely deleted block is not overwritten by a buffered unref block
- Handling versions of requests in transit

Crash Handling

- At recovery time
  - Replay journal and reissue incomplete deletion operations, with all operations handled securely
  - For flash, securely delete the journal and sensitive blocks not referenced by the file system
  - For disk, securely overwrite journal and all free space

TrueErase Implementation

- Linux 2.6.25
- File system: ext3 with its jbd journaling layer
  - Proven to adhere to the file-system-consistency properties [SIVA05]
- NAND flash: SanDisk's DiskOnChip
  - Lack of access to flash development environ.
  - Dated hardware, but the same design principle
- Storage-management layer: Inverse NAND File Translation Layer (INFTL)

Implementation-level Highlights

- Steps in deletion sequence can be expressed in secure write/delete data/metadata
- Exploited group-commit semantics
  - Reduced the number of secure operations
- Handled buffer/journal copies
- Handled consolidation within and across journal transactions

Verification

- Basic cases
  - Sanity checks
  - PostMark with 20% sensitive files
  - Reporting of all updates
  - File-system-consistency-based corner cases
- TAP state-space verification

TAP State-space Verification

- State-space enumeration
  - Tracked down ~10K unique reachable states, ~2.7M state transitions
  - Reached depth of 16 in the state-space tree
- Used two-version programming for verification
  - One based on conceptual rules
  - One based on the TAP kernel module
  - Identified 4 incorrect rules and 3 bugs

Empirical Evaluation

- Workloads
  - PostMark
    - Modified with up to 10% of sensitive files
      - Sensitive files can be chosen randomly
    - Each file operation takes < 0.17 seconds
      - Good enough for interactive use
  - OpenSSH **`make`** + sync with 27% of files that are newly created marked sensitive
    - Overhead within a factor of two

Related Work

- TRIM command
- FADED
- Type-safe disk
- Modified YAFFS with secure-deletion support

- TrueErase
  - Legacy-compatible, persistent-state-light, centralized info-propagation channel

Lessons Learned

- Retrofitting security features is more complex than we thought
- The general lack of raw flash access and development environments
  - Vendors try to hide complexities
  - File-system consistency and secure deletion rely on exposed controls/details for data layout/removal

Lessons Learned

- A holistic solution would not be possible
  - Without expertise across layers and research fields
- Highlights the importance of knowledge integration

Conclusion

- We have presented the design, implementation, evaluation, and verification of TrueErase
  - Legacy-compatible, per-file, secure-deletion framework
- A secure-deletion solution that can withstand diverse threats remains elusive
  - TrueErase is a promising step toward this goal

Acknowledgements

- National Science Foundation
- Department of Education
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- Florida State University Research Foundation

Questions?

- Google keyword: TrueErase

Thank you for your attention!