CS 591: Formal Methods in Security and Privacy

Formal Proofs for Cryptography — Continued

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Turn on Recording!

Definitions of IND-CPA Security and Our Encryption Scheme

Symmetric Encryption Schemes

- Our treatment of symmetric encryption schemes is parameterized by three types:

```
type key.  (* encryption keys, key_len bits *)
type text.  (* plaintexts, text_len bits *)
type cipher.  (* ciphertexts - scheme specific *)
```

- An encryption scheme is a *stateless* implementation of this module interface:

```
module type ENC = {
  proc key_gen() : key  (* key generation *)
  proc enc(k : key, x : text) : cipher  (* encryption *)
  proc dec(k : key, c : cipher) : text  (* decryption *)
}.
```

Encryption Oracles

- To define IND-CPA security of encryption schemes, we need the notion of an *encryption oracle*, which both the adversary and IND-CPA game will interact with:

```
module type EO = {
  (* initialization - generates key *)
  proc * init() : unit
  (* encryption by adversary before game's encryption *)
  proc enc_pre(x : text) : cipher
  (* one-time encryption by game *)
  proc genc(x : text) : cipher
  (* encryption by adversary after game's encryption *)
  proc enc_post(x : text) : cipher
}.
```

Standard Encryption Oracle

- Here is the standard encryption oracle, parameterized by an encryption scheme, `Enc`:

```
module EncO (Enc : ENC) : EO = {
  var key : key
  var ctr_pre : int
  var ctr_post : int

  proc init() : unit = {
    key <@ Enc.key_gen();
    ctr_pre <- 0; ctr_post <- 0;
  }
```

Standard Encryption Oracle

```
proc enc_pre(x : text) : cipher = {
  var c : cipher;
  if (ctr_pre < limit_pre) {
    ctr_pre <- ctr_pre + 1;
    c <@ Enc.enc(key, x);
  }
  else {
    c <- ciph_def;  (* default result *)
  }
  return c;
}
```

Standard Encryption Oracle

```
proc genc(x : text) : cipher = {
  var c : cipher;
  c <@ Enc.enc(key, x);
  return c;
}
```

Standard Encryption Oracle

```
  proc enc_post(x : text) : cipher = {
    var c : cipher;
    if (ctr_post < limit_post) {
      ctr_post <- ctr_post + 1;
      c <@ Enc.enc(key, x);
    }
    else {
      c <- ciph_def;  (* default result *)
    }
    return c;
  }
}.
```

Encryption Adversary

- An *encryption adversary* is parameterized by an encryption oracle:

```
module type ADV (EO : EO) = {
  (* choose a pair of plaintexts, x1/x2 *)
  proc * choose() : text * text {EO.enc_pre}

  (* given ciphertext c based on a random boolean b
     (the encryption using EO.genc of x1 if b = true,
      the encryption of x2 if b = false), try to guess b
  *)
  proc guess(c : cipher) : bool {EO.enc_post}
}.
```

- Adversaries may be probabilistic.

IND-CPA Game

- The IND-CPA Game is parameterized by an encryption scheme and an encryption adversary:

```
module INDCPA (Enc : ENC, Adv : ADV) = {
  module EO = EncO(Enc)           (* make EO from Enc *)
  module A = Adv(EO)              (* connect Adv to EO *)
  proc main() : bool = {
    var b, b' : bool; var x1, x2 : text; var c : cipher;
    EO.init();                    (* initialize EO *)
    (x1, x2) <@ A.choose();       (* let A choose x1/x2 *)
    b <$ {0,1};                   (* choose boolean b *)
    c <@ EO.genc(b ? x1 : x2);    (* encrypt x1 or x2 *)
    b' <@ A.guess(c);             (* let A guess b from c *)
    return b = b';                (* see if A won *)
  }
}.
```

Pseudorandom Functions

- Our pseudorandom function (PRF) is an operator `F` with this type:

```
op F : key -> text -> text.
```

- We will assume that `dtext` (`dkey`) is a sub-distribution on `text` (`key`) that is a distribution (is “lossless”), and where every element of `text` (`key`) has the same non-zero value:

```
op dtext : text distr.
op dkey  : key distr.
```

Pseudorandom Functions

- A *random function* is a module with the following interface:

```
module type RF = {
  (* initialization *)
  proc * init() : unit
  (* application to a text *)
  proc f(x : text) : text
}.
```

Pseudorandom Functions

- Here is a random function made from our PRF **F**:

```
module PRF : RF = {
  var key : key
  proc init() : unit = {
    key <$ dkey;
  }
  proc f(x : text) : text = {
    var y : text;
    y <- F key x;
    return y;
  }
}.
```

Pseudorandom Functions

- Here is a random function made from true randomness:

```
module TRF : RF = {
  (* mp is a finite map associating texts with texts *)
  var mp : (text, text) fmap
  proc init() : unit = {
    mp <- empty;  (* empty map *)
  }
  proc f(x : text) : text = {
    var y : text;
    if (! x \in mp) {   (* give x a random value in *)
      y <$ dtext;  (* mp if not already in mp's domain *)
      mp.[x] <- y;
    }
   return oget mp.[x];  (* return value of x in mp *)
  }
}.
```

Pseudorandom Functions

- A *random function adversary* is parameterized by a random function module:

```
module type RFA (RF : RF) = {
  proc * main() : bool {RF.f}
}.
```

- Here is the random function game:

```
module GRF (RF : RF, RFA : RFA) = {
  module A = RFA(RF)
  proc main() : bool = {
    var b : bool;
    RF.init();
    b <@ A.main();
    return b;
  }
}.
```

Pseudorandom Functions

- Our PRF F is "good" if and only if the following is small, whenever RFA is limited in the amount of computation it may do (maybe we say it runs in polynomial time):

```
`|Pr[GRF(PRF, RFA).main() @ &m : res] -
  Pr[GRF(TRF, RFA).main() @ &m : res]|
```

Our Symmetric Encryption Scheme

- We construct our encryption scheme `Enc` out of `F`:

```
(+^) : text -> text -> text  (* bitwise exclusive or *)

type cipher = text * text.  (* ciphertexts *)

module Enc : ENC = {
  proc key_gen() : key = {
    var k : key;
    k <$ dkey;
    return k;
  }
```

Our Symmetric Encryption Scheme

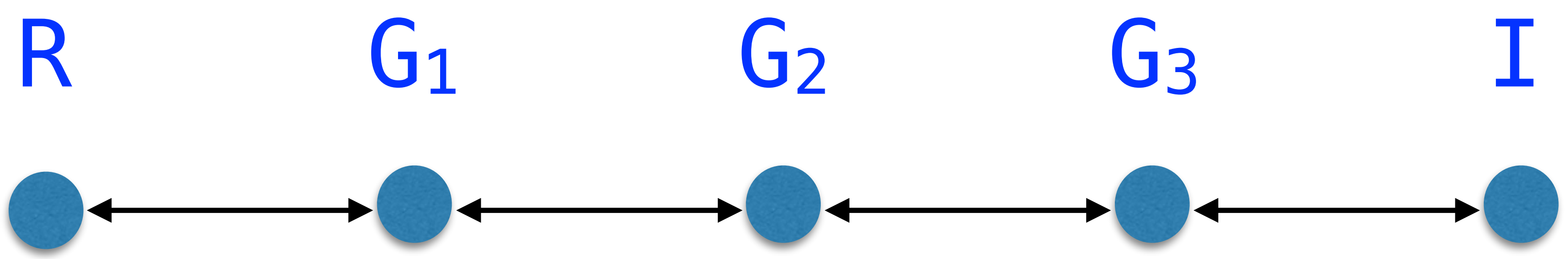
```
  proc enc(k : key, x : text) : cipher = {
    var u : text;
    u <$ dtext;
    return (u, x +^ F k u);
  }

  proc dec(k : key, c : cipher) : text = {
    var u, v : text;
    (u, v) <- c;
    return v +^ F k u;
  }
}.
```

Sequence of Games Approach

- Our proof of IND-CPA security uses the *sequence of games approach*, which is used to connect a “real” game `R` with an *“ideal”* game `I` via a sequence of intermediate games.
- Each of these games is parameterized by the adversary, and each game has a `main` procedure returning a boolean.
- We want to establish an upper bound for

```
`| Pr[R.main() @ &m : res] - Pr[I.main() : res] |
```



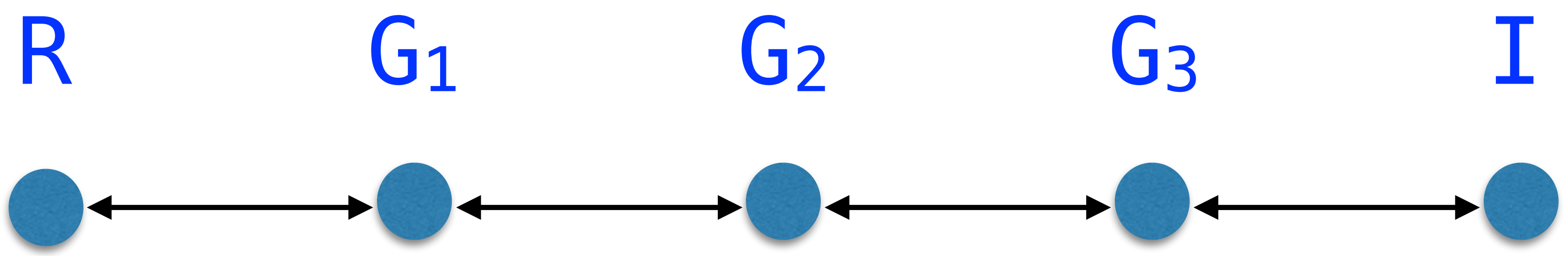
Sequence of Games Approach

- Suppose we can prove

```
`| Pr[R.main() @ &m : res] - Pr[G₁.main() : res] | <= b₁
`| Pr[G₁.main() @ &m : res] - Pr[G₂.main() : res] | <= b₂
`| Pr[G₂.main() @ &m : res] - Pr[G₃.main() : res] | <= b₃
`| Pr[G₃.main() @ &m : res] - Pr[I.main() : res] | <= b₄
```

for some b_1, b_2, b_3 and b_4. Then we can conclude

```
`| Pr[R.main() @ &m : res] - Pr[I.main() @ &m : res] | <=
   b₁ + b₂ + b₃ + b₄
```



Sequence of Games Approach

- To establish an upper bound for

`` `|Pr[INDCPA(Enc, Adv).main() @ &m : res] - 1%r / 2%r|, ``

  we can use a sequence of games to connect `INDCPA(Enc, Adv)` to an ideal game `I` such that

  `Pr[I.main() @ &m : res] = 1%r / 2%r`.

- The overall upper bound will be the sum `b`$_1$ `+ … + b`$_n$ of the sequence `b`$_1$`, …, b`$_n$ of upper bounds of the steps of the sequence of games.

- We start with `INDCPA(Enc, Adv)` and make a sequence of simplifications, hoping to get to such an `I`.

Starting the Proof in a Section

- First, we enter a "section", and declare our adversary `Adv` as not interfering with certain modules and as being lossless:

```
section.

declare module Adv : ADV{EncO, PRF, TRF, Adv2RFA}.

axiom Adv_choose_ll :

  forall (EO <: EO{Adv}),

  islossless EO.enc_pre => islossless Adv(EO).choose.

axiom Adv_guess_ll :

  forall (EO <: EO{Adv}),

  islossless EO.enc_post => islossless Adv(EO).guess.
```

From the Previous Class

Step 1: Replacing PRF with TRF

- In our first step, we switch to using a true random function instead of a pseudorandom function in our encryption scheme.
- When doing this, we inline the encryption scheme into a new kind of encryption oracle, `EO_RF`, which is parameterized by a random function.
- We also instrument `EO_RF` to detect two kinds of “clashes” (repetitions) in the generation of the inputs to the random function.
    - This is in preparation for Steps 2 and 3.

Step 1: Replacing PRF with TRF

```
local module EO_RF (RF : RF) : EO = {
  var ctr_pre : int
  var ctr_post : int
  var inps_pre : text fset
  var clash_pre : bool
  var clash_post : bool
  var genc_inp : text

  proc init() = {
    RF.init();
    ctr_pre <- 0; ctr_post <- 0; inps_pre <- fset0;
    clash_pre <- false; clash_post <- false;
    genc_inp <- text0;
  }
```

Step 1: Replacing PRF with TRF

```
proc enc_pre(x : text) : cipher = {
  var u, v : text; var c : cipher;
  if (ctr_pre < limit_pre) {
    ctr_pre <- ctr_pre + 1;
    u <$ dtext;
    inps_pre <- inps_pre `|` fset1 u;
    v <@ RF.f(u);
    c <- (u, x +^ v);
  }
  else {
    c <- (text0, text0);
  }
  return c;
}
```

size of `inps_pre`
is at most `limit_pre`

Step 1: Replacing PRF with TRF

```
proc genc(x : text) : cipher = {
  var u, v : text; var c : cipher;
  u <$ dtext;
  if (mem inps_pre u) {
    clash_pre <- true;
  }
  genc_inp <- u;
  v <@ RF.f(u);
  c <- (u, x +^ v);
  return c;
}
```

Step 1: Replacing PRF with TRF

```
  proc enc_post(x : text) : cipher = {
    var u, v : text; var c : cipher;
    if (ctr_post < limit_post) {
      ctr_post <- ctr_post + 1;
      u <$ dtext;
      if (u = genc_inp) {
        clash_post <- true;
      }
      v <@ RF.f(u);
      c <- (u, x +^ v);
    }
    else {
      c <- (text0, text0);
    }
    return c;
  }
}.
```

Step 1: Replacing PRF with TRF

- Now, we define a game `G1` using `EO_RF`:

```
local module G1 (RF : RF) = {
  module E = EO_RF(RF)
  module A = Adv(E)

  proc main() : bool = {
    var b, b' : bool; var x1, x2 : text; var c : cipher;
    E.init();
    (x1, x2) <@ A.choose();
    b <$ {0,1};
    c <@ E.genc(b ? x1 : x2);
    b' <@ A.guess(c);
    return b = b';
  }
}.
```

Step 1: Replacing PRF with TRF

- Then it is easy to prove:

```
local lemma INDCPA_G1_PRF &m :
  Pr[INDCPA(Enc, Adv).main() @ &m : res] =
  Pr[G1(PRF).main() @ &m : res].
```

- To upper-bound

```
`| Pr[G1(PRF).main() @ &m : res] -
   Pr[G1(TRF).main() @ &m : res] |,
```

we need to construct a module `Adv2RFA` that transforms `Adv` into a random function adversary:

```
module Adv2RFA(Adv : ADV, RF : RF) = {
 …
  proc main() : bool = { … }
}.
```

`Adv2RFA(Adv)` is a random function adversary

Step 1: Replacing PRF with TRF

- Our goal in defining `Adv2RFA` is for this lemma to be provable:

```
local lemma G1_GRF (RF <: RF{EO_RF, Adv, Adv2RFA}) &m :
  Pr[G1(RF).main() @ &m : res] =
  Pr[GRF(RF, Adv2RFA(Adv)).main() @ &m : res].
```

- Recall the definition of `GRF`:

```
module GRF (RF : RF, RFA : RFA) = {
  module A = RFA(RF)
  proc main() : bool = {
    var b : bool;
    RF.init();
    b <@ A.main();
    return b;
  }
}.
```

Step 1: Replacing PRF with TRF

```
module Adv2RFA(Adv : ADV, RF : RF) = {
  module EO : EO = {  (* uses RF *)
    var ctr_pre : int
    var ctr_post : int

    proc init() : unit = {
      (* RF.init will be called by GRF *)
      ctr_pre <- 0; ctr_post <- 0;
    }
```

Step 1: Replacing PRF with TRF

```
proc enc_pre(x : text) : cipher = {
  var u, v : text; var c : cipher;
  if (ctr_pre < limit_pre) {
    ctr_pre <- ctr_pre + 1;
    u <$ dtext;
    v <@ RF.f(u);
    c <- (u, x +^ v);
  }
  else {
    c <- (text0, text0);
  }
  return c;
}
```

identical to EO_RF

Step 1: Replacing PRF with TRF

```
proc genc(x : text) : cipher = {
  var u, v : text; var c : cipher;
  u <$ dtext;
  v <@ RF.f(u);
  c <- (u, x +^ v);
  return c;
}
```

identical to EO_RF

Step 1: Replacing PRF with TRF

```
  proc enc_post(x : text) : cipher = {
    var u, v : text; var c : cipher;
    if (ctr_post < limit_post) {
      ctr_post <- ctr_post + 1;
      u <$ dtext;
      v <@ RF.f(u);
      c <- (u, x +^ v);
    }
    else {
      c <- (text0, text0);
    }
    return c;
  }
}
```

identical to
EO_RF

Step 1: Replacing PRF with TRF

```
  module A = Adv(EO)

  proc main() : bool = {
    var b, b' : bool; var x1, x2 : text; var c : cipher;
    EO.init();
    (x1, x2) <@ A.choose();
    b <$ {0,1};
    c <@ EO.genc(b ? x1 : x2);
    b' <@ A.guess(c);
    return b = b';
  }
}.
```

Like `G1`, except `Adv` and `main` use `EO` instead of `EncO(RF)`

Step 1: Replacing PRF with TRF

- From

```
local lemma G1_GRF (RF <: RF{EO_RF, Adv, Adv2RFA}) &m :
  Pr[G1(RF).main() @ &m : res] =
  Pr[GRF(RF, Adv2RFA(Adv)).main() @ &m : res].
```

we can conclude

```
  Pr[INDCPA(Enc, Adv).main() @ &m : res] =
  Pr[G1(PRF).main() @ &m : res] =
  Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res]
```

and

```
  Pr[G1(TRF).main() @ &m : res] =
  Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]
```

Step 1: Replacing PRF with TRF

- Thus

```
local lemma INDCPA_G1_TRF &m :
  `|Pr[INDCPA(Enc, Adv).main() @ &m : res] -
    Pr[G1(TRF).main() @ &m : res]| =
  `|Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res] -
    Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]|.
```

- Here, we have an exact upper bound.

Step 2: Oblivious Update in `genc`

- In Step 2, we make use of up to bad reasoning, to transition to a game in which the encryption oracle, `EO_O`, uses a true random function and "obliviously" ("O" for "oblivious") updates the true random function's map — i.e., overwrites what may already be stored in the map.

Step 2: Oblivious Update in `genc`

```
local module EO_O : EO = {
  var ctr_pre : int
  var ctr_post : int
  var clash_pre : bool
  var clash_post : bool
  var genc_inp : text

  proc init() = {
    TRF.init();
    ctr_pre <- 0; ctr_post <- 0; clash_pre <- false;
    clash_post <- false; genc_inp <- text0;
  }
```

don't need `inps_pre` — can use `TRF.mp`'s domain

Step 2: Oblivious Update in `genc`

```
proc enc_pre(x : text) : cipher = {
  var u, v : text; var c : cipher;
  if (ctr_pre < limit_pre) {
    ctr_pre <- ctr_pre + 1;
    u <$ dtext;
    v <@ TRF.f(u);
    c <- (u, x +^ v);
  }
  else {
    c <- (text0, text0);
  }
  return c;
}
```

size of domain of `TRF.mp` is at most `limit_pre`

Step 2: Oblivious Update in genc

```
proc genc(x : text) : cipher = {
  var u, v : text; var c : cipher;
  u <$ dtext;
  if (u \in TRF.mp) {
    clash_pre <- true;
  }
  genc_inp <- u;
  v <$ dtext;
  TRF.mp.[u] <- v;
  c <- (u, x +^ v);
  return c;
}
```

can now use `TRF.mp`'s domain

Step 2: Oblivious Update in genc

```
proc enc_post(x : text) : cipher = {
  var u, v : text; var c : cipher;
  if (ctr_post < limit_post) {
    ctr_post <- ctr_post + 1;
    u <$ dtext;
    if (u = genc_inp) {
      clash_post <- true;
    }
    v <@ TRF.f(u);
    c <- (u, x +^ v);
  }
  else {
    c <- (text0, text0);
  }
  return c;
}
```

Step 2: Oblivious Update in `genc`

```
local module G2 = {
  module A = Adv(EO_O)

  proc main() : bool = {
    var b, b' : bool; var x1, x2 : text; var c : cipher;
    EO_O.init();
    (x1, x2) <@ A.choose();
    b <$ {0,1};
    c <@ EO_O.genc(b ? x1 : x2);
    b' <@ A.guess(c);
    return b = b';
  }
}.
```

Step 2: Oblivious Update in genc

```
local lemma G1_TRF_G2_main :
  equiv
  [G1(TRF).main ~ G2.main :
   true ==>
   ={clash_pre}(EO_RF, EO_O) /\
   (! EO_RF.clash_pre{1} => ={res})].

local lemma G2_main_clash_ub &m :
  Pr[G2.main() @ &m : EO_O.clash_pre] <=
  limit_pre%r / (2 ^ text_len)%r.

local lemma G1_TRF_G2 &m :
  `|Pr[G1(TRF).main() @ &m : res] -
    Pr[G2.main() @ &m : res]| <=
  limit_pre%r / (2 ^ text_len)%r.
```

Step 2: Oblivious Update in genc

- Then we can use the triangular inequality to summarize:

```
local lemma INDCPA_G2 &m :
  `|Pr[INDCPA(Enc, Adv).main() @ &m : res] -
    Pr[G2.main() @ &m : res]| <=
  `|Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res] -
    Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]| +
  limit_pre%r / (2 ^ text_len)%r.
```

New Material

Step 3: Independent Choice in `genc`

- In Step 3, we again make use of up to bad reasoning, this time transitioning to a game in which the encryption oracle, `EO_I`, chooses the text value to be exclusive or-ed with the plaintext in a way that is “independent” (“I” for “independent”) from the true random function’s map, i.e., without updating that map.
- We no longer need to detect “pre” clashes (clashes in `genc` with a `u` chosen in a call to `enc_pre`).

Step 3: Independent Choice in `genc`

```
local module EO_I : EO = {
  var ctr_pre : int
  var ctr_post : int
  var clash_post : bool
  var genc_inp : text

  proc init() = {
    TRF.init();
    ctr_pre <- 0; ctr_post <- 0;
    clash_post <- false; genc_inp <- text0;
  }
```

no longer need `clash_pre`

Step 3: Independent Choice in `genc`

```
proc enc_pre(x : text) : cipher = {
  var u, v : text; var c : cipher;
  if (ctr_pre < limit_pre) {
    ctr_pre <- ctr_pre + 1;
    u <$ dtext;
    v <@ TRF.f(u);
    c <- (u, x +^ v);
  }
  else {
    c <- (text0, text0);
  }
  return c;
}
```

no changes from E0_0

Step 3: Independent Choice in genc

```
proc genc(x : text) : cipher = {
  var u, v : text; var c : cipher;
  u <$ dtext;
  genc_inp <- u;
  v <$ dtext;
  (* removed: TRF.mp.[u] <- v; *)
  c <- (u, x +^ v);
  return c;
}
```

Step 3: Independent Choice in genc

```
  proc enc_post(x : text) : cipher = {
    var u, v : text; var c : cipher;
    if (ctr_post < limit_post) {
      ctr_post <- ctr_post + 1;
      u <$ dtext;
      if (u = genc_inp) {
        clash_post <- true;
      }
      v <@ TRF.f(u);
      c <- (u, x +^ v);
    }
    else {
      c <- (text0, text0);
    }
    return c;
  }
}.
```

no changes from E0_0

Step 3: Independent Choice in `genc`

```
local module G3 = {
  module A = Adv(EO_I)

  proc main() : bool = {
    var b, b' : bool; var x1, x2 : text; var c : cipher;
    EO_I.init();
    (x1, x2) <@ A.choose();
    b <$ {0,1};
    c <@ EO_I.genc(b ? x1 : x2);
    b' <@ A.guess(c);
    return b = b';
  }
}.
```

Step 3: Independent Choice in `genc`

```
local lemma G2_G3_main :
  equiv
  [G2.main ~ G3.main :
   true ==>
   ={clash_post}(EO_O, EO_I) /\
   (! EO_O.clash_post{1} => ={res})].
```

- The subtle issue with this proof is that after the calls to `EO_O.genc` / `EO_I.genc` the maps will almost certainly give different values to `genc_inp` — but if `clash_post` doesn't get set, that won't matter.
- Because the up to bad reasoning involves `Adv`'s `guess` procedure (which uses `enc_post`), we need that `guess` is lossless.

Step 3: Independent Choice in `genc`

```
local lemma G3_main_clash_ub &m :
  Pr[G3.main() @ &m : EO_I.clash_post] <=
  limit_post%r / (2 ^ text_len)%r.
```

- This is proved using the `fel` (failure event lemma) tactic, which lets us upper-bound the probability that calling `Adv.guess` (which calls `EO_I.enc_post`) will cause `EO_I.clash_post` to be set.
  - Until the limit `limit_post` is exceeded, each call of `EO_I.enc_post` has a `1%r / (2 ^ text_len)%r` chance of generating an input `u` to the true random function that clashes with `genc_inp`, and so of setting `EO_I.clash_post`.

Step 3: Independent Choice in `genc`

```
local lemma G2_G3 &m :
  `|Pr[G2.main() @ &m : res] -
    Pr[G3.main() @ &m : res]| <=
  limit_post%r / (2 ^ text_len)%r.

local lemma INDCPA_G3 &m :
  `|Pr[INDCPA(Enc, Adv).main() @ &m : res] -
    Pr[G3.main() @ &m : res]| <=
  `|Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res] -
    Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]| +
  limit_pre%r / (2 ^ text_len)%r +
  limit_post%r / (2 ^ text_len)%r.
```

Step 3: Independent Choice in `genc`

```
local lemma G2_G3 &m :
  `|Pr[G2.main() @ &m : res] -
    Pr[G3.main() @ &m : res]| <=
  limit_post%r / (2 ^ text_len)%r.

local lemma INDCPA_G3 &m :
  `|Pr[INDCPA(Enc, Adv).main() @ &m : res] -
    Pr[G3.main() @ &m : res]| <=
  `|Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res] -
    Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]| +
  (limit_pre%r + limit_post%r) / (2 ^ text_len)%r.
```

Step 4: One-time Pad Argument

- In Step 4, we can switch to an encryption oracle `EO_N` in which the right side of the ciphertext produced by `EO_N.genc` makes no ("N" for "no") reference to the plaintext.
- We no longer need any instrumentation for detecting clashes.

Step 4: One-time Pad Argument

```
local module EO_N : EO = {
  var ctr_pre : int
  var ctr_post : int

  proc init() = {
    TRF.init();
    ctr_pre <- 0; ctr_post <- 0;
  }
```

Step 4: One-time Pad Argument

```
proc enc_pre(x : text) : cipher = {
  var u, v : text; var c : cipher;
  if (ctr_pre < limit_pre) {
    ctr_pre <- ctr_pre + 1;
    u <$ dtext;
    v <@ TRF.f(u);
    c <- (u, x +^ v);
  }
  else {
    c <- (text0, text0);
  }
  return c;
}
```

Step 4: One-time Pad Argument

```
proc genc(x : text) : cipher = {
  var u, v : text; var c : cipher;
  u <$ dtext;
  v <$ dtext;
  c <- (u, v);
  return c;
}
```

c is independent from x

Step 4: One-time Pad Argument

```
  proc enc_post(x : text) : cipher = {
    var u, v : text; var c : cipher;
    if (ctr_post < limit_post) {
      ctr_post <- ctr_post + 1;
      u <$ dtext;
      v <@ TRF.f(u);
      c <- (u, x +^ v);
    }
    else {
      c <- (text0, text0);
    }
    return c;
  }
}.
```

Step 4: One-time Pad Argument

```
local module G4 = {
  module A = Adv(EO_N)

  proc main() : bool = {
    var b, b' : bool; var x1, x2 : text; var c : cipher;
    EO_N.init();
    (x1, x2) <@ A.choose();
    b <$ {0,1};
    c <@ EO_N.genc(text0);
    b' <@ A.guess(c);
    return b = b';
  }
}.
```

what is different, here?

Step 4: One-time Pad Argument

```
local module G4 = {
  module A = Adv(EO_N)

  proc main() : bool = {
    var b, b' : bool; var x1, x2 : text; var c : cipher;
    EO_N.init();
    (x1, x2) <@ A.choose();
    b <$ {0,1};
    c <@ EO_N.genc(text0);
    b' <@ A.guess(c);
    return b = b';
  }
}.
```

argument to `genc` is irrelevant

Step 4: One-time Pad Argument

- When proving

```
local lemma EO_I_EO_N_genc :
  equiv[EO_I.genc ~ EO_N.genc :
        true ==> ={res}].
```

we apply a standard one-time pad use of the `rnd` tactic to show that

```
v <$ dtext;
c <- (u, x +^ v);
```

is equivalent to

```
v <$ dtext;
c <- (u, v);
```

Step 4: One-time Pad Argument

```
local lemma G3_G4 &m :
  Pr[G3.main() @ &m : res] = Pr[G4.main() @ &m : res].

local lemma INDCPA_G4 &m :
  `|Pr[INDCPA(Enc, Adv).main() @ &m : res] -
    Pr[G4.main() @ &m : res]| <=
  `|Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res] -
    Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]| +
  (limit_pre%r + limit_post%r) / (2 ^ text_len)%r.
```

Step 5: Proving G4's Probability

- When proving

```
local lemma G4_prob &m :
  Pr[G4.main() @ &m : res] = 1%r / 2%r.
```

we can reorder

```
  b <$ {0,1};
  c <@ EO_N.genc(text0);
  b' <@ A.guess(c);
  return b = b';
```

to

```
  c <@ EO_N.genc(text0);
  b' <@ A.guess(c);
  b <$ {0,1};
  return b = b';
```

- We use that Adv's procedures are lossless.

IND-CPA Security Result

```
lemma INDCPA' &m :
  `|Pr[INDCPA(Enc, Adv).main() @ &m : res] -
    1%r / 2%r| <=
  `|Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res] -
    Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]| +
  (limit_pre%r + limit_post%r) / (2 ^ text_len)%r.

end section.
```

- When we exit the section, the universal quantification of `Adv`, and the assumptions that its procedures are lossless are automatically added to `INDCPA'`. By moving the quantification over `&m` to before the losslessness assumptions, we get our security result:

IND-CPA Security Result

```
lemma INDCPA (Adv <: ADV{Enc0, PRF, TRF, Adv2RFA}) &m :
  (forall (EO <: EO{Adv}),
   islossless EO.enc_pre => islossless Adv(EO).choose) =>
  (forall (EO <: EO{Adv}),
   islossless EO.enc_post => islossless Adv(EO).guess) =>
  `|Pr[INDCPA(Enc, Adv).main() @ &m : res] -
    1%r / 2%r| <=
  `|Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res] -
    Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]| +
  (limit_pre%r + limit_post%r) / (2 ^ text_len)%r.
```

- Q: How small is this upper bound?
- A: We can make assumptions about the efficiency of `Adv` (and inspect `Adv2RFA` to see it too is efficient), and we can tune `limit_pre`, `limit_post` and `text_len`.

IND-CPA Security Result

```
lemma INDCPA (Adv <: ADV{EncO, PRF, TRF, Adv2RFA}) &m :
  (forall (EO <: EO{Adv}),
   islossless EO.enc_pre => islossless Adv(EO).choose) =>
  (forall (EO <: EO{Adv}),
   islossless EO.enc_post => islossless Adv(EO).guess) =>
  `|Pr[INDCPA(Enc, Adv).main() @ &m : res] -
    1%r / 2%r| <=
  `|Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res] -
    Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]| +
  (limit_pre%r + limit_post%r) / (2 ^ text_len)%r.
```

- Q: If we remove the restriction on `Adv` (`{EncO, PRF, TRF, Adv2RFA}`), what would happen?
- A: Various tactic applications would fail; e.g., calls to the `Adv`'s procedures, as they could invalidate assumptions.

IND-CPA Security Result

```
lemma INDCPA (Adv <: ADV{EncO, PRF, TRF, Adv2RFA}) &m :
  (forall (EO <: EO{Adv}),
   islossless EO.enc_pre => islossless Adv(EO).choose) =>
  (forall (EO <: EO{Adv}),
   islossless EO.enc_post => islossless Adv(EO).guess) =>
  `|Pr[INDCPA(Enc, Adv).main() @ &m : res] -
    1%r / 2%r| <=
  `|Pr[GRF(PRF, Adv2RFA(Adv)).main() @ &m : res] -
    Pr[GRF(TRF, Adv2RFA(Adv)).main() @ &m : res]| +
  (limit_pre%r + limit_post%r) / (2 ^ text_len)%r.
```

- Q: If we remove the losslessness assumptions, what would happen?
- A: Up to bad reasoning and proof that `G4.main` returns `true` with probability `1%r / 2%r` would fail.

IND-CPA Security Result

- Q: Why did we start our sequence of games by switching from using the PRF F to using a true random function?
- A: We need true randomness for one-time pad argument.

```
proc genc(x : text) : cipher = {
  var u, v : text; var c : cipher;
  u <$ dtext;
  if (u \in TRF.mp) {
    clash_pre <- true;
  }
  genc_inp <- u;
  v <$ dtext;
  TRF.mp.[u] <- v;
  c <- (u, x +^ v);
  return c;
}
```

We could have still been using `inps_pre`

`E0_0`

IND-CPA Security Result

```
proc genc(x : text) : cipher = {
  var u, v : text; var c : cipher;
  u <$ dtext;
  genc_inp <- u;
  v <$ dtext;
  (* removed: TRF.mp.[u] <- v; *)
  c <- (u, x +^ v);
  return c;
}
```

now, v is only used once, so we can use one-time pad technique

EO_I

IND-CPA Security Result

```
proc genc(x : text) : cipher = {
  var u, v : text; var c : cipher;
  u <$ dtext;
  v <$ dtext;
  c <- (u, v);
  return c;
}
```

Lets us prove `G4` returns `true` with probability `1%r / 2%r`

`EO_N`