Secure content distribution using untrusted servers

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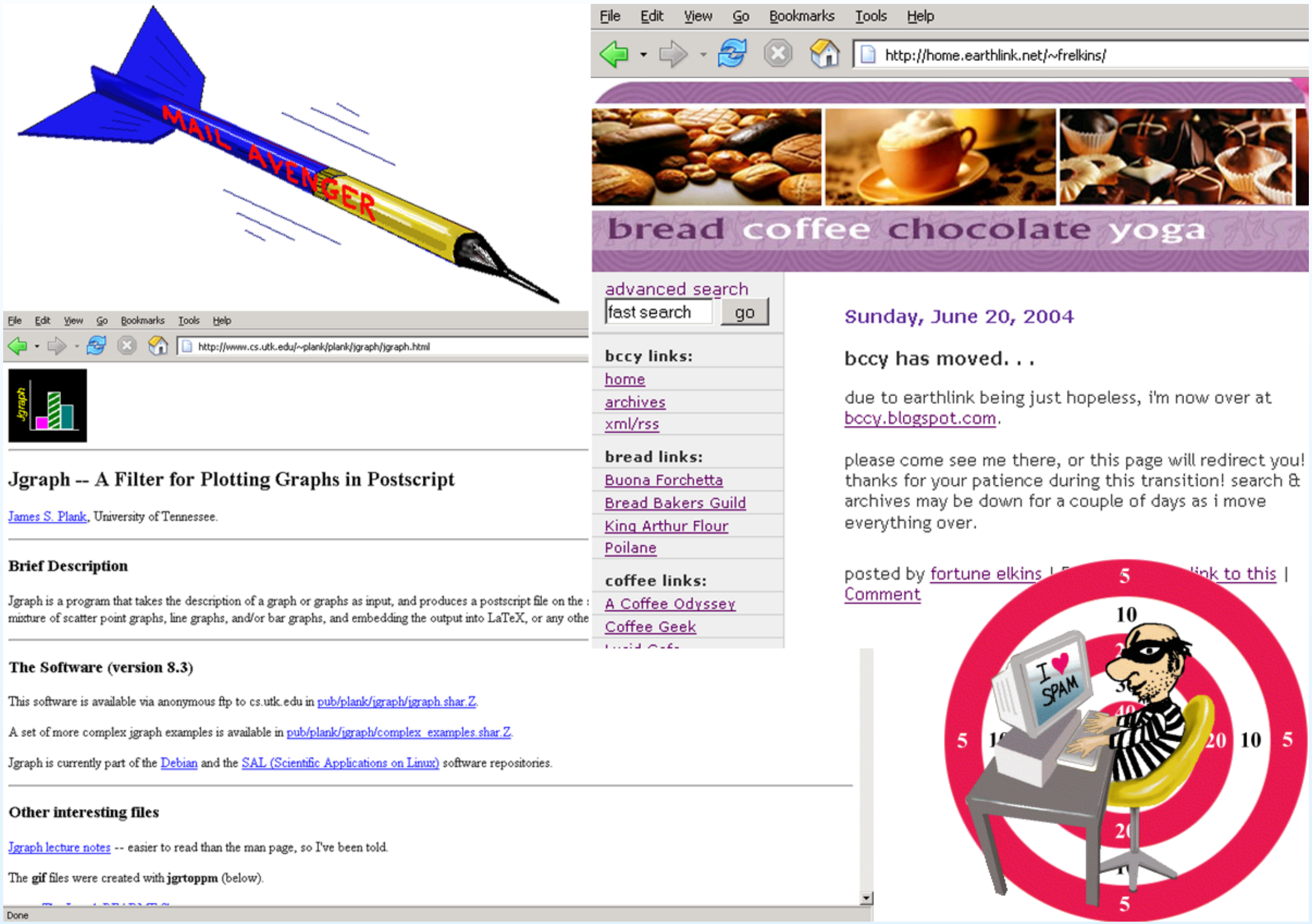
January-April 2005

How do we distribute content?



We pay services

Akamai

mirror image®

RSS cache.com

The bandwidth saver solution for your RSS feeds!

We coerce friends

We coerce friends

We enlist volunteers

BitTorrent

CoDeeN

CORAL

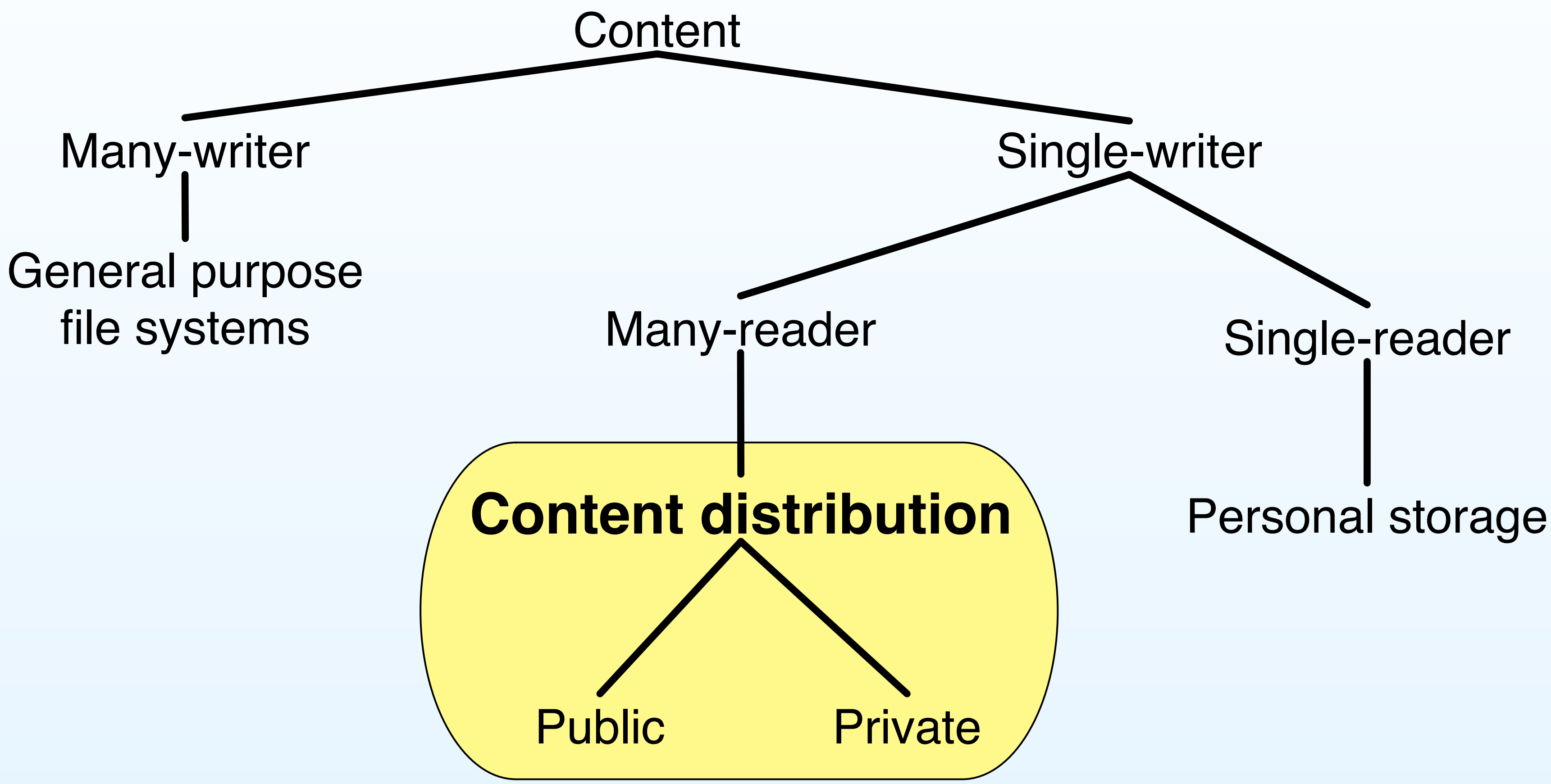
Fast content distribution, so what's left?

- Clients want
  - Authenticated content
  - Example: software updates, virus scanners
- Publishers want
  - Access control
  - Example: online newspapers

But what if

- Servers are untrusted
- Malicious parties control the network

Taxonomy of content



Framework

- Publishers ←write content, manage keys
- Clients ←read/verify content, trust publisher
- Untrusted servers ←replicate content
- File system ←protects data and metadata

Contributions

- Authenticated content distribution ←SFSRO
  - Self-certifying File System Read-Only
  - Public content distributed by untrusted servers
- Decentralized access control
  - Private content distributed by untrusted servers
  - Efficient client eviction
  - Efficient key distribution
- Implementation and performance measurements

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  - Efficient key distribution ←Key regression
- Implementation and performance measurements ←It works too!

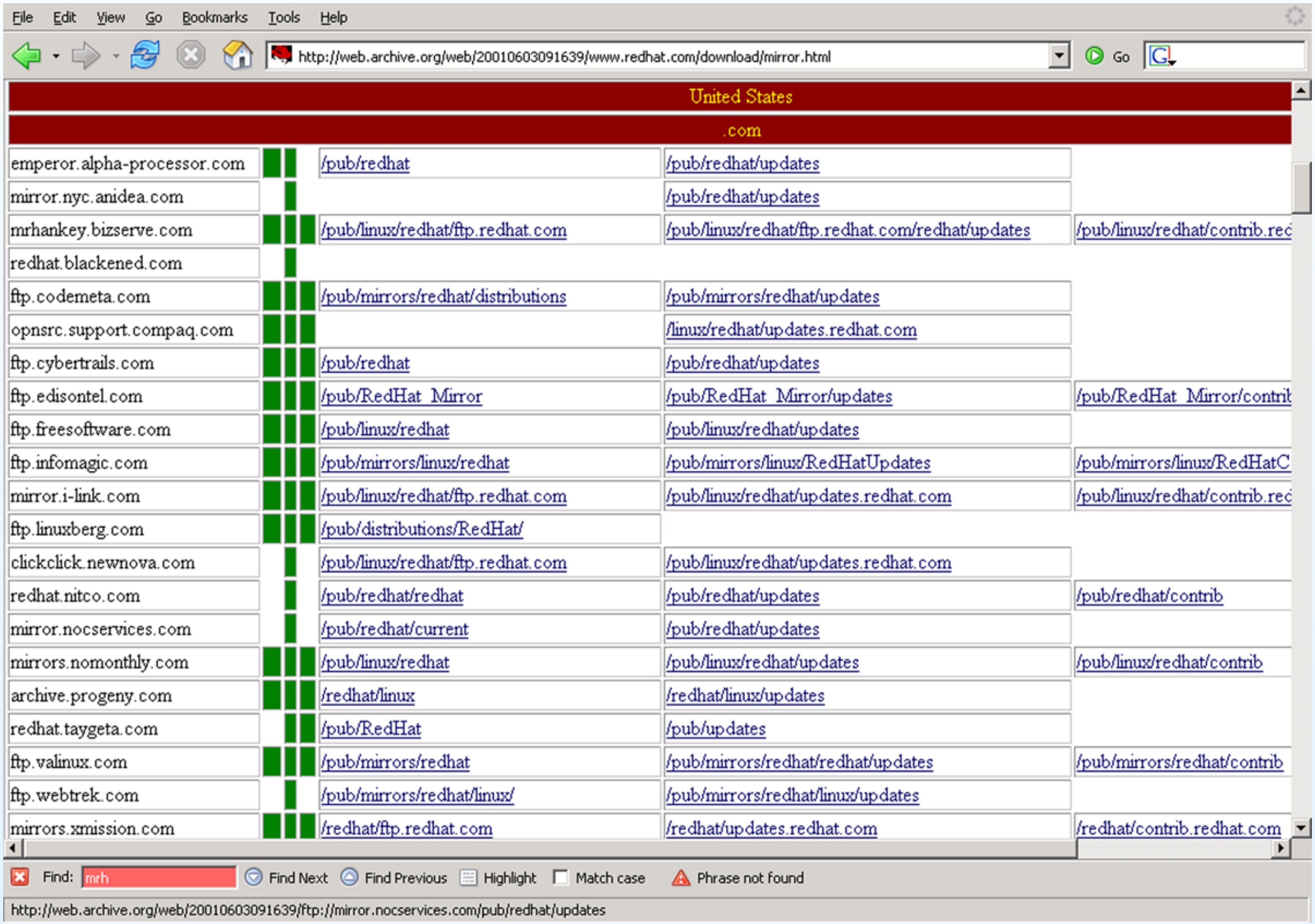
SFSRO

SFSRO challenges

How can we authenticate content and also

- Provide incremental updates?
- Authenticate partial downloads?
- Scale servers to many clients?

Signed software packages: part of your complete breakfast



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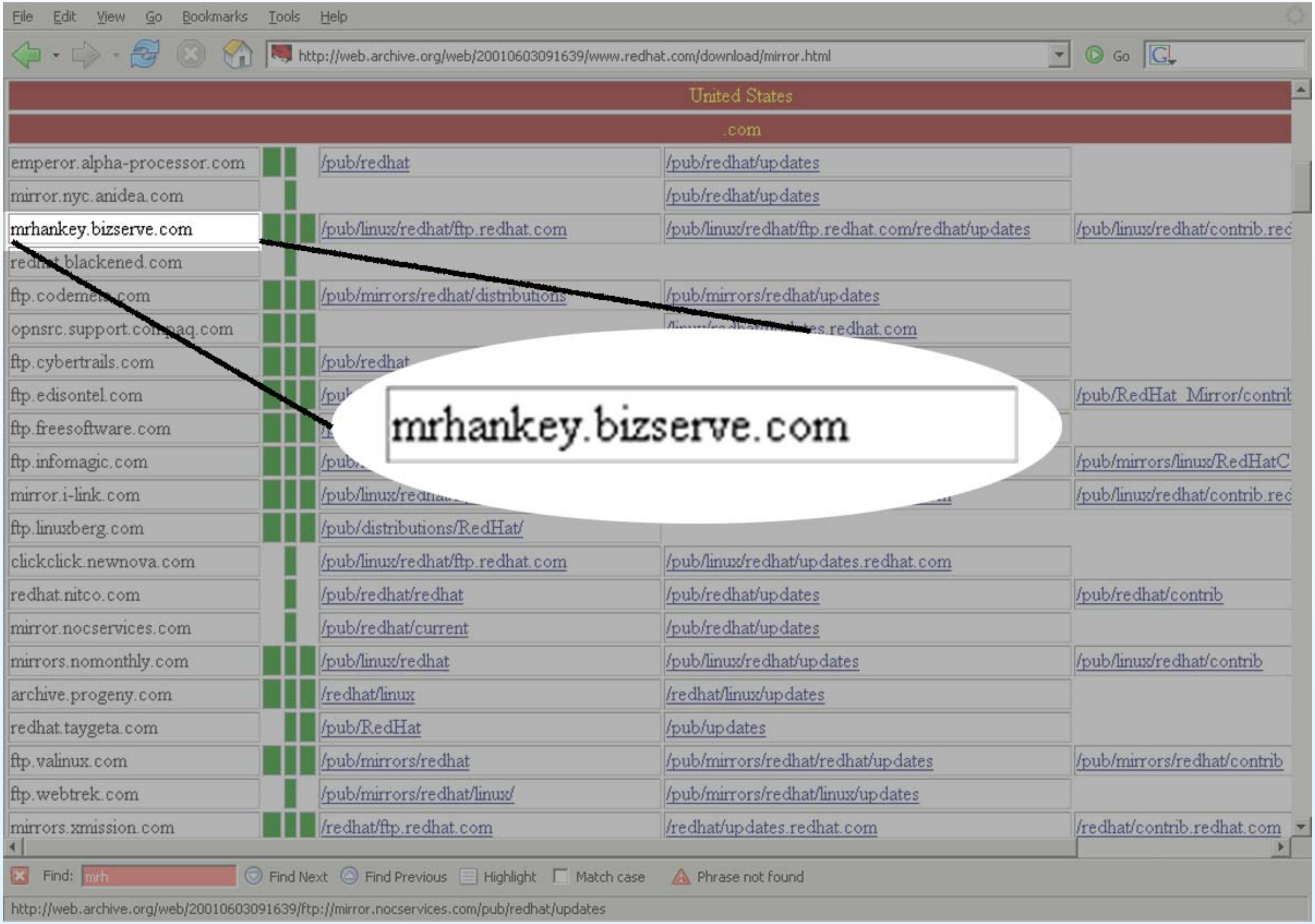

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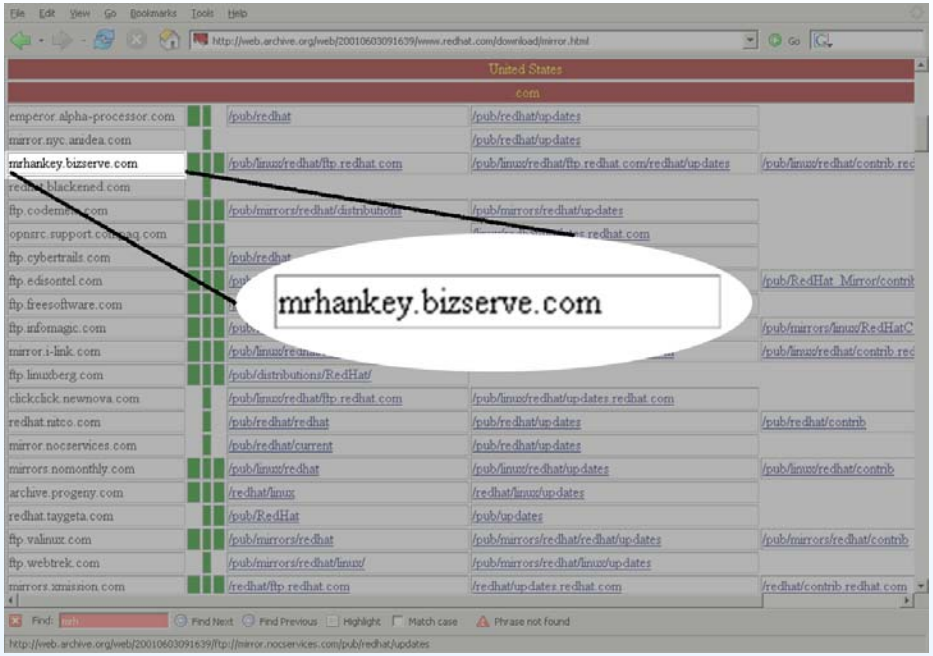
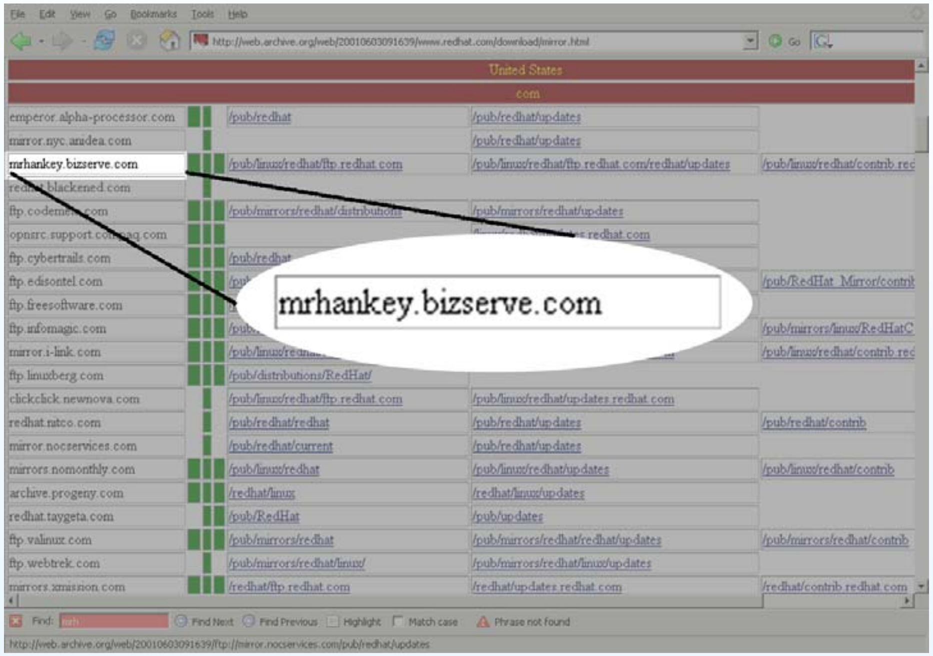


- Authenticated

Signed software packages: part of your complete breakfast

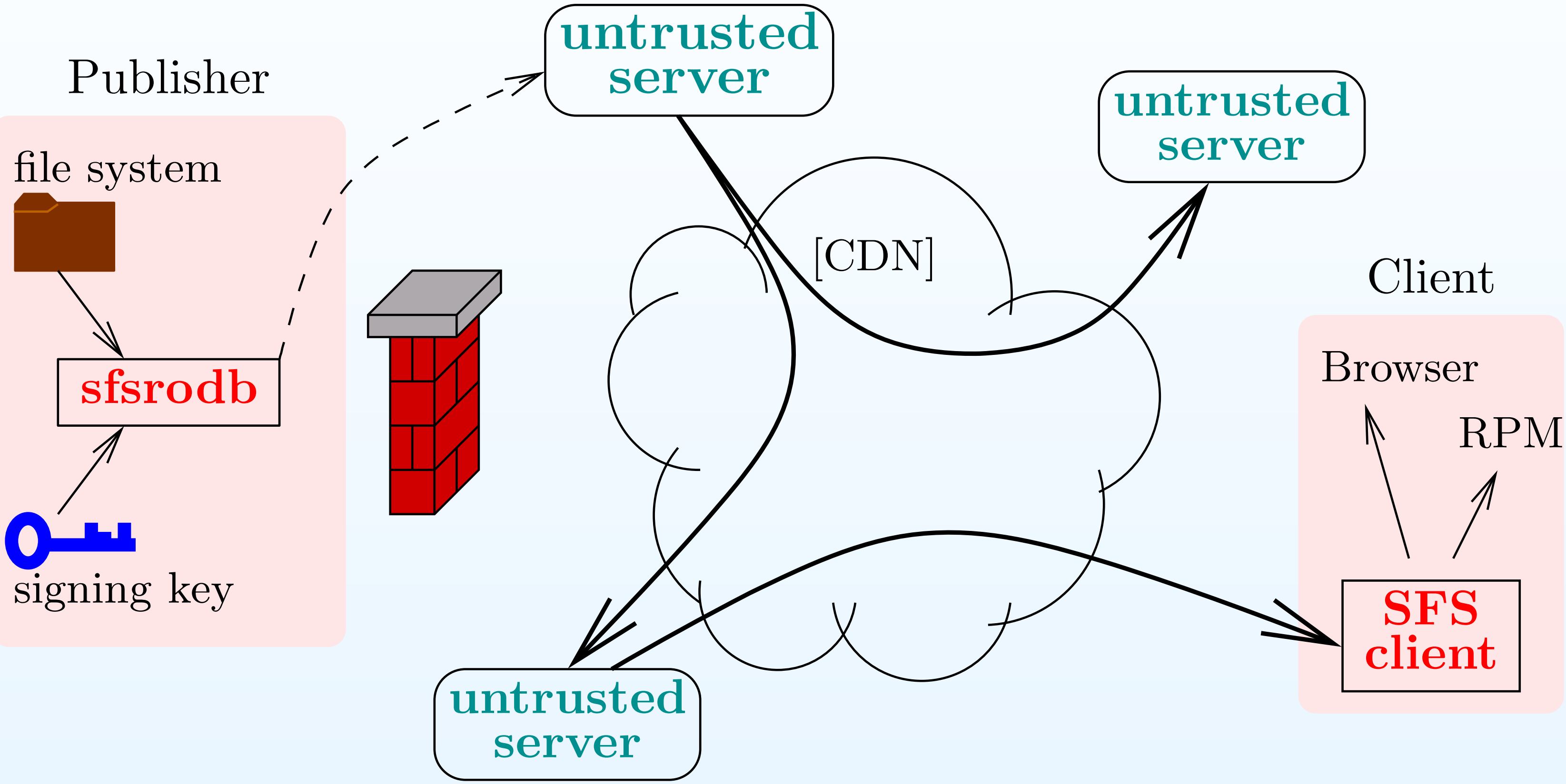


- Authenticated
- No revocation ✘
- No incremental updates ✘
- No integrity of file collections ✘

Is your collection of software authentic?

- Is the collection as a whole authentic? Rolled back?

SFSRO architecture

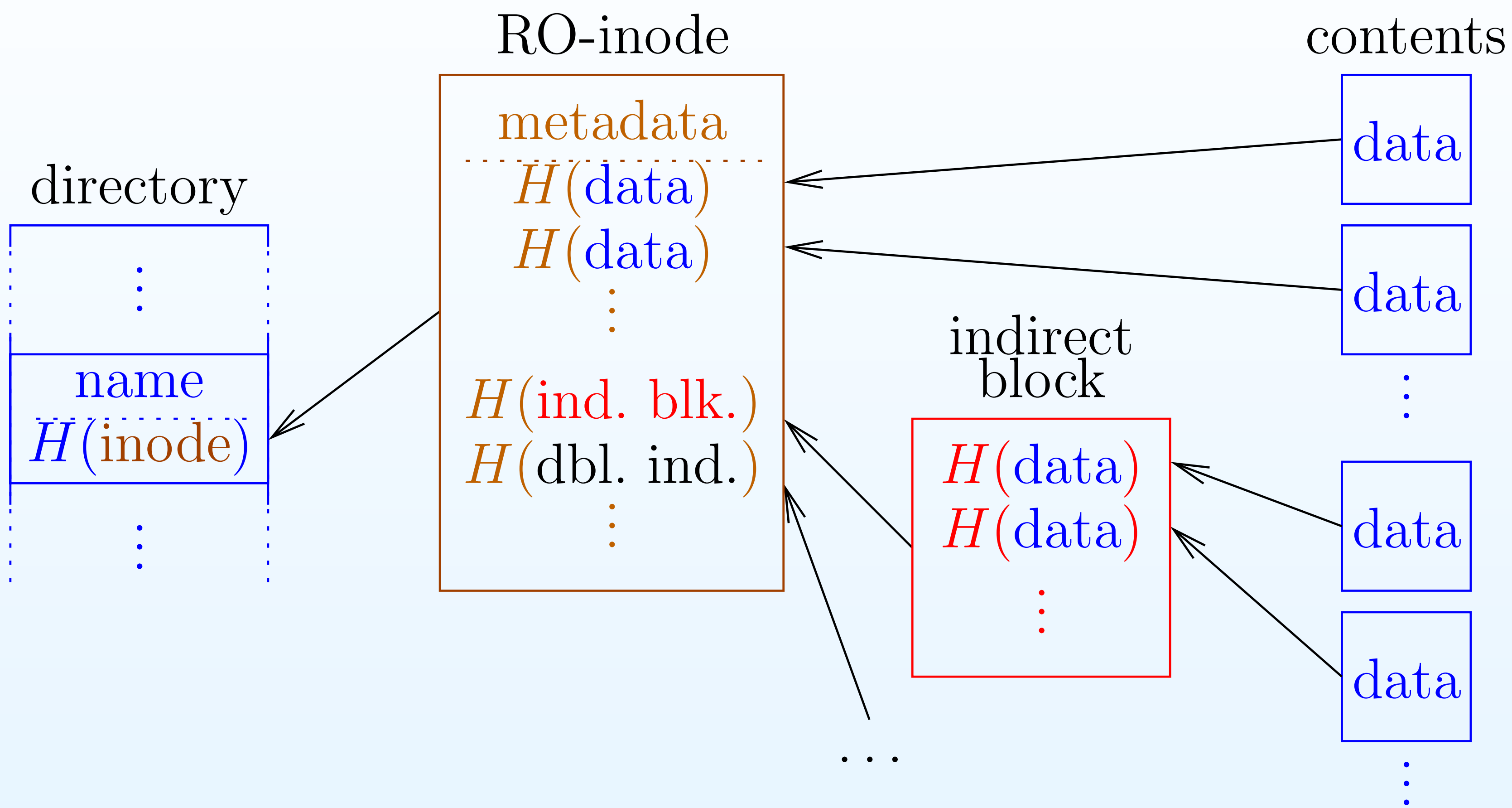


- SFSRO signs complete file system (data and metadata)
- Publisher stores files in replicated database ($\sim$ a disk image)
- Clients verify files without trusting servers

Authenticity via hash trees [Merkle:79]

- Proves membership of a leaf in an n-node tree with O(log n) hashes
- Matches structure of a file system directory tree
- Ideal performance for incremental updates

Merkle hash tree mapped over directory tree



- Merkle hash tree of the file system [Haber:91, Devanbu:02]
- One public key operation and O(log n) hashes to authenticate

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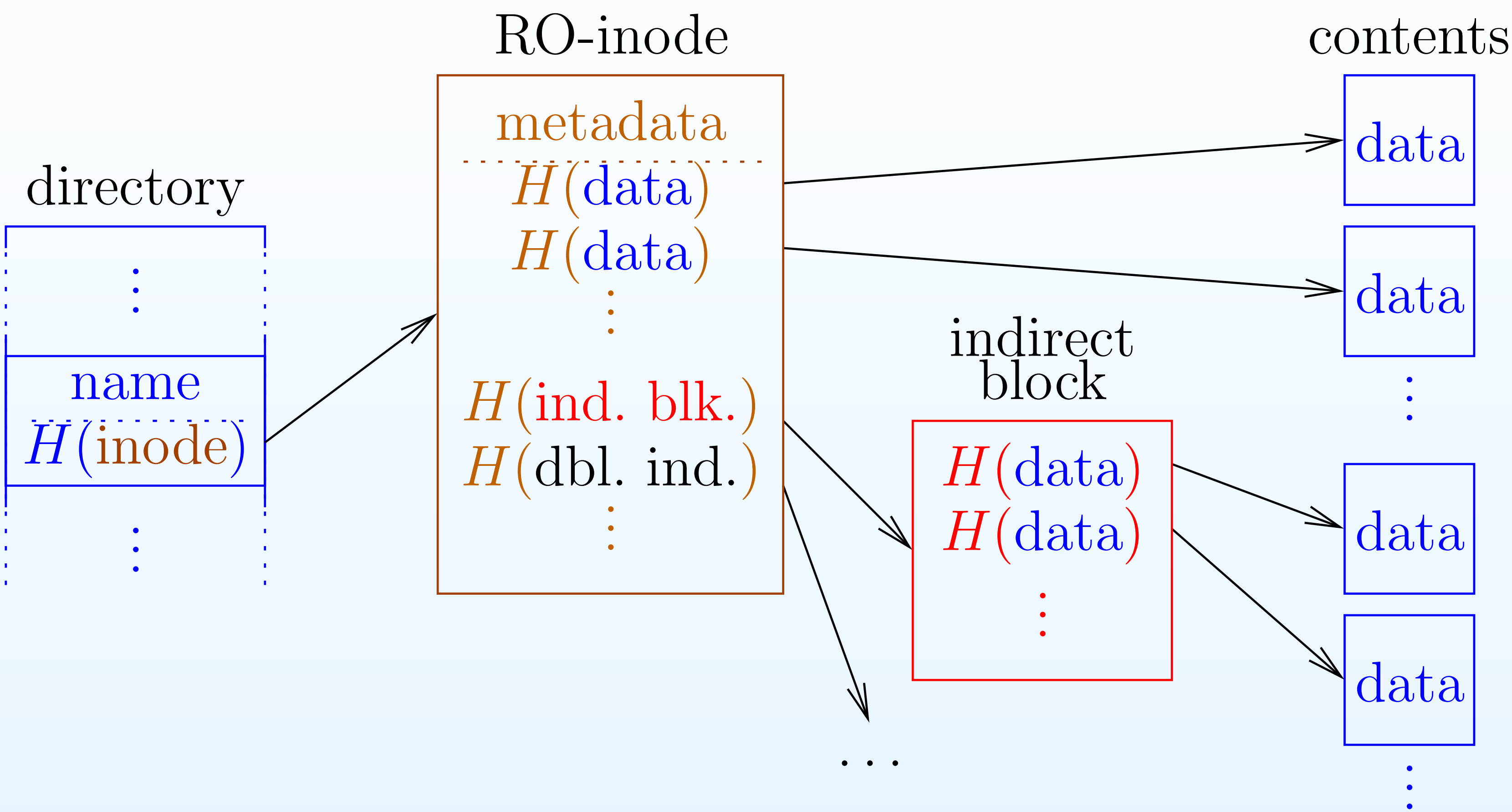
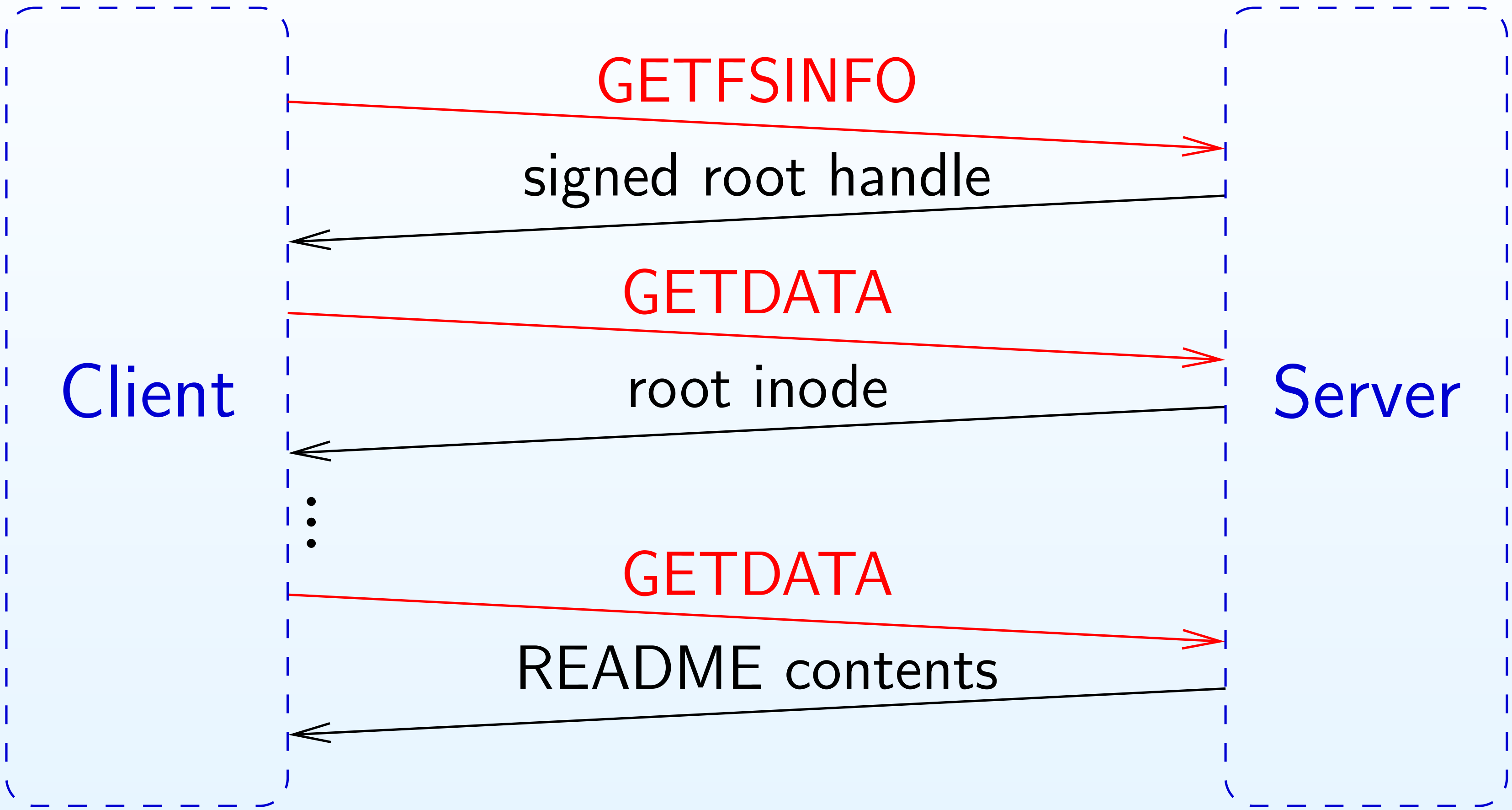


- Merkle hash tree of the file system [Haber:91, Devanbu:02]
- One public key operation and O(log n) hashes to authenticate
- SFSRO protocol designed to walk Merkle trees

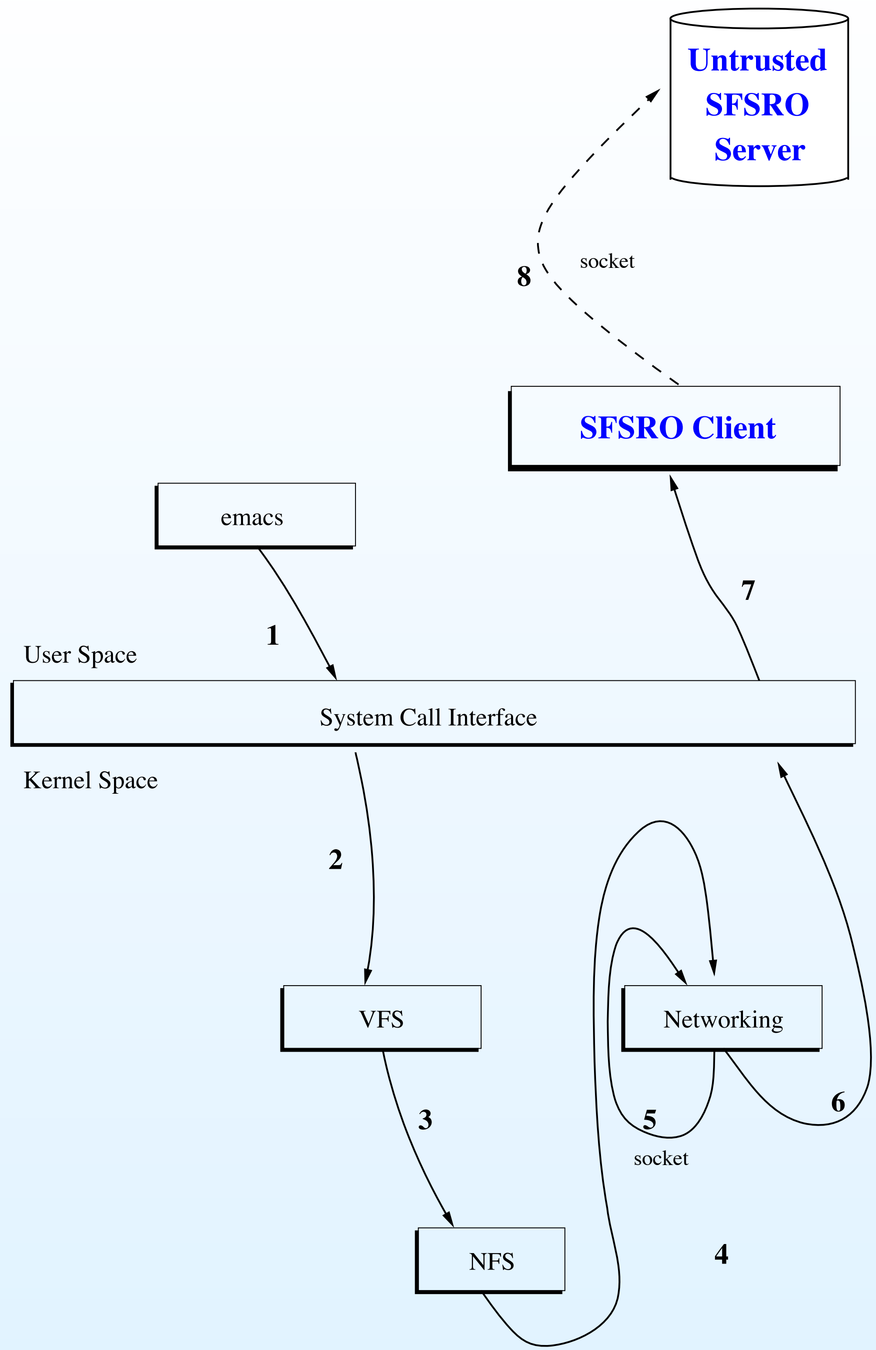
Example of reading `/shome/sfs.fs.net/README`



- SFSRO servers perform no online cryptography

Implementation of SFSRO

- Publisher
  - SHA-1 Merkle hash tree
  - Rabin-Williams signature
- Block server
  - Uses sleepycat database
  - Incremental updates
  - Influenced CFS [Dabek:01]
- Client
  - Transparent integrity checking
  - Implemented as NFS loopback



Chefs

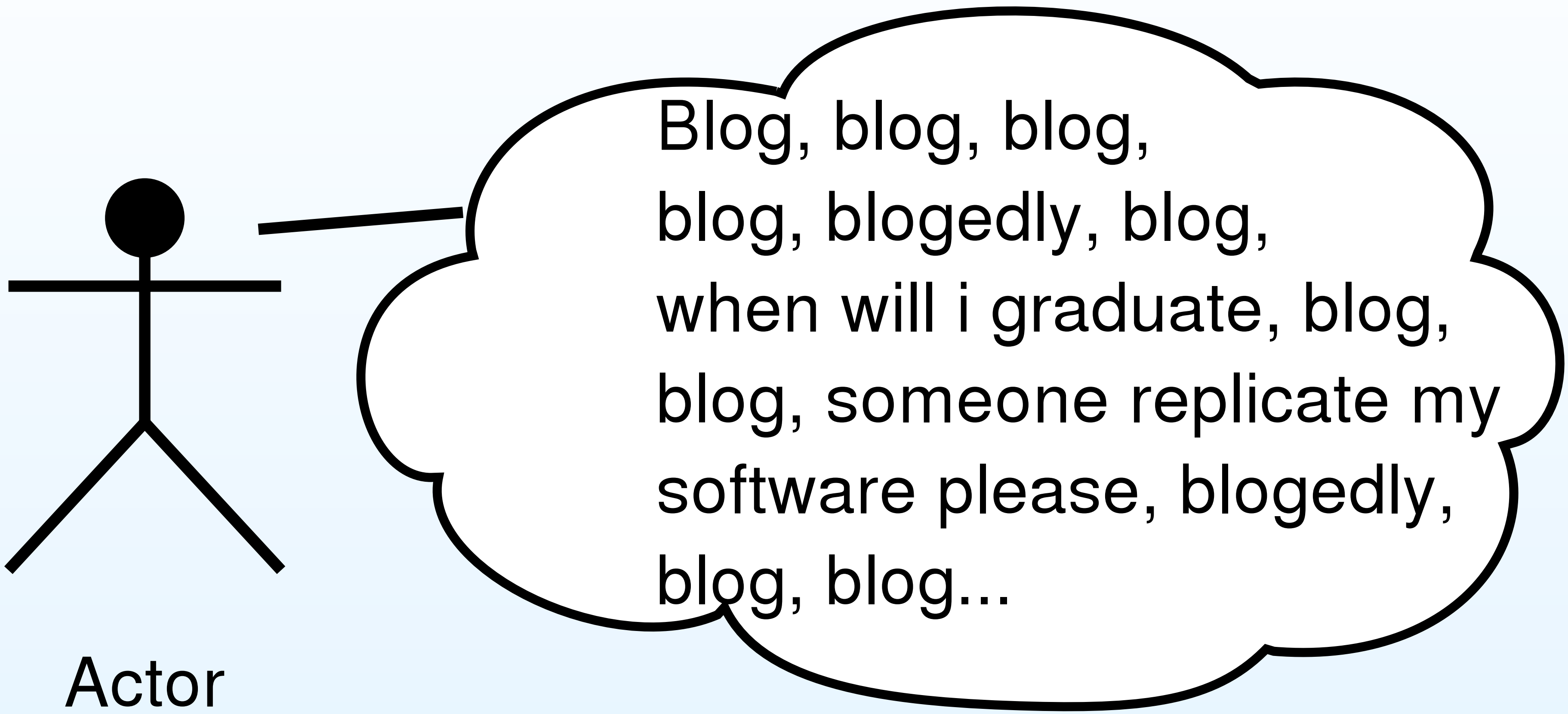
A brief timeline of SFS

- Read-write security in SFS [Mazieres:99]
- Read-only dialect [Fu:00] ←SFSRO
- Decentralized access control

A brief timeline of SFS

- Read-write security in SFS [Mazieres:99]
- Read-only dialect [Fu:00] ←SFSRO
- Decentralized access control ←Chefs
  - Servers remain untrusted
  - Clients with key can read content
  - Problem: Reduce key distribution

Access control using untrusted servers



A private blog

Potential approaches

- Proxy SSL Web server? [Laas:03]
  - Untrusted servers cannot replicate confidential content ✘

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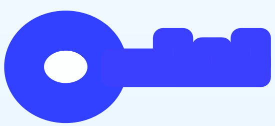
- Proxy SSL Web server? [Laas:03]
  - Untrusted servers cannot replicate confidential content ✘
- File encryption (e.g., PGP [Zimmermann:91])
  - Access controlled
  - Not transparent ✘
  - Ciphertext linear in number of clients ✘
  - No incremental updates ✘

Chefs approach extends SFSRO

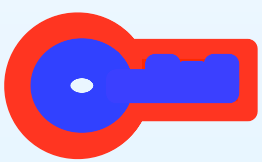
- Content encrypted for confidentiality [Swallow:81, Blaze:93, Waldman:00] ←decentralized access control
- Efficient client eviction ←lazy revocation
- Efficient key distribution ←key regression

Decentralized access control

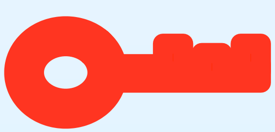
- Clients download content encrypted with content keys
- Encrypted content tagged with lockbox
- Open lockbox with the group key



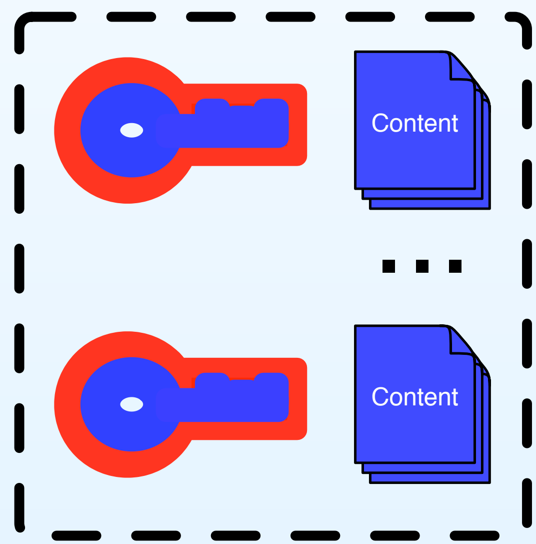
Content keys protect blocks



A lockbox contains a content key



Group key opens lockboxes



Database of encrypted content + name of group key

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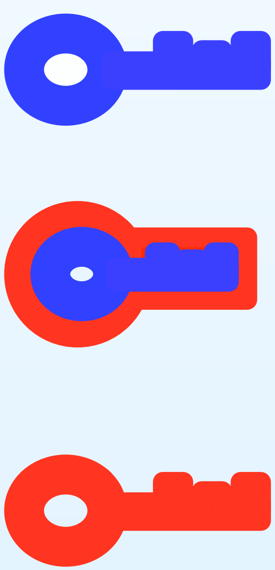

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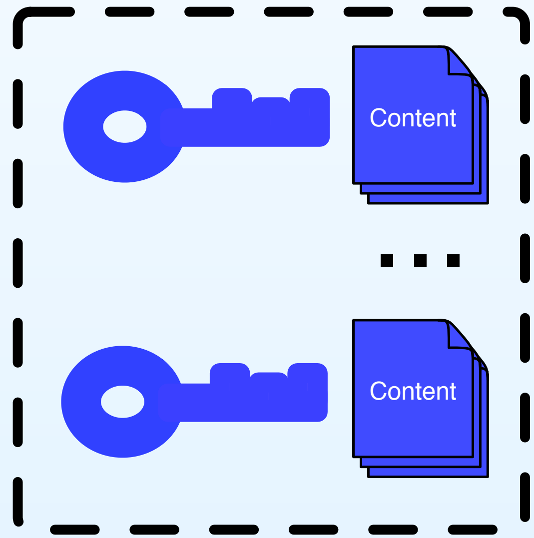

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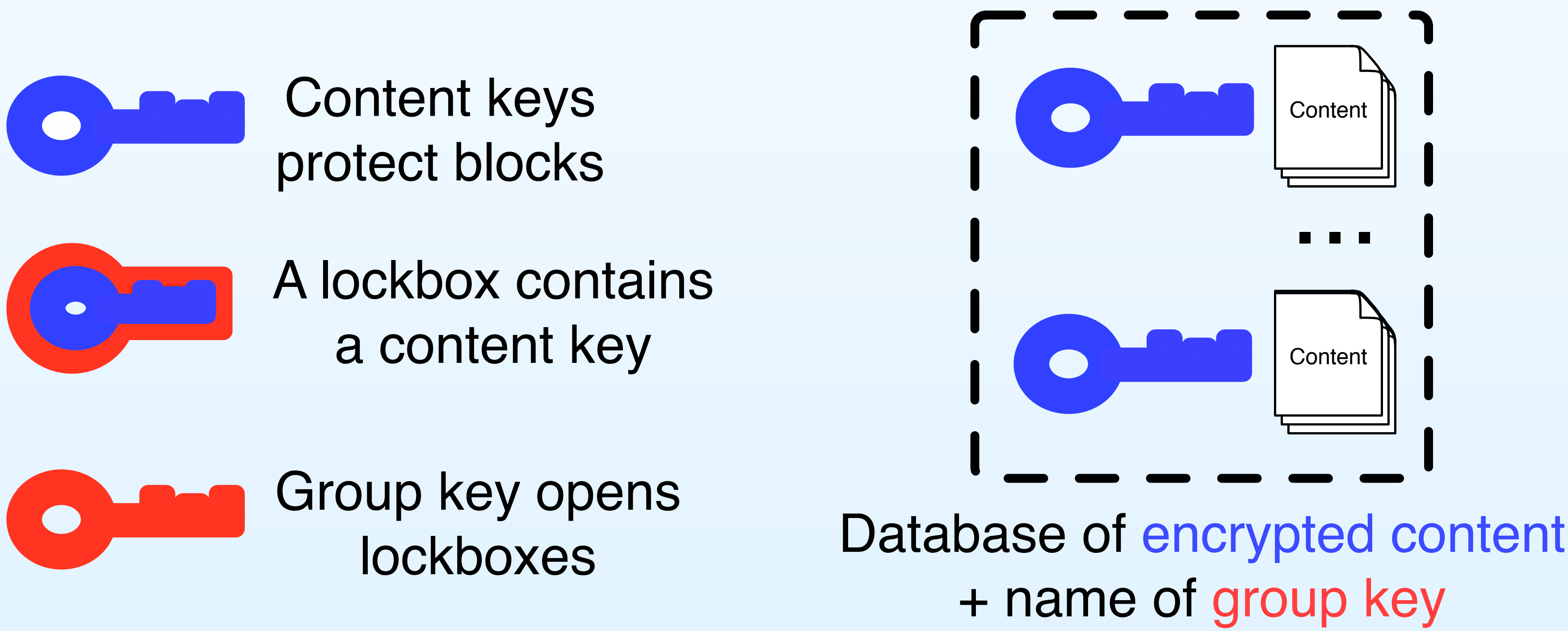
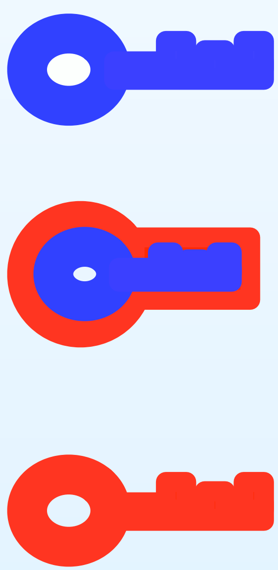


Decentralized access control

- Clients download content encrypted with content keys
- Encrypted content tagged with lockbox
- Open lockbox with the group key
- No key distribution required to add new content!



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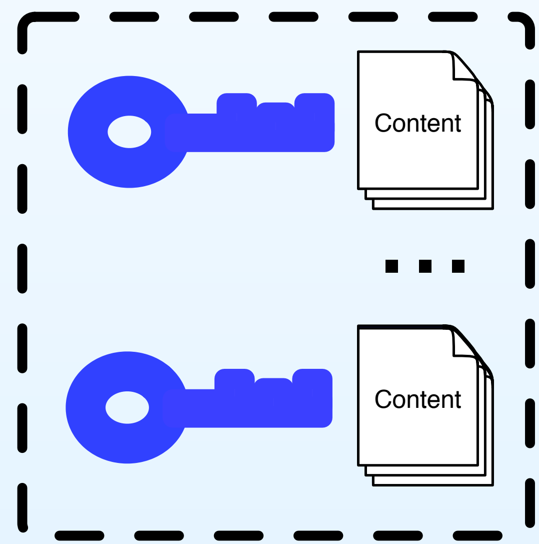
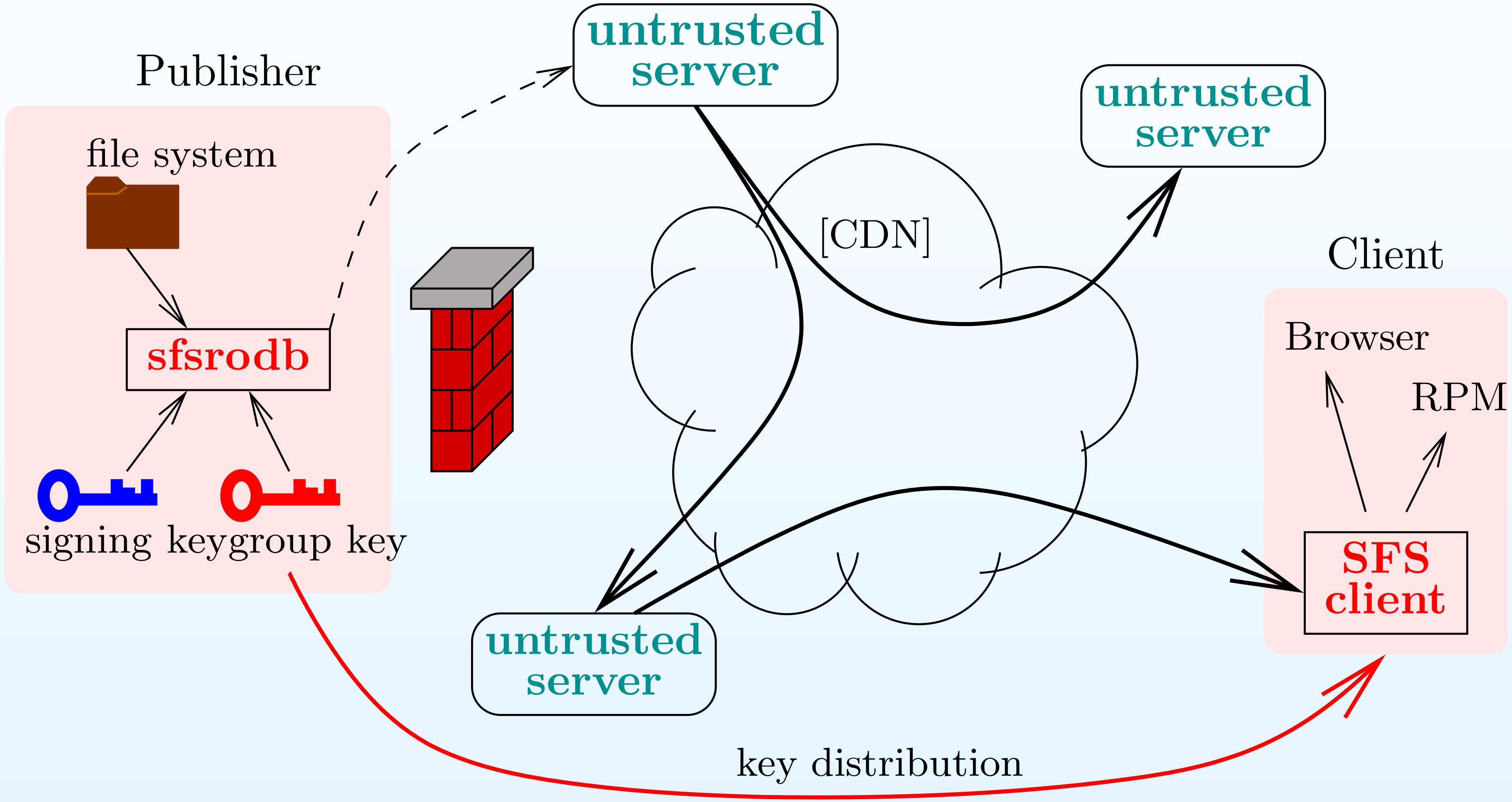


Database of encrypted content + name of group key

Overview of Chefs



Chefs = SFSRO + access control

Costly approach to coping with eviction

- Re-encrypt content after eviction
- Distribute new key to remaining clients

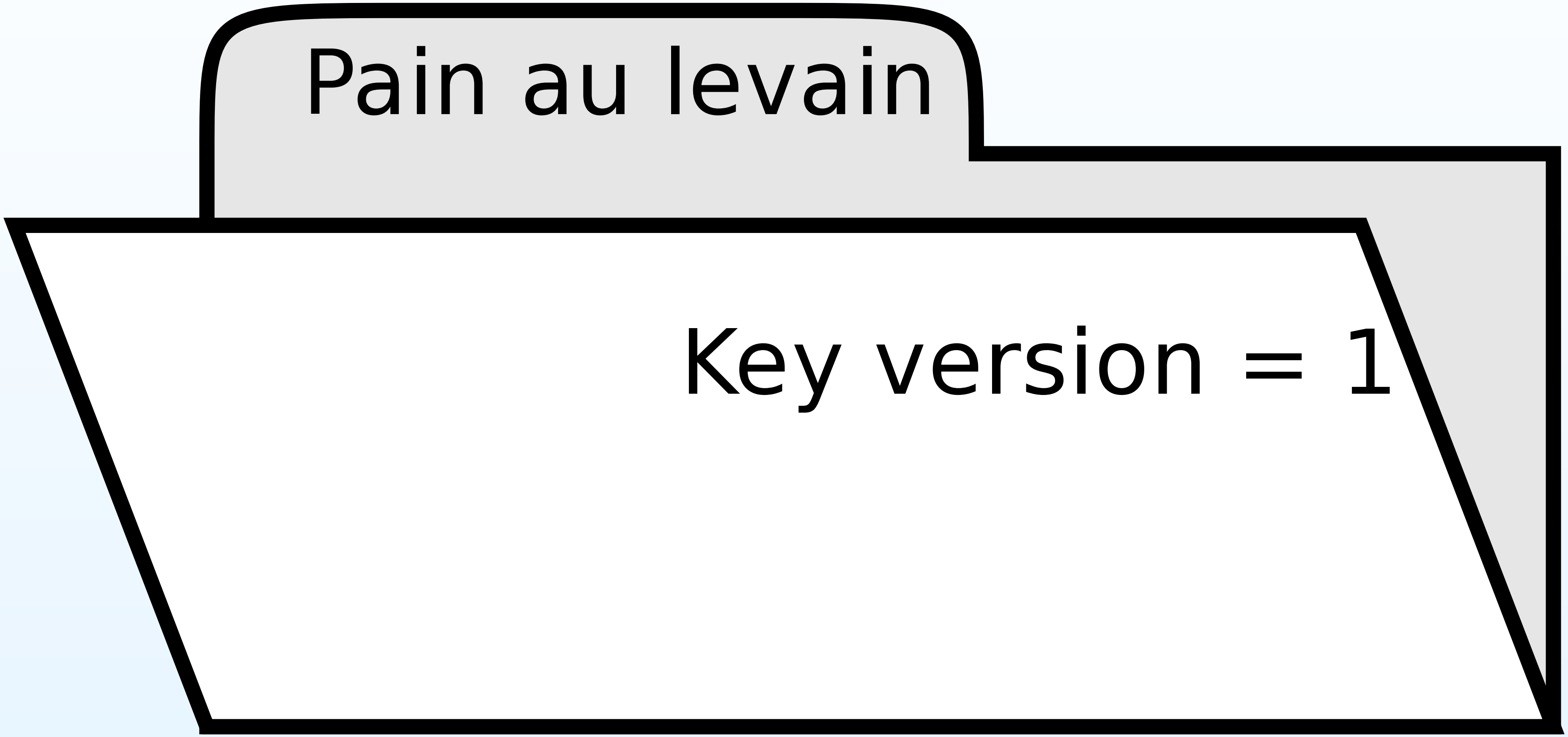
Costly approach to coping with eviction

- Re-encrypt content after eviction ←Unnecessary
- Distribute new key to remaining clients

Chefs solution: lazy revocation

- Guarantees evicted client cannot access new content
- After eviction, generate a new key for future updates
- Matches semantics of untrusted storage

Lazy revocation results in many keys



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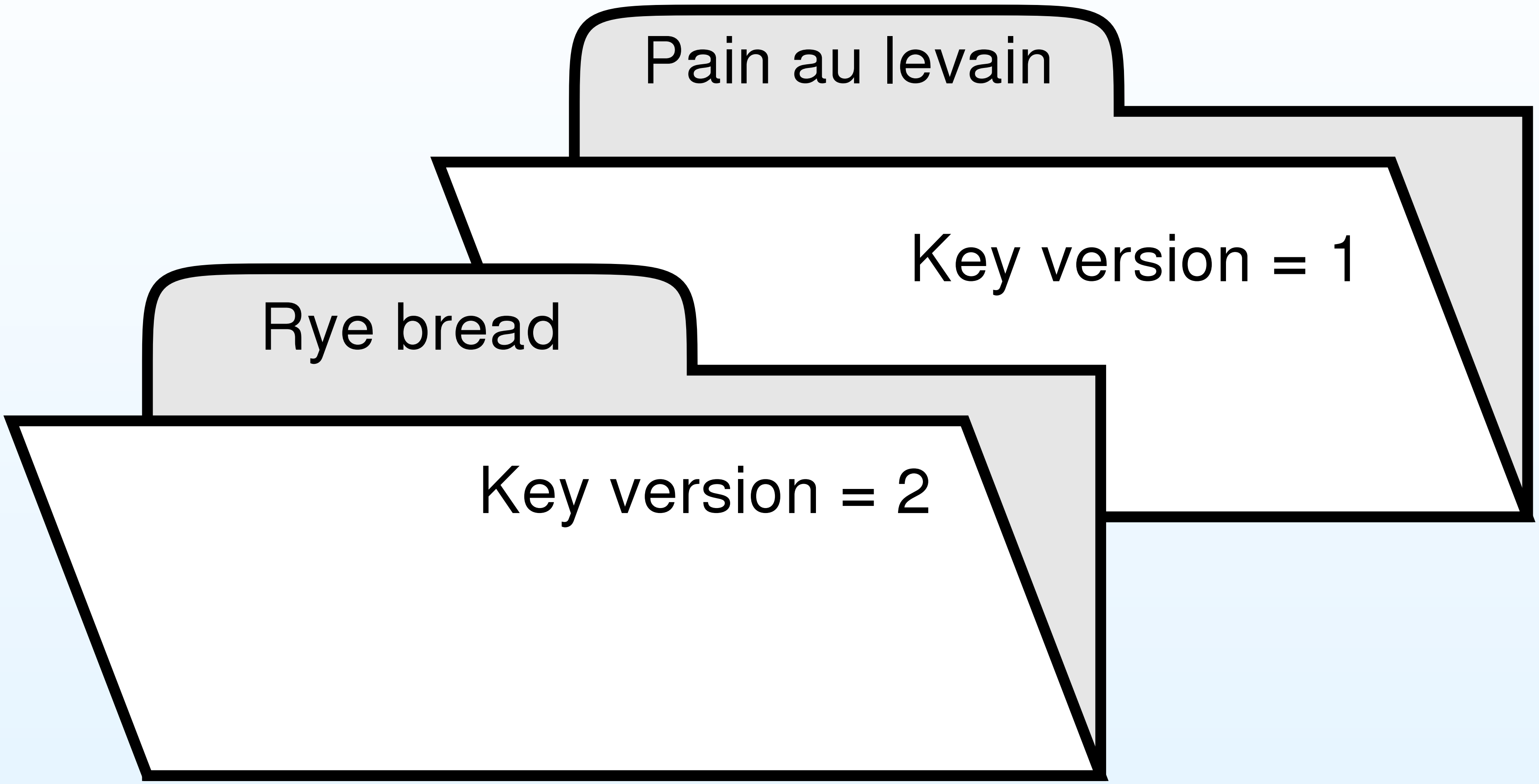

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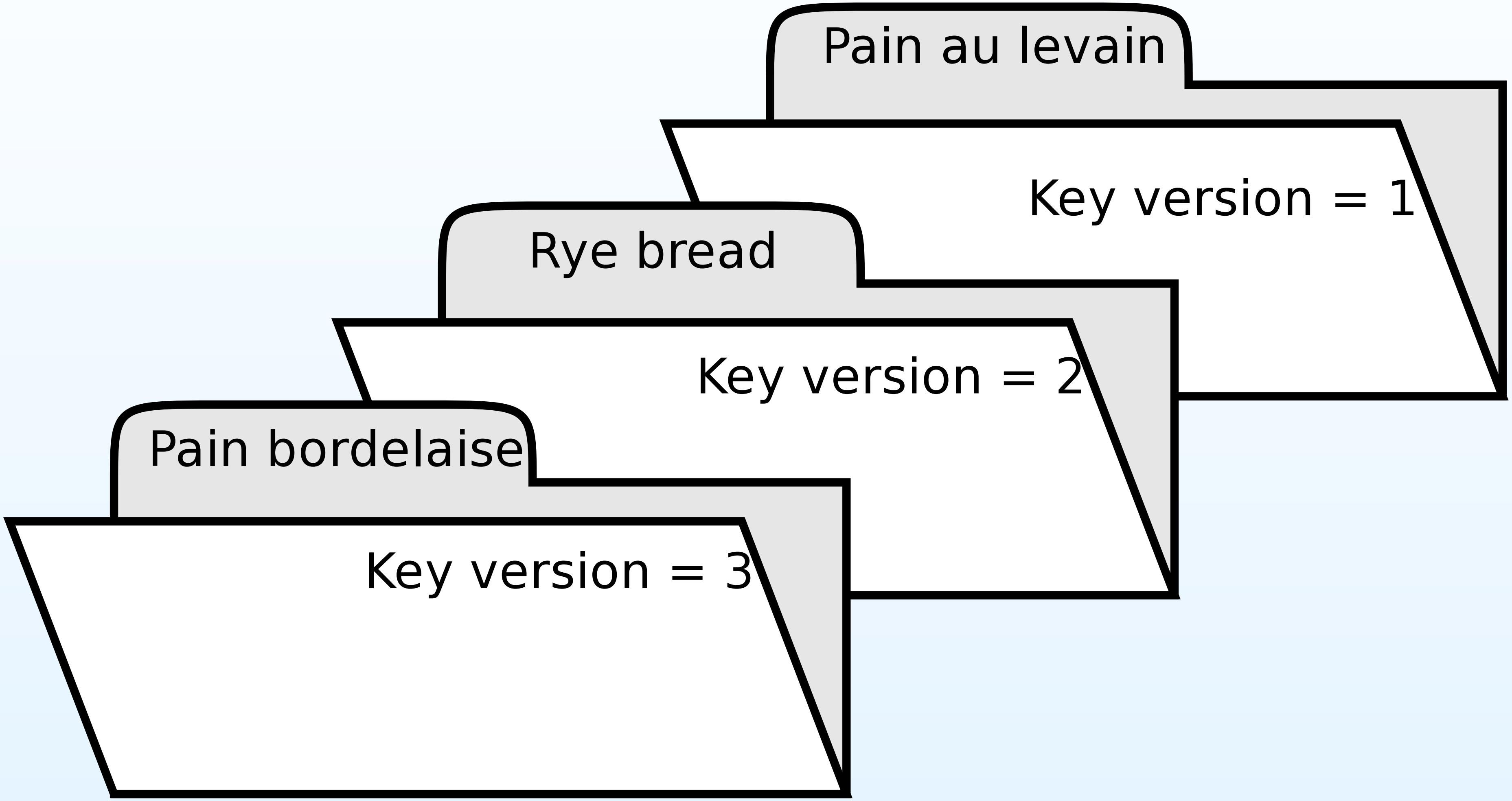

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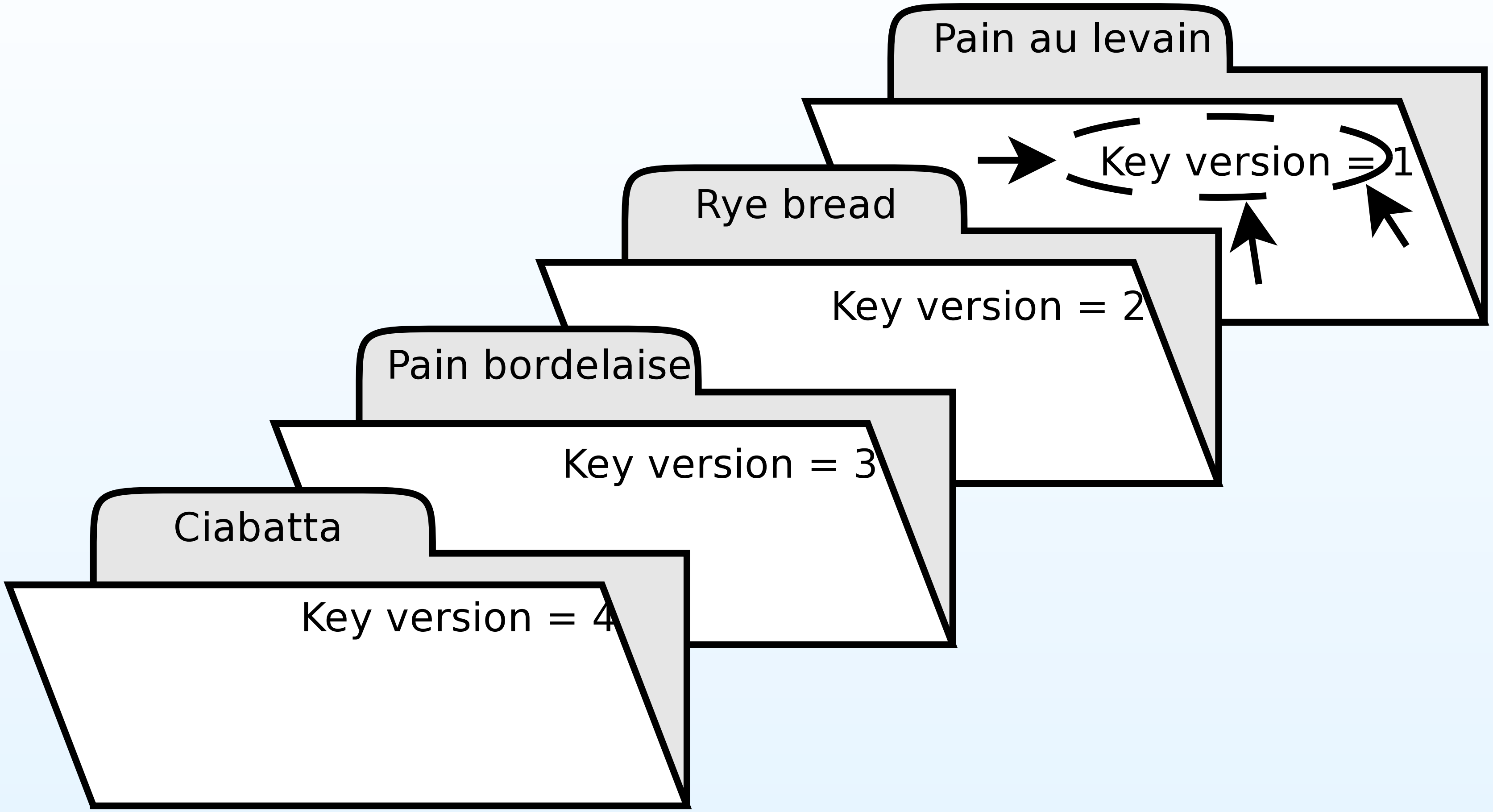

- How can a client coalesce group key versions?

Key regression: coping with many keys

- Guarantees clients
  - Can access old content
  - Cannot yet access future content
- Clients derive past keys from current key
- Low-bandwidth publishers make new keys available

Downloading all the keys can be costly

- Searching encrypted content
  - Client must perform search, not untrusted server
  - Client downloads all encrypted recipes and keys
- Scenarios
  - 60,000 membership events/year on Salon.com online journal
  - Offline publisher

What does "secure" key regression mean?

- Only clients can unwind keys
  - $K_i = \text{unwind}(K_{i+1})$
- Only publisher can wind key forward
  - $K_{i+1} = \text{wind}(K_i)$
- Should behave like randomly selected keys

Simplest way to use key regression

- Publisher initialization:
  - Generate a random K_{t-1}

Publisher:

K_{t-1}

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Publisher:

$$K_{t-2} \xleftarrow{U(K_{t-1})} K_{t-1}$$

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- Publisher initialization:
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Publisher:

$$K_0 \xleftarrow{U(K_1)} K_1 \xleftarrow{U(K_2)} \cdots \xleftarrow{U(K_{t-2)}} K_{t-2} \xleftarrow{U(K_{t-1})} K_{t-1}$$

Simplest way to use key regression

- Publisher initialization:
  - Generate a random K_{t-1}
  - Compute $K_0, \ldots, K_{t-2}$ by unwinding
  - Distribute K_0 to clients

Publisher:

$$K_0 \xleftarrow{U(K_1)} K_1 \xleftarrow{U(K_2)} \cdots \xleftarrow{U(K_{t-2})} K_{t-2} \xleftarrow{U(K_{t-1})} K_{t-1}$$

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- Client joining at time i
  - Receive K_i from publisher
  - To read content encrypted with K_j for $j < i$, unwind K_i

Publisher:

$$K_0 \xleftarrow{U(K_1)} K_1 \xleftarrow{U(K_2)} \cdots \xleftarrow{U(K_{t-2})} K_{t-2} \xleftarrow{U(K_{t-1})} K_{t-1}$$

Client:

$$K_i$$

Simplest way to use key regression

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Client:

$$K_{i-1} \xleftarrow{U(K_i)} K_i$$

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Client:

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  - Distribute K_0 to clients

- Client joining at time i
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  - To read content encrypted with K_j for $j < i$, unwind K_i
  - Decrypt content with K_j

Publisher:

$$K_0 \xleftarrow{U(K_1)} K_1 \xleftarrow{U(K_2)} \cdots \xleftarrow{U(K_{t-2})} K_{t-2} \xleftarrow{U(K_{t-1})} K_{t-1}$$

Client:

$$K_j \xleftarrow{U(K_{j+1})} \cdots \xleftarrow{U(K_{i-1})} K_{i-1} \xleftarrow{U(K_i)} K_i$$

Key regression produces a key sequence

$K_i = \mathsf{H}(K_{i+1})$

$$\underbrace{K_0 \xleftarrow{H(K_1)} K_1 \xleftarrow{H(K_2)} \cdots \xleftarrow{H(K_{t-1})} K_{t-1}}_{\text{group key sequence}}$$

where H could be

In practice: SHA-1 $(\cdot)$ hash function

In theory: PRF $F(\cdot)$ in random oracle model

[Lamport:81], [Anderson:97]

An extension to key regression

- Dynamically grow a key sequence
  - Sequence length not determined a priori
  - Use a trapdoor pseudorandom *permutation*

RSA-based key regression: mechanics

- Publisher winds keys forward to grow a sequence:

$K_{i+1} = K_i^d \bmod N$

$$K_0$$

- Client unwinds keys:

$K_{i-1} = K_i^e \bmod N$

RSA-based key regression: mechanics

- Publisher winds keys forward to grow a sequence:

$K_{i+1} = K_i^d \text{ mod } N$

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- Client unwinds keys:

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$$\xleftarrow{K_2^e \bmod N} \cdots \xleftarrow{K_{t-1}^e \bmod N} K_{t-1}$$

RSA-based key regression: mechanics

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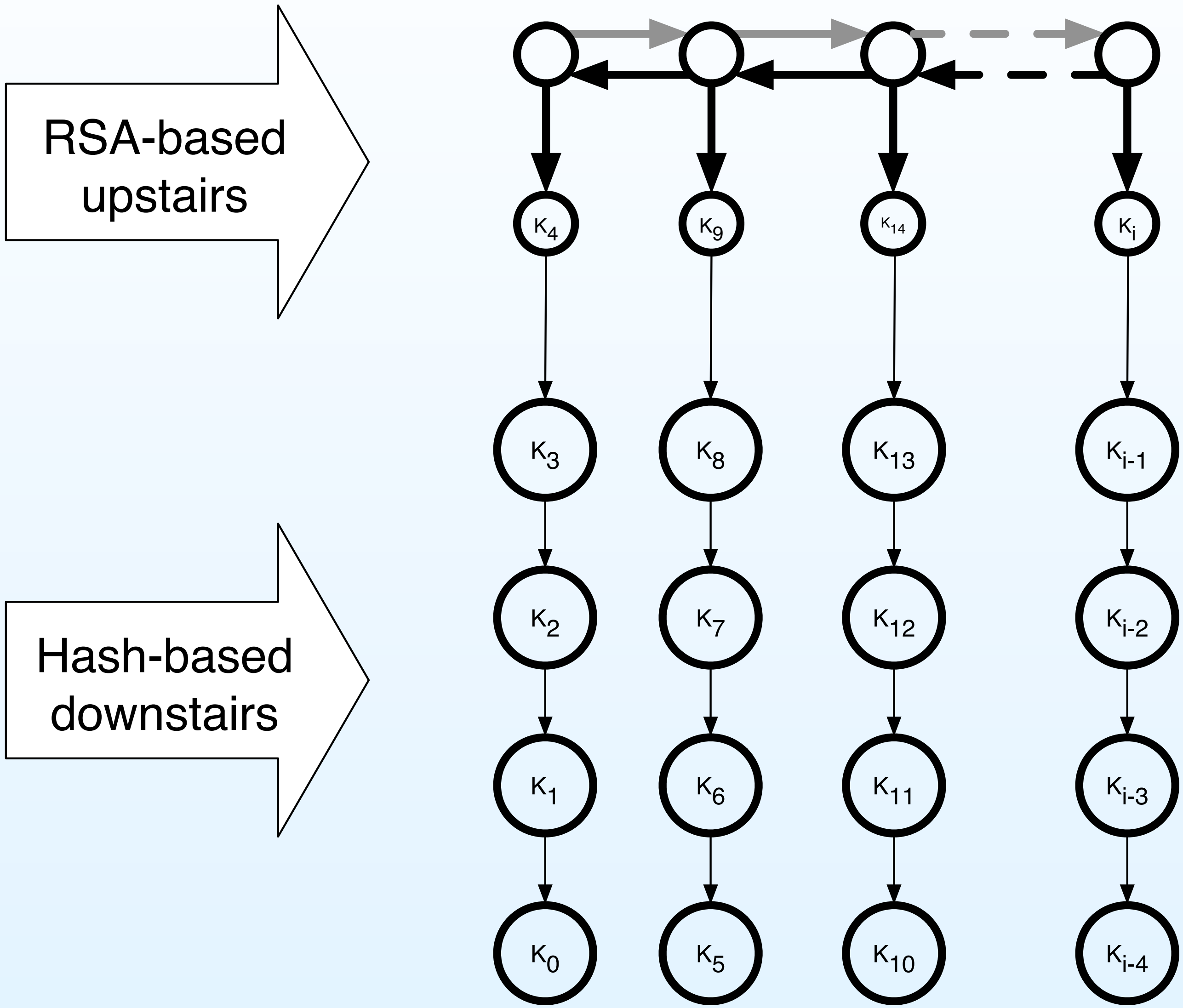
$$K_0 \xleftarrow{K_1^e \text{ mod } N} K_1 \xleftarrow{K_2^e \text{ mod } N} \cdots \xleftarrow{K_{t-1}^e \text{ mod } N} K_{t-1}$$

Dynamically growing + efficient



[Micali:87]
[Jakobsson:02]

Implementation of Chefs = SFSRO + access control

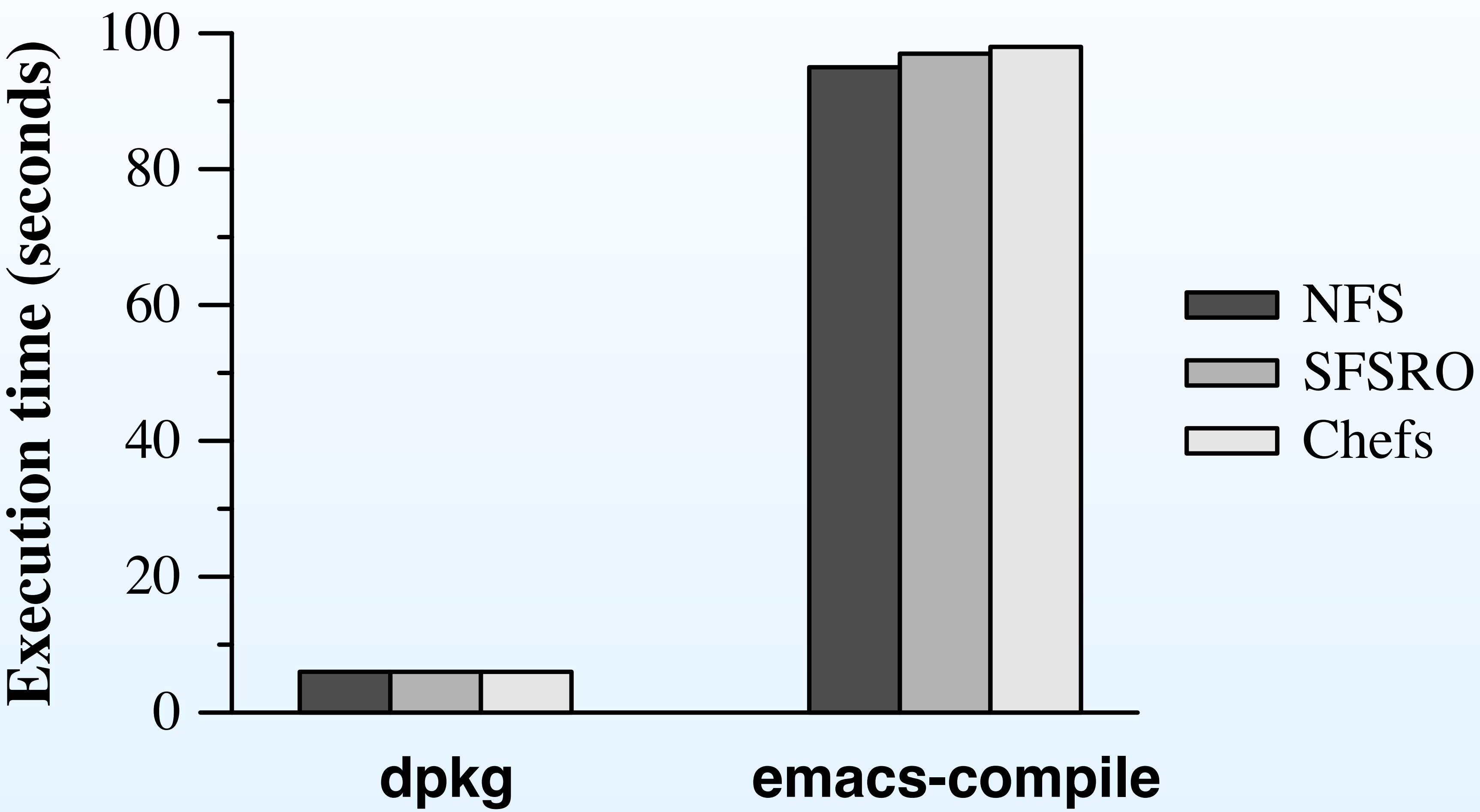
- Server remains unmodified
- More sophisticated algorithm for incremental updates
  - Lazy revocation
  - Database re-generation not idempotent
- Key regression based on SHA-1
  - Keys downloaded out-of-band
  - Must extract pseudorandom keys from unpredictable keys

Performance evaluation

Performance evaluation

- Throughput independent of a publisher's local resources
- Individual servers support many simultaneous clients
- Acceptable latency for clients
- Chefs performs equally to SFSRO, except for downloading keys

SFSRO and Chefs are efficient despite cryptography



2.8GHz Pentium 4 machines, 100 Mbit network, 266 μsec round-trip

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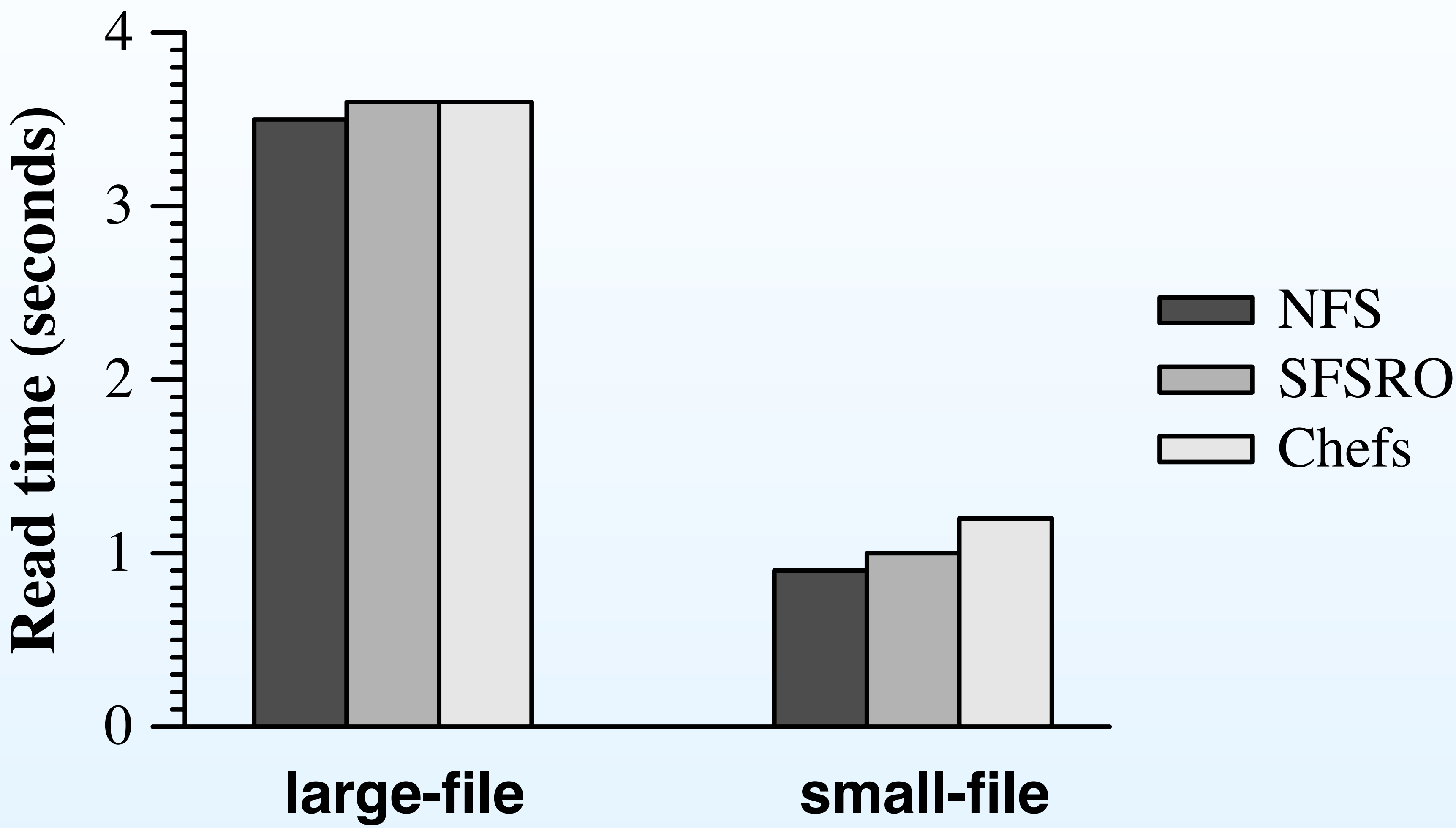

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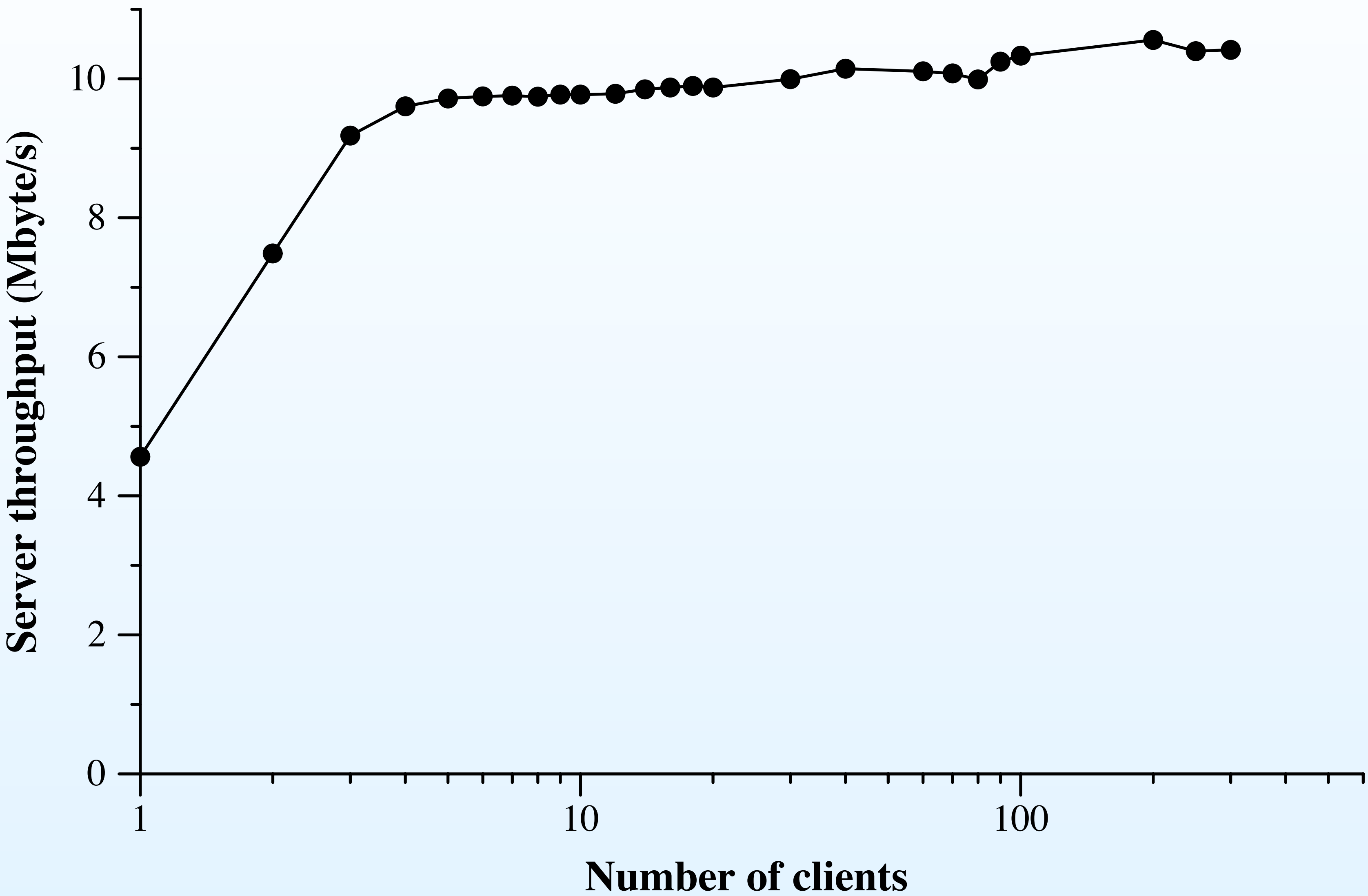
Servers scale because no online crypto



550 MHz Pentium III machines, 100 Mbit (12.5 Mbyte/s) network

Wrap up

Related work

- Secure file systems:
  Swallow [Reed:81], Cryptographic FS [Blaze:93], Byzantine FS [Castro:99], OceanStore [Kubi:00], Farsite [Adya:02], Untrusted data repositories (SUNDR) [Mazières:02], Venti [Quinlan:02], Snapdragon [Aguilera:03]
- Content distribution networks:
  SHTTP [Rescorla:99], Consistent hashing [Karger:99], Publius [Waldman:2000], Cooperative FS [Dabek:01], Publish-Subscribe [Wang:02], Authentic data publication [Devanbu:02], BitTorrent [Cohen:03], CoDeeN [Pai:03], SSL splitting [Laas:03], XML access control [Miklau:03], Coral [Freedman:04]
- Cryptography:
  One-time signatures [Lamport:79], One-time passwords [Lamport:81], Merkle trees [Merkle:79], Timestamping [Haber:91], Key escrow [Micali:92], Forward-secure encryption [Anderson:97,Bellare:99], Fractal hash sequence traversal [Jakobsson:02], Self-healing keys [Staddon:02], Related-key attacks [Bellare:03], group key distribution

Future work

Past	Present	Future

Untrusted Storage and File Systems

Cepheus	SFSRO	Plutus	Key regression
[Masters'99]	[OSDI'00,TOCS'02]	[FAST'03]	[any day now]

Future work

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Untrusted Storage and File Systems

Email revocation [ACISP'97]	Cepheus [Masters'99]	SFSRO [OSDI'00,TOCS'02]	Plutus [FAST'03]	REX [USENIX'04]	Key regression [any day now]

Future work

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Web authentication

[USENIX Security '01, CACM Sept '01]

Future work

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Email revocation	Cepheus	SFSRO	Plutus	REX	Key regression
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Web authentication
[USENIX Security '01, CACM Sept '01]

Proxy Re-Encryption
[NDSS'05], [ePrint '05]

RFID Security
[Reading signals]

Summary

- Distributing public content
  - Authenticity, integrity, freshness
  - High throughput
- Access control of private content
  - Efficient eviction
  - Efficient key distribution
- Implementation and performance measurements

Summary

- Distributing public content ←SFSRO
  - Authenticity, integrity, freshness
  - High throughput
- Access control of private content ←Chefs
  - Efficient eviction ←Lazy revocation
  - Efficient key distribution ←Key regression
- Implementation and performance measurements ←Works in practice

Linux BSDs Mac OS X

Bon Appetit

Download SFSRO and Chefs.

`http://www.fs.net/`

Questions?

Break in case of emergency

Key regression security

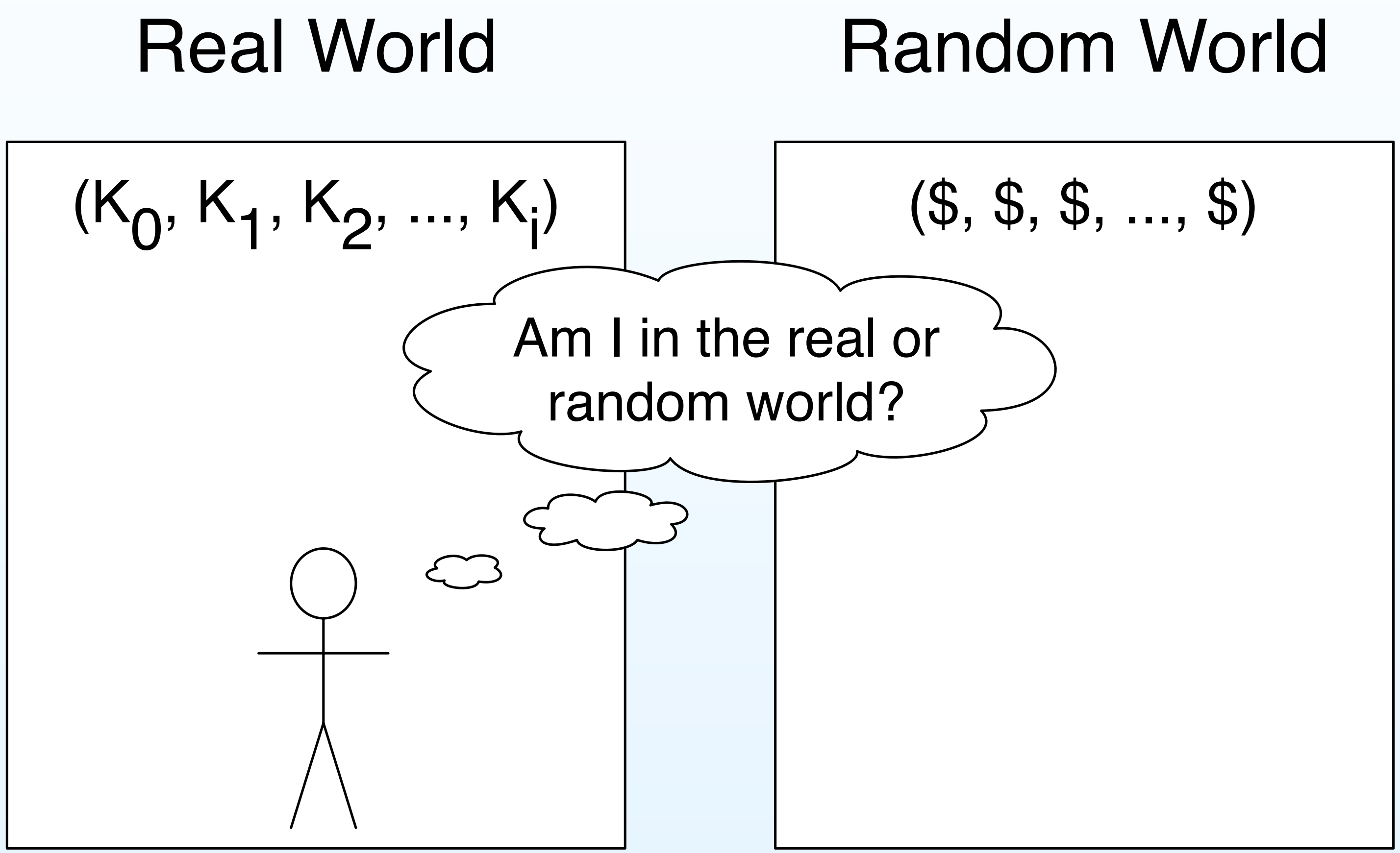
Real World

$(K_0, K_1, K_2, \ldots, K_i)$

Random World

(\$, \$, \$, ..., \$)

Key regression security



- Distinguish randomly generated sequence from key regression sequence?
- [Bellare:99, Bellare:03]

Represents a natural notion of security

- Why distinguishability instead of key recovery?
  - Captures notion of partial information
  - Only publisher can wind (unpredictable)
  - Only clients can unwind (pseudorandom)

- But are the hash-based and RSA-based schemes secure?

Keys must be unpredictable AND pseudorandom

- Hash-based scheme easily distinguishable
  - Given challenge, attempt to unwind
  - Check whether past keys match

Keys must be unpredictable AND pseudorandom

- Hash-based scheme easily distinguishable
  - Given challenge, attempt to unwind
  - Check whether past keys match
- RSA-based scheme easily distinguishable
  - What if $e = 3$
  - Guess N by looking at the size of keys
  - Check if unwinding works with $(e = 3, N)$

Solution: extract pseudorandomness

- Publisher winds *intermediate* keys:

  $\kappa_{i+1} = \kappa_i^d \bmod N$

$$\kappa_0 \xrightarrow{\kappa_0^d \bmod N} \kappa_1 \xrightarrow{\kappa_1^d \bmod N} \cdots \xrightarrow{\kappa_{t-2}^d \bmod N} \kappa_{t-1}$$

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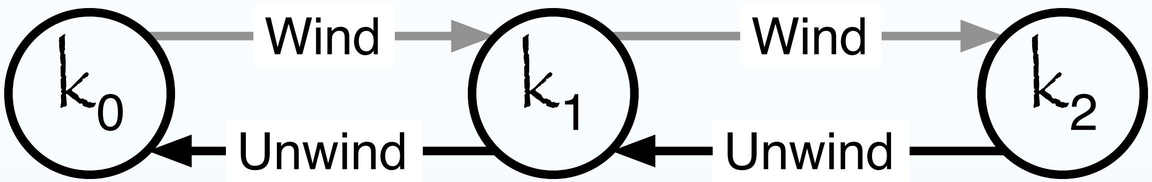
- Extract pseudorandom K_i from unpredictable κ_i
  - Using a one-way function: $K_i = F(\kappa_i)$

Security of key regression with extractor



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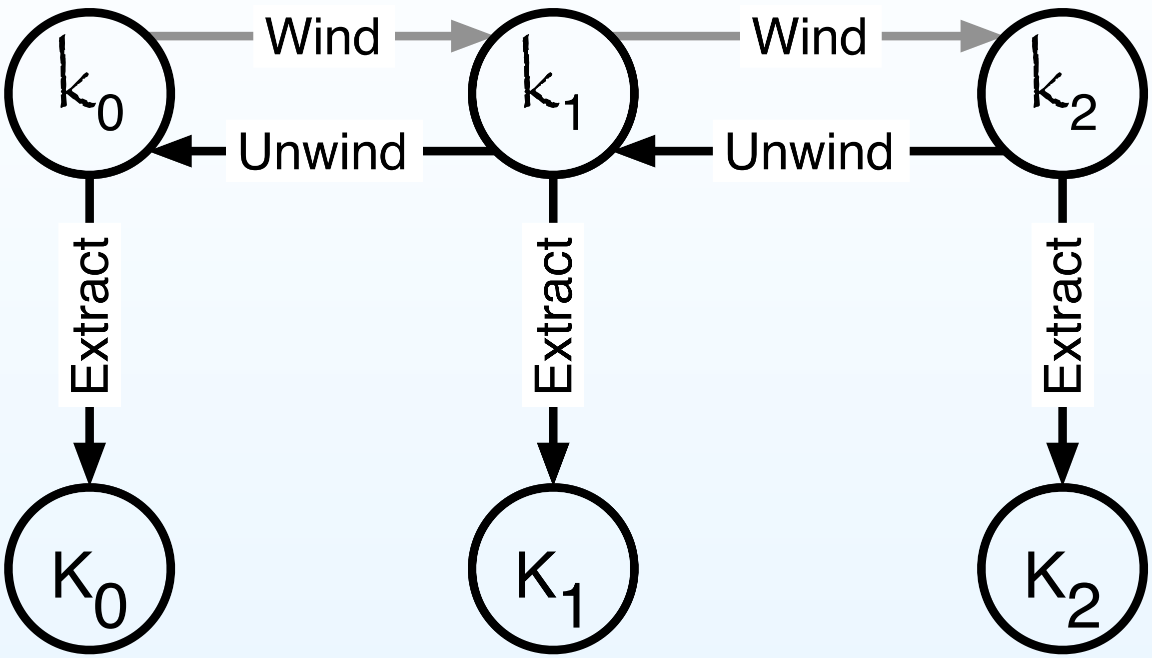

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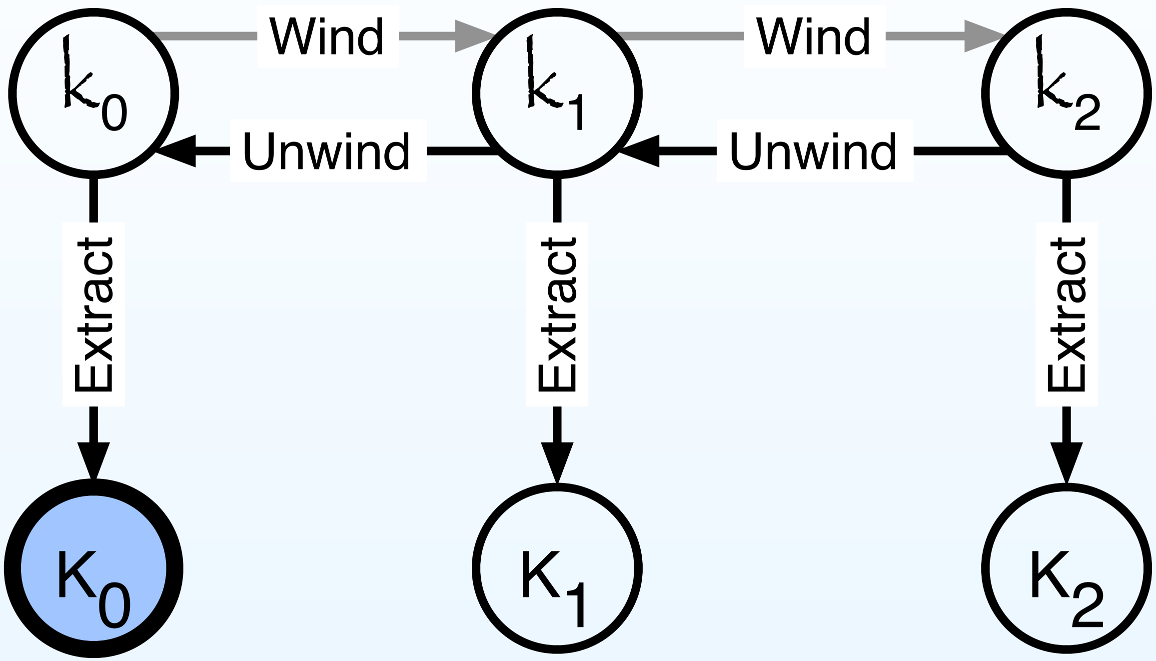

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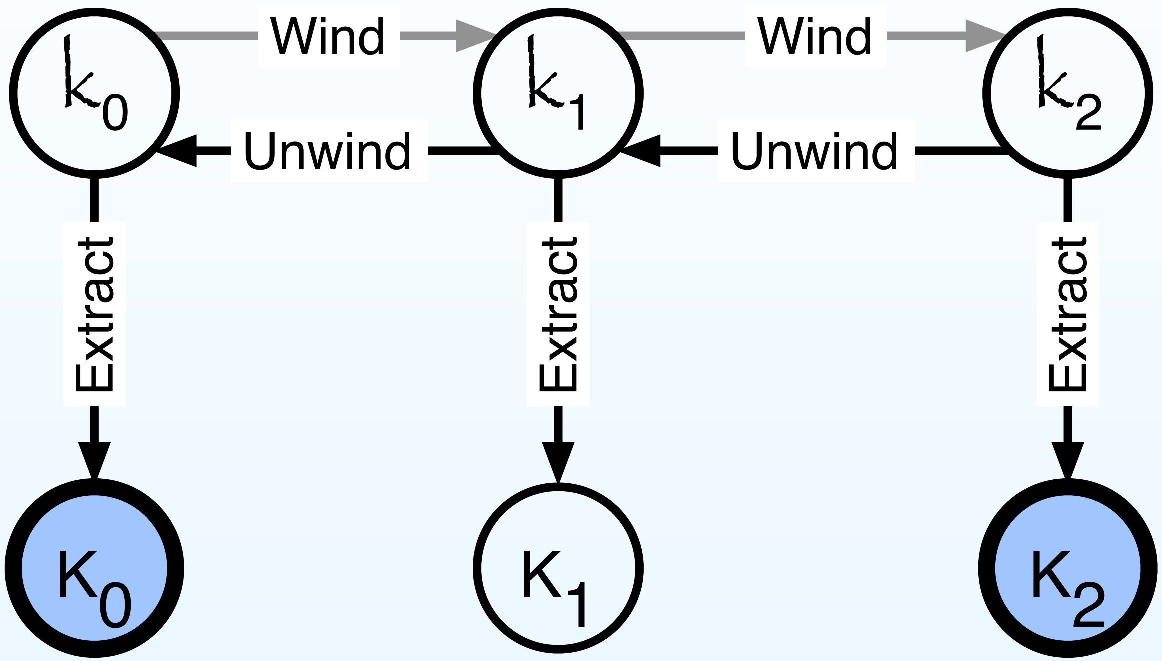
Security of key regression with extractor



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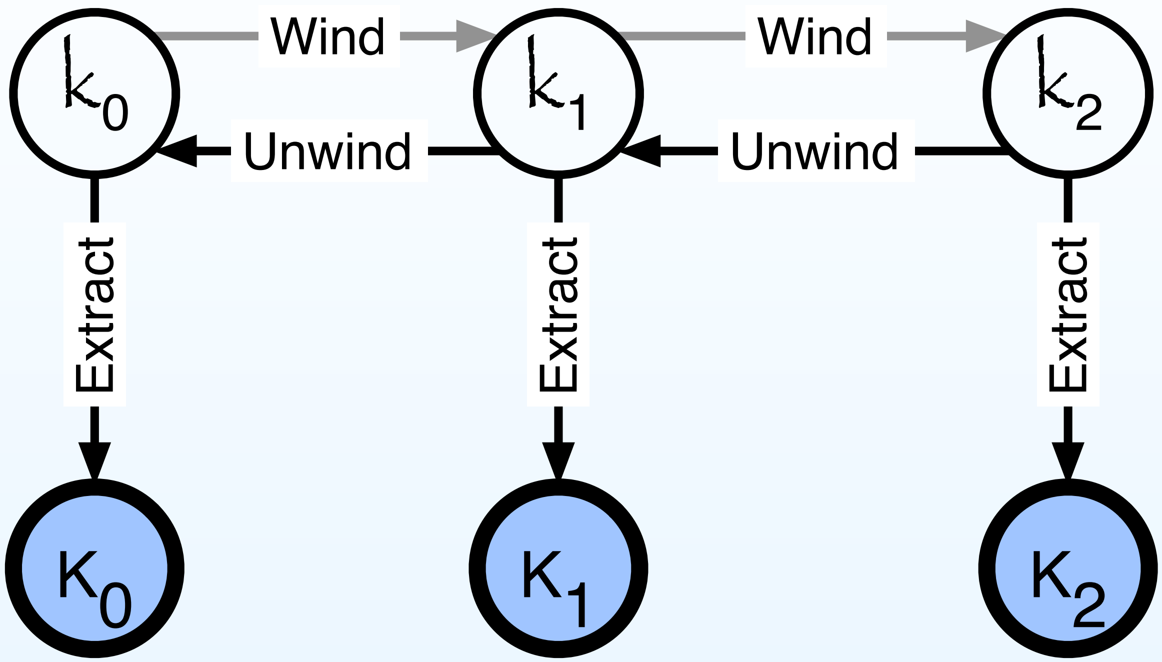

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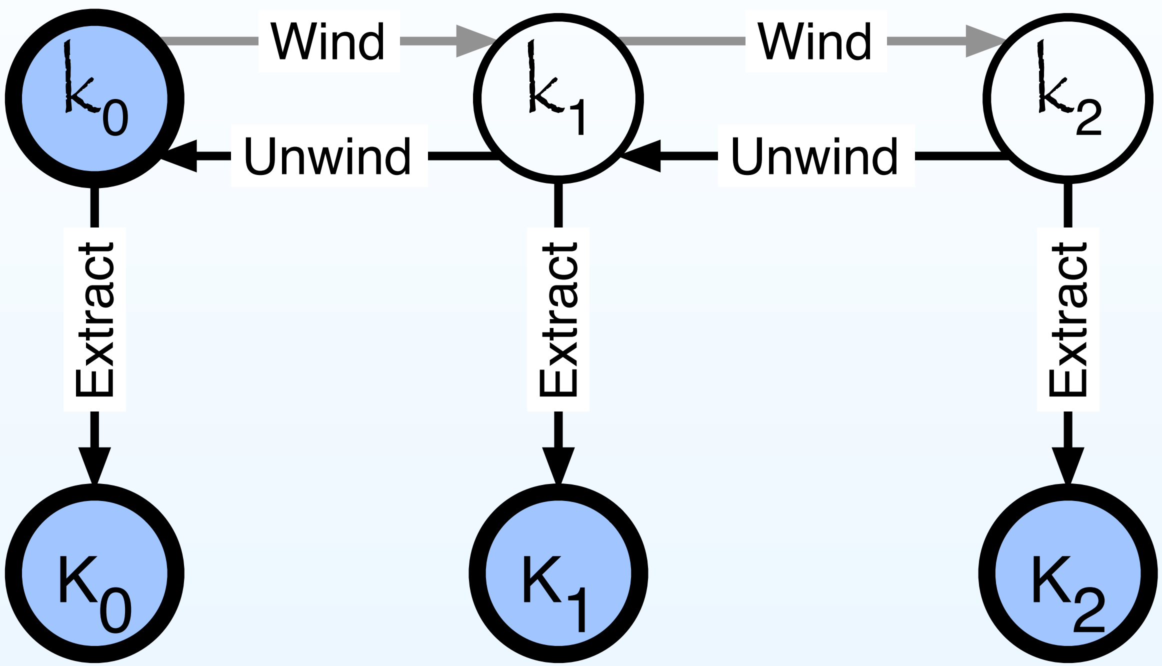

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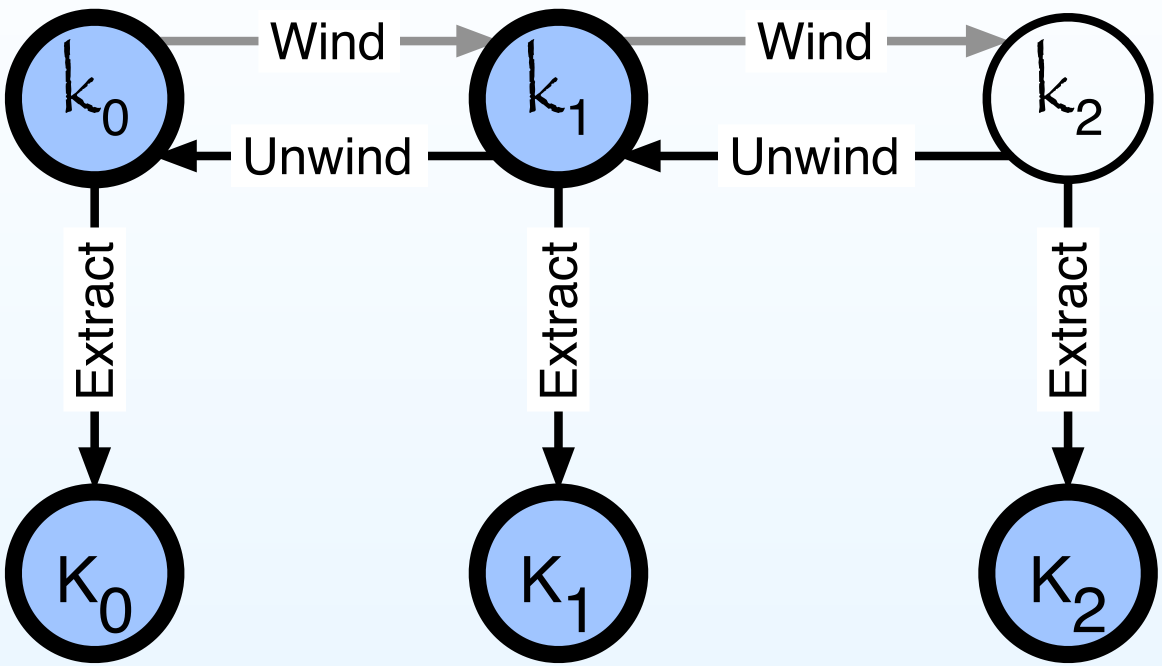

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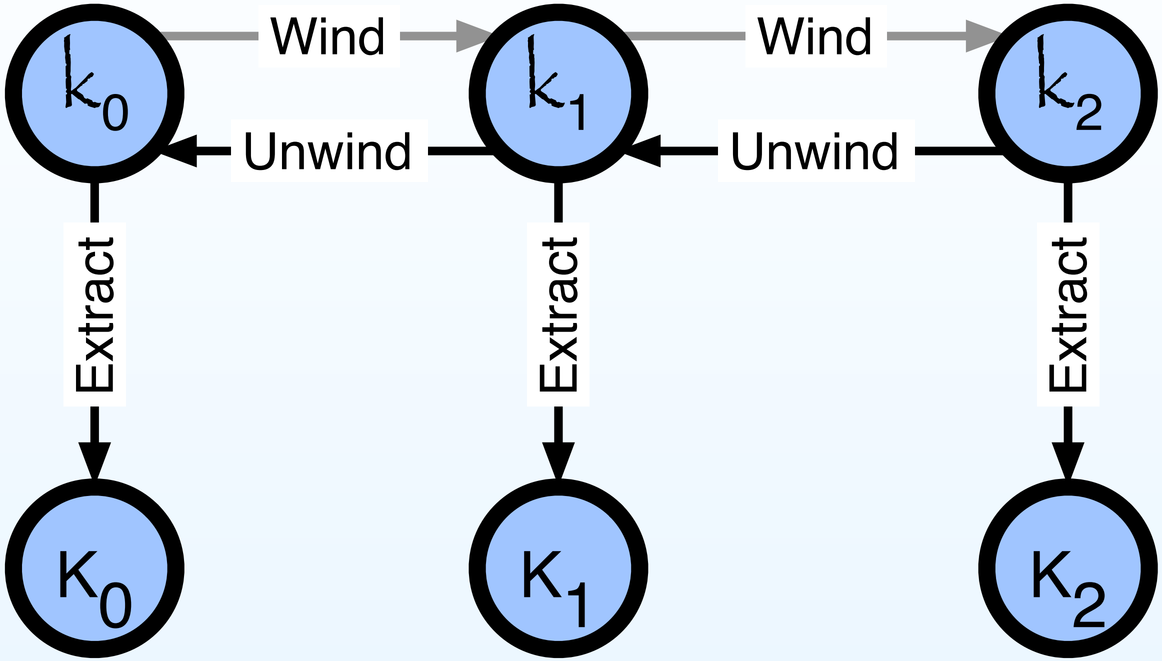

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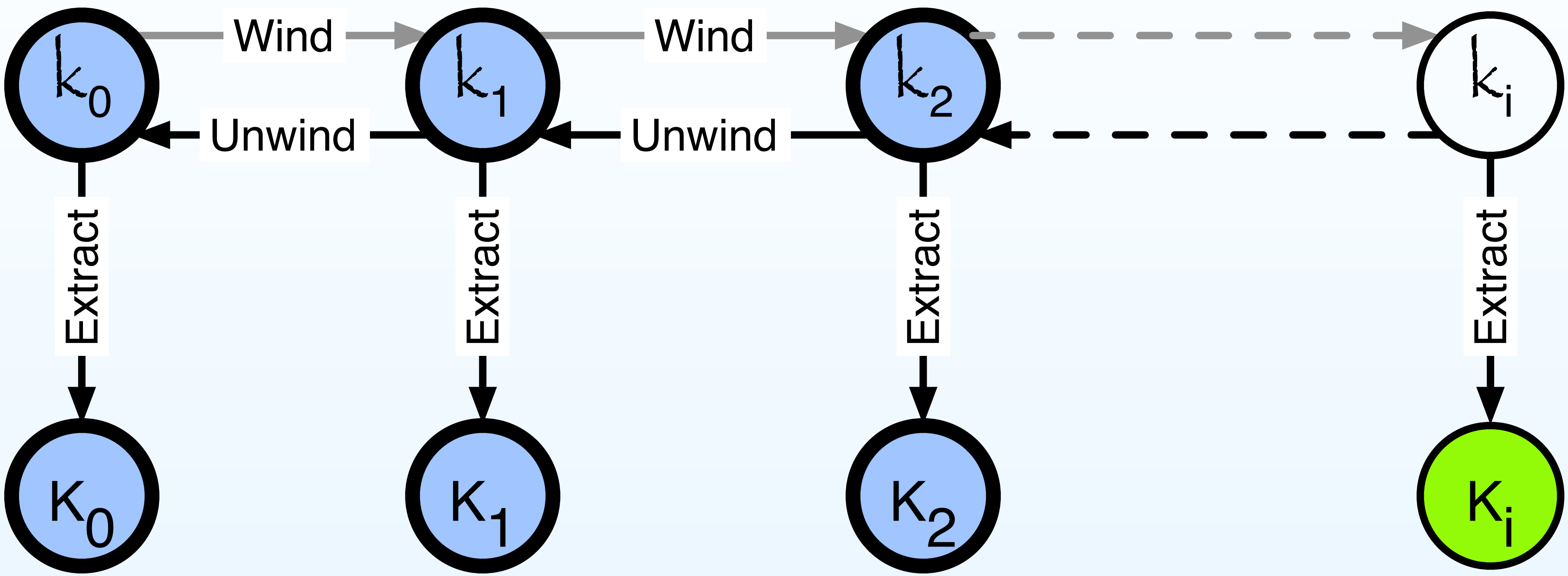

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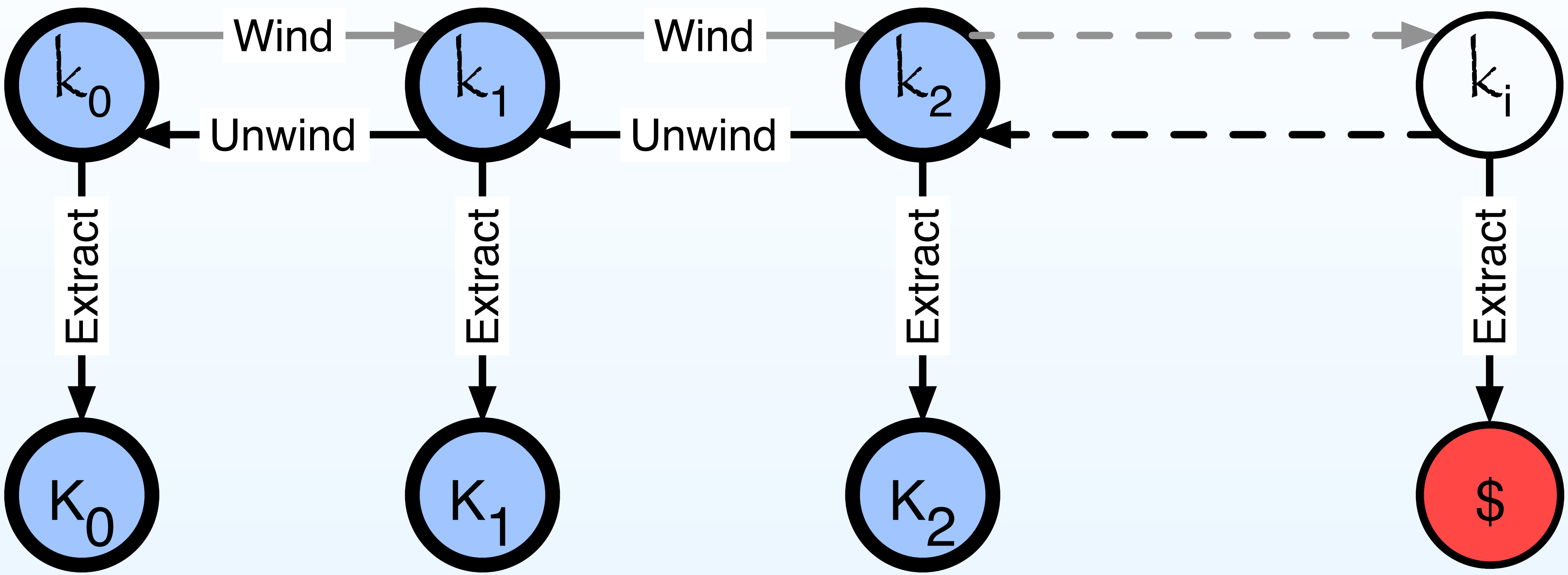
Security of key regression with extractor



- Adversary queries oracle for keys
- Adversary queries oracle for intermediate keys
- Adversary receives real or random challenge
- Notion works for arbitrary constructions

Emergency Slide: Hash collisions

- Collision resistance (find any two inputs)
  - Brute force 2^{80}
  - Wang, Yin, Yu attack (2^{69})
  - 2^{69} bytes $\equiv$ 524,288 Pbytes
- 2nd pre-image resistance (find a second input)
  - Brute force 2^{159}
  - Kesley, Schneier 2^{106} for particular messages

Emergency Slide: Economics

- Incentives
- How to collect payments
- Fair sharing

Emergency Slide: Applications

- Public content
  - Certificate authorities
  - Software distribution
- Private content
  - Subscriptions
  - Time-delayed release

Emergency Slide: SFSRO protocol

- CONNECT () – Initiate SFSRO protocol
- GETFSINFO () – Get signed hash of root directory
- GETDATA (*hash*) – Get block with *hash* value
- All data interpreted entirely by client
  - Server need know nothing about file system structure
  - Makes server fast and simple (< 400 lines of code)

Emergency Slide: SHA-1 broken!

- Move cautiously to SHA-256 or others
- Rely on different type of collision resistance

Emergency Slide: Broadcast encryption

- Modified Naor-Pinkas non-interactive key distribution
- $K_i = g^{r_i P(0)}$ ←secret sharing in the exponent
- New this year: Boneh/Waters ePrint manuscript
- Communication vs. storage (lazy revocation)
- Broadcast imposes constraints on the key

Emergency Slide: Forward security

- Forward-secure encryption (signatures...)
- Key regression differences
  - Opposite of FSE + trapdoor
  - Adversary can ask oracle for future keys
  - Adversary can ask for intermediate keys
  - Secure enough for chosen-plaintext attack with XOR
  - Equivalency of key regression and FSE

Emergency Slide: Incremental replication

- Servers need transfer only modified data
  - Traverse file system w/ SFSRO protocol
  - Stores all hashes/values encountered in new database
  - Avoids re-transferring any hashes already in old database
  - Unchanged directories automatically pruned from transfer
- Makes short signature durations practical

Emergency Slide: Evicted clients?

- Easy to distinguish worlds
- Given a key sequence, run unwind
- If previous key matches, we are using real key regression

Emergency Slide: Limit unwinding

- Line segment rather than ray of keys
- Double hash chain method
- Join-leave-join