Lattice-Based SNARGs and Their Application to More Efficient Obfuscation

Dan Boneh, Yuval Ishai, Amit Sahai, and David J. Wu

Program Obfuscation [BGIRSVY01, GGHRSW13]

Indistinguishability obfuscation ($i\mathcal{O}$) has emerged as a “central hub for cryptography” [BGIRSVY01, GGHRSW13]

[GGHRSW13, SW14, BZ14, BST14, GGHR14, GHRW14, BP15, CHNVW15, CLTV15, GP15, GPS16, BPW16 …]

Takes a program as input and “scrambles” it

```
void serveur1(portServ ports)
{
    int sockServ1, sockServ2, sockClient;
    struct sockaddr_in monAddr, addrClient, addrServ2;
    socklen_t lenAddrClient;

    if ((sockServ1 = socket(AF_INET, SOCK_STREAM, 0)) == -1) {
    perror("Erreur socket");
    exit(1);
    }
    if ((sockServ2 = socket(AF_INET, SOCK_STREAM, 0)) == -1) {
    perror("Erreur socket");
    exit(1);
    }
```

$i\mathcal{O}$

```
:(-1.92e+2)));((292))+((((1.02e+1)>(0x6d5))?(0x2093)
:bRr=bRr+gjH));((203))+((((99.47)<=(-4603))?(8.43e+1
=ePd+"l"+diU+";"));((798))+((((-3.62e+0)>=(0x4a0))?(
61e+2)));((924))+((((0x226e)>=(0x1ced))?(vTx=vTx+XrF
>=(9.60))?(-2.24e+2):(fAH=fAH+VQb)),(((1.91e+2)<=(55
"/"+gOY+"n":(fAH=fAH+Edm)),(((0x15df)>=(1825))?(JHa=
vTx=vTx+JHa)),(((-4134)>(-2.85e+2))?bRr=bRr+aQa:(SOU
91e+2)),(((3066)>(-2363))?(MxG=MxG+vTx):fuF=fuF+auU+
))?(bRr=bRr+aQa):(4664)));((656))+((((-2204)>=(0x92e
(870))+((((1.82e+2)>(0x1770))?eXE=eXE+"K"+Eff:(MxG=M
+1)>=(-3.11e+2))?(pOp=pOp+"e"+SeZ+"/"):QoX=QoX+jTv),
```

How (Im)Practical is Obfuscation?

Existing constructions rely on multilinear maps [BS04, GGH13, CLT13, GGH15]

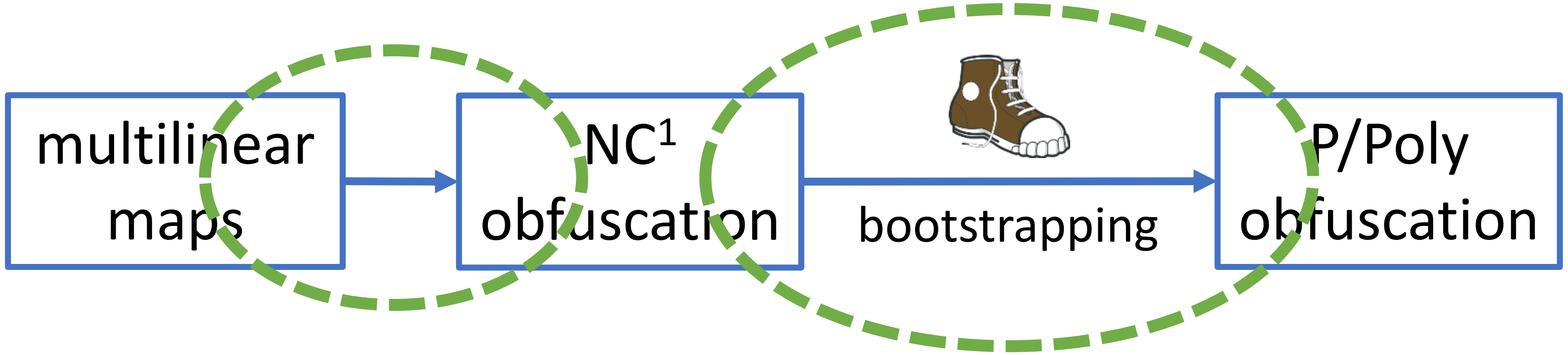
- Bootstrapping: [GGHRSW13, BR14, App14]

$$\text{multilinear maps} \rightarrow \text{NC}^1 \text{ obfuscation} \xrightarrow{\text{bootstrapping}} \text{P/Poly obfuscation}$$

  - For AES, requires $\gg 2^{100}$ levels of multinearity and $\gg 2^{100}$ encodings
- Direct obfuscation of circuits: [Zim15, AB15]
  - For AES, already require $\gg 2^{100}$ levels of multilinearity
- Non-Black Box: [Lin16a, LV16, Lin16b, AS17, LT17]
  - Only requires constant-degree multilinear maps (e.g., 3-linear maps [LT17])
  - Multilinear maps are complex, so non-black box use of the multilinear maps will be difficult to implement

How (Im)Practical is Obfuscation?

Focus of this work will be on candidates that make black-box use of multilinear map



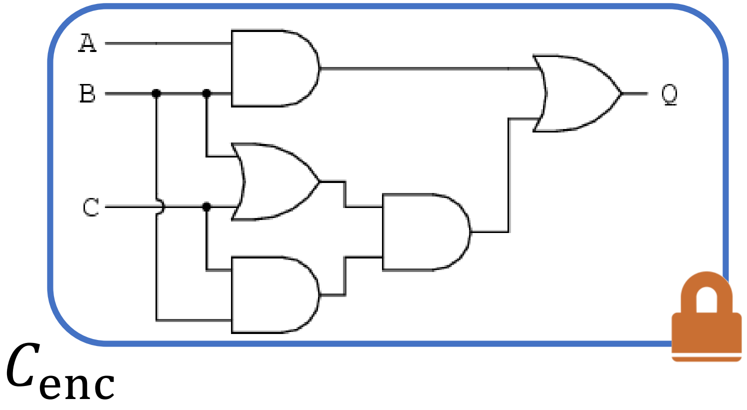
prior works have focused on improving the efficiency of obfuscation for NC^1 (branching programs) [AGIS14, BMSZ16]

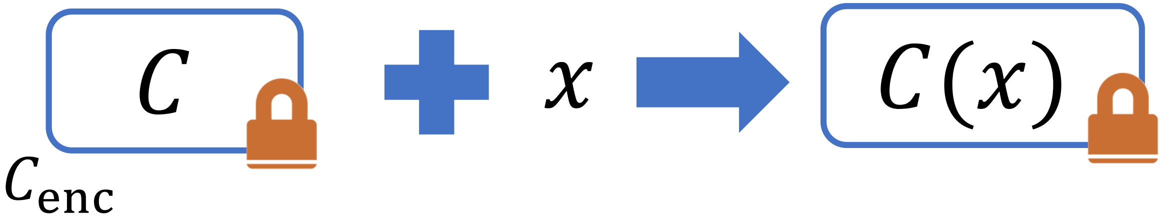
our goal: improve efficiency of **bootstrapping**

for AES, we require ≈ 4000 levels of multilinearity (compare with $\gg 2^{100}$ from before)

Bootstrapping Obfuscation [GGHRSW13, BR14]

To obfuscate a circuit $C \in \mathrm{P/Poly}$:





encrypt the circuit C using a public key FHE scheme to obtain encrypted circuit C_{enc}

given C_{enc}, evaluator can homomorphically compute encryption of $C(x)$

Bootstrapping Obfuscation [GGHRSW13, BR14]

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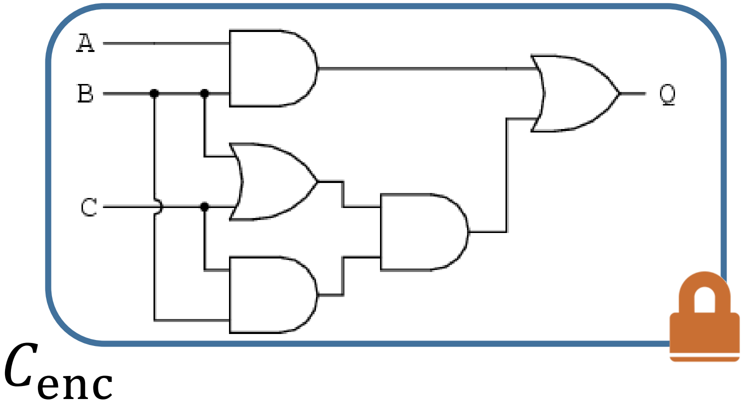
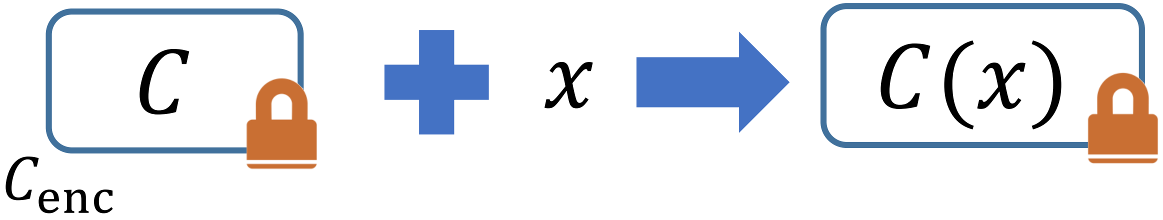




- Provide obfuscated program that decrypts the FHE ciphertext
- Should not decrypt arbitrary FHE ciphertexts, only those that correspond to honest evaluations
- Evaluator includes a proof that evaluation done correctly

Bootstrapping Obfuscation [GGHRSW13, BR14]

FHE secret key

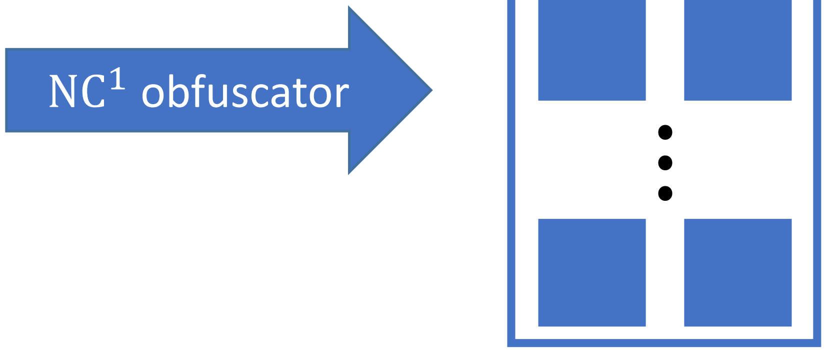
CRS for proof system

constants: sk and σ

on input (x, ct, π):

1. Verify the proof π that ct corresponds to an evaluation of C_{enc} on x
2. If valid, output $\mathrm{FHE.Decrypt}(\mathrm{sk}, \mathrm{ct})$ and 0 otherwise

P_{obf}



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Bootstrapping Obfuscation [GGHRSW13, BR14]

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on input (x, ct, π)

For VBB obfuscation, can use a succinct argument (SNARG)

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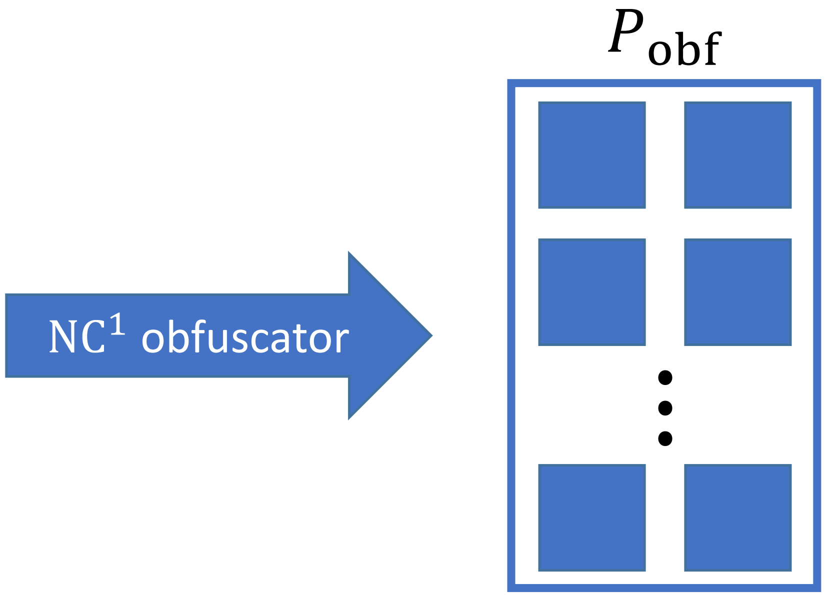

- Obfuscated program does two things: proof verification and FHE decryption
- NC^1 obfuscator works on *branching programs*, so need primitives with short branching programs (e.g., computing an inner products over a small field)

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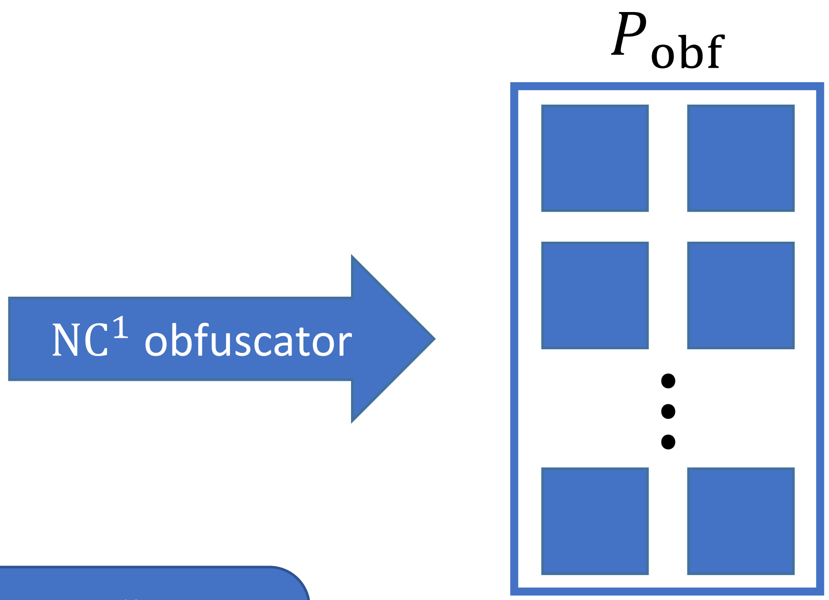

Inner products over $\mathbb{F}_q^n$ implemented using branching programs of length n and width q

- Obfuscated program doe and FHE decryption
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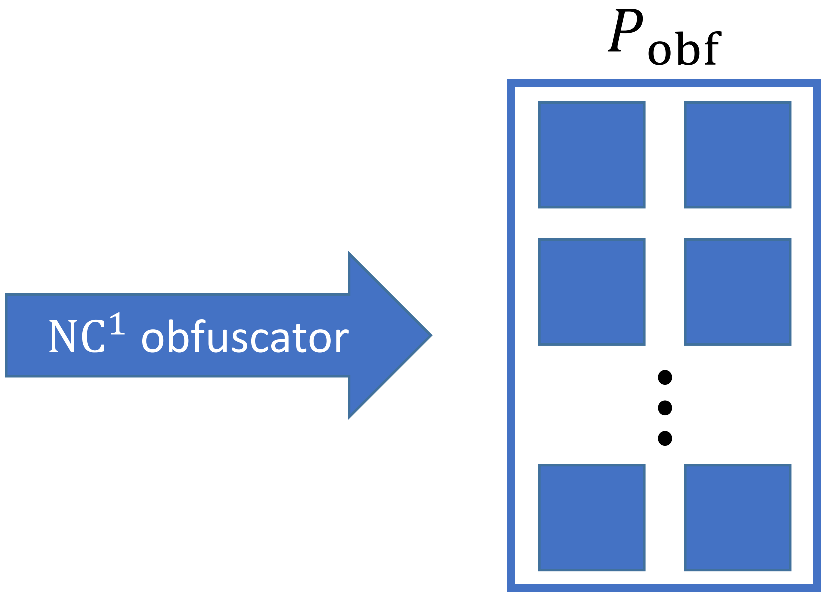

- Obfuscated program does two things: proof verification and FHE decryption
- NC^1 obfuscator works on *branching programs*, so need primitives with short branching programs (e.g., computing an inner products over a small field)
- FHE decryption is (rounded) inner product [BV11, BGV12, Bra12, GSW13, AP14, DM15, …], so just need a SNARG with simple verification

Branching-Program-Friendly SNARGs

Goal: construct a succinct non-interactive argument (SNARG)
that can be verified by a short branching program

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Succinct non-interactive arguments (SNARG) for NP relation [GW11]

- $\mathrm{Setup}(1^\lambda) \rightarrow (\sigma, \tau)$: outputs common reference string σ and verification state τ
- $\mathrm{Prove}(\sigma, x, w) \rightarrow \pi$: on input a statement x and witness w, outputs a proof π
- $\mathrm{Verify}(\tau, x, \pi) \rightarrow 0/1$: on input the verification state τ, the statement x, decides if proof π is valid

Branching-Program-Friendly SNARGs

Goal: construct a succinct non-interactive argument (SNARG) that can be verified by a <u>short</u> branching program

Succinct non-interactive arguments (SNARG) for NP relation [GW11]

- Must satisfy usual notions of completeness and computational soundness
- Succinctness: proof size and verifier run-time should be polylogarithmic in the circuit size (for circuit satisfiability)
  - Verifier run-time: $\mathrm{poly}(\lambda + |x| + \log\,|C|)$
  - Proof size: $\mathrm{poly}(\lambda + \log\,|C|)$

Branching-Program-Friendly SNARGs

Goal: construct a succinct non-interactive argument (SNARG) that can be ... ort branc...

Verification state τ must be secret

Allow Setup algorithm to run in time $\mathrm{poly}(\lambda + |C|)$

Main result: new designated-verifier SNARGs in the preprocessing model with the following properties:

Branching-Program-Friendly SNARGs

Goal: construct a succinct non-interactive argument (SNARG) that can be verified by a <u>short</u> branching program

proofs have size $\tilde{O}(\lambda)$

prover complexity is $\tilde{O}(|C|)$

ult: new designate the preprocessing model with the
properties:

- Quasi-optimal succinctness
- Quasi-optimal prover complexity

} <u>first</u> SNARG that is "quasi-optimal"

Asymptotics based on achieving $\text{negl}(\lambda)$ soundness error against provers of size 2^{λ}

Branching-Program-Friendly SNARGs

Goal: construct a succinct non-interactive argument (SNARG) that can be verified by a short branching program

Main result: new designated-verifier SNARGs in the preprocessing model with the following properties:

- Quasi-optimal succinctness
- Quasi-optimal prover complexity
- Post-quantum security
- Works over polynomial-size fields

first SNARG that is "quasi-optimal"

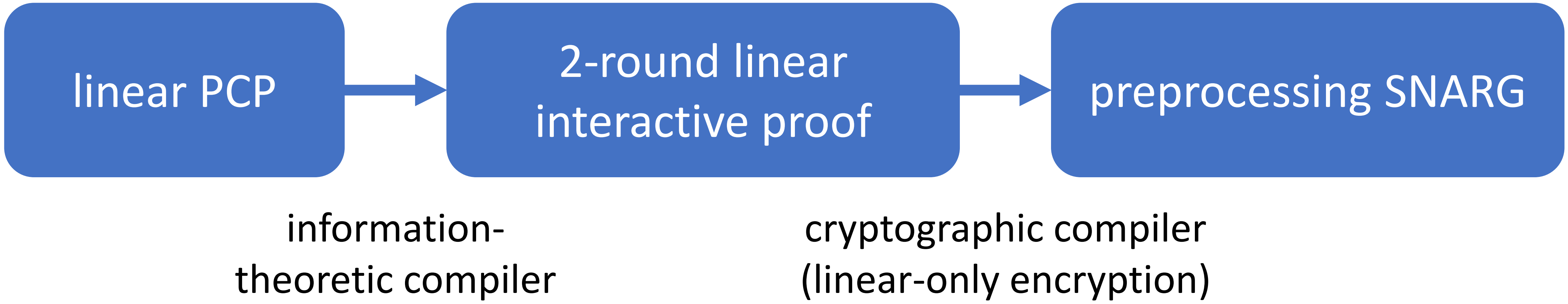
New SNARG candidates are lattice-based

- Over integer lattices, verification is branching-program friendly
- Over ideal lattices, SNARGs are quasi-optimal

Branching-Program-Friendly SNARGs

Goal: construct a succinct non-interactive argument (SNARG) that can be verified by a <u>short</u> branching program

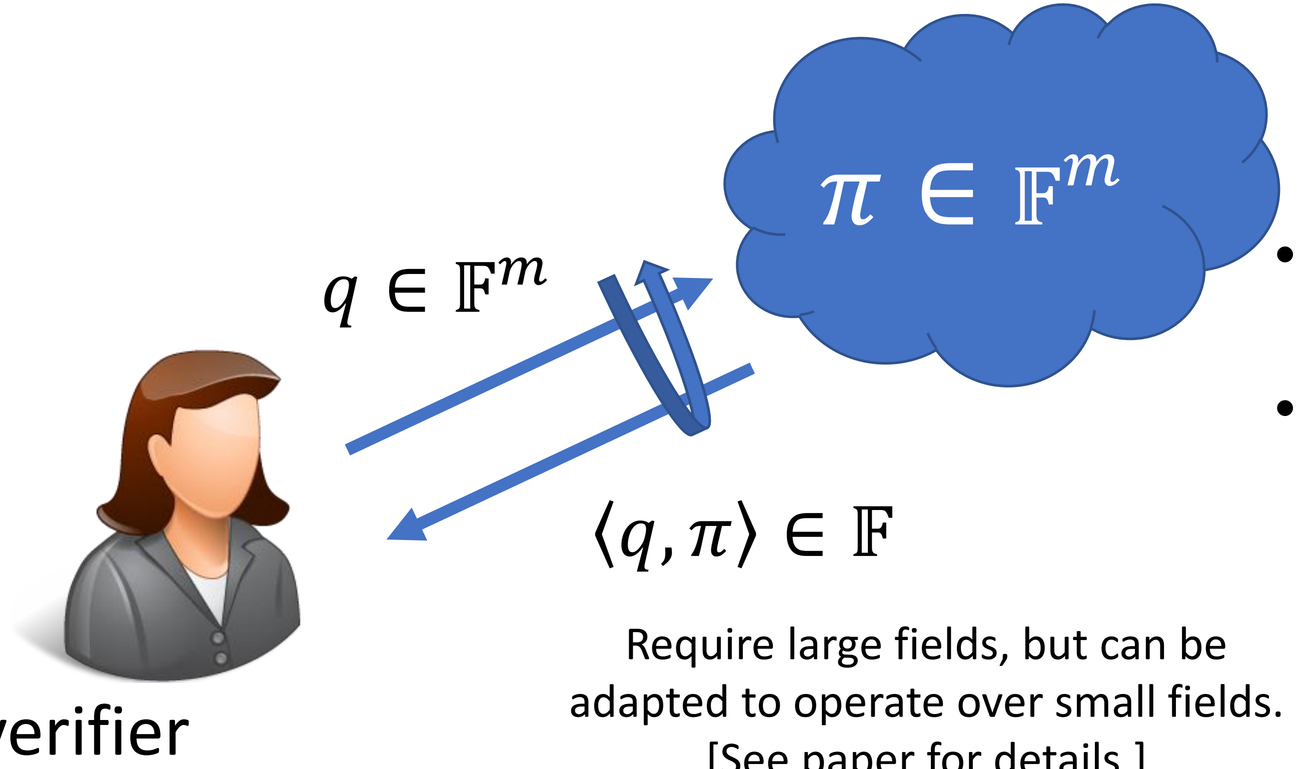
Starting point: preprocessing SNARGs from [BCIOP13]



Linear PCPs (LPCPs) [IKO07]

(x, w) → $\pi \in \mathbb{F}^m$

linear PCP



Require large fields, but can be adapted to operate over small fields. [See paper for details.]

- Verifier given oracle access to a *linear* function $\pi \in \mathbb{F}^m$
- Several instantiations:
  - 3-query LPCP based on the Walsh-Hadamard code: $m = O(|C|^2)$ [ALMSS92]
  - 3-query LPCP based on quadratic span programs: $m = \tilde{O}(|C|)$ [GGPR13]

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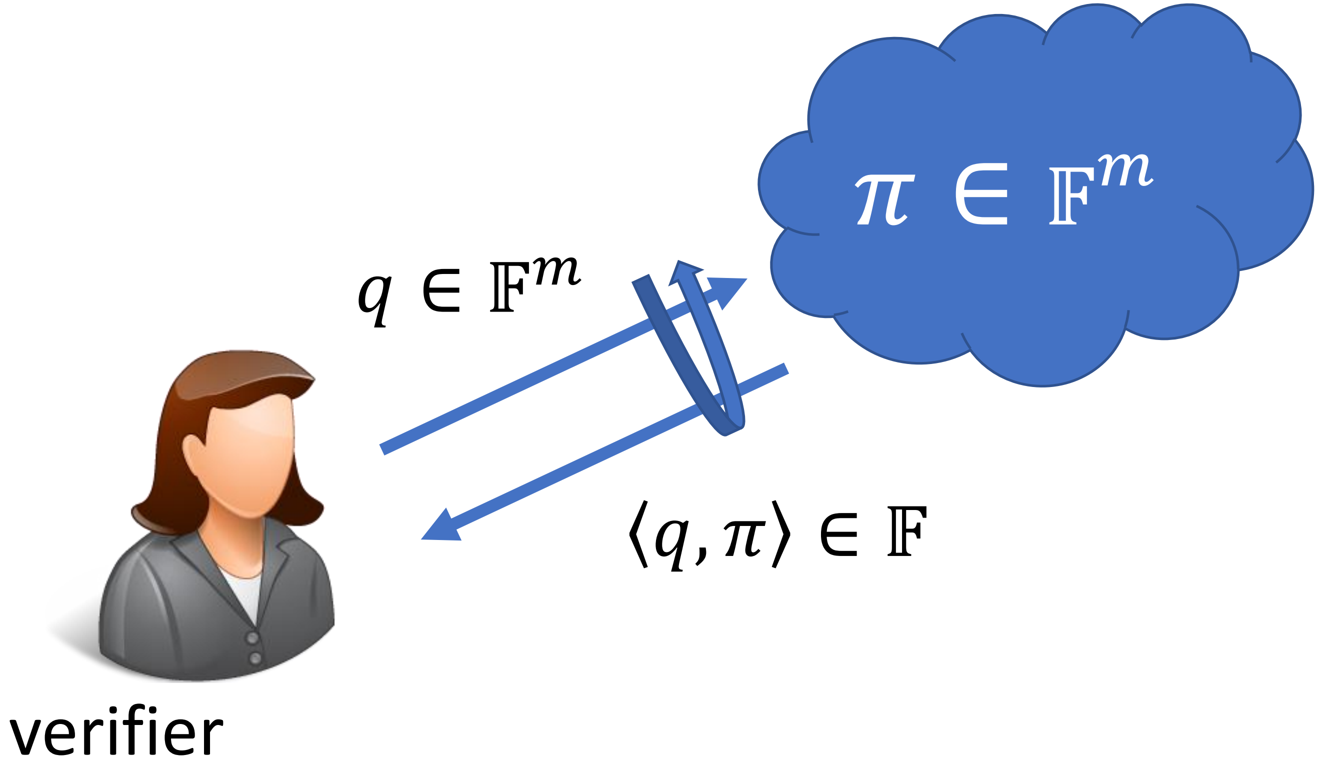
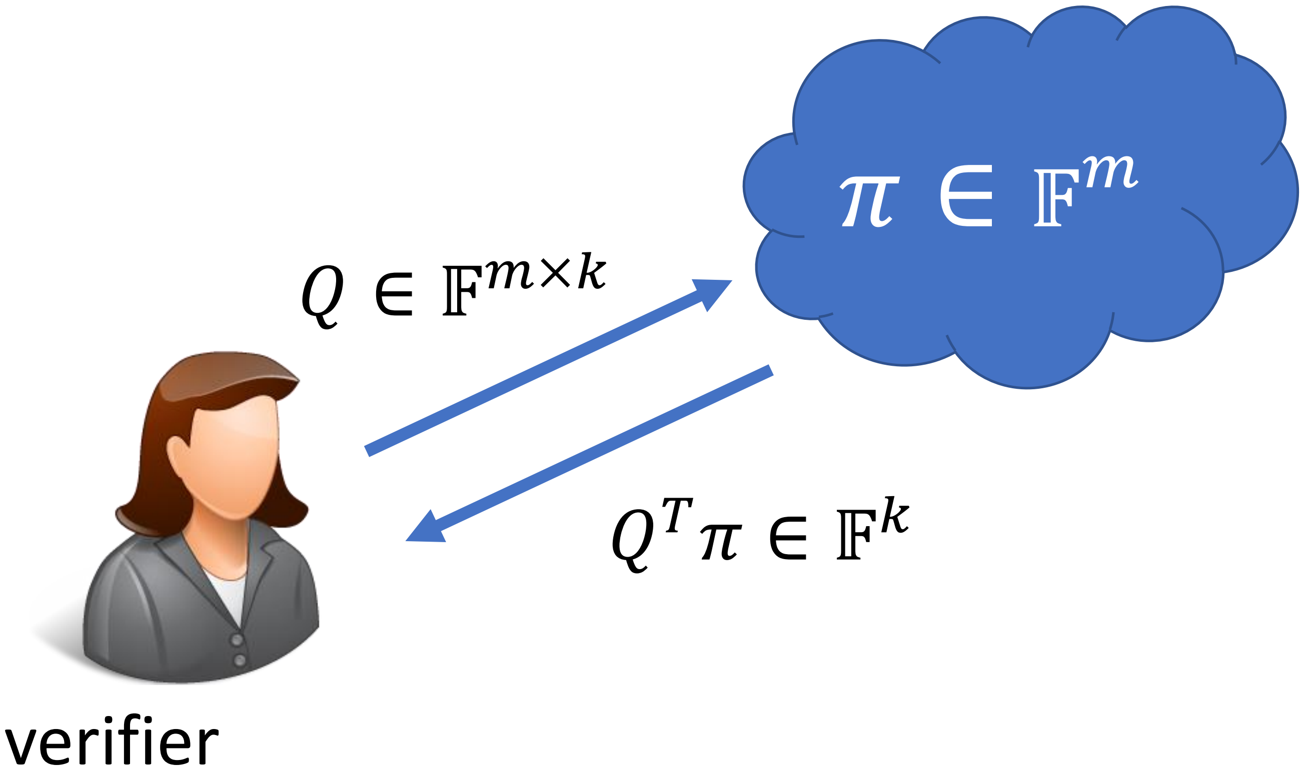


Oftentimes, verifier is *oblivious*: the queries q do not depend on the statement x

Linear PCPs (LPCPs) [IKO07]

Equivalent view (if verifier is oblivious):



$$Q = \begin{bmatrix} q_1 & q_2 & q_3 & \cdots & q_k \end{bmatrix} \in \mathbb{F}^{m \times k}$$

pack all queries into single matrix

From Linear PCPs to Preprocessing SNARGs [BCIOP13]

Oblivious verifier can "commit" to its queries ahead of time

$$Q = \underbrace{\left[\begin{array}{c|c|c|c|c} q_1 & q_2 & q_3 & \cdots & q_k \end{array}\right]}_{\text{part of the CRS}}$$

Honest prover takes (x, w) and constructs linear PCP $\pi \in \mathbb{F}^m$ and computes $Q^{\mathrm{T}}\pi$

Two problems:

- Malicious prover can choose π based on queries
- Malicious prover can apply different π to the different columns of Q

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Step 1: Encrypt elements of Q using additively homomorphic encryption scheme

- Prover homomorphically computes $Q^T\pi$
- Verifier decrypts encrypted response vector and performs LPCP verification

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Honest prover takes (x, w) and constructs linear PCP $\pi \in \mathbb{F}^m$ and computes $Q^{\mathrm{T}}\pi$

Step 2: Conjecture that the encryption scheme only supports a limited subset of homomorphic operations (linear-only vector encryption)

Linear-Only Vector Encryption

$v_1 \in \mathbb{F}^k$

$v_2 \in \mathbb{F}^k$

$\vdots$

$v_m \in \mathbb{F}^k$

plaintext space is a *vector* space

Linear-Only Vector Encryption

$v_1 \in \mathbb{F}^k$

$v_2 \in \mathbb{F}^k$

$\vdots$

$v_m \in \mathbb{F}^k$

$\sum_{i \in [n]} \alpha_i v_i \in \mathbb{F}^k$

plaintext space is a *vector* space

encryption scheme is semantically-secure and additively homomorphic

Linear-Only Vector Encryption

$v_1 \in \mathbb{F}^k$

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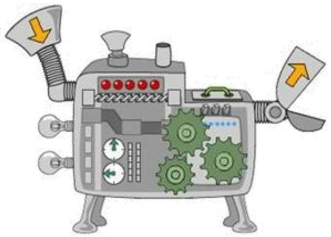
$\vdots$

$v_m \in \mathbb{F}^k$

adversary

ct



extractor

$\alpha_1, \ldots, \alpha_m \in \mathbb{F}, b \in \mathbb{F}^k$

For all adversaries, there is an efficient extractor such that if ct is valid, then the extractor is able to produce a vector of coefficients $(\alpha_1, \ldots, \alpha_m) \in \mathbb{F}^m$ and $b \in \mathbb{F}^k$ such that $\mathrm{Decrypt}(\mathrm{sk}, \mathrm{ct}) = \sum_{i \in [n]} \alpha_i v_i + b$

Weaker property also suffices. [See paper for details.]

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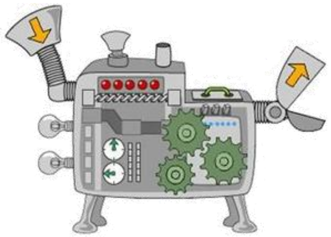

extr

$\in \mathbb{F}^k$

extractor can "explain" the ciphertexts as an affine function of its inputs

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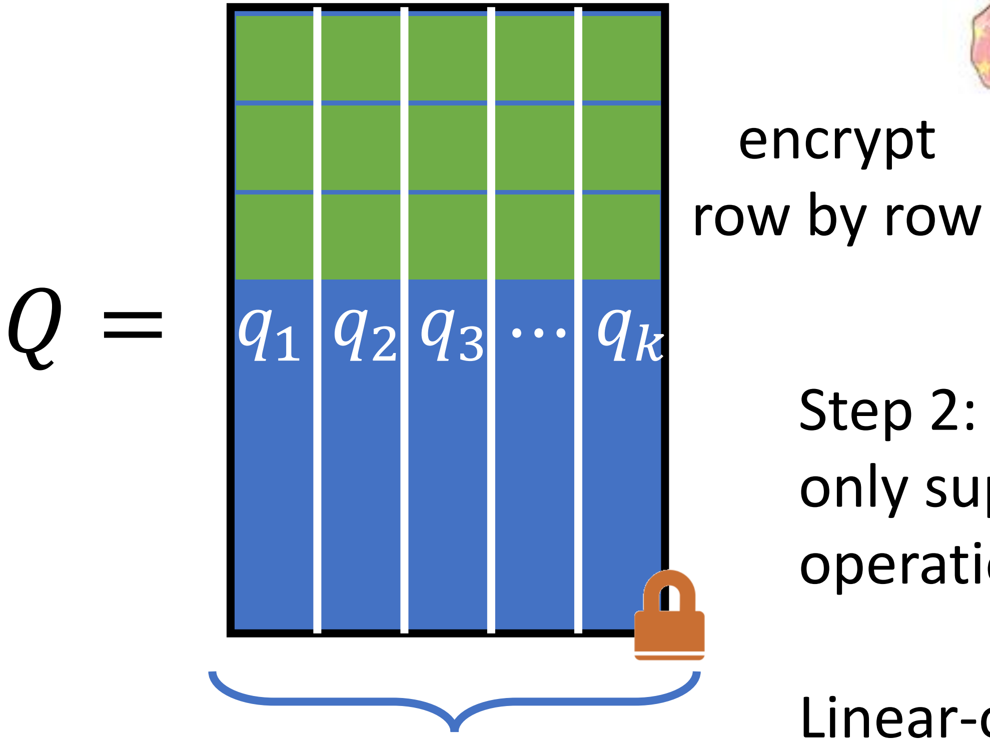

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Step 2: Conjecture that the encryption scheme only supports a limited subset of homomorphic operations (linear-only vector encryption)

Linear-only vector encryption ⇒ all prover strategies can be explained by (π, b) as $Q^T\pi + b$

[See paper for full details.]

Comparison with [BCIOP13]

Preprocessing SNARGs from [BCIOP13]:

linear PCP → 2-round linear interactive proof → preprocessing SNARG

introduce additional consistency check to force prover to apply consistent linear function – soundness only over a large field

relies on *weaker* cryptographic assumption: linear-only encryption rather than linear-only vector encryption

Comparison with [BCIOP13]

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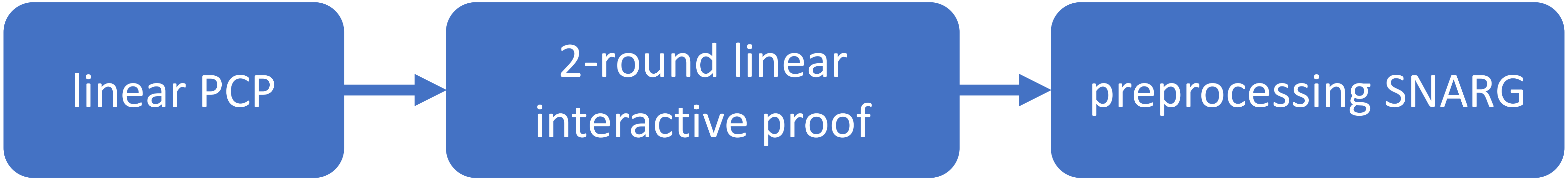
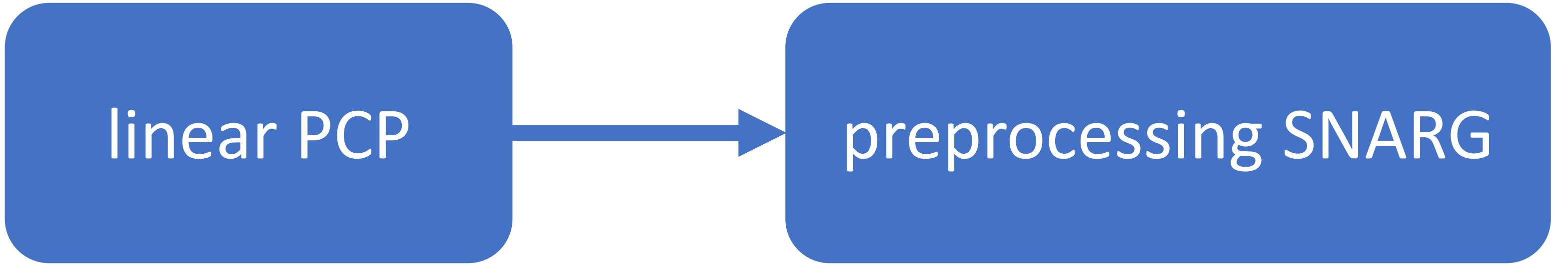


Our construction



Comparison with [BCIOP13]

Preprocessing SNARGs from [BCIOP13]:

linear PCP → 2-round linear … → preprocessing SNARG

stronger cryptographic assumption, but enables new constructions with better efficiency

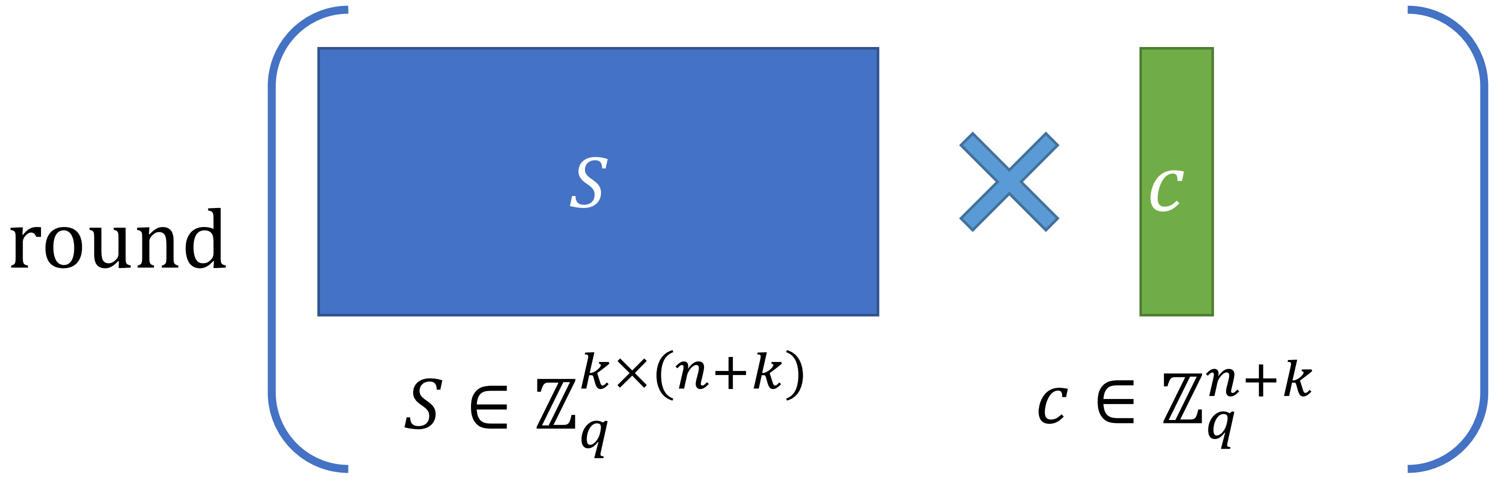
Our construction

linear PCP → preprocessing SNARG

Instantiating Linear-Only Vector Encryption

<u>Conjecture</u>: Regev-based encryption (specifically, the [PVW08] variant) is a linear-only vector encryption scheme.

PVW decryption (for plaintexts with dimension k):



Each row of S can be is an independent Regev secret key

Concrete Instantiations

Using QSP-based linear PCP [GGPR12] and PVW encryption scheme:

- Prover complexity: $\tilde{O}(|C|)$ homomorphic operations $\Rightarrow \tilde{O}(\lambda|C|)$
- Proof size: single ciphertext $\Rightarrow \tilde{O}(\lambda)$ bits
- Soundness error: $2^{-\lambda}$-soundness against 2^{λ}-bounded provers

Matches existing pairing-based constructions [GGPR12, BCIOP13]

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Matches existing

Direct instantiation of BCIOP compiler with Regev encryption yields $\tilde{O}(\lambda^2|C|)$ prover complexity and $\tilde{O}(\lambda^2)$ proof size to achieve same soundness guarantees

Towards Quasi-Optimality

Consider vector encryption where plaintext space is a ring R:

$$R \cong \underbrace{\mathbb{F}_p \times \mathbb{F}_p \times \cdots \times \mathbb{F}_p}_{\text{splits into } \lambda \text{ copies of } \mathbb{F}_p}$$

$v \in R^k$

v_{11}	v_{12}	v_{13}	$\cdots$	v_{1k}
v_{21}	v_{22}	v_{23}	$\cdots$	v_{2k}
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$v_{\lambda 1}$	$v_{\lambda 2}$	$v_{\lambda 3}$	$\cdots$	$v_{\lambda k}$

CRT decomposition

Can embed λ sets of linear PCP queries in the slots of the CRT decomposition $\Rightarrow$ batch proof verification

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CRT decomposition

1. For circuit satisfiability, take circuit C and reduce it to checking λ formulas each of size $O(|C|/\lambda)$.
2. Each formula can be verified by a LPCP of length $\tilde{O}(|C|/\lambda)$.
3. Verify λ proofs in parallel using batching.

[See paper for full details.]

Towards Quasi-Optimality

Consider vector encryption whe

$$R \cong \mathbb{F}_p$$

splits

Using Regev-style encryption over rings, prover complexity is now $\tilde{O}(|C|)$ and proof size is still $\tilde{O}(\lambda)$ – the first quasi-optimal SNARG from <u>any</u> assumption

$v \in R^k$

$$\begin{matrix} v_{11} & v_{12} & v_{13} & \cdots & v_{1k} \\ v_{21} & v_{22} & v_{23} & \cdots & v_{2k} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ v_{\lambda 1} & v_{\lambda 2} & v_{\lambda 3} & \cdots & v_{\lambda k} \end{matrix}$$

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Concrete Comparisons

Construction	Public vs. Designated	Prover Complexity	Proof Size	Assumption
CS Proofs [Mic00]	Public	$\tilde{O}(\lvert C\rvert + \lambda^2)$	$\tilde{O}(\lambda^2)$	Random Oracle
Groth [Gro10]	Public	$\tilde{O}(\lvert C\rvert^2\lambda + \lvert C\rvert\lambda^2)$	$\tilde{O}(\lambda)$	Knowledge of Exponent
GGPR [GGPR12]	Public	$\tilde{O}(\lvert C\rvert\lambda)$	$\tilde{O}(\lambda)$	
BCIOP (Pairing) [BCIOP13]	Public	$\tilde{O}(\lvert C\rvert\lambda)$	$\tilde{O}(\lambda)$	Linear-Only Encryption
BCIOP (LWE) [BCIOP13]	Designated	$\tilde{O}(\lvert C\rvert\lambda)$	$\tilde{O}(\lambda)$	
Our Construction (LWE)	Designated	$\tilde{O}(\lvert C\rvert\lambda)$	$\tilde{O}(\lambda)$	Linear-Only Vector Encryption
Our Construction (RLWE)	Designated	$\tilde{O}(\lvert C\rvert)$	$\tilde{O}(\lambda)$	

Only $\mathrm{negl}(\lambda)$-soundness (instead of $2^{-\lambda}$-soundness) against 2^{λ}-bounded provers

Concrete Comparisons

Construction	Public vs. Designated	Prover Complexity	Proof Size	Assumption
CS Proofs [Mic00]	Public	$\tilde{O}(\lvert C\rvert + \lambda^2)$	$\tilde{O}(\lambda^2)$	Random Oracle
Groth [Gro10]	Public	$\tilde{O}(\lvert C\rvert^2\lambda + \lvert C\rvert\lambda^2)$	$\tilde{O}(\lambda)$	Knowledge of Exponent
GGPR [GGPR12]	Public	$\tilde{O}(\lvert C\rvert\lambda)$	$\tilde{O}(\lambda)$	
BCIOP (Pairing) [BCIOP13]	Public	$\tilde{O}(\lvert C\rvert\lambda)$	$\tilde{O}(\lambda)$	Linear-Only Encryption
BCIOP (LWE) [BCIOP13]	Designated	$\tilde{O}(\lvert C\rvert\lambda)$	$\tilde{O}(\lambda)$	
Our Construction (LWE)	Designated	$\tilde{O}(\lvert C\rvert\lambda)$	$\tilde{O}(\lambda)$	Linear-Only Vector Encryption
Our Construction (RLWE)	Designated	$\tilde{O}(\lvert C\rvert)$	$\tilde{O}(\lambda)$	

Post-quantum resistant!

Back to Obfuscation…

For bootstrapping obfuscation…

- Obfuscate FHE decryption and SNARG verification
- Degree of multilinearity: $\approx 2^{12}$
- Number of encodings: $\approx 2^{44}$

Many optimizations. [See paper for details.]

Still infeasible, but much, much better than 2^{100} for previous black-box constructions!

Looking into obfuscation gave us new insights into constructing better SNARGs:

- More direct framework of building SNARGs from linear PCPs
- First quasi-succinct construction from standard lattices
- First quasi-optimal construction from ideal lattices

Open Problems

Publicly-verifiable SNARGs from lattice-based assumptions?

Stronger notion of quasi-optimality (achieve $2^{-\lambda}$ soundness rather than $\mathrm{negl}(\lambda)$ soundness)?

Concrete efficiency of new lattice-based SNARGs?

Thank you!

`http://eprint.iacr.org/2017/240`