

Automated Security Proofs with Sequences of Games

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Proofs of cryptographic protocols

There are two main frameworks for analyzing security protocols:

- The **Dolev-Yao model**: a formal, abstract model.

The cryptographic primitives are **ideal blackboxes**.

The adversary uses only those primitives.

Proofs can be done automatically.

- The **computational model**: a realistic model.

The cryptographic primitives are functions on bit-strings.

The adversary is a polynomial-time Turing machine.

Proofs are done manually.

Our goal: achieve **automatic provability** under the realistic **computational** assumptions.

An automatic prover

We have implemented an **automatic prover** sound in the **computational model**:

- proves **secrecy** properties and that **events** can be executed only with negligible probability.
- handles various **cryptographic primitives**: MACs (message authentication codes), stream and block ciphers, public-key encryption, signatures, hash functions, . . .
- works for **N sessions** with an **active adversary**.
- gives a bound on the **probability** of an attack (exact security).

As in Shoup's or Bellare and Rogaway's method, the proof is a **sequence of games**:

- In the first game, the adversary plays against the **real protocol**.
- One goes from one game to the next by syntactic transformations or by applying security assumptions on cryptographic primitives.

The difference of probability between consecutive games is bounded.

- The last game is **"ideal"**: the security property can be read directly on it.

(The advantage of the adversary is 0 for this game.)

Games are formalized in a process calculus.

Case study: Full Domain Hash signature scheme

$hash$ hash function (in the random oracle model)

$f(pk, m)$ one-way trapdoor permutation, with inverse $invf(sk, m)$

We define a **signature scheme** as follows:

- signature: $sign(m, sk) = invf(sk, hash(m))$
- verification: $verify(m, pk, s) = (f(pk, s) = hash(m))$

Our goal is to show that this signature scheme is UF-CMA (satisfies unforgeability under chosen message attacks).

Formalizing the security of a signature scheme (1)

Key generation oracle:

$$Ogen() := r \xleftarrow{R} \text{seed}; pk \leftarrow pkgen(r); sk \leftarrow skgen(r); \mathbf{return}(pk)$$

Chooses a random seed uniformly in the set of bit-strings $seed$ (consisting of all bit-strings of a certain length), generates a public key pk , a secret key sk , and returns the public key.

Formalizing the security of a signature scheme (2)

Signature oracle:

$$OS(m : \textit{bitstring}) := \mathbf{return}(sign(sk, m))$$

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This oracle can be called at most q_S times:

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In fact, this is an abbreviation for:

$$\mathbf{foreach} \ i_S \leq q_S \ \mathbf{do} \ OS[i_S](m[i_S] : \textit{bitstring}) := \mathbf{return}(sign(sk, m[i_S]))$$

The variables in repeated oracles are arrays, with one cell for each call, to remember the values used in each oracle call.

These arrays are indexed with the call number i_S .

Formalizing the security of a signature scheme (3)

Test oracle:

$OT(m' : \text{bitstring}, s : D) :=$ **if** $\text{verify}(m', pk, s)$ **then**
 find $u \leq q_S$ **suchthat** $(\text{defined}(m[u]) \wedge m' = m[u])$
 then end else event *forge*

If s is a signature for m' and the signed message m' is not contained in the array m of messages passed to signing oracle, then the signature is a **forgery**, so we execute **event** *forge*.

Formalizing the security of a signature scheme (summary)

The signature and test oracles make sense only **after** the key generation oracle has been called, hence a **sequential composition**.

The signature and test oracles are **simultaneously** available, hence a **parallel composition**.

```
Ogen() :=  $r \stackrel{R}{\leftarrow}$  seed;  $pk \leftarrow$  pkgen( $r$ );  $sk \leftarrow$  skgen( $r$ ); return( $pk$ );  
(foreach  $i_S \leq q_S$  do OS( $m$  : bitstring) := return(sign( $sk$ ,  $m$ ))  
| OT( $m'$  : bitstring,  $s$  :  $D$ ) := if verify( $m'$ ,  $pk$ ,  $s$ ) then  
  find  $u \leq q_S$  suchthat (defined( $m[u]$ )  $\wedge$   $m' = m[u]$ )  
  then end else event forge)
```

The probability of executing **event** *forge* in this game is the probability of forging a signature.

Application to the FDH signature scheme

We add a hash oracle because the adversary must be able to call the random oracle (even though it cannot be implemented).

```
foreach  $i_H \leq q_H$  do  $OH(x : \text{bitstring}) := \text{return}(\text{hash}(x))$   
|  $Ogen() := r \xleftarrow{R} \text{seed}; pk \leftarrow pkgen(r); sk \leftarrow skgen(r); \text{return}(pk);$   
  (foreach  $i_S \leq q_S$  do  $OS(m : \text{bitstring}) := \text{return}(\text{invf}(sk, \text{hash}(m)))$ )  
|  $OT(m' : \text{bitstring}, s : D) := \text{if } f(pk, s) = \text{hash}(m') \text{ then}$   
  find  $u \leq q_S$  suchthat ( $\text{defined}(m[u]) \wedge m' = m[u]$ )  
  then end else event forge)
```

Our goal is to bound the probability that event *forge* is executed in this game.

This game is given as input to the prover in the syntax above.

Indistinguishability as observational equivalence

Two processes (games) Q_1, Q_2 are **observationally equivalent** up to probability p when an adversary running in time t has probability at most $p(t)$ of distinguishing them:

$$Q_1 \approx_p Q_2$$

The adversary is represented by an acceptable **evaluation context** C (essentially a process put in parallel with the considered games).

- Observational equivalence is reflexive and symmetric.
- If $Q_1 \approx_p Q_2$ and $Q_2 \approx_{p'} Q_3$ then $Q_1 \approx_{p+p'} Q_3$.
- It is **contextual**: $Q_1 \approx_p Q_2$ implies $C[Q_1] \approx_{p'} C[Q_2]$ where C is any acceptable evaluation context running in time t_C and $p'(t) = p(t + t_C)$.

We transform a game G_0 into an observationally equivalent one using:

- **observational equivalences** $L \approx_p R$ given as **axioms** and that come from security properties of primitives. These equivalences are used inside a context:

$$G_1 \approx_0 C[L] \approx_{p'} C[R] \approx_0 G_2$$

- **syntactic transformations**: simplification, expansion of assignments, ...

We obtain a **sequence of games** $G_0 \approx_{p_1} G_1 \approx_{p_2} \dots \approx_{p_m} G_m$, which implies $G_0 \approx_{p_1 + \dots + p_m} G_m$.

If **event** *forge* cannot be executed in G_m , it can be executed with probability at most $p_1 + \dots + p_m$ in G_0 .

The adversary inverts f when, given the public key $pk = pkgen(r_0)$ and the image of some x_0 by f_{pk} , it manages to find x_0 (without having the trapdoor).

The function f is **one-way** when the adversary has negligible probability of inverting f , say at most probability $\text{Succ}_{\mathcal{P}}^{\text{ow}}(t)$ when the adversary runs in time t .

$LR = Ogen() := r_0 \xleftarrow{R} \text{seed}; x_0 \xleftarrow{R} D; \text{return}(pkgen(r_0), f(pkgen(r_0), x_0));$
 $Oeq(x' : D) := \text{if } x' = x_0 \text{ then event } invert$

LR executes **event** *invert* with probability at most $\text{Succ}_{\mathcal{P}}^{\text{ow}}(t)$ in the presence of a context that runs in time t .
(The event *invert* is executed when the adversary inverts f .)

One-wayness as an observational equivalence

Security assumptions have to be given as **equivalences**. The following equivalence formalizes one-wayness:

```
foreach  $i_k \leq n_k$  do  $r \stackrel{R}{\leftarrow} \text{seed}; (Opk() := \text{return}(pkgen(r))$   
  | foreach  $i_f \leq n_f$  do  $x \stackrel{R}{\leftarrow} D; (Oy() := \text{return}(f(pkgen(r), x))$   
    | foreach  $i_1 \leq n_1$  do  $Oeq(x' : D) := \text{return}(x' = x)$   
      |  $Ox() := \text{return}(x))$ )  
  
 $\approx_{n_k \times n_f \times \text{ Succ}_P^{\text{ow}}(t + (n_k n_f - 1)t_f + (n_k - 1)t_{pkgen})}$   
foreach  $i_k \leq n_k$  do  $r \stackrel{R}{\leftarrow} \text{seed}; (Opk() := \text{return}(pkgen'(r))$   
  | foreach  $i_f \leq n_f$  do  $x \stackrel{R}{\leftarrow} D; (Oy() := \text{return}(f'(pkgen'(r), x))$   
    | foreach  $i_1 \leq n_1$  do  $Oeq(x' : D) :=$   
      if defined}(k) \text{ then return}(x' = x) \text{ else return}(false)  
      |  $Ox() := k \leftarrow \text{mark}; \text{return}(x))$ )
```

This equivalence is proved manually, **once** for one-way trapdoor permutations. It can be reused in the proof of many schemes.

Other properties of one-way trapdoor permutations (1)

- $x \mapsto f(pkgen(r), x)$ and $x \mapsto invf(skgen(r), x)$ are **inverse permutations**:

$$invf(skgen(r), f(pkgen(r), x)) = x$$

- $x \mapsto f(pk, x)$ is **injective**:

$$(f(pk, x) = f(pk, x')) = (x = x')$$

Other properties of one-way trapdoor permutations (2)

When x is a uniformly distributed random number, we can **replace x with $f(pk, x)$** without changing the probability distribution ($x \mapsto f(pk, x)$ is a permutation).

This is again expressed by an observational equivalence:

```
foreach  $i_k \leq n_k$  do  $r \stackrel{R}{\leftarrow} \text{seed}$ ; ( $\text{Opk}() := \text{return}(pkgen(r))$ )  
  | foreach  $i_f \leq n_f$  do  $x \stackrel{R}{\leftarrow} D$ ; ( $\text{Oant}() := \text{return}(invf(skgen(r), x))$ )  
    | ( $\text{Oim}() := \text{return}(x)$ )  
 $\approx_0$  foreach  $i_k \leq n_k$  do  $r \stackrel{R}{\leftarrow} \text{seed}$ ; ( $\text{Opk}() := \text{return}(pkgen(r))$ )  
  | foreach  $i_f \leq n_f$  do  $x \stackrel{R}{\leftarrow} D$ ; ( $\text{Oant}() := \text{return}(x)$ )  
    | ( $\text{Oim}() := \text{return}(f(pkgen(r), x))$ )
```

which allows to perform the previous replacement only when x is used in calls to $invf(skgen(r), x)$, where r is a random number such that r occurs only in $pkgen(r)$ and $invf(skgen(r), x)$ for some random numbers x .

Hash function in the random oracle model

A **random oracle** is formalized by the following equivalence:

```
foreach  $i_h \leq n_h$  do  $OH(x : \text{bitstring}) := \text{return}(\text{hash}(x))$   
 $\approx_0$  foreach  $i_h \leq n_h$  do  $OH(x : \text{bitstring}) :=$   
  find  $u \leq n_h$  suchthat  $(\text{defined}(x[u], r[u]) \wedge x = x[u])$   
  then  $\text{return}(r[u])$  else  $r \stackrel{R}{\leftarrow} D; \text{return}(r)$ 
```

The hash function is equivalent to a function that looks up the argument x in the array of previous arguments given to OH .

- If x is not found, it returns a **fresh random number** r .
- If x is found, it returns the same result as in the previous call.

Automatic proof of FDH: result

Our prover is given as input

- the **security assumptions** of one-way trapdoor permutations and of the hash function,
- the **initial game** that formalizes the security of FDH.

It **automatically** produces a proof that this game executes **event** *forge* with probability at most

$$(q_H + q_S + 1)\text{Succ}_{\mathcal{P}}^{\text{ow}}(t + (q_H + q_S)t_f)$$

where t_f is the time of one evaluation of f (ignoring the time of bit-string comparisons).

This is the standard upper-bound [Bellare, Rogaway, CCS'93].

The prover also outputs

- the **sequence of games** that leads to this proof,
- a **succinct explanation** of the transformations performed between games.

Proof strategy

- The prover tries to apply **all equivalences** given as axioms, which represent security assumptions.

It transforms the left-hand side into the right-hand side of the equivalence.

- If such a **transformation succeeds**, the obtained game is then simplified, using in particular equations given as axioms.
- When these **transformations fail**, they may return syntactic transformations to apply in order to make them succeed, called **advised transformations**.

The prover then applies the advised transformations, and retries the initial transformation.

Proof of FDH: Initial game

```
(
  foreach  $i_H \leq q_H$  do
     $OH(x : \text{bitstring}) := \mathbf{return}(hash(x))$ 
  |
   $Ogen() := r \stackrel{R}{\leftarrow} \text{seed}; pk \leftarrow pkgen(r); sk \leftarrow skgen(r); \mathbf{return}(pk);$ 
  ( (* signature oracle *)
    foreach  $i_S \leq q_S$  do
       $OS(m : \text{bitstring}) := \mathbf{return}(invf(sk, hash(m)))$ 
    | (* forged signature? *)
       $OT(m' : \text{bitstring}, s : D) :=$ 
      if  $f(pk, s) = hash(m')$  then
      find  $u \leq q_S$  suchthat  $\mathbf{defined}(m[u]) \wedge (m' = m[u])$ 
      then end else event forge
    )
  )
)
```

Proof of FDH step 1: apply the security of the hash function

Replace each occurrence of $hash(M)$ with a lookup in the arguments of previous calls to $hash$.

- If M is found, return the same result as the previous result.
- Otherwise, pick a new random number and return it.

For instance, $\mathbf{return}(hash(x))$ is replaced with

find **suchthat** **defined**(m', r_{30}) && ($x = m'$) **then**
return(r_{30})

⊕ $@i_1 \leq q_S$ **suchthat** **defined**($m[@i_1], r_{32}[@i_1]$)
&& ($x = m[@i_1]$) **then** **return**($r_{32}[@i_1]$)

⊕ $@i_2 \leq q_H$ **suchthat** **defined**($x[@i_2], r_{34}[@i_2]$)
&& ($x = x[@i_2]$) **then** **return**($r_{34}[@i_2]$)

else

$r_{34} \stackrel{R}{\leftarrow} D$; **return**(r_{34})

Proof of FDH step 2: simplify

(* forged signature? *)

$OT(m' : \text{bitstring}, s : D) :=$

find **suchthat** **defined**(m', r_{30}) && ($m' = m'$) **then**

if $f(pk, s) = r_{30}$ **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) && ($m' = m[u]$) **then end else event** *forge*

\oplus $@i_5 \leq q_S$ **suchthat** **defined**($m[@i_5], r_{32}[@i_5]$) && ($m' = m[@i_5]$) **then**

if $f(pk, s) = r_{32}[@i_5]$ **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) && ($m' = m[u]$) **then end else event** *forge*

\oplus $@i_6 \leq q_H$ **suchthat** **defined**($x[@i_6], r_{34}[@i_6]$) && ($m' = x[@i_6]$) **then**

if $f(pk, s) = r_{34}[@i_6]$ **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) && ($m' = m[u]$) **then end else event** *forge*

else

$r_{30} \stackrel{R}{\leftarrow} D;$

if $f(pk, s) = r_{30}$ **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) && ($m' = m[u]$) **then end else event** *forge*

r_{30} is not defined at the third line, so the first blue part is removed.

The red test always succeeds, so the second blue part becomes

end.

Proof of FDH step 3: substitute sk with its value

The variable sk is replaced with $skgen(r)$, and the assignment $sk \leftarrow skgen(r)$ is removed.

This transformation is advised in order to be able to apply the permutation property.

Proof of FDH step 4: permutation

(* signature oracle *)

foreach $i_S \leq q_S$ **do**

$OS(m : \text{bitstring}) :=$

find **suchthat** **defined**(m', r_{30}) && ($m = m'$) **then**

return($\text{invf}(\text{skgen}(r), r_{30})$)

\oplus $@i_3 \leq q_S$ **suchthat** **defined**($m[@i_3], r_{32}[@i_3]$) && ($m = m[@i_3]$) **then**

return($\text{invf}(\text{skgen}(r), r_{32}[@i_3])$)

\oplus $@i_4 \leq q_H$ **suchthat** **defined**($x[@i_4], r_{34}[@i_4]$) && ($m = x[@i_4]$) **then**

return($\text{invf}(\text{skgen}(r), r_{34}[@i_4])$)

else

$r_{32} \stackrel{R}{\leftarrow} D;$

return($\text{invf}(\text{skgen}(r), r_{32})$)

$r_i \stackrel{R}{\leftarrow} D$ becomes $y_i \stackrel{R}{\leftarrow} D,$

$\text{invf}(\text{skgen}(r), r_i)$ becomes $y_i,$

r_i becomes $f(\text{pkgen}(r), y_i)$

Proof of FDH step 5: simplify

(* forged signature? *)

$OT(m' : \text{bitstring}, s : D) :=$

find $@i_5 \leq q_S$ **suchthat** **defined**($m[@i_5], r_{32}[@i_5]$) $\&\&$ ($m' = m[@i_5]$) **then end**

\oplus $@i_6 \leq q_H$ **suchthat** **defined**($x[@i_6], r_{34}[@i_6]$) $\&\&$ ($m' = x[@i_6]$) **then**

if ($f(pk, s) = f(pkgen(r), y_{34}[@i_6])$) **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) $\&\&$ ($m' = m[u]$) **then end else event** *forge*

else

$y_{30} \stackrel{R}{\leftarrow} D;$

if ($f(pk, s) = f(pkgen(r), y_{30})$) **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) $\&\&$ ($m' = m[u]$) **then end else event** *forge*

$f(pk, s) = f(pkgen(r), y_i)$ becomes $s = y_i$,

knowing $pk = pkgen(r)$ and the injectivity of f :

$\forall pk : pkey, x : D, x' : D; (f(pk, x) = f(pk, x')) = (x = x')$

Proof of FDH step 6: one-wayness

(* forged signature? *)

$OT(m' : \text{bitstring}, s : D) =$

find $@i_5 \leq q_S$ **suchthat** **defined**($m[@i_5], r_{32}[@i_5]$) && ($m' = m[@i_5]$) **then end**

\oplus $@i_6 \leq q_H$ **suchthat** **defined**($x[@i_6], r_{34}[@i_6]$) && ($m' = x[@i_6]$) **then**

if $s = y_{34}[@i_6]$ **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) && ($m' = m[u]$) **then end else event** *forge*
else

$y_{30} \stackrel{R}{\leftarrow} D;$

if $s = y_{30}$ **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) && ($m' = m[u]$) **then end else event** *forge*

$s = y_i$ becomes **find** $@j_i \leq q_S$ **suchthat** **defined**($k_i[@j_i]$)

then $s = y_i$ **else** *false*.

In **hash oracle**, $f(\text{pkgen}(r), y_i)$ becomes $f'(\text{pkgen}'(r), y_i)$.

In **signature oracle**, y_i becomes $k_i : \text{bitstring} \leftarrow \text{mark}; y_i$.

Difference of probability: $(q_H + q_S + 1)\text{Succ}_P^{\text{ow}}(t + (q_H + q_S)t_f)$.

Proof of FDH step 7: simplify (1)

(* forged signature? *)

$OT(m' : \text{bitstring}, s : D) :=$

find $@i_5 \leq q_S$ **suchthat** **defined**($m[@i_5], r_{32}[@i_5]$) $\&\&$ ($m' = m[@i_5]$) **then end**

\oplus $@i_6 \leq q_H$ **suchthat** **defined**($x[@i_6], r_{34}[@i_6]$) $\&\&$ ($m' = x[@i_6]$) **then**

find $@j_{34} \leq q_S$ **suchthat** **defined**($k_{34}[@j_{34}]$) $\&\&$ ($@i_4[@j_{34}] = @i_6$) **then**

if $s = y_{34}[@i_6]$ **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) $\&\&$ ($m' = m[u]$) **then end** **else event** *forge*

else

$y_{30} \xleftarrow{R} D;$

find $@j_{30} \leq q_S$ **suchthat** **defined**($k_{30}[@j_{30}]$) **then**

if $s = y_{30}$ **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) $\&\&$ ($m' = m[u]$) **then end** **else event** *forge*

The tests in **red** always succeed, so **event** *forge* disappears, which proves the desired property.

FDH step 7: simplify (2)

(* forged signature? *)

$OT(m' : \text{bitstring}, s : D) :=$

...

$\oplus @i_6 \leq q_H$ **suchthat** **defined**($x[@i_6], r_{34}[@i_6]$) $\&\&$ ($m' = x[@i_6]$) **then**
 find $@j_{34} \leq q_S$ **suchthat** **defined**($k_{34}[@j_{34}]$) $\&\&$ ($@i_4[@j_{34}] = @i_6$) **then**
 if $s = y_{34}[@i_6]$ **then**
 find $u \leq q_S$ **suchthat** **defined**($m[u]$) $\&\&$ ($m' = m[u]$) **then end else event** *forge*

Definition of k_{34} :

foreach $i_S \leq q_S$ **do**

$OS(m : \text{bitstring}) :=$

...

$\oplus @i_4 \leq q_H$ **suchthat** **defined**($x[@i_4], y_{34}[@i_4]$) $\&\&$ ($m = x[@i_4]$) **then**
 let $k_{34} : \text{bitstring} = \text{mark}$ **in** ...

When $k_{34}[@j_{34}]$ is defined, $m[@j_{34}]$ is defined and

$m[@j_{34}] = x[@i_4[@j_{34}]] = x[@i_6] = m'$

so the **red** test succeeds with $j = @j_{34}$.

Proof of FDH step 7: simplify (3)

(* forged signature? *)

$OT(m' : \text{bitstring}, s : D) :=$

...

$y_{30} \stackrel{R}{\leftarrow} D;$

find $@j_{30} \leq q_S$ **suchthat** **defined**($k_{30}[@j_{30}]$) **then**

if $s = y_{30}$ **then**

find $u \leq q_S$ **suchthat** **defined**($m[u]$) **&&** ($m' = m[u]$) **then end else event** *forge*

Definition of k_{30} :

foreach $i_S \leq q_S$ **do**

$OS(m : \text{bitstring}) :=$

find **suchthat** **defined**(m', y_{30}) **&&** ($m = m'$) **then**

let $k_{30} : \text{bitstring} = \text{mark}$ **in** ...

When $k_{30}[@j_{30}]$ is defined, $m[@j_{30}]$ is defined and $m[@j_{30}] = m'$, so the **red** test succeeds with $j = @j_{30}$.

Other examples: Encryption schemes

Our prover has successfully proved many protocols and the following properties of encryption schemes:

- $\mathcal{E}(m, r) = f(r) \| \text{hash}(r) \text{ xor } m$ is IND-CPA.
- $\mathcal{E}(m, r) = f(r) \| \text{hash}(r) \text{ xor } m \| \text{hash}'(\text{hash}(r) \text{ xor } m, r)$ is IND-CCA2.
- With an improved treatment of the equational theory of *xor*, we believe that it could also show that $\mathcal{E}(m, r) = f(r) \| \text{hash}(r) \text{ xor } m \| \text{hash}'(m, r)$ is IND-CCA2.

The proofs of these encryption schemes use a **manual mode** of the prover, in which the user indicates the main game transformations to perform.

We have presented a **new tool** that can prove automatically the security of cryptographic primitives and protocols.

- The **security assumptions** are given as **observational equivalences**.

The manual proof of these equivalences is done **once** for all proofs, and has already been done for many primitives.

- The **protocol or scheme** to prove is specified using a syntax close to the notations classically used in cryptography.
- The prover provides a **sequence of indistinguishable games** which leads to a final game in which the adversary has advantage 0.
- The user is allowed (but does not have) to interact with the prover to make it follow a specific sequence of games.

Details at <http://www.di.ens.fr/~blanchet/cryptoc/FDH/>