# Balancing Storage Efficiency and Data Confidentiality with Tunable Encrypted Deduplication

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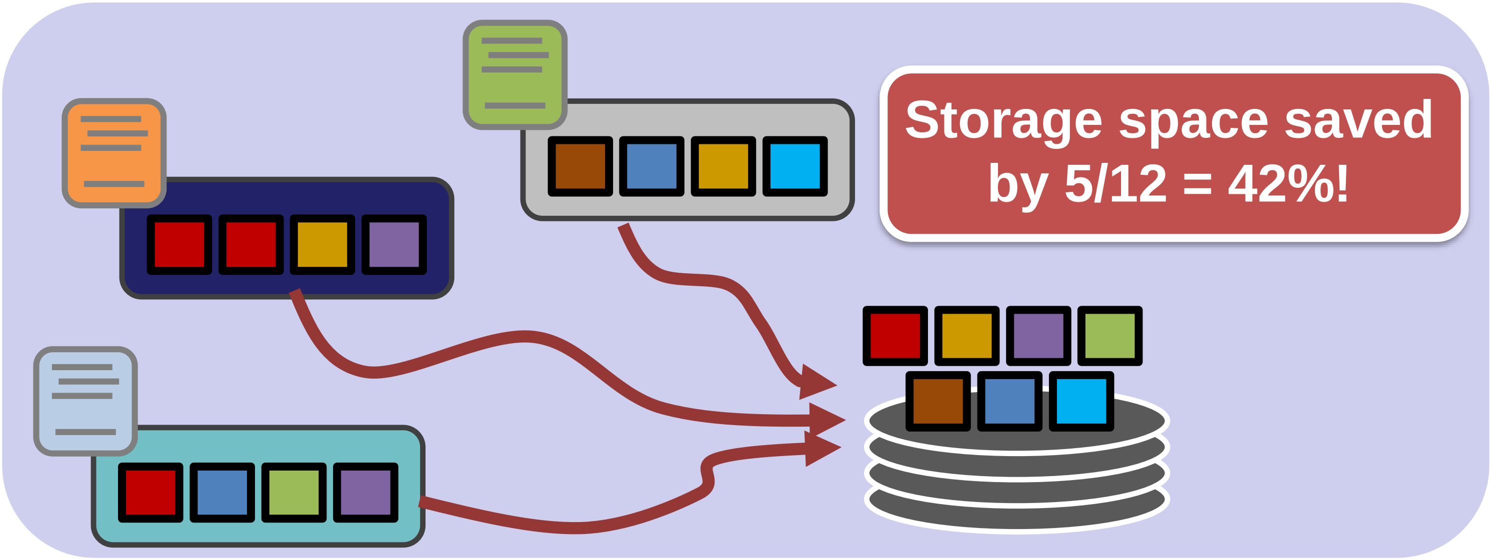
EuroSys 2020

# Deduplication

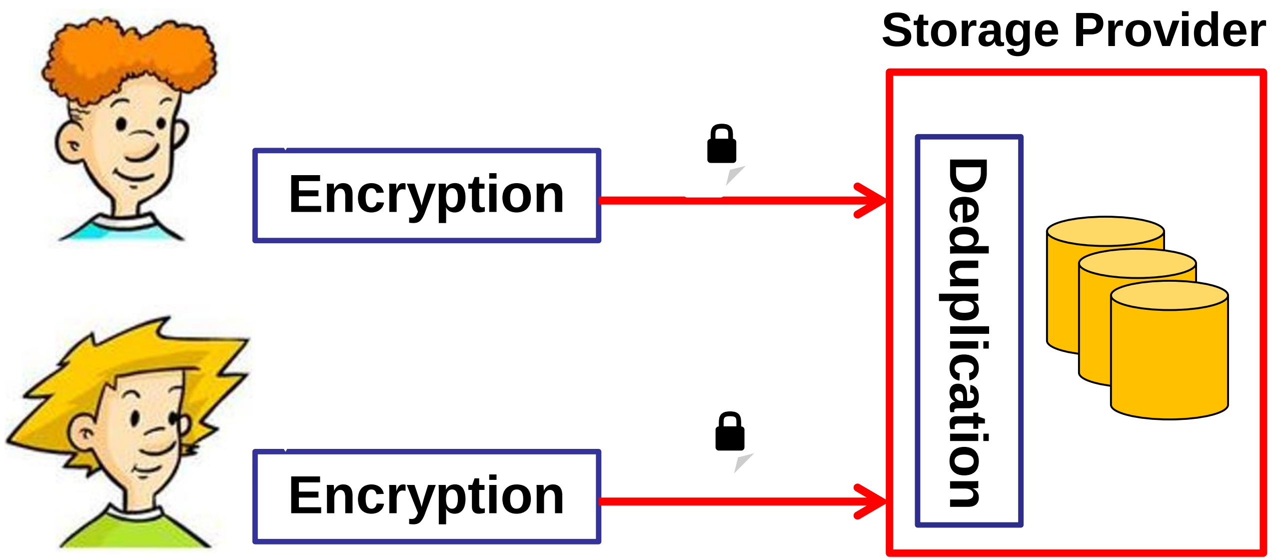
- ➢ Deduplication → coarse-grained compression
  - Units: **chunks** (fixed- or variable-size)
- ➢ Stores only one copy of duplicate chunks



# Encrypted Deduplication

- Augments deduplication with encryption for data confidentiality
- Application: outsourced storage

***Which crypto primitive should be used?***



# Encryption Primitives

- **Symmetric-key encryption (SKE)**
  - Derives a random key for chunk encryption/decryption
  - Ensures confidentiality, but **prohibits deduplication** of duplicate chunks
- **Message-locked encryption (MLE)** [Bellare et al., Eurocrypt'13]
  - Derives a deterministic key from chunk content
  - Supports deduplication, but **leaks frequency distribution** of plaintext chunks [Li et al., DSN'17]

**Pose a dilemma of choosing the right cryptographic primitive**

# Our Contributions

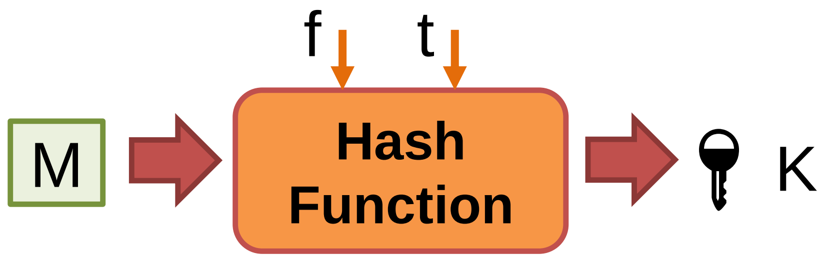
- **TED**: a tunable encrypted deduplication primitive for balancing trade-off between storage efficiency and data confidentiality
  - Includes three new designs
  - Minimizes frequency leakage via a configurable storage blowup factor

- **TEDStore**: encrypted deduplication prototype based on TED
  - TED incurs only limited performance overhead

- Extensive trace-driven analysis and prototype experiments

# Main Idea

- Key derivation with three inputs: chunk **M**, current frequency **f**, and balance parameter **t**

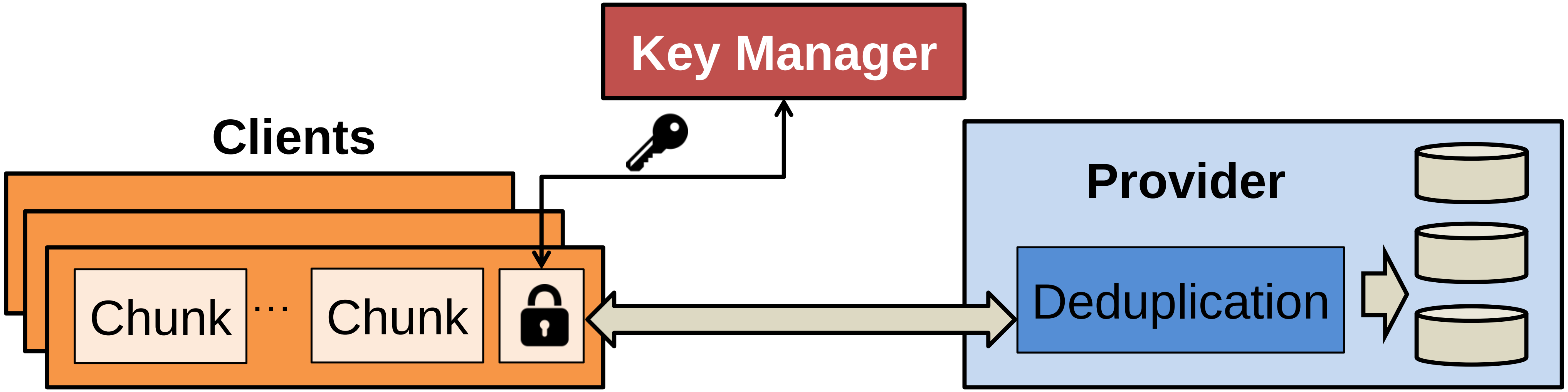



$K = \mathbf{H}(M \,||\, \lfloor f/t \rfloor)$

- f: cumulative and increases with number of duplicates of M
- t: controls maximum allowed number of duplicate copies for a ciphertext chunk

- Special cases:
  - $t = 1 \rightarrow$ SKE
  - $t \rightarrow \infty \rightarrow$ MLE

# Design Overview




- TED builds on **server-aided MLE architecture** in DupLESS [Bellare et al., Security'13]
  - Key generation by **key manager** to prevent offline brute-force attacks

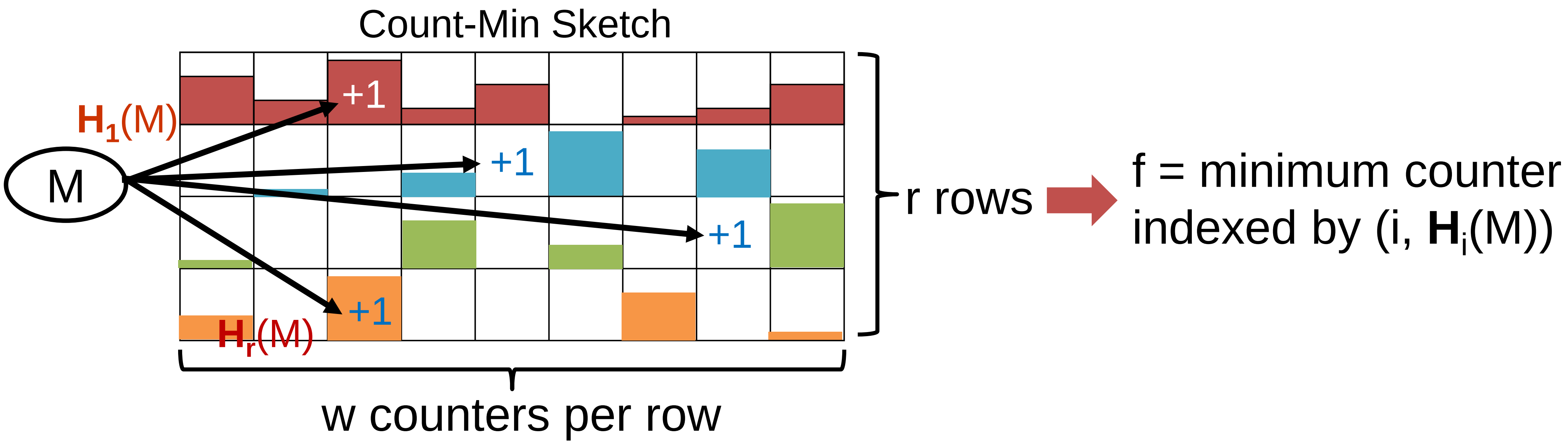
# Questions

- Q1: How does the key manager learn chunk frequencies?
  - Low overhead required even for many chunks

- Q2: How does the key manager generate keys for chunks?
  - Distinct sequences of ciphertext chunks required for identical files

- Q3: How should the balance parameter t be configured in practice?
  - Adaptive for different workloads

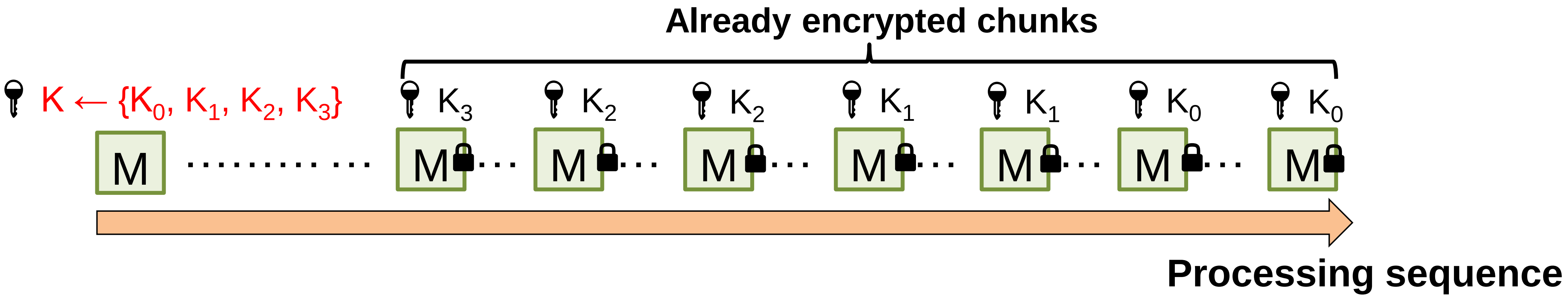
# Sketch-based Frequency Counting




- Key manager estimates f via Count-Min Sketch [Cormode 2005]
  - Fixed memory usage with provable error bounds
- Client sends **short hashes** {$\mathbf{H}_i$(M)} to key manager
  - Key manager cannot readily infer M from short hashes

# Probabilistic Key Generation

- Selects K uniformly from candidate keys derived from 0, 1,…, $\lfloor f/t \rfloor$
  - Enables probabilistic encryption on identical files
  - **Maintains deduplication effectiveness**
    - **Reason**: f is cumulative; keys derived from 0, 1,…, $\lfloor f/t \rfloor$-1 have been used to encrypt some old copies of M



# Automated Parameter Configuration

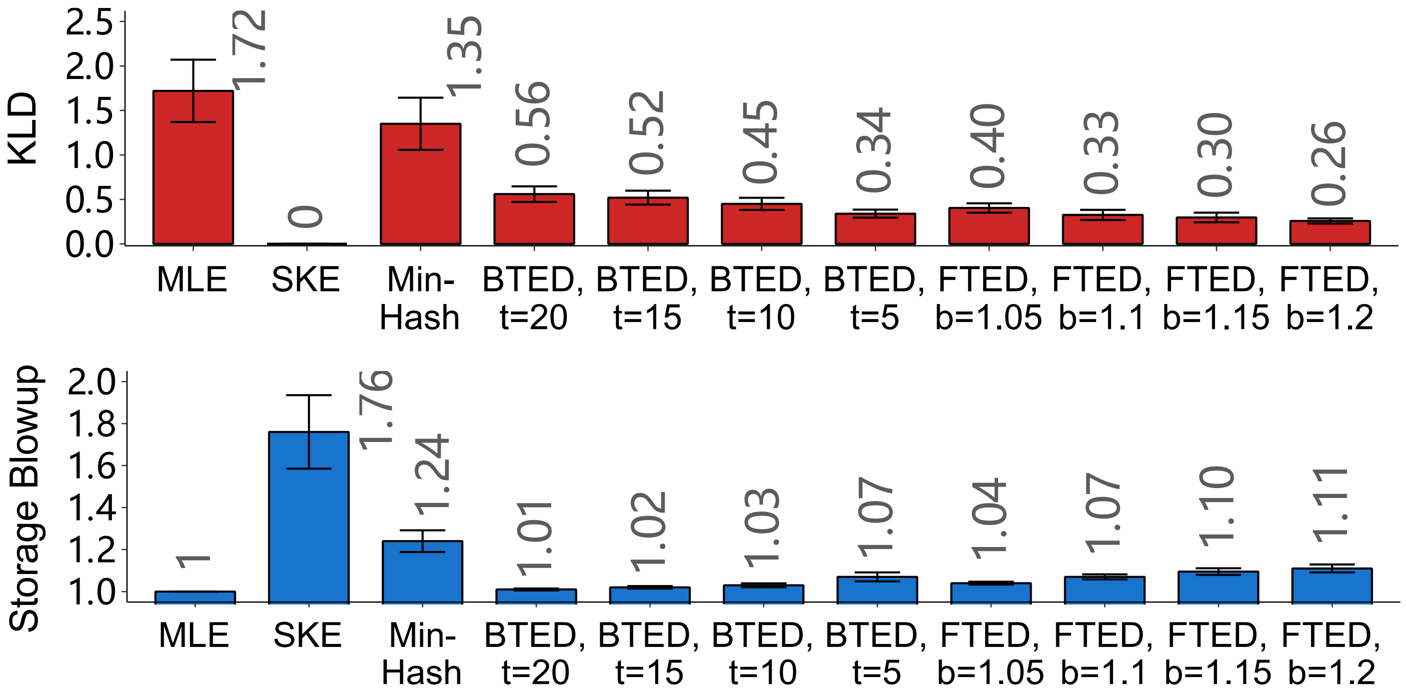
- Configure t by **solving optimization problem**, given:
  - Frequency distribution for a batch of plaintext chunks
  - Affordable storage blowup b over exact deduplication

- Goal: **minimize frequency leakage**
  - Quantify frequency leakage by Kullback-Leibler distance (KLD)
    - KLD: relative entropy to uniform distribution
  - A lower KLD implies higher robustness against frequency analysis
  - Configure t from the returned optimal frequency distribution of ciphertext chunks

# Evaluation

- TEDStore realizes TED in encrypted deduplication storage
  - ~4.5K line of C++ code in Linux
- Trace analysis
  - FSL: file system snapshots (42 backups; 3.08TB raw data)
  - MS: windows file system snapshots (30 backups; 3.91TB raw data)
- Prototype experiments
  - Local 10 GbE cluster

# Trade-off Analysis (FSL Dataset)




- Schemes
  - MLE
  - SKE
  - MinHash [Li et al., DSN'17]
  - Basic TED (varying t)
  - Full TED (varying b)

- Basic TED and Full TED effectively balance trade-off
- Full TED readily configures actual storage blowup

# Prototype Experiments

| Steps | Fast (MD5, AES-128) | Secure (SHA-256, AES-256) |
|---|---|---|
| Chunking | 0.8ms | |
| Fingerprinting | 1.7ms | 2.6ms |
| Hashing | 0.4ms | |
| Key Seeding | 0.01ms | 0.04ms |
| Key Derivation | 0.07ms | 0.1ms |
| Encryption | 3.7ms | 4.9ms |

TED operations

**Computational time per 1MB of uploads**

- TED incurs limited overhead (7.2% for Fast; 6.1% for Secure)
- More results in paper:
  - TED achieves ~**30X** key generation speedup over existing approaches
  - Multi-client upload/download performance

# Conclusion

- TED: encrypted deduplication primitive that enables controllable trade-off between storage efficiency and data confidentiality
  - Sketch-based frequency counting
  - Probabilistic key generation
  - Automated parameter configuration

- Source code: **http://adslab.cse.cuhk.edu.hk/software/ted**