Fourth Bertinoro PhD. Summer School on Security of Wireless Networks

July 6th –July 10th 2009, Forli-Cesna, Italy

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&

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Summer School Objectives

- **Exposure to current research topics that are cross-cutting wireless networking and security**
- **Provide multi-faceted view from cryptography, networking and network-security**
- **Cover one or two topics in depth that form the theme of the workshop**
- **Encourage research activities and collaborations based on the workshop**

Professor Radha Poovendran

- **Networking Framework that forms the basis of the lectures**
- **Monday-Control Channel Jamming with Node Capture (with and without back channels; with and without prior known bounds on the # of nodes to be exposed; includes collusion/insider attacks)**
- **Tuesday-Modeling and mitigating jamming(in general throughput reduction attacks) on wireless networks- a network flow and convex optimization framework**
- **Wednesday— I will not lecture on Wednesday**
- **Thursday—Understanding source anonymity in sensor networks (give impossibility result first and then proceed with practical approaches); RFID search.**
- **Friday—Network vulnerability metrics for the first part; networking coding result; and information theoretic notion of keying; key establishment based on channel reciprocity. (topics here will be chosen based on time availability)**

Professor Dawn Song

- **Applied Cryptography for Privacy in Wireless Applications**
  - **Searches over Encrypted Data; Private stream search (M)**
  - **Computation over Encrypted Data (Tu)**
- **Defending against Malicious Code in Mobile Computing**
  - **Techniques and Tools for in-depth Malware Analysis (W & Th)**

Summer School Lecture Schedules

Time	Monday	Tuesday	Wednesday	Thursday	Friday
9:30-11:00	DS	DS	DS	DS	RP
11:30-1:00	RP	RP	GS	RP	RP
15:00-16:00	DS				

Background Assessment

- **Which year are you in?**
- **Have you taken undergrad & grad classes in**
  - **Security?**
  - **Cryptography?**
  - **Program analysis?**
  - **Networking?**
  - **Statistics?**
- **Have you done research in security?**

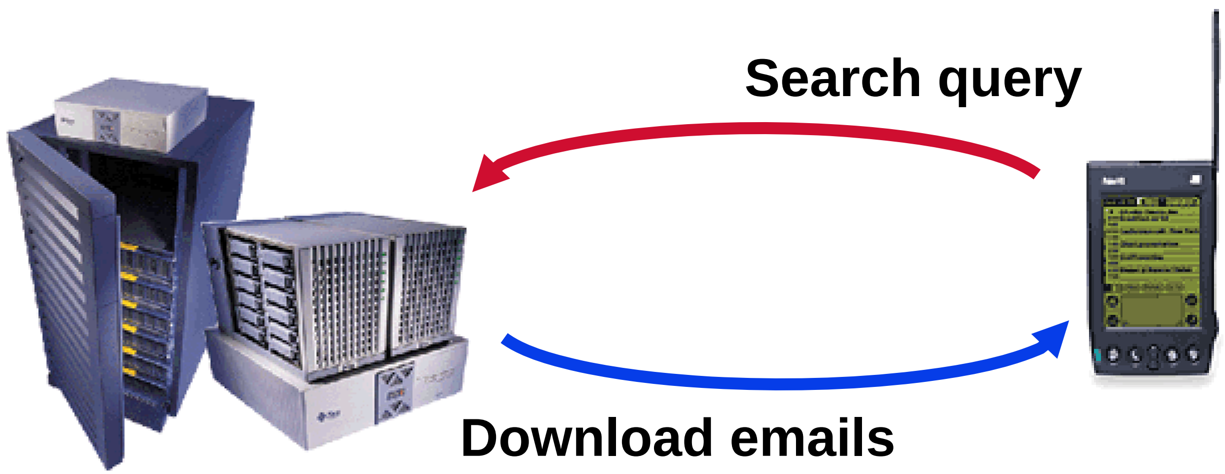
Part I: Applied Cryptography for Privacy in Wireless Applications

Overview

- **Privacy is importat in information age**
- **Many mobile devices are thin**
  - **How to have servers help mobile devices and preserve users' privacy at the same time?**
  - **How to enable private applications in community of mobile devices?**
- **Example techniques & applications**
  - **Searching on encrypted data**
    - » **Keyword search (equality test)**
    - » **Predicate encryption & multi-dimentional range query**
  - **Private stream search**
    - » **Techniques**
    - » **Application in analysis-resilient malware**
  - **Computation over encrypted data**
    - » **Private set operations**
    - » **Fully homomorphic encryption**

Motivation

- **Why searches on encrypted data?**
  - **Searching on encrypted e-mails on mail servers**
  - **Searching on encrypted files on file servers**
  - **Searching on encrypted databases**
- **Why is this hard?**
  - **Perform computations on encrypted data is often hard**
  - **Usual tradeoffs: security and functionality**



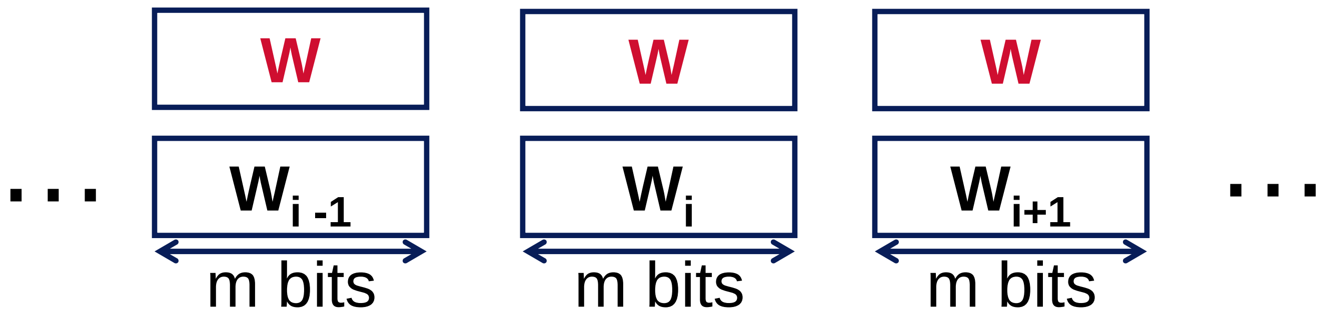
Outline

- **Searching on encrypted data**
  - **Keyword search (equality test) [SongWagnerPerrig]**
  - **Multi-dimentional range query**
- **Private stream search**
  - **Techniques**
  - **Application in analysis-resilient malware**
- **Computation over encrypted data**
  - **Private set operations**
  - **Fully homomorphic encryption**

Sequential Scan and Straw Man Example

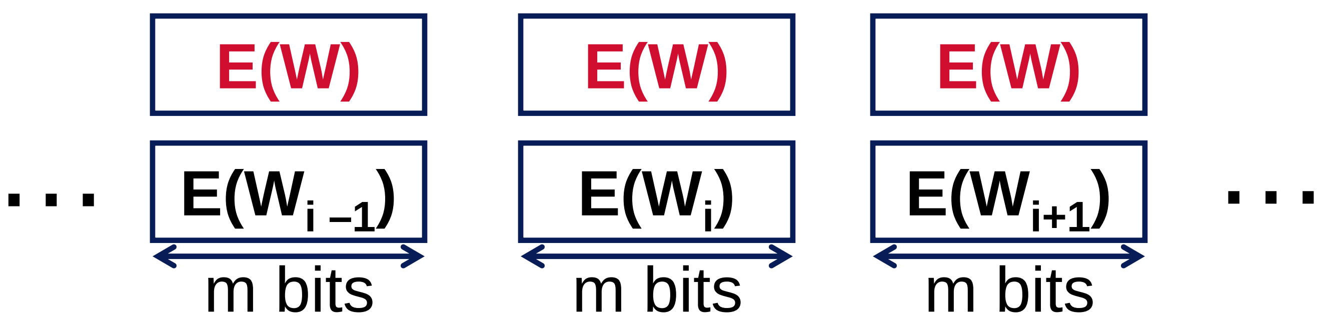
- **Search by sequential scan:**

Search for W



- **Naïve approach:**

Search for W

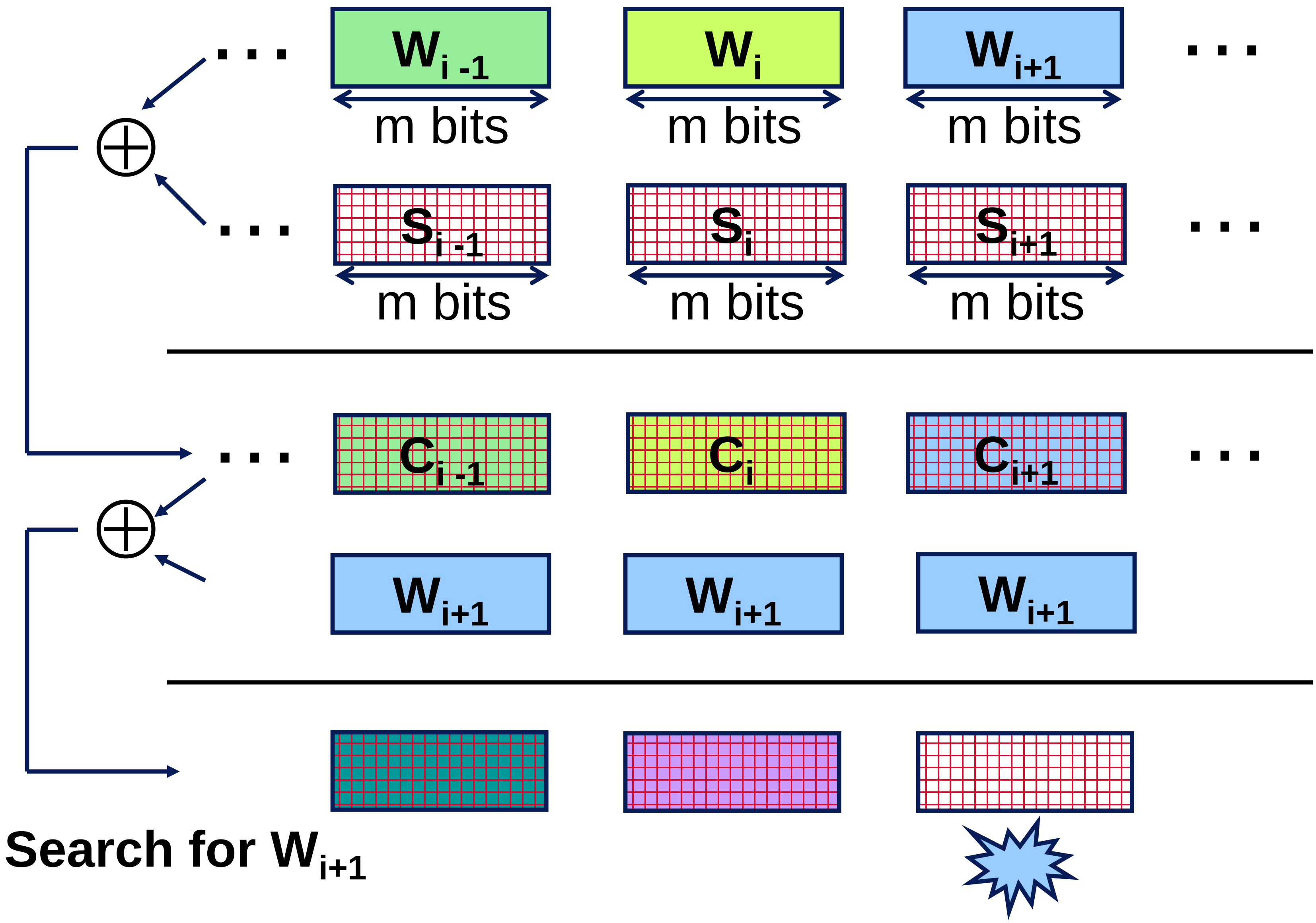


Desired Properties

- **Provable security**
  - **Provable secrecy:**
    encryption scheme is provable secure
  - **Controlled search:**
    server cannot search for arbitrary word
  - **Query isolation:**
    search for one word does not leak information about other different words
  - **Hidden queries:**
    does not reveal the search words

- **Efficiency**
  - **Low computation overhead**
  - **Low space and communication overhead**
  - **Low management overhead**

The Key Idea



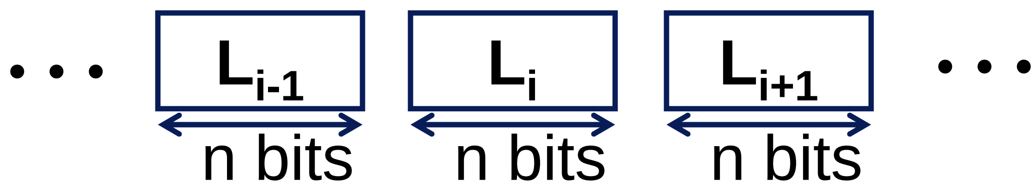
. . . W_{i-1} W_i W_{i+1} . . .
m bits
m bits
m bits
. . . S_{i-1} S_i S_{i+1} . . .
m bits
m bits
m bits
. . . C_{i-1} C_i C_{i+1} . . .
W_{i+1} W_{i+1} W_{i+1}
Search for W_{i+1}

Setup and Notations

- **Document: sequence of fixed length words**

- **Pseudorandom Generator *G* and *seed*:**

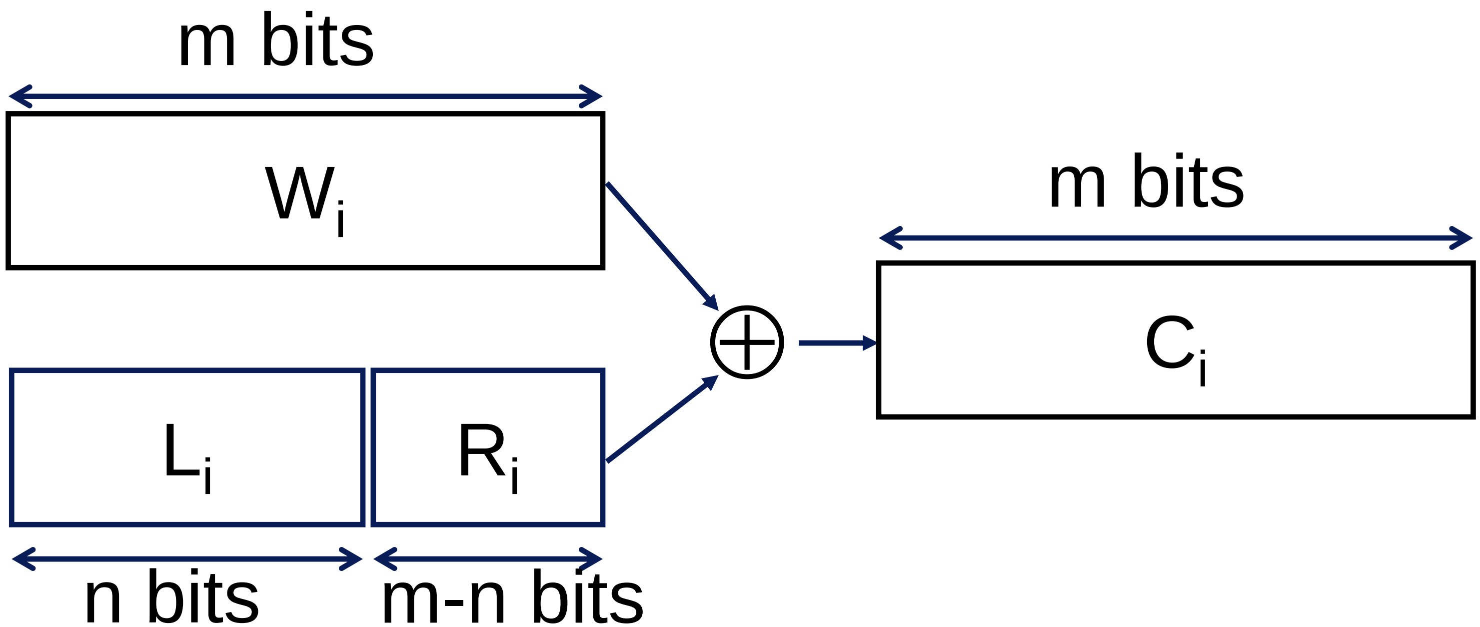
  $L \leftarrow G(\text{seed})$, $L_i \leftarrow G_i(\text{seed})$



- **Pseudorandom Function *F* and *K* :**

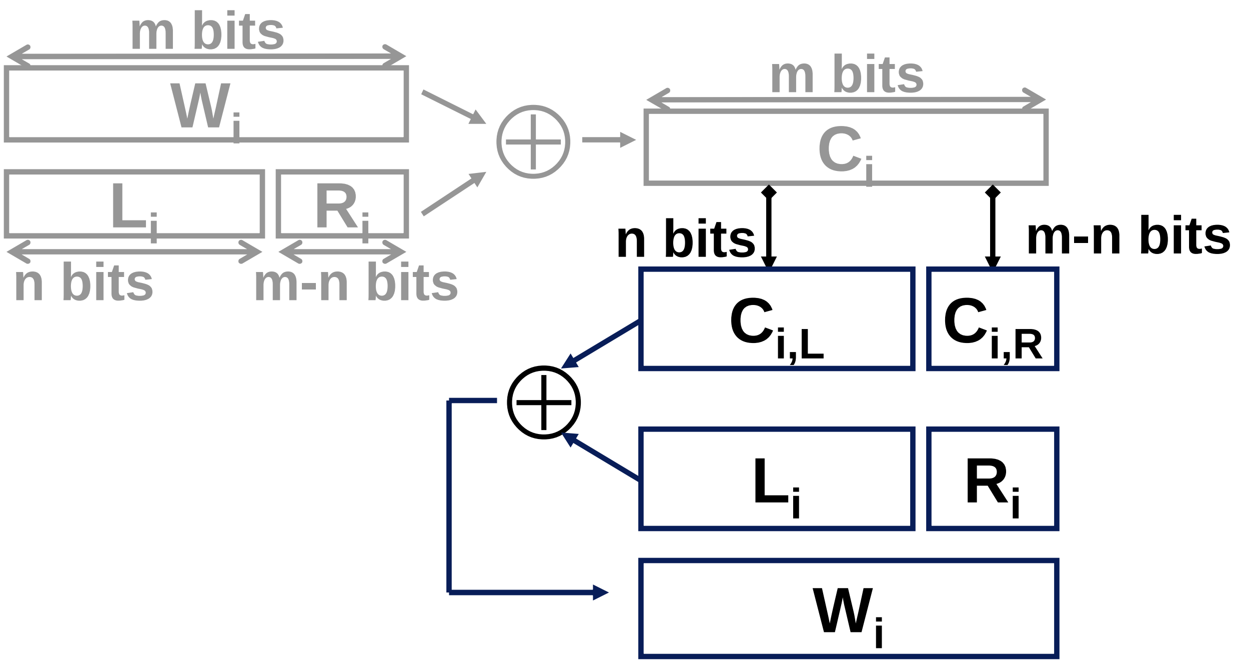
  F_K maps n bits to m-n bits

Basic Scheme (Encryption)



$L_i \leftarrow G_i\,(\text{seed}),\quad R_i \leftarrow F_K(L_i)$

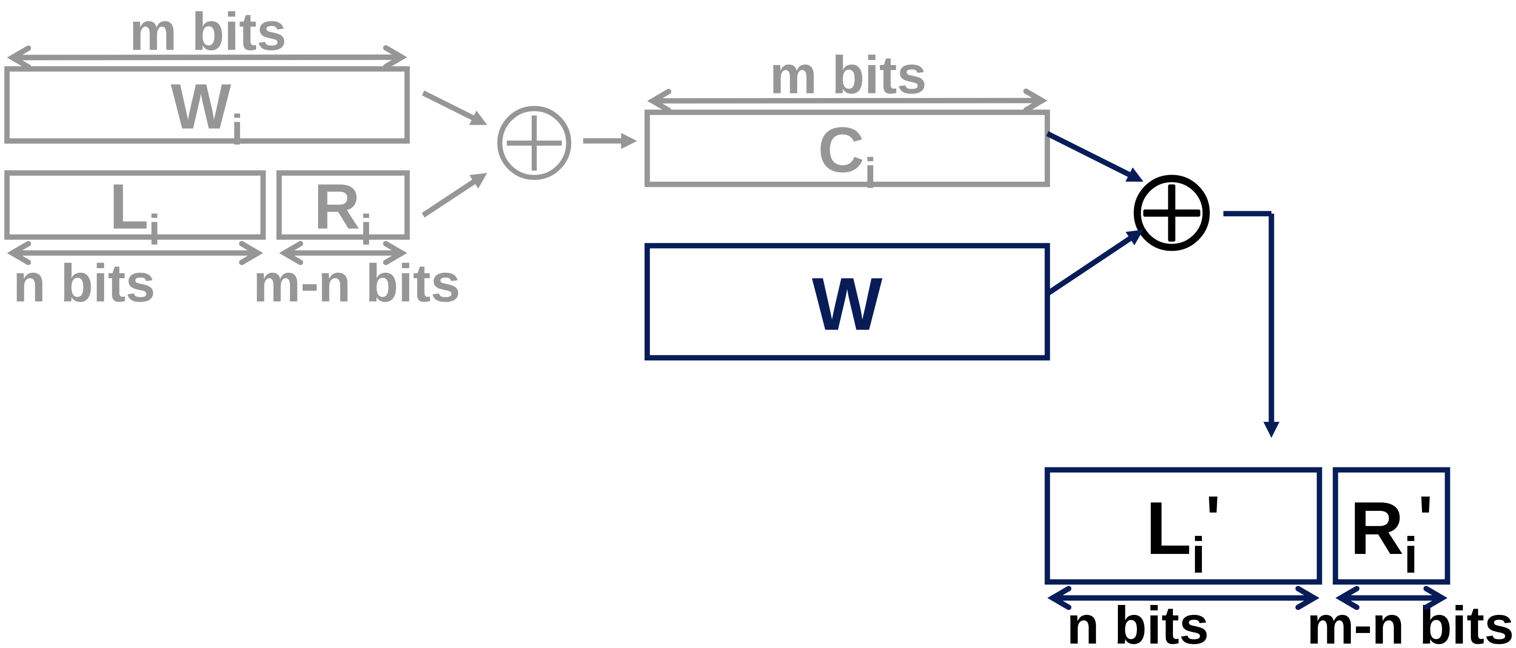
Basic Scheme (Decryption)



$L_i \leftarrow G_i\,(\text{seed}), \quad R_i \leftarrow F_K(\,L_i\,)$

Basic Scheme (Searches)

Search for word W, give server W and K



Check: $R_i' = F_K (L_i')$?

Yes $\Rightarrow$ **match,**

(**false positive rate =** $1 / 2^{m-n}$)

Controlled Searches and Query Isolation

- **Controlled searches on words**

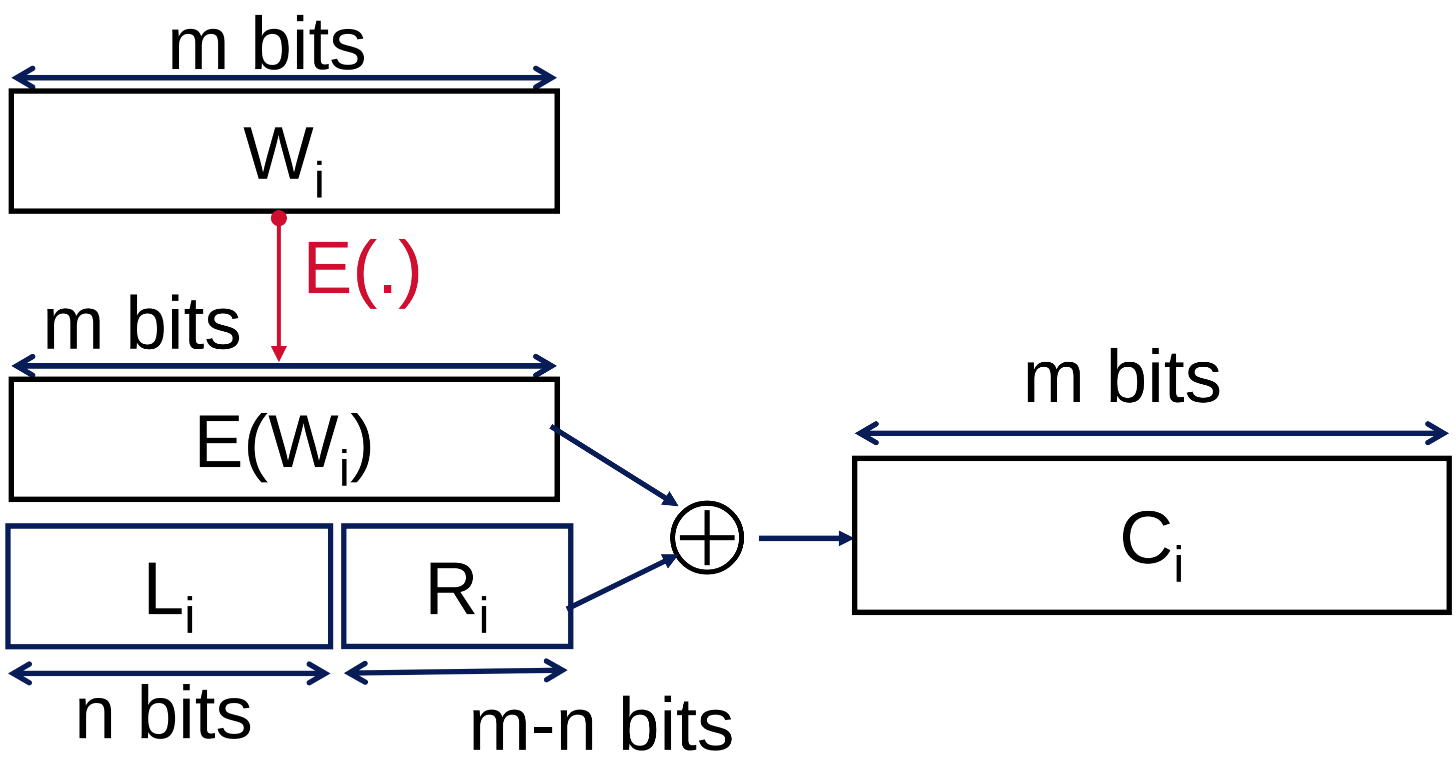
  Instead of $R_i \leftarrow F_K(L_i)$,

  $R_i \leftarrow F_{K_i}(L_i)$,

  where $K_i = F'_K(W_i)$

- **Enhancements (in paper) :**
  - **Check for a word in a single chapter/section only**
  - **Check only for "word occurs at least once" in document**
  - **Check only for "word occurs at least N times" in document**

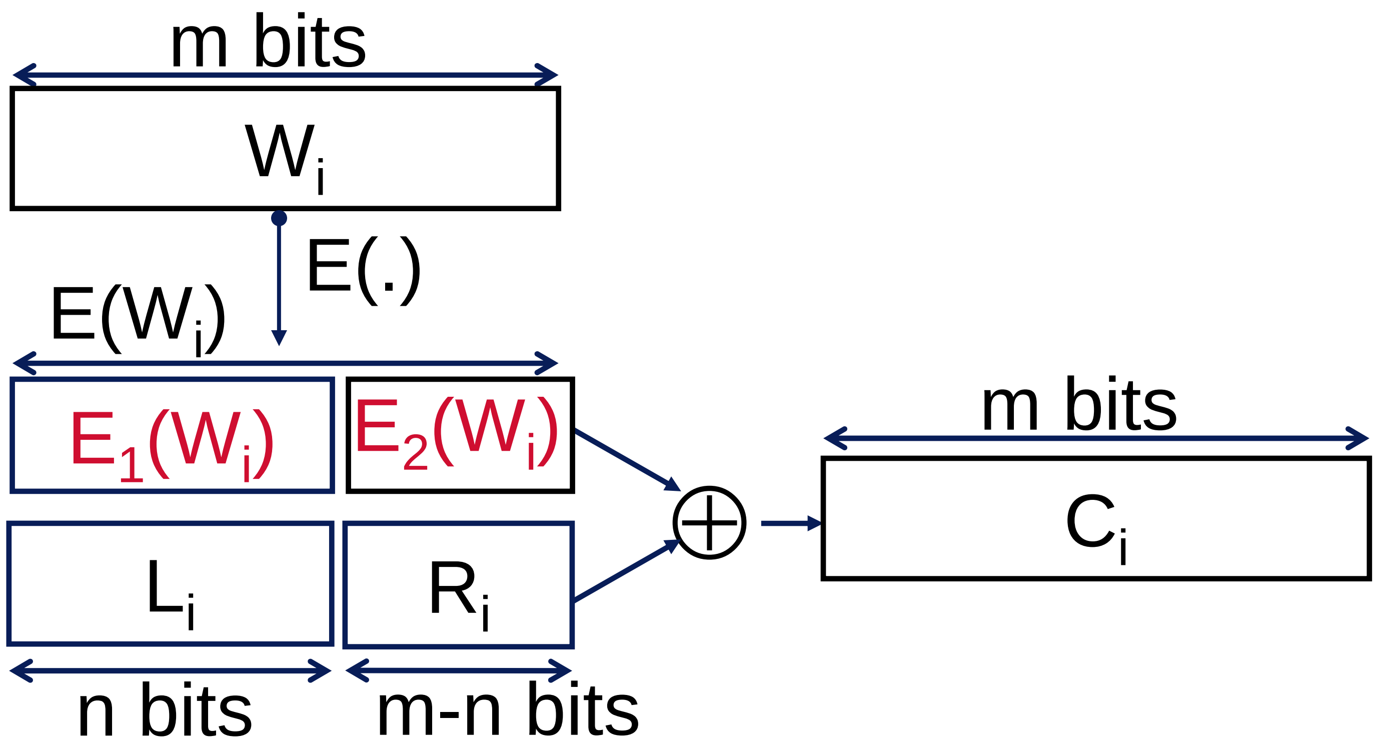
Hidden Queries



$L_i \leftarrow G_i$ (seed), $R_i \leftarrow F_{K_i}(L_i)$

where $K_i = F'_K(E(W_i))$

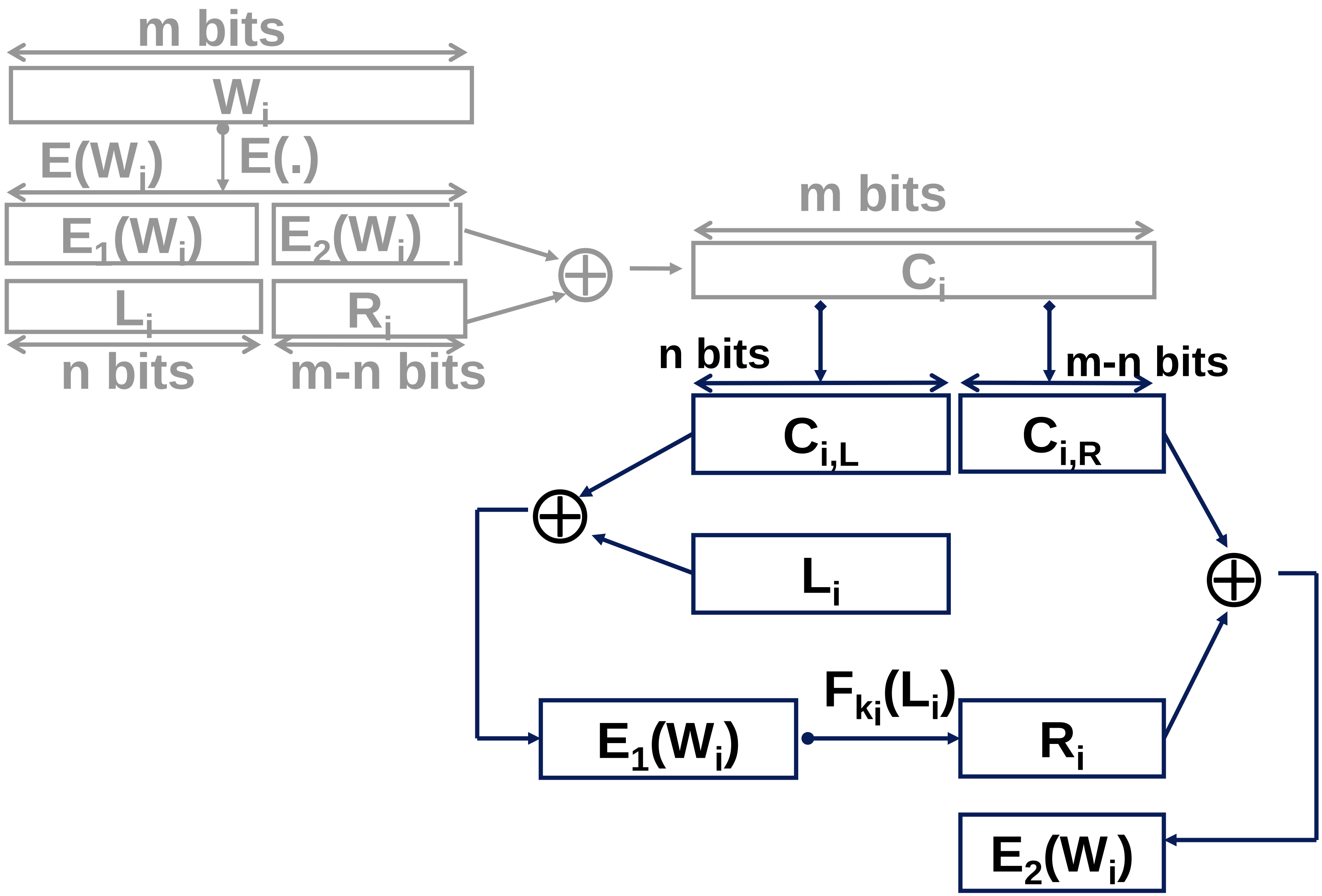
Final Scheme (Encryption)



$L_i \leftarrow G_i(\text{seed}), \quad R_i \leftarrow F_{K_i}(L_i)$

where $K_i = F'_K(E_1(W_i))$

Final Scheme (Decryption)



Advanced Search Queries

- **Building blocks for advanced search queries:**
  W_1 <u>and</u> W_2 ,
  W_1 <u>near</u> W_2 ,
  W_1 <u>immediately precedes</u> W_2

- **Supports variable length words:**
  - **Same provable security**
  - **Similar efficiency**

Summary

- **Provable security**
  - **Provable secrecy**
  - **Controlled search**
  - **Query isolation**
  - **Hidden queries**
- **Simple and efficient**
  - **O(n) stream cipher and block cipher operations per search**
  - **Almost no space and communication overhead**
  - **Easy to add documents**
  - **Convenient key management :**

    user needs only one master key
- **Embedding information in pseudorandom bit streams**

Student Forum

- **We want to hear about your research too ☺**
- **Voluntary (but encouraged ☺)**
- **Thu morning**
- **10 min each**
  - **8 min presentation**
  - **2 min Q&A and feedback**
- **Structure**
  - **What is the problem?**
  - **Why is it important (motivation)?**
  - **What is the approach (overview)?**
  - **Comparison to related work**

Public-key based Search on Encrypted Data

- **Based on parings and identity-based encryption**
  - **Boneh, Crescenzo, Ostrovsky, Persiano, [Eurocrypt 2004]**

Outline

- **Searching on encrypted data**
  - **Keyword search (equality test) [SWP]**
  - **Multi-dimentional range query and predicate encryption**
- **Private stream search**
  - **Techniques**
  - **Application in analysis-resilient malware**
- **Computation over encrypted data**
  - **Private set operations**
  - **Fully homomorphic encryption**

Motivating example

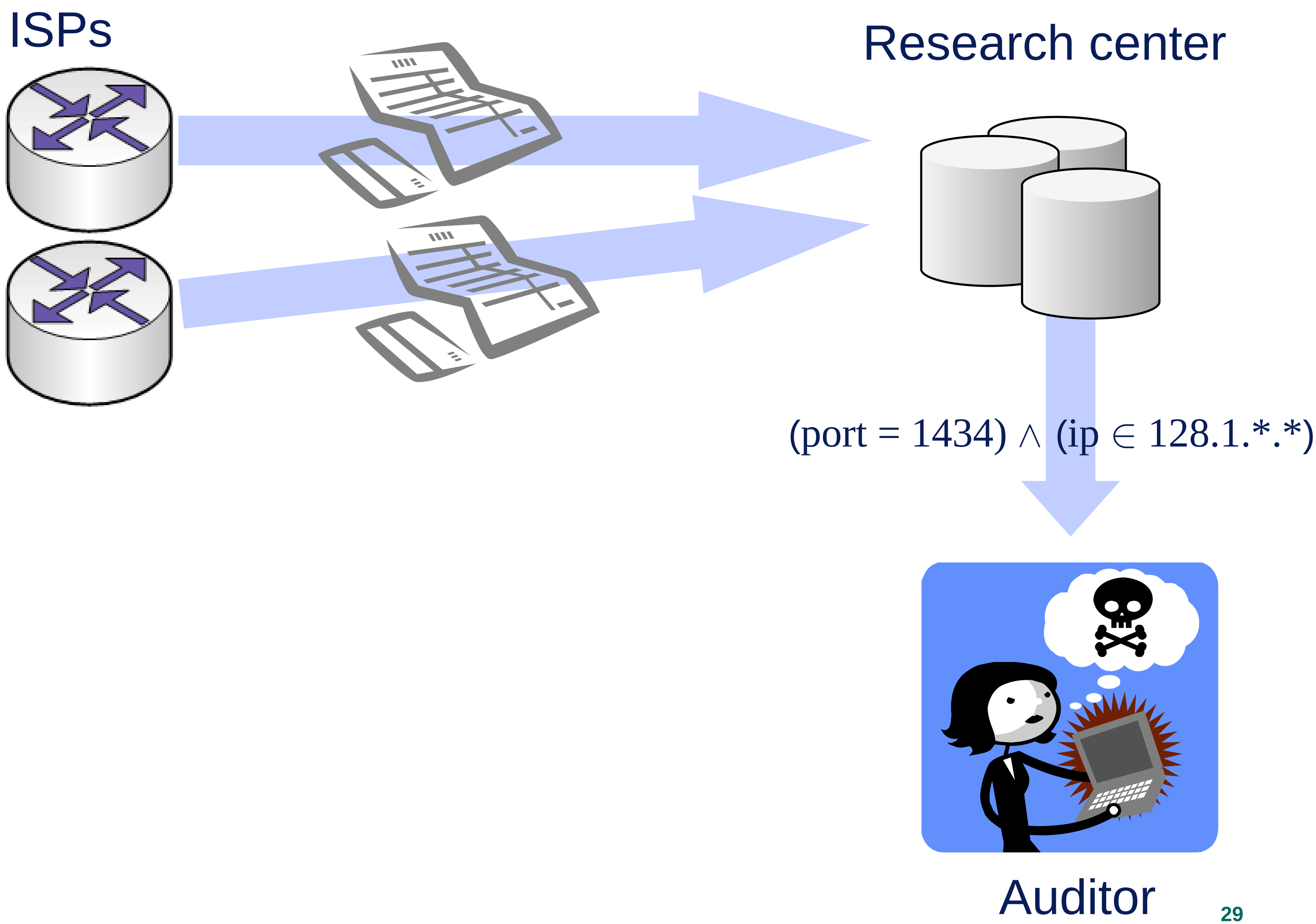
- **Network worms**
  - **Malicious program**
  - **Worm characteristic, e.g.,**

    port = 1434 for SQL slammer
- **Collecting network audit logs**
  - **Study origin, dynamics of worms**
- **Privacy concerns**

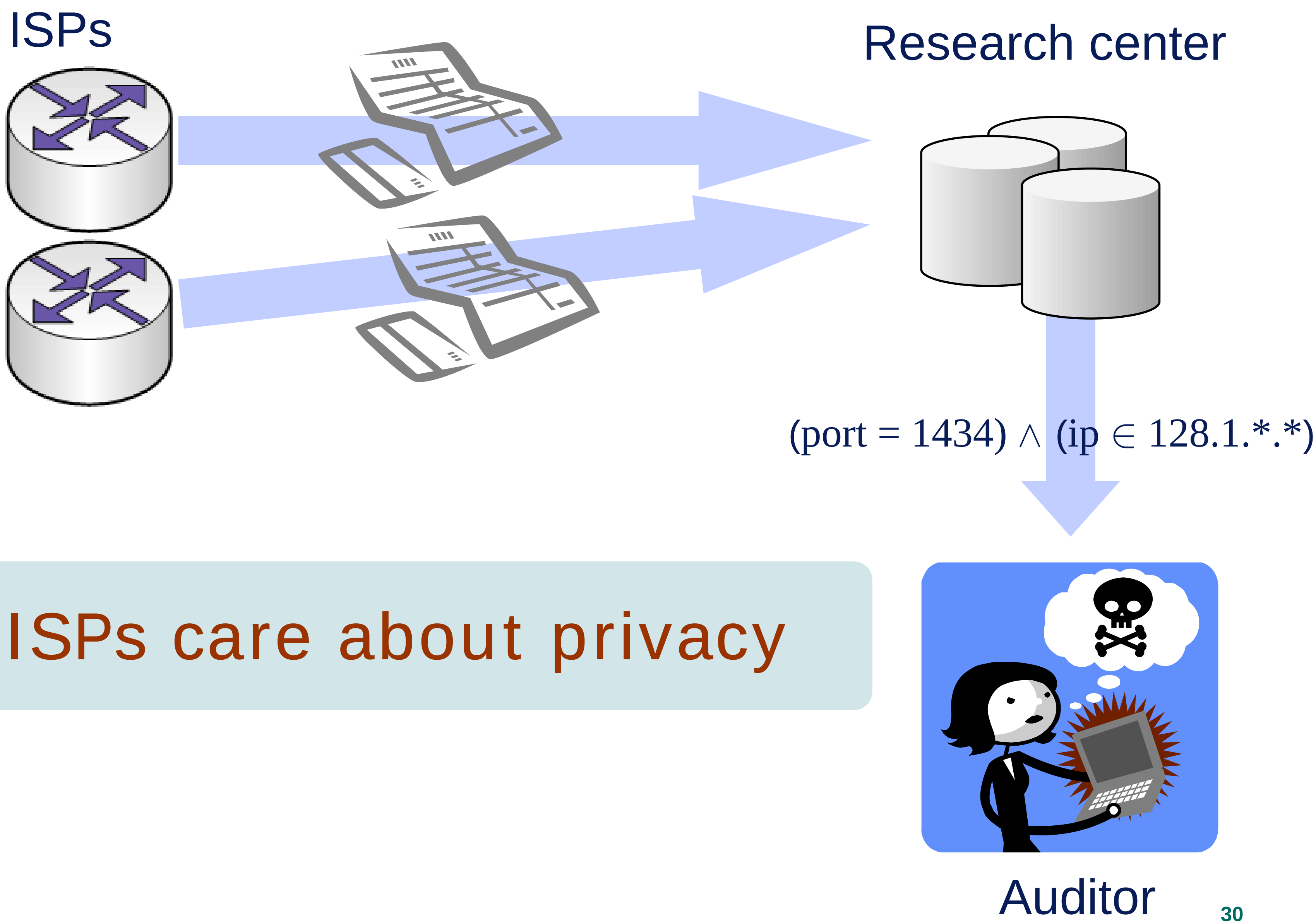
Typical network audit log

Src IP	Dest IP	Time	Src Port	Payload
1.1.1.1	1.1.1.2	Jan 1, 3:22	80	xYdcaYi
2.2.2.1	2.2.2.2	Jan 2, 4:22	90	czUEhc
3.3.3.3	3.3.3.2	Jan 3, 5:22	100	caeYD
4.4.4.1	4.4.4.2	Jan 4, 6:18	3389	caefU
...	...	...	...	...

Network Audit Logs

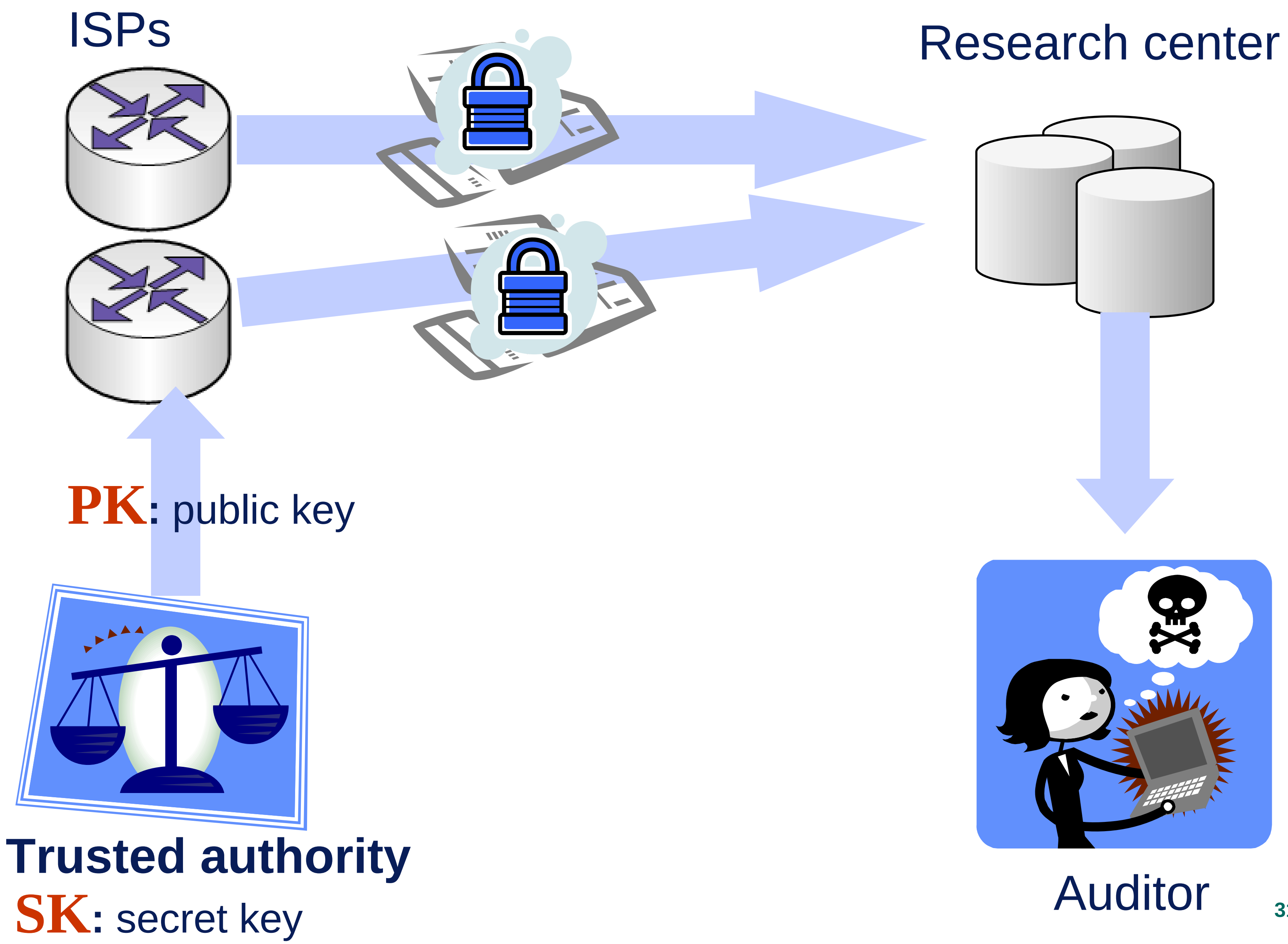


Network Audit Logs

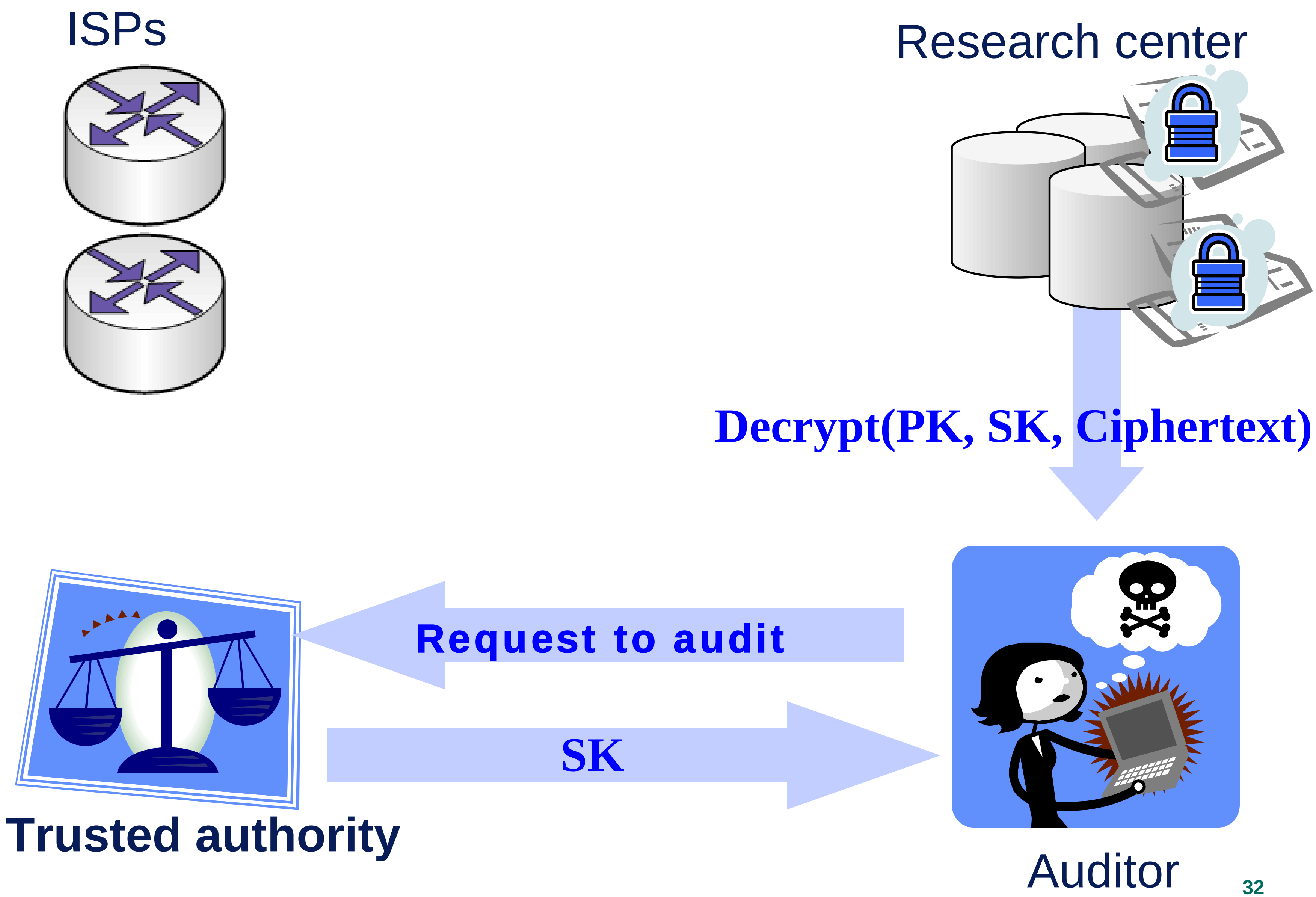


ISPs care about privacy

A naïve solution



A naïve solution



The privacy perspective

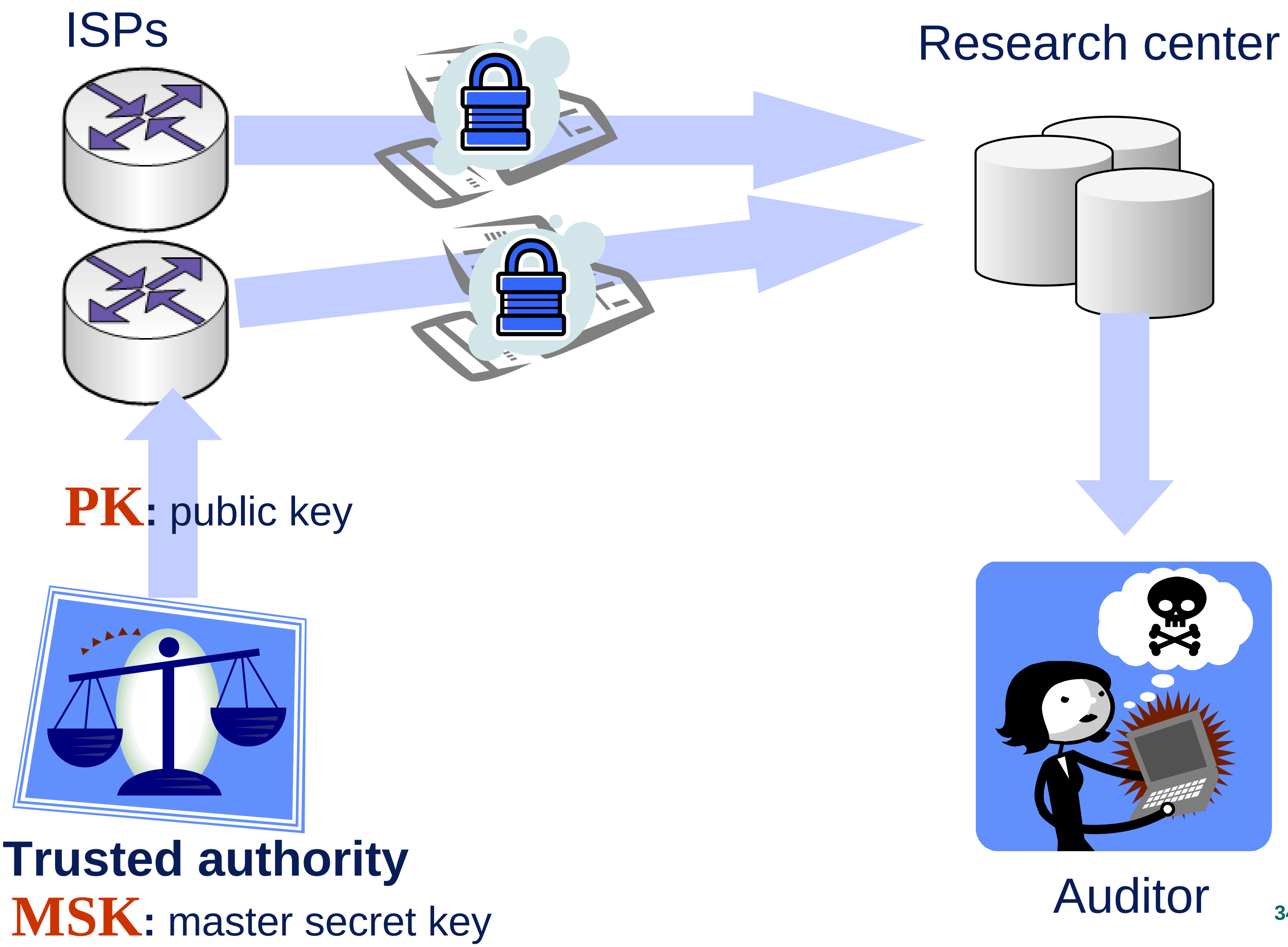
Naive solution:

- **Auditor is able to decrypt everything**

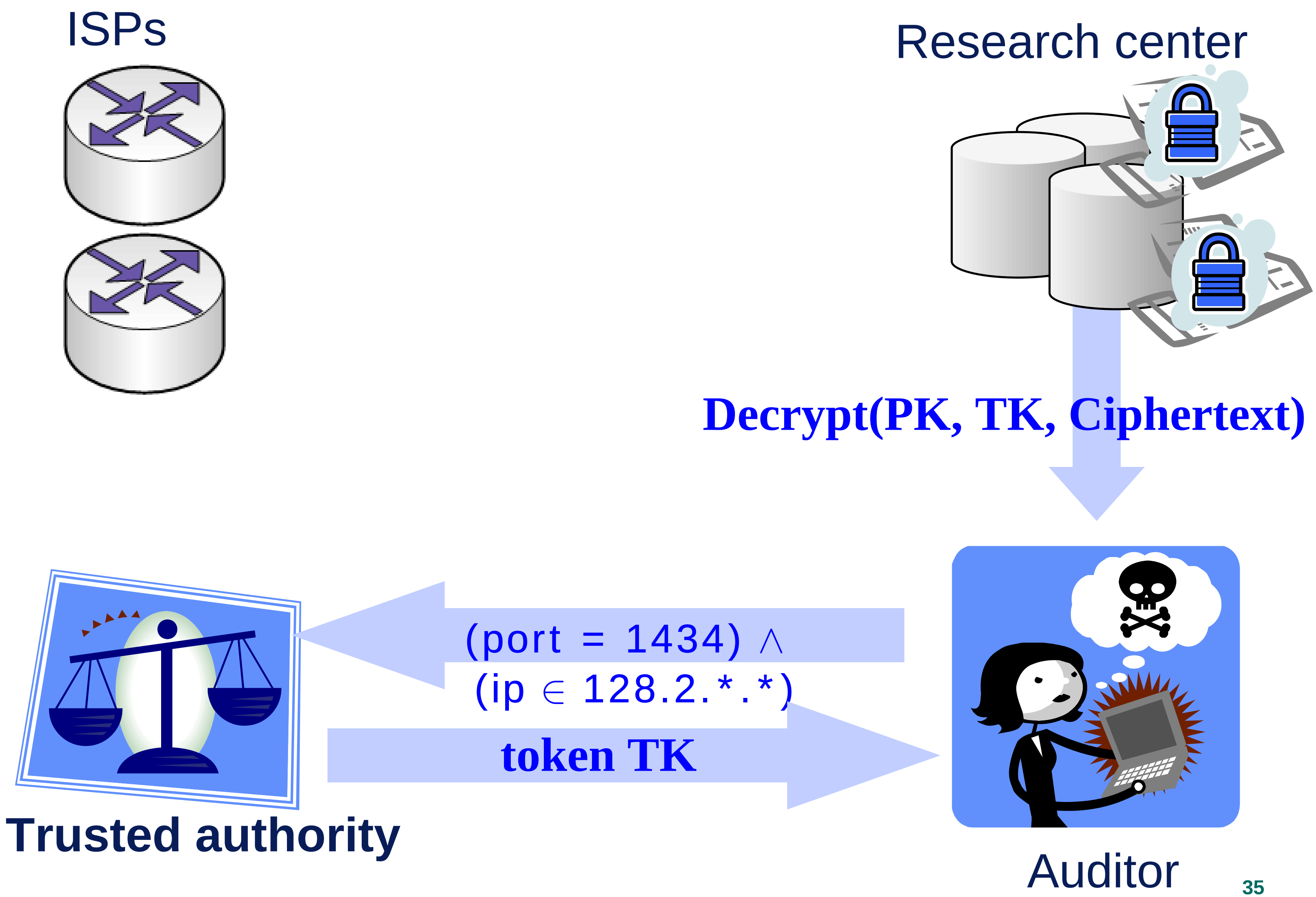
Ideal solution:

- **Auditor should be able to decrypt only suspicious flows**
- **Benign users' flows still remain secret**

Predicate Encryption



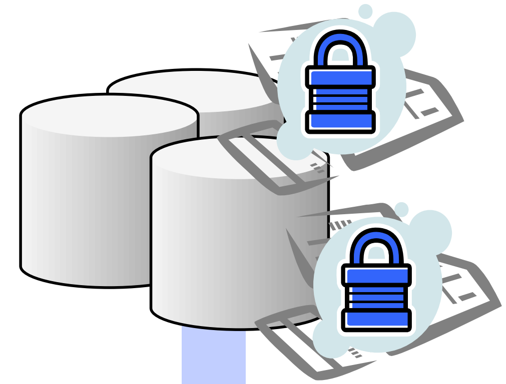
Predicate Encryption



Predicate Encryption

- **TK is a partial decryption key**
- **Allows auditor to decrypt entries satisfying attack characteristic**
- **All other entries remain secret**

Research center



Decrypt(PK, TK, Ciphertext)

Trusted authority

(port = 1434) $\wedge$ (ip $\in$ 128.2.*.*)

token TK

Auditor

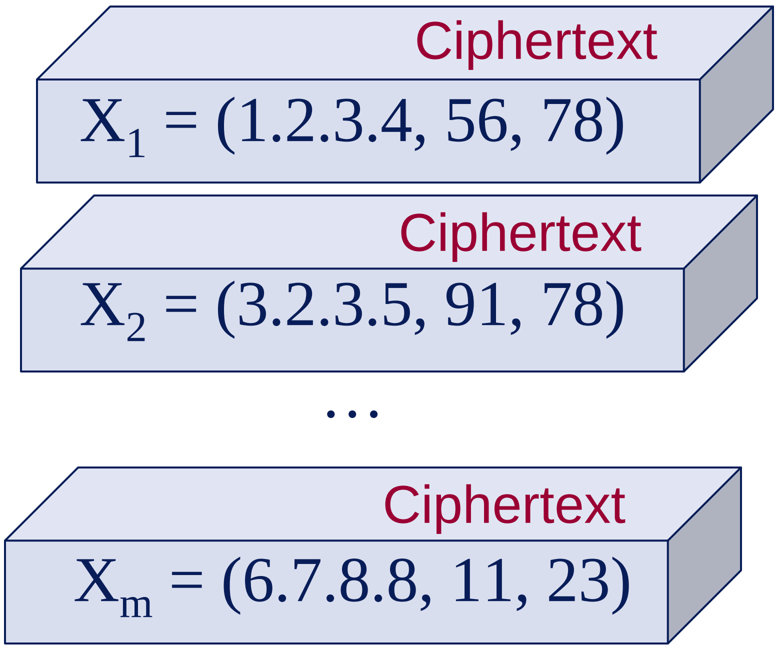
Recap: Predicate Encryption

- **Traditional Encryption**
  - **all-or-nothing decryption**

- **Predicate Encryption**
  - **A token allows one to learn partial information**
  - **Controlled release of information**

Predicate encryption: Definition

X = (IP, port, pkt_len)



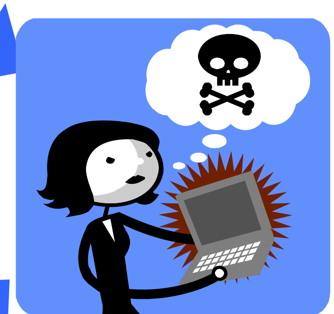
Predicate encryption: Definition

Ciphertext

X = (IP, port, pkt_len)

Token

$$f(X) = \begin{cases} 1 & X.IP \in 128.1.2.* \\ 0 & o.w. \end{cases}$$



f(X)

Support expressive predicates

Predicate encryption: Prior Work

- **Equality test:**
  - Goldreich, Ostrovsky, [JACM 1996]
  - Song, Wagner, Perrig, [S&P 2000]
  - Boneh, Crescenzo, Ostrovsky, Persiano, [Eurocrypt 2004]

$$\mathrm{f}_a(X) = \begin{cases} 1 & X = a \\ 0 & o.w. \end{cases}$$

Multi-dimensional Range Query

- **Multi-dimensional range queries:** X= (x_1, x_2, …, x_n)

$$\mathrm{f}_{a_1,a_2,b_1,b_2}(X) = \begin{cases} 1 & (x_1 \in [a_1, a_2]) \wedge (x_3 \in [b_1, b_2]) \\ 0 & o.w. \end{cases}$$

- **Core technique: conjunctive queries**

(IP ∈ 128.2.*.*) ∧ (port ∈ [1000, 2000])

(IP ∈ 128.2.*.*) ∧ (port = 1434)

$$\mathrm{f}_{a,b}(X) = \begin{cases} 1 & (x_1 = a) \wedge (x_3 = b) \\ 0 & o.w. \end{cases}$$

Match-revealing security

Ciphertext

X = (IP, port, pkt_len)

f(X)

Token

$$f(X) = \begin{cases} 1 & X.IP \in 128.1.2.* \\ 0 & o.w. \end{cases}$$

Does not care about secrecy

Learns nothing more

a.k.a. one-sided security

Multi-dimensional Range Query

- **Plaintext:** **$X = (IP, port, pkt\_len)$**
- **Queries:**

$$(IP \in 128.2.*.*) \wedge (port \in [1000, 2000])$$

$$(IP \in 128.2.*.*) \wedge (port = 1434)$$

- **Consider match-revealing security**
  - **If X satisfies predicate, then auditor actually would like to decrypt entire entry**
  - **Otherwise, preserve secrecy of encrypted point X**

Multi-dimensional range query

Scheme	PK. size	Enc. Time per entry	Ciphertext Size per entry	TK. Size	Dec. Time per entry
AIBE 05	**O(1)**	**O(1)**	**O(1)**	**$O(T^D)$**	**$O(T^D)$**
[BW06]	**O(D·T)**	**O(D·T)**	**O(D·T)**	**O(D)**	**O(D)**
Our Scheme	O(D·logT)	O(D·logT)	O(D·logT)	O(D·logT)	$O((\log T)^D)$

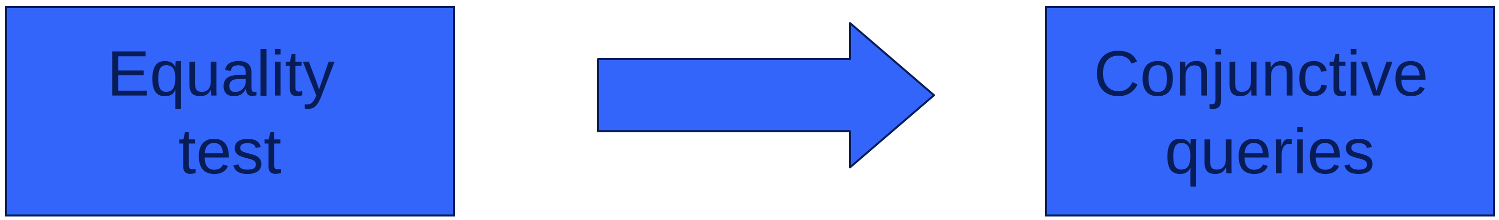
[BW06]: Boneh and Waters, TCC 2007: "Conjunctive, Subset, and Range Queries on Encrypted Data", match concealing

Our scheme: S&P 2007

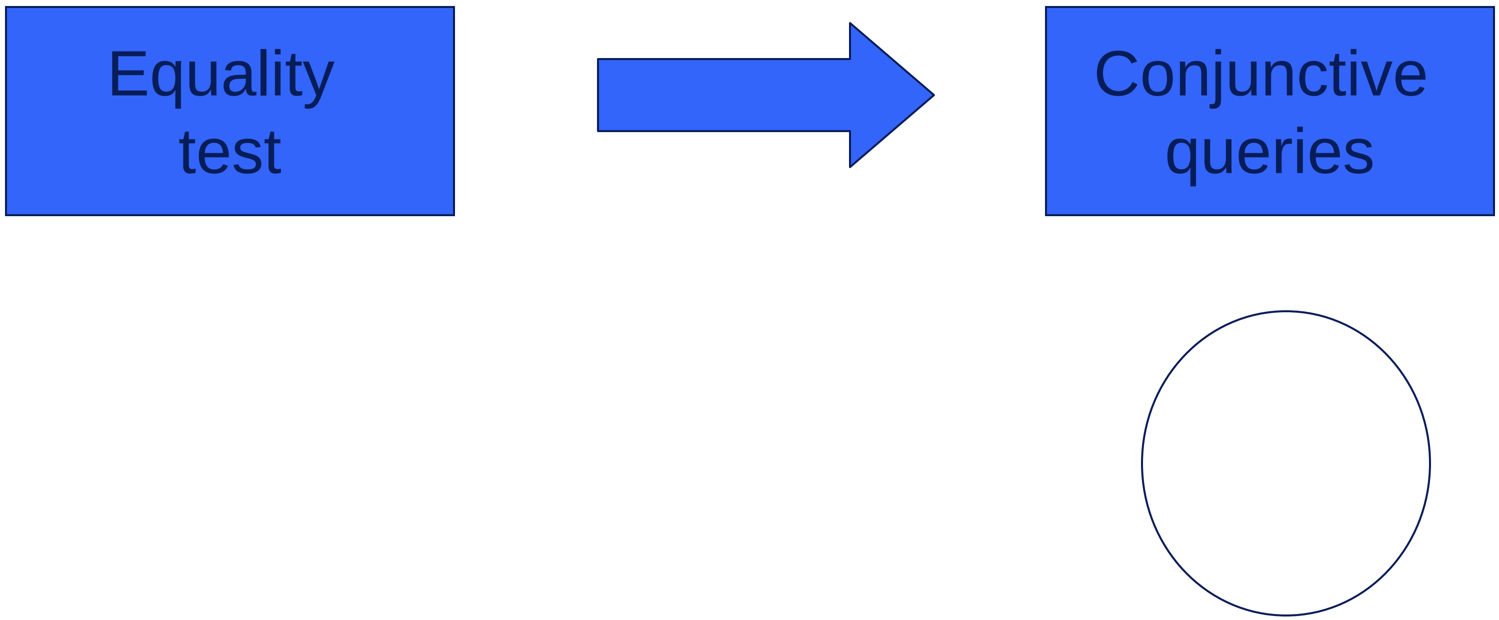
T: # different values for each field

D: # fields

Scheme for Conjunctive Equality Test



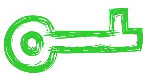
Naïve solution

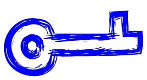


$(IP = 1.2.3.4) \wedge (port = 1434)$

Naïve solution

Equality test → Conjunctive queries

 (IP = 1.2.3.4)

 (port = 1434)

(IP = 1.2.3.4) ∧ (port = 1434)

Security requirement

- **Given a token for**

$$(IP = 1.2.3.4) \wedge (port = 1434)$$

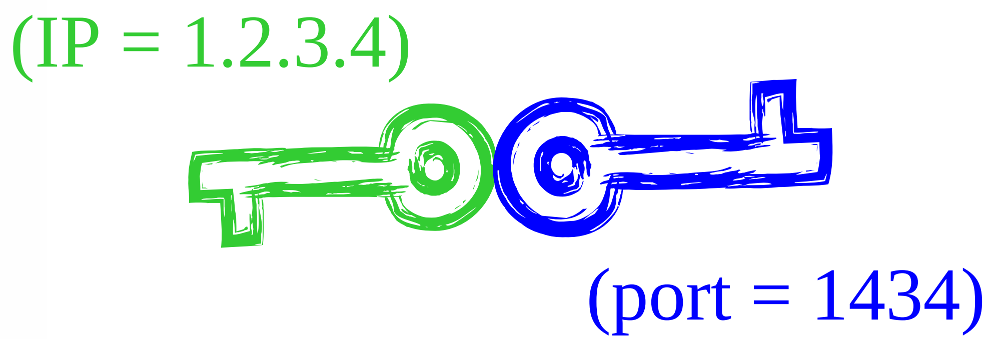
- **One should not be able to learn individual clauses:**

$$(IP = 1.2.3.4)$$

$$(port = 1434)$$

Idea for a fix

- **Go to store, buy some industrial glue:**



Our construction [SBCSP]

- **D: number of fields in an entry**
- **5 relevant performance measures: all O(D)**
  - **Public key size**
  - **Ciphertext size (per entry)**
  - **Encryption time (per entry)**
  - **Token size**
  - **Decryption time (per entry)**
- **Security: reduced to hard problems in certain mathematical groups (pairings)**

Summary

- **Searching on encrypted data is an important primitive**
- **Techniques for keyword search (equality test)**
- **Generalization---predicate encryption**
- **Techniques for multi-dimensional range query**
- **Open problems**
  - **more efficient match-concealing multi-dimentional range query**
  - **Other predicate encryption classes**