CSCI 1515 Applied Cryptography

This Lecture:

- BFV: SWHE from RLWE (Continued)
- Private Information Retrieval
- Bootstrapping SWHE to FHE

FHE Constructions

Step 1: Somewhat Homomorphic Encryption (SWHE)

- over Integers
- from RLWE (BFV)

Step 2: Bootstrapping

Ring LWE (RLWE) Assumption

Polynomial ring $R = \mathbb{Z}[x] / (x^m + 1)$ where $m = 2^k$

↑ polynomials with integer coefficients modulo $(x^m + 1)$

$$R_q = \mathbb{Z}_q[x] / (x^m + 1)$$

↑ polynomials with integer coefficients modulo q and $(x^m + 1)$

χ : "noise" distribution over R

$a \xleftarrow{\$} R_q \qquad s \xleftarrow{\$} R_q \text{ (or } s \leftarrow \chi) \qquad e \leftarrow \chi$

$$(a,\ [a \cdot s + e]_q) \overset{c}{\simeq} (a,\ b \xleftarrow{\$} R_q)$$

SWHE from RLWE (BFV)

Plaintext space $R_t = \mathbb{Z}_t[x]/(x^m+1)$ $\quad \Delta := \lfloor \frac{q}{t} \rfloor$ $\quad t \ll q$

Ciphertext space $R_q \times R_q$

Gen:

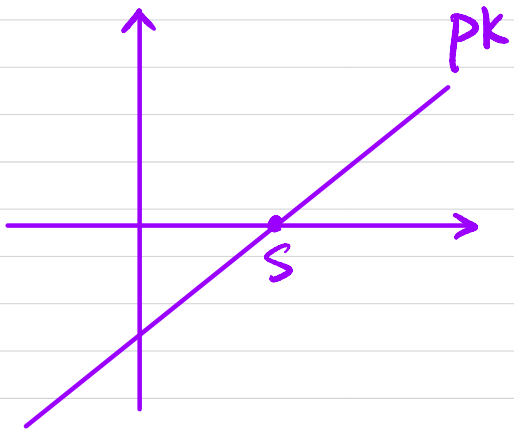
Sample $a \xleftarrow{\$} R_q$ $\quad s, e \leftarrow \chi$

$sk = s$

$pk = \left([-(a \cdot s + e)]_q, \; a \right)$

$= (pk_0, pk_1)$

$[pk(s)]_q = pk_0 + pk_1 \cdot s = e \simeq 0$



$Enc_{pk}(m)$: $m \in R_t$

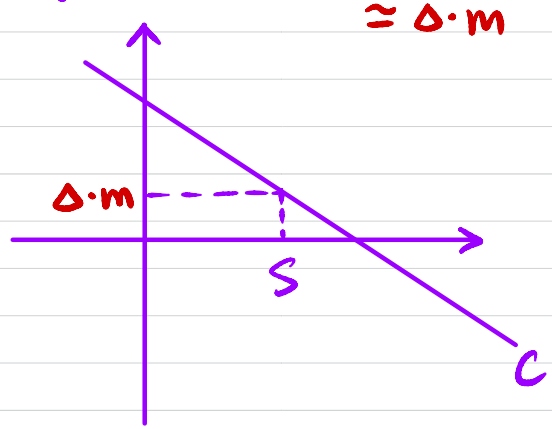
Sample $u, e_1, e_2 \leftarrow \chi$

$c = \left([pk_0 \cdot u + e_1 + \Delta \cdot m]_q, \; [pk_1 \cdot u + e_2]_q \right)$

$= (c_0, c_1)$

$[c(s)]_q = c_0 + c_1 \cdot s = -e \cdot u + e_1 + e_2 \cdot s + \Delta \cdot m$

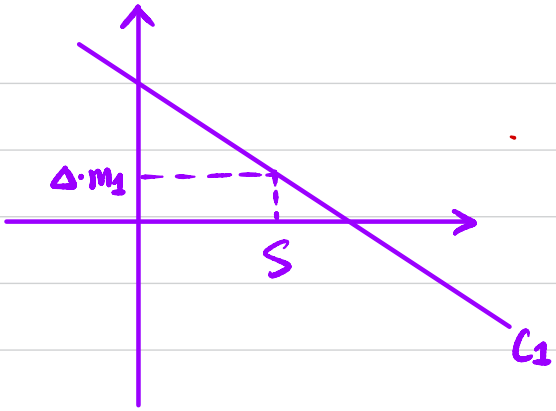
$\simeq \Delta \cdot m$



$Dec_{sk}(c)$? $\quad c_0 + c_1 \cdot s \rightarrow \Delta \cdot m + \text{error}$

SWHE from RLWE (BFV)

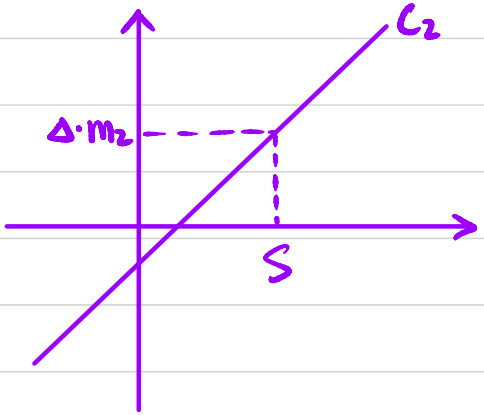
$$[C(s)]_q = c_0 + c_1 \cdot s = \Delta \cdot m + e$$



Homomorphism:

$$[C^{(1)}(s)]_q = \Delta \cdot m_1 + e_1$$

$$[C^{(2)}(s)]_q = \Delta \cdot m_2 + e_2$$



Additive Homomorphism?

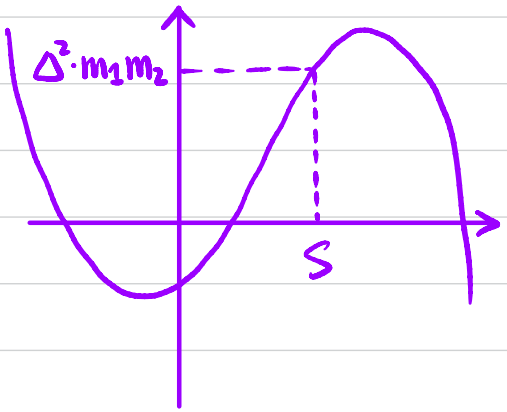
$$[C^{(1)}(s) + C^{(2)}(s)]_q = [\Delta \cdot (m_1 + m_2) + e_1 + e_2]_q$$

Multiplicative Homomorphism?

$$C^{(1)}(s) \cdot C^{(2)}(s)$$

$$= (\Delta \cdot m_1 + e_1 + \alpha_1 \cdot q) \cdot (\Delta \cdot m_2 + e_2 + \alpha_2 \cdot q)$$

$$= \Delta^2 \cdot m_1 m_2 + \Delta m_1 e_2 + \Delta m_1 \cdot \alpha_2 q + e_1 \cdot \Delta m_2 + e_1 e_2$$
$$+ e_1 \alpha_2 q + \alpha_1 q \Delta m_2 + \alpha_1 q e_2 + \alpha_1 \alpha_2 q^2$$



WANT: $\Delta \cdot m_1 m_2 + \text{small}$

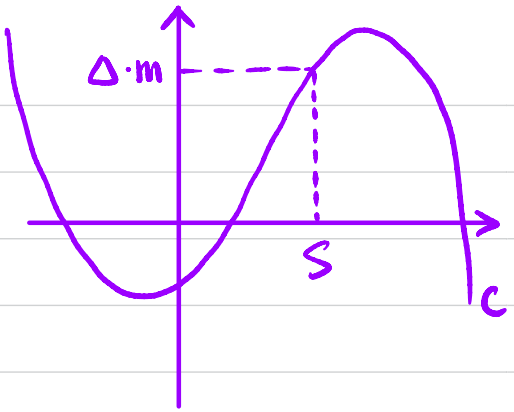
$$\Delta = \left\lfloor \frac{q}{t} \right\rfloor$$

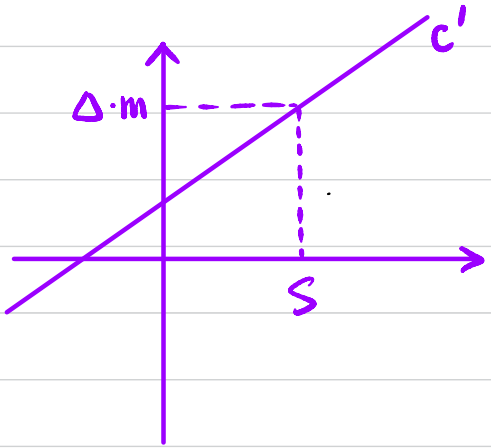
SWHE from RLWE (BFV)

$$[C(s)]_q = C_0 + C_1 \cdot s + C_2 \cdot s^2 = \Delta \cdot m + e$$

$$\downarrow$$

$$[C'(s)]_q = C_0' + C_1' \cdot s = \Delta \cdot m + e$$





Relinearization:

Relinearization key:

$$rlk = \left([-(a \cdot s + e + s^2)]_q,\ a\right)$$

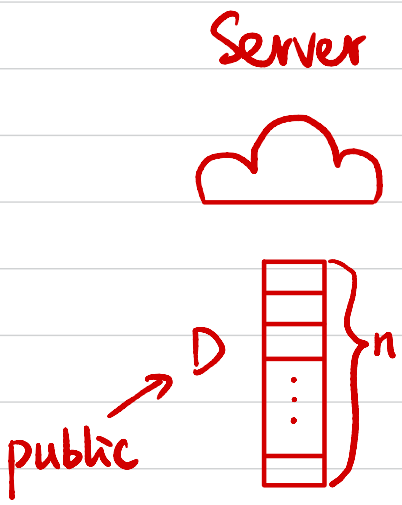
$$[rlk(s)]_q = -s^2 + \text{small}$$

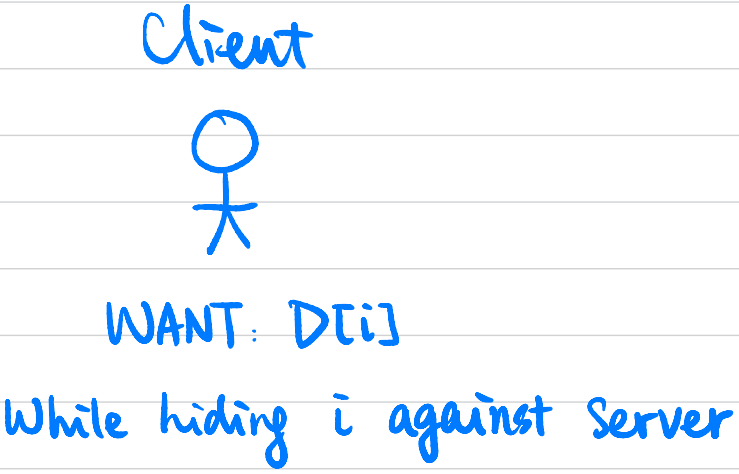
$$C(s) + C_2 \cdot rlk(s) = ?$$

$$rlk_i = \left([-(a \cdot s + e + 2^i \cdot s^2)]_q,\ a\right)$$

$$[rlk_i(s)]_q = -2^i \cdot s^2 + \text{small}$$

Application: Private Information Retrieval (PIR)





Query i
Key sk
$ct \leftarrow Enc(i)$

ct ←

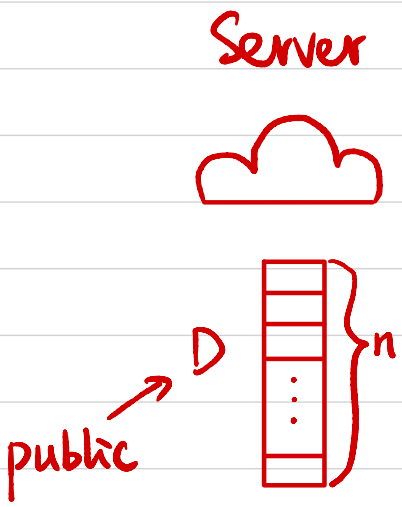
$ct' \leftarrow Eval(f, ct)$

$f_D(i) = D[i]$

→ ct'

$D[i] \leftarrow Dec_{sk}(ct')$

Private Information Retrieval (PIR)



WANT: D[i]

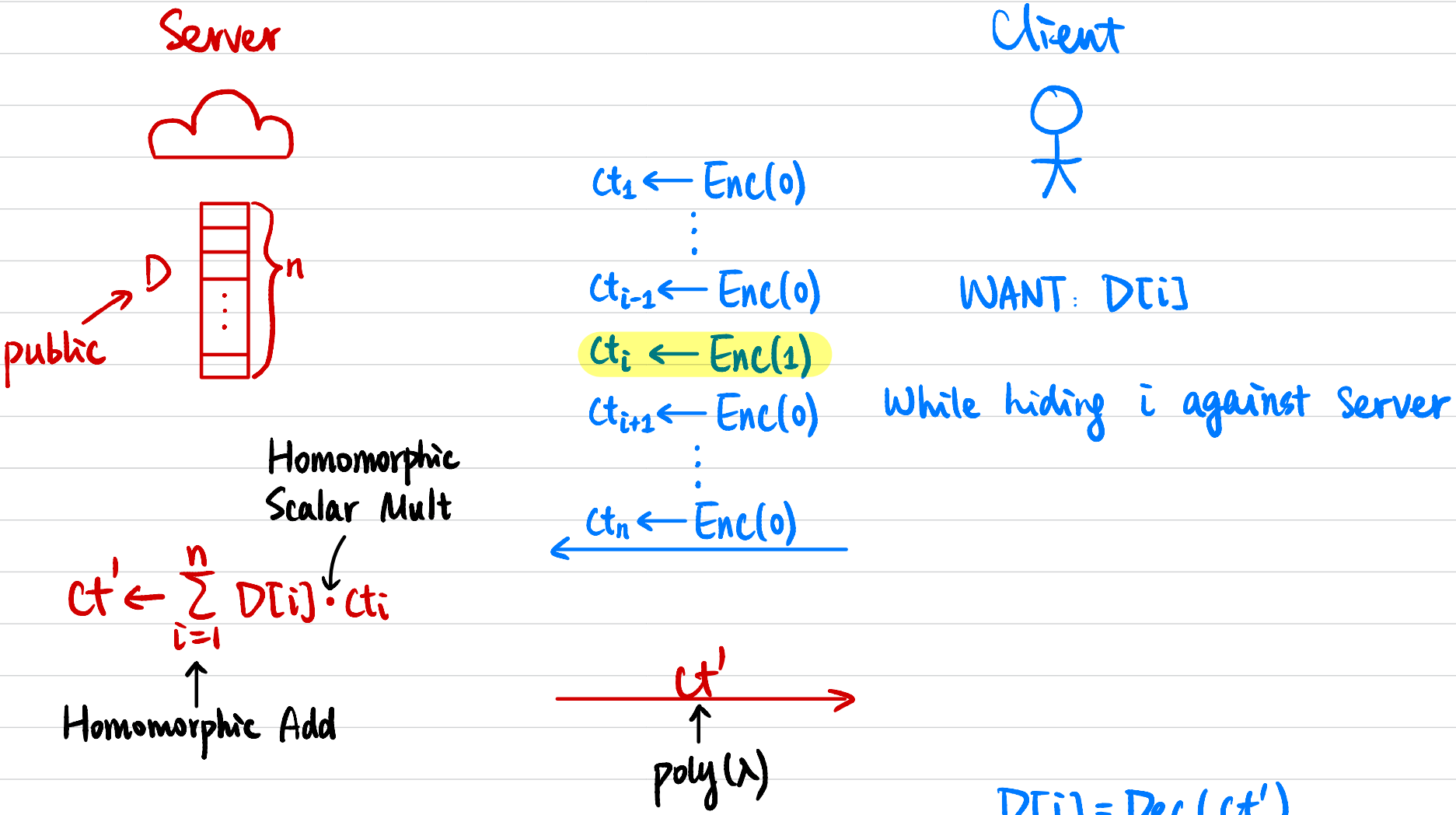
While hiding i against Server

Trivial Solution:

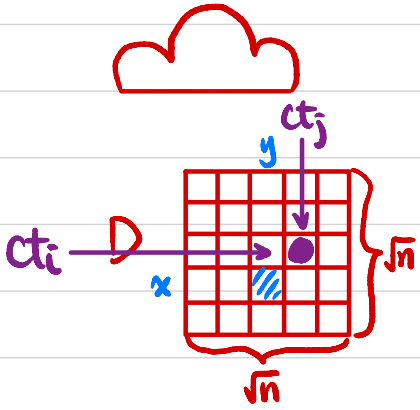
Communication complexity $O(n)$

Goal: Communication complexity $o(n)$

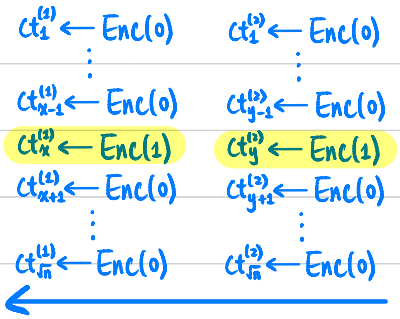
Private Information Retrieval (PIR)



Private Information Retrieval (PIR)



WANT: $D[x,y]$



While hiding (x,y) against Server

↑

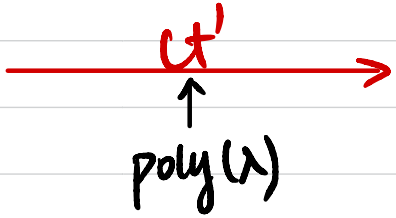
Why?

Homomorphic Scalar Mult

$$ct' \leftarrow \sum_{i,j=1}^{\sqrt{n}} D[i,j] \cdot ct_i^{(1)} \cdot ct_j^{(2)}$$

↑ Homomorphic Add

↑ Homomorphic Mult



$D[x,y] = Dec(ct')$

↑

Why?

Extend to dimension d ?

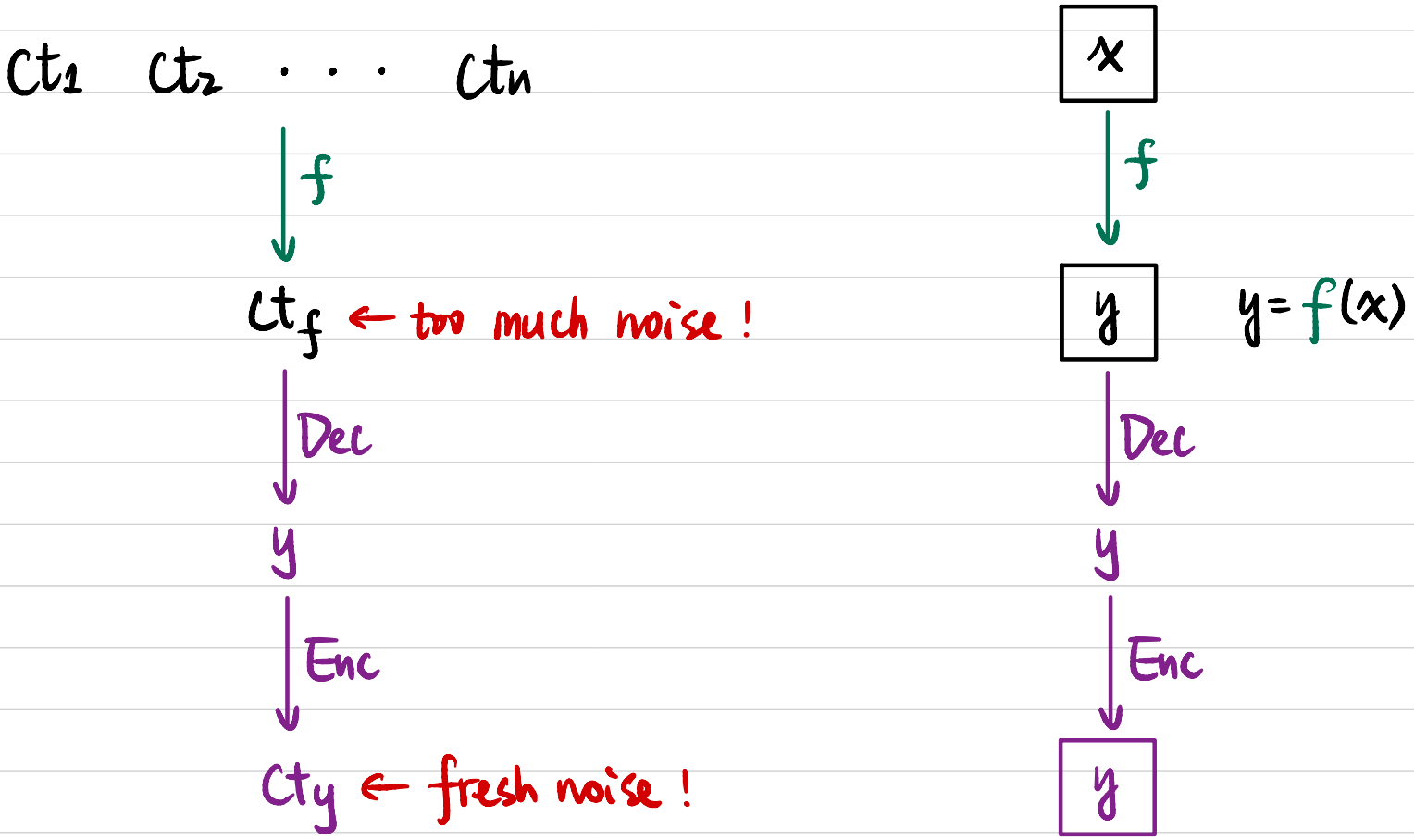
Homomorphic Mult = ?

Homomorphic Scalar Mult = ?

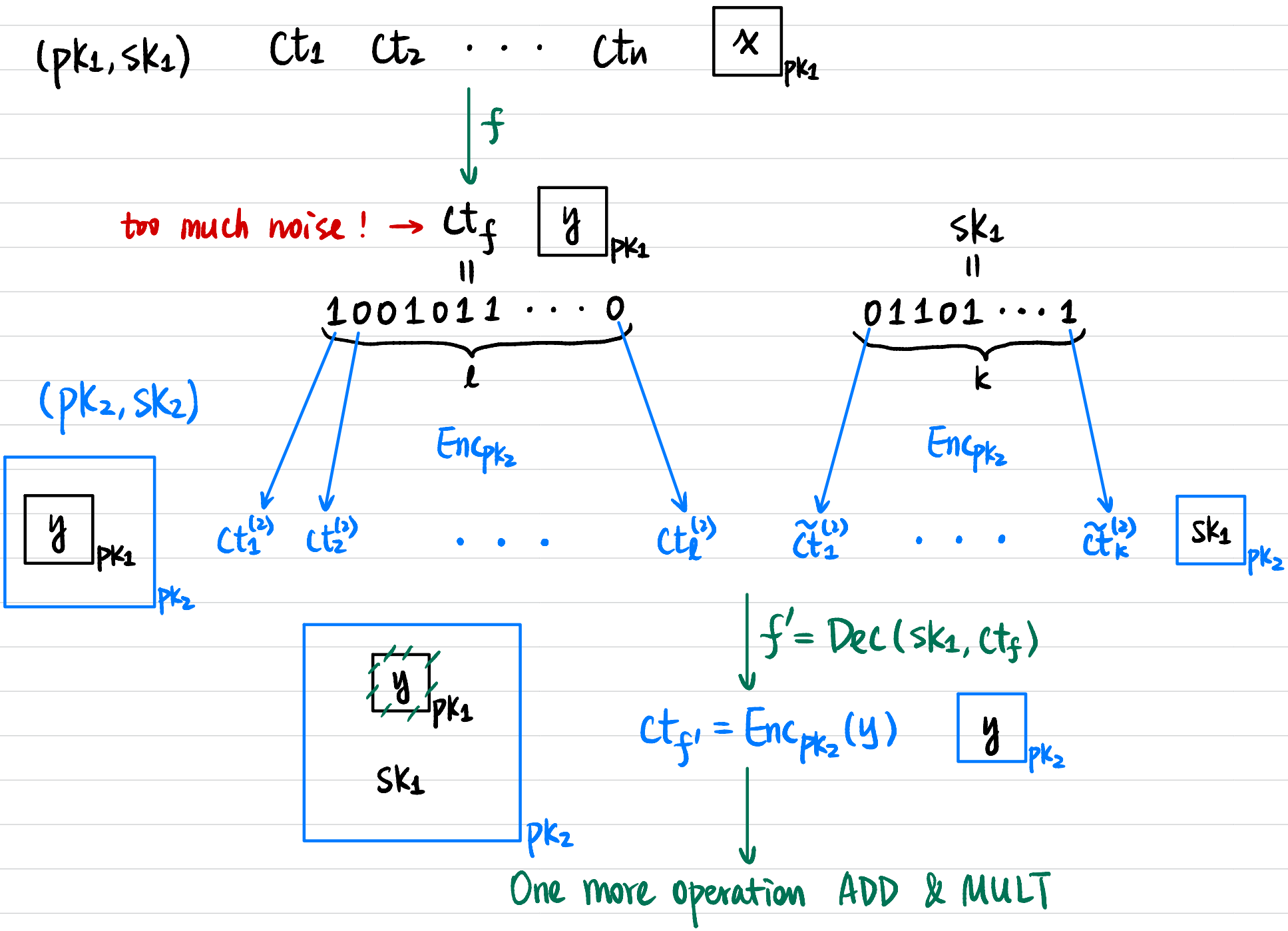
Homomorphic Add = ?

Communication = ?

Step 2: Bootstrapping



Leveled FHE


(pk_1, sk_1)
Ct_1 Ct_2 · · · Ct_n
x_{pk_1}
f
too much noise ! → Ct_f
y_{pk_1}
sk_1
=
1001011 · · · 0
l
01101 · · · 1
k
(pk_2, sk_2)
Enc_{pk_2}
Enc_{pk_2}
y_{pk_1} pk_2
$Ct_1^{(2)}$ $Ct_2^{(2)}$ · · · $Ct_l^{(2)}$
$\tilde{Ct}_1^{(2)}$ · · · $\tilde{Ct}_k^{(2)}$
sk_1 pk_2
y_{pk_1}
sk_1
pk_2
$f' = Dec(sk_1, Ct_f)$
$Ct_{f'} = Enc_{pk_2}(y)$
y_{pk_2}
One more operation ADD & MULT

Step 2: Bootstrapping

Leveled FHE: pk_1, pk_2, pk_3, . . . , pk_n

$Enc_{pk_2}(sk_1)$ $Enc_{pk_3}(sk_2)$ $Enc_{pk_n}(sk_{n-1})$

FHE: pk. $Enc_{pk}(sk)$

"circular secure" assumption