Secure Data Deletion from Persistent Media

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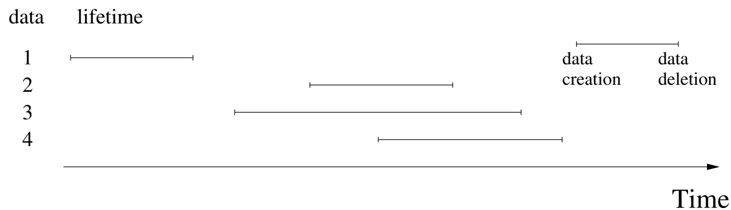
Secure deletion: the task of deleting data from a physical medium so that the data is irrecoverable by an adversary.

Security Model: Coercive Adversary

- A coercive adversary can:
  - Unexpectedly compromise all data stored on the user's storage media
  - Obtain any secret keys / passphrases to access this data
  - May strike multiple times
- Consequently:
  - No extraordinary actions can be taken to delete data
  - Any data the user can access when the adversary strikes is exposed to the adversary
- Models, for example, a subpoena

Data Life Timeline



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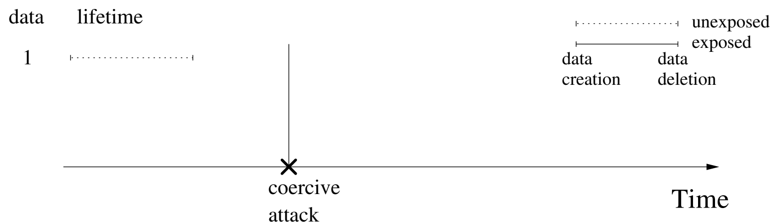

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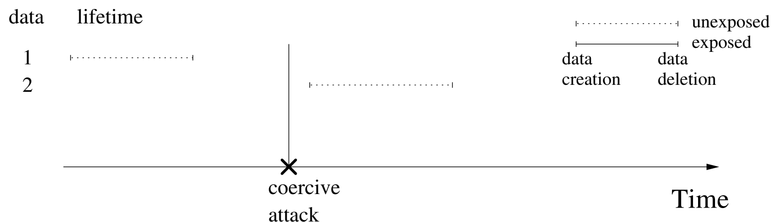

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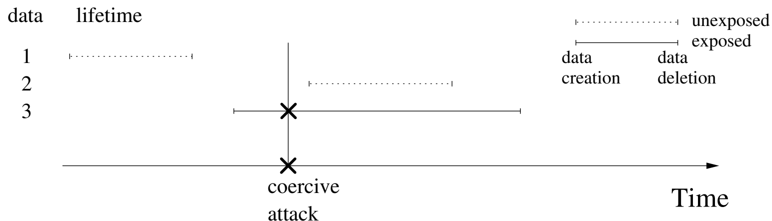

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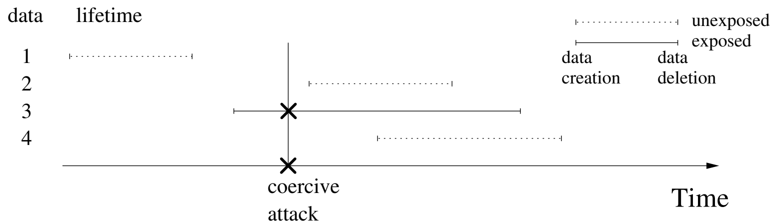
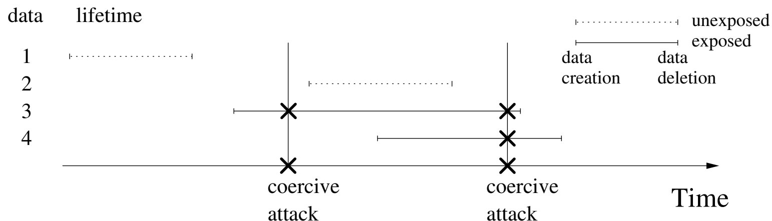


Data Life Timeline

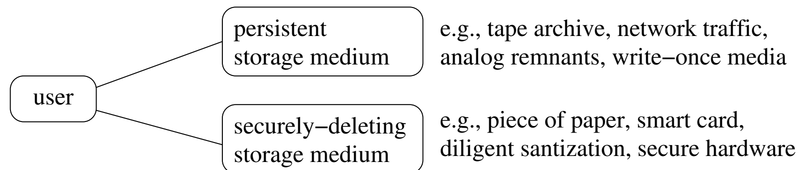


Persistent Storage Medium

- **Persistent Storage Medium** is a storage medium that does not provide deletion
- Data written onto it is permanently available
- We assume that an adversary who compromises it see the entire write history

So if we assume the adversary eventually compromises the persistent storage, how can we securely delete *anything*?

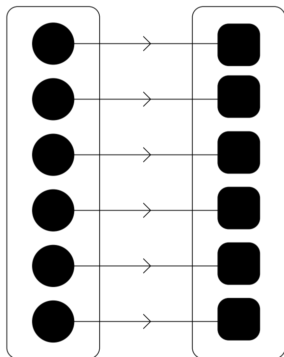
Our Model



Our Contributions

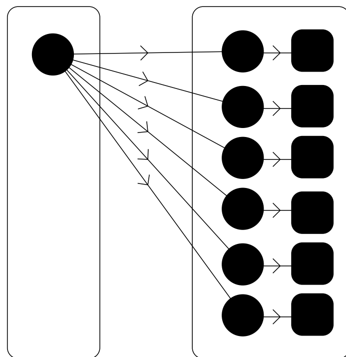
- We present the **key disclosure graph**: a tool to model and reason about worst-case adversarial knowledge for persistent storage
- We present a generic **shadowing graph mutation**: a graph mutation that can express the update behaviour of arborescent data structures, obeys the "rules" of the key disclosure graph, and facilitates secure deletion
- We characterize related work by their key disclosure graphs
- We design and implement an efficient caching B-Tree that uses shadowing graph mutations and securely deletes data from persistent storage
- We examine the performance and overhead for different caching strategies and file system workloads

Background: Two Extreme Solutions



securely−deleting storage medium

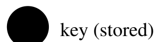
persistent storage medium

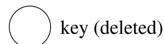


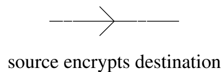
securely−deleting storage medium

persistent storage medium

Legend







Background: Two Extreme Solutions

A

B

C

$E_A(D_1)$

$E_B(D_2)$

$E_C(D_3)$

securely–deleting storage medium

persistent storage medium

A

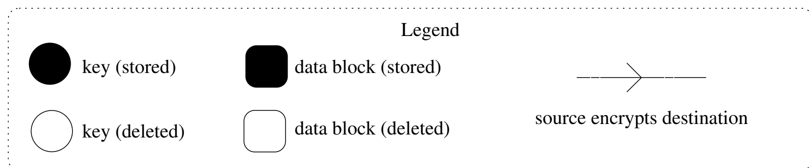
$E_A(B)$ $E_B(D_1)$

$E_A(C)$ $E_C(D_2)$

$E_A(F)$ $E_F(D_3)$

securely–deleting storage medium

persistent storage medium



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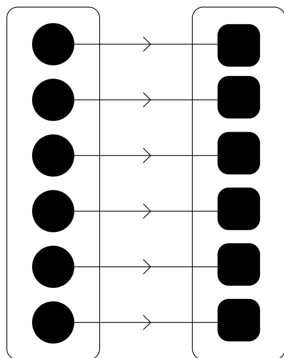
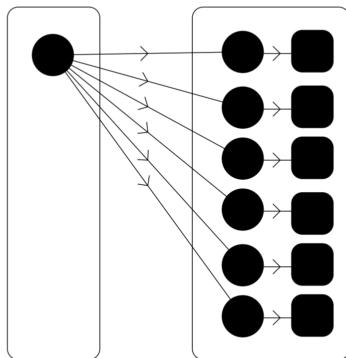


securely–deleting storage medium

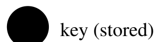
persistent storage medium



securely–deleting storage medium

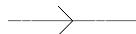
persistent storage medium

Legend

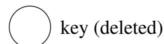


key (stored)

data block (stored)



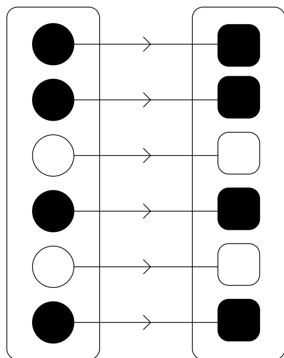
source encrypts destination



key (deleted)

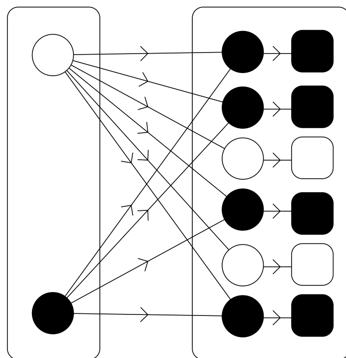
data block (deleted)

Background: Two Extreme Solutions



securely–deleting storage medium

persistent storage medium



securely–deleting storage medium

persistent storage medium

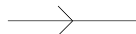
Legend

key (stored)

data block (stored)

key (deleted)

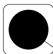
data block (deleted)



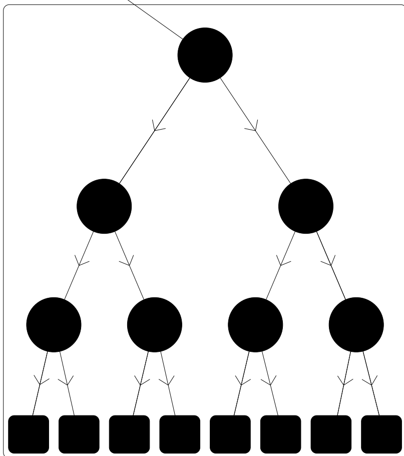
source encrypts destination

Background: Static Tree Solution

securely–deleting
storage medium



persistent
storage medium



Legend

key (stored)

key (deleted)

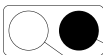
data block (stored)

data block (deleted)

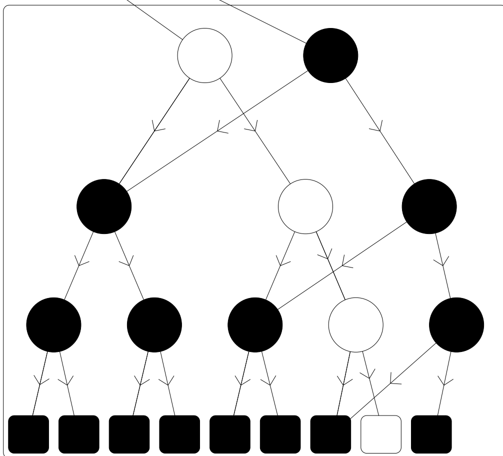
source encrypts destination

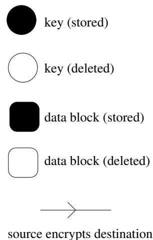
Background: Update Mechanism

securely–deleting
storage medium



persistent
storage medium

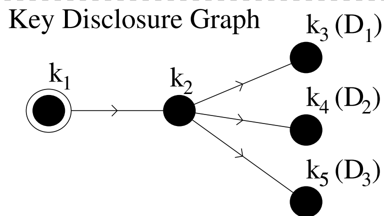




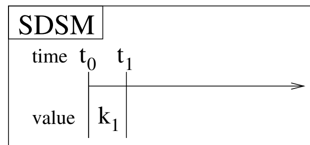
Static Tree Discussion

- Tree size/shape is fixed for eternity
  - Cannot accommodate new data
  - Tree-depth fixed even when sparse
- Proof of deletion is based on fixed shape
- Dynamic structures (e.g., B-Trees, balancing trees, etc) are more versatile
  - But the proofs become trickier with increased sophistication
- We provide a proof for all arborescent data structures by imposing condition on the update mechanism

Key Disclosure Graph

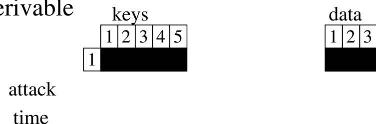


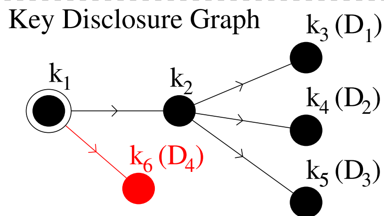
Storage Media Content



PSM

$E_{k_3}(D_1)$	$E_{k_4}(D_2)$	$E_{k_1}(k_2)$
$E_{k_2}(k_3)$	$E_{k_2}(k_4)$	$E_{k_5}(D_3)$
$E_{k_2}(k_5)$		





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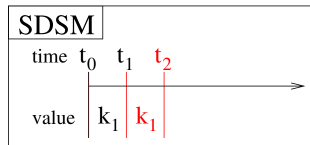

PSM			
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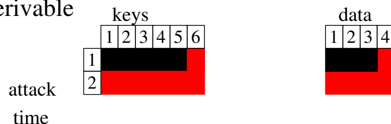
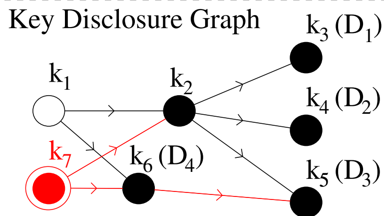
	$E_{k_2}(k_3)$	$E_{k_2}(k_4)$	$E_{k_5}(D_3)$
	$E_{k_2}(k_5)$	$E_{k_1}(k_6)$	$E_{k_6}(D_4)$



Key Disclosure Graph



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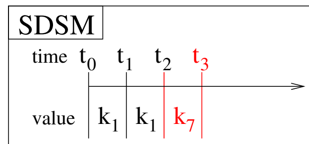

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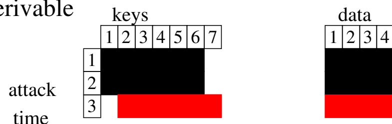
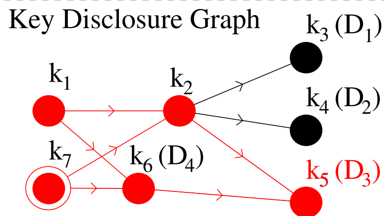
	$E_{k_2}(k_3)$	$E_{k_2}(k_4)$	$E_{k_5}(D_3)$
	$E_{k_2}(k_5)$	$E_{k_1}(k_6)$	$E_{k_6}(D_4)$
	$E_{k_6}(k_5)$	$E_{k_7}(k_2)$	$E_{k_7}(k_6)$



Key Disclosure Graph



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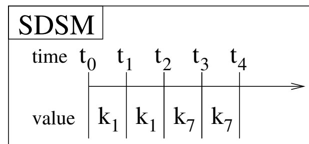

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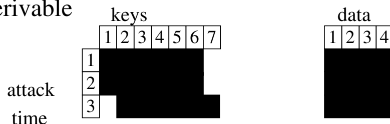

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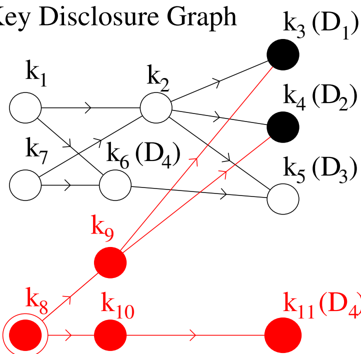

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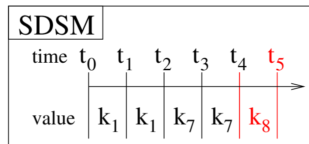

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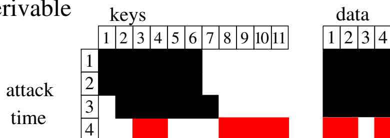
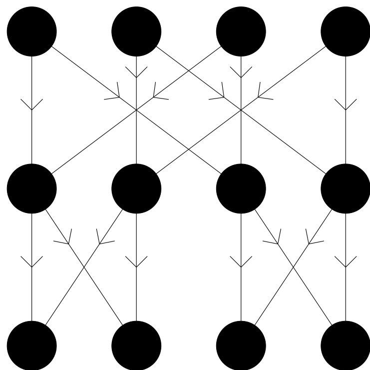
	$E_{k_2}(k_3)$	$E_{k_2}(k_4)$	$E_{k_5}(D_3)$
	$E_{k_2}(k_5)$	$E_{k_1}(k_6)$	$E_{k_6}(D_4)$
	$E_{k_6}(k_5)$	$E_{k_7}(k_2)$	$E_{k_7}(k_6)$
	$E_{k_8}(k_9)$	$E_{k_8}(k_{10})$	$E_{k_{10}}(k_3)$
	$E_{k_{10}}(k_4)$	$E_{k_{10}}(k_{11})$	$E_{k_{11}}(D_4)$



Secure deletion

- Secure deletion of data requires:
  - when writing data, ensuring all previous values stored in the SDSM cannot derive its key
  - when deleting data, determining all of the derivable ancestors in the KDG
  - making these ancestors all underivable
  - ancestor relation based on the ever-growing KDG
- How do we avoid storing the entire KDG?
  - require that in the KDG there is at most one unique path that connects any pair of vertices
  - in graph theory, such a graph is called a **mangrove**

Mangroves

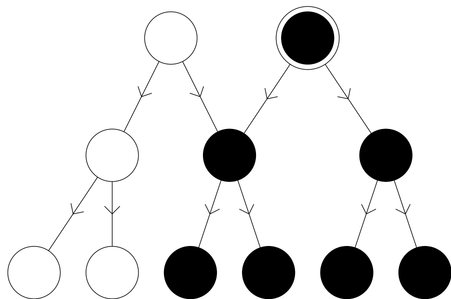


How do we ensure that the KDG is always a mangrove?
We use shadowed updates.

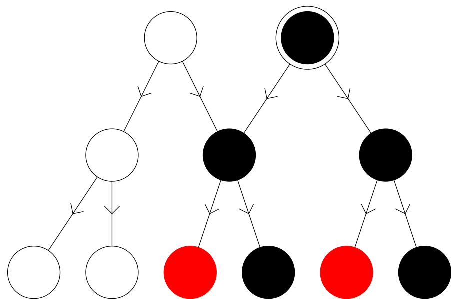
Shadowing

- Shadowed updates in a technique in file systems
  - New versions of data are written to new (empty) locations
  - Old version remains but is no longer valid
  - Anything that references the old version is also shadow-updated when referring to the new location
- We use **keys** instead of versions
  - Any change results in a new key being generated to encrypt the new version
  - Key wrappers must then change to store the new key, etc.

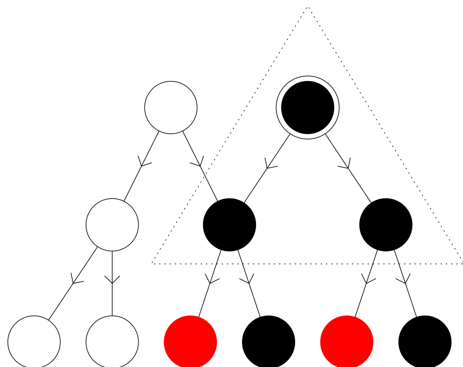
Shadowing Mutation



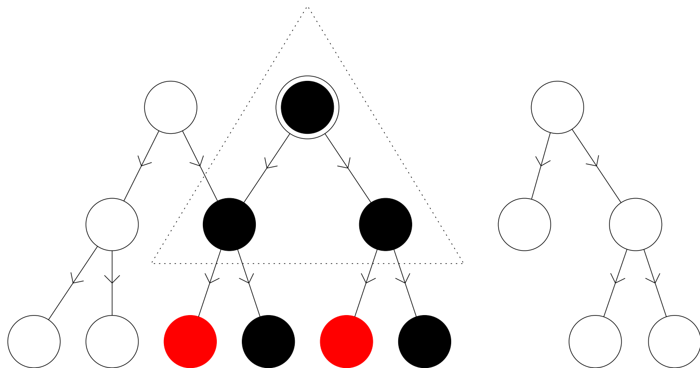
Shadowing Mutation



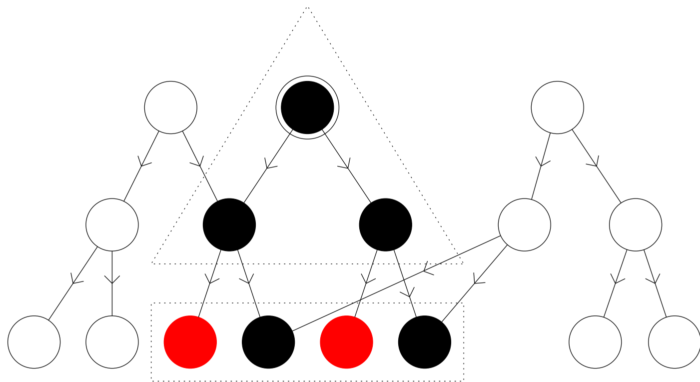
Shadowing Mutation



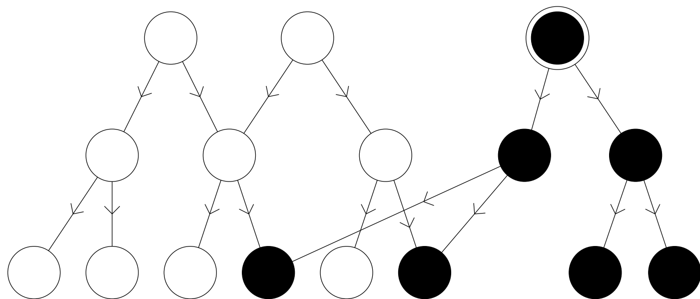
Shadowing Mutation



Shadowing Mutation



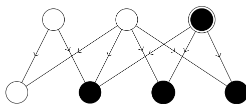
Shadowing Mutation



Shadowing Mutation

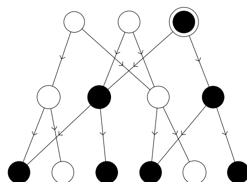
- Shadowing mutations can implement any arborescent data structure
- A shadowing mutation applied on a mangrove results in a mangrove
- Shadowing mutations do not permit old (pre-mutation) nodes to access new (post-mutation) nodes
- Computing the ancestors of a node requires only following its unique path

Related Work



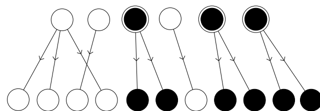
Boneh and Lipton

persistant storage: magnetic tape
securely−deleting: e.g., paper, floppy disk
update mechanism: re−encrypt keys with new master secret



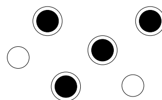
Di Crescenzo et al.

persistent and securely−deleting medium are explicitly considered
update mechanism: re−encrypt keys on static path to root



Perlman's Ephemerizer

persistant storage: communication channel
securely−deleting: trusted−third party
update mechanism: master keys correspond to expiration times

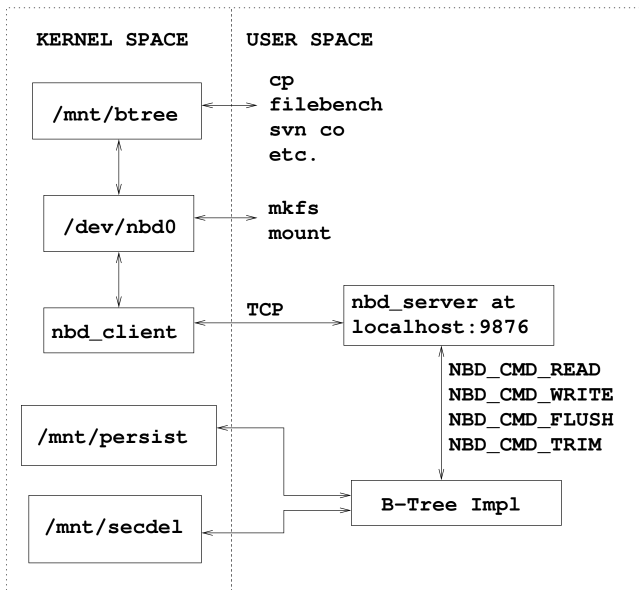


DNEFS

persistant storage: flash memory
securely−deleting: reserved area of flash
update mechanism: erase flash memory in reserved area

We implement a caching B-Tree version of this solution.

Implementation



Caching Hits (in percent)

Workload	block size	Cache size: 10			Cache size: 20			Cache size: 50		
		LRU	LFU	Belady	LRU	LFU	Belady	LRU	LFU	Belady
sequential	1 KiB	98.1	60.8	97.9	98.3	70.1	98.1	99.1	74.7	99
	16 KiB	99.7	56.6	99.8	99.7	83.3	99.8	99.8	99.5	99.8
random (1KiB)	1 KiB	11.8	15.3	19.8	15.6	21.3	25	26.4	26.3	33.5
	16 KiB	49.3	40.1	58.2	53.6	56	64.5	63.4	67.2	70.3
random (1MiB)	1 KiB	97.5	25.4	97.7	97.7	31.6	97.8	97.9	38	98
	16 KiB	98.6	62.6	98.7	98.7	85.2	99	98.9	98.3	99.1
svn	1 KiB	96	47.2	96.1	96.5	57.1	96.9	97.1	75.9	97.4
	16 KiB	97.8	81.2	97.8	98.2	88	98.2	98.6	96.2	99

Overhead Results

		B-Tree block size			
		4 KiB	16 KiB	64 KiB	256 KiB
general	total data blocks	6553600	1638400	409600	102400
	tree height	5	3	2	2
	cache size (nodes)	2048	512	128	32
	MiBs sharing path	0.16	2.65	42.6	682.5
sequent.	cache hits (%)	99.3	99.7	99.9	1
	storage overhead (%)	2.4	0.6	0.1	0.03
	comm overhead (%)	2.4	0.6	0.1	0.03
	block size ovrhd (%)	0	5.3	26.3	58.1
rand 1k	cache hits (%)	64.7	59	43.2	73.8
	storage overhead (%)	2.4	0.6	0.1	0.03
	comm overhead (%)	1308.5	3129	8623.5	20671.4
	block size ovrhd (%)	497.9	2293.2	9473	38191.8
rand 1m	cache hits (%)	99.2	98.9	96.5	95.5
	storage overhead (%)	2.47	0.59	0.14	0.03
	comm overhead (%)	4.9	3.7	7.8	17.7
	block size ovrhd (%)	1	7.7	34.6	82.1
svn	cache hits (%)	99.2	98.9	96.5	95.5
	storage overhead (%)	1.74	0.42	0.1	0.02
	comm overhead (%)	4.4	4.9	5.4	2.6
	block size ovrhd (%)	0	63.4	247.9	750.2

Summary and Future Work

- Contributions
  - We introduce the key disclosure graph to characterize adversarial knowledge growth for settings with a small securely-deleting medium and a large persistent medium
  - We prove that a generic shadowing graph mutation preserves the mangrove property on the KDG, facilitating secure deletion
  - We design and implement a B-Tree-based secure-deletion solution that shows promising performance
  - We characterize related work as instances of our general model
- Future Work
  - Extensively test our implementation with real-world workloads
  - Compare overheads against related work
  - Characterize the workloads best suited for dynamic structures and static structures