Simple, Efficient and Strongly KI-Secure Hierarchical Key Assignment Schemes

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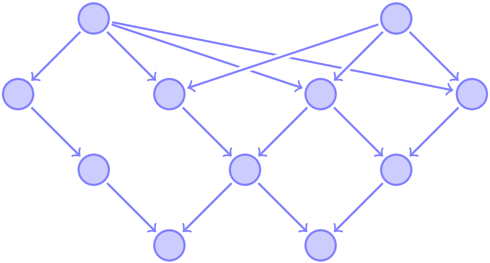
CT-RSA, February 27, 2013

Information Security Group

Hierarchical Key Assignment Scheme (KAS)



Setting and terminology

- topology: poset $(V, \leq)$ (reflexive, antisymmetric, transitive)
- representation by transitive reduction, called access graph
- nodes $u \in V$ called (security) class
  - individual private information S_u
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- functionality: given S_u, compute k_v for any $v \leq u$

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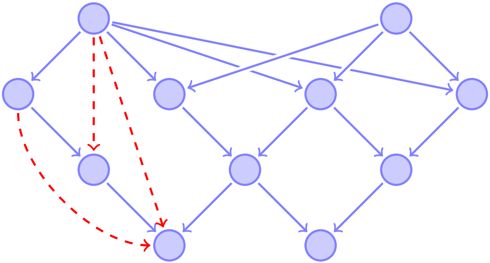

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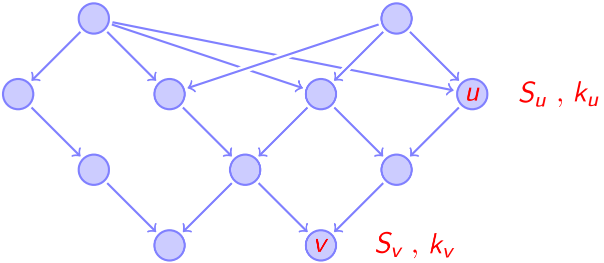

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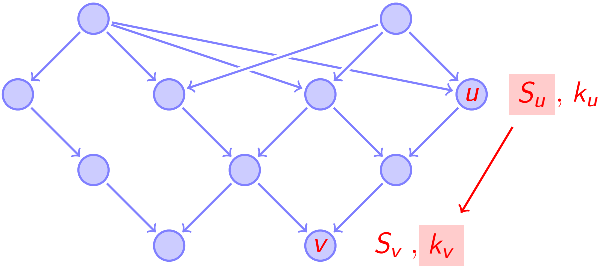

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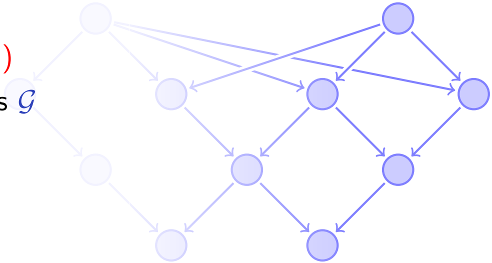

Syntax of KAS (simplified)

- class of access graphs $\mathcal{G}$

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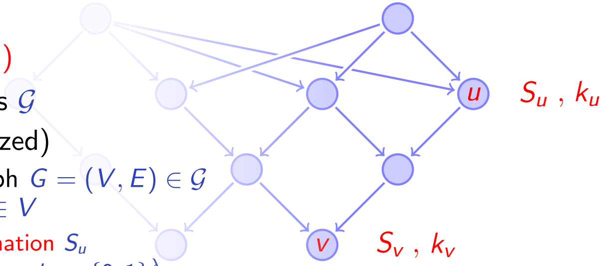

Syntax of KAS (simplified)

- class of access graphs $\mathcal{G}$
- $\mathsf{Gen}(1^\lambda, G)$ (randomized)
  - input: access graph $G = (V, E) \in \mathcal{G}$
  - output: for all $u \in V$
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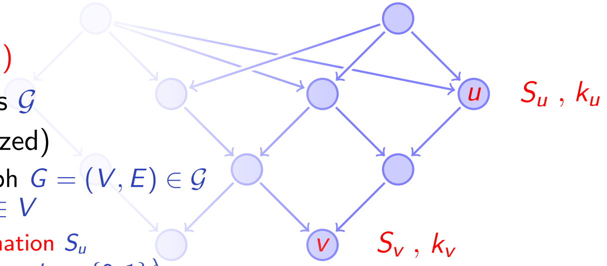

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- $\mathsf{Derive}(S_u, v)$ (deterministic)
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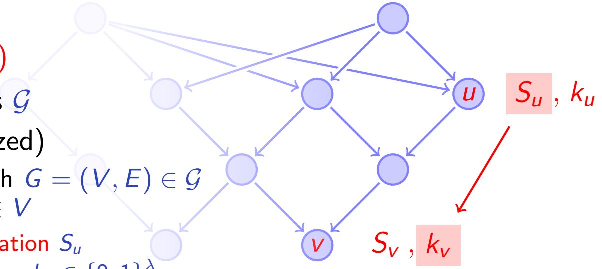

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Correctness requirement

we require $\mathrm{Derive}(S_u, v) = k_v$ for all u and $v \leq u$.

Applications of Key Assignment Schemes

Applications of KAS

- access control
  - example: patient records in hospital
    - limited access for nurses
    - access rights of doctors in dependence of seniority
  - example: sensors in building management
    - employees can access local light and temperature sensors
    - managers can access all sensors installed on given floor
    - facility manager can access smoke sensors and intrusion detection on all floors
    - firefighters can access smoke sensors on all floors
- database security
- content distribution and digital broadcasting
- military/government communication

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Variants of KAS

- time-dependent constraints
- dynamic addition or removal of classes
- revocation handling

History of Key Assignment Schemes

Important achievements in key assignment (heavily biased excerpt)

- [AklTay83]
  - idea to implement access control through key assignment
  - RSA-based construction (w/o proof)
- [AtaBlaFazFri05]
  - first formal security model (KR+KI)
  - PRF-based construction
- [CraMarWil06]
  - overview paper, classifying 27 schemes into 5 design categories
- [D'ArSanFerMas10]
  - formal analysis of Akl-Taylor scheme
  - RSA vs. strong RSA?
- [CraDauMar10]
  - idea of chain partition method (w/o proof)

Contributions of this work

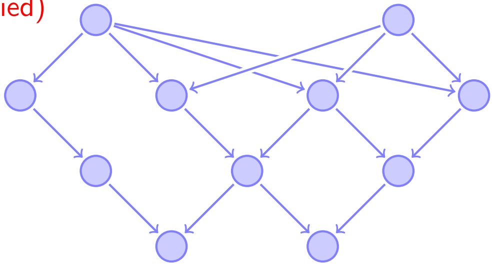
Our contributions

- new security model
  - we claim: security definitions published so far are unrealistic
  - we introduce new formal security model, fixing all problems
  - we give counterexample to separate new from old models
- security analysis of chain-based construction
  - we prove generic security of the chain partition method
- new constructions of KAS
  - we construct highly efficient KAS, based on PRFs, PRGs, ...
  - we establish formal security via reductionist proofs
- assessment of practicality
  - we propose parameters for concrete instantiations of our KAS
    - based on HMAC, AES, BBS, others
  - we compare our schemes with other published KAS
  - we discuss possible efficiency tradeoffs

Security notions of KAS: previous models

Previous security definitions (unified)

$\mathsf{Exp}^{\mathsf{KI\text{-}ST},b}_{\mathcal{A},G}(1^\lambda)$



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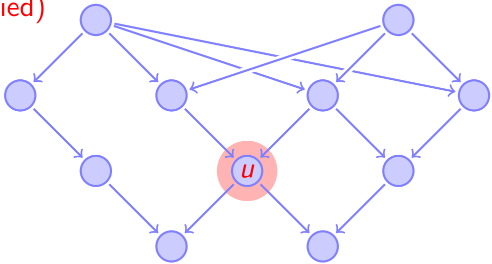

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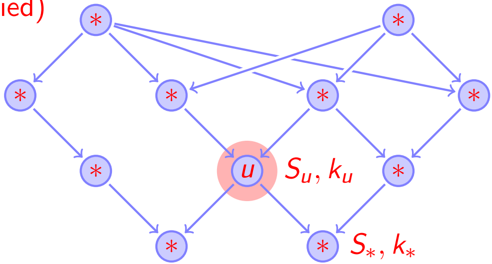

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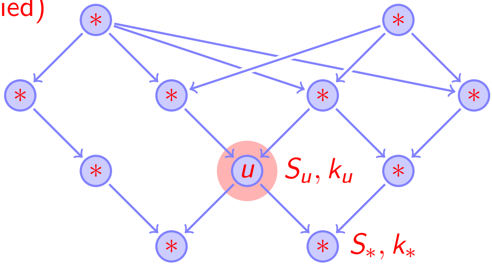

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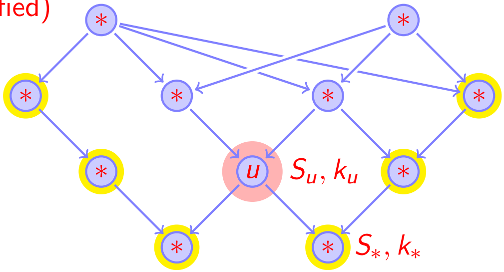

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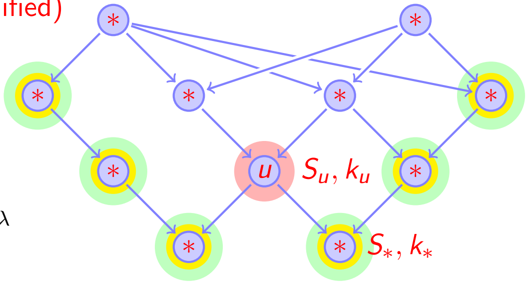

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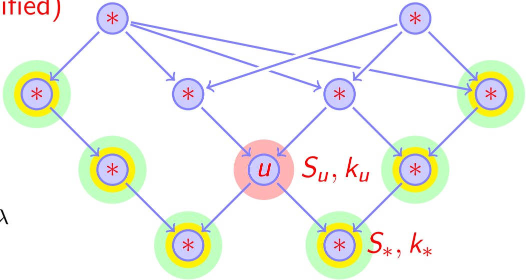

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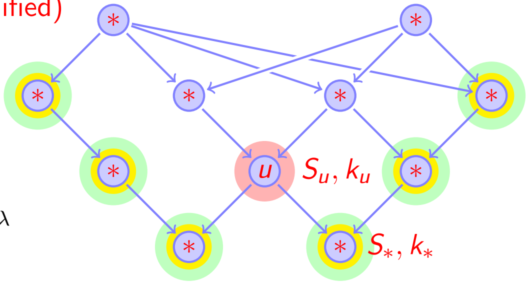

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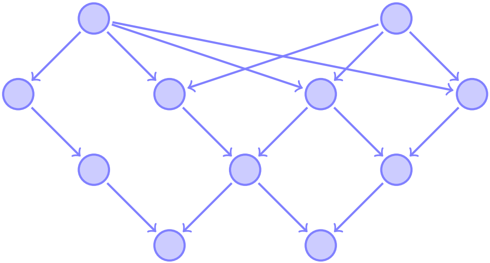
Variants

- key indistinguishability vs. key recoverability
- static vs. dynamic adversaries

Security notions of KAS: revised model

Updated security model



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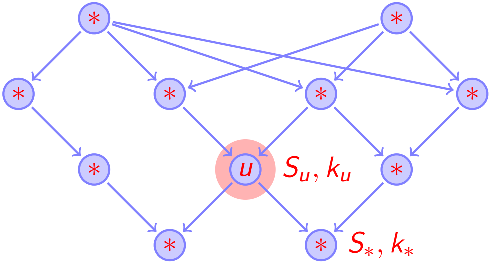

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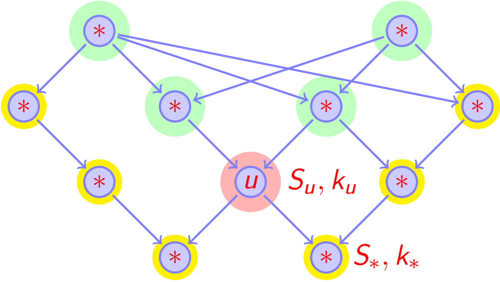

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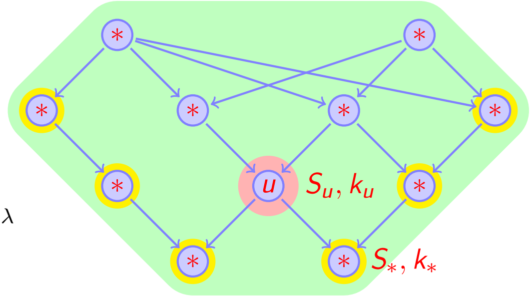

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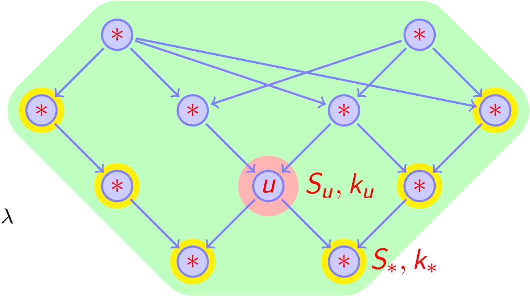

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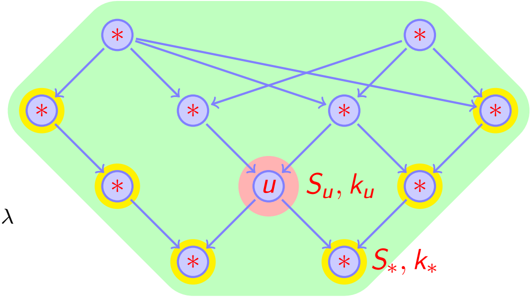

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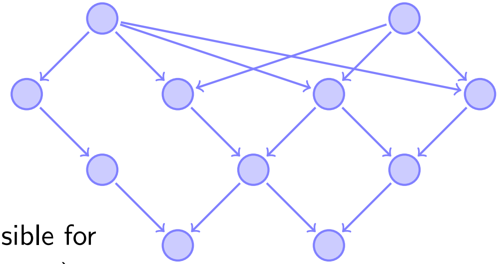
Comparing the models

- Claim: all previous security models useless in practice
- we give counterexample to formally separate the models

Constructing key assignment: from chains to posets



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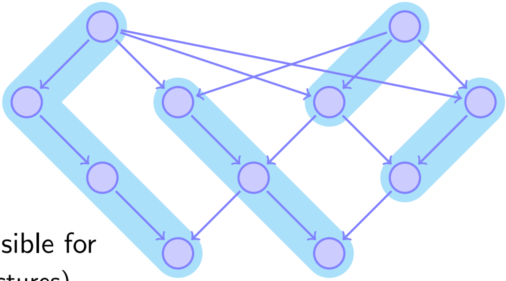

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Chain partition method ([CraDauMar10], w/o proof)

- cover poset with disjoint key assignment chains

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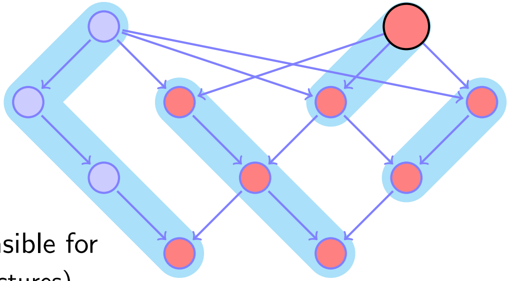

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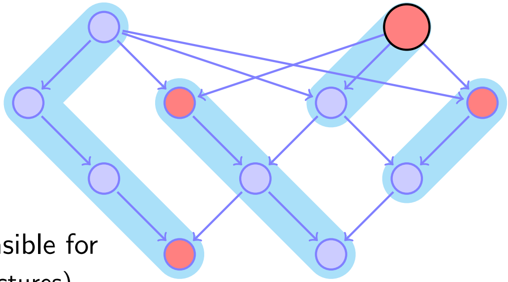

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Chain partition method ([CraDauMar10], w/o proof)

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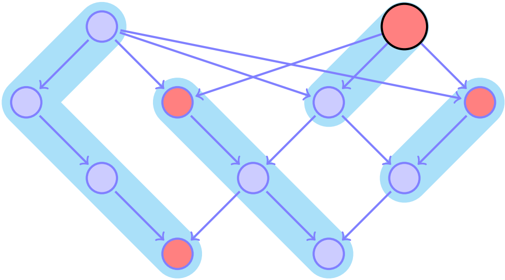
- for each class u, intersection of chains with $\{v : v \leq u\}$ is suffix
- each class stores (at most) one entry per chain

Constructing key assignment: from chains to posets



Dilworth's theorem (1950)

> *In finite posets, the minimum number of chains in any partition into chains equals the maximum cardinality of any antichain. We call this number the width of the poset.*

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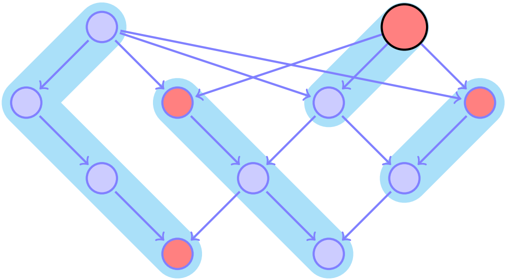

Dilworth's theorem (1950)

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Theorem

The chain partition method provides S-KI-ST *security, assuming all KAS chains are* S-KI-ST *secure.*

PRF-based KAS construction for chains

Remaining challenge: KAS for chains

- [AtaBlaFazFri05]
  - PRF-based, possibly insecure
- [CraDauMar10]
  - factoring-based construction (w/o proof)
- [FrePat11]
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Construction based on pseudorandom functions

- for totally ordered access graphs
- $\mathrm{PRF}_k : D \to R$
  - $K = R = \{0,1\}^\lambda$ and 'k', 'S' $\in D$
  - instantiations: HMAC, BBS+GGM

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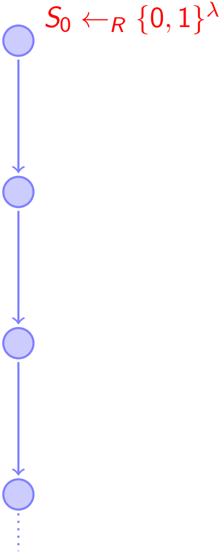

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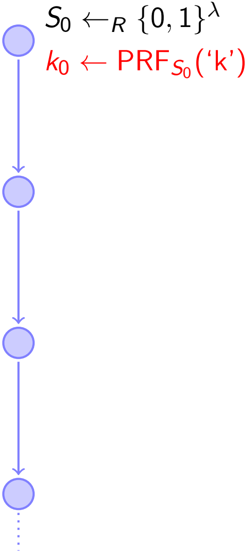
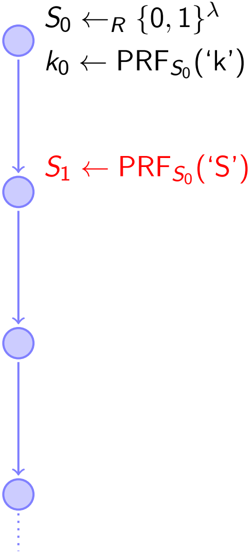
Construction based on pseudorandom functions

- for totally ordered access graphs
- $\mathrm{PRF}_k : D \to R$
  - $K = R = \{0,1\}^\lambda$ and ‘k’, ‘S’ $\in D$
  - instantiations: HMAC, BBS+GGM



PRF-based KAS construction for chains



Remaining challenge: KAS for chains

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$S_0 \leftarrow_R \{0,1\}^\lambda$

$k_0 \leftarrow \mathrm{PRF}_{S_0}(\text{'k'})$

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Theorem

Our PRF-based scheme offers S-KI-ST security, assuming security of PRF.

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- forward-secure stateful PRGs [BelYee03]
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- $\mathrm{Next}(St_i)$ (deterministic)
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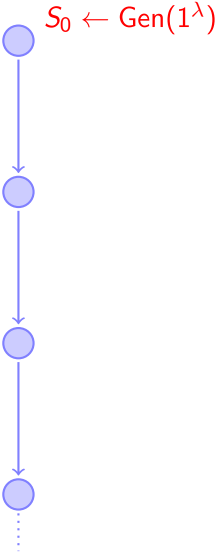

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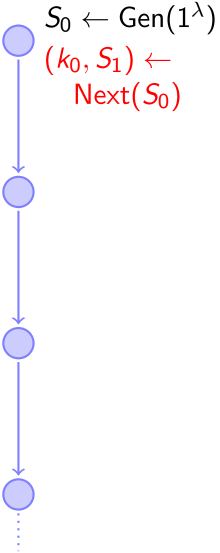

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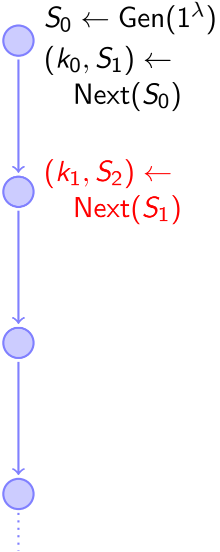

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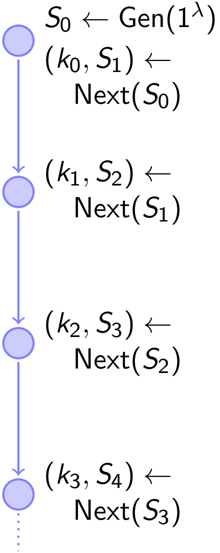

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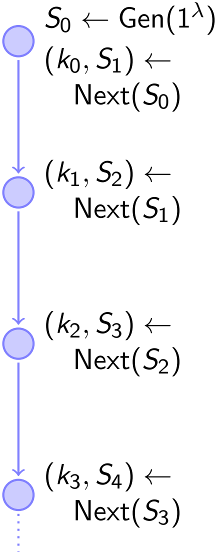

Conclusion

Our contributions

- new security model
  - we introduced new security definition, fixing problems of previous ones
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Future work

- are established schemes secure in our stronger model?
- 'tree partition' vs. chain partition
- investigate reduction of [D'ArSanFerMas10]

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Randomized Partial Checking Revisited

Shahram Khazaei*
Douglas Wikström**

*Sharif University, Teheran, Iran (work done at KTH)
**KTH Royal Institute of Technology, Stockholm, Sweden

February 27, 2013

Voting systems vs mix-nets

1. Servers/trustees run **distributed key generation** protocol to generate a public key *pk* for which the secret key is verifiably secret shared.

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3. Servers/trustees execute a **mix-net** to simultaneously permute and decrypt the ciphertexts.

Mix-net [Chaum]

$\boxed{\text{Mix-Net}}$

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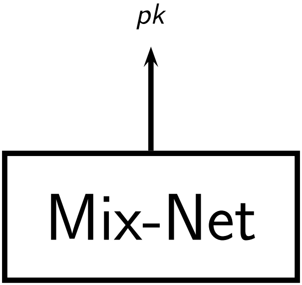

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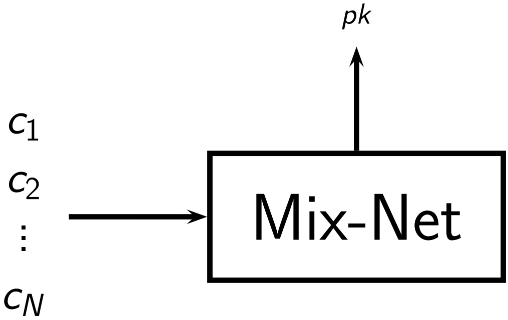

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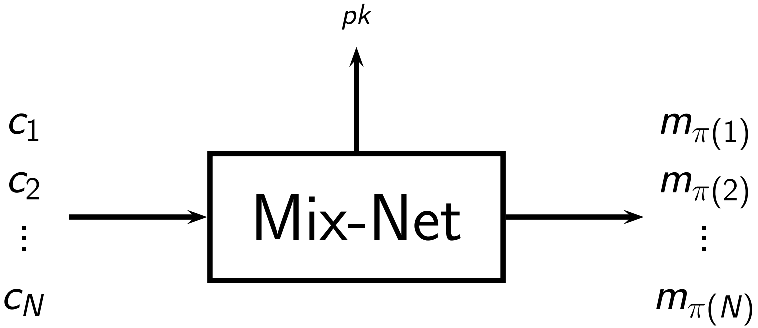

Simultanously decrypt and randomly permute ciphertexts.

Re-encryption Mix-Nets

Homomorphic cryptosystem

$$\mathsf{E}_{pk}(m_0) \times \mathsf{E}_{pk}(m_1) = \mathsf{E}_{pk}(m_0 m_1)$$

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This property can be used to **re-encrypt** ciphertexts

$$\mathsf{E}_{pk}(m_0, r_0) \times \mathsf{E}_{pk}(1, r_1) = \mathsf{E}_{pk}(m_0, r_0 + r_1)$$

Re-encryption mix-net

Mix-servers $M_1, \ldots, M_k$.

Execution of mix-net:

1. Run distributed key generation protocol to generate joint El Gamal public key pk.
2. Simultaneously re-encrypt and permute all ciphertexts.
3. Run distributed decryption protocol on the re-encrypted and permuted ciphertexts.

Re-encryption mix-net

$$\boxed{M_1} \qquad \boxed{M_2} \qquad \cdots \qquad \boxed{M_k}$$

Re-encryption mix-net

L_0 = list of input ciphertexts

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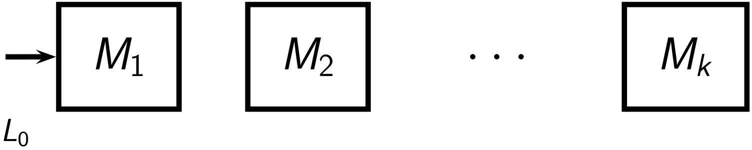

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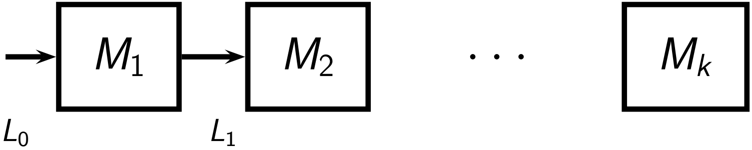

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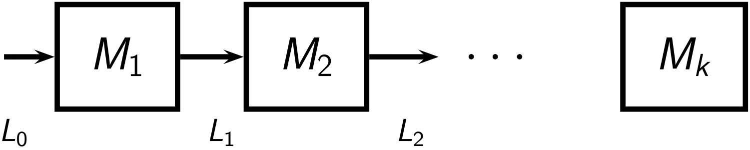

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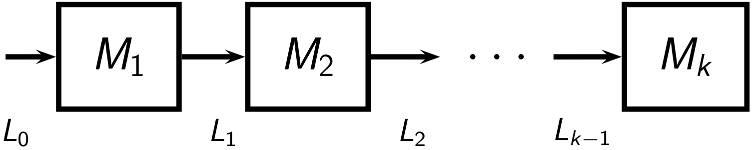

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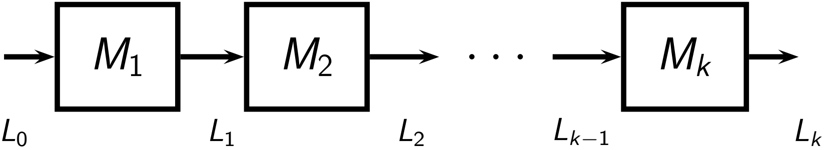

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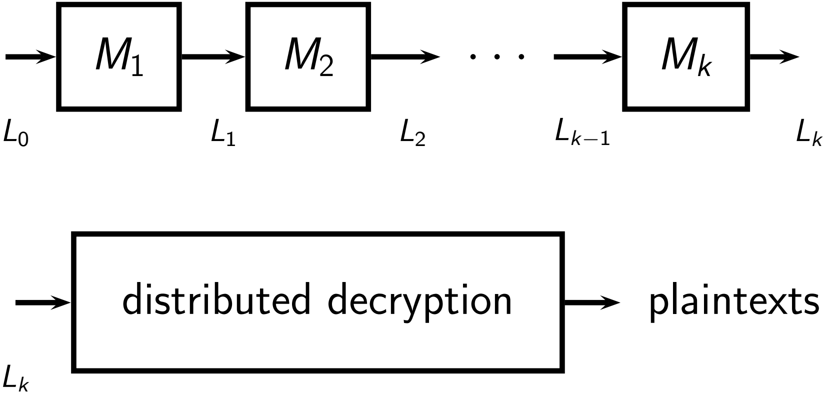

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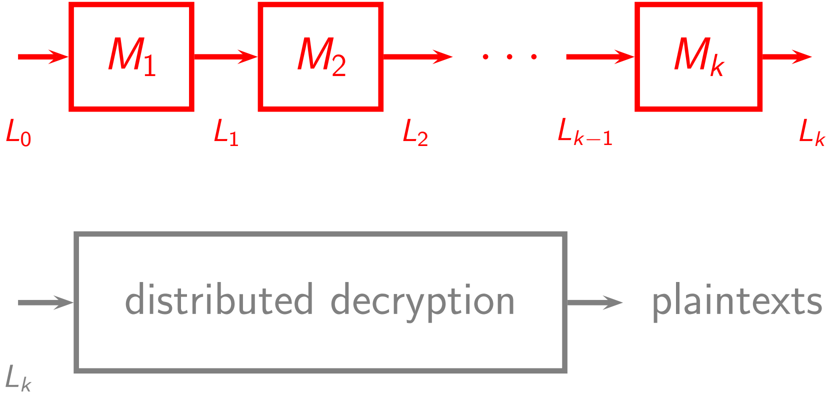

Re-encryption mix-net

$$L_{j-1} = (c_{j-1,1}, \ldots, c_{j-1,N})$$

$$L_{j-1} \longrightarrow \boxed{M_j} \longrightarrow L_j$$

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$c_{j-1,i}$ (input ciphertext)

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$$\mathrm{E}_{pk}(1, r_{j,i}) \times c_{j-1,i} \quad \text{(re-encrypt)}$$

Re-encryption mix-net

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$$L_{j-1} \longrightarrow \boxed{M_j} \longrightarrow L_j$$

$$c_{j,i} = \mathsf{E}_{pk}(1, r_{j,\pi_j(i)}) \times c_{j-1,\pi_j(i)}$$ (re-encrypt and permute)

$$L_j = (c_{j,1}, \ldots, c_{j,N})$$

Re-encryption mix-net

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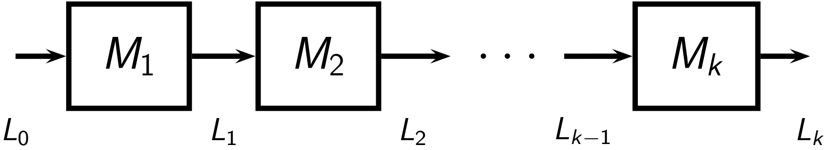
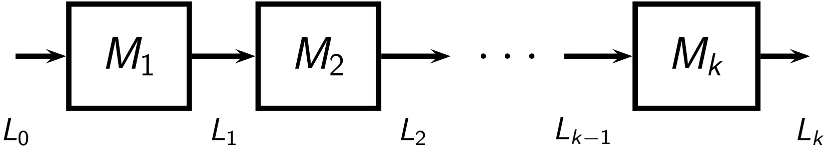


What if a mix-server is malicious?

Re-encryption mix-net

L_0 = list of input ciphertexts



Each mix-server proves that it behaves!

Randomized Partial Checking

Randomized partial checking: basic idea

Proposed by Jakobsson, Juels and Rivest USENIX 2002.

Each mix-server is challenged to **reveal a little** about what it did. **Privacy** should still be **preserved jointly** by the mix-servers.

Motivation

- Beautiful idea with potential to solve the problem for **any cryptosystem**.
- Used in numerous papers about **verifiable** electronic voting systems.
- Implemented in **Civitas** by Clarkson, ... at Cornell.
- Similar idea used in **Scantegrity** developed by Chaum, Rivest, ... at MIT, Maryland, Ottowa, Waterloo, George Washington. **Used** in real municipal elections in Takoma Park.
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I had a GOOD gut feeling about this!

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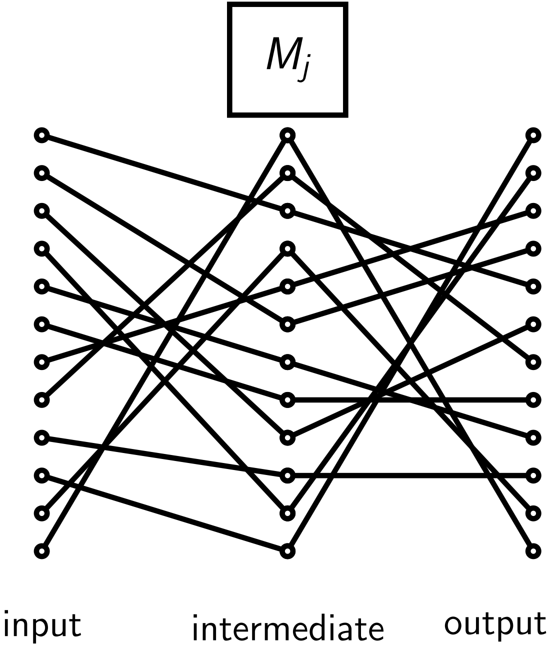
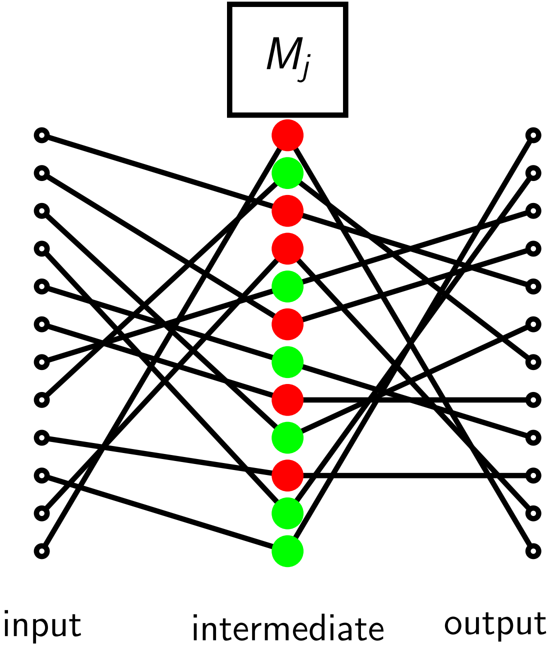


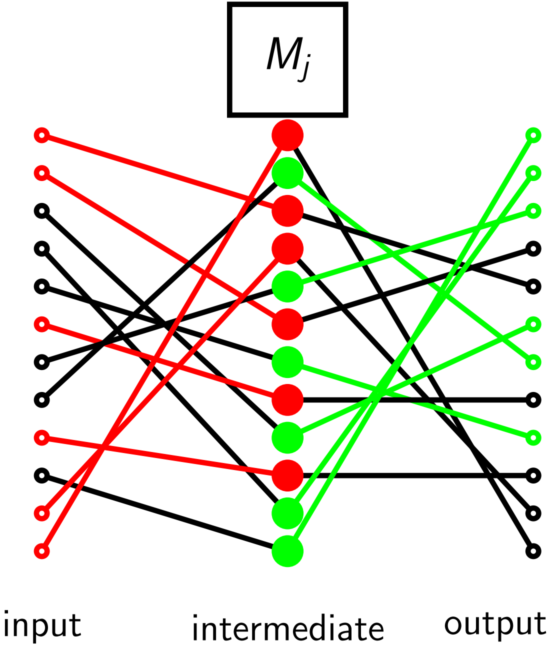
Randomized partial checking

1. Partition



Randomized partial checking

1. Partition
2. Open



More details

Before challenge, M_j also commits to:

- Origin index of each intermediate ciphertext.
- Destination index of each intermediate ciphertext.

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Open chosen commitments along with randomness.

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Attacks works as if this was not in place.

Attacks

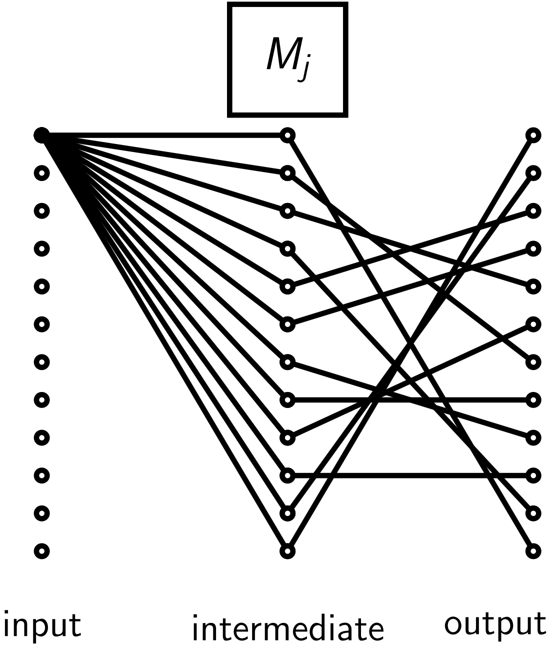
Attack on soundness

It is never verified that the revealed indices are distinct.

Thus, nothing prevents M_j to replace all origin indices by one.

This allows **replacing all ciphertexts without detection.**

Attack on soundness



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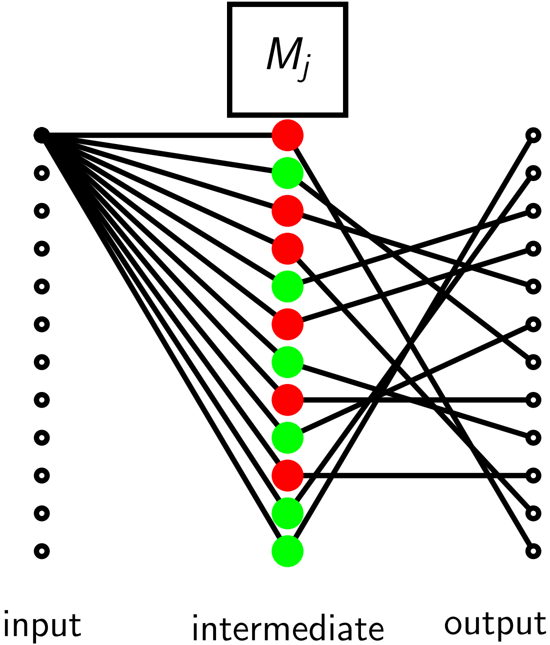

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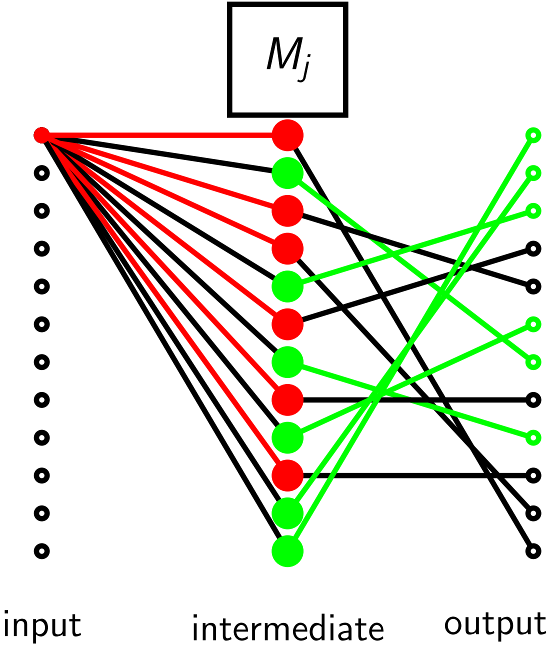

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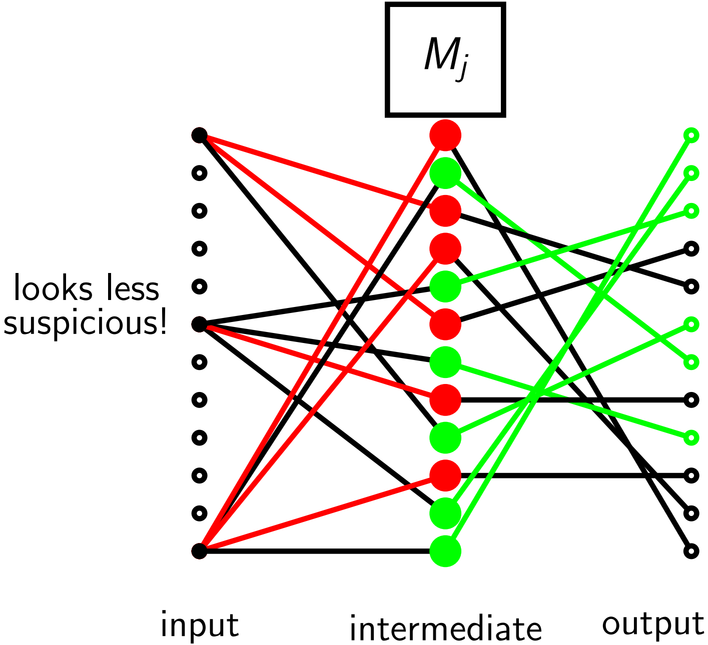
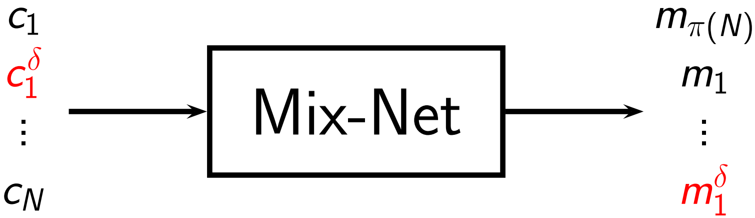


Recall Pfitzmann's attack



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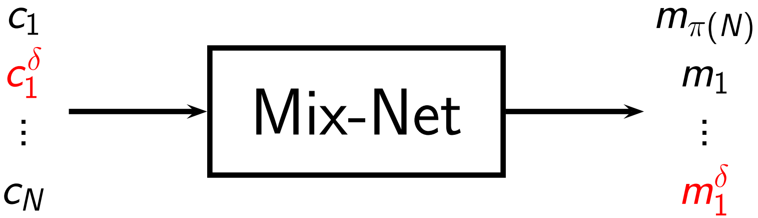
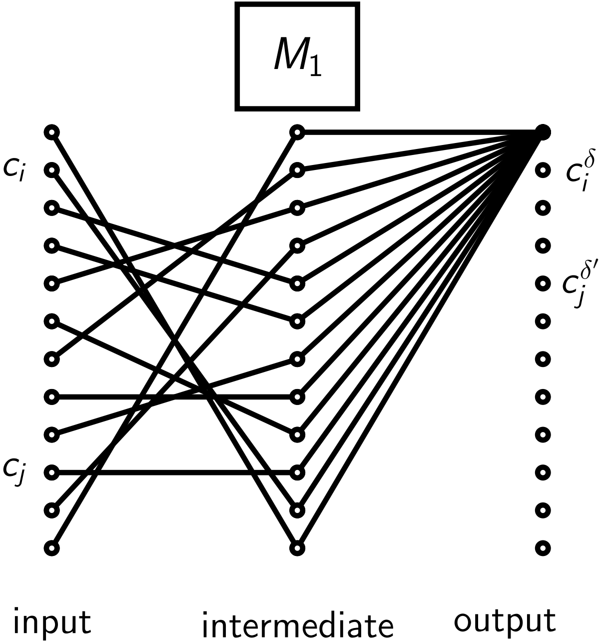


Force non-malleability, e.g., ZKPoK!

Attack on privacy



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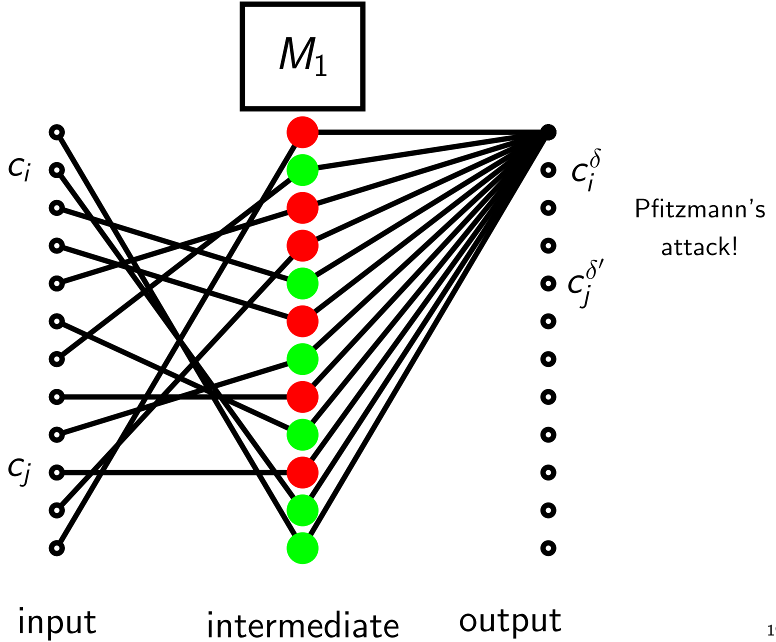
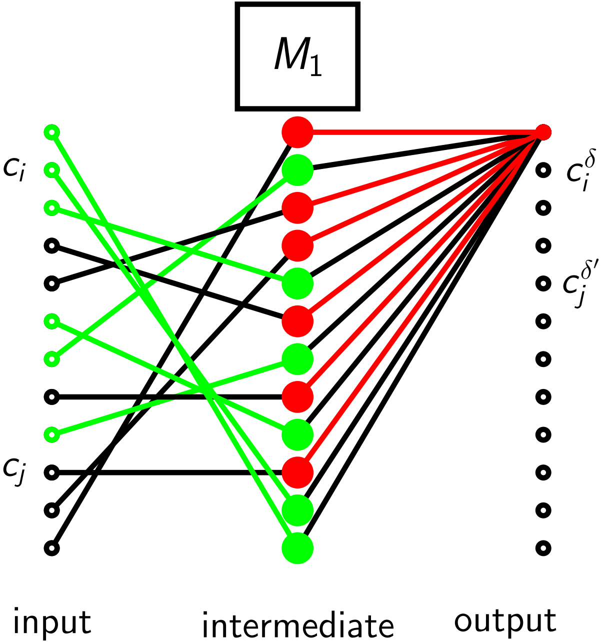
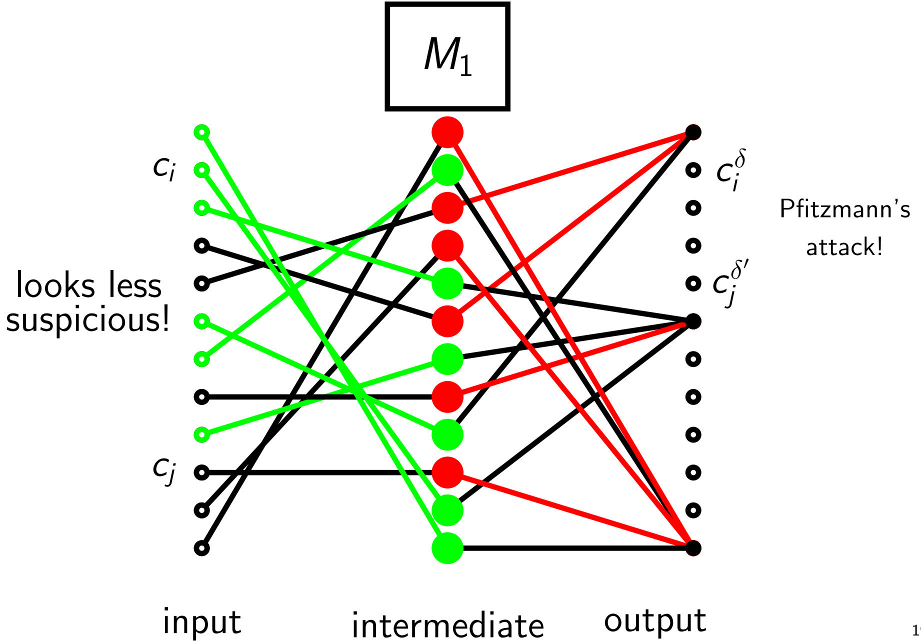


Attack on privacy



Pfitzmann's attack!

Attack on privacy



Privacy

Combined with Pfitzmann we can break privacy of almost everybody, but it would be noticed in the output (one-off attack).

...some additional observations.

Yeah, yeah, a very serious bug, but can it be patched?

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Claim. c ciphertexts can be replaced with probability roughly $(1/2)^c$.

Correct. c ciphertexts can be replaced with probability roughly $(3/4)^c$.

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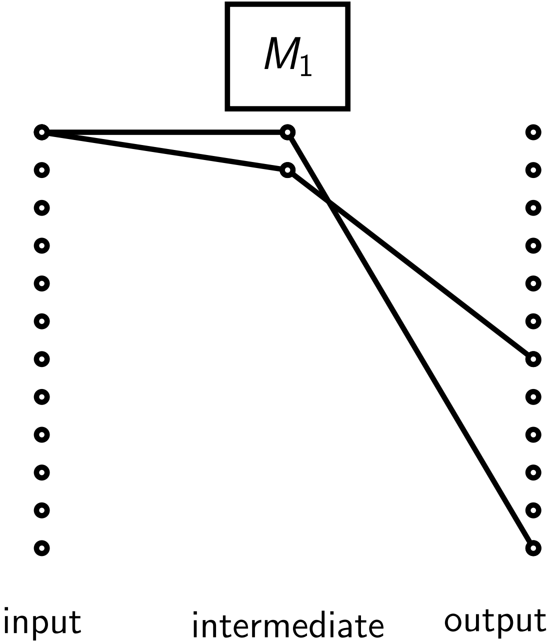
Correct. c ciphertexts can be replaced with probability roughly $(3/4)^c$.

Important! Universal verifiability can be violated for changes of c ciphertexts with work $O\big((4/3)^c\big)$ instead of $O(2^c)$.

Wrong bound!



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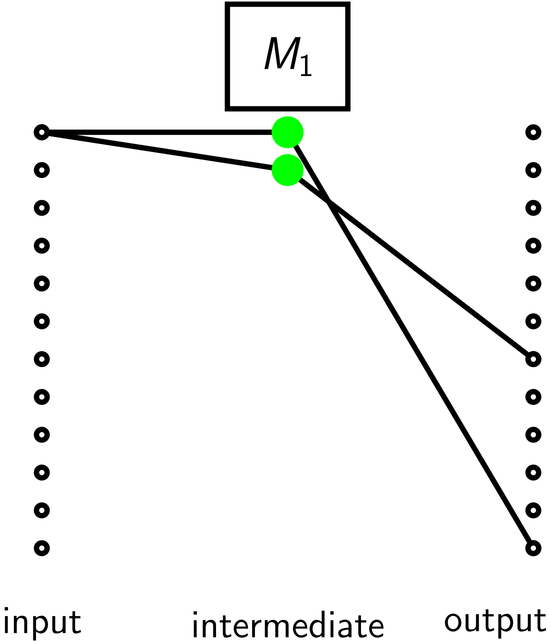

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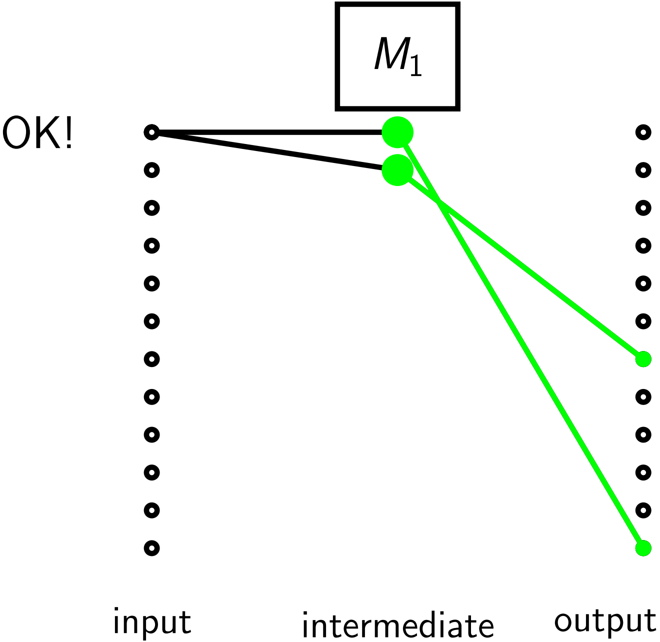

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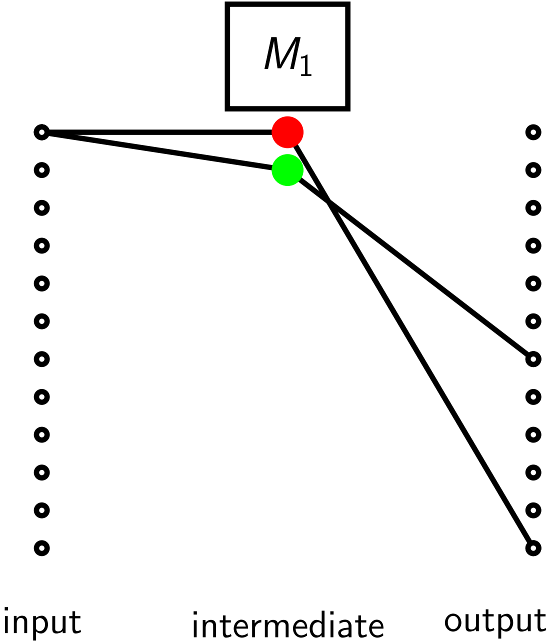

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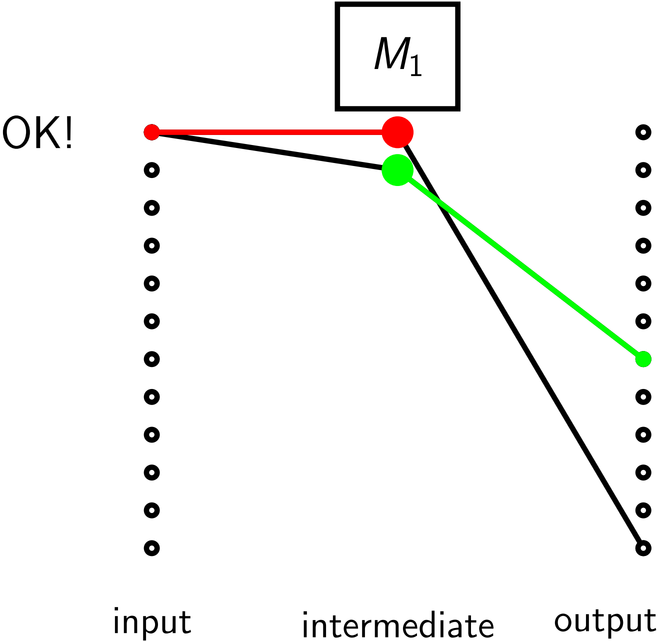

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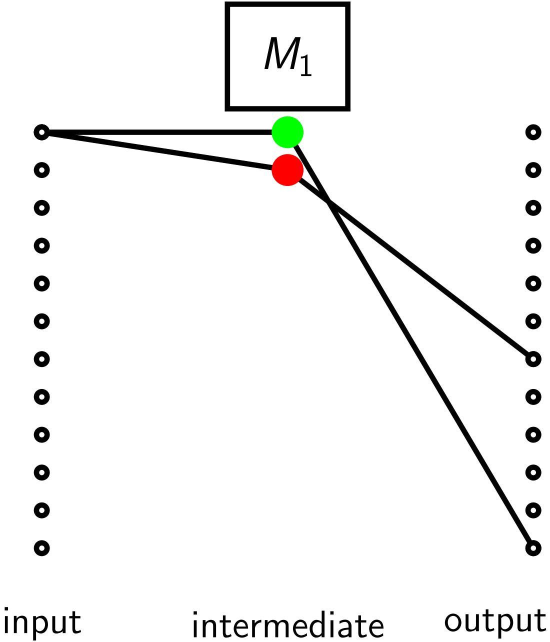

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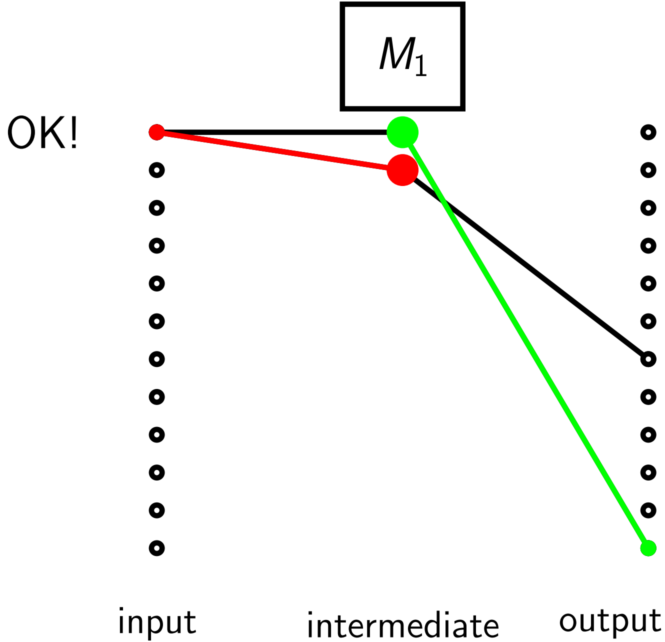

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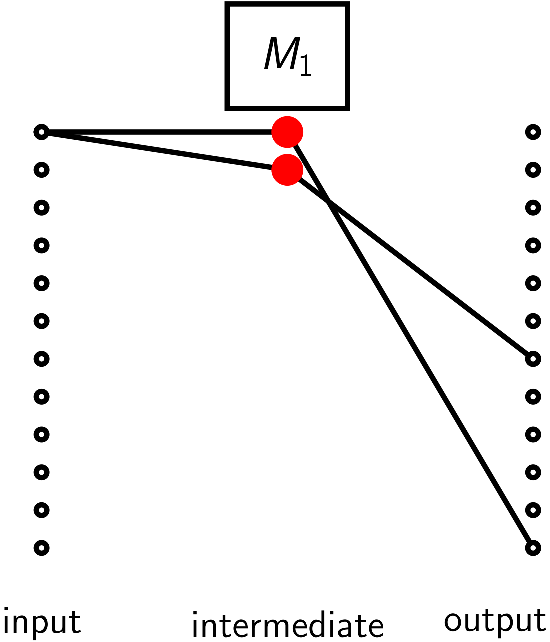

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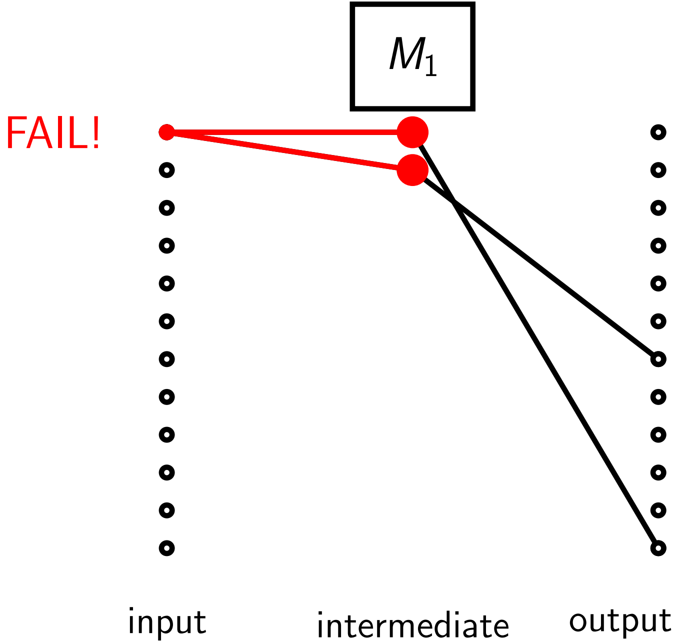

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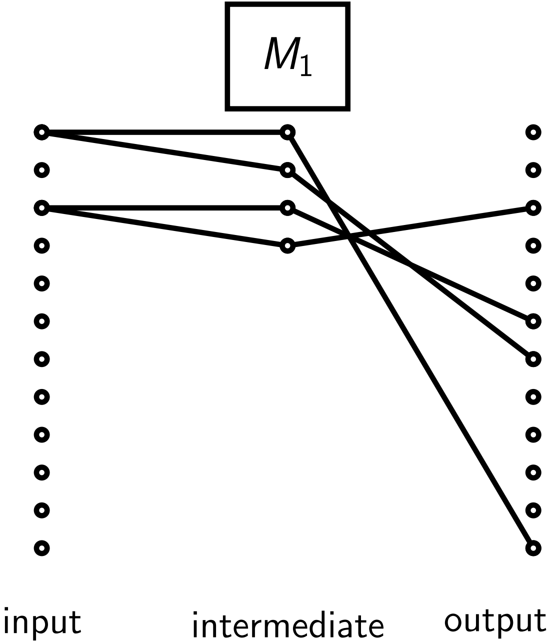

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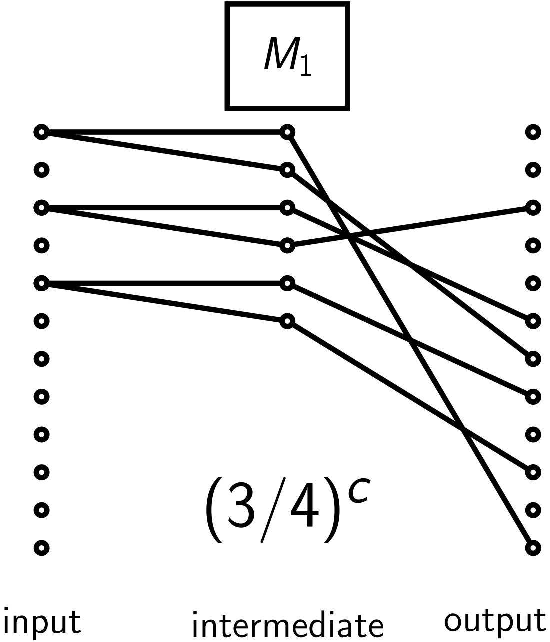

Conclusion

Current work

We are writing down a rigorous proof of security for mix-nets with randomized partial checking.

Non-standard weaker security properties than claimed and hairy proof, but it works almost as expected.

Recent attacks

Flaws have been found in all “big” verifiable systems!

- Scytl mix-net (non-fatal vulnerabilities) [KTW EVT/WOTE ’12]
- Helios (universal verifiability fails) [BPW Asiacrypt ’12]
- Civitas, Scantegrity, N.N.,... (soundness fails) [KW today]

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I am still optimistic about the whole thing!

What we need

Unless at least the counting in an electronic election scheme is provably sound/verifiable it should not be used.

We need **several independent** cryptographers and/or machines to verify the proofs of security.

We must spend more time scrutinizing the proposals of the community and the underlying assumptions.

Questions?