Practical Solutions for Format-Preserving Encryption

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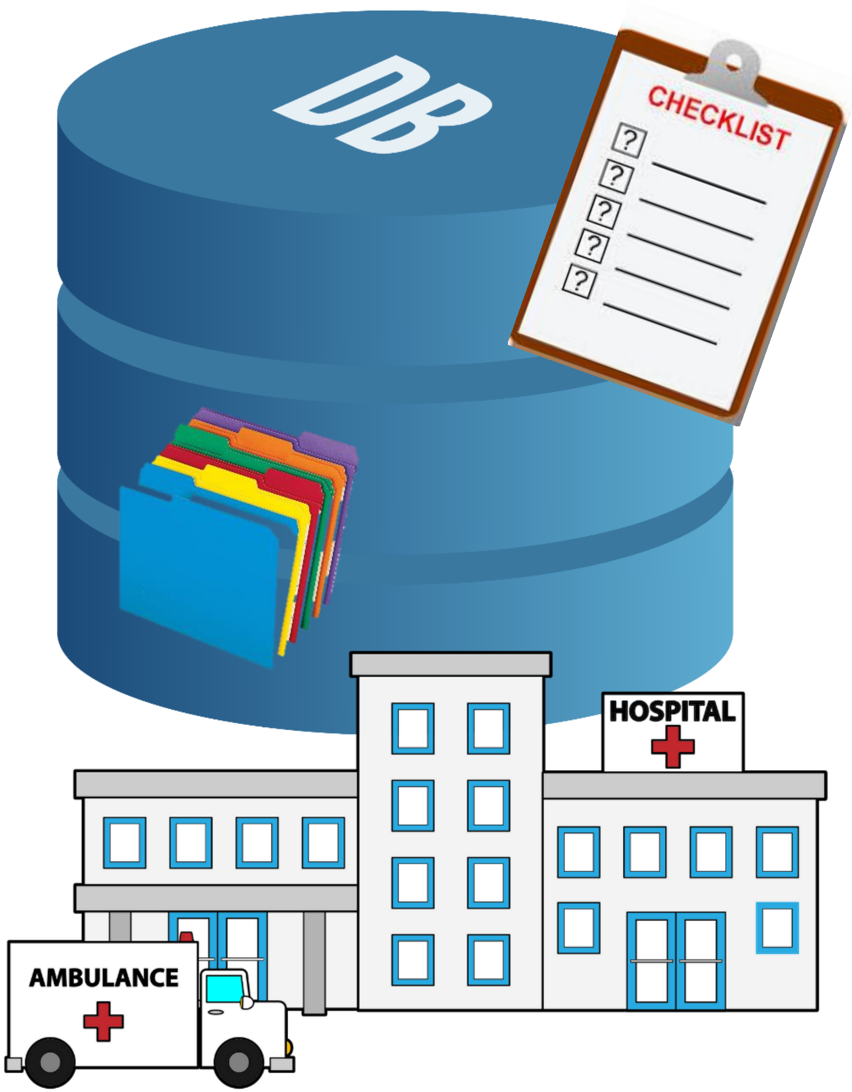
Joint work with Boris Rozenberg and Muhammad Barham

Research conducted while all authors were at IBM Research Labs, Haifa

Why Format Preserving Encryption?



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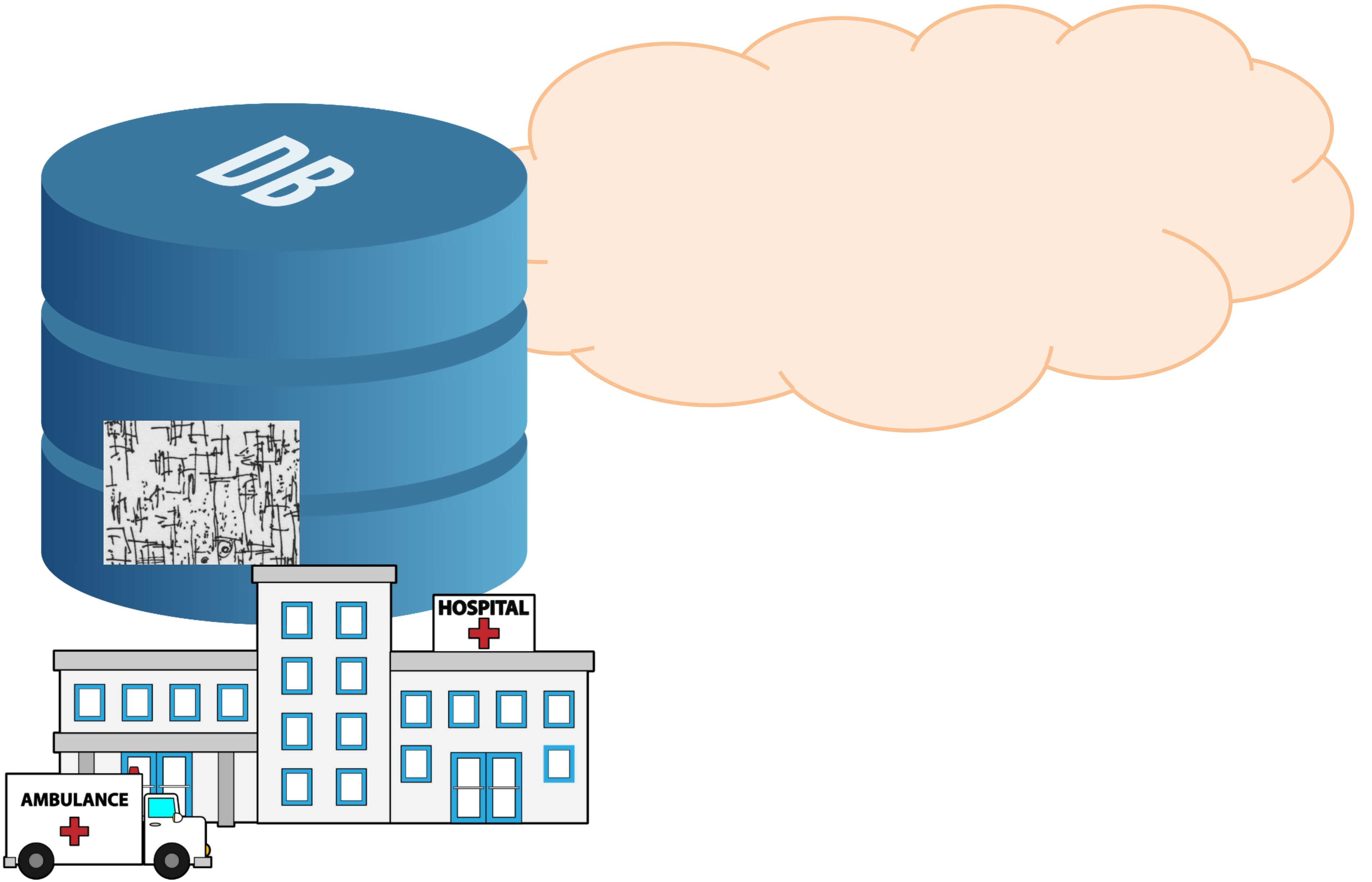

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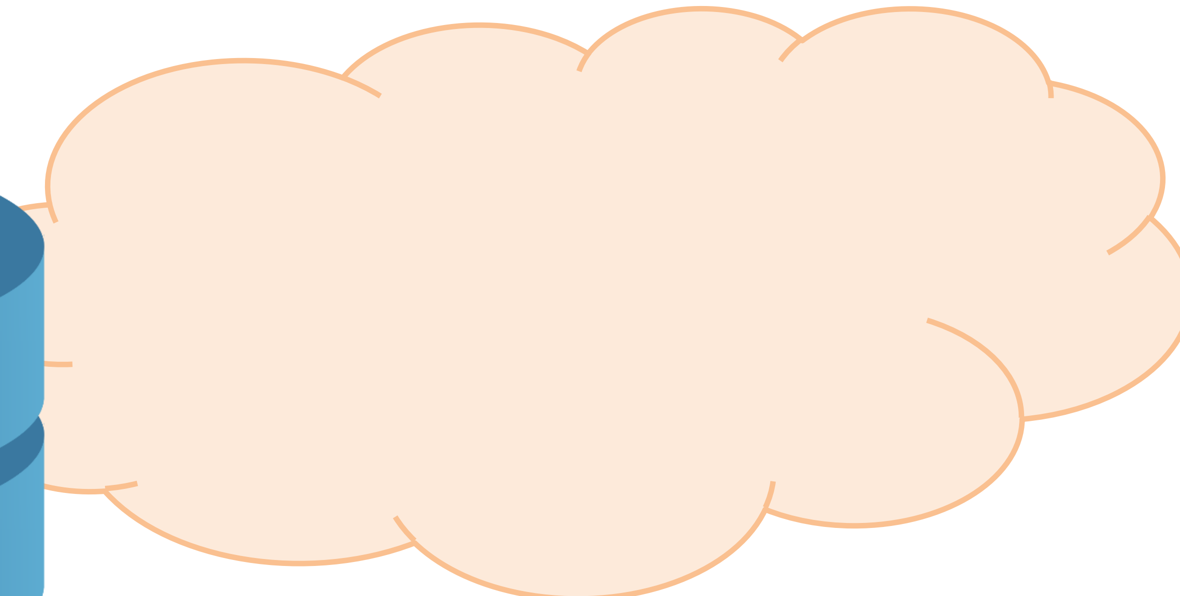

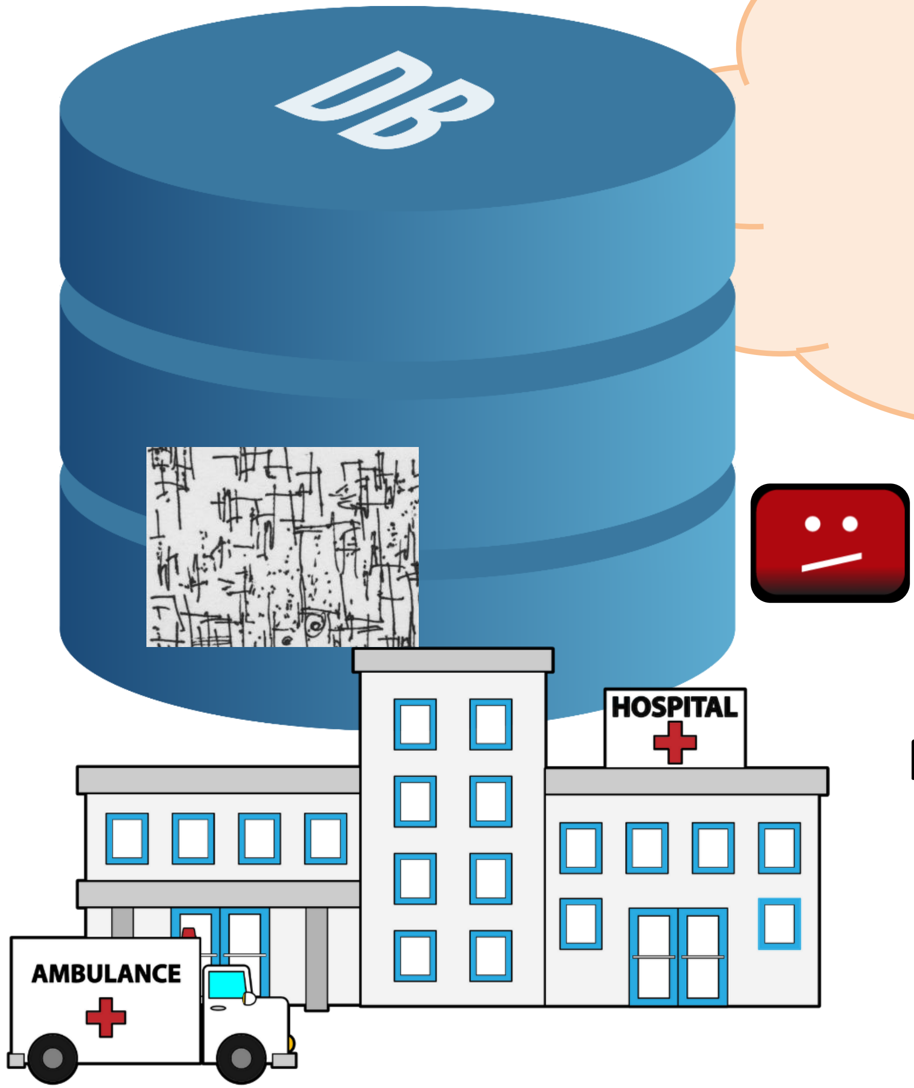

Problem (1): encrypted entry incompatible with database entry structure

Non-solution (1): generate new tables

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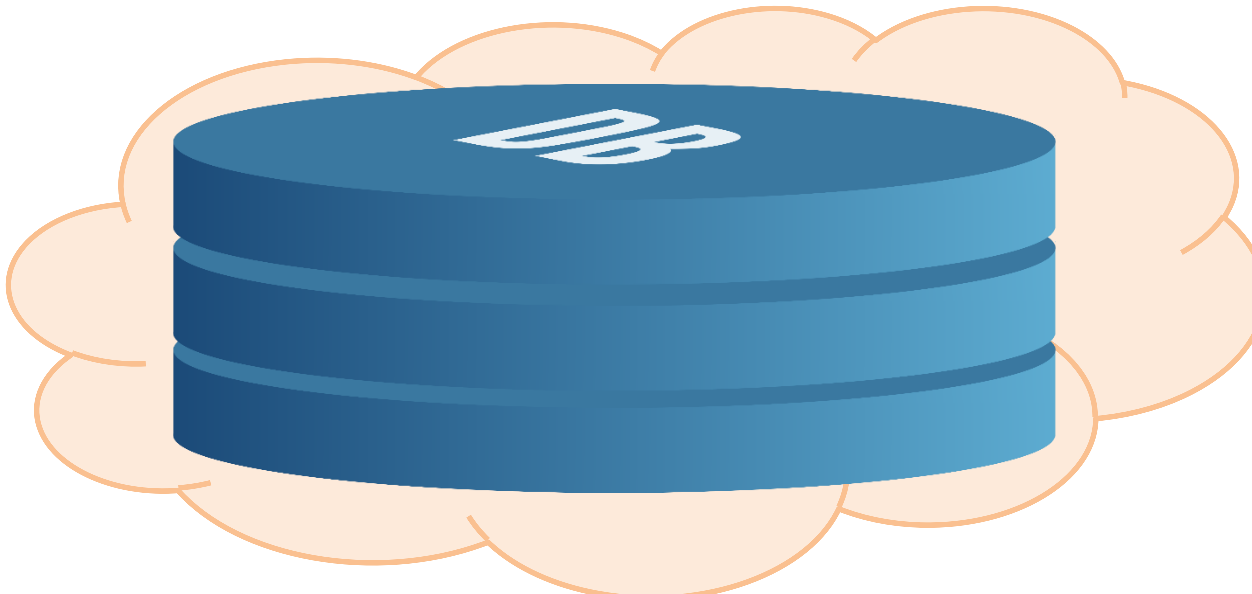

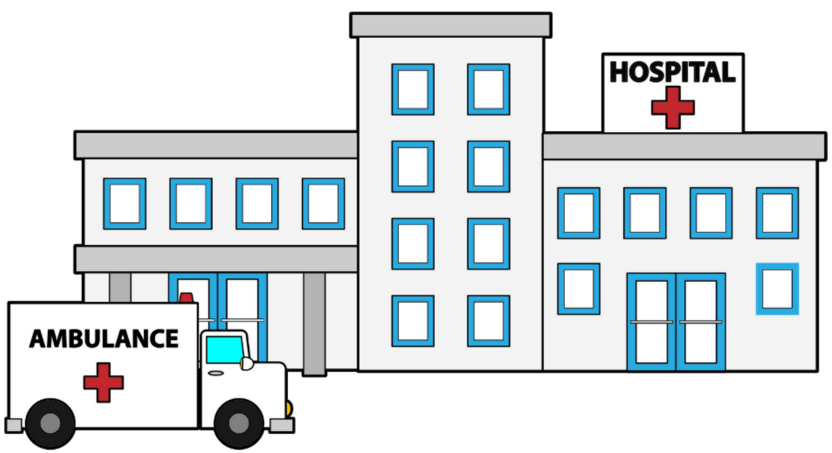

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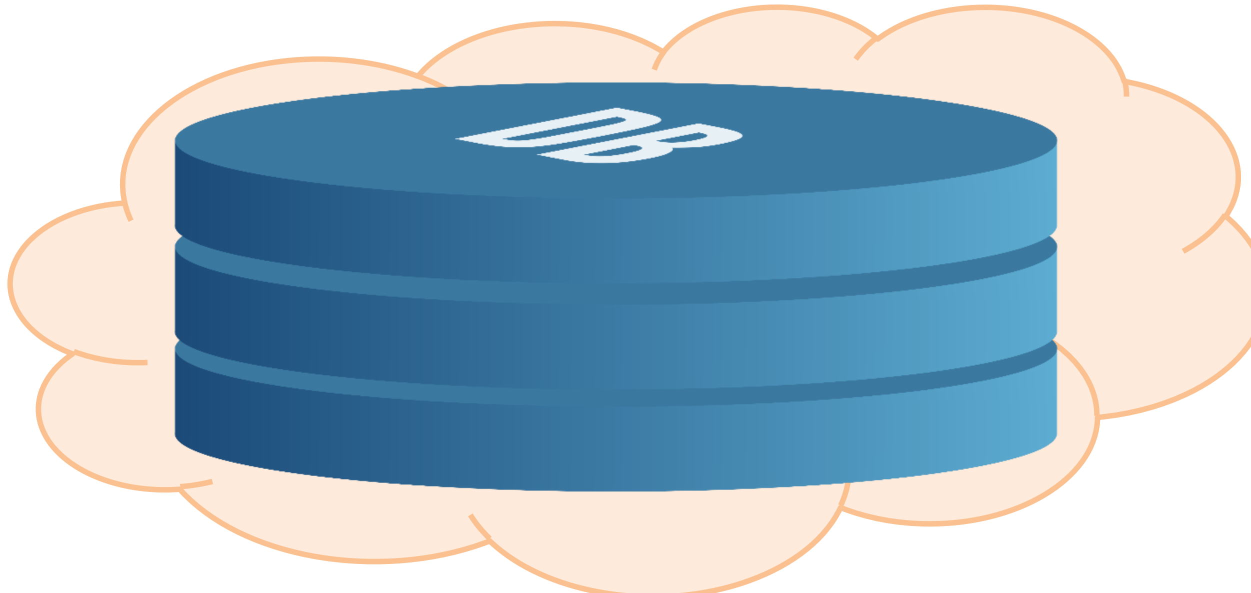

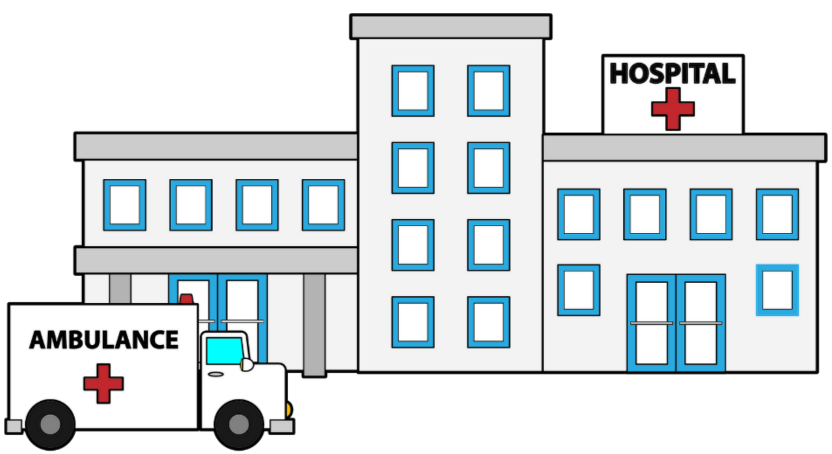

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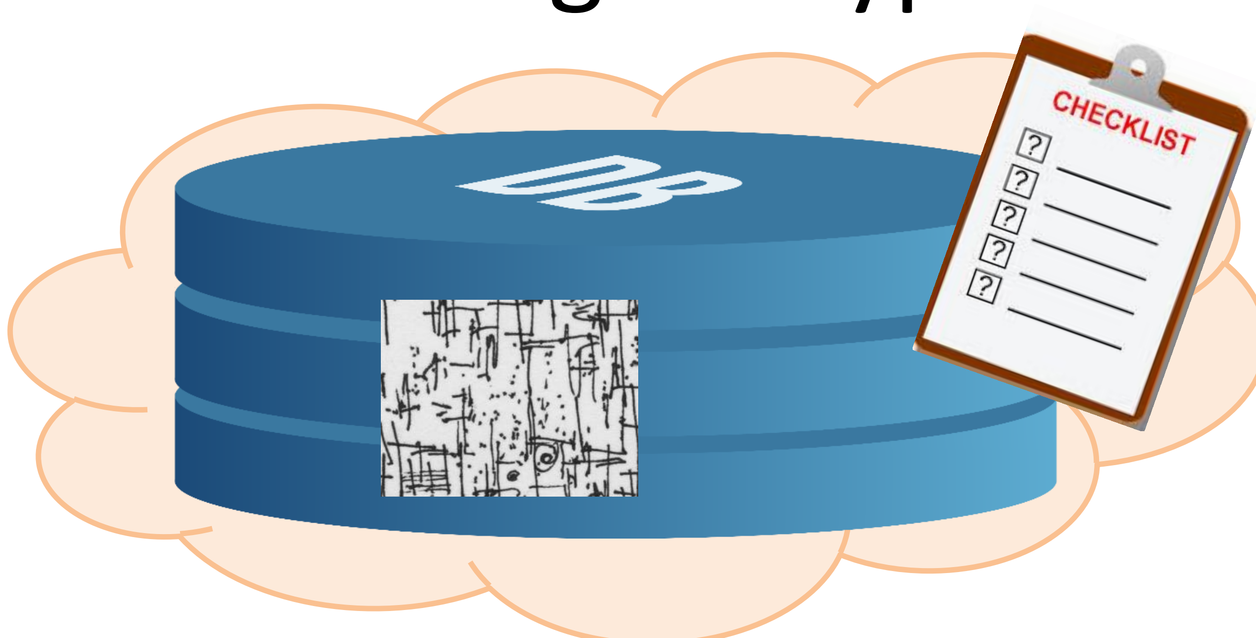
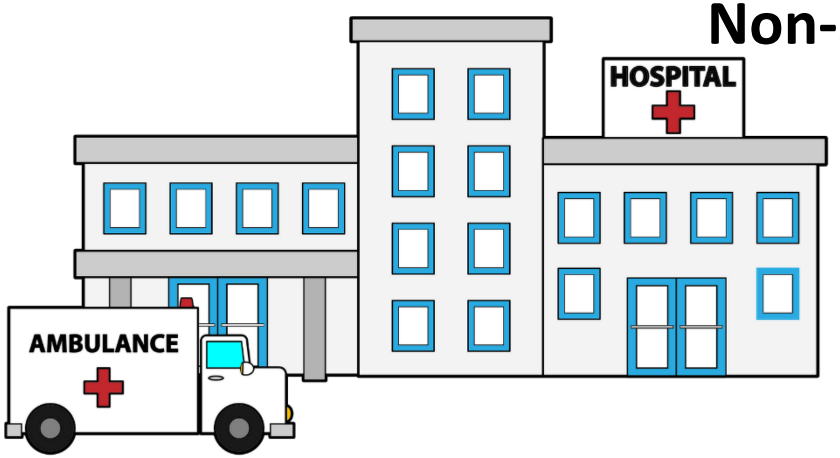


Problem (2): encrypted entry incompatible with applications using data

Non-solution (2): re-write applications



Talk Outline

- Definitions
- Methodology for format-preserving encryption of general formats
- Analysis of known constructions
- GFPE
- Optimizations for large formats

Format-Preserving Encryption: Definition

- A deterministic private-key **Encryption Scheme** Π:
  - Message space $\mathcal{M}$
  - Randomized $KeyGen: \mathbb{N} \to \mathcal{K}$
  - Deterministic $Enc: \mathcal{K} \times \mathcal{M} \to \mathcal{C}$
  - Deterministic $Dec: \mathcal{K} \times \mathcal{C} \to \mathcal{M}$
- **Notation:** $Enc_k = Enc(k,\cdot)$, $Dec_k = Dec(k,\cdot)$
- Encryption key ***random and secret*** $\Rightarrow$ encryption "hides" plaintext
- Standard encryption: ciphertexts usually "look like garbage", possibly causing
  - Applications using data to crash
  - Tables designed to store data unsuitable for storing encrypted data
- $\Rightarrow$ Sometimes plaintext properties should be preserved
- **Format-Preserving Encryption (FPE):** $\mathcal{M} = \mathcal{C}$
  - Enc_k is a permutation over plaintext space $\mathcal{M}$
  - Ciphertexts have same format as plaintexts!

FPE: Definition (cont.)

- Correctness: for every $k \in \mathcal{K}$ and every $m \in \mathcal{M}$
$$Dec_k\big(Enc_k(m)\big) = m$$
- Secrecy:
  - For ***secret and random*** $k \in \mathcal{K}$
  - Hierarchy of security notions [BRRS`09]
  - **Strongest:** random $k \Rightarrow Enc_k$ close to pseudorandom permutation
    - An “overkill” for many typical applications
      - Guaranteed security against (improbable) attacks incurs expensive overhead
  - **Weakest:** Message Recovery
    - Only require that adversary cannot **completely** recover message
      - Even given advantageous distribution over $\mathcal{M}$
    - *Very* weak: adversary may learn some message properties

What We Know About FPE

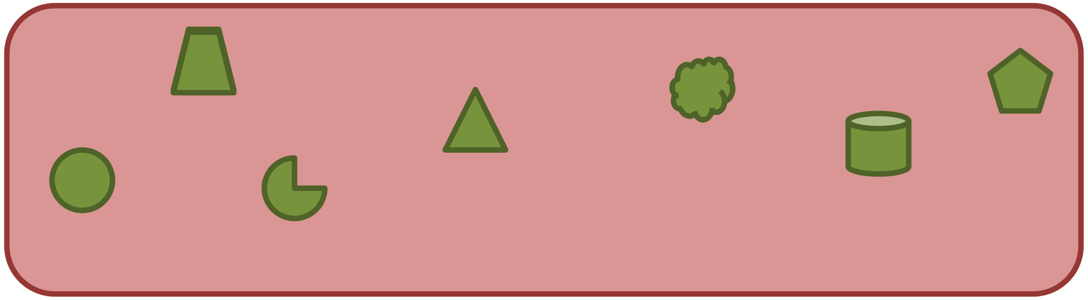
- Term coined by Terence Spies, Voltage Security's CTO
- First formal definitions due to [BRRS`09]
- Constructions for specific formats
  - Social Security Numbers (SSNs) [Hoo`11]
  - Credit Card Numbers (CCNs)
  - Dates [LJLC`10]
  - …
- **Drawbacks:**
  - Designed for specific formats (different scheme for every format)
  - New encryption techniques, little (if any) security analysis
- Integral domains $\{1, \ldots, M\}$ [BR`02,BRRS`09]
- "Almost integral" domains $\mathcal{M} = \{1, \ldots, m\}^n$ for $n, m \in \mathbb{N}$
  - Methods described as early as 1981
  - FFX [BRS`10], BPS [BPS`10] submitted to NIST for consideration

Useful for general-format FPE

Format-Preserving Encryption for General (Complex) Formats

Techniques for General-Format FPE (Part 2)

- Rank-then-Encipher (RtE) [BRRS`09]: **general-format** FPEs from **int**-FPE
  - Order $\mathcal{M}$ arbitrarily: $\mathbf{rank}$: $\mathcal{M} \rightarrow \{1, .., M\}$



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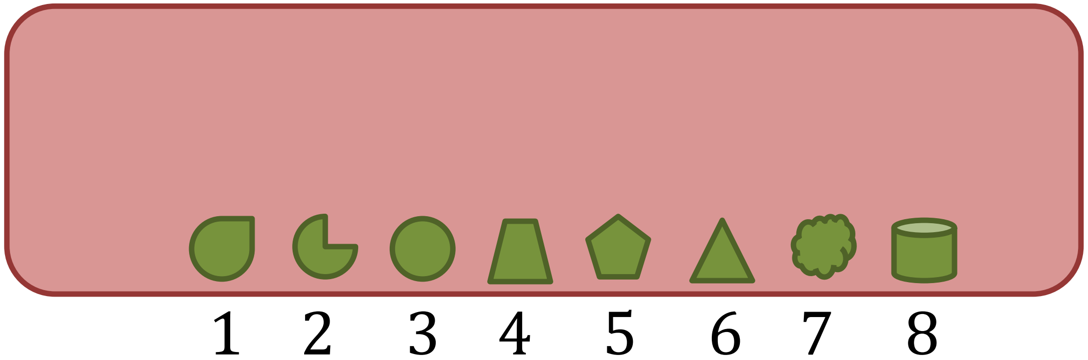

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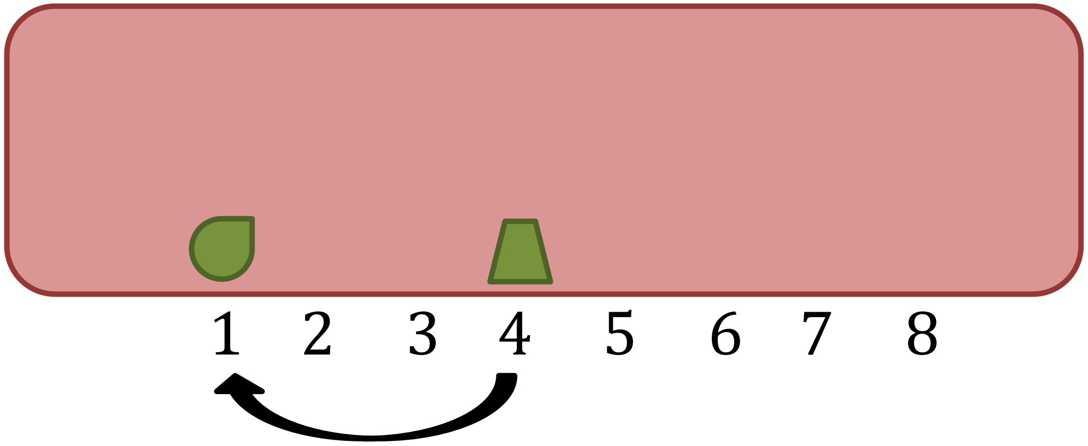
  - To encrypt message m:
    - **Rank *m*:** $i = \text{rank}(m)$
    - **Encipher *i*:** $j = intE(K, i)$
    - **Unrank *j*:** $c = \text{rank}^{-1}(j)$



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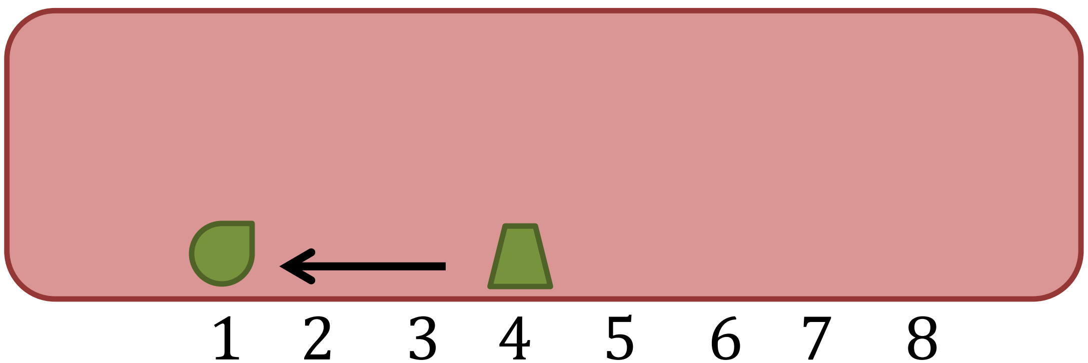


Techniques for General-Format FPE

- Rank-then-Encipher (RtE) [BRRS`09]: **general-format** FPE from **integer**-FPE
  - Order $\mathcal{M}$ arbitrarily: $\mathbf{rank}: \mathcal{M} \to \{1, .., M\}$
  - To encrypt plaintext m:
    - **Rank $\boldsymbol{m}$:** $i = \mathrm{rank}(m)$
    - **Encipher $\boldsymbol{i}$:** $j = integerEnc_k(i)$
    - **Unrank $\boldsymbol{j}$:** $c = \mathrm{rank}^{-1}(j)$
- Security: from security of integer-FPE
  - rank not meant to, and does not, add security
- Efficiency: only if $\mathrm{rank}, \mathrm{unrank}$ are efficient
- **Main challenge (1):** design efficient rank procedure
  - "Meta" ranking technique for regular languages [BRRS`09]
- **Main challenge (2):** representing formats

FPEs for General Formats: Previous solutions

Simplification-Based FPE [MYHC`11,MSP`11]

- Represent formats as union of simpler sub-formats
  - Plaintexts interpreted as strings
  - $\mathcal{M}$ divided into subsets $\mathcal{M}_1, \ldots, \mathcal{M}_k$ defined by
    - Length
    - Index-specific character sets
- Encrypt each $\mathcal{M}_i$ ***separately*** using Rank-then-Encipher
  - Ranking computed using generalized lexicographic ordering

$\mathcal{F}_{name}$: format of valid names
Name: 1-4 space-separated words
Word: upper case letter followed by 1-15 lower case letters

Subsets:

$\mathcal{M}_1$ contains Al
$\mathcal{M}_2$ contains Tal
…
$\mathcal{M}_{15}$ contains Muthuramakrishna
$\mathcal{M}_{16}$ contains El Al

Simplification-Based FPE: Security Concerns

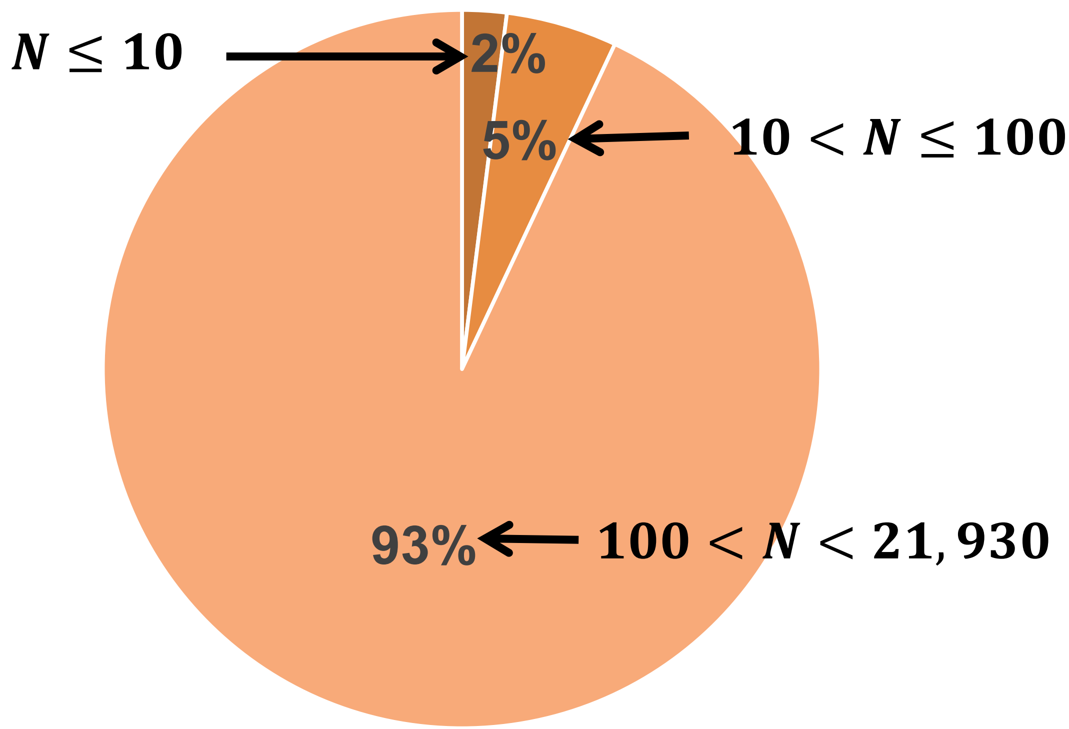
- **The problem:** encryption preserves ***plaintext-specific*** properties
  - **Reason:** each sub-format $\mathcal{M}_i$ encrypted separately
  - "John Doe" can encrypt "Jane Roe" but not "Johnnie Dee"
  - If only one of them is possible, adversary knows plaintext for sure
- Simplification-based FPE is Message-Recovery insecure [WRB`15]
  - MR (message recovery) is the weakest notion
  - Implies insecurity according to other FPE security notions
- **Reason:** ciphertext *length* reveals plaintext length, can be used to recover message

Simplification-Based FPE: Experimental Results

- Our experiments performed on 1M records of the Federal Election Commission (FEC) reports of 2008-2012
  - Regulates campaign finance legislation in the US
  - Report lists all donors over $200:
    - Name
    - Town
    - Employer
    - Job title
- Attack model reflects typical threat
  - Data stored at remote server
  - Attacker has access to all or part of database
  - No access to secret encryption key
  - $\mathcal{A}$ may have prior knowledge

Simplification-Based FPE: Experimental Results (Cont.)

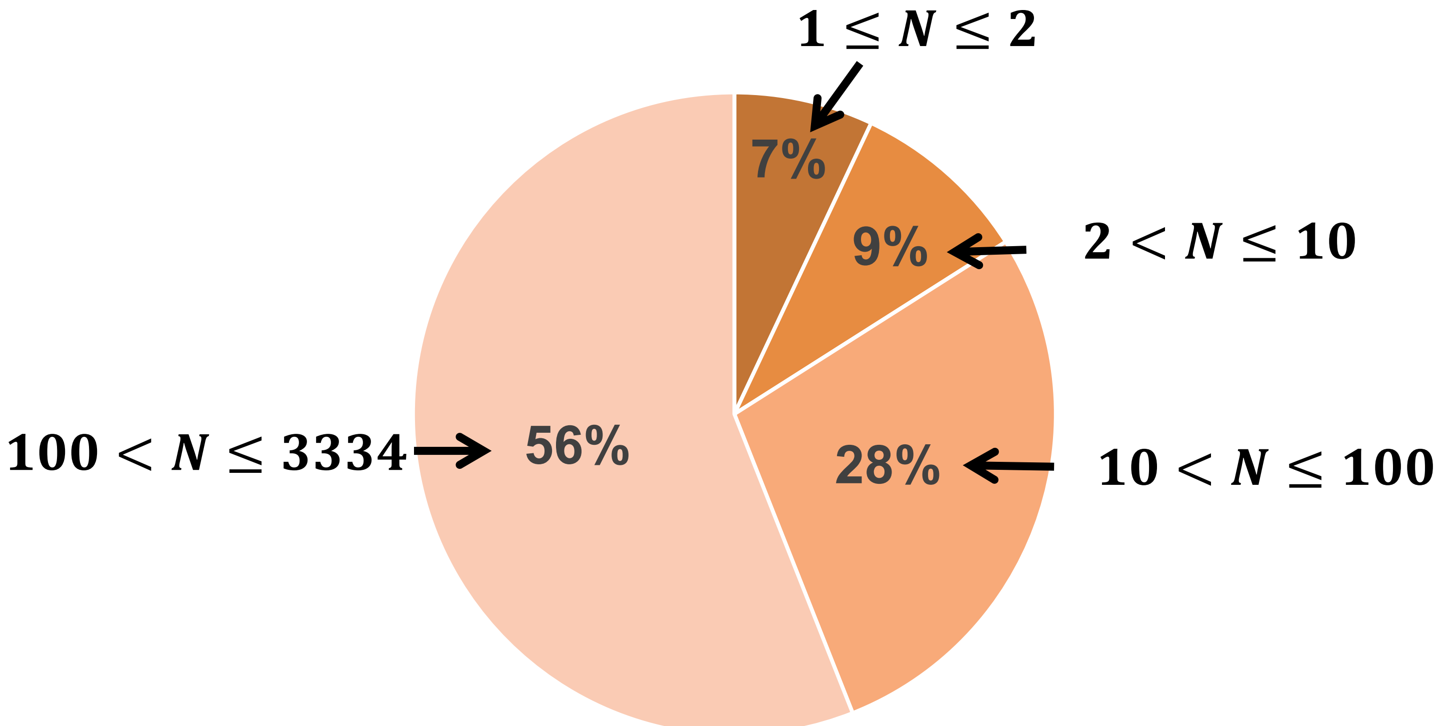
When $\mathcal{A}$ recovers *only name* column



- If we're lucky – Bar in 7% of donors whose encryptions match only 100 entries

Simplification-Based FPE: Experimental Results (Cont.)

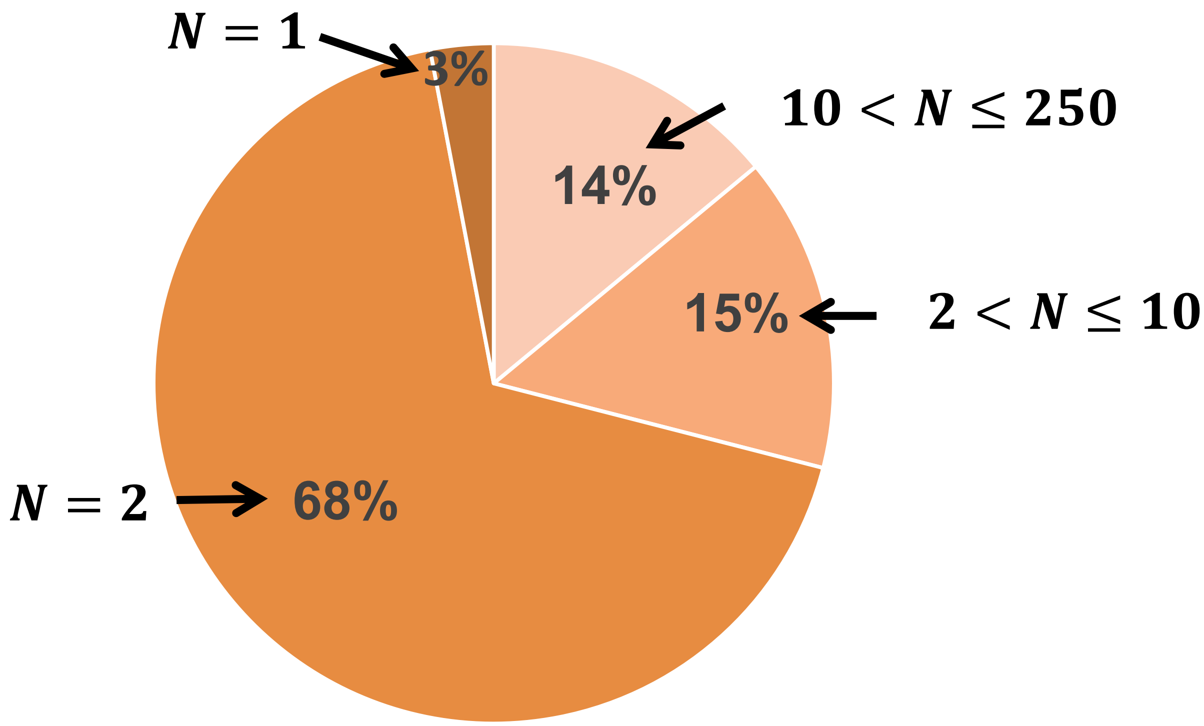
When $\mathcal{A}$ recovers *name and town* columns



- If we're lucky, Bar in 7% of donors whose encryptions match only 2 entries
- **Pretty likely** that Bar in 44% of donors whose encryptions match only 100 entries

Simplification-Based FPE: Experimental Results (Cont.)

When $\mathcal{A}$ recovers *entire database*



- For *all* donors: encryptions match ≤ 250 entries!
- **Most likely** Bar in 71% of donors whose encryption matches only 2 entries!

GFPE

GFPE [WRB`15]

FPE "Wish List"

- **Functionality, efficiency:**
  - *Simple* method of representing formats
  - *Efficient* rank, unrank procedures
- **Security:** preserve *only format-specific* properties
  - Hide *all plaintext-specific* properties

The Scheme:

- Encryption\decryption using Rank-then-Encipher
  - Support integer-FPEs for integral *and* almost integral domains
- **Main challenge:** user-friendly format representation
  - Scheme is user-oriented
- **Structure:** formats represented using bottom-up framework
  - **"Basic" building-blocks (primitives)**
    - Usually "rigid" formats (e.g., SSNs, CCNs, dates, fixed-length strings…)
    - Also "less rigid" formats (e.g., variable-length strings)
  - **Operations** used to construct complex formats

GFPE: Representing Formats

- **“Basic” building-blocks (primitives):**
  - $\mathcal{F}_{upper}$ = {A,B,…,Z}
  - $\mathcal{F}_{lower}$ = length-k lower-case letter strings, $1 \leq k \leq 15$
  - $\mathcal{F}_{ssn}$ = social-security numbers (SSNs)
- **Operations:**
  - *Concatenation:*
    - $\mathcal{F} = \mathcal{F}_1 \cdot \ldots \cdot \mathcal{F}_k$
      - Words: $\mathcal{F}_{word} = \mathcal{F}_{upper} \cdot \mathcal{F}_{lower}$
    - $\mathcal{F} = \mathcal{F}_1 \cdot d_1 \cdot \mathcal{F}_2 \cdot \ldots \cdot d_{n-1} \cdot \mathcal{F}_n$ ($d_1, \ldots, d_{n-1}$ are delimiters)
  - *Range:* $\mathcal{F} = (\mathcal{F}_1 \cdot d)^k, min \leq k \leq max$
    - Names: $\mathcal{F}_{name} = (\mathcal{F}_{word} \cdot space)^k$ for $1 \leq k \leq 4$
  - *Union:* $\mathcal{F} = \mathcal{F}_1 \cup \cdots \cup \mathcal{F}_k$
    - “Names or SSNs”: $\mathcal{F} = \mathcal{F}_{name} \cup \mathcal{F}_{ssn}$

Example: Representing Addresses

name **house #** **street** **city** **zip**

- $\mathcal{F}_{name} = (\mathcal{F}_{word} \cdot space)^k$ for $1 \leq k \leq 4$ (range)
- $\mathcal{F}_{num} = \{1, \dots, 100\}$ (integral domain)
- $\mathcal{F}_{zip} = \{0,1, \dots, 9\}^5$ (fixed length string)
- Valid addresses obtained through concatenation:

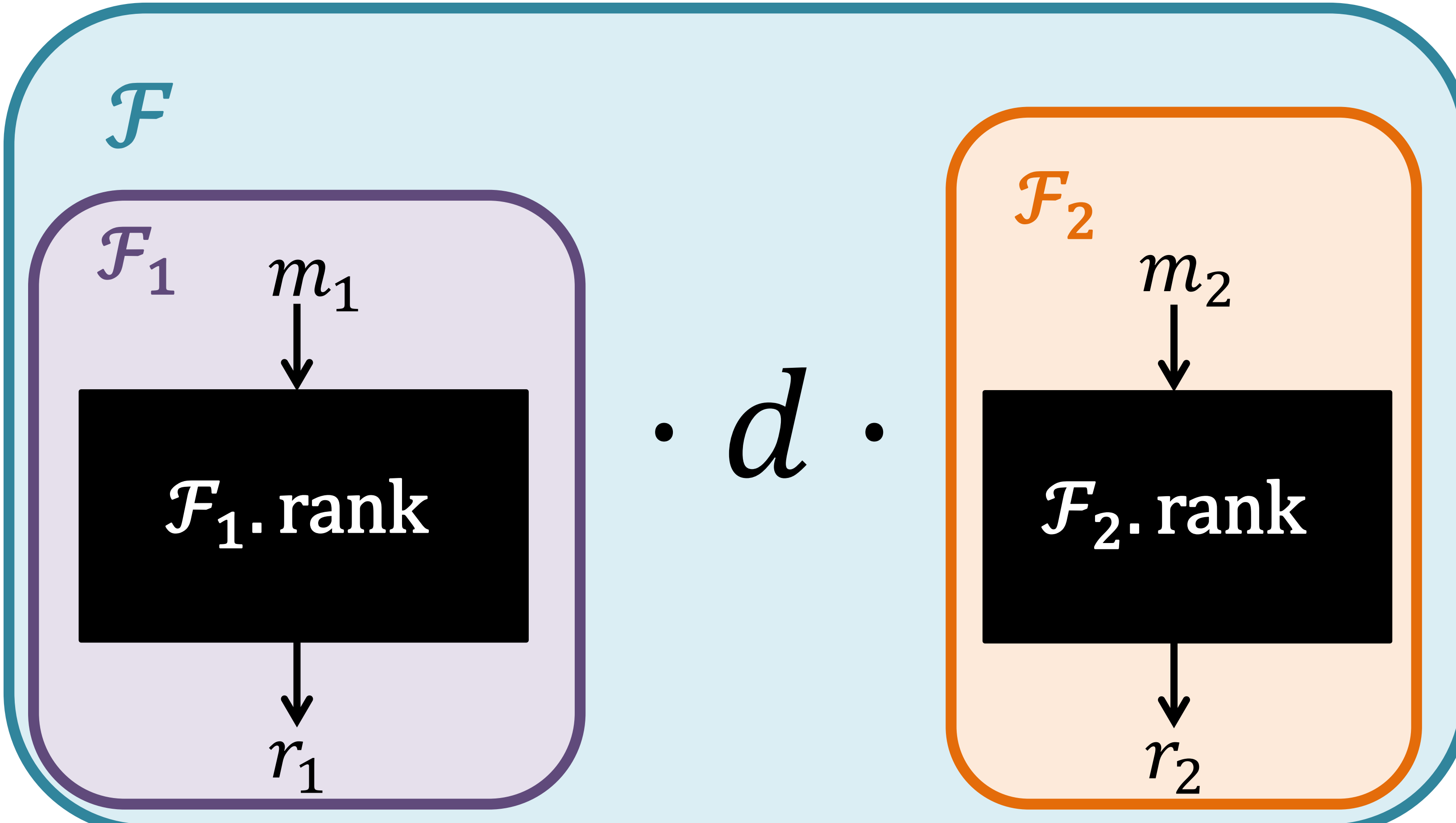
$$\mathcal{F}_{add} = \underbrace{\mathcal{F}_{name}}_{\text{name}} \cdot \underbrace{\mathcal{F}_{num}}_{\text{house \#}} \cdot \underbrace{\mathcal{F}_{name}}_{\text{street}} \cdot \underbrace{\mathcal{F}_{name}}_{\text{city}} \cdot \underbrace{\mathcal{F}_{zip}}_{\text{zip}}$$

GFPE: Encryption

- Use Rank-then-Encipher method
  - Use “off-the-shelf” integer-FPE schemes
  - Inherit security of underlying integer-FPE
- **Challenge:** how to rank and unrank?
- Define ranking for **primitives** and **operations**
- Rank of compound formats computed top-down:
  - Parse string to components
  - Delegate substring ranking to format components
  - “Glue” ranks together using ranking for operations

Example: Ranking Concatenation

$$\mathcal{F} = \mathcal{F}_1 \cdot d \cdot \mathcal{F}_2$$
$$m = m_1 \cdot d \cdot m_2$$



Example: Ranking Concatenation

$$\mathcal{F} = \mathcal{F}_1 \cdot d \cdot \mathcal{F}_2$$

$$m = m_1 \cdot d \cdot m_2$$

$$\boxed{\boldsymbol{r} = \boldsymbol{r}_1 \quad + \quad \boldsymbol{r}_2 \cdot \boldsymbol{\mathcal{F}}_1.\mathbf{size}()}$$

Scale by size of sub-formats

GFPE: Supporting Large Formats

- Scheme supports integer-FPEs [BR`02,BRRS`09]
  - Only ***provably secure*** schemes
- Integer-FPEs are inefficient for large domains!
  - Require factoring domain size
- **Supporting large formats:** keep formats small
  - Divide large formats, encrypt each sub-format separately
  - Minimize security loss by “hiding” ***plaintext-specific*** properties:
    - Division according to ***format structure*** ← **Main challenge!**
    - Maximizing sub-format size
  - $maxSize$ determined by user-defined performance constraints

Example: Dividing Address Format

name **house #** **street** **city** **zip**

- Valid addresses obtained through concatenation:

$$\mathcal{F}_{add} = \boxed{\underbrace{\mathcal{F}_{name}}_{\text{name}} \cdot \underbrace{\mathcal{F}_{num}}_{\text{house \#}}} \cdot \boxed{\underbrace{\mathcal{F}_{name}}_{\text{street}}} \cdot \boxed{\underbrace{\mathcal{F}_{name}}_{\text{city}} \cdot \underbrace{\mathcal{F}_{zip}}_{\text{zip}}}$$

- Jane Doe 23 | Delaford | New York 12345
- Jane Doe 23 | Bedford | New York 90210
- Smaller $maxSize \Rightarrow$ further division
  - E.g., $\mathcal{F}_{name}$ divided according to number of words in name

Security of GFPE: Large Formats

- Format division introduces complications in ranking and unranking
  - Generalize $\mathrm{rank}, \mathrm{unrank}$ to lists of ranks
- GFPE format-division strategy:
  - Usually hides *all* plaintext-specific properties
  - Small $maxSize$ ⇒ may preserve some properties in *huge* formats
    - But properties defined by "semantic" sub-format, not "cosmetic" plaintext properties
  - Maximizes sub-format size
    - Minimizes possibilities of attacks
- "Wise" choice of parameters ⇒ "reasonable" tradeoff

Security of GFPE: Large Formats (2)

- Given user-define efficiency constraints, we can evaluate security loss
- **Experimental results:** compared GFPE with simplification-based FPE
  - On 1M records of the Federal Election Commission (FEC) reports of 2008-2012
- **Simplification-based FPE:** ***every*** encrypted record matches ***at most 250*** records
- **GFPE:** when *maximizing* efficiency
  - 99% encrypted records match $> \mathbf{1000}$ records
  - 94% encrypted records match $> \mathbf{10,000}$ records
  - 67% encrypted records match $> \mathbf{100,000}$ records
  - …

Concurrent Work: libFTE [LDJRS'14]

- Library for format-preserving and format transforming encryption of general formats
  - Also based on Rank-then-Encipher
    - Support less integer-FPE schemes
  - Formats represented using Regular Expressions
  - Ranking uses automatons (deterministic or non-deterministic)
- Different goal: developer-oriented
  - Defining new formats
  - Choosing "right" scheme to use
- Same security guarantee
- Comparable "best case" efficiency
  - libFTE "worst case" can be much worse

Summary

- **Goal:** FPE for general formats
- Analyze existing schemes
  - Show security vulnerabilities
  - Inefficiencies also exist
- Propose a new FPE scheme for general formats
  - Based on Rank-the-Encipher
  - Simple and efficient methodology of representing and ranking formats
  - **Flexible scheme:**
    - Can use any FPE for integral or almost integral domains
    - Easy to add new primitives: just provide $\mathrm{rank}, \mathrm{unrank}$
    - User-controlled efficiency-security tradeoff (through $maxSize$ param)


THANK YOU