



Mathematics & Algorithms

Walter Ray-Dulany

*raydulany@apache.org*



# Introduction

Pirk uses the Wideskies algorithm to accomplish scalable PIR.

This algorithm can be broken down into two distinct conceptual pieces:

- ▶ Paillier Encryption
- ▶ The Query-Response-Result algorithms



# Paillier Encryption

Paillier encryption is a partially homomorphic public key scheme that relies on the function

$$\mathcal{E}_g : \mathbf{Z}/N\mathbf{Z} \times (\mathbf{Z}/N\mathbf{Z})^\times \rightarrow (\mathbf{Z}/N^2\mathbf{Z})^\times$$

given by

$$\mathcal{E}_g(x, y) = g^x y^N \mod N^2,$$

$$g \in (\mathbf{Z}/N^2\mathbf{Z})^\times.$$

When  $g$  has order a non-zero multiple of  $N$ ,  $\mathcal{E}_g$  is a bijection.

- ▶ Public key:  $(N, g)$ ,  $N$  an RSA modulus  $N = pq$ ,  $p$  and  $q$  primes of approximately the same bit-length, and  $g \in (\mathbf{Z}/N^2\mathbf{Z})^\times$  such that the order of  $g$  is a nonzero multiple of  $N$ .
- ▶ Private key:  $\lambda(N)$ , where  $\lambda$  is the Carmichael function

$$\lambda(N) = \text{lcm}(p-1, q-1)$$

that gives the exponent of  $(\mathbf{Z}/N\mathbf{Z})^\times$ .

- ▶ Plaintext space:  $\mathbf{Z}/N\mathbf{Z}$ .
- ▶ Ciphertext space:  $(\mathbf{Z}/N^2\mathbf{Z})^\times$ .

We can also consider the pair  $(p, q)$  to be the private key, as  $\lambda(N)$  is quickly and easily derived from it. Note that  $\lambda(N)$  is coprime to  $N$ .

# What Do We Mean By 'Homomorphic Encryption'?



An encryption scheme is fully homomorphic if it is a homomorphism from plaintext space to ciphertext space for arbitrary operations and arbitrary numbers of such operations. If this definition seems squishy and not very mathematical, that's because it is; it's hard to find a proper mathematical definition of this term.

An encryption scheme is partially homomorphic if it is a homomorphism for only some operations, or for only a few consecutive operations.

# Paillier Encryption is Homomorphic



Paillier encryption is a partial homomorphism between addition in  $\mathbf{Z}/N\mathbf{Z}$  and multiplication in  $(\mathbf{Z}/N^2\mathbf{Z})^\times$ .

Denote Paillier encryption by  $\mathcal{E}_g$  and decryption by  $\mathcal{D}_g$ , and let  $m$  and  $m' \in \mathbf{Z}/N\mathbf{Z}$ . Then

$$\begin{aligned} D(\mathcal{E}(m)\mathcal{E}(m') \bmod N^2) &= (m + m') \bmod N \\ D(\mathcal{E}(m)^k \bmod N^2) &= km \bmod N, \quad k \in \mathbf{N} \end{aligned}$$

Note that the second equality follows immediately from the first.





## General Paillier Algorithm

Let  $X = \{u < N^2 : u = 1 \pmod N\}$  and let  $L : X \rightarrow \mathbf{Z}/N\mathbf{Z}$  be defined by

$$L(u) = \frac{u - 1}{N} \pmod N.$$

This function is well defined over  $(\mathbf{Z}/N^2\mathbf{Z})^\times$ .

The general Paillier algorithm differs only slightly from Pirk's version.

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**Algorithm 1** General Paillier encryption and decryption.

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- 1: **procedure** Paillier encryption
  - 2:     **given**  $N$ , a random  $g \in (\mathbf{Z}/N^2\mathbf{Z})^\times$  of order a nonzero multiple of  $N$ , and a message  $m \in \mathbf{Z}/N\mathbf{Z}$
  - 3:     **select** a random value  $\zeta \in (\mathbf{Z}/N\mathbf{Z})^\times$
  - 4:     **return**  $\mathcal{E}(m) = g^m \zeta^N \bmod N^2$
  
  - 1: **procedure** Paillier decryption
  - 2:     **given**  $N$ ,  $\lambda(N)$ ,  $g$ , and ciphertext  $c \in (\mathbf{Z}/N^2\mathbf{Z})^\times$
  - 3:     **return**  $m = \frac{L(c^{\lambda(N)} \bmod N^2)}{L(g^{\lambda(N)} \bmod N^2)} \bmod N$
-



It is a straightforward exercise to check that

- ▶  $D(\mathcal{E}(m)) = m$
- ▶  $D(\mathcal{E}(m)\mathcal{E}(m') \bmod N^2) = (m + m') \bmod N$



## Paillier As Used In Wideskies



The version of Paillier used in Wideskies is a computationally simpler variant of the full Paillier scheme that sacrifices no security over the general case.

Pirk's simplified version of Paillier simply uses

$$g \equiv 1 + N \pmod{N^2}$$
$$\implies L(g^{\lambda(N)} \pmod{N^2}) = \lambda(N),$$

the proof of which is a straightforward exercise.

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**Algorithm 2** Paillier encryption and decryption

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- 1: **procedure** Paillier encryption
  - 2:     **given**  $N$  and a message  $m \in \mathbf{Z}/N\mathbf{Z}$
  - 3:     **select** a random value  $\zeta \in (\mathbf{Z}/N^2\mathbf{Z})^\times$
  - 4:     **return**  $\mathcal{E}(m) = (1 + mN)\zeta^N \bmod N^2$
  
  - 1: **procedure** Paillier decryption
  - 2:     **given**  $N$ ,  $\lambda(N)$ , and a ciphertext  $c \in (\mathbf{Z}/N^2\mathbf{Z})^\times$
  - 3:     **set**  $\mu = \lambda(N)^{-1} \bmod N$                      $\triangleright$  Recall  $\gcd(\lambda(N), N) = 1$
  - 4:     **set**  $\hat{c} = c^{\lambda(N)} \bmod N^2$
  - 5:     **set**  $\hat{m} = L(c^{\lambda(N)} \bmod N^2)$
  - 6:     **return**  $\hat{m}\mu \bmod N$
-





For more on Paillier encryption and the (hypothesized) hard problem upon which it is based, see

[https://pirk.incubator.apache.org/papers/1999\\_asiacrypt\\_paillier\\_paper.pdf](https://pirk.incubator.apache.org/papers/1999_asiacrypt_paillier_paper.pdf)

on Pirk's website.

## Wideskies

The algorithm requires the following parameters, which are not independent (see the next slide).

- ▶  $N$ , the Paillier modulus
- ▶  $B$ , the bit-length of  $N$
- ▶  $H$  (or  $H_k$ ), a keyed hash function (with key  $k$ )
- ▶  $\ell$ , the bit length of the output of  $H$ , i.e.  $H_k : \mathbf{Z} \rightarrow (\mathbf{Z}/2\mathbf{Z})^\ell$
- ▶  $\tau$ , the number of search terms
- ▶  $\delta$ , the number of bits of data returned for each search hit
- ▶  $b$  the chunk size, in bits, determining how data is split among responses.
- ▶  $r$ , the number of responses that can be returned per query request period per search term

- ▶  $2^{b\tau} < N$ : there must be space in the modulus to hold all the data, even if each search term hits as often as possible.
- ▶  $\tau < 2^\ell$ : Although the paper permits search term hash collisions, Pirk does not permit them. Typically  $\tau \ll 2^\ell$
- ▶  $b|\delta$ : Chunk size must evenly divide the data size
- ▶  $\frac{\delta}{b}|r$ : the number of chunks per returned datum must divide the number of responses, for bandwidth efficiency.
- ▶  $H$ : Must be pseudo-random but need not be cryptographically secure.

All of

$$H, \ell, N, B, \delta, b, \text{ and } r$$

are public, that is, must be shared between the client and server.

Note that the fact that  $2^{b\tau} < N$  gives some information on the number of search terms the client is using; the amount of this information can be decreased without bound by choosing  $N$  and  $\ell$  to be much larger than would be otherwise necessary; this necessarily causes a performance hit.



## Wideskies Algorithm, Without Encryption

# Wideskies Without Encryption?



The Wideskies algorithm is of sufficient complexity that it can be useful to go through the algorithm without the encryption and decryption steps first, in order to orient ourselves.

After, it will be straightforward to see the changes that using the Paillier encryption requires.



Query, Without Encryption



# The Query Algorithm, Without Encryption



Let  $T_0, \dots, T_{\tau-1} \in \mathbf{Z}/N\mathbf{Z}$  be our search terms.

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## Algorithm 3 Query Formation Algorithm version 1

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- 1: Choose a random key  $k$  for  $H$ .
  - 2: Compute  $H_k(T_0), \dots, H_k(T_{\tau-1})$ .
  - 3: **while**  $\text{card}(\{H_k(T_0), \dots, H_k(T_{\tau-1})\}) < \tau$  **do**
  - 4:     **go to** 1              $\triangleright$  If there are hash collisions, pick a new key.
  - 5: **for**  $i = 0, \dots, 2^\ell - 1$  **do**
  - 6:     Set
$$E_i = \begin{cases} 2^{jb} & \text{if } i = H_k(T_j); \\ 0 & \text{otherwise.} \end{cases}$$
  - 7: **return**  $\{E_0, \dots, E_{2^\ell-1}, H, k, N\}$
-

Since  $\tau \ll 2^\ell$ , we expect most of the  $E_i$  to be zero.

We will typically denote  $H_k(T)$  by  $\mathcal{T}$  and its associated  $E$  by  $E_{\mathcal{T}}$ . If we wish to keep track of a specific  $T$  we will write  $\mathcal{T}_j$  and  $E_{\mathcal{T}_j}$ .



Response, Without Encryption

We must initialize some values before forming the response.

1.  $c_0, \dots, c_{2^\ell-1} = 0$ , counters to keep track of the number of times each  $E_{\mathcal{T}}$  has been seen.
2.  $Y_0, \dots, Y_{r-1} = 0$ , response vectors.

# Response Data, Without Encryption



Responder information comes in pairs  $(T, D)$  where  $T$  is a (potential) search term, and  $D$  is  $T$ 's associated response datum, which will be returned if  $T$  is a search term.

We view  $D$  as a  $\delta$ -long bit stream  $(d_0, \dots, d_{\delta-1})$ , and break  $D$  up into  $\delta/b$  chunks  $D_i$  as

$$D_i = (d_{i \cdot b}, d_{i \cdot b + 1}, \dots, d_{(i+1) \cdot b - 1}), \quad i = 0, \dots, \delta/b - 1.$$

For example, if  $D = 011010$  and  $b = 3$ , then

$$D_0 = 011$$

$$D_1 = 010$$

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**Algorithm 4** Stream processing, plaintext version

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```
1: Input:  $\mathbf{T} = \{(T, D)\}$ 
2: for  $(T, D) \in \mathbf{T}$  do
3:   Compute  $\mathcal{T} = H_k(T)$ 
4:   if  $c_{\mathcal{T}} + \frac{\delta}{b} > r$  then  $\triangleright$  The space allocated for term  $T$  is full.
5:     return
6:   else
7:     Split  $D$  into  $b$ -bit chunks  $D_0, \dots, D_{(\delta/b)-1}$ .
8:     for  $i = 0, \dots, (\delta/b) - 1$  do
9:       Set  $\mathcal{D}_i = D_i E_{\mathcal{T}} \bmod N$   $\triangleright$  Nonzero only if  $E_{\mathcal{T}} \neq 0$ .
10:      Set  $Y_{i+c_{\mathcal{T}}} = Y_{i+c_{\mathcal{T}}} + \mathcal{D}_i \bmod N$ 
11:      Set  $c_{\mathcal{T}} = c_{\mathcal{T}} + (\delta/b)$ 
12: Output:  $Y_0, \dots, Y_{r-1}$ 
```

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## Response Example, Without Encryption



Let's look at how the response would look on the first four  $(T, D)$  pairs that pass through the algorithm.

Suppose that among our search terms are  $T$  and  $T'$ , with

$$H_k(T) = j \text{ and} \\ H_k(T') = j'.$$

Suppose that  $T''$ , with  $H_k(T'') = j''$ , is *not* a search term.

Let the responder see, in order, the pairs  $(T, D^0)$ ,  $(T', D^1)$ ,  $(T'', D^2)$ ,  $(T, D^3)$ .

The  $Y_i$  are formed by summing down the columns in following matrices.



# Response Example Start, Without Encryption



No terms have yet been evaluated.

Index	$Y_0$	$\dots$	$Y_{\delta/b-1}$	$Y_{\delta/b}$	$\dots$	$Y_{2\delta/b-1}$
$\vdots$						
$j$	0	$\dots$	0	0	$\dots$	0
$\vdots$						
$j'$	0	$\dots$	0	0	$\dots$	0
$\vdots$						
$j''$	0	$\dots$	0	0	$\dots$	0
$\vdots$						

$$c_j = 0, c_{j'} = 0, c_{j''} = 0.$$

# Response Example: First Term, Without Encryption



$(T, D^0)$  enters and is processed; hit:

Index	$Y_0$	$\dots$	$Y_{\delta/b-1}$	$Y_{\delta/b}$	$\dots$	$Y_{2\delta/b-1}$
$\vdots$						
$j$	$D_0^0 2^{jb}$	$\dots$	$D_{\delta/b-1}^0 2^{jb}$	0	$\dots$	0
$\vdots$						
$j'$	0	$\dots$	0	0	$\dots$	0
$\vdots$						
$j''$	0	$\dots$	0	0	$\dots$	0
$\vdots$						

$$c_j = \delta/b, c_{j'} = 0, c_{j''} = 0.$$

# Response Example Second Term, Without Encryption



$(T', D^1)$  enters and is processed; hit:

Index	$Y_0$	$\dots$	$Y_{\delta/b-1}$	$Y_{\delta/b}$	$\dots$	$Y_{2\delta/b-1}$
$\vdots$						
$j$	$D_0^0 2^{jb}$	$\dots$	$D_{\delta/b-1}^0 2^{jb}$	0	$\dots$	0
$\vdots$						
$j'$	$D_0^1 2^{j'b}$	$\dots$	$D_{\delta/b-1}^1 2^{j'b}$	0	$\dots$	0
$\vdots$						
$j''$	0	$\dots$	0	0	$\dots$	0
$\vdots$						

$$c_j = \delta/b, \mathbf{c}_{j'} = \delta/b, c_{j''} = 0.$$

# Response Example Third Term, Without Encryption



$(T'', D^2)$  enters and is processed; no hit:

Index	$Y_0$	$\dots$	$Y_{\delta/b-1}$	$Y_{\delta/b}$	$\dots$	$Y_{2\delta/b-1}$
$\vdots$						
$j$	$D_0^0 2^{jb}$	$\dots$	$D_{\delta/b-1}^0 2^{jb}$	0	$\dots$	0
$\vdots$						
$j'$	$D_0^1 2^{j'b}$	$\dots$	$D_{\delta/b-1}^1 2^{j'b}$	0	$\dots$	0
$\vdots$						
$j''$	$D_0^2 \cdot 0$	$\dots$	$D_{\delta/b-1}^2 \cdot 0$	0	$\dots$	0
$\vdots$						

$c_j = \delta/b$ ,  $c_{j'} = \delta/b$ ,  **$c_{j''} = \delta/b$** .

# Response Example Fourth Term, Without Encryption



$(T, D^3)$  enters and is processed; hit:

Index	$Y_0$	$\dots$	$Y_{\delta/b-1}$	$Y_{\delta/b}$	$\dots$	$Y_{2\delta/b-1}$
$\vdots$						
$j$	$D_0^0 2^{jb}$	$\dots$	$D_{\delta/b-1}^0 2^{jb}$	$D_0^3 2^{jb}$	$\dots$	$D_{\delta/b-1}^3 2^{jb}$
$\vdots$						
$j'$	$D_0^1 2^{j'b}$	$\dots$	$D_{\delta/b-1}^1 2^{j'b}$	0	$\dots$	0
$\vdots$						
$j''$	$D_0^2 \cdot 0$	$\dots$	$D_{\delta/b-1}^2 \cdot 0$	0	$\dots$	0
$\vdots$						

$$c_j = 2\delta/b, c_{j'} = \delta/b, c_{j''} = \delta/b.$$



Result, Without Encryption

The algorithm for getting the results out of the response return is straightforward. To begin,

- ▶ Write  $Y_i = \sum_{k=0}^{\tau-1} 2^{kb} P_{ki}$  in base  $2^b$ , where  $P_{ki}$  is the value of the  $k^{\text{th}}$  row in the  $i^{\text{th}}$  column. Note each  $P_{ki}$  is  $b$ -bits long, and therefore  $Y_i < N$ .
- ▶  $Y_i$  will have data on search term  $T$  if and only if  $T$  was seen  $i + 1$  times before the responder returned.

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**Algorithm 5** Data recovery, plaintext version

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- 1: Set  $M = 2^{jb}(2^b - 1)$   $\triangleright b$  1s left-shifted  $jb$  places.
  - 2: **for**  $\eta = 1, \dots, (rb/\delta)$  **do**  $\triangleright$  At most  $rb/\delta$  hits can be returned.
  - 3:     **for**  $i = 0, \dots, (\delta/b) - 1$  **do**  $\triangleright$  Each hit uses  $\delta/b$  chunks.
  - 4:         Set  $D_i = Y_{(\eta-1)(\delta/b)+i} \& M$   $\triangleright$  "&" denotes bit-wise AND.
  - 5:         Set  $D_i = D_i / 2^{jb}$   $\triangleright$  Step 4 ensures  $2^{jb} \mid D_i$
  - 6:     Set  $X_\eta = D_0 \parallel D_1 \parallel \dots \parallel D_{(\delta/b)-1}$
  - 7: **return**  $X_1, \dots, X_{(rb/\delta)}$   $\triangleright$  the data corresponding to selector  $T_j$
-





## Wideskies Algorithm, With Encryption

# Adding Encryption To The Mix



Adding encryption is straightforward. The following slides have the encryption-enabled algorithms, with the differences from the earlier slides in bold.



Query, Encrypted

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**Algorithm 6** Query formation, ciphertext version 1

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- 1: Choose a random key  $k$  for  $H$ .
- 2: Compute  $H_k(T_0), \dots, H_k(T_{\tau-1})$ .
- 3: **while**  $\text{card}(\{H_k(T_0), \dots, H_k(T_{\tau-1})\}) < \tau$  **do**
- 4:     **go to** 1
- 5: **for**  $i = 0, \dots, 2^\ell - 1$  **do**
- 6:     Set

$$\mathcal{E}_i = \begin{cases} \mathcal{E}(2^{jb}) & \text{if } i = H_k(T_j) \text{ for some } j \in \{0, \dots, \tau - 1\} \\ \mathcal{E}(0) & \text{otherwise.} \end{cases}$$

- 7: **return**  $\{\mathcal{E}_0, \dots, \mathcal{E}_{2^\ell-1}, H, k, N\}$
-



Response, Encrypted

As before, we must initialize some values before forming the response.

1.  $c_0, \dots, c_{2^\ell-1} = 0$ , counters to keep track of the number of times each  $\mathcal{E}_{\mathcal{T}}$  has been seen.
2.  $\mathbf{Y}_0, \dots, \mathbf{Y}_{r-1} = \mathbf{1}$ , response vectors.

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**Algorithm 7** Stream processing, ciphertext version
 

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```

1: Input:  $\mathbf{T} = \{(T, D)\}$ 
2: Initialize:
3:   Counters  $c_i = 0, 0 \leq i \leq (2^l - 1)$ 
4:   Paillier ciphertext values  $\mathcal{Y}_j = 1, 0 \leq j \leq (r - 1)$ 
5: for  $(T, D) \in \mathbf{T}$  do
6:   Compute  $\mathcal{T} = H_k(T)$ 
7:   if  $c_{\mathcal{T}} + \frac{\delta}{b} > r$  then
8:     return
9:   else
10:    Split  $D$  into  $b$ -bit chunks,  $D = D_0, \dots, D_{(\delta/b)-1}$ 
11:    for  $i = 0, \dots, (\delta/b) - 1$  do
12:      Set  $\mathcal{D}_i = \mathcal{E}_{\mathcal{T}}^{D_i} \bmod N^2$ 
13:      Set  $\mathcal{Y}_{i+c_{\mathcal{T}}} = \mathcal{Y}_{i+c_{\mathcal{T}}} \mathcal{D}_i \bmod N^2$ 
14:    Set  $c_{\mathcal{T}} = c_{\mathcal{T}} + (\delta/b)$ 
15: Output:  $\mathcal{Y}_0, \dots, \mathcal{Y}_{r-1}$ 
  
```

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Result, Encrypted



## Result, Encrypted (and then Decrypted)



Actually literally the same algorithm as before is used; the only difference is that we first decrypt the encrypted  $\mathcal{Y}_i$ .



## Distributed Version



The paper goes over how to do the distributed version; the change is straightforward, and our earlier example slides make it easy to see how it works.

# Distributed Difference: Unencrypted Sums, Encrypted Products



Recall our example matrix:

Index	$Y_0$	$\dots$	$Y_{\delta/b-1}$	$Y_{\delta/b}$	$\dots$	$Y_{2\delta/b-1}$
$\vdots$						
$j$	$D_0^0 2^{jb}$	$\dots$	$D_{\delta/b-1}^0 2^{jb}$	$D_0^3 2^{jb}$	$\dots$	$D_{\delta/b-1}^3 2^{jb}$
$\vdots$						
$j'$	$D_0^1 2^{j'b}$	$\dots$	$D_{\delta/b-1}^1 2^{j'b}$	0	$\dots$	0
$\vdots$						
$j''$	$D_0^2 \cdot 0$	$\dots$	$D_{\delta/b-1}^2 \cdot 0$	0	$\dots$	0
$\vdots$						

# Distributed Difference: Unencrypted Sums, Encrypted Products



When we moved to an encrypted algorithm, all of the  $D_i$ -long sums of  $E_i$  became  $\mathcal{E}_i^{D_i}$ .

In the distributed version, we actually make matrix components rather than the fake matrix of  $D_i$  in certain bit-positions we had earlier.

In the matrix, rows are indexed by  $0 \leq \mathcal{T} \leq 2^\ell - 1$ , columns by  $0 \leq j \leq r - 1$ .

# Distributed Difference: Unencrypted Sums, Encrypted Products



As before, let

$$\begin{aligned}H_k(T) &= j, \\H_k(T') &= j', \text{ and} \\H_k(T'') &= j'',\end{aligned}$$

with  $T$  and  $T'$  search terms and  $T''$  not.

Notice that this time we won't simply discard the data  $D_2$  from  $T''$ ; we no longer multiply it by zero, but use it as the exponent of  $\mathcal{E}_{j''}$ , which is an encryption of 0.

# Distributed Difference: Unencrypted Sums, Encrypted Products



The matrix in the encrypted setting:

Index	$\mathcal{Y}_0$	$\cdots$	$\mathcal{Y}_{\delta/b-1}$	$\mathcal{Y}_{\delta/b}$	$\cdots$	$\mathcal{Y}_{2\delta/b-1}$
$\vdots$						
$j$	$\mathcal{E}_j^{D_0^0}$	$\cdots$	$\mathcal{E}_j^{D_{\delta/b-1}^0}$	$\mathcal{E}_j^{D_0^3}$	$\cdots$	$\mathcal{E}_j^{D_{\delta/b-1}^3}$
$\vdots$						
$j'$	$\mathcal{E}_{j'}^{D_0^1}$	$\cdots$	$\mathcal{E}_{j'}^{D_{\delta/b-1}^1}$	1	$\cdots$	1
$\vdots$						
$j''$	$\mathcal{E}_{j''}^{D_0^2}$	$\cdots$	$\mathcal{E}_{j''}^{D_{\delta/b-1}^2}$	1	$\cdots$	1
$\vdots$						

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## Algorithm 8 Responder - Matrix Variant

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```
1: Input:  $\mathbf{T} = \{(T, D)\}$ 
2: Initialize:
3:   Counters  $c_i = 0$ ,  $0 \leq i \leq (2^l - 1)$ 
4:   Paillier ciphertext values  $\mathcal{Y}_j = 1$ ,  $0 \leq j \leq (r - 1)$ 
5: for  $(T, D) \in \mathbf{T}$  do
6:   Compute  $\mathcal{T} = H_k(T)$  ▷ View as the row index of  $M$  :  $m_{\mathcal{T}, j}$ 
7:   if  $c_{\mathcal{T}} + \frac{\delta}{b} > r$  then
8:     return
9:   else
10:    Split  $D$  into  $b$ -bit chunks,  $D = D_0 \| D_1 \| \dots \| D_{(\delta/b)-1}$ 
11:    for  $k = 0, \dots, (\delta/b) - 1$  do
12:      Set  $m_{\mathcal{T}, c_{\mathcal{T}}+k} = \mathcal{E}_{\mathcal{T}}^{D_k} \bmod N^2$ 
13:      Set  $c_{\mathcal{T}} = c_{\mathcal{T}} + (\delta/b)$ 
14: for  $0 \leq j \leq (r - 1)$ : do
15:    $\mathcal{Y}_j = \prod_{i=0}^{2^l-1} m_{i,j}$ 
16: Output:  $\mathcal{Y}_0, \dots, \mathcal{Y}_{r-1}$ 
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## Algorithm 9 Responder - Distributed Variant

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1: Input:  $\mathbf{T} = \{(T, D)\}$ 
2: for  $(T, D) \in \mathbf{T}$  in parallel do
3:   Compute  $\mathcal{T} = H_k(T)$  ▷ View as the row index of  $M : m_{\mathcal{T}, j}$ 
4:   Split  $D$  into  $b$ -bit chunks,  $D = D_0 \| D_1 \| \dots \| D_{(\delta/b)-1}$ 
5:   Form  $\mathbf{D} = \{D_k : 0 \leq k \leq (\delta/b) - 1\}$ 
6:   Emit  $(\mathcal{T}, \mathbf{D})$ 
7: for each  $\mathcal{T}$  in parallel do
8:   Initialize  $c_{\mathcal{T}} = 0$ 
9:   while  $c_{\mathcal{T}} < r$  do
10:    for each  $(\mathcal{T}, \mathbf{D})$  do
11:      for each  $D_k \in \mathbf{D}, 0 \leq k \leq \dots, (\delta/b) - 1$  do
12:        Set  $m_{\mathcal{T}, c_{\mathcal{T}}} = \mathcal{E}_{\mathcal{T}}^{D_k} \bmod N^2$ 
13:        Emit  $(c_{\mathcal{T}}, m_{\mathcal{T}, c_{\mathcal{T}}})$ 
14:         $c_{\mathcal{T}} = c_{\mathcal{T}} + 1$ 
15: for  $0 \leq j \leq (r-1)$  in parallel: do
16:    $\mathcal{Y}_j = \prod_{i=0}^{2^j-1} m_{i,j}$ 
17: Output:  $\mathcal{Y}_0, \dots, \mathcal{Y}_{r-1}$ 

```

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## 'Actual' Example

We run through the above actual numbers.

Let

- ▶  $N = 35$ ,  $p = 5$ ,  $q = 7$ ,  $\lambda(N) = 12$ ,  $B = 5$ .
- ▶  $\tau$ , the number of terms we'll search for, is 2. These terms are  $T_0 = 0$  and  $T_1 = 3$ .
- ▶ We won't specify most of  $H$ ; only that  $\ell = 4$ ,  $H(T_0) = 0110 = 6$  and  $H(T_3) = 0010 = 2$ .
- ▶ Our return data are  $\delta = 4$  bits long; let  $b = 2$ . We limit ourselves to  $r = 4$ .
- ▶ Let's consult an RNG to choose values of  $\zeta$  for use in Paillier.

# Let's Consult an RNG



```
int getRandomNumber()  
{  
    return 4; // chosen by fair dice roll.  
              // guaranteed to be random.  
}
```

Source: [http://imgs.xkcd.com/comics/random\\_number.png](http://imgs.xkcd.com/comics/random_number.png)

## Actual Example Setup



Great, we will randomly set  $\zeta = 4$  for all encryptions.

- ▶ Since  $H(T_0) = 6$ ,

$$\begin{aligned}\mathcal{E}_6 &= \mathcal{E}(2^{0.2}) \\ &= 639\end{aligned}$$

- ▶ Similarly, since  $H(T_1) = 2$ ,

$$\begin{aligned}\mathcal{E}_2 &= \mathcal{E}(2^{1.2}) \\ &= 359.\end{aligned}$$

- ▶ All other terms are encryptions of 0; we will write these as 1 even though they would in fact be distributed across a wide array of values in  $(\mathbf{Z}/N^2\mathbf{Z})^\times$ .

## Example Response



Suppose, as in our example above, that the responder inputs, in order, are  $(T_0, D^0)$ ,  $(T_1, D^1)$ ,  $(5, D^2)$ , and  $(T_0, D^3)$ , after which point the responder returns (perhaps another  $T_0$  comes in, thus causing  $c_{T_0}$  to be greater than  $r$ ). Here,

$$D^0 = 0000 = (D_0^0, D_1^0) = (00, 00),$$

$$D^1 = 0110 = (D_0^1, D_1^1) = (01, 10),$$

$$D^2 = 0111 = (D_0^2, D_1^2) = (01, 11),$$

$$D^3 = 0010 = (D_0^3, D_1^3) = (00, 10),$$

Note that since 5 is not a search term, it will result in raising an encrypted zero to  $D^2 = 7$ ; again, we're just going to write 1, even though the actual algorithm may (will) have any encryption of 0 instead.

# Example Response Matrix



The responder forms the matrix

Index	$\mathcal{Y}_0$	$\mathcal{Y}_1$	$\mathcal{Y}_2$	$\mathcal{Y}_3$
$\vdots$				
2	$\varepsilon_2^{D_0^1} \bmod N^2 = 359$	$\varepsilon_2^{D_1^1} \bmod N^2 = 256$	1	1
$\vdots$				
6	$\varepsilon_6^{D_0^0} \bmod N^2 = 1$	$\varepsilon_6^{D_1^0} \bmod N^2 = 1$	$\varepsilon_6^{D_2^3} \bmod N^2 = 1$	$\varepsilon_6^{D_3^3} \bmod N^2 = 396$
7	1	1	1	1
$\vdots$				



The only interesting responses are  $\mathcal{Y}_0 = 359$ ,  $\mathcal{Y}_1 = 256$ , and  $\mathcal{Y}_3 = 396$  (products are taken down columns).

We decrypt to  $Y_0 = 0100$ ,  $Y_1 = 8 = 1000$  and  $Y_3 = 2 = 0010$ , and then run through the processing algorithm:

- ▶ Data For  $T_0$ :  $M = 0011$ 
  - ▶  $X_1 = 0$ :
    - ▶  $D_0 = (Y_0 \& 0011) / 2^0 = 00$
    - ▶  $D_1 = (Y_1 \& 0011) / 2^0 = 00$
  - ▶  $X_2 = 2$ :
    - ▶  $D_0 = (Y_2 \& 0011) / 2^0 = 00$
    - ▶  $D_1 = (Y_3 \& 0011) / 2^0 = 10$

We decrypted to  $Y_0 = 0100$ ,  $Y_1 = 8 = 1000$  and  $Y_3 = 2 = 0010$ , and then run through the processing algorithm:

- ▶ Data For  $T_1$ :  $M = 1100$ .
  - ▶  $X_1 = 6$ :
    - ▶  $D_0 = (Y_0 \& 1100) / 2^2 = 01$
    - ▶  $D_1 = (Y_1 \& 1100) / 2^2 = 10$
  - ▶  $X_2 = 0$ :
    - ▶  $D_0 = (Y_2 \& 1100) / 2^2 = 00$
    - ▶  $D_1 = (Y_3 \& 1100) / 2^2 = 00$

These results are precisely the data the responder had.\*

\*: We cannot distinguish the fact that  $X_2$  is a non-response from the possibility that  $X_2$  represents an actual return of a datum  $D = 0$  from the responder. In practice, one must avoid using  $D = 0$  to eliminate this ambiguity