

# *One-time trapdoor one-way functions*

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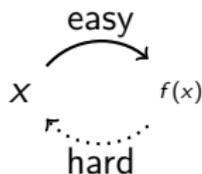
<sup>1</sup> Smals      <sup>2</sup> UCL Crypto Group



# Trapdoors in cryptography

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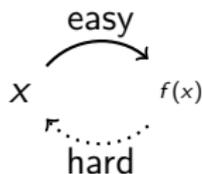
- ▶ One-way function (OWF)
  - ▶ Easy to compute but hard to invert
- ▶ Trapdoor one-way function (TOWF)
  - ▶ Can be inverted with the help of a *trapdoor*
  - ▶ Useful for public key cryptography :  
public key encryption, digital signatures,...



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public key encryption, digital signatures,...
- ▶ In general, a trapdoor gives some power to its holder



# *RSA and Rabin TOWF*

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- ▶ Oldest and most famous TOWF [RSA78,R79]

$$f : \mathbb{Z}_n^* \rightarrow \mathbb{Z}_n^* : x \rightarrow x^e \bmod n$$

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- ▶ One-way if  $n = pq$ ,  $p$  and  $q$  large primes, and  $1 < e < n$
- ▶ Trapdoor : given  $p, q$  we can invert  $f$



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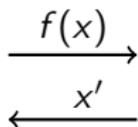
- ▶ One-way if  $n = pq$ ,  $p$  and  $q$  large primes, and  $1 < e < n$
- ▶ Trapdoor : given  $p, q$  we can invert  $f$
- ▶ Can we use the trapdoor and keep it secret?  
Does inverting  $f$  reveal  $p, q$ ?



## Leaking trapdoors

---

- ▶ Suppose Bob has a trapdoor.  
Alice chooses  $x$ , sends  $y = f(x)$  to Bob.  
Bob uses the trapdoor to compute  $x'$  such  
that  $f(x') = y$ . Bob sends  $x'$  to Alice.



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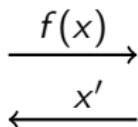
$$\begin{array}{c} \xrightarrow{f(x)} \\ \xleftarrow{x'} \end{array}$$

- ▶ RSA :
  - ▶  $\gcd(e, \varphi(n)) = 1$
  - ▶  $f : x \rightarrow x^e \bmod n$  is bijective
  - ▶  $x' = x$  so  $x'$  **does not leak anything**



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  - ▶  $f : x \rightarrow x^e \bmod n$  is bijective
  - ▶  $x' = x$  so  $x'$  **does not leak anything**
- ▶ Rabin :
  - ▶  $f : x \rightarrow x^2 \bmod n$  is four to one
  - ▶  $x' = x\epsilon$  where  $\epsilon^2 = 1 \bmod n$  (there are 4 values)
  - ▶ If  $\epsilon \neq \pm 1$ , **the trapdoor is leaked**



# Limiting the trapdoor's power

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- ▶ Typically leaking trapdoors are undesirable... but what about *positive* applications?



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- ▶ **Useful to restrict the trapdoor's power**
  - ▶ To ensure that it is used only once  $\Rightarrow$  e-coins?
  - ▶ To prove that it has been used  $\Rightarrow$  right delegation system?
  - ▶ To achieve some delayed fairness  $\Rightarrow$  fair exchange?



# Outline

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Introduction

One-time trapdoor one-way functions (OTTOWF)

Constructions

Fair exchange protocols

Conclusion



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# Definition

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- ▶ A one-time trapdoor one-way function (OTTOWF) is given by 5 algorithms
  - ▶ **Setup** : generates  $\langle k, t \rangle$  where  $k$  is a *key* (parameter) and  $t$  is the *trapdoor*
  - ▶ **Eval** : upon input of  $\langle k, m \rangle$  where  $m$  is some *message*, outputs a *hash value*  $h$
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  - ▶ **Preimage** : upon input of  $\langle k, h, t \rangle$ , outputs a message  $m$
  - ▶ **TrapExtr** : upon input of  $\langle k, m, m' \rangle$  where  $m, m'$  are two messages, outputs either  $\perp$  or a trapdoor  $t$



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  - ▶ **Trapdoor** : with the trapdoor, possible to “invert” in the sense of satisfying **Verify**
  - ▶ **Fairness** : **TrapExtr** recovers the trapdoor if it gets two messages with the same hash value, one of them computed with the trapdoor



## *Definition remarks*

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- ▶ An OTTOWF is not necessarily a TOWF
  - ▶ **Eval** can be probabilistic
  - ▶ **Correctness** does not require  $\mathbf{Eval}(\mathbf{Preimage}(h)) = h$ , but only that the **Preimage** algorithm finds a value that satisfies the **Verify** algorithm



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- ▶ An OTTOWF is a TOWF if **Eval** is deterministic and **Verify** just recomputes it



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## 3 OTTOWF constructions

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- ▶ 3 constructions
  - ▶ Tweak of Rabin's TOWF
  - ▶ Tweak of Paillier's TOWP
  - ▶ Based on generic OWF
- ▶ Various assumptions
  - ▶ Factoring assumption for  $n = pq$
  - ▶ Factoring assumption for  $n = p^2q$
  - ▶ OWF
- ▶ Different flavors of our definition



# OTTOWF based on Rabin

---

- ▶ Tentative construction :
  - ▶ **Setup** :  $t = \langle p, q \rangle$  and  $k = n := pq$
  - ▶ **Eval** : given  $\langle n, m \rangle$ , returns  $h = m^2 \bmod n$
  - ▶ **Verify** : given  $\langle n, m, h \rangle$ , outputs 1 iff  $h = \mathbf{Eval}(n, m)$
  - ▶ **Preimage** : given  $\langle n, h, \langle p, q \rangle \rangle$ , uses CRT to compute  $m'$  such that  $m'^2 = h \bmod n$



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- ▶ Fairness only satisfied with probability  $1/2$ 
  - ▶ Trapdoor recovered iff  $m \neq \pm m'$
  - ▶ If  $m = m'$  then  $p' = n$
  - ▶ If  $m = -m'$  then  $p' = 1$



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- ▶ Improve fairness probability
  - ▶ Choose  $m \in \mathbb{Z}_n^N$
  - ▶ **Eval** : given  $n$  and  $m = (m_1, \dots, m_N)$ , returns  $h = (m_1^2 \bmod n, \dots, m_N^2 \bmod n)$



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- ▶ Resulting OTTOWF
  - ▶ Fairness up to  $1 - 2^{-N}$
  - ▶ Messages and hash values are quite long
  - ▶ Not surjective



# OTTOWF based on Paillier

---

- ▶ Paillier [P99]
  - ▶  $f(m_1, m_2) = g^{m_1} m_2^n \bmod n$  with  $n = p^2 q$  and  $p \approx q$
  - ▶  $m_1 \approx p$  and  $m_2 \approx pq \Rightarrow f \approx$  bijective
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- ▶ Idea : **make Paillier non injective**
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- ▶ **Two distinct inverses leak trapdoor**  
 $f(m_1, m_2) = f(m'_1, m'_2) \Rightarrow m_1 = m'_1 \bmod p$  and  
 $f(m_1, m_2) = f(m_1, m'_2) \Leftrightarrow m_2 = m'_2 \bmod pq$



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- ▶ **Setup**

- ▶ Generate a OWF  $f$
- ▶ Trapdoor  $t$  is random domain element
- ▶ Key  $k = \langle f, \beta \rangle$  where  $\beta := f(t)$

- ▶ **Eval** : given  $m$  returns  $h = f(m)$



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returns 1 if either  $f(m) = h$  or  $f(m) = \beta$



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- ▶ **Preimage** : returns  $t$



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- ▶ **Preimage** : returns  $t$

- ▶ **TrapExtr** : given  $\langle t, m \rangle$  returns  $t$



# *OTTOWF based on OWF*

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- ▶ **Onewayness** : to satisfy **Verify** we must invert  $f$  either on  $h$  or on  $\beta$
- ▶ **Trapdoor** and **fairness** are clear
- ▶ Not a TOWF !



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# *Signature scheme*

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- ▶ **Sign** : given a message  $m$  and a private key  $SK$ , returns a signature  $\sigma$
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- ▶ **Existential unforgeability against adaptive adversaries** : impossible to create a valid signature without the private key, even after seeing many valid signatures



# *The fair exchange problem*

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- ▶ Two parties want to exchange their own signatures  
Each party should get the other one's signature  
*if and only if* he has sent his own signature



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- ▶ Typical protocols have four rounds
  - ▶ Exchange of *partial* signatures
  - ▶ Exchange of *full* signatures



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- ▶ Issue : prevent abortions
- ▶ Typical protocols have four rounds
  - ▶ Exchange of *partial* signatures
  - ▶ Exchange of *full* signatures
- ▶ Semi-trusted third party (STTP) may help
  - ▶ Can convert partial signatures into full signatures
  - ▶ *Optimistic* if it only works in case of conflict



# *Verifiably committed signatures (VCS)*

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- ▶ State of the art with STTP [DR03]



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  - ▶ Exchange of partial signatures then full ones
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- ▶ State of the art with STTP [DR03]
  - ▶ Exchange of partial signatures then full ones
  - ▶ STTP converts partial signatures into full ones (if one party aborts)
  - ▶ Full signatures  $\approx$  converted partial signatures
- ▶ Fairness relies on STTP
  - ▶ OK if STTP honest
  - ▶ KO if STTP colludes with one of the parties



# *Concurrent signatures*

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Full signature = partial signature + keystone



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- ▶ No STTP but *delayed* fairness :  
fairness iff the responder sees the keystone



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Full signature = partial signature + keystone
- ▶ No STTP but *delayed* fairness :  
fairness iff the responder sees the keystone
- ▶ Even the willingness to sign is hidden in partial signatures
- ▶ **Partial signatures are non committing for the initiator**



# Fair exchange with OTTOWF

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- ▶ General idea :
  - ▶ Take a randomness  $r$ , let  $h = OTTOWF(r)$
  - ▶ Partial signature = signature on  $\langle \text{text}, h \rangle$
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- ▶ **Conversion** partial signatures into full ones
  - ▶ Hard without the trapdoor
  - ▶ Easy with the trapdoor



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- ▶ Possible to check partial and full signatures
- ▶ **Conversion** partial signatures into full ones
  - ▶ Hard without the trapdoor
  - ▶ Easy with the trapdoor
- ▶ **If used once, the trapdoor becomes public**  
If *one* partial signature converted, then *any* partial signature can be converted (fairness!)



# Protocol 1 (no STTP)

---

► **The initiator holds the trapdoor**

1. (I) Generates OTTOWF ; keeps the trapdoor, sends the key.  
Generates  $r_I$  and sends  $\sigma(\text{text}||\text{OTTOWF}(r_I))$
- 2.(R) Generates  $r_R$  and sends  $\sigma(\text{text}||\text{OTTOWF}(r_R))$
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- 4.(R) Sends  $r_R$



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- ▶ Fairness :

- ▶ I or R aborts before Step 2 : none has full signature
- ▶ R aborts after Step 3 : I uses his trapdoor
- ▶ I aborts after Step 2 and uses its trapdoor : the trapdoor is leaked, R can use it as well



# Comparison with concurrent signatures

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- ▶ *Delayed* fairness
  - ▶ If I uses his trapdoor to convert R's partial signature, then the resulting full signature leaks the trapdoor. R will therefore be able to convert I's partial signature as well, but *only after seeing this full signature*
  - ▶ Fairness also delayed in concurrent signatures



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  - ▶ Fairness also delayed in concurrent signatures
- ▶ *Committing* partial signatures
  - ▶ Not true for concurrent signatures because of ambiguity



## Protocol 2 (with an STTP)

---

► **STTP has the trapdoor**

STTP generates an OTTOWF, keeps  $t$ , sends  $k$

1. (I) Generates  $r_I$  and sends  $\sigma(m || OTTOWF(r_I))$
2. (R) Generates  $r_R$  and sends  $\sigma(m || OTTOWF(r_R))$
3. (I) Sends  $r_I$
4. (R) Sends  $r_R$



## Protocol 2 (with an STTP)

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- ▶ **STTP has the trapdoor**

STTP generates an OTTOWF, keeps  $t$ , sends  $k$

1. (I) Generates  $r_I$  and sends  $\sigma(m || OTTOWF(r_I))$
2. (R) Generates  $r_R$  and sends  $\sigma(m || OTTOWF(r_R))$
3. (I) Sends  $r_I$
4. (R) Sends  $r_R$

- ▶ If STTP honest :

- ▶ If abortion after Step 2, STTP can convert partial signatures



## *Protocol 2 reduces the trust on the STTP*

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- ▶ If STTP and R collude :
  - ▶ R has the trapdoor.  
R aborts after Step 1 and converts I's partial signature
  - ▶ Fairness KO (same in VCS)



## *Protocol 2 reduces the trust on the STTP*

---

- ▶ If STTP and R collude :
  - ▶ R has the trapdoor.  
R aborts after Step 1 and converts I's partial signature
  - ▶ Fairness KO (same in VCS)
- ▶ If STTP and I collude :
  - ▶ Amounts to Protocol 1 : I has the trapdoor
  - ▶ Still some delayed fairness (KO in VCS)



## *Protocol 2 reduces the trust on the STTP*

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- ▶ If STTP and R collude :
  - ▶ R has the trapdoor.
  - ▶ R aborts after Step 1 and converts I's partial signature
  - ▶ Fairness KO (same in VCS)
- ▶ If STTP and I collude :
  - ▶ Amounts to Protocol 1 : I has the trapdoor
  - ▶ Still some delayed fairness (KO in VCS)

⇒ Compared to VCS, Protocol 2 reduces the trust that R needs to put on the STTP



# Outline

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Introduction

One-time trapdoor one-way functions (OTTOWF)

Constructions

Fair exchange protocols

Conclusion



# Conclusion

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- ▶ Leaking the trapdoor might be useful
- ▶ This paper :
  - ▶ OTTOWF definition
  - ▶ 3 constructions
  - ▶ Application to fair exchange
- ▶ Two new fair exchange protocols
  - ▶ Some advantages over previous protocols
- ▶ Other applications of OTTOWFs?



## Main references

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- ▶ [DR03] Y Dodis, L Reyzin, *Breaking and repairing optimistic fair exchange from PODC 2003*



# Conclusion

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- ▶ Leaking the trapdoor might be useful
- ▶ This paper :
  - ▶ OTTOWF definition
  - ▶ 3 constructions
  - ▶ Application to fair exchange
- ▶ Two new fair exchange protocols
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