A Formal Treatment of End-to-End Encrypted Cloud Storage

Matilda Backendal[1], Hannah Davis[2], Felix Günther[3], Miro Haller[4], Kenny Paterson[1]

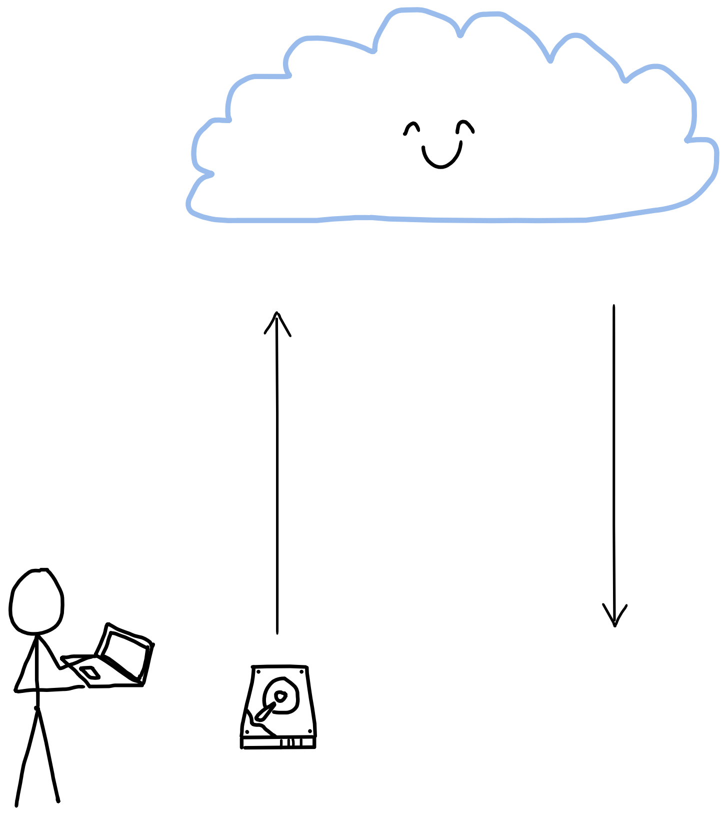
[1]ETH Zurich , [2]Seagate Technology, [3]IBM Research Zurich, [4]UC San Diego

Amazon, October 29, 2024

Cloud Storage

Benefits:

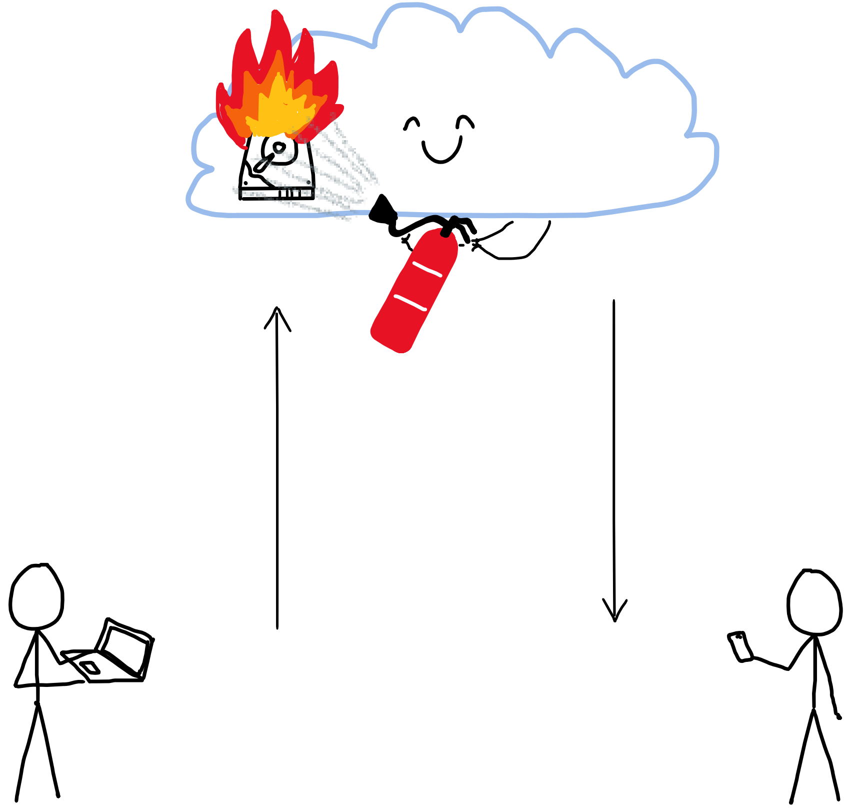
+ Availability



Cloud Storage

Benefits:

+ Availability
+ Redundancy

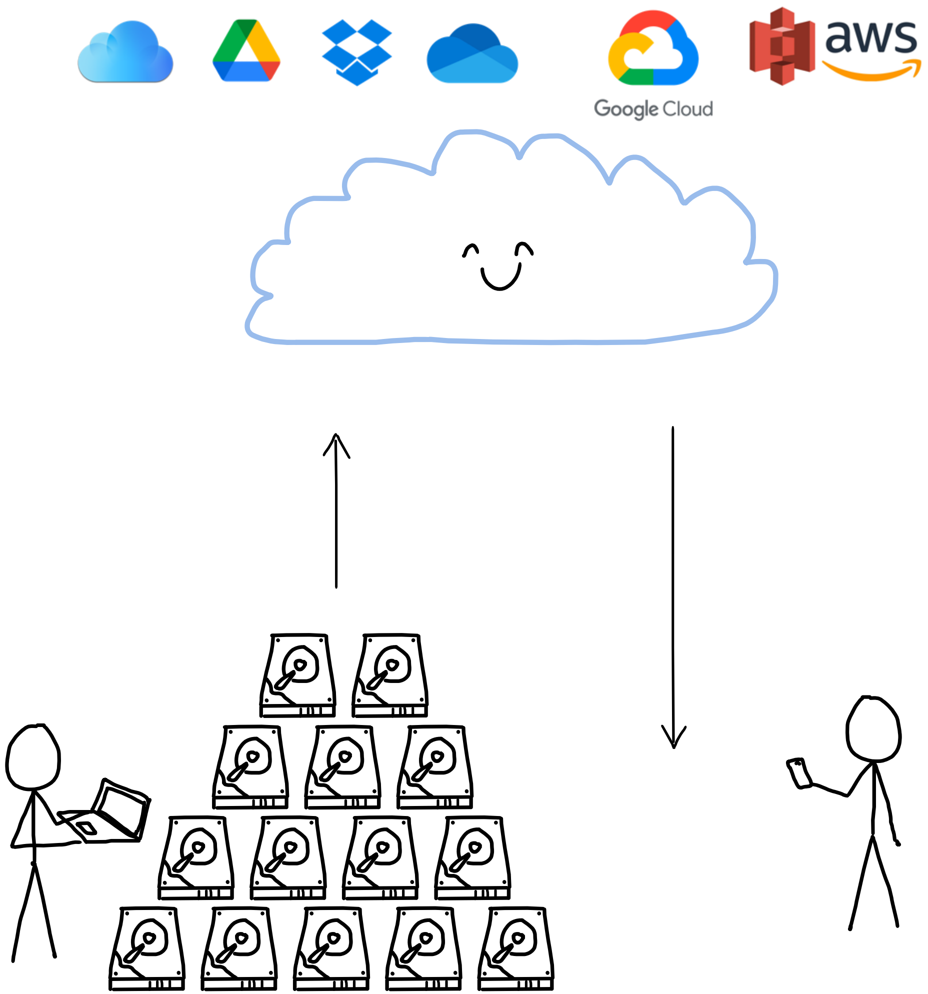


Cloud Storage

Benefits:

+ Availability
+ Redundancy
+ Scalability

STORING 50% OF ALL DATA BY 2025 [1]



[1] https://cybersecurityventures.com/the-world-will-store-200-zettabytes-of-data-by-2025/ (Sausalito, Calif., Feb. 1, 2024)

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Concerns:

- Data leaks

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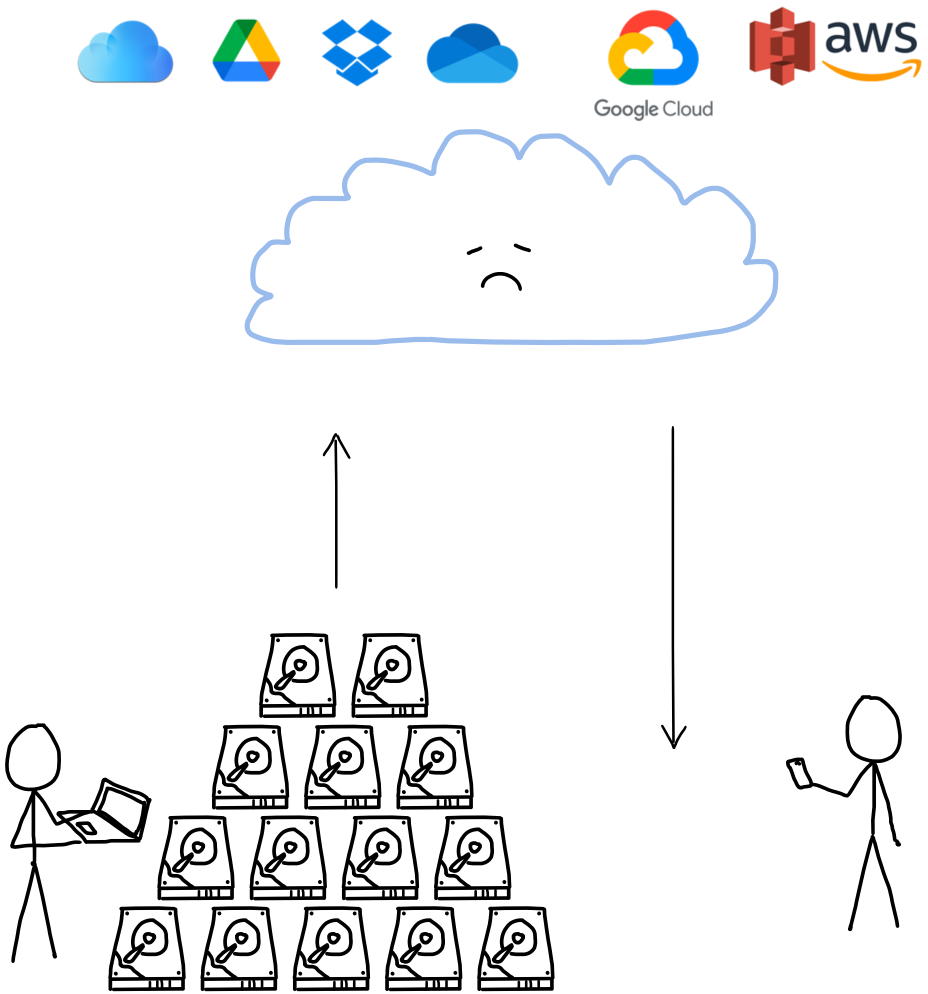

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Cloud Storage

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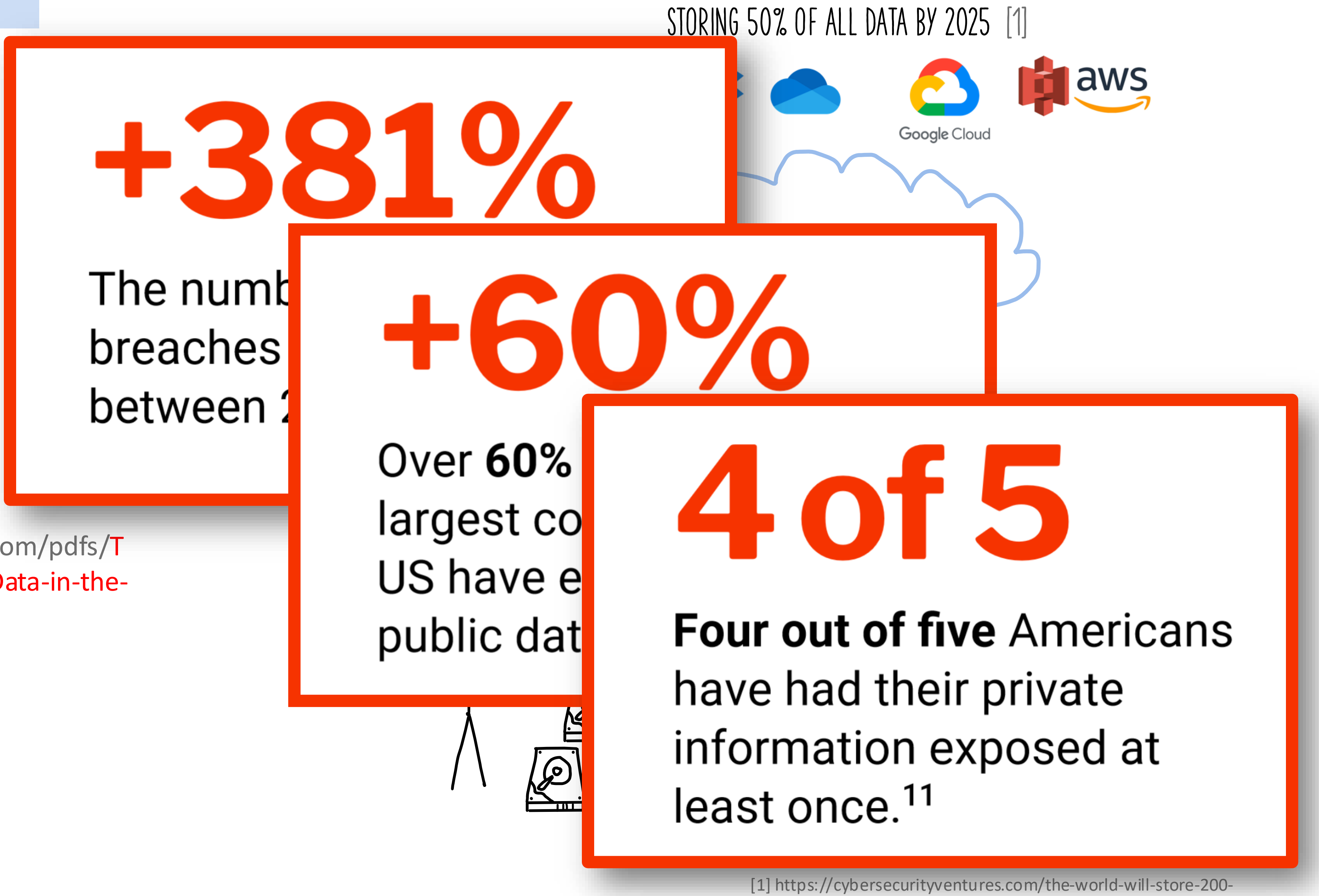
https://www.apple.com/newsroom/pdfs/The-Rising-Threat-to-Consumer-Data-in-the-Cloud.pdf (December 2022)



STORING 50% OF ALL DATA BY 2025 [1]

+381%

The numb
breaches
between 2

+60%

Over **60%**
largest co
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4 of 5

Four out of five Americans have had their private information exposed at least once.[11]

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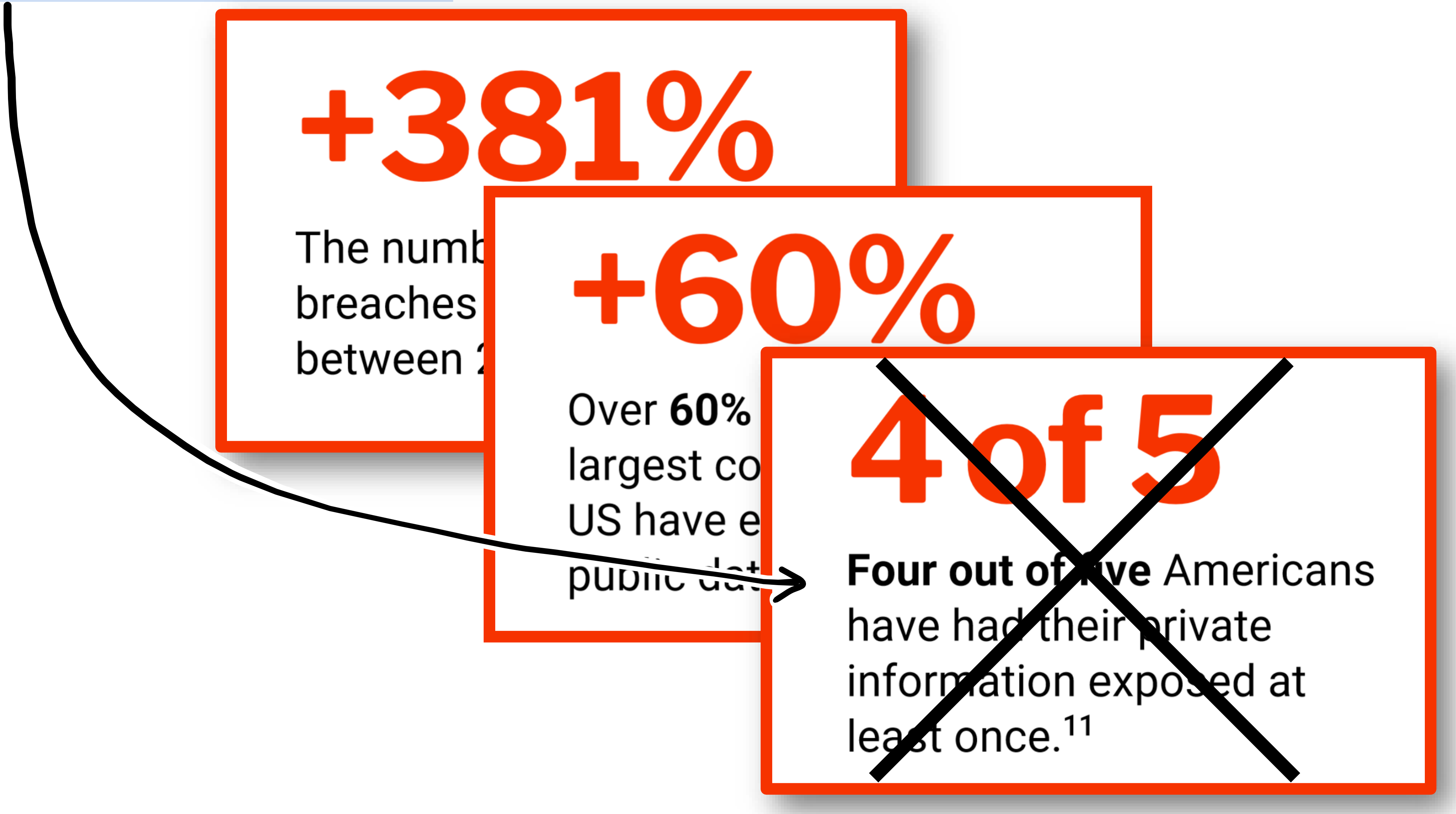
Why E2E Security?



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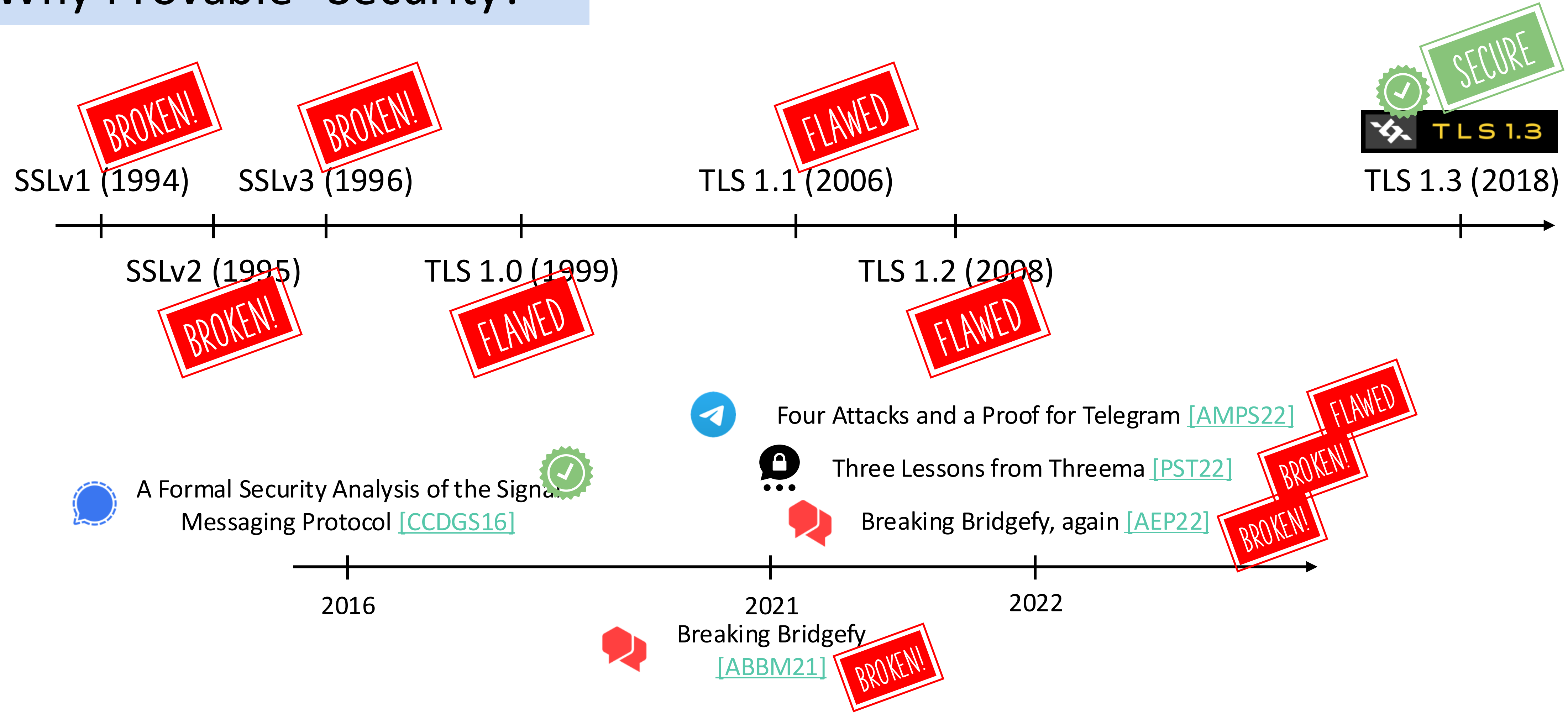
Why Provable Security?



SSLv1 (1994) BROKEN!

SSLv2 (1995) BROKEN!

SSLv3 (1996) BROKEN!

TLS 1.0 (1999) FLAWED

TLS 1.1 (2006) FLAWED

TLS 1.2 (2008) FLAWED

TLS 1.3 (2018) SECURE

A Formal Security Analysis of the Signal Messaging Protocol [CCDGS16]

Breaking Bridgefy [ABBM21] BROKEN!

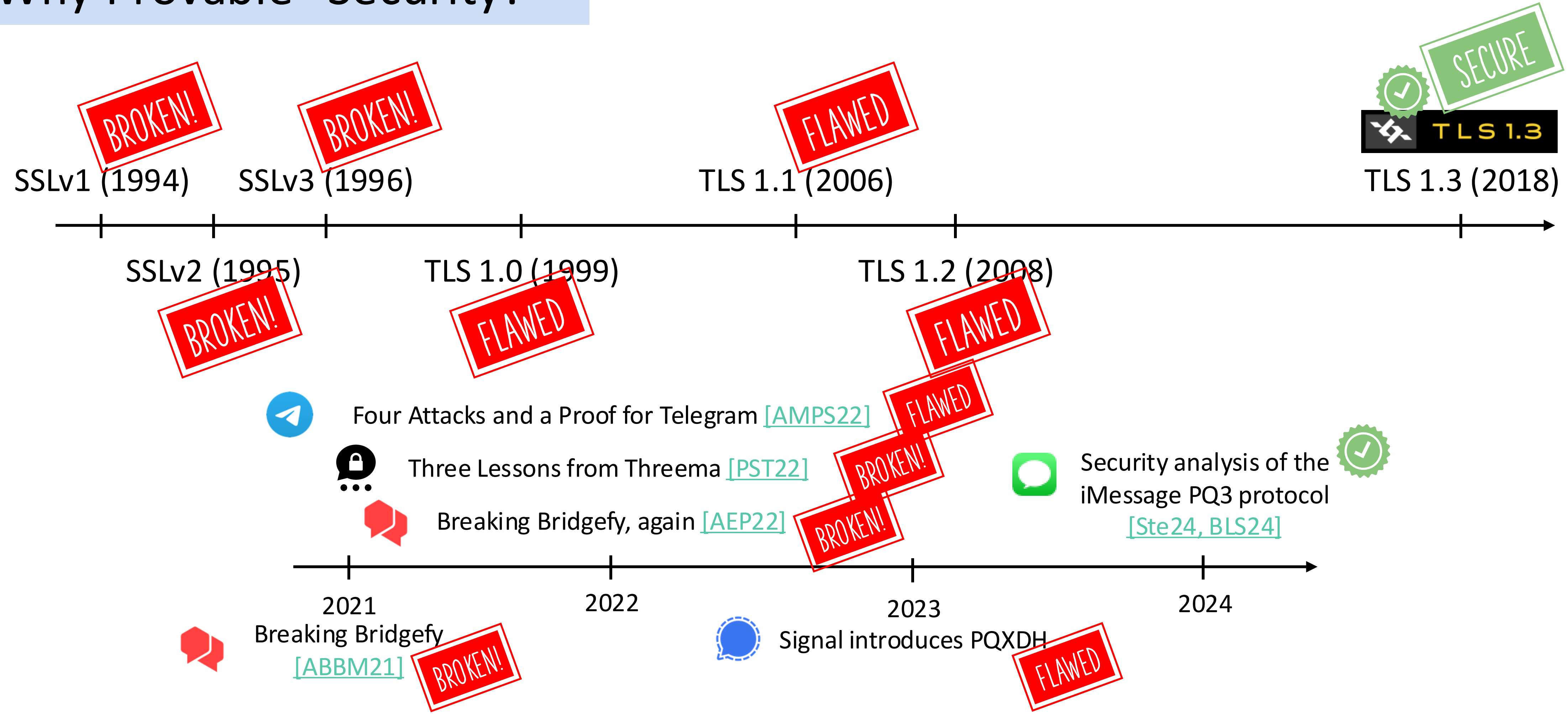
Four Attacks and a Proof for Telegram [AMPS22] FLAWED

Three Lessons from Threema [PST22] BROKEN!

Breaking Bridgefy, again [AEP22] BROKEN!

Logos from https://bridgefy.me/, fr.logodownload.org, vecteezy.com, https://threema.ch/en/press & https://commons.wikimedia.org/wiki/File:IMessage_logo.svgSecurity analysis of the iMessage PQ3 protocol

Why Provable Security?



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2021

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2022

2023

Signal introduces PQXDH FLAWED

Security analysis of the iMessage PQ3 protocol [Ste24, BLS24] ✓

2024

Logos from https://bridgefy.me/, fr.logodownload.org, vecteezy.com, https://threema.ch/en/press & https://commons.wikimedia.org/wiki/File:IMessage_logo.svgSecurity analysis of the iMessage PQ3 protocol

2022: Cloud Storage

Provider	Active users
Google Drive	> 1 billion
OneDrive	0.5 – 1 billion
iCloud	> 850 million
Dropbox	>700 million

Sources:

Google Drive (2018): https://techcrunch.com/2018/07/25/google-drive-will-hit-a-billion-users-this-week/?guccounter=1

OneDrive (2015, 2022): https://www.computerworld.com/article/3003140/microsofts-onedrive-changes-follow-the-money.html, https://news.microsoft.com/bythenumbers/en/give

iCloud (2018): https://www.cnbc.com/2018/02/11/apple-could-sell-icloud-for-the-enterprise-barclays-says.html

Dropbox (2022): https://dropbox.gcs-web.com/news-releases/news-release-details/dropbox-announces-second-quarter-fiscal-2022-results

2022: Cloud Storage Lacks Privacy

Provider	Active users	E2EE
Google Drive	> 1 billion	❌
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OneDrive (2015, 2022): https://www.computerworld.com/article/3003140/microsofts-onedrive-changes-follow-the-money.html, https://news.microsoft.com/bythenumbers/en/give

iCloud (2018): https://www.cnbc.com/2018/02/11/apple-could-sell-icloud-for-the-enterprise-barclays-says.html

Dropbox (2022): https://dropbox.gcs-web.com/news-releases/news-release-details/dropbox-announces-second-quarter-fiscal-2022-results

2024: Cloud Storage

Provider	Active users	E2EE
Google Drive	> 1 billion	Optional and limited
OneDrive	0.5 – 1 billion	❌
iCloud	> 850 million	Optional and limited
Dropbox	>700 million	Optional for enterprises

Sources:

Google Drive (2024): https://support.google.com/a/answer/10745596?hl=en
iCloud (2024): https://support.apple.com/guide/security/advanced-data-protection-for-icloud-sec973254c5f/web
Dropbox: https://blog.dropbox.com/topics/company/new-solutions-to-secure-organize-and-share-cloud-content

E2EE Cloud Storage Providers

"WITH **MEGA**, YOU
CONTROL THE ENCRYPTION"

300 MILLION USERS

MEGA

THE GERMAN FEDERAL GOVERNMENT,
AMNESTY INTERNATIONAL,
& ETH Zurich

"ULTIMATE SECURITY"

Nextcloud

"FREE, ENCRYPTED, AND SECURE CLOUD STORAGE.
YOUR PRIVACY, SECURED BY MATH"

Proton Drive

"EXCEPTIONALLY PRIVATE CLOUD"

sync.com

icedrive

"THE STRONGEST ENCRYPTED
CLOUD STORAGE IN THE WORLD"

"EUROPE'S MOST SECURE CLOUD STORAGE"

pCloud

Seafile™

"SUPPORTS CLIENT-SIDE
END-TO-END ENCRYPTION"

Case Studies: E2EE Cloud Storage

Challenges:

1. Stateless clients
2. No ciphertext integrity
3. Key recovery attacks [1,2]
4. Key reuse
5. File re-encryption infeasible
6. PKE has no authentication [3]

[1] Matilda Backendal, Miro Haller and Kenneth G. Paterson. (2023). "MEGA: Malleable Encryption Goes Awry”. IEEE S&P 2023.

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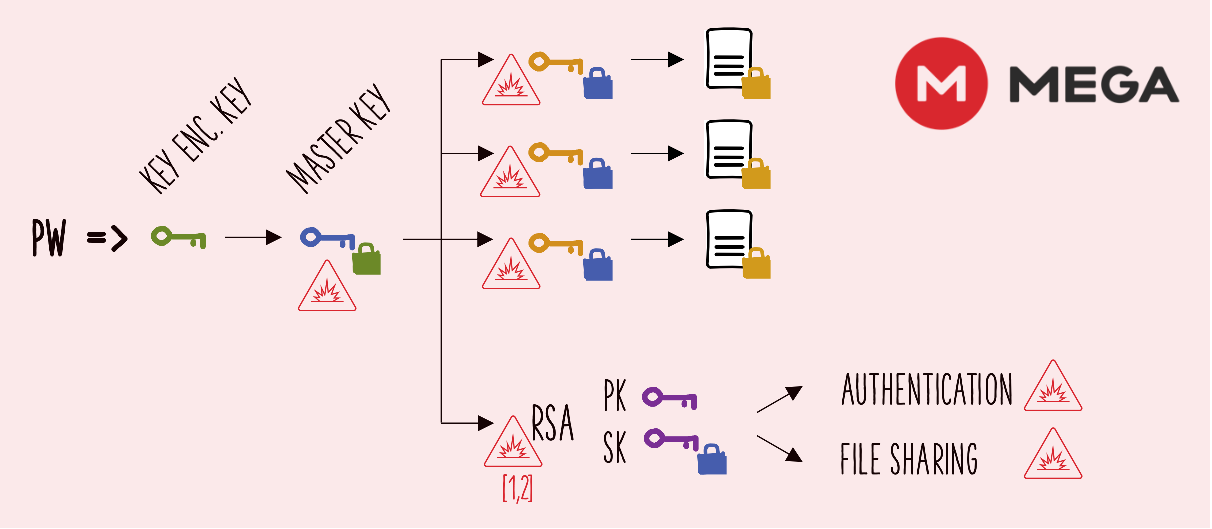

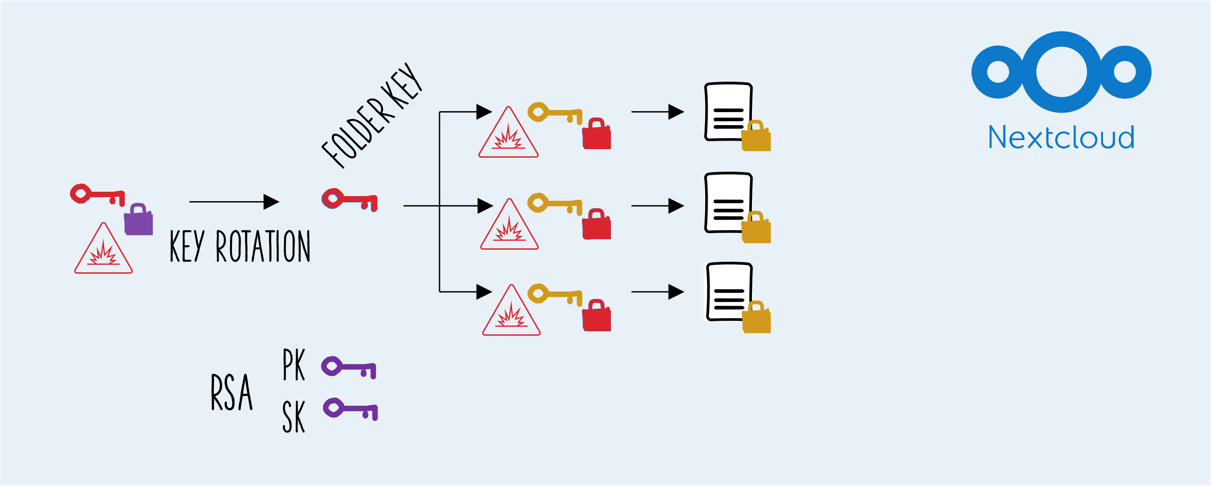

Case Studies: E2EE Cloud Storage

... is surprisingly hard!

Challenges:

1 Stateless clients

2 No ciphertext integrity

3 Key recovery attacks [1,2]

4 Key reuse

5 File re-encryption infeasible

6 PKE has no authentication [3]

Implications:

- Design issues 2 4
- Password-based security 1
- Key distribution problem 1
- File sharing causes complex interactions 3 6
- Need to get it right the first time 5

[1] Matilda Backendal, Miro Haller and Kenneth G. Paterson. (2023). "MEGA: Malleable Encryption Goes Awry”. IEEE S&P 2023.

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INSECURE!

[SP:BHP23]
[EC:AHMP23]

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INSECURE!

[EuroSP:ABCP23]

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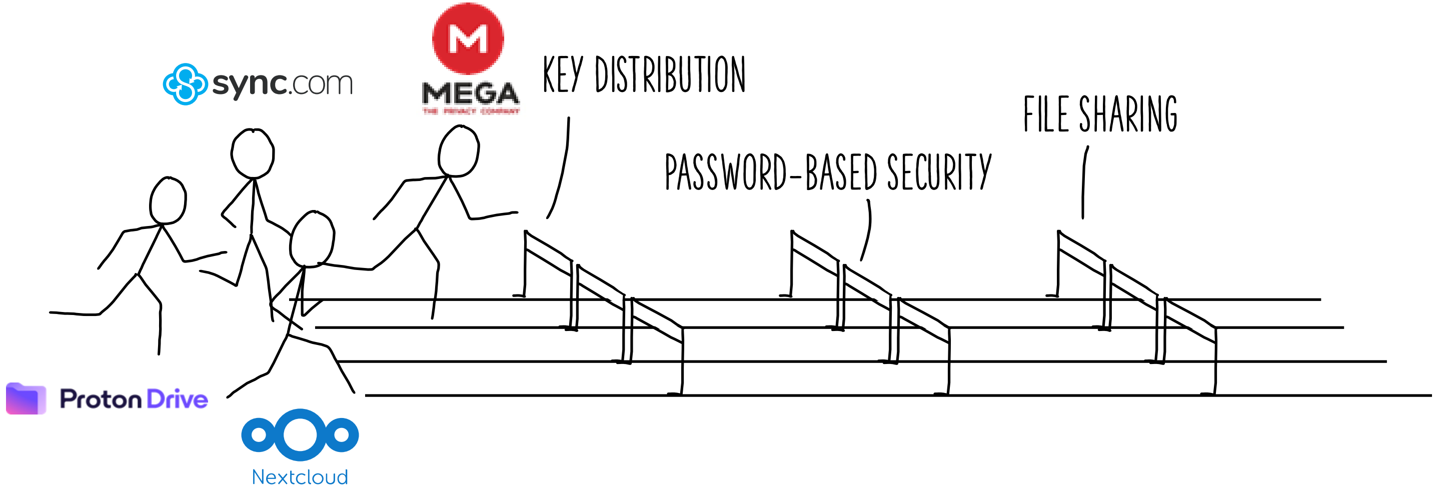
INSECURE!

[CCS:TH24]

Why Is It Hard?



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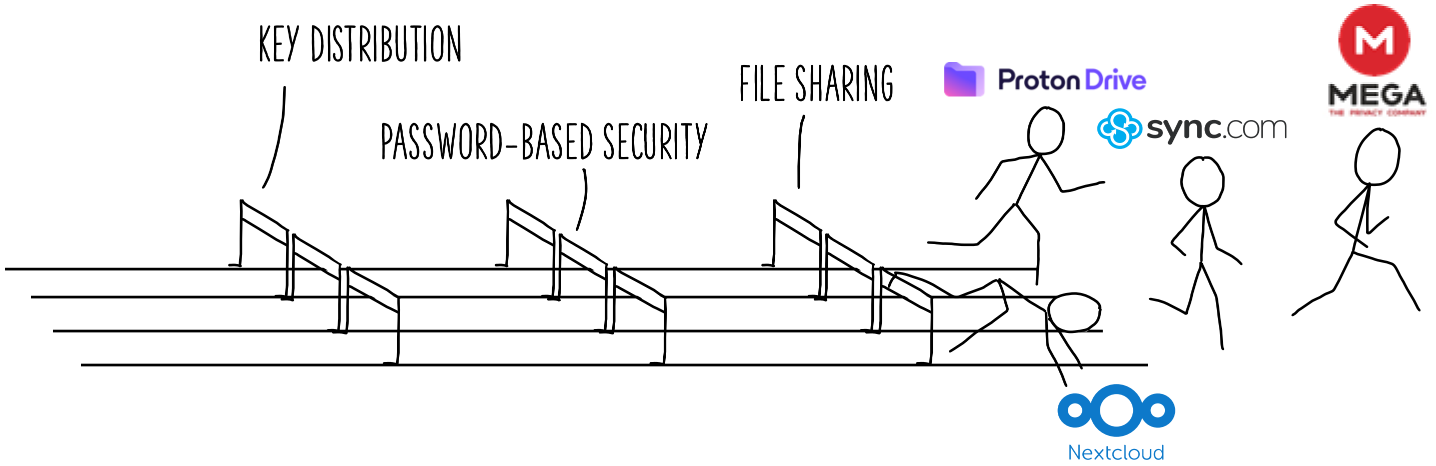

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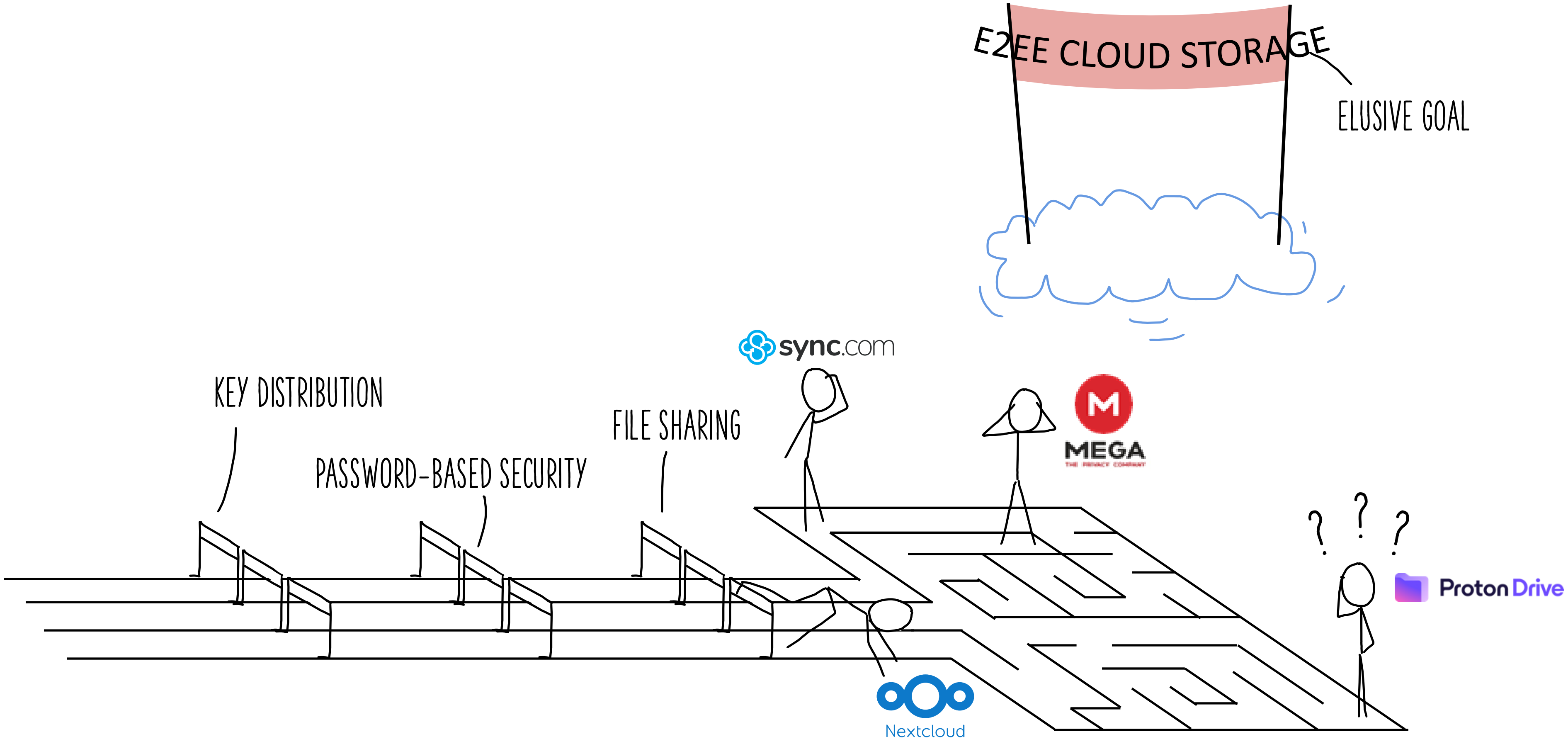
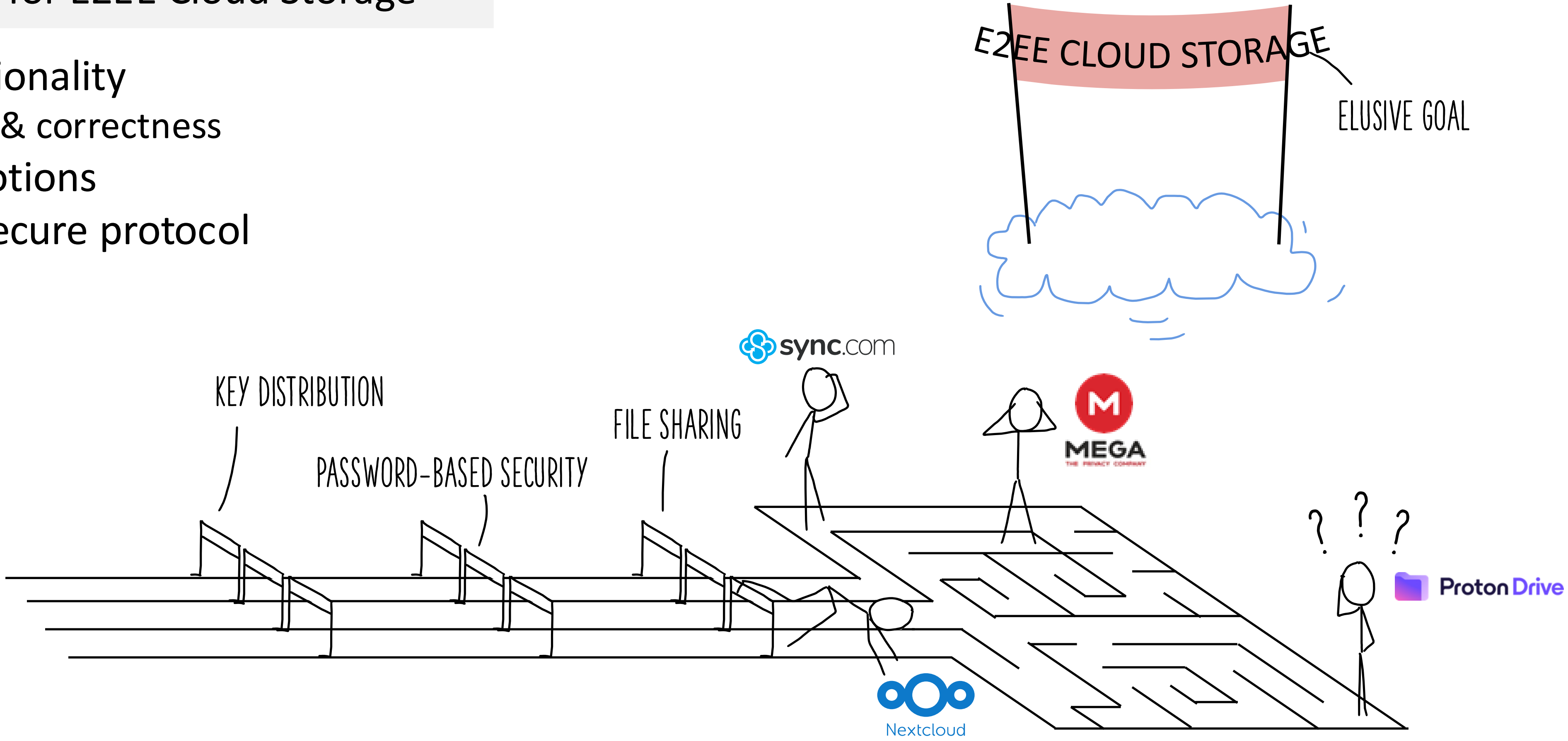


Our Work

Formal Model for E2EE Cloud Storage

- Core functionality
  → Syntax & correctness
- Security notions
- Provably secure protocol



1. Formalizing E2EE Cloud Storage

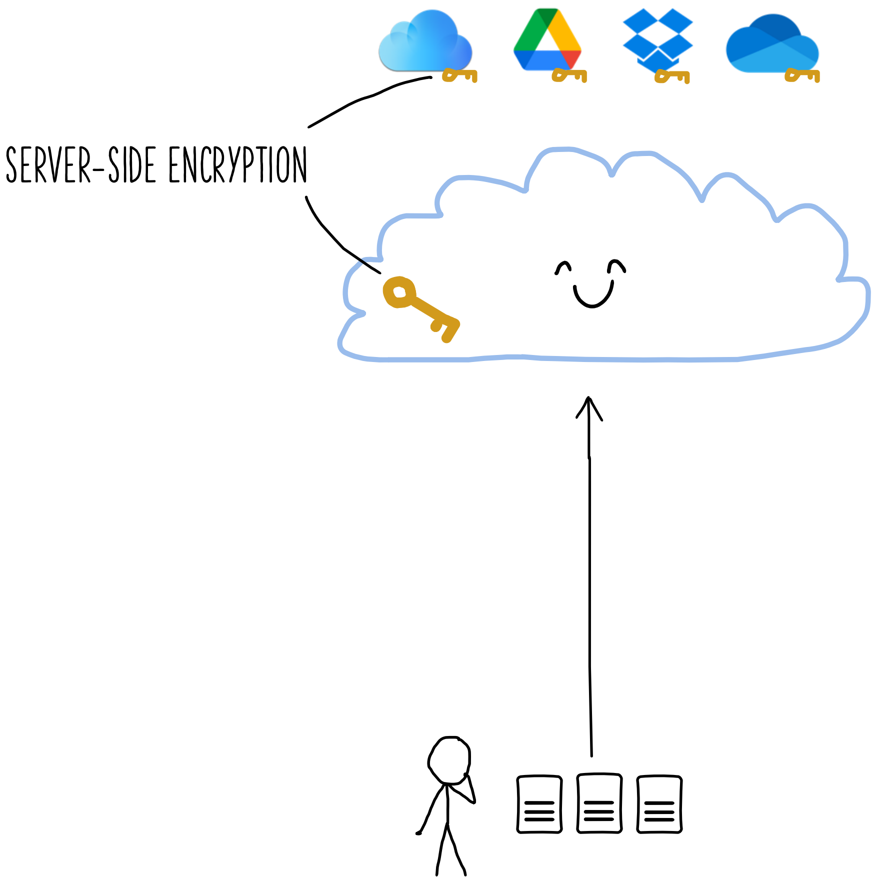
Formalizing E2EE Cloud Storage

Goal:

- Secure data at rest
- …with maximal functionality

Methods:

- Server-side encryption
  - + Plaintext access -> features
  - - Plaintext access -> less privacy



Formalizing E2EE Cloud Storage

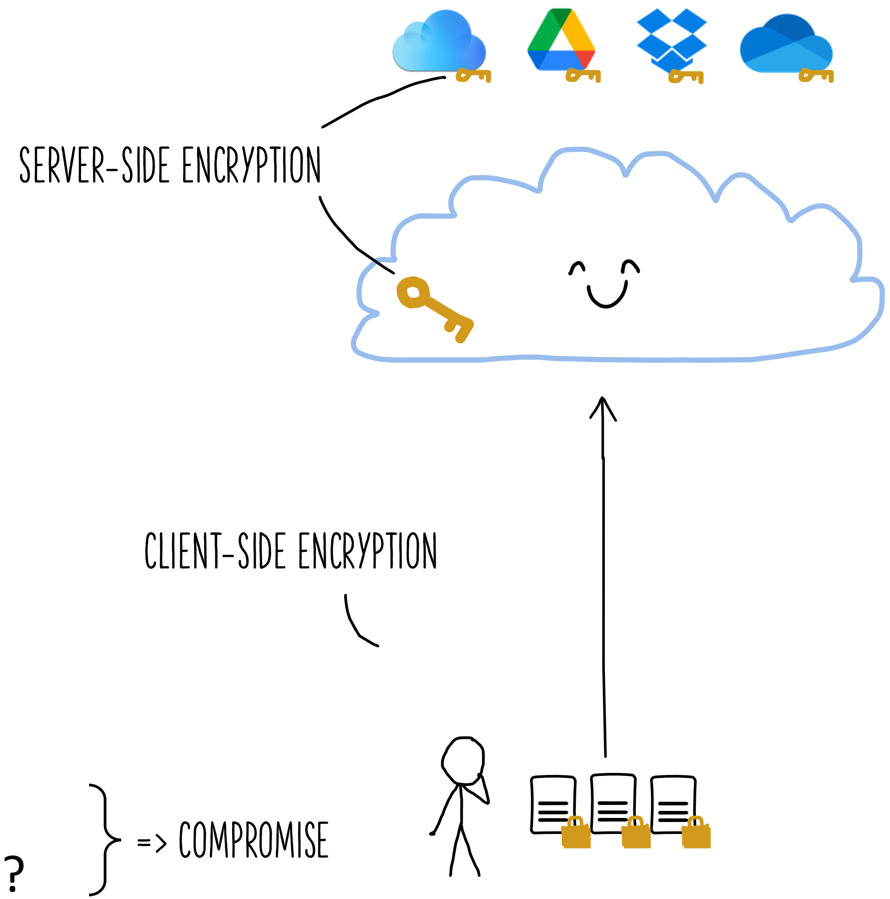
Goal:

- Secure data at rest
- …with maximal functionality
- …against a compromised server

Methods:

- Server-side encryption
  - + Plaintext access -> features
  - - Plaintext access -> less privacy
- End-to-end encryption
  - + No plaintext access -> privacy
  - - No plaintext access -> less features?

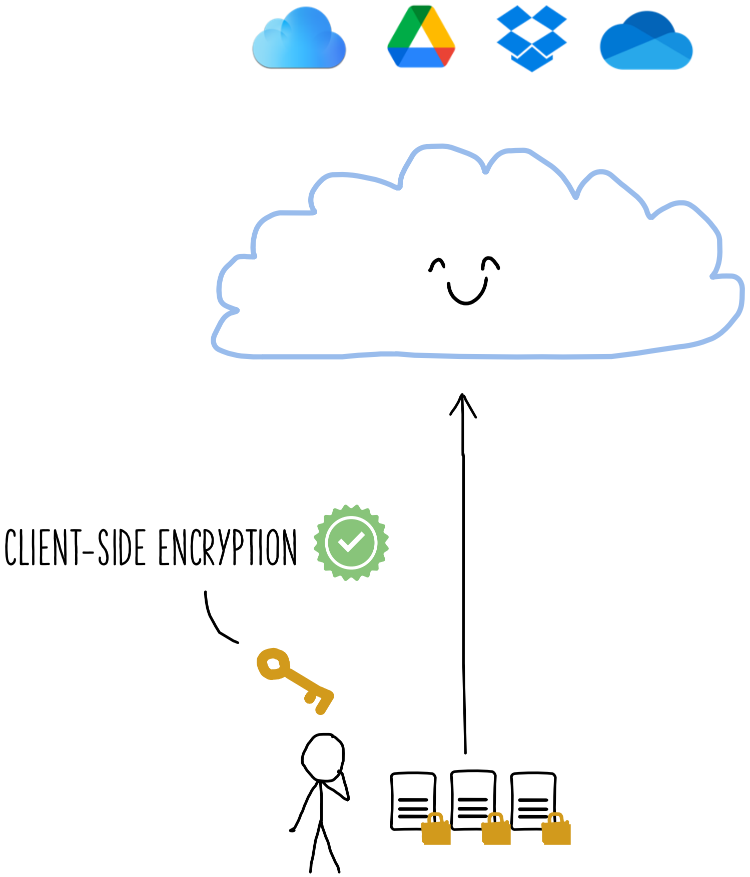
} => COMPROMISE



Formalizing E2EE Cloud Storage

In scope:

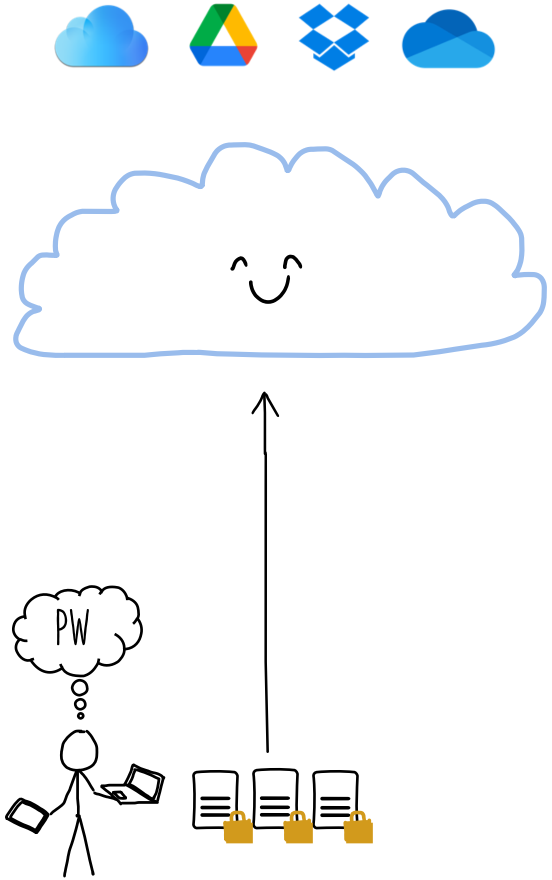
- 🟩 Provable security



Formalizing E2EE Cloud Storage

In scope:

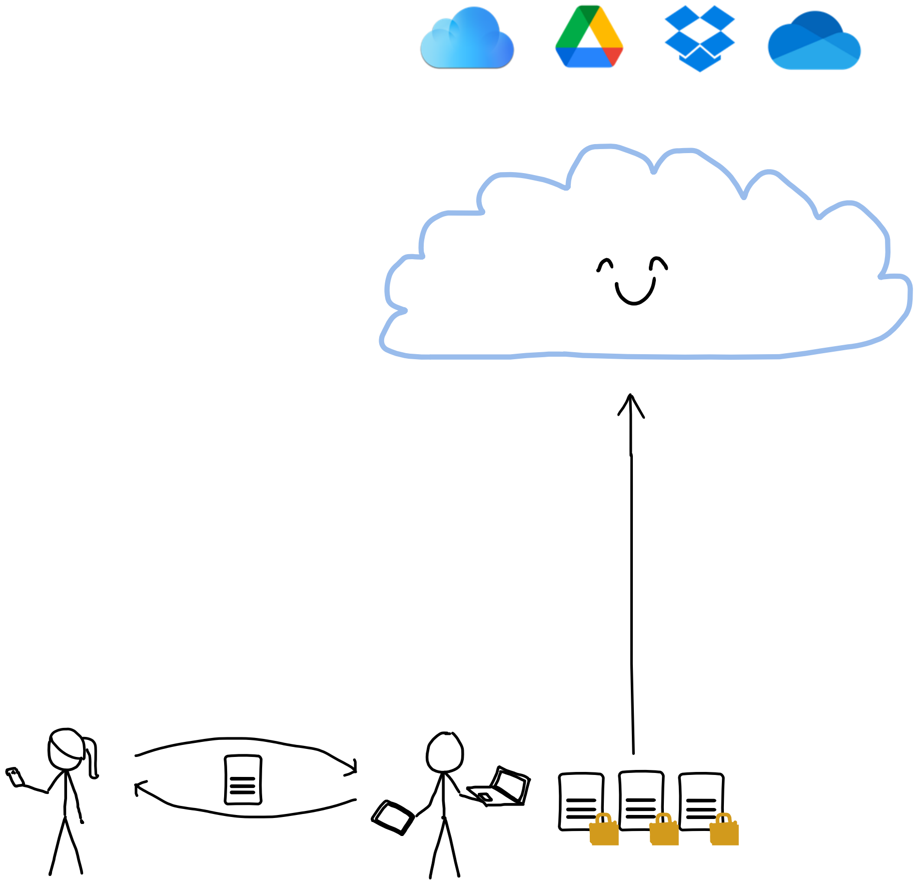
- 🟩 Provable security
- 🟩 Multi-device access



Formalizing E2EE Cloud Storage

In scope:

- Provable security
- Multi-device access
- File sharing



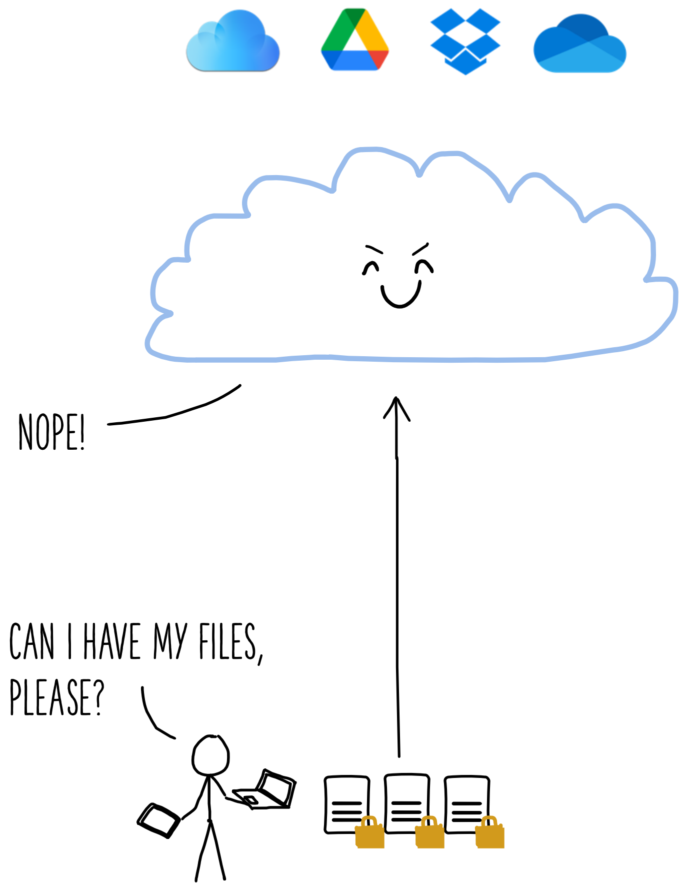
Formalizing E2EE Cloud Storage

In scope:

- 🟩 Provable security
- 🟩 Multi-device access
- 🟩 File sharing

Out of scope:

- 🟥 Availability



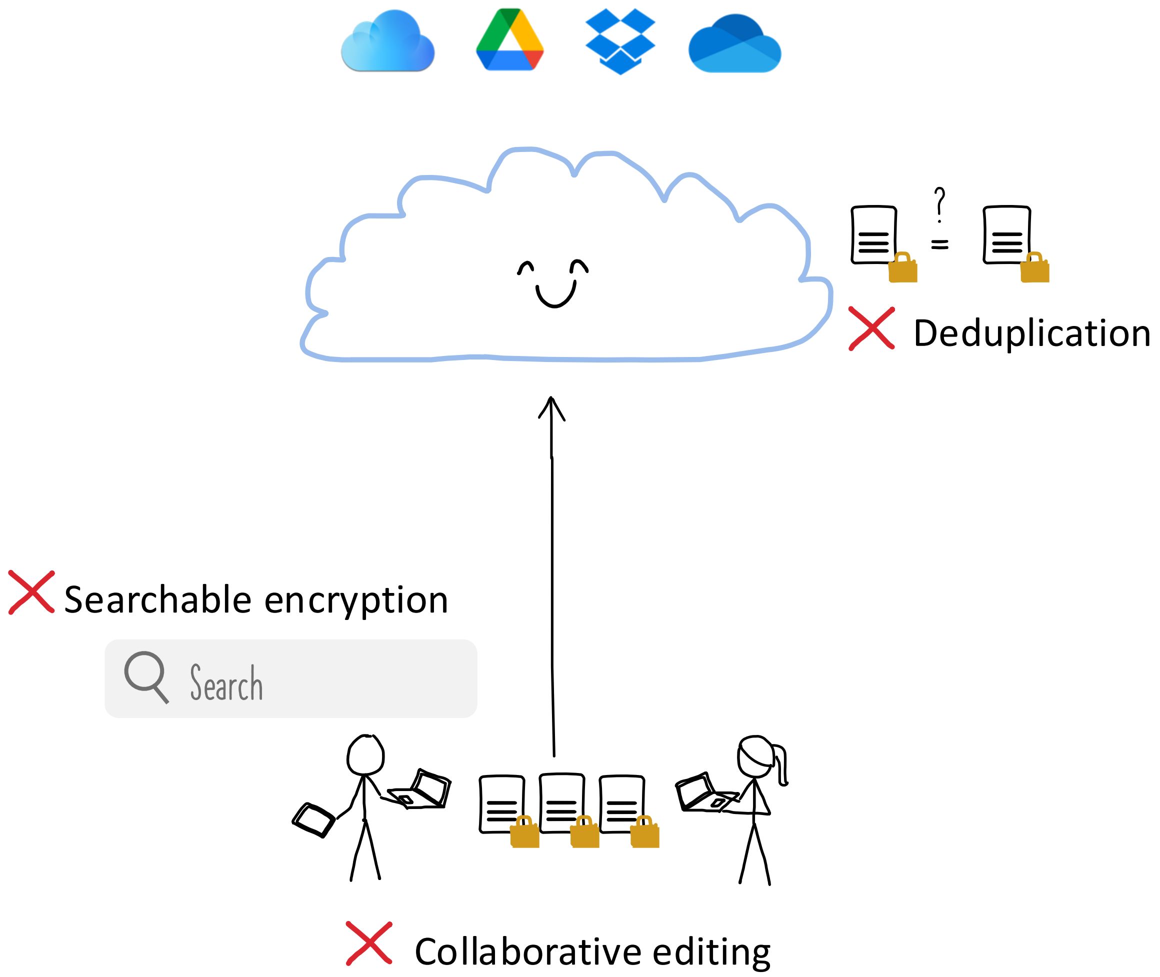
Formalizing E2EE Cloud Storage

In scope:

- 🟩 Provable security
- 🟩 Multi-device access
- 🟩 File sharing

Out of scope:

- 🟥 Availability
- 🟥 Server-side processing



✗ Deduplication

✗ Searchable encryption

✗ Collaborative editing

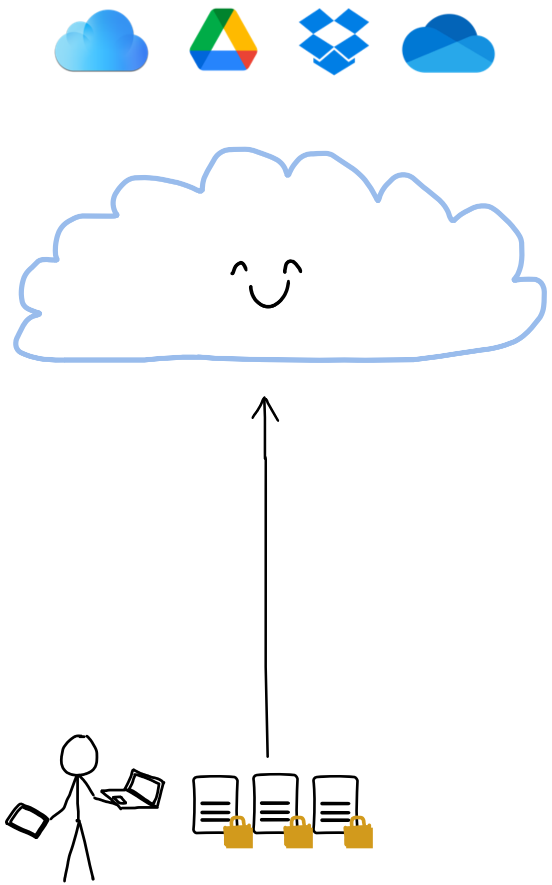
Formalizing E2EE Cloud Storage

In scope:

- 🟩 Provable security
- 🟩 Multi-device access
- 🟩 File sharing

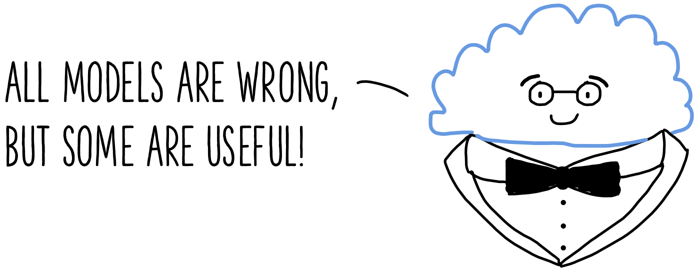
Out of scope:

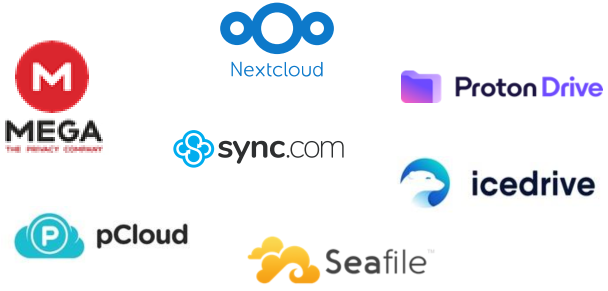
- 🟥 Availability
- 🟥 Server-side processing
- 🟥 Advanced Security
    - Metadata & access pattern hiding
    - Revocable access
    - Forward secrecy
    - …



Formalizing E2EE Cloud Storage

Model Goals



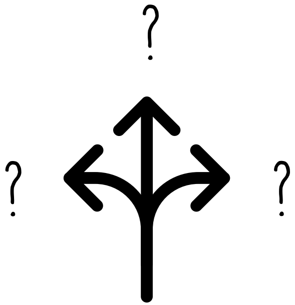


Capture existing systems

1 Expressive

Capture *real-world* systems

2 Faithful



Capture future systems

3 Generic

Syntax

WHAT MAKES A CLOUD STORAGE A CLOUD STORAGE?

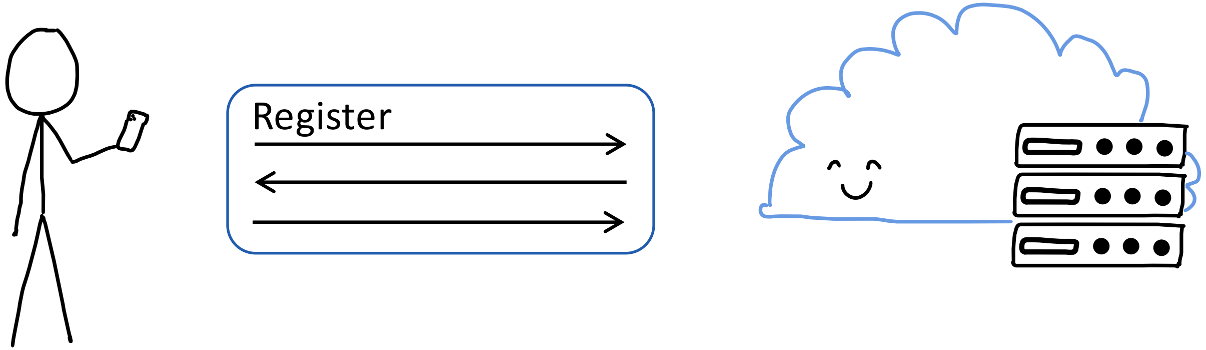
Core Functionality

? Anything missing?

- Register (create account)
- Authenticate (log in)

- Put (upload a file)
- Update (modify content)
- Get (download)
- Share
- Accept (receive share)

INTERACTIVE PROTOCOLS



Syntax

HOW DO WE MAKE THE MODEL USEFUL?

? Anything missing?

Core Functionality

- Register (create account)
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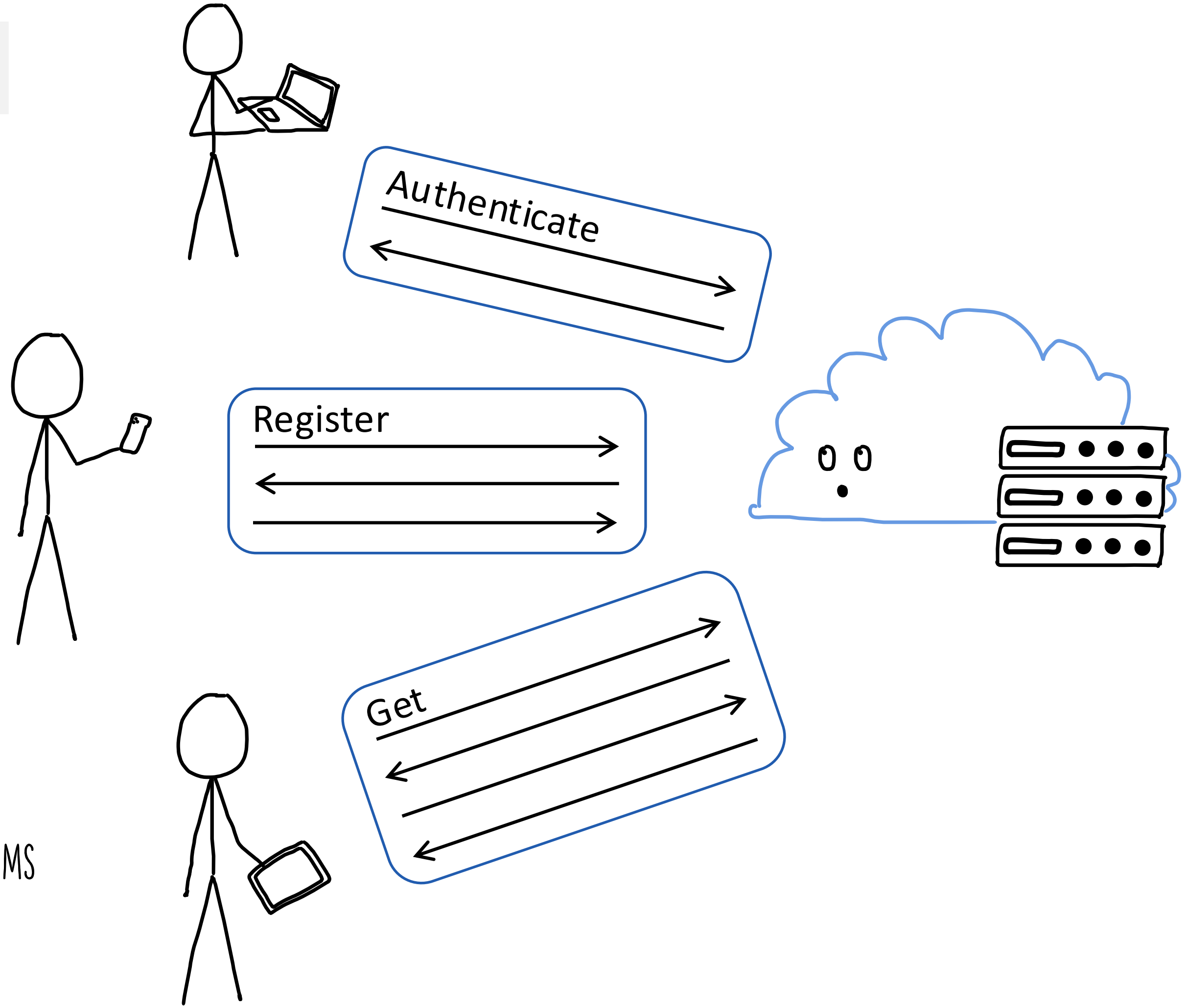
} INTERACTIVE PROTOCOLS

Model Choices

- Non-atomic operations → FAITHFUL TO REAL-WORLD SYSTEMS



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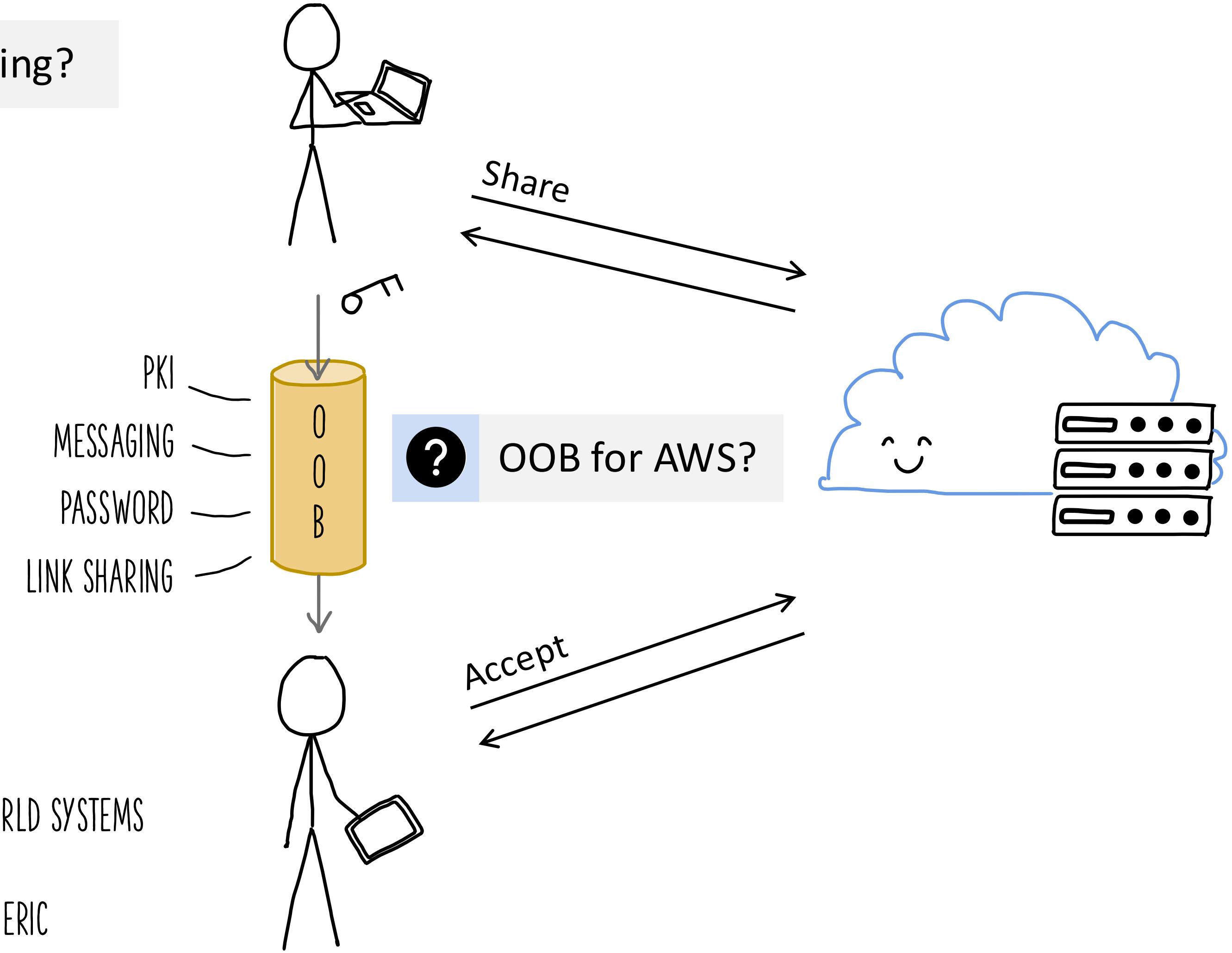
INTERACTIVE PROTOCOLS

Model Choices

- Non-atomic operations → FAITHFUL TO REAL-WORLD SYSTEMS
- Abstract OOB channel for sharing → GENERIC



? OOB for AWS?

Security Notions

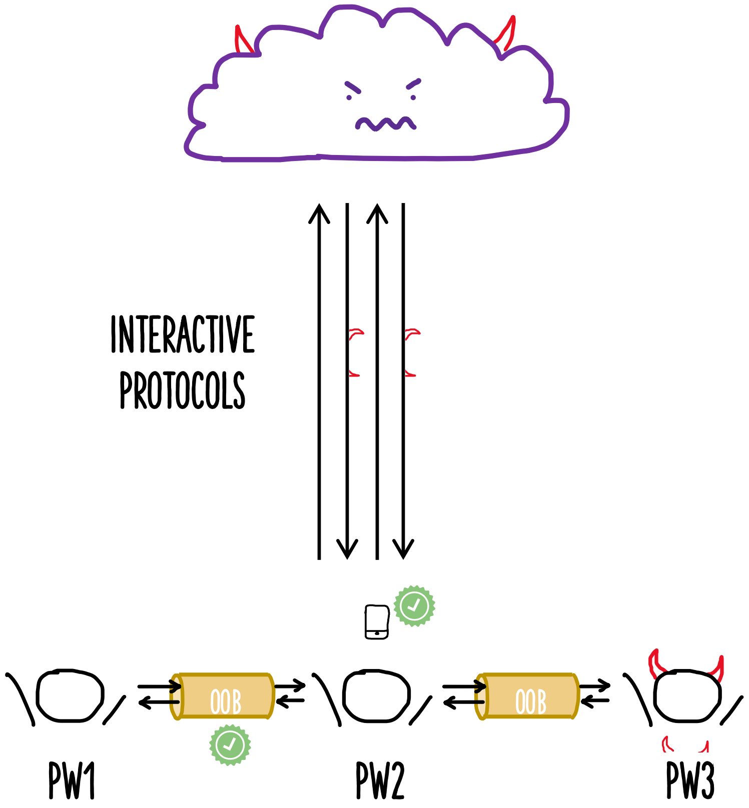
MALICIOUS SERVER SETTING

Threat model:

- Malicious cloud provider
- Trusted OOB-channels between honest users
- Trusted client code

Adversary capabilities:

- Control client protocol steps (which & when)
- Specify server responses
- Guess honest user passwords
- Compromise users (adaptive/selective)



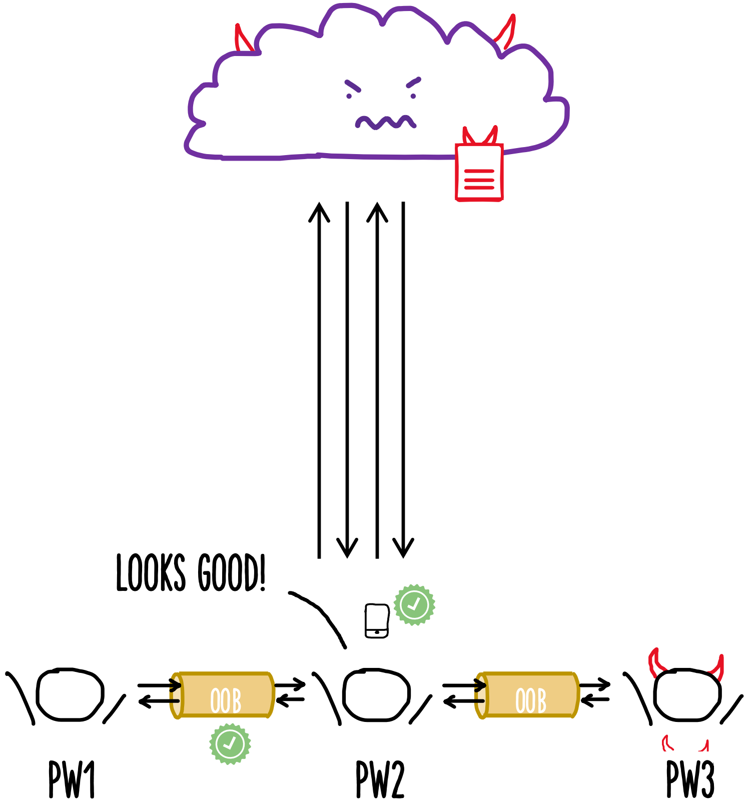
Security Notions

MALICIOUS SERVER SETTING

Integrity:

- Wins if adversary can, for an honest user,
  1. inject a file, or
  2. modify a file.

INT-PTXT-STYLE GAME



Security Notions

MALICIOUS SERVER SETTING

Integrity:

- Wins if adversary can, for an honest user,
  1. inject a file, or
  2. modify a file.

INT-PTXT-STYLE GAME

! Not INT-CTXT

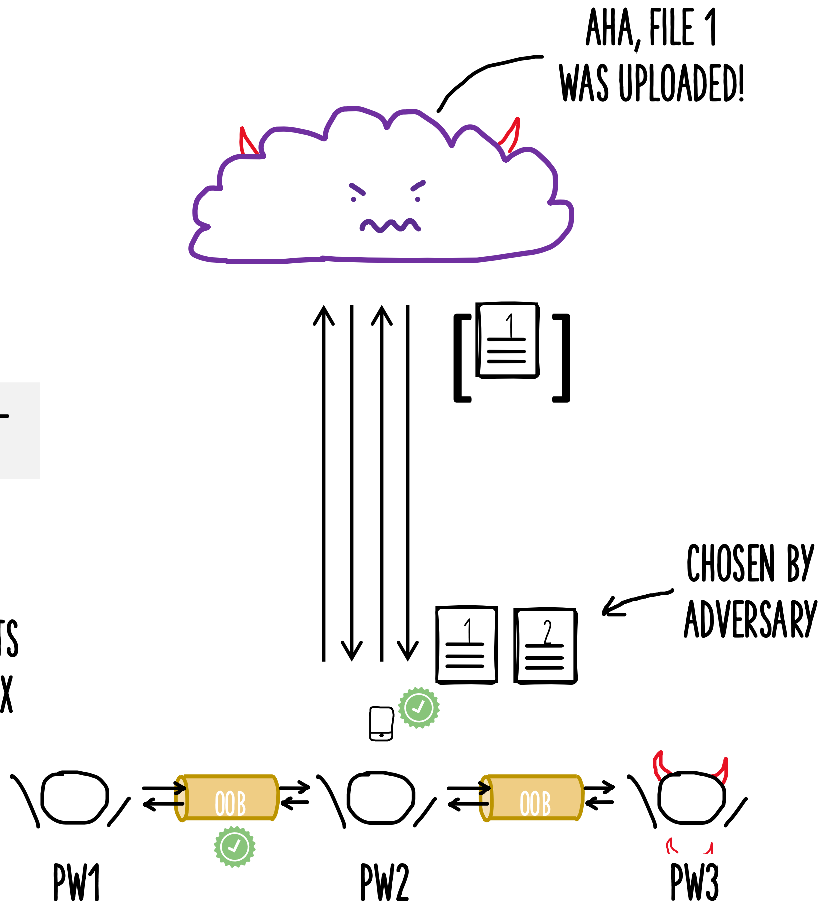
NO CIPHERTEXTS IN OUR SYNTAX

Confidentiality:

- Wins if adversary can, for an honest user,
  - learn any information and distinguish files

IND-CCA-STYLE GAME

! Not IND$



Security Notions

MALICIOUS CLIENT SETTING [ONGOING WORK]

Threat model:

- ~~Malicious~~ honest cloud provider, malicious clients
- Trusted OOB-channels between honest users
- Trusted client code

+ Trusted client-to-server channels?

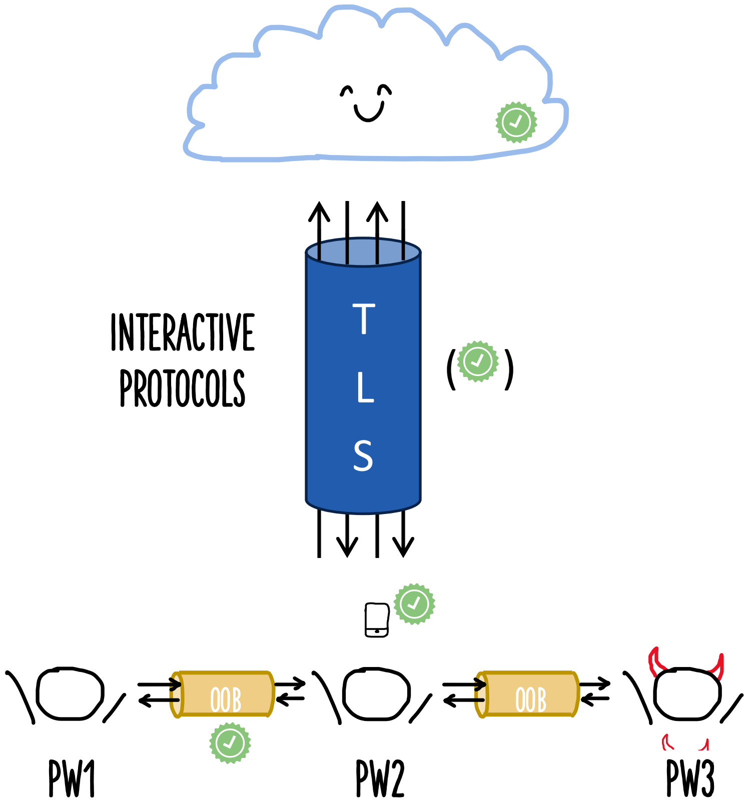
Adversary capabilities:

- Control client protocol steps (which & when)
- ~~Specify server responses~~
- Guess honest user passwords
- Compromise users (adaptive/selective)

Additional goals:

INFEASIBLE IN THE MALICIOUS SERVER SETTING!

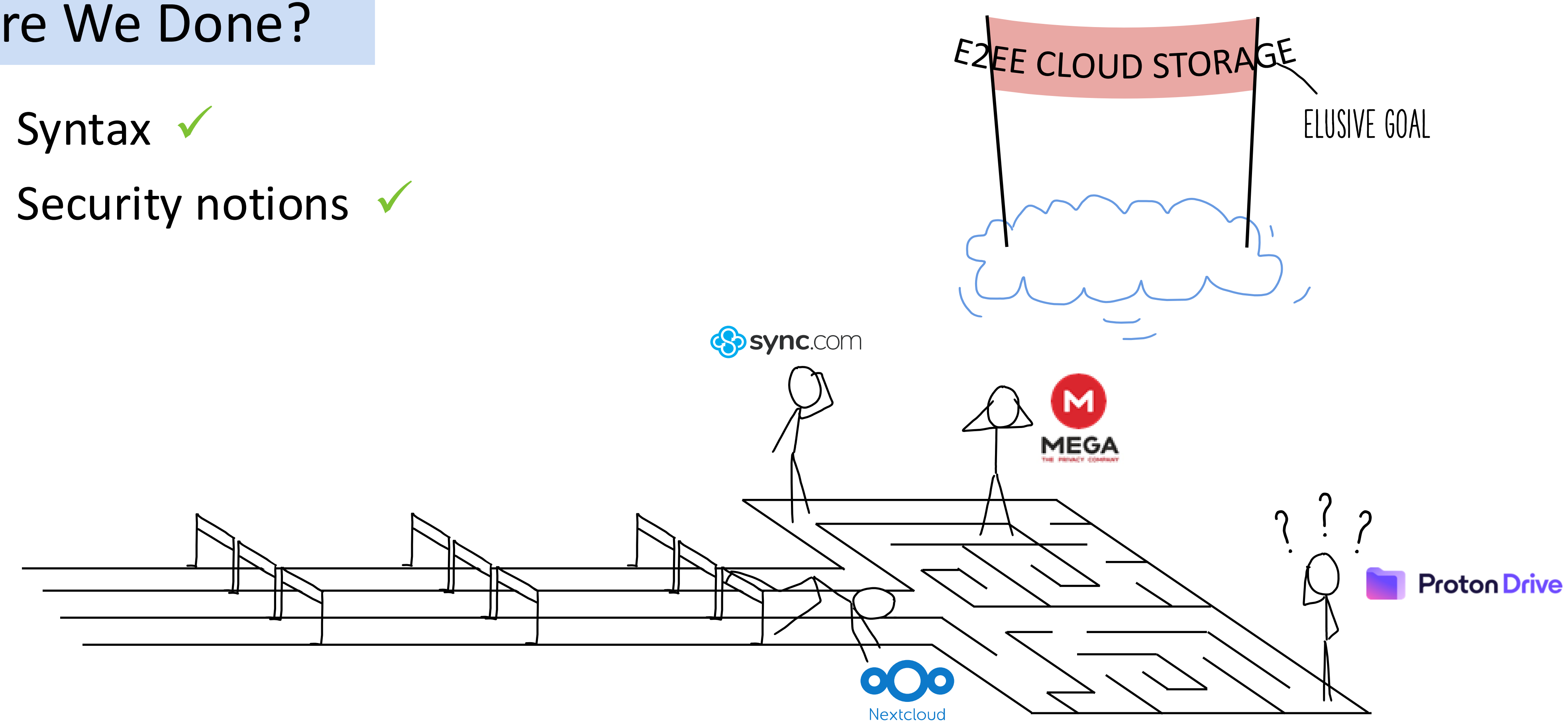
- Authentication & authorization
- No offline dictionary attacks on pw
- Availability for honest user files



? Are we missing any goals or attacks in both settings?

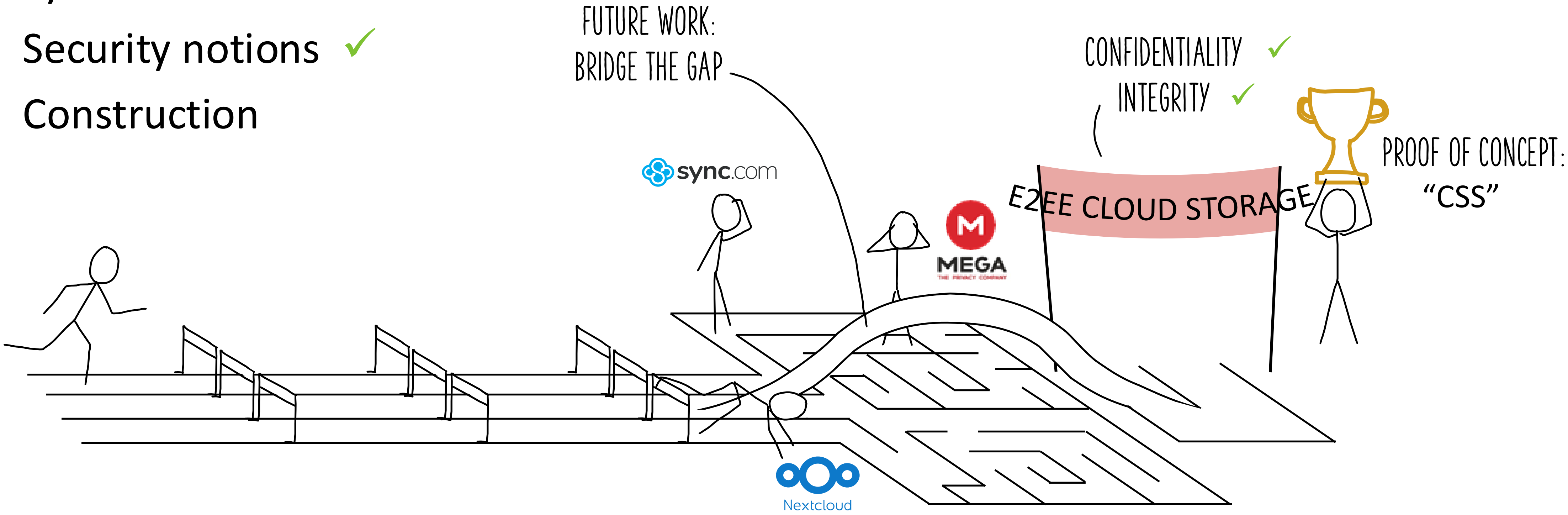
Are We Done?

- Syntax ✓
- Security notions ✓



Are We Done?

- Syntax ✓
- Security notions ✓
- Construction



2. Constructing E2EE Cloud Storage

CSS (Cloud Storage Scheme)

Building Blocks

OPRF

2HashDH
HANDLES PWS => ROM

PRF

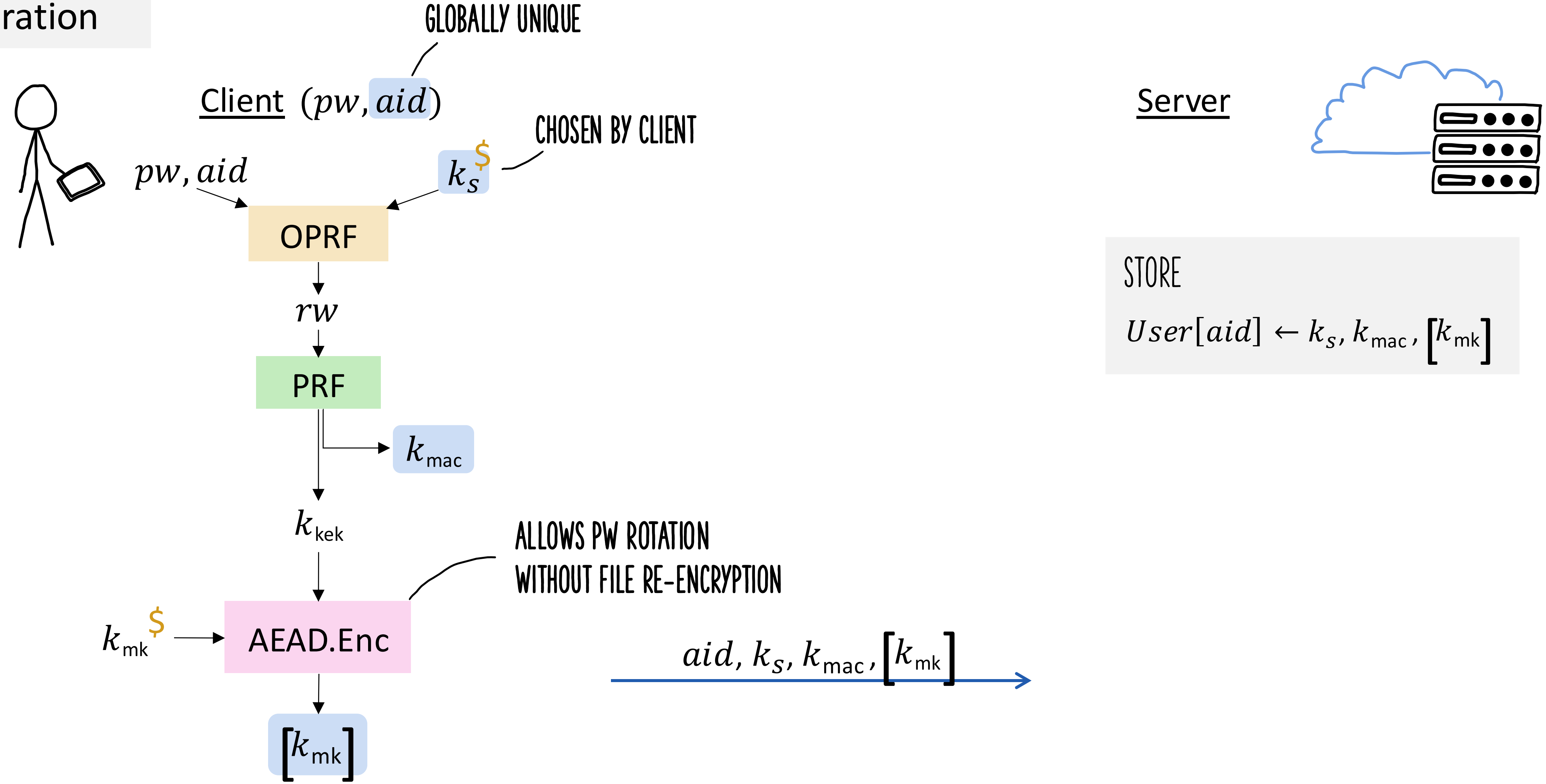
AEAD

MAC

ONLY NEEDED FOR
C2S SECURITY

CSS (Cloud Storage Scheme)

Registration



<u>Client</u> (pw, aid)

GLOBALLY UNIQUE

pw, aid

$k_s^{\$}$

CHOSEN BY CLIENT

OPRF

rw

PRF

k_{mac}

k_{kek}

ALLOWS PW ROTATION
WITHOUT FILE RE-ENCRYPTION

$k_{\text{mk}}^{\$}$

AEAD.Enc

$[k_{\text{mk}}]$

$aid, k_s, k_{\text{mac}}, [k_{\text{mk}}]$

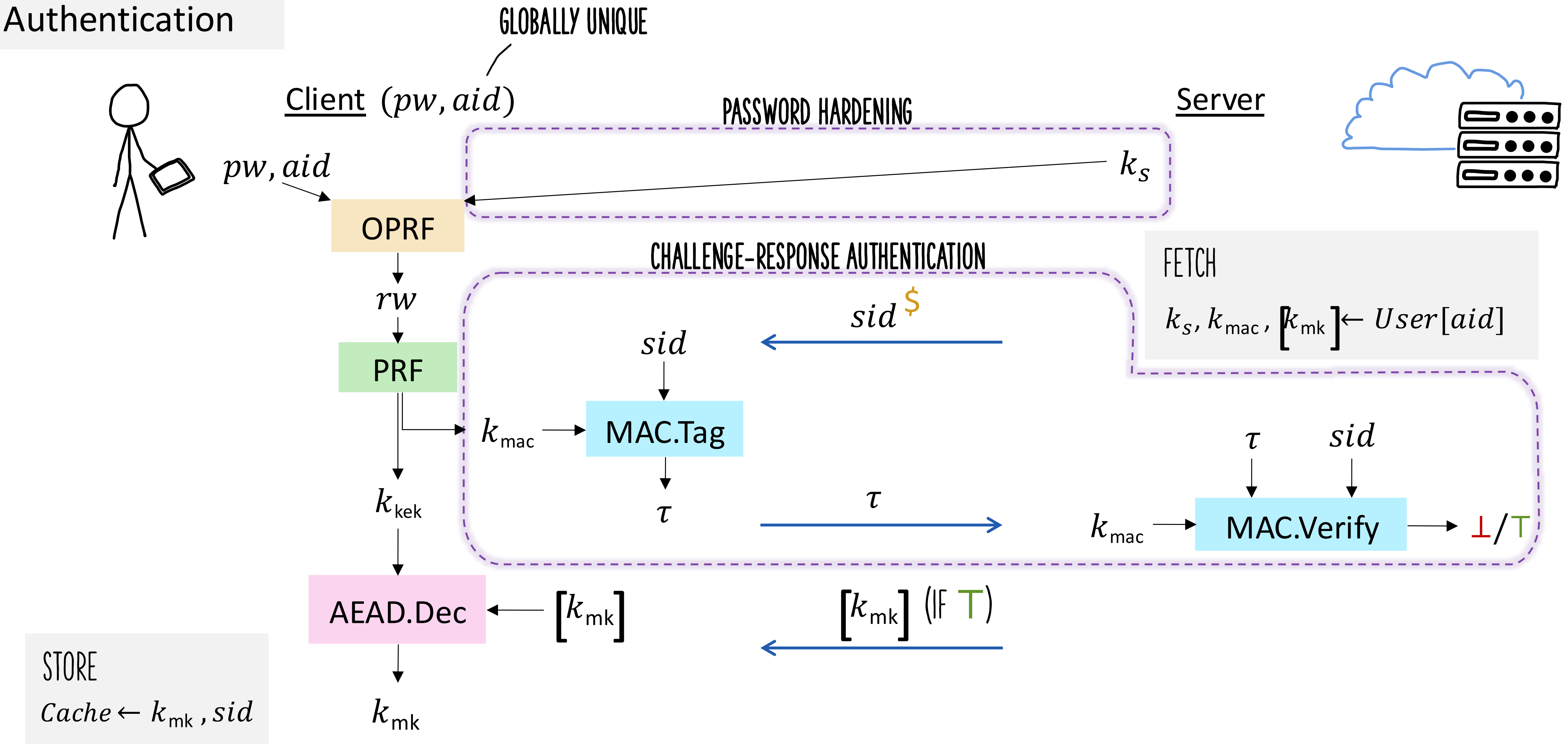
<u>Server</u>

STORE

$User[aid] \leftarrow k_s, k_{\text{mac}}, [k_{\text{mk}}]$

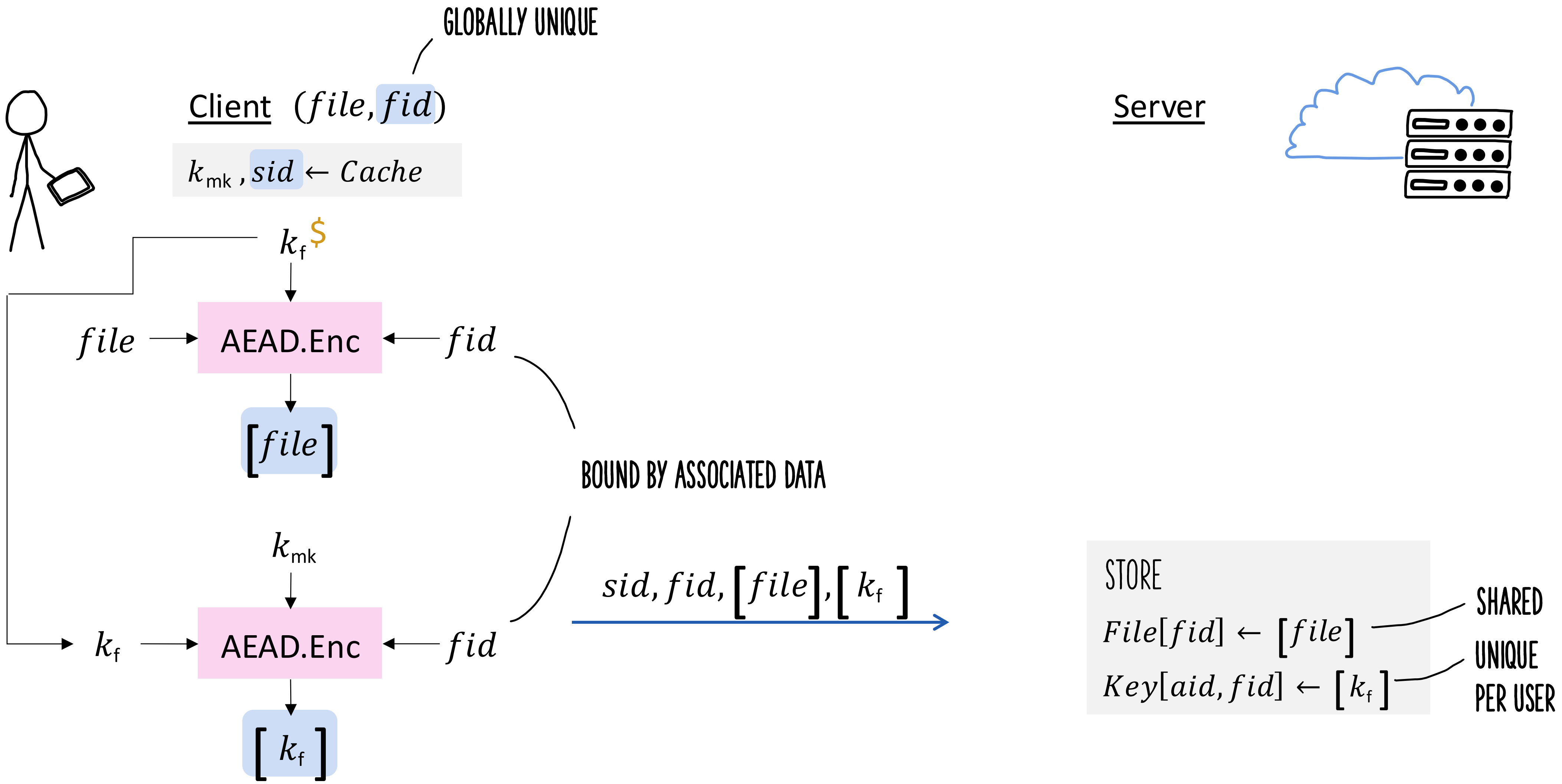
CSS (Cloud Storage Scheme)

Authentication



CSS (Cloud Storage Scheme)

Put



GLOBALLY UNIQUE

Client $(file, fid)$

$k_{mk}, sid \leftarrow Cache$

$k_f \overset{\$}{}$

$file \rightarrow$ AEAD.Enc $\leftarrow fid$

$[file]$

k_{mk}

$k_f \rightarrow$ AEAD.Enc $\leftarrow fid$

$[k_f]$

BOUND BY ASSOCIATED DATA

$sid, fid, [file], [k_f]$

Server

STORE

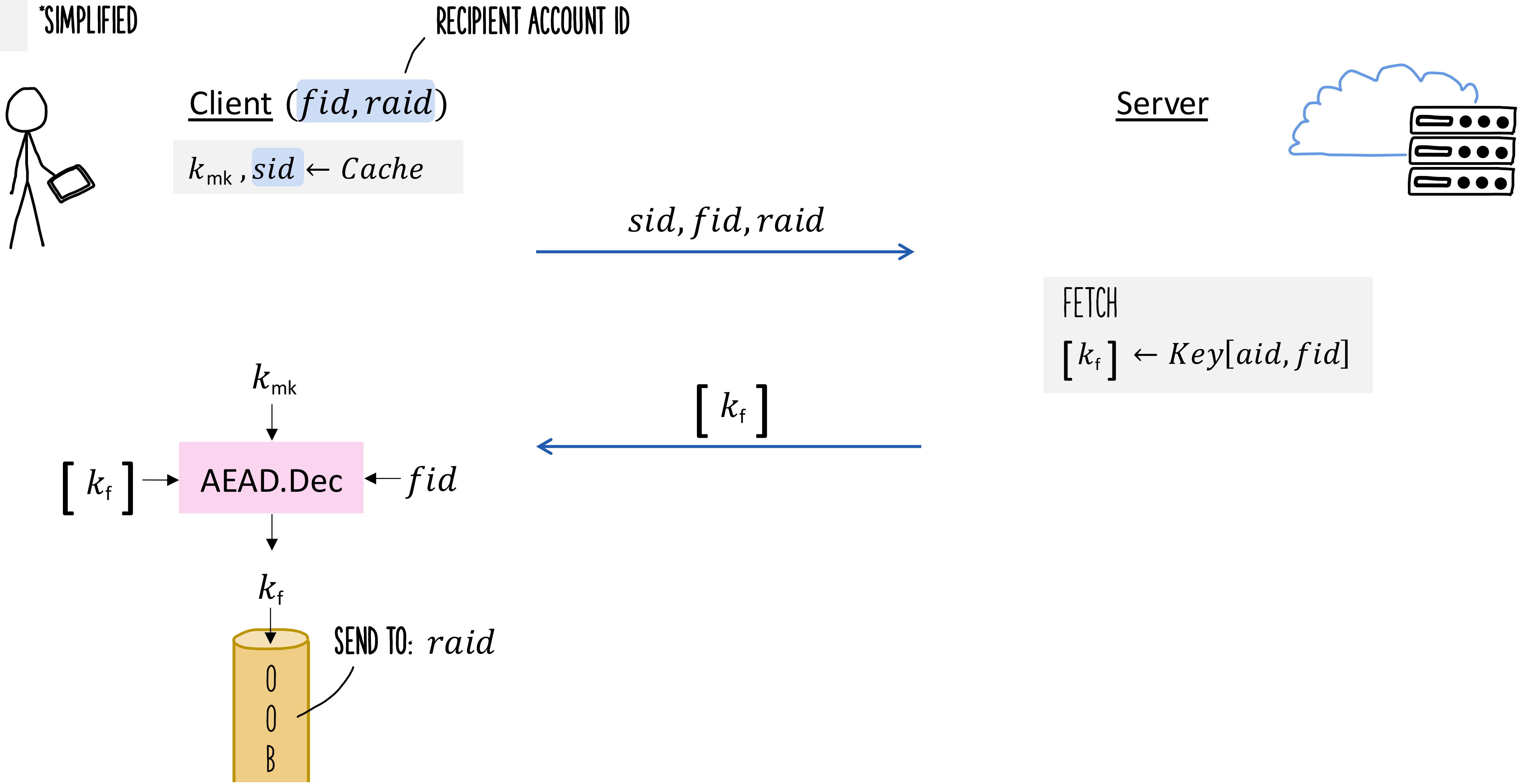
$File[fid] \leftarrow [file]$ SHARED

$Key[aid, fid] \leftarrow [k_f]$ UNIQUE PER USER

CSS (Cloud Storage Scheme)

Share

*SIMPLIFIED



RECIPIENT ACCOUNT ID

Client $(fid, raid)$

$k_{\text{mk}}, sid \leftarrow Cache$

Server

$sid, fid, raid$

FETCH

$[k_{\text{f}}] \leftarrow Key[aid, fid]$

$[k_{\text{f}}]$

k_{mk}

$[k_{\text{f}}]$ → AEAD.Dec ← fid

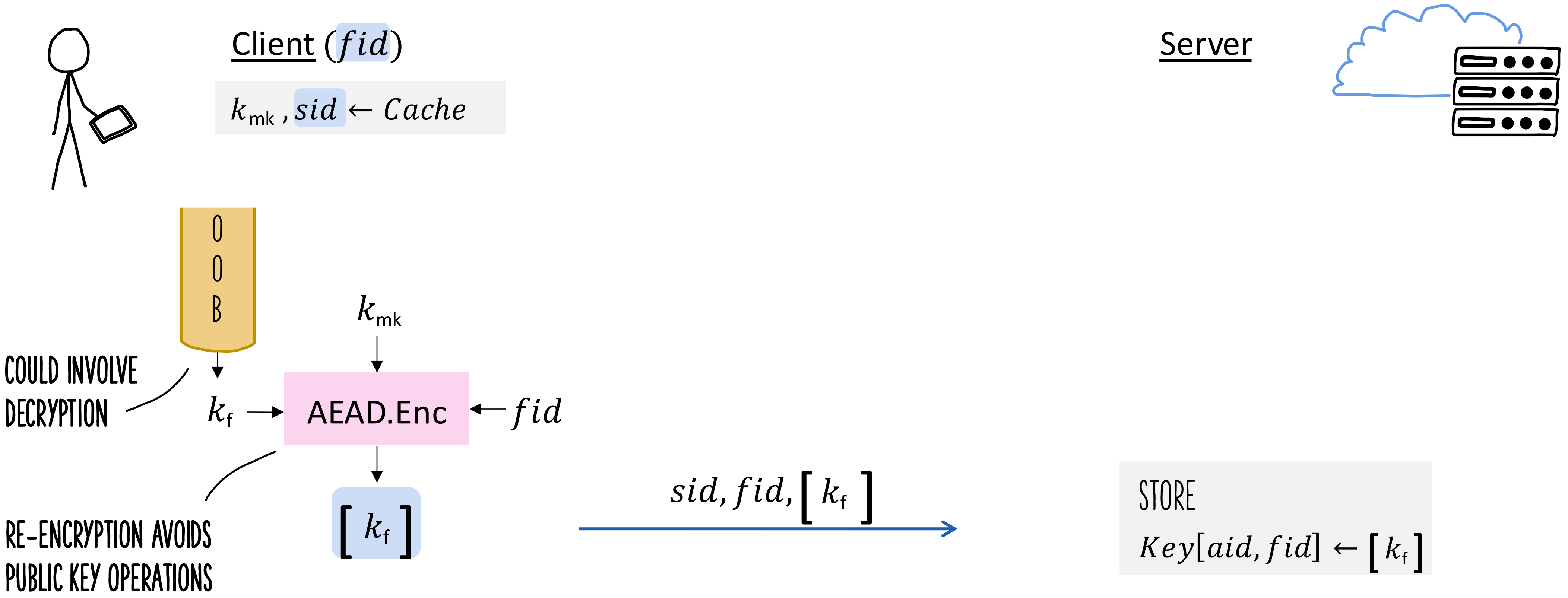
k_{f}

OOB

SEND TO: $raid$

CSS (Cloud Storage Scheme)

Accept *SIMPLIFIED



Client (fid)

$k_{\text{mk}}, sid \leftarrow Cache$

Server

OOB

k_{mk}

COULD INVOLVE DECRYPTION

$k_{\text{f}} \rightarrow$ AEAD.Enc $\leftarrow fid$

$[\, k_{\text{f}} \,]$

RE-ENCRYPTION AVOIDS PUBLIC KEY OPERATIONS

$sid, fid, [\, k_{\text{f}} \,]$

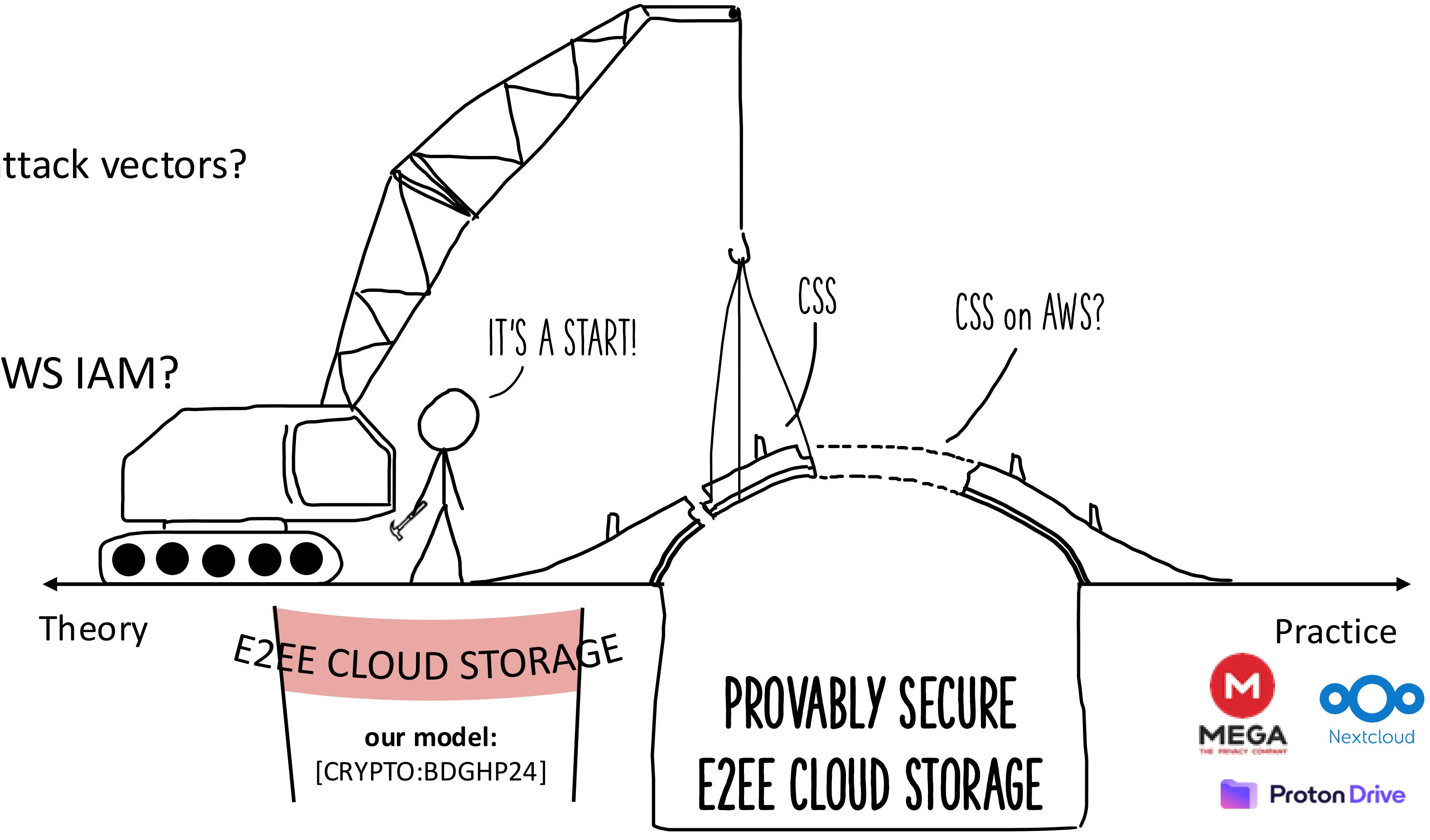
STORE

$Key[aid, fid] \leftarrow [\, k_{\text{f}} \,]$

Discussing The Future of E2EE Cloud Storage

Your thoughts on:

- Our model:
  - Missing guarantees, or attack vectors?
- Our core functionality:
  - Missing features?
- Integrate reg + auth into AWS IAM?
- OOB channel for sharing:
  - Instantiation for AWS?
- Scalability of CSS?



A Formal Treatment of End-to-End Encrypted Cloud Storage

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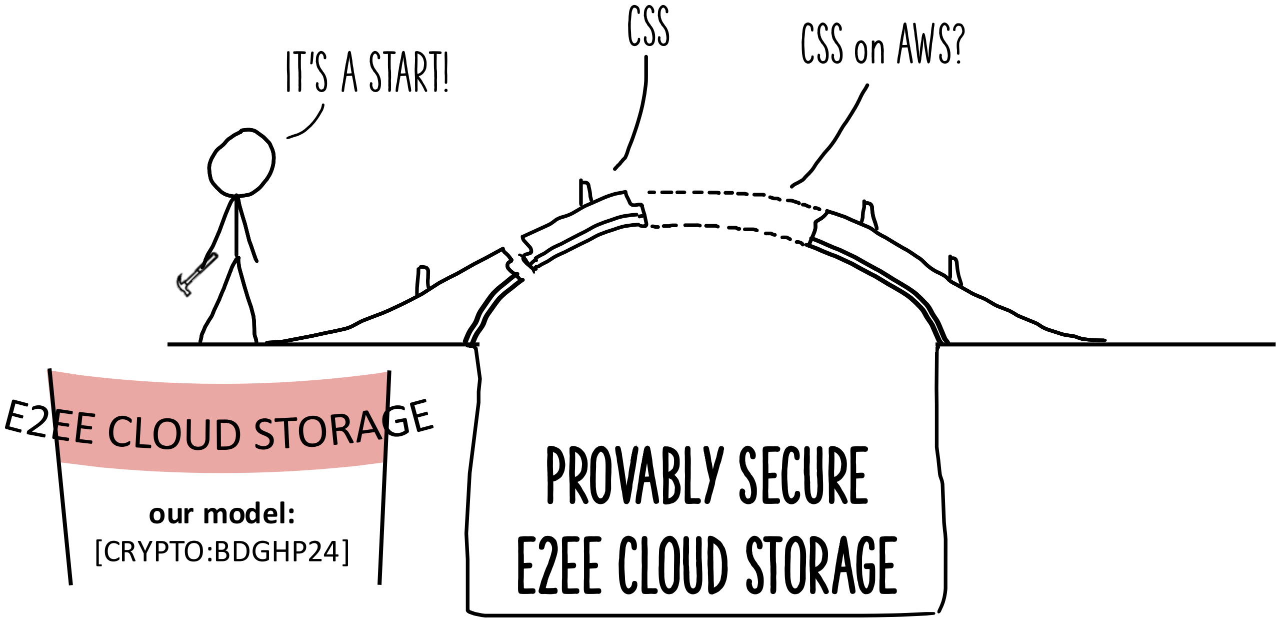
IT'S A START!
CSS
CSS on AWS?
E2EE CLOUD STORAGE
our model:
[CRYPTO:BDGHP24]
PROVABLY SECURE
E2EE CLOUD STORAGE