Encrypted Search

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ENCRYPTED SYSTEMS LAB

14,717,618,286*

4%

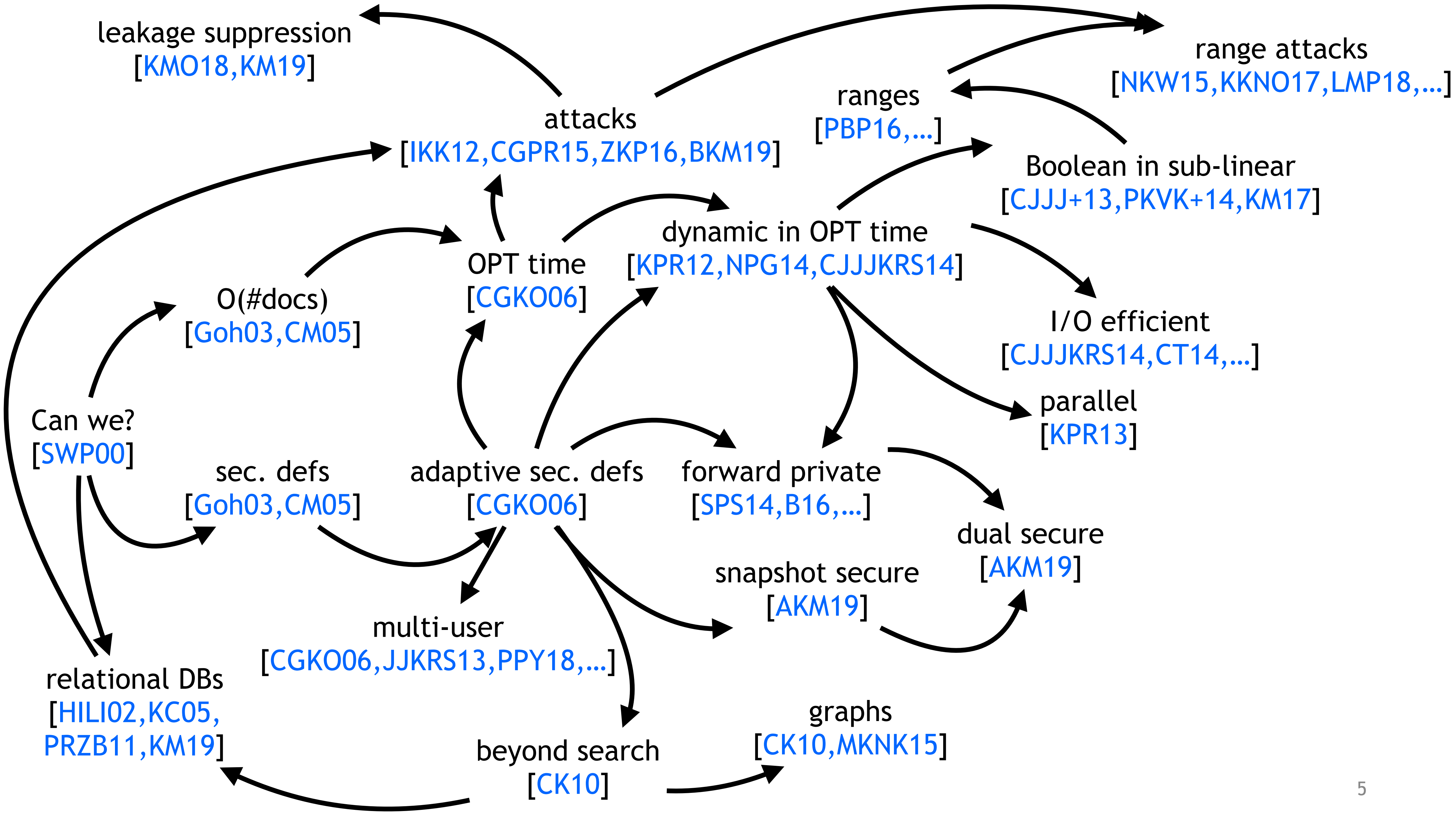
* since 2013

Why so Few?

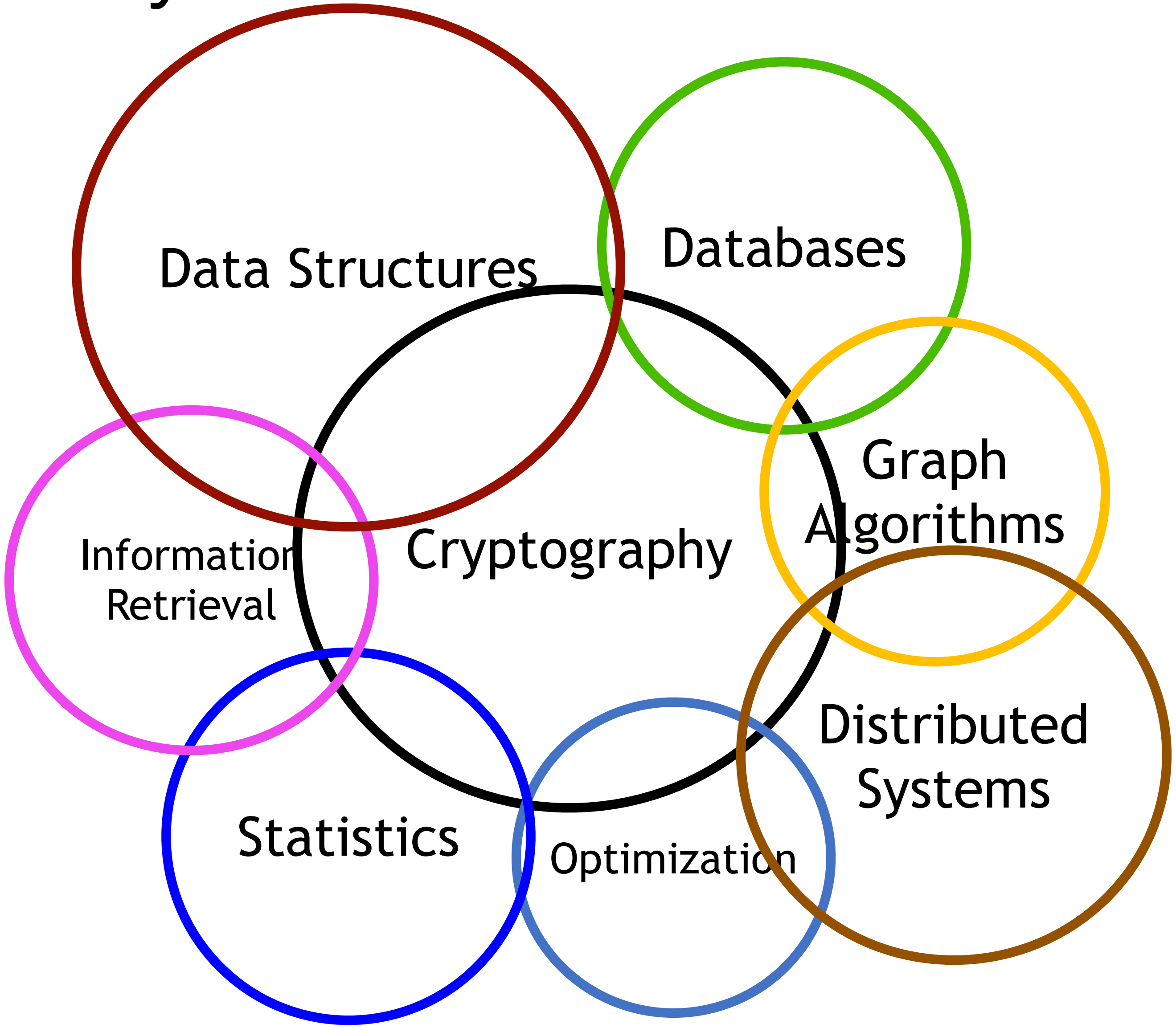
"…because it would have hurt Yahoo's ability to index and search message data…"

— J. Bonforte in NY Times

Q: can we search on encrypted data?


leakage suppression
[KMO18,KM19]
range attacks
[NKW15,KKNO17,LMP18,...]
ranges
[PBP16,...]
attacks
[IKK12,CGPR15,ZKP16,BKM19]
Boolean in sub-linear
[CJJJ+13,PKVK+14,KM17]
dynamic in OPT time
[KPR12,NPG14,CJJJKRS14]
OPT time
[CGKO06]
O(#docs)
[Goh03,CM05]
I/O efficient
[CJJJKRS14,CT14,...]
parallel
[KPR13]
Can we?
[SWP00]
sec. defs
[Goh03,CM05]
adaptive sec. defs
[CGKO06]
forward private
[SPS14,B16,...]
dual secure
[AKM19]
snapshot secure
[AKM19]
multi-user
[CGKO06,JJKRS13,PPY18,...]
relational DBs
[HILI02,KC05,
PRZB11,KM19]
beyond search
[CK10]
graphs
[CK10,MKNK15]

Interdisciplinary



Real-World Problem

- Major companies
  - Microsoft, SAP
  - Cisco, Google Research
  - Hitachi, Fujitsu
  - more…
- Funding agencies
  - NSF
  - IARPA
  - DARPA
- Startups
  - too many to list

Q: what about real-world *customers*?

Is this Real?

- Banks
- Government agencies (US & Europe)
- Fintech companies
- Tech companies
- Healthcare
- Biotech
- …

Encrypted Search

Encrypted Search

- Sub-field focused on designing
  - *sub-linear* algorithms over encrypted data
  - search engines & databases

- Searchable (symmetric) encryption (SSE)
  - keyword search over collection of encrypted files/documents
  - ElasticSearch, Lucene, …

- Encrypted databases (EDBs)
  - encrypted NoSQL & SQL (relational) databases
  - Postgres, SQL Server, MongoDB, CouchDB, …

Encrypted Search (Building Blocks)

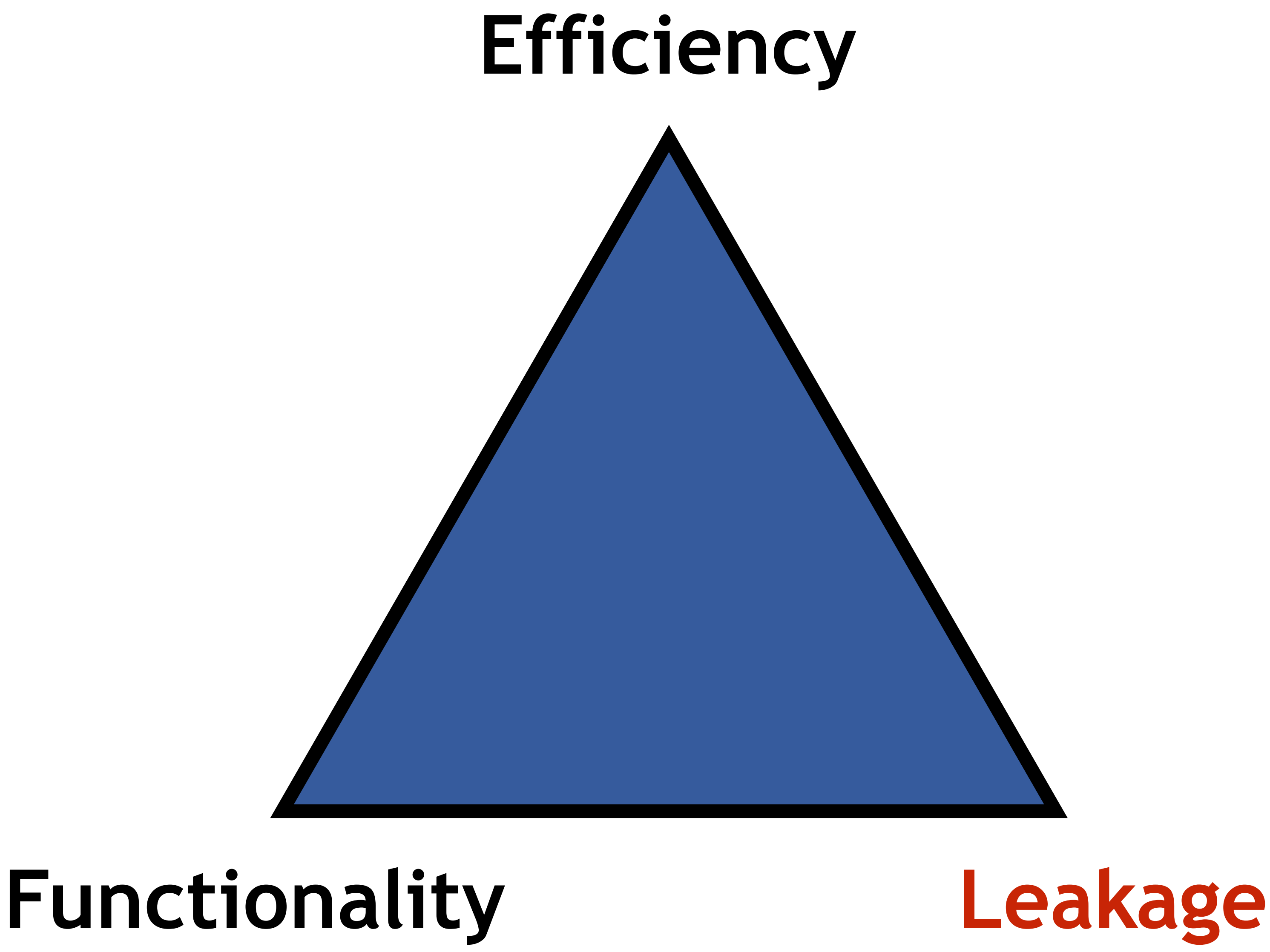
Very leaky

O(n)

Structured Encryption (STE)

Ω(n)

Oblivious RAM (ORAM)

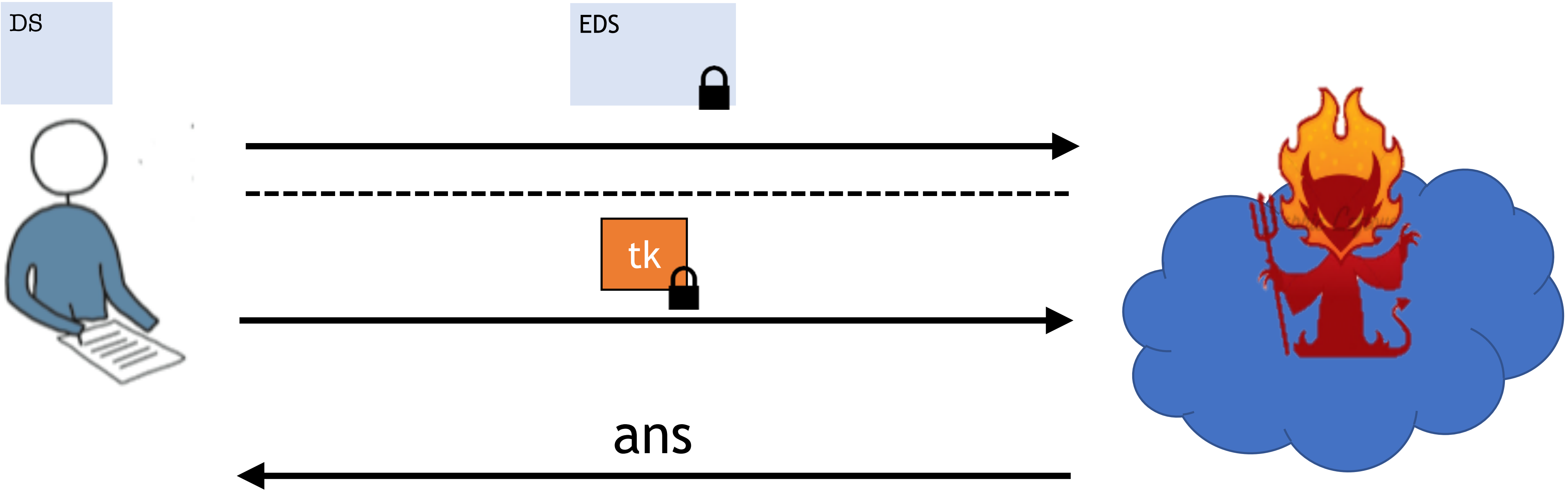

Efficiency
Functionality
Leakage

Core Primitive: **Structured Encryption**

- Schemes that
  - encrypt data structures (e.g., multi-maps, dictionaries, …)
  - support private queries on encrypted structures

- Applications
  - sub-linear searchable encryption (i.e., index-based SSE)
  - encrypted NoSQL & SQL databases
  - encrypted graph algorithms
  - secure multi-party computation

Structured Encryption
[Chase-K.10]

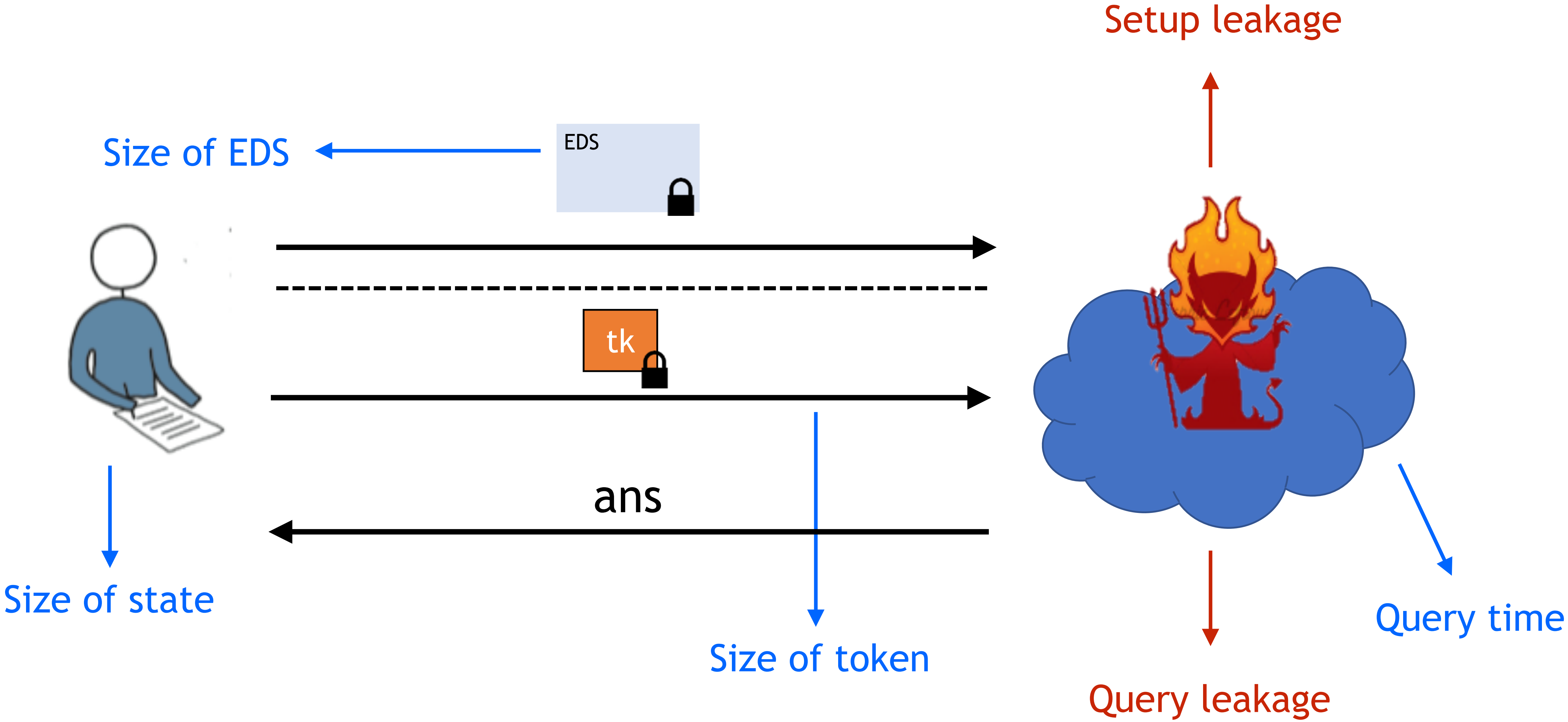


Setup(1^k, DS) $\longrightarrow$ (K, EDS)

Query(EDS, tk) $\longrightarrow$ ans

Token(K, q) $\longrightarrow$ tk

Desiderata


Setup leakage
Size of EDS
EDS
tk
ans
Size of state
Size of token
Query time
Query leakage

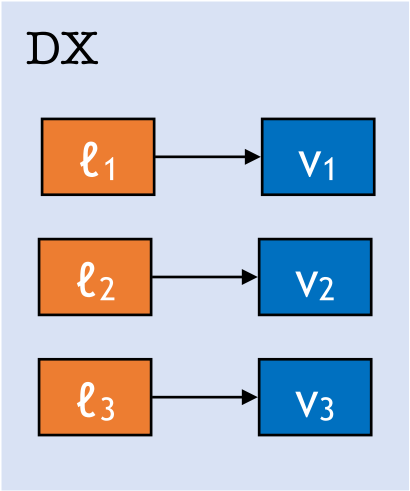
Structured Encryption

[Chase-K.10]

- Many variants of STE
  - response-revealing
    - EDS query reveals answer in plaintext
  - response-hiding
    - EDS query reveals encrypted answer
  - non-interactive queries
    - clients sends single message called a token
  - interactive queries
    - client and server execute multi-round protocol

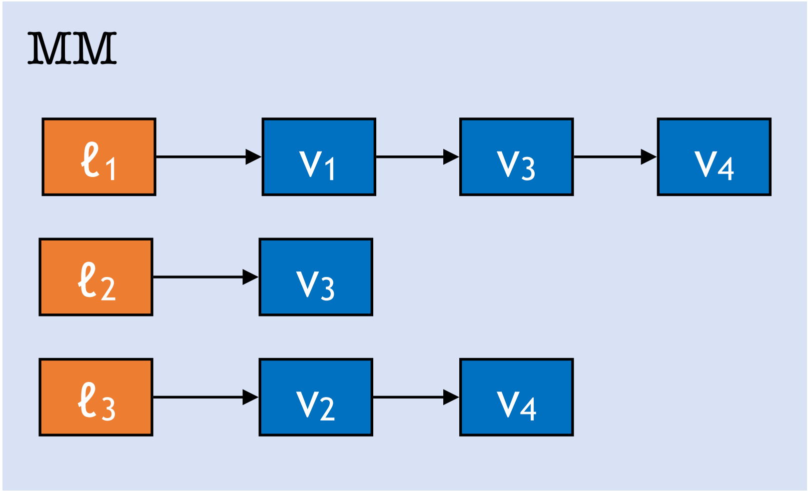
Background: Data Structures

- Dictionaries map labels to values



- Put: **DX[ℓ_2] :=** v_2
- Get: **DX[ℓ_2]** returns v_2

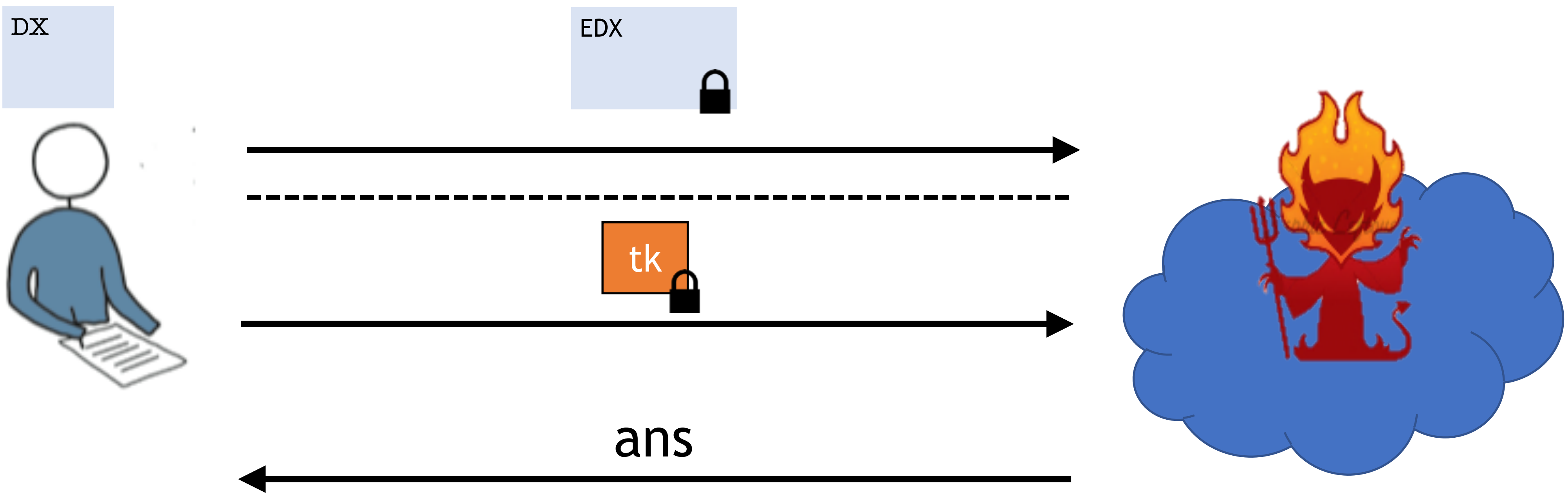
- Multi-Maps map labels to tuples



- Put: **MM[ℓ_3]:= (v_2,v_4)**
- Get: **MM[ℓ_3]** returns **(v_2,v_4)**

Structured Encryption: Encrypted Dictionary

[Chase-K.10]



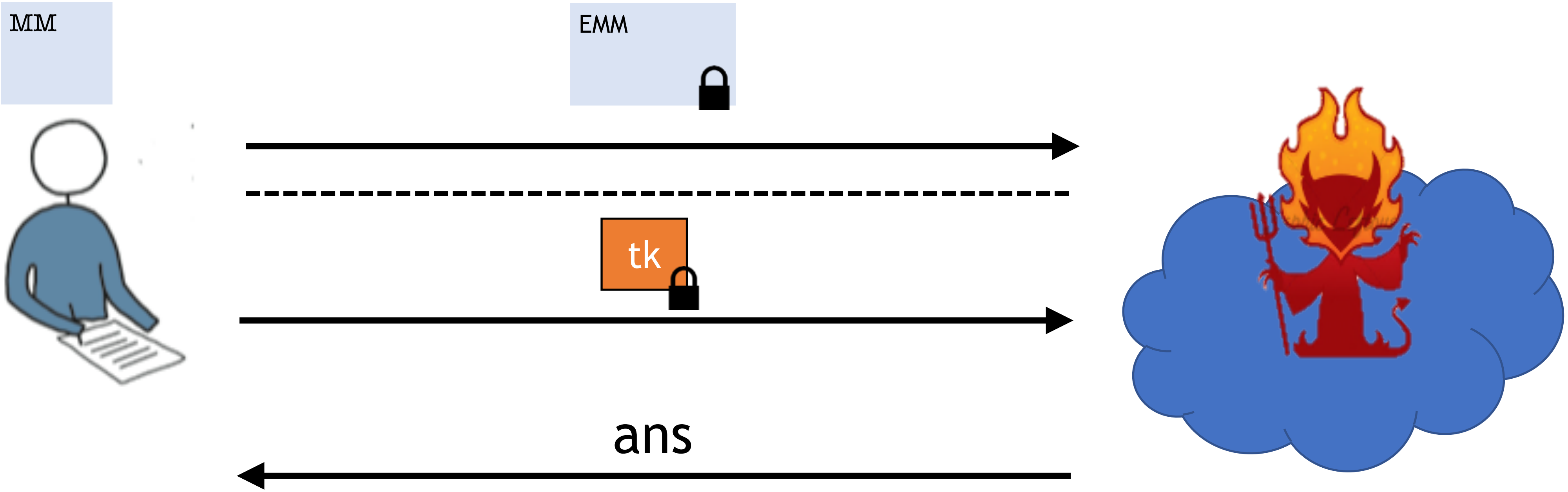
Setup(1^k, DS) $\longrightarrow$ (K, EDX)

Query(EDX, tk) $\longrightarrow$ ans

Token(K, q) $\longrightarrow$ tk

Structured Encryption: Encrypted Multi-Map

[Chase-K.10]



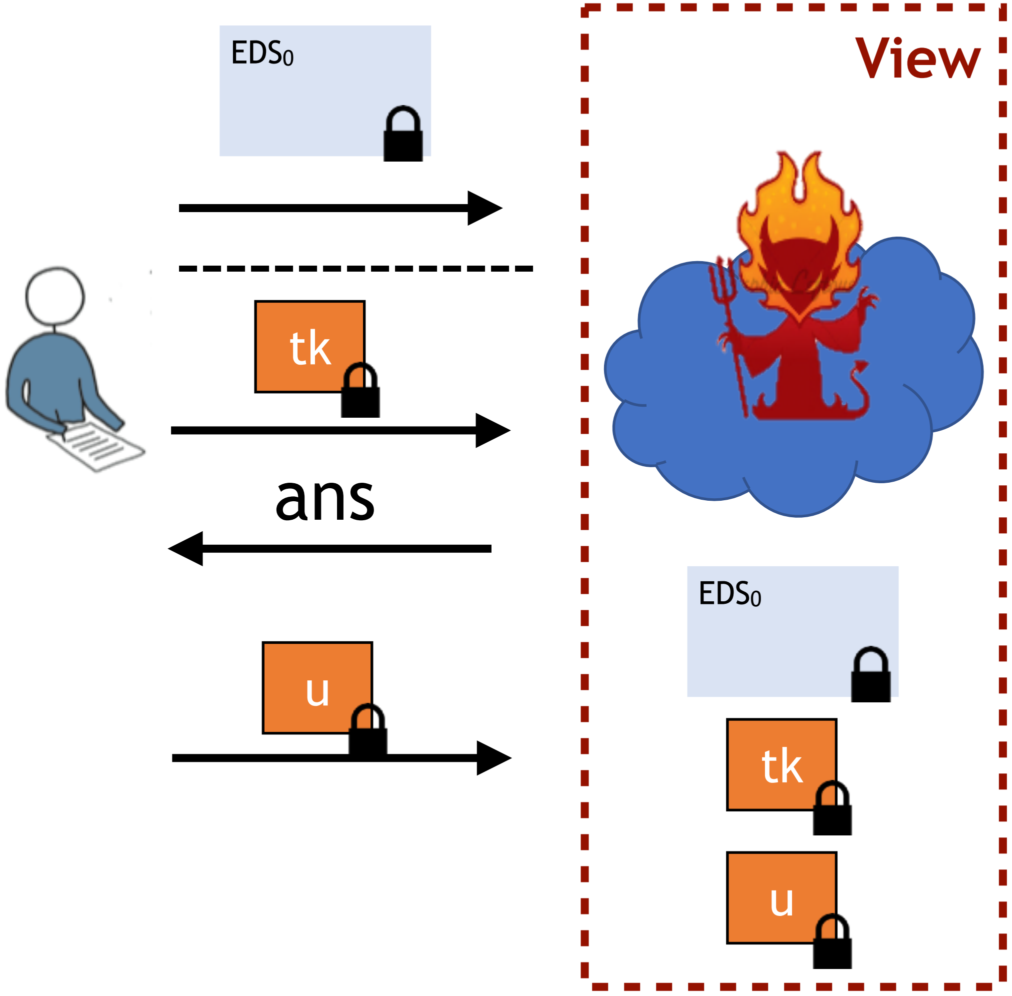
Setup(1^k, DS) $\longrightarrow$ (K, EMM)

Query(EMM, tk) $\longrightarrow$ ans

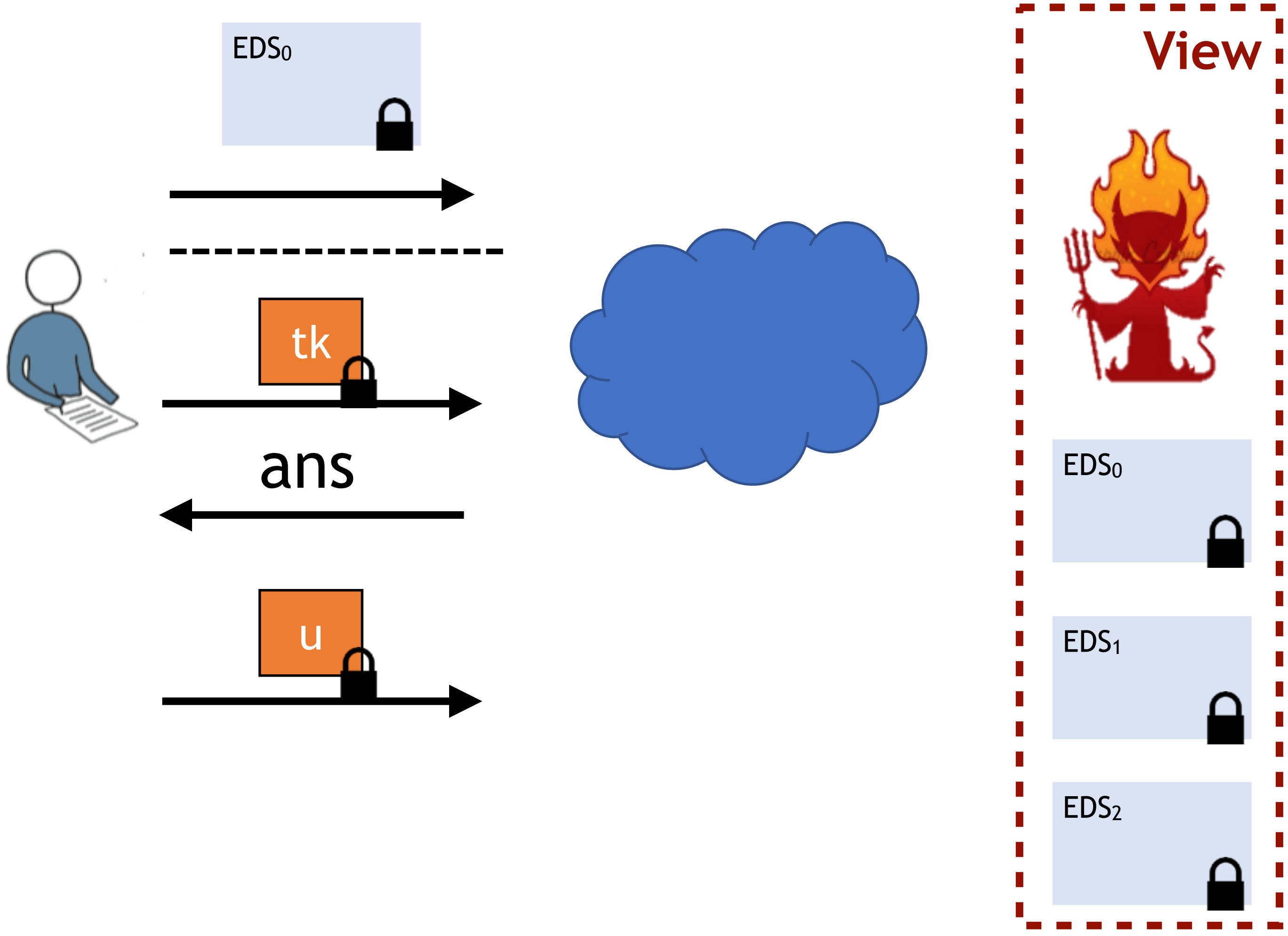
Token(K, q) $\longrightarrow$ tk

Adversarial Models

<u>Persistent</u>



<u>Snapshot</u>



Persistent (Adaptive) Security

[Curtmola-Garay-K.-Ostrovsky06,Chase-K.10]

- An STE scheme is ($\mathscr{L}_S$, $\mathscr{L}_Q$)-secure vs. a persistent adv. if
  - it reveals no information about the *structure* beyond $\mathscr{L}_S$
  - it reveals no information about the *structure* and *query* beyond $\mathscr{L}_Q$

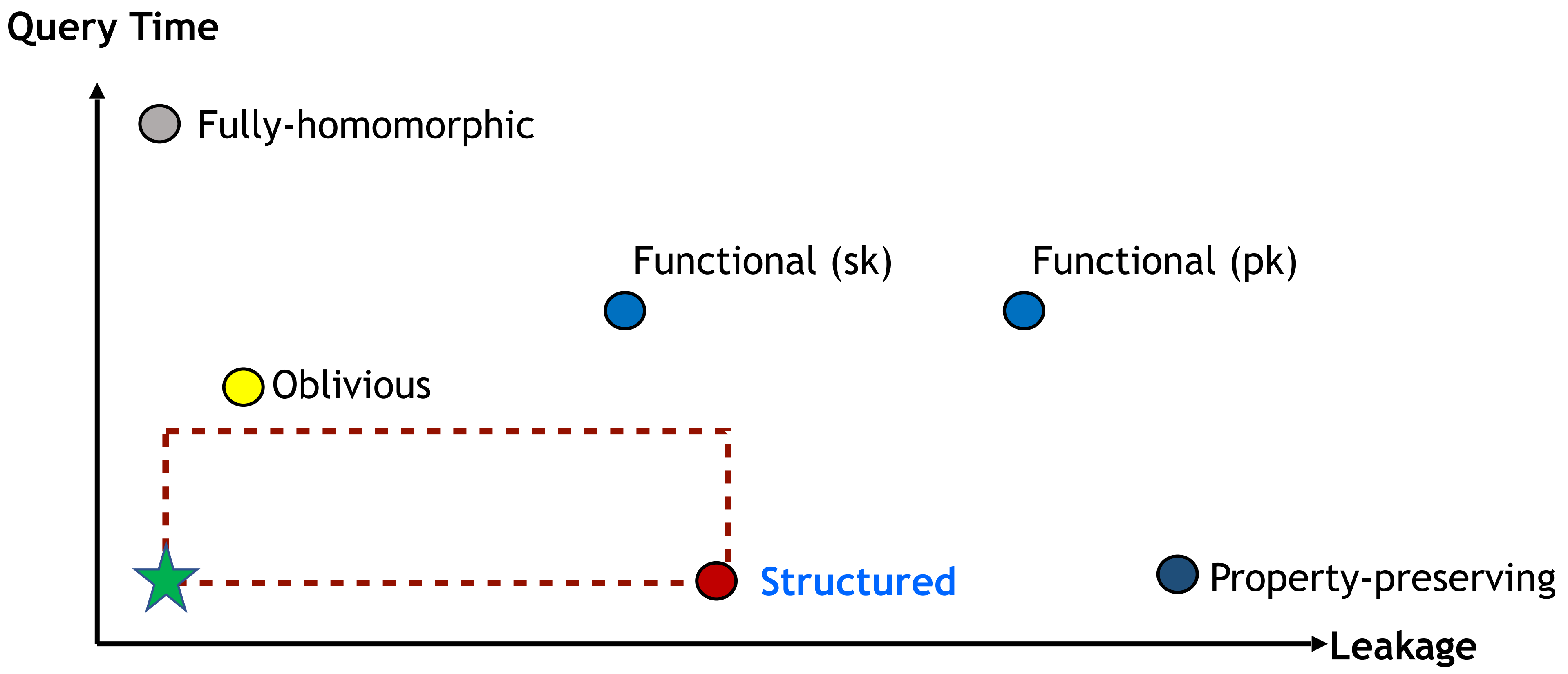
Snapshot (Adaptive) Security

[Amjad-K.-Moataz19]

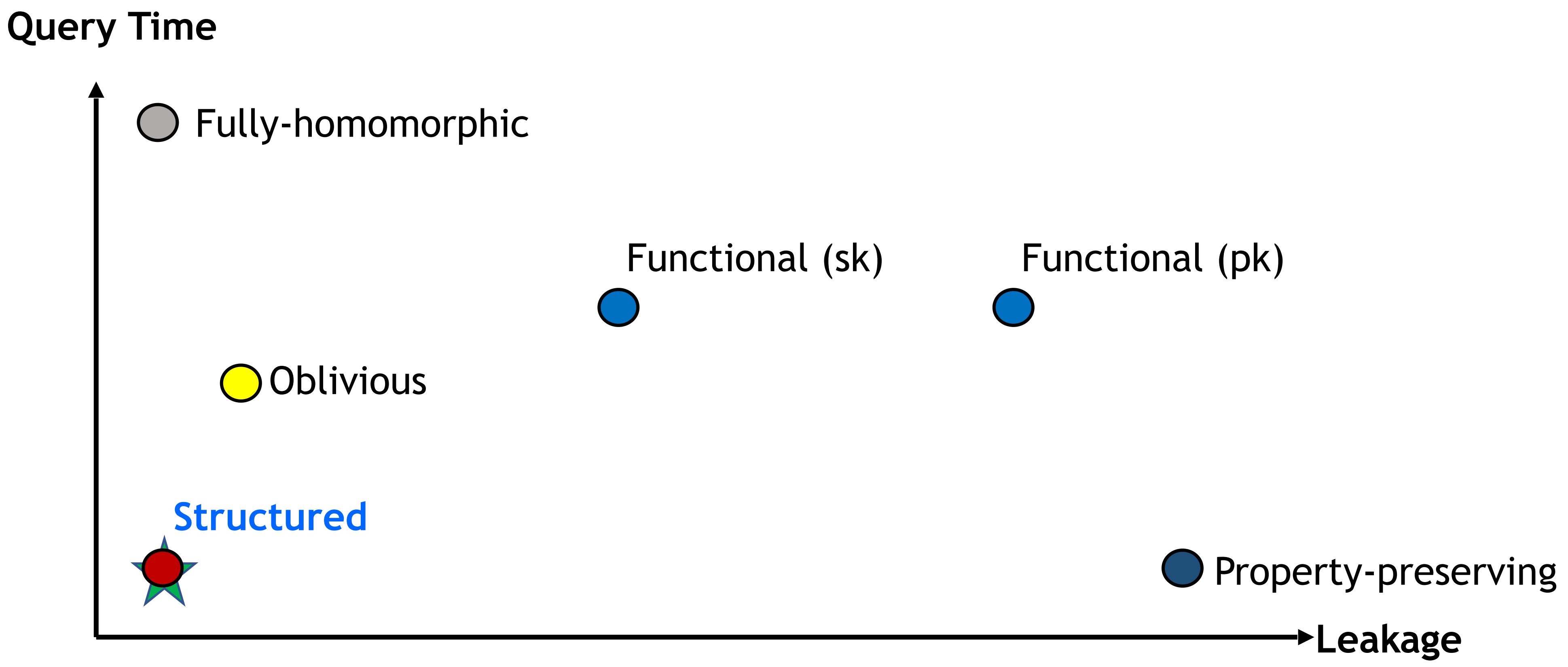
- We say that an STE scheme is $\mathscr{L}_{\mathsf{Snp}}$-secure vs. a snapshot adv. if
  - it reveals no information about the *structure* beyond $\mathscr{L}_{\mathsf{Snp}}$

Not Scientific!

Efficiency vs. **Persistent** Security



Efficiency vs. **Snapshot** Security



Leakage

Leakage-Parameterized Definitions

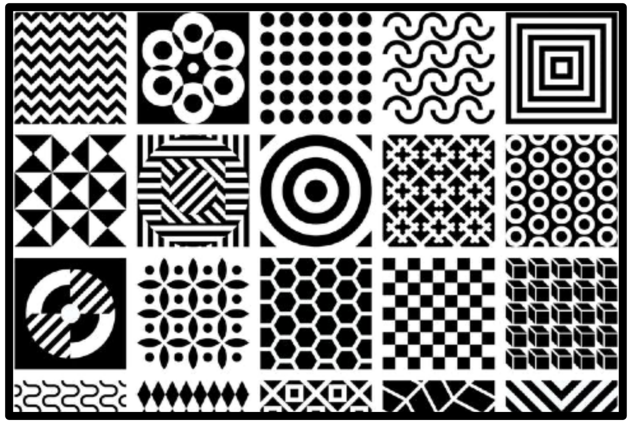
[Curtmola-Garay-K.-Ostrovsky, Chase-K.10]

- This area is about tradeoffs
  - but traditional cryptographic definitions don't capture tradeoffs
- in 00's, different approaches were proposed to capture leakage
  - #1: limit adversary's power in the proof
  - #2: make assumptions on data (e.g., high entropy)
- Original motivations for leakage-parameterized definitions
  - Approaches #1 & #2 are misleading (sweep leakage under the rug)
  - Leakage should be made explicit and not be implicit
    - gives clear target for cryptanalysis
    - makes it (somewhat) easier to compare schemes

Modeling Leakage

- Each scheme has a leakage profile: $\mathbf{\Lambda} = (\mathscr{L}_{S}, \mathscr{L}_{Q}, \mathscr{L}_{U})$
    - where $\mathscr{L}_{S}$ = ($patt_1$, …, $patt_n$) is the Setup leakage
    - $\mathscr{L}_{Q}$ = ($patt_1$, …, $patt_n$) is the Query leakage
    - $\mathscr{L}_{U}$ = ($patt_1$, …, $patt_n$) is the Update leakage
- Each “operational” leakage is composed of leakage patterns
    - ($patt_1$, …, $patt_n$)

Common Leakage Patterns



- **qeq**: query equality
  - a.k.a. search pattern
- **rid**: response identity
  - a.k.a. access pattern
- **qlen**: query length
- **trlen**: total resp. length
- **rlen/vol:** response length
  - a.k.a. volume pattern
- **req**: response equality
- **mqlen**: max query length
- **mrlen**: max resp. length
- **srlen**: sequence resp. length
- **dsize**: data size
- **usize**: update size
- **did**: data identity

Example Leakage Profiles

- The "Baseline" leakage profile for response-revealing EMMs
  - $\boldsymbol{\Lambda} = (\mathscr{L}_S, \mathscr{L}_Q, \mathscr{L}_U) = (\text{dsize}, (\text{qeq}, \text{rid}), \text{usize})$
- The "Baseline" leakage profile for response-hiding EMMs
  - $\boldsymbol{\Lambda} = (\mathscr{L}_S, \mathscr{L}_Q, \mathscr{L}_U) = (\text{dsize}, \text{qeq}, \text{usize})$
- Several new constructions have better leakage profiles
  - AZL and FZL [K.-Moataz-Ohrimenko18]
  - VLH and AVLH [K.-Moataz19]

Structured Encryption vs. Other Primitives

- Encrypted structures appear implicitly throughout crypto
- Oblivious RAM can be viewed as a
  - response-hiding encrypted array
  - with leakage profile $\mathbf{\Lambda}_{\text{ORAM}} = (\mathscr{L}_{\text{S}}, \mathscr{L}_{\text{Q}}, \mathscr{L}_{\text{U}})$ = (dsize, vol, vol)
- Garbled gates can be viewed as
  - response-revealing 2x2 arrays
  - $\mathbf{\Lambda}_{\text{GG}} = (\mathscr{L}_{\text{S}}, \mathscr{L}_{\text{Q}})$ = (dsize, qeq)

How do we Deal with Leakage?

- Our definitions allow us to prove that our schemes
  - achieve a certain leakage profile
  - but doesn’t tell us if a leakage profile is exploitable?

- We need more than proofs

The Methodology

- Leakage analysis: what is being leaked?
- Proof: prove that scheme leaks no more
- Cryptanalysis: can we exploit this leakage?

Leakage Attacks

Leakage Attacks

- Target
  - *query recovery*: recovers information about query
  - *data recovery*: recovers information about data
- Adversarial model
  - *persistent*: needs EDS and tokens
  - *snapshot*: needs EDS
- Auxiliary information
  - *known sample*: needs sample from same distribution
  - *known data*: needs actual data
- Passive vs. active
  - *injection*: needs to inject data

Leakage Attacks

- Leakage cryptanalysis is crucial but…

- …unfortunately much of the attack literature
  - lacks experimental rigor
  - is just plain wrong
  - overhyped

- there is a need for higher standards

Leakage Attacks

- IKK attack
  - highly cited but doesn't work
  - too few keywords, auxiliary & test data correlated, …
- Count attack
  - based on strong assumptions
  - adversary needs to know ≥ 75% of client's data!
- Some target very niche applications & rely on strong assumptions

Leakage Attacks

- Should we discount attacks? Of course not
  - More rigorous
  - Less hyperbolic
  - More upfront about attack limitations & assumptions

- [Blackstone-K.-Moataz'20]: Revisiting Leakage-Abuse Attacks

- [KKMSTY'21]: re-implementation & re-evaluation of most known attacks

How Should we Handle Leakage?

- **Approach #1:** ORAM simulation
  - Store and simulate data structure with ORAM
  - polylog overhead per read/write on top of simulation
  - still leaks information that is exploitable
    - [Kellaris-Kollios-O'neill-Nissim'16, Blackstone-K.-Moataz'20]

- **Approach #2:** Custom oblivious structures

How Should we Handle Leakage?

- **Approach #3:** Rebuild [K.14]
  - Rebuild encrypted structure after `t` queries
  - Set `t` using cryptanalysis
  - Open question: can you rebuild encrypted structures?
    - Yes [K.-Moataz-Ohrimenko'18, George-K.-Moataz'21]

- **Approach #4:** Leakage suppression
  - Suppression compilers
  - Suppression transforms

Leakage Suppression

- Techniques to reduce/eliminate leakage

- Suppressing query equality (aka access pattern)
  - general compiler [K.-Moataz-Ohrimenko'18, Geoge-K.-Moataz'21]

- Suppressing co-occurrence (needed by IKK and Count attacks)
  - see appendix in [Blackstone-K.-Moataz19]

Leakage Suppression

- Suppressing volume (aka response size)
  - padding & clustering techniques [Bost-Fouque17]
  - computational techniques
    [K.-Moataz19, Patel-Persiano-Yeo-Yung'20]

- "General-purpose" suppression
  - worst-case vs. average-case leakage [Agarwal-K.1'9]
  - distributing data [Agarwal-K.'19]

Leakage Suppression

- New tradeoffs to explore
  - leakage vs. correctness [K.-Moataz19]
  - leakage vs. latency [K.-Moataz-Ohrimenko18]

Thanks!