

Verification of The SET Protocol

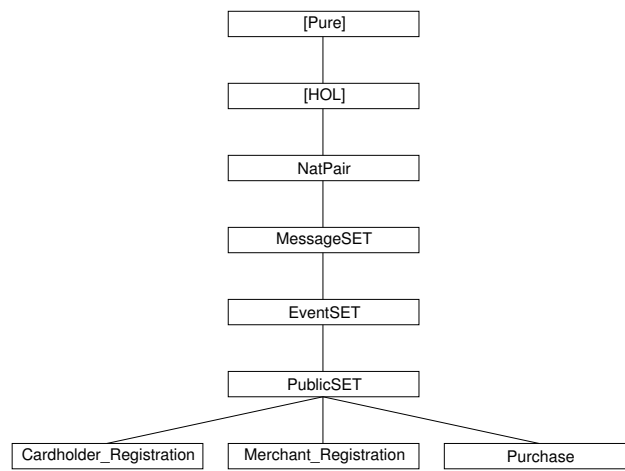
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1 The Message Theory, Modified for SET

theory *MessageSET* **imports** *NatPair* **begin**

1.1 General Lemmas

Needed occasionally with *spy_analz_tac*, e.g. in *analz_insert_Key_newK*

lemma *Un_absorb3 [simp]* : " $A \cup (B \cup A) = B \cup A$ "
 $\langle proof \rangle$

Collapses redundant cases in the huge protocol proofs

lemmas *disj_simps* = *disj_comms disj_left_absorb disj_assoc*

Effective with assumptions like $K \notin \text{range pubK}$ and $K \notin \text{invKey} \text{ ` } \text{range pubK}$

lemma *notin_image_iff*: " $(y \notin f'I) = (\forall i \in I. f\ i \neq y)$ "
 $\langle proof \rangle$

Effective with the assumption $KK \subseteq - \text{range } (\text{invKey} \circ \text{pubK})$

lemma *disjoint_image_iff*: " $(A \subseteq - (f'I)) = (\forall i \in I. f\ i \notin A)$ "
 $\langle proof \rangle$

types

key = *nat*

consts

all_symmetric :: *bool* — true if all keys are symmetric
invKey :: "*key*=>*key*" — inverse of a symmetric key

specification (*invKey*)

invKey [simp]: "*invKey* (*invKey* *K*) = *K*"
invKey_symmetric: "*all_symmetric* --> *invKey* = *id*"
 $\langle proof \rangle$

The inverse of a symmetric key is itself; that of a public key is the private key and vice versa

constdefs

symKeys :: "*key set*"
"*symKeys* == {*K*. *invKey* *K* = *K*}"

Agents. We allow any number of certification authorities, cardholders merchants, and payment gateways.

datatype

agent = *CA nat* | *Cardholder nat* | *Merchant nat* | *PG nat* | *Spy*

Messages

datatype

msg = *Agent agent* — Agent names
| *Number nat* — Ordinary integers, timestamps, ...
| *Nonce nat* — Unguessable nonces

```

| Pan    nat      — Unguessable Primary Account Numbers (??)
| Key    key      — Crypto keys
| Hash   msg      — Hashing
| MPair  msg msg   — Compound messages
| Crypt  key msg   — Encryption, public- or shared-key

```

syntax

```
"@MTuple"      :: "[ 'a, args ] => 'a * 'b"      ("(2{|_,/ _|})")
```

syntax (*xsymbols*)

```
"@MTuple"      :: "[ 'a, args ] => 'a * 'b"      ("(2{⌊_,/ _⌋})")
```

translations

```

"{|x, y, z|}" == "{|x, {|y, z|}|}"
"{|x, y|}"    == "MPair x y"

```

constdefs

```

nat_of_agent :: "agent => nat"
"nat_of_agent == agent_case (curry nat2_to_nat 0)
                           (curry nat2_to_nat 1)
                           (curry nat2_to_nat 2)
                           (curry nat2_to_nat 3)
                           (nat2_to_nat (4,0))"
— maps each agent to a unique natural number, for specifications

```

The function is indeed injective

```

lemma inj_nat_of_agent: "inj nat_of_agent"
<proof>

```

constdefs

```

keysFor :: "msg set => key set"
"keysFor H == invKey ' {K. ∃X. Crypt K X ∈ H}"

```

1.1.1 Inductive definition of all "parts" of a message.

```
consts parts :: "msg set => msg set"
```

```
inductive "parts H"
```

```
intros
```

```

Inj [intro]:      "X ∈ H ==> X ∈ parts H"
Fst:              "{|X,Y|} ∈ parts H ==> X ∈ parts H"
Snd:              "{|X,Y|} ∈ parts H ==> Y ∈ parts H"
Body:             "Crypt K X ∈ parts H ==> X ∈ parts H"

```

```

lemma parts_mono: "G<=H ==> parts(G) <= parts(H)"
<proof>

```

1.1.2 Inverse of keys

lemma `Key_image_eq [simp]: "(Key x ∈ Key'A) = (x ∈ A)"`
`<proof>`

lemma `Nonce_Key_image_eq [simp]: "(Nonce x ∉ Key'A)"`
`<proof>`

lemma `Cardholder_image_eq [simp]: "(Cardholder x ∈ Cardholder'A) = (x ∈ A)"`
`<proof>`

lemma `CA_image_eq [simp]: "(CA x ∈ CA'A) = (x ∈ A)"`
`<proof>`

lemma `Pan_image_eq [simp]: "(Pan x ∈ Pan'A) = (x ∈ A)"`
`<proof>`

lemma `Pan_Key_image_eq [simp]: "(Pan x ∉ Key'A)"`
`<proof>`

lemma `Nonce_Pan_image_eq [simp]: "(Nonce x ∉ Pan'A)"`
`<proof>`

lemma `invKey_eq [simp]: "(invKey K = invKey K') = (K=K')"`
`<proof>`

1.2 keysFor operator

lemma `keysFor_empty [simp]: "keysFor {} = {}"`
`<proof>`

lemma `keysFor_Un [simp]: "keysFor (H ∪ H') = keysFor H ∪ keysFor H'"`
`<proof>`

lemma `keysFor_UN [simp]: "keysFor (⋃ i ∈ A. H i) = (⋃ i ∈ A. keysFor (H i))"`
`<proof>`

lemma `keysFor_mono: "G ⊆ H ==> keysFor(G) ⊆ keysFor(H)"`
`<proof>`

lemma `keysFor_insert_Agent [simp]: "keysFor (insert (Agent A) H) = keysFor H"`
`<proof>`

lemma `keysFor_insert_Nonce [simp]: "keysFor (insert (Nonce N) H) = keysFor H"`
`<proof>`

lemma `keysFor_insert_Number [simp]: "keysFor (insert (Number N) H) = keysFor H"`
`<proof>`

lemma `keysFor_insert_Key [simp]: "keysFor (insert (Key K) H) = keysFor H"`

<proof>

lemma *keysFor_insert_Pan* [simp]: "keysFor (insert (Pan A) H) = keysFor H"
<proof>

lemma *keysFor_insert_Hash* [simp]: "keysFor (insert (Hash X) H) = keysFor H"
<proof>

lemma *keysFor_insert_MPair* [simp]: "keysFor (insert {|X,Y|} H) = keysFor H"
<proof>

lemma *keysFor_insert_Crypt* [simp]:
 "keysFor (insert (Crypt K X) H) = insert (invKey K) (keysFor H)"
<proof>

lemma *keysFor_image_Key* [simp]: "keysFor (Key'E) = {}"
<proof>

lemma *Crypt_imp_invKey_keysFor*: "Crypt K X ∈ H ==> invKey K ∈ keysFor H"
<proof>

1.3 Inductive relation "parts"

lemma *MPair_parts*:
 "[| {|X,Y|} ∈ parts H;
 [| X ∈ parts H; Y ∈ parts H |] ==> P |] ==> P"
<proof>

declare *MPair_parts* [elim!] *parts.Body* [dest!]

NB These two rules are UNSAFE in the formal sense, as they discard the compound message. They work well on THIS FILE. *MPair_parts* is left as SAFE because it speeds up proofs. The *Crypt* rule is normally kept UNSAFE to avoid breaking up certificates.

lemma *parts_increasing*: " $H \subseteq \text{parts}(H)$ "
<proof>

lemmas *parts_insertI* = *subset_insertI* [THEN *parts_mono*, THEN *subsetD*, standard]

lemma *parts_empty* [simp]: " $\text{parts}\{\} = \{\}$ "
<proof>

lemma *parts_emptyE* [elim!]: " $X \in \text{parts}\{\} \implies P$ "
<proof>

lemma *parts_singleton*: " $X \in \text{parts } H \implies \exists Y \in H. X \in \text{parts } \{Y\}$ "
<proof>

1.3.1 Unions

lemma *parts_Un_subset1*: " $\text{parts}(G) \cup \text{parts}(H) \subseteq \text{parts}(G \cup H)$ "

$\langle proof \rangle$

lemma *parts_Un_subset2*: " $parts(G \cup H) \subseteq parts(G) \cup parts(H)$ "
 $\langle proof \rangle$

lemma *parts_Un [simp]*: " $parts(G \cup H) = parts(G) \cup parts(H)$ "
 $\langle proof \rangle$

lemma *parts_insert*: " $parts(insert\ X\ H) = parts\ \{X\} \cup parts\ H$ "
 $\langle proof \rangle$

lemma *parts_insert2*:
 " $parts(insert\ X\ (insert\ Y\ H)) = parts\ \{X\} \cup parts\ \{Y\} \cup parts\ H$ "
 $\langle proof \rangle$

lemma *parts_UN_subset1*: " $(\bigcup_{x \in A}. parts(H\ x)) \subseteq parts(\bigcup_{x \in A}. H\ x)$ "
 $\langle proof \rangle$

lemma *parts_UN_subset2*: " $parts(\bigcup_{x \in A}. H\ x) \subseteq (\bigcup_{x \in A}. parts(H\ x))$ "
 $\langle proof \rangle$

lemma *parts_UN [simp]*: " $parts(\bigcup_{x \in A}. H\ x) = (\bigcup_{x \in A}. parts(H\ x))$ "
 $\langle proof \rangle$

This allows *blast* to simplify occurrences of *parts* $(G \cup H)$ in the assumption.

declare *parts_Un [THEN equalityD1, THEN subsetD, THEN UnE, elim!]*

lemma *parts_insert_subset*: " $insert\ X\ (parts\ H) \subseteq parts(insert\ X\ H)$ "
 $\langle proof \rangle$

1.3.2 Idempotence and transitivity

lemma *parts_partsD [dest!]*: " $X \in parts\ (parts\ H) \implies X \in parts\ H$ "
 $\langle proof \rangle$

lemma *parts_idem [simp]*: " $parts\ (parts\ H) = parts\ H$ "
 $\langle proof \rangle$

lemma *parts_trans*: " $[| X \in parts\ G; \ G \subseteq parts\ H \ |] \implies X \in parts\ H$ "
 $\langle proof \rangle$

lemma *parts_cut*:
 " $[| Y \in parts\ (insert\ X\ G); \ X \in parts\ H \ |] \implies Y \in parts\ (G \cup H)$ "
 $\langle proof \rangle$

lemma *parts_cut_eq [simp]*: " $X \in parts\ H \implies parts\ (insert\ X\ H) = parts\ H$ "
 $\langle proof \rangle$

1.3.3 Rewrite rules for pulling out atomic messages

lemmas *parts_insert_eq_I = equalityI [OF subsetI parts_insert_subset]*


```
lemma parts_insert_Agent [simp]:
  "parts (insert (Agent agt) H) = insert (Agent agt) (parts H)"
<proof>
```

```
lemma parts_insert_Nonce [simp]:
  "parts (insert (Nonce N) H) = insert (Nonce N) (parts H)"
<proof>
```

```
lemma parts_insert_Number [simp]:
  "parts (insert (Number N) H) = insert (Number N) (parts H)"
<proof>
```

```
lemma parts_insert_Key [simp]:
  "parts (insert (Key K) H) = insert (Key K) (parts H)"
<proof>
```

```
lemma parts_insert_Pan [simp]:
  "parts (insert (Pan A) H) = insert (Pan A) (parts H)"
<proof>
```

```
lemma parts_insert_Hash [simp]:
  "parts (insert (Hash X) H) = insert (Hash X) (parts H)"
<proof>
```

```
lemma parts_insert_Crypt [simp]:
  "parts (insert (Crypt K X) H) =
    insert (Crypt K X) (parts (insert X H))"
<proof>
```

```
lemma parts_insert_MPair [simp]:
  "parts (insert {|X,Y|} H) =
    insert {|X,Y|} (parts (insert X (insert Y H)))"
<proof>
```

```
lemma parts_image_Key [simp]: "parts (Key'N) = Key'N"
<proof>
```

```
lemma parts_image_Pan [simp]: "parts (Pan'A) = Pan'A"
<proof>
```

```
lemma msg_Nonce_supply: "∃N. ∀n. N ≤ n --> Nonce n ∉ parts {msg}"
<proof>
```

```
lemma msg_Number_supply: "∃N. ∀n. N ≤ n --> Number n ∉ parts {msg}"
<proof>
```

1.4 Inductive relation "analz"

Inductive definition of "analz" – what can be broken down from a set of messages, including keys. A form of downward closure. Pairs can be taken apart; messages decrypted with known keys.

```

consts  analz    :: "msg set => msg set"
inductive "analz H"
  intros
    Inj [intro,simp] :    "X ∈ H ==> X ∈ analz H"
    Fst:    "{|X,Y|} ∈ analz H ==> X ∈ analz H"
    Snd:    "{|X,Y|} ∈ analz H ==> Y ∈ analz H"
    Decrypt [dest]:
      "[|Crypt K X ∈ analz H; Key(invKey K): analz H|] ==> X ∈ analz
H"

```

```

lemma analz_mono: "G<=H ==> analz(G) <= analz(H)"
<proof>

```

Making it safe speeds up proofs

```

lemma MPair_analz [elim!]:
  "[| {|X,Y|} ∈ analz H;
      [| X ∈ analz H; Y ∈ analz H |] ==> P
  |] ==> P"
<proof>

```

```

lemma analz_increasing: "H ⊆ analz(H)"
<proof>

```

```

lemma analz_subset_parts: "analz H ⊆ parts H"
<proof>

```

```

lemmas analz_into_parts = analz_subset_parts [THEN subsetD, standard]

```

```

lemmas not_parts_not_analz = analz_subset_parts [THEN contra_subsetD, standard]

```

```

lemma parts_analz [simp]: "parts (analz H) = parts H"
<proof>

```

```

lemma analz_parts [simp]: "analz (parts H) = parts H"
<proof>

```

```

lemmas analz_insertI = subset_insertI [THEN analz_mono, THEN [2] rev_subsetD,
standard]

```

1.4.1 General equational properties

```

lemma analz_empty [simp]: "analz{} = {}"
<proof>

```

```

lemma analz_Un: "analz(G) ∪ analz(H) ⊆ analz(G ∪ H)"

```

<proof>

lemma *analz_insert*: "insert X (analz H) \subseteq analz(insert X H)"
<proof>

1.4.2 Rewrite rules for pulling out atomic messages

lemmas *analz_insert_eq_I* = equalityI [OF subsetI *analz_insert*]

lemma *analz_insert_Agent* [simp]:
 "analz (insert (Agent agt) H) = insert (Agent agt) (analz H)"
<proof>

lemma *analz_insert_Nonce* [simp]:
 "analz (insert (Nonce N) H) = insert (Nonce N) (analz H)"
<proof>

lemma *analz_insert_Number* [simp]:
 "analz (insert (Number N) H) = insert (Number N) (analz H)"
<proof>

lemma *analz_insert_Hash* [simp]:
 "analz (insert (Hash X) H) = insert (Hash X) (analz H)"
<proof>

lemma *analz_insert_Key* [simp]:
 "K \notin keysFor (analz H) ==>
 analz (insert (Key K) H) = insert (Key K) (analz H)"
<proof>

lemma *analz_insert_MPair* [simp]:
 "analz (insert {|X,Y|} H) =
 insert {|X,Y|} (analz (insert X (insert Y H)))"
<proof>

lemma *analz_insert_Crypt*:
 "Key (invKey K) \notin analz H
 ==> analz (insert (Crypt K X) H) = insert (Crypt K X) (analz H)"
<proof>

lemma *analz_insert_Pan* [simp]:
 "analz (insert (Pan A) H) = insert (Pan A) (analz H)"
<proof>

lemma *lemma1*: "Key (invKey K) \in analz H ==>
 analz (insert (Crypt K X) H) \subseteq
 insert (Crypt K X) (analz (insert X H))"
<proof>

lemma *lemma2*: "Key (invKey K) \in analz H ==>
 insert (Crypt K X) (analz (insert X H)) \subseteq
 analz (insert (Crypt K X) H)"

$\langle proof \rangle$

lemma *analz_insert_Decrypt*:
 "Key (invKey K) \in analz H \implies
 analz (insert (Crypt K X) H) =
 insert (Crypt K X) (analz (insert X H))"
 $\langle proof \rangle$

lemma *analz_Crypt_if [simp]*:
 "analz (insert (Crypt K X) H) =
 (if (Key (invKey K) \in analz H)
 then insert (Crypt K X) (analz (insert X H))
 else insert (Crypt K X) (analz H))"
 $\langle proof \rangle$

lemma *analz_insert_Crypt_subset*:
 "analz (insert (Crypt K X) H) \subseteq
 insert (Crypt K X) (analz (insert X H))"
 $\langle proof \rangle$

lemma *analz_image_Key [simp]*: "analz (Key 'N) = Key 'N"
 $\langle proof \rangle$

lemma *analz_image_Pan [simp]*: "analz (Pan 'A) = Pan 'A"
 $\langle proof \rangle$

1.4.3 Idempotence and transitivity

lemma *analz_analzD [dest!]*: "X \in analz (analz H) \implies X \in analz H"
 $\langle proof \rangle$

lemma *analz_idem [simp]*: "analz (analz H) = analz H"
 $\langle proof \rangle$

lemma *analz_trans*: "[| X \in analz G; G \subseteq analz H |] \implies X \in analz H"
 $\langle proof \rangle$

lemma *analz_cut*: "[| Y \in analz (insert X H); X \in analz H |] \implies Y \in analz H"
 $\langle proof \rangle$

lemma *analz_insert_eq*: "X \in analz H \implies analz (insert X H) = analz H"
 $\langle proof \rangle$

A congruence rule for "analz"

lemma *analz_subset_cong*:
 "[| analz G \subseteq analz G'; analz H \subseteq analz H' |]

```

      [] ==> analz (G ∪ H) ⊆ analz (G' ∪ H')"
⟨proof⟩

lemma analz_cong:
  "[| analz G = analz G'; analz H = analz H'
    |] ==> analz (G ∪ H) = analz (G' ∪ H')"
⟨proof⟩

lemma analz_insert_cong:
  "analz H = analz H' ==> analz(insert X H) = analz(insert X H')"
⟨proof⟩

lemma analz_trivial:
  "[| ∀X Y. {|X,Y|} ∉ H; ∀X K. Crypt K X ∉ H |] ==> analz H = H"
⟨proof⟩

lemma analz_UN_analz_lemma:
  "X ∈ analz (⋃ i ∈ A. analz (H i)) ==> X ∈ analz (⋃ i ∈ A. H i)"
⟨proof⟩

lemma analz_UN_analz [simp]: "analz (⋃ i ∈ A. analz (H i)) = analz (⋃ i ∈ A.
H i)"
⟨proof⟩

```

1.5 Inductive relation "synth"

Inductive definition of "synth" – what can be built up from a set of messages. A form of upward closure. Pairs can be built, messages encrypted with known keys. Agent names are public domain. Numbers can be guessed, but Nonces cannot be.

```

consts synth  :: "msg set => msg set"
inductive "synth H"
  intros
    Inj      [intro]:  "X ∈ H ==> X ∈ synth H"
    Agent    [intro]:  "Agent agt ∈ synth H"
    Number   [intro]:  "Number n ∈ synth H"
    Hash     [intro]:  "X ∈ synth H ==> Hash X ∈ synth H"
    MPair    [intro]:  "[| X ∈ synth H; Y ∈ synth H |] ==> {|X,Y|} ∈ synth
H"
    Crypt    [intro]:  "[| X ∈ synth H; Key(K) ∈ H |] ==> Crypt K X ∈ synth
H"

```

```

lemma synth_mono: "G ≤ H ==> synth(G) ≤ synth(H)"
⟨proof⟩

```

```

inductive_cases Nonce_synth [elim!]: "Nonce n ∈ synth H"
inductive_cases Key_synth   [elim!]: "Key K ∈ synth H"
inductive_cases Hash_synth  [elim!]: "Hash X ∈ synth H"
inductive_cases MPair_synth [elim!]: "{|X,Y|} ∈ synth H"

```

```

inductive_cases Crypt_synth [elim!]: "Crypt K X  $\in$  synth H"
inductive_cases Pan_synth [elim!]: "Pan A  $\in$  synth H"

```

```

lemma synth_increasing: "H  $\subseteq$  synth(H)"
<proof>

```

1.5.1 Unions

```

lemma synth_Un: "synth(G)  $\cup$  synth(H)  $\subseteq$  synth(G  $\cup$  H)"
<proof>

```

```

lemma synth_insert: "insert X (synth H)  $\subseteq$  synth(insert X H)"
<proof>

```

1.5.2 Idempotence and transitivity

```

lemma synth_synthD [dest!]: "X  $\in$  synth (synth H)  $\implies$  X  $\in$  synth H"
<proof>

```

```

lemma synth_idem: "synth (synth H) = synth H"
<proof>

```

```

lemma synth_trans: "[| X  $\in$  synth G; G  $\subseteq$  synth H |]  $\implies$  X  $\in$  synth H"
<proof>

```

```

lemma synth_cut: "[| Y  $\in$  synth (insert X H); X  $\in$  synth H |]  $\implies$  Y  $\in$  synth H"
<proof>

```

```

lemma Agent_synth [simp]: "Agent A  $\in$  synth H"
<proof>

```

```

lemma Number_synth [simp]: "Number n  $\in$  synth H"
<proof>

```

```

lemma Nonce_synth_eq [simp]: "(Nonce N  $\in$  synth H) = (Nonce N  $\in$  H)"
<proof>

```

```

lemma Key_synth_eq [simp]: "(Key K  $\in$  synth H) = (Key K  $\in$  H)"
<proof>

```

```

lemma Crypt_synth_eq [simp]: "Key K  $\notin$  H  $\implies$  (Crypt K X  $\in$  synth H) = (Crypt K X  $\in$  H)"
<proof>

```

```

lemma Pan_synth_eq [simp]: "(Pan A  $\in$  synth H) = (Pan A  $\in$  H)"
<proof>

```

```

lemma keysFor_synth [simp]:
  "keysFor (synth H) = keysFor H  $\cup$  invKey '{K. Key K  $\in$  H}"
<proof>

```

1.5.3 Combinations of parts, analz and synth

lemma *parts_synth [simp]: "parts (synth H) = parts H \cup synth H"*
<proof>

lemma *analz_analz_Un [simp]: "analz (analz G \cup H) = analz (G \cup H)"*
<proof>

lemma *analz_synth_Un [simp]: "analz (synth G \cup H) = analz (G \cup H) \cup synth G"*
<proof>

lemma *analz_synth [simp]: "analz (synth H) = analz H \cup synth H"*
<proof>

1.5.4 For reasoning about the Fake rule in traces

lemma *parts_insert_subset_Un: "X \in G \implies parts(insert X H) \subseteq parts G \cup parts H"*
<proof>

lemma *Fake_parts_insert: "X \in synth (analz H) \implies parts (insert X H) \subseteq synth (analz H) \cup parts H"*
<proof>

lemma *Fake_parts_insert_in_Un:*
"[| Z \in parts (insert X H); X: synth (analz H) |]
 \implies Z \in synth (analz H) \cup parts H"
<proof>

lemma *Fake_analz_insert:*
"X \in synth (analz G) \implies analz (insert X H) \subseteq synth (analz G) \cup analz (G \cup H)"
<proof>

lemma *analz_conj_parts [simp]:*
"(X \in analz H & X \in parts H) = (X \in analz H)"
<proof>

lemma *analz_disj_parts [simp]:*
"(X \in analz H | X \in parts H) = (X \in parts H)"
<proof>

lemma *MPair_synth_analz [iff]:*
"({|X,Y|} \in synth (analz H)) = (X \in synth (analz H) & Y \in synth (analz H))"
<proof>

lemma *Crypt_synth_analz:*
"[| Key K \in analz H; Key (invKey K) \in analz H |]
 \implies (Crypt K X \in synth (analz H)) = (X \in synth (analz H))"
<proof>

```

lemma Hash_synth_analz [simp]:
  "X ∉ synth (analz H)
   ==> (Hash{|X,Y|} ∈ synth (analz H)) = (Hash{|X,Y|} ∈ analz H)"
  <proof>

```

```

declare parts.Body [rule del]

```

Rewrites to push in Key and Crypt messages, so that other messages can be pulled out using the *analz_insert* rules

<ML>

Cannot be added with [simp] – messages should not always be re-ordered.

```

lemmas pushes = pushKeys pushCrypts

```

1.6 Tactics useful for many protocol proofs

<ML>

```

declare o_def [simp]

```

```

lemma Crypt_notin_image_Key [simp]: "Crypt K X ∉ Key ‘ A"
  <proof>

```

```

lemma Hash_notin_image_Key [simp] : "Hash X ∉ Key ‘ A"
  <proof>

```

```

lemma synth_analz_mono: "G<=H ==> synth (analz(G)) <= synth (analz(H))"
  <proof>

```

```

lemma Fake_analz_eq [simp]:
  "X ∈ synth (analz H) ==> synth (analz (insert X H)) = synth (analz H)"
  <proof>

```

Two generalizations of *analz_insert_eq*

```

lemma gen_analz_insert_eq [rule_format]:
  "X ∈ analz H ==> ALL G. H ⊆ G --> analz (insert X G) = analz G"
  <proof>

```

```

lemma synth_analz_insert_eq [rule_format]:
  "X ∈ synth (analz H)
   ==> ALL G. H ⊆ G --> (Key K ∈ analz (insert X G)) = (Key K ∈ analz
G)"
  <proof>

```

```

lemma Fake_parts_sing:
  "X ∈ synth (analz H) ==> parts{X} ⊆ synth (analz H) ∪ parts H"
  <proof>

```



```
lemmas Fake_parts_sing_imp_Un = Fake_parts_sing [THEN [2] rev_subsetD]
```

```
<ML>
```

```
end
```

2 Theory of Events for SET

```
theory EventSET imports MessageSET begin
```

The Root Certification Authority

```
syntax          RCA :: agent
translations "RCA" == "CA 0"
```

Message events

```
datatype
  event = Says  agent agent msg
        | Gets  agent      msg
        | Notes agent      msg
```

compromised agents: keys known, Notes visible

```
consts bad :: "agent set"
```

Spy has access to his own key for spoof messages, but RCA is secure

```
specification (bad)
  Spy_in_bad      [iff]: "Spy ∈ bad"
  RCA_not_bad     [iff]: "RCA ∉ bad"
  <proof>
```

2.1 Agents' Knowledge

```
consts
  initState :: "agent => msg set"
  knows    :: "[agent, event list] => msg set"
```

```
primrec
```

```
knows_Nil:
  "knows A [] = initState A"
knows_Cons:
  "knows A (ev # evs) =
    (if A = Spy then
      (case ev of
        Says A' B X => insert X (knows Spy evs)
      | Gets A' X => knows Spy evs
      | Notes A' X =>
          if A' ∈ bad then insert X (knows Spy evs) else knows Spy evs)
    else
      (case ev of
```

```

    Says A' B X =>
      if A'=A then insert X (knows A evs) else knows A evs
  | Gets A' X    =>
      if A'=A then insert X (knows A evs) else knows A evs
  | Notes A' X   =>
      if A'=A then insert X (knows A evs) else knows A evs))"

```

2.2 Used Messages

consts

```
used :: "event list => msg set"
```

primrec

```

used_Nil: "used [] = (UN B. parts (initState B))"
used_Cons: "used (ev # evs) =
  (case ev of
    Says A B X => parts {X} Un (used evs)
  | Gets A X   => used evs
  | Notes A X  => parts {X} Un (used evs))"

```

lemmas parts_insert_knows_A = parts_insert [of _ "knows A evs", standard]

lemma knows_Spy_Says [simp]:

```

  "knows Spy (Says A B X # evs) = insert X (knows Spy evs)"
<proof>

```

Letting the Spy see "bad" agents' notes avoids redundant case-splits on whether $A = \text{Spy}$ and whether $A \in \text{bad}$

lemma knows_Spy_Notes [simp]:

```

  "knows Spy (Notes A X # evs) =
    (if A:bad then insert X (knows Spy evs) else knows Spy evs)"
<proof>

```

lemma knows_Spy_Gets [simp]: "knows Spy (Gets A X # evs) = knows Spy evs"

<proof>

lemma initState_subset_knows: "initState A <= knows A evs"

<proof>

lemma knows_Spy_subset_knows_Spy_Says:

```

  "knows Spy evs <= knows Spy (Says A B X # evs)"
<proof>

```

lemma knows_Spy_subset_knows_Spy_Notes:

```

  "knows Spy evs <= knows Spy (Notes A X # evs)"
<proof>

```

```

lemma knows_Spy_subset_knows_Spy_Gets:
  "knows Spy evs <= knows Spy (Gets A X # evs)"
<proof>

```

```

lemma Says_imp_knows_Spy [rule_format]:
  "Says A B X ∈ set evs --> X ∈ knows Spy evs"
<proof>

```

```

lemmas knows_Spy_partsEs =
  Says_imp_knows_Spy [THEN parts.Inj, THEN revcut_rl, standard]
  parts.Body [THEN revcut_rl, standard]

```

2.3 The Function used

```

lemma parts_knows_Spy_subset_used: "parts (knows Spy evs) <= used evs"
<proof>

```

```

lemmas usedI = parts_knows_Spy_subset_used [THEN subsetD, intro]

```

```

lemma initState_subset_used: "parts (initState B) <= used evs"
<proof>

```

```

lemmas initState_into_used = initState_subset_used [THEN subsetD]

```

```

lemma used_Says [simp]: "used (Says A B X # evs) = parts{X} Un used evs"
<proof>

```

```

lemma used_Notes [simp]: "used (Notes A X # evs) = parts{X} Un used evs"
<proof>

```

```

lemma used_Gets [simp]: "used (Gets A X # evs) = used evs"
<proof>

```

```

lemma Notes_imp_parts_subset_used [rule_format]:
  "Notes A X ∈ set evs --> parts {X} <= used evs"
<proof>

```

NOTE REMOVAL—laws above are cleaner, as they don't involve "case"

```

declare knows_Cons [simp del]
  used_Nil [simp del] used_Cons [simp del]

```

For proving theorems of the form $X \notin \text{analz} (\text{knows Spy evs}) \longrightarrow P$ New events added by induction to "evs" are discarded. Provided this information isn't needed, the proof will be much shorter, since it will omit complicated reasoning about *analz*.

```

lemmas analz_mono_contra =
  knows_Spy_subset_knows_Spy_Says [THEN analz_mono, THEN contra_subsetD]
  knows_Spy_subset_knows_Spy_Notes [THEN analz_mono, THEN contra_subsetD]
  knows_Spy_subset_knows_Spy_Gets [THEN analz_mono, THEN contra_subsetD]

```

$\langle ML \rangle$

end

3 The Public-Key Theory, Modified for SET

theory *PublicSET* **imports** *EventSET* **begin**

3.1 Symmetric and Asymmetric Keys

definitions influenced by the wish to assign asymmetric keys - since the beginning - only to RCA and CAs, namely we need a partial function on type *Agent*

The SET specs mention two signature keys for CAs - we only have one

consts
publicKey :: "[*bool*, *agent*] => *key*"
 — the boolean is TRUE if a signing key

syntax
pubEK :: "*agent* => *key*"
pubSK :: "*agent* => *key*"
priEK :: "*agent* => *key*"
priSK :: "*agent* => *key*"

translations
"pubEK" == "*publicKey False*"
"pubSK" == "*publicKey True*"

"priEK A" == "*invKey (pubEK A)*"
"priSK A" == "*invKey (pubSK A)*"

By freeness of agents, no two agents have the same key. Since *True* \neq *False*, no agent has the same signing and encryption keys.

specification (*publicKey*)
injective_publicKey:
"publicKey b A = publicKey c A' ==> b=c & A=A'" $\langle proof \rangle$
axioms

privateKey_neq_publicKey [iff]:
"invKey (publicKey b A) \neq publicKey b' A'"

declare *privateKey_neq_publicKey* [THEN *not_sym*, *iff*]

3.2 Initial Knowledge

This information is not necessary. Each protocol distributes any needed certificates, and anyway our proofs require a formalization of the Spy's knowledge only. However, the initial knowledge is as follows: All agents know RCA's public keys; RCA and CAs know their own respective keys; RCA (has already certified and therefore) knows all CAs public keys; Spy knows all keys of all bad agents.

```

primrec initState_Spy:
  "initState Spy = Key ` (invKey ` pubEK ` bad Un
    invKey ` pubSK ` bad Un
    range pubEK Un range pubSK)"

```

Injective mapping from agents to PANs: an agent can have only one card

```

consts pan :: "agent => nat"

```

```

specification (pan)
  inj_pan: "inj pan"
  — No two agents have the same PAN <proof>
declare inj_pan [THEN inj_eq, iff]

```

```

consts
  XOR :: "nat*nat => nat" — no properties are assumed of exclusive-or

```

3.3 Signature Primitives

constdefs

```

sign :: "[key, msg]=>msg"
"sign K X == {|X, Crypt K (Hash X) |}"

```

```

signOnly :: "[key, msg]=>msg"
"signOnly K X == Crypt K (Hash X)"

```

```

signCert :: "[key, msg]=>msg"
"signCert K X == {|X, Crypt K X |}"

```

```

cert :: "[agent, key, msg, key] => msg"
"cert A Ka T signK == signCert signK {|Agent A, Key Ka, T|}"

```

```

certC :: "[nat, key, nat, msg, key] => msg"
"certC PAN Ka PS T signK ==
  signCert signK {|Hash {|Nonce PS, Pan PAN|}, Key Ka, T|}"

```

syntax

```

"onlyEnc" :: msg
"onlySig" :: msg
"authCode" :: msg

```

translations

```

"onlyEnc" == "Number 0"
"onlySig" == "Number (Suc 0)"
"authCode" == "Number (Suc (Suc 0))"

```

3.4 Encryption Primitives

constdefs

```

EXcrypt :: "[key,key,msg,msg] => msg"
— Extra Encryption

"EXcrypt K EK M m ==
  {|Crypt K {|M, Hash m|}, Crypt EK {|Key K, m|}|}"

EXHcrypt :: "[key,key,msg,msg] => msg"
— Extra Encryption with Hashing

"EXHcrypt K EK M m ==
  {|Crypt K {|M, Hash m|}, Crypt EK {|Key K, m, Hash M|}|}"

Enc :: "[key,key,key,msg] => msg"
— Simple Encapsulation with SIGNATURE

"Enc SK K EK M ==
  {|Crypt K (sign SK M), Crypt EK (Key K)|}"

EncB :: "[key,key,key,msg,msg] => msg"
— Encapsulation with Baggage. Keys as above, and baggage b.
"EncB SK K EK M b ==
  {|Enc SK K EK {|M, Hash b|}, b|}"

```

3.5 Basic Properties of pubEK, pubSK, priEK and priSK

```

lemma publicKey_eq_iff [iff]:
  "(publicKey b A = publicKey b' A') = (b=b' & A=A')"
<proof>

lemma privateKey_eq_iff [iff]:
  "(invKey (publicKey b A) = invKey (publicKey b' A')) = (b=b' & A=A')"
<proof>

lemma not_symKeys_publicKey [iff]: "publicKey b A ∉ symKeys"
<proof>

lemma not_symKeys_privateKey [iff]: "invKey (publicKey b A) ∉ symKeys"
<proof>

lemma symKeys_invKey_eq [simp]: "K ∈ symKeys ==> invKey K = K"
<proof>

lemma symKeys_invKey_iff [simp]: "(invKey K ∈ symKeys) = (K ∈ symKeys)"
<proof>

Can be slow (or even loop) as a simprule

lemma symKeys_neq_imp_neq: "(K ∈ symKeys) ≠ (K' ∈ symKeys) ==> K ≠ K'"
<proof>

```

These alternatives to `symKeys_neq_imp_neq` don't seem any better in practice.

lemma `publicKey_neq_symKey`: " $K \in \text{symKeys} \implies \text{publicKey } b \ A \neq K$ "
 $\langle \text{proof} \rangle$

lemma `symKey_neq_publicKey`: " $K \in \text{symKeys} \implies K \neq \text{publicKey } b \ A$ "
 $\langle \text{proof} \rangle$

lemma `privateKey_neq_symKey`: " $K \in \text{symKeys} \implies \text{invKey } (\text{publicKey } b \ A) \neq K$ "
 $\langle \text{proof} \rangle$

lemma `symKey_neq_privateKey`: " $K \in \text{symKeys} \implies K \neq \text{invKey } (\text{publicKey } b \ A)$ "
 $\langle \text{proof} \rangle$

lemma `analz_symKeys_Decrypt`:

$$"[| \text{Crypt } K \ X \in \text{analz } H; \ K \in \text{symKeys}; \ \text{Key } K \in \text{analz } H \ |] \implies X \in \text{analz } H"$$
 $\langle \text{proof} \rangle$

3.6 "Image" Equations That Hold for Injective Functions

lemma `invKey_image_eq [iff]`: " $(\text{invKey } x \in \text{invKey } 'A) = (x \in A)$ "
 $\langle \text{proof} \rangle$

holds because `invKey` is injective

lemma `publicKey_image_eq [iff]`:

$$"(\text{publicKey } b \ A \in \text{publicKey } c \ ' \ AS) = (b=c \ \& \ A \in AS)"$$
 $\langle \text{proof} \rangle$

lemma `privateKey_image_eq [iff]`:

$$"(\text{invKey } (\text{publicKey } b \ A) \in \text{invKey } ' \text{publicKey } c \ ' \ AS) = (b=c \ \& \ A \in AS)"$$
 $\langle \text{proof} \rangle$

lemma `privateKey_notin_image_publicKey [iff]`:

$$"\text{invKey } (\text{publicKey } b \ A) \notin \text{publicKey } c \ ' \ AS"$$
 $\langle \text{proof} \rangle$

lemma `publicKey_notin_image_privateKey [iff]`:

$$"\text{publicKey } b \ A \notin \text{invKey } ' \text{publicKey } c \ ' \ AS"$$
 $\langle \text{proof} \rangle$

lemma `keysFor_parts_initState [simp]`: " $\text{keysFor } (\text{parts } (\text{initState } C)) = \{\}$ "
 $\langle \text{proof} \rangle$

for proving `new_keys_not_used`

lemma `keysFor_parts_insert`:

$$"[| K \in \text{keysFor } (\text{parts } (\text{insert } X \ H)); \ X \in \text{synth } (\text{analz } H) \ |] \implies K \in \text{keysFor } (\text{parts } H) \ \vee \ \text{Key } (\text{invKey } K) \in \text{parts } H"$$
 $\langle \text{proof} \rangle$

lemma `Crypt_imp_keysFor [intro]`:

$$"[| K \in \text{symKeys}; \ \text{Crypt } K \ X \in H \ |] \implies K \in \text{keysFor } H"$$
 $\langle \text{proof} \rangle$

Agents see their own private keys!

lemma `privateKey_in_initStateCA [iff]`:

"Key (invKey (publicKey b A)) ∈ initState A"
 ⟨proof⟩

Agents see their own public keys!

lemma publicKey_in_initStateCA [iff]: "Key (publicKey b A) ∈ initState A"
 ⟨proof⟩

RCA sees CAs' public keys!

lemma pubK_CA_in_initState_RCA [iff]:
 "Key (publicKey b (CA i)) ∈ initState RCA"
 ⟨proof⟩

Spy knows all public keys

lemma knows_Spy_pubEK_i [iff]: "Key (publicKey b A) ∈ knows Spy evs"
 ⟨proof⟩

declare knows_Spy_pubEK_i [THEN analz.Inj, iff]

Spy sees private keys of bad agents! [and obviously public keys too]

lemma knows_Spy_bad_privateKey [intro!]:
 "A ∈ bad ==> Key (invKey (publicKey b A)) ∈ knows Spy evs"
 ⟨proof⟩

3.7 Fresh Nonces for Possibility Theorems

lemma Nonce_notin_initState [iff]: "Nonce N ∉ parts (initState B)"
 ⟨proof⟩

lemma Nonce_notin_used_empty [simp]: "Nonce N ∉ used []"
 ⟨proof⟩

In any trace, there is an upper bound N on the greatest nonce in use.

lemma Nonce_supply_lemma: "∃ N. ∀ n. N ≤ n --> Nonce n ∉ used evs"
 ⟨proof⟩

lemma Nonce_supply1: "∃ N. Nonce N ∉ used evs"
 ⟨proof⟩

lemma Nonce_supply: "Nonce (@ N. Nonce N ∉ used evs) ∉ used evs"
 ⟨proof⟩

3.8 Specialized Methods for Possibility Theorems

⟨ML⟩

3.9 Specialized Rewriting for Theorems About analz and Image

lemma insert_Key_singleton: "insert (Key K) H = Key ' {K} Un H"
 ⟨proof⟩

lemma insert_Key_image:


```
"insert (Key K) (Key'KK Un C) = Key ' (insert K KK) Un C"
⟨proof⟩
```

Needed for *DK_fresh_not_KeyCryptKey*

```
lemma publicKey_in_used [iff]: "Key (publicKey b A) ∈ used evs"
⟨proof⟩
```

```
lemma privateKey_in_used [iff]: "Key (invKey (publicKey b A)) ∈ used evs"
⟨proof⟩
```

Reverse the normal simplification of "image" to build up (not break down) the set of keys. Based on *analz_image_freshK_ss*, but simpler.

```
lemmas analz_image_keys_simps =
  simp_thms mem_simps — these two allow its use with only:
  image_insert [THEN sym] image_Un [THEN sym]
  rangeI symKeys_neq_imp_neq
  insert_Key_singleton insert_Key_image Un_assoc [THEN sym]
```

3.10 Controlled Unfolding of Abbreviations

A set is expanded only if a relation is applied to it

```
lemma def_abbrev_simp_relation:
  "A == B ==> (A ∈ X) = (B ∈ X) &
               (u = A) = (u = B) &
               (A = u) = (B = u)"
⟨proof⟩
```

A set is expanded only if one of the given functions is applied to it

```
lemma def_abbrev_simp_function:
  "A == B
  ==> parts (insert A X) = parts (insert B X) &
       analz (insert A X) = analz (insert B X) &
       keysFor (insert A X) = keysFor (insert B X)"
⟨proof⟩
```

3.10.1 Special Simplification Rules for *signCert*

Avoids duplicating X and its components!

```
lemma parts_insert_signCert:
  "parts (insert (signCert K X) H) =
   insert {|X, Crypt K X|} (parts (insert (Crypt K X) H))"
⟨proof⟩
```

Avoids a case split! [X is always available]

```
lemma analz_insert_signCert:
  "analz (insert (signCert K X) H) =
   insert {|X, Crypt K X|} (insert (Crypt K X) (analz (insert X H)))"
⟨proof⟩
```

```
lemma keysFor_insert_signCert: "keysFor (insert (signCert K X) H) = keysFor
H"
```

<proof>

Controlled rewrite rules for *signCert*, just the definitions of the others. Encryption primitives are just expanded, despite their huge redundancy!

```

lemmas abbrev_simps [simp] =
  parts_insert_signCert analz_insert_signCert keysFor_insert_signCert
  sign_def      [THEN def_abbrev_simp_relation]
  sign_def      [THEN def_abbrev_simp_function]
  signCert_def  [THEN def_abbrev_simp_relation]
  signCert_def  [THEN def_abbrev_simp_function]
  certC_def     [THEN def_abbrev_simp_relation]
  certC_def     [THEN def_abbrev_simp_function]
  cert_def      [THEN def_abbrev_simp_relation]
  cert_def      [THEN def_abbrev_simp_function]
  EXcrypt_def   [THEN def_abbrev_simp_relation]
  EXcrypt_def   [THEN def_abbrev_simp_function]
  EXHcrypt_def  [THEN def_abbrev_simp_relation]
  EXHcrypt_def  [THEN def_abbrev_simp_function]
  Enc_def       [THEN def_abbrev_simp_relation]
  Enc_def       [THEN def_abbrev_simp_function]
  EncB_def      [THEN def_abbrev_simp_relation]
  EncB_def      [THEN def_abbrev_simp_function]

```

3.10.2 Elimination Rules for Controlled Rewriting

```

lemma Enc_partsE:
  "!!R. [|Enc SK K EK M ∈ parts H;
    [|Crypt K (sign SK M) ∈ parts H;
      Crypt EK (Key K) ∈ parts H|] ==> R|]
  ==> R"

```

<proof>

```

lemma EncB_partsE:
  "!!R. [|EncB SK K EK M b ∈ parts H;
    [|Crypt K (sign SK {|M, Hash b|}) ∈ parts H;
      Crypt EK (Key K) ∈ parts H;
      b ∈ parts H|] ==> R|]
  ==> R"

```

<proof>

```

lemma EXcrypt_partsE:
  "!!R. [|EXcrypt K EK M m ∈ parts H;
    [|Crypt K {|M, Hash m|} ∈ parts H;
      Crypt EK {|Key K, m|} ∈ parts H|] ==> R|]
  ==> R"

```

<proof>

3.11 Lemmas to Simplify Expressions Involving *analz*

```

lemma analz_knows_absorb:
  "Key K ∈ analz (knows Spy evs)
  ==> analz (Key ‘ (insert K H) ∪ knows Spy evs) =
    analz (Key ‘ H ∪ knows Spy evs)"

```

<proof>

lemma *analz_knows_absorb2*:

"Key K ∈ analz (knows Spy evs)
 ==> analz (Key ' (insert X (insert K H)) ∪ knows Spy evs) =
 analz (Key ' (insert X H) ∪ knows Spy evs)"

<proof>

lemma *analz_insert_subset_eq*:

"[|X ∈ analz (knows Spy evs); knows Spy evs ⊆ H|]
 ==> analz (insert X H) = analz H"

<proof>

lemmas *analz_insert_simps* =

analz_insert_subset_eq Un_upper2
subset_insertI [THEN [2] subset_trans]

3.12 Freshness Lemmas

lemma *in_parts_Says_imp_used*:

"[|Key K ∈ parts {X}; Says A B X ∈ set evs|] ==> Key K ∈ used evs"

<proof>

A useful rewrite rule with *analz_image_keys_simps*

lemma *Crypt_notin_image_Key*: "Crypt K X ∉ Key ' KK"

<proof>

lemma *fresh_notin_analz_knows_Spy*:

"Key K ∉ used evs ==> Key K ∉ analz (knows Spy evs)"

<proof>

end

4 The SET Cardholder Registration Protocol

theory *Cardholder_Registration* **imports** *PublicSET* **begin**

Note: nonces seem to consist of 20 bytes. That includes both freshness challenges (Chall-EE, etc.) and important secrets (CardSecret, PANsecret)

Simplifications involving *analz_image_keys_simps* appear to have become much slower. The cause is unclear. However, there is a big blow-up and the rewriting is very sensitive to the set of rewrite rules given.

4.1 Predicate Formalizing the Encryption Association between Keys

consts

KeyCryptKey :: "[key, key, event list] => bool"

primrec

KeyCryptKey_Nil:

"KeyCryptKey DK K [] = False"

KeyCryptKey_Cons:

— Says is the only important case. 1st case: CR5, where KC3 encrypts KC2. 2nd case: any use of *priEK C*. Revision 1.12 has a more complicated version with separate treatment of the dependency of KC1, KC2 and KC3 on *priEK (CA i)*. Not needed since *priEK C* is never sent (and so can't be lost except at the start).

```
"KeyCryptKey DK K (ev # evs) =
  (KeyCryptKey DK K evs |
   (case ev of
     Says A B Z =>
       (( $\exists N X Y. A \neq \text{Spy} \ \&$ 
          $DK \in \text{symKeys} \ \&$ 
          $Z = \{|Crypt\ DK\ \{|Agent\ A, Nonce\ N, Key\ K, X|\}, Y|\}$ ) |
        ( $\exists C. DK = \text{priEK } C$ ))
     | Gets A' X => False
     | Notes A' X => False))"
```

4.2 Predicate formalizing the association between keys and nonces

consts

KeyCryptNonce :: "[key, key, event list] => bool"

primrec

KeyCryptNonce_Nil:

"KeyCryptNonce EK K [] = False"

KeyCryptNonce_Cons:

— Says is the only important case. 1st case: CR3, where KC1 encrypts NC2 (distinct from CR5 due to EXH); 2nd case: CR5, where KC3 encrypts NC3; 3rd case: CR6, where KC2 encrypts NC3; 4th case: CR6, where KC2 encrypts NonceCCA; 5th case: any use of *priEK C* (including CardSecret). NB the only Nonces we need to keep secret are CardSecret and NonceCCA. But we can't prove *Nonce_compromise* unless the relation covers ALL nonces that the protocol keeps secret.

```
"KeyCryptNonce DK N (ev # evs) =
  (KeyCryptNonce DK N evs |
   (case ev of
     Says A B Z =>
       A  $\neq$  Spy &
       (( $\exists X Y. DK \in \text{symKeys} \ \&$ 
          $Z = (\text{EXHcrypt } DK\ X\ \{|Agent\ A, Nonce\ N|\}\ Y)$ ) |
        ( $\exists X Y. DK \in \text{symKeys} \ \&$ 
          $Z = \{|Crypt\ DK\ \{|Agent\ A, Nonce\ N, X|\}, Y|\}$ ) |
        ( $\exists K i X Y.
          K \in \text{symKeys} \ \&$ 
           $Z = \text{Crypt } K\ \{|sign\ (\text{priSK } (CA\ i))\ \{|Agent\ B, Nonce\ N, X|\}, Y|\} \ \&$ 
          ( $DK=K \mid \text{KeyCryptKey } DK\ K\ evs$ )) |
        ( $\exists K C NC3 Y.
          K \in \text{symKeys} \ \&$ 
           $Z = \text{Crypt } K$ 
            $\{|sign\ (\text{priSK } C)\ \{|Agent\ B, Nonce\ NC3, Agent\ C, Nonce\ N|\},$ 
```

```

      Y/} &
      (DK=K | KeyCryptKey DK K evs)) |
      (∃ C. DK = priEK C))
    | Gets A' X => False
    | Notes A' X => False))"

```

4.3 Formal protocol definition

consts set_cr :: "event list set"

inductive set_cr

intros

Nil: — Initial trace is empty
 "[] ∈ set_cr"

Fake: — The spy MAY say anything he CAN say.
 "[| evsf ∈ set_cr; X ∈ synth (analz (knows Spy evsf)) |]
 ==> Says Spy B X # evsf ∈ set_cr"

Reception: — If A sends a message X to B, then B might receive it
 "[| evsr ∈ set_cr; Says A B X ∈ set evsr |]
 ==> Gets B X # evsr ∈ set_cr"

SET_CR1: — CardCInitReq: C initiates a run, sending a nonce to CCA
 "[| evs1 ∈ set_cr; C = Cardholder k; Nonce NC1 ∉ used evs1
 |]
 ==> Says C (CA i) {|Agent C, Nonce NC1|} # evs1 ∈ set_cr"

SET_CR2: — CardCInitRes: CA responds sending NC1 and its certificates
 "[| evs2 ∈ set_cr;
 Gets (CA i) {|Agent C, Nonce NC1|} ∈ set evs2 |]
 ==> Says (CA i) C
 {|sign (priSK (CA i)) {|Agent C, Nonce NC1|},
 cert (CA i) (pubEK (CA i)) onlyEnc (priSK RCA),
 cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)|}
 # evs2 ∈ set_cr"

SET_CR3:
 — RegFormReq: C sends his PAN and a new nonce to CA. C verifies that - nonce received is the same as that sent; - certificates are signed by RCA; - certificates are an encryption certificate (flag is onlyEnc) and a signature certificate (flag is onlySig); - certificates pertain to the CA that C contacted (this is done by checking the signature). C generates a fresh symmetric key KC1. The point of encrypting {|Agent C, Nonce NC2, Hash (Pan (pan C))|} is not clear.

"[| evs3 ∈ set_cr; C = Cardholder k;
 Nonce NC2 ∉ used evs3;
 Key KC1 ∉ used evs3; KC1 ∈ symKeys;
 Gets C {|sign (invKey SKi) {|Agent X, Nonce NC1|},
 cert (CA i) EKi onlyEnc (priSK RCA),
 cert (CA i) SKi onlySig (priSK RCA)|}
 ∈ set evs3;
 Says C (CA i) {|Agent C, Nonce NC1|} ∈ set evs3 |]
 ==> Says C (CA i) (EXHcrypt KC1 EKi {|Agent C, Nonce NC2|} (Pan(pan C)))
 # Notes C {|Key KC1, Agent (CA i)|}"

evs3 ∈ set_cr"

SET_CR4:

— RegFormRes: CA responds sending NC2 back with a new nonce NCA, after checking that - the digital envelope is correctly encrypted by $\text{pubEK } (CA \ i)$ - the entire message is encrypted with the same key found inside the envelope (here, KC1)

```
"[| evs4 ∈ set_cr;
  Nonce NCA ∉ used evs4; KC1 ∈ symKeys;
  Gets (CA i) (EXHcrypt KC1 EKi {|Agent C, Nonce NC2|} (Pan(pan X)))
    ∈ set evs4 |]
==> Says (CA i) C
      {|sign (priSK (CA i)) {|Agent C, Nonce NC2, Nonce NCA|},
       cert (CA i) (pubEK (CA i)) onlyEnc (priSK RCA),
       cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)|}
# evs4 ∈ set_cr"
```

SET_CR5:

— CertReq: C sends his PAN, a new nonce, its proposed public signature key and its half of the secret value to CA. We now assume that C has a fixed key pair, and he submits (pubSK C). The protocol does not require this key to be fresh. The encryption below is actually EncX.

```
"[| evs5 ∈ set_cr; C = Cardholder k;
  Nonce NC3 ∉ used evs5; Nonce CardSecret ∉ used evs5; NC3 ≠ CardSecret;
  Key KC2 ∉ used evs5; KC2 ∈ symKeys;
  Key KC3 ∉ used evs5; KC3 ∈ symKeys; KC2 ≠ KC3;
  Gets C {|sign (invKey SKi) {|Agent C, Nonce NC2, Nonce NCA|},
          cert (CA i) EKi onlyEnc (priSK RCA),
          cert (CA i) SKi onlySig (priSK RCA) |}
    ∈ set evs5;
  Says C (CA i) (EXHcrypt KC1 EKi {|Agent C, Nonce NC2|} (Pan(pan C)))
    ∈ set evs5 |]
==> Says C (CA i)
      {|Crypt KC3
        {|Agent C, Nonce NC3, Key KC2, Key (pubSK C),
         Crypt (priSK C)
           (Hash {|Agent C, Nonce NC3, Key KC2,
                  Key (pubSK C), Pan (pan C), Nonce CardSecret|})|},
         Crypt EKi {|Key KC3, Pan (pan C), Nonce CardSecret|} |}
# Notes C {|Key KC2, Agent (CA i)|}
# Notes C {|Key KC3, Agent (CA i)|}
# evs5 ∈ set_cr"
```

— CertRes: CA responds sending NC3 back with its half of the secret value, its signature certificate and the new cardholder signature certificate. CA checks to have never certified the key proposed by C. NOTE: In Merchant Registration, the corresponding rule (4) uses the "sign" primitive. The encryption below is actually EncK , which is just $\text{Crypt } K (\text{sign } SK \ X)$.

SET_CR6:

```
"[| evs6 ∈ set_cr;
  Nonce NonceCCA ∉ used evs6;
  KC2 ∈ symKeys; KC3 ∈ symKeys; cardSK ∉ symKeys;
  Notes (CA i) (Key cardSK) ∉ set evs6;
```

```

Gets (CA i)
  {/Crypt KC3 {/Agent C, Nonce NC3, Key KC2, Key cardSK,
    Crypt (invKey cardSK)
      (Hash {/Agent C, Nonce NC3, Key KC2,
        Key cardSK, Pan (pan C), Nonce CardSecret/})/},
    Crypt (pubEK (CA i)) {/Key KC3, Pan (pan C), Nonce CardSecret/} /}
  ∈ set evs6 []
==> Says (CA i) C
  (Crypt KC2
    {/sign (priSK (CA i))
      {/Agent C, Nonce NC3, Agent(CA i), Nonce NonceCCA/},
      certC (pan C) cardSK (XOR(CardSecret,NonceCCA)) onlySig (priSK
(CA i)),
        cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)/})
    # Notes (CA i) (Key cardSK)
    # evs6 ∈ set_cr"

```

```

declare Says_imp_knows_Spy [THEN parts.Inj, dest]
declare parts.Body [dest]
declare analz_into_parts [dest]
declare Fake_parts_insert_in_Un [dest]

```

A "possibility property": there are traces that reach the end. An unconstrained proof with many subgoals.

```

lemma Says_to_Gets:
  "Says A B X # evs ∈ set_cr ==> Gets B X # Says A B X # evs ∈ set_cr"
<proof>

```

The many nonces and keys generated, some simultaneously, force us to introduce them explicitly as shown below.

```

lemma possibility_CR6:
  "[/NC1 < (NC2::nat); NC2 < NC3; NC3 < NCA ;
    NCA < NonceCCA; NonceCCA < CardSecret;
    KC1 < (KC2::key); KC2 < KC3;
    KC1 ∈ symKeys; Key KC1 ∉ used [];
    KC2 ∈ symKeys; Key KC2 ∉ used [];
    KC3 ∈ symKeys; Key KC3 ∉ used [];
    C = Cardholder k/]
  ==> ∃ evs ∈ set_cr.
    Says (CA i) C
      (Crypt KC2
        {/sign (priSK (CA i))
          {/Agent C, Nonce NC3, Agent(CA i), Nonce NonceCCA/},
          certC (pan C) (pubSK (Cardholder k)) (XOR(CardSecret,NonceCCA))
            onlySig (priSK (CA i)),
          cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)/})
        ∈ set evs"
<proof>

```

General facts about message reception

```

lemma Gets_imp_Says:
  "[/ Gets B X ∈ set evs; evs ∈ set_cr [] ==> ∃ A. Says A B X ∈ set evs"

```

<proof>

lemma *Gets_imp_knows_Spy*:

"[| Gets B X ∈ set evs; evs ∈ set_cr |] ==> X ∈ knows Spy evs"

<proof>

declare *Gets_imp_knows_Spy* [THEN parts.Inj, dest]

4.4 Proofs on keys

Spy never sees an agent's private keys! (unless it's bad at start)

lemma *Spy_see_private_Key* [simp]:

"evs ∈ set_cr

==> (Key(invKey (publicKey b A)) ∈ parts(knows Spy evs)) = (A ∈ bad)"

<proof>

lemma *Spy_analz_private_Key* [simp]:

"evs ∈ set_cr ==>

(Key(invKey (publicKey b A)) ∈ analz(knows Spy evs)) = (A ∈ bad)"

<proof>

declare *Spy_see_private_Key* [THEN [2] rev_iffD1, dest!]

declare *Spy_analz_private_Key* [THEN [2] rev_iffD1, dest!]

4.5 Begin Piero's Theorems on Certificates

Trivial in the current model, where certificates by RCA are secure

lemma *Crypt_valid_pubEK*:

"[| Crypt (priSK RCA) {|Agent C, Key EKi, onlyEnc|}

∈ parts (knows Spy evs);

evs ∈ set_cr |] ==> EKi = pubEK C"

<proof>

lemma *certificate_valid_pubEK*:

"[| cert C EKi onlyEnc (priSK RCA) ∈ parts (knows Spy evs);

evs ∈ set_cr |]

==> EKi = pubEK C"

<proof>

lemma *Crypt_valid_pubSK*:

"[| Crypt (priSK RCA) {|Agent C, Key SKi, onlySig|}

∈ parts (knows Spy evs);

evs ∈ set_cr |] ==> SKi = pubSK C"

<proof>

lemma *certificate_valid_pubSK*:

"[| cert C SKi onlySig (priSK RCA) ∈ parts (knows Spy evs);

evs ∈ set_cr |] ==> SKi = pubSK C"

<proof>

lemma *Gets_certificate_valid*:

"[| Gets A {| X, cert C EKi onlyEnc (priSK RCA),

cert C SKi onlySig (priSK RCA) |} ∈ set evs;

evs ∈ set_cr |]


```

==> EKi = pubEK C & SKi = pubSK C"
<proof>

```

Nobody can have used non-existent keys!

```

lemma new_keys_not_used:
  "[|K ∈ symKeys; Key K ∉ used evs; evs ∈ set_cr|]
  ==> K ∉ keysFor (parts (knows Spy evs))"
<proof>

```

4.6 New versions: as above, but generalized to have the KK argument

```

lemma gen_new_keys_not_used:
  "[|Key K ∉ used evs; K ∈ symKeys; evs ∈ set_cr|]
  ==> Key K ∉ used evs --> K ∈ symKeys -->
    K ∉ keysFor (parts (Key'KK Un knows Spy evs))"
<proof>

```

```

lemma gen_new_keys_not_analz:
  "[|Key K ∉ used evs; K ∈ symKeys; evs ∈ set_cr|]
  ==> K ∉ keysFor (analz (Key'KK Un knows Spy evs))"
<proof>

```

```

lemma analz_Key_image_insert_eq:
  "[|K ∈ symKeys; Key K ∉ used evs; evs ∈ set_cr|]
  ==> analz (Key ' (insert K KK) ∪ knows Spy evs) =
    insert (Key K) (analz (Key ' KK ∪ knows Spy evs))"
<proof>

```

```

lemma Crypt_parts_imp_used:
  "[|Crypt K X ∈ parts (knows Spy evs);
    K ∈ symKeys; evs ∈ set_cr|] ==> Key K ∈ used evs"
<proof>

```

```

lemma Crypt_analz_imp_used:
  "[|Crypt K X ∈ analz (knows Spy evs);
    K ∈ symKeys; evs ∈ set_cr|] ==> Key K ∈ used evs"
<proof><proof><proof><proof><proof><proof><proof>

```

4.7 Useful lemmas

Rewriting rule for private encryption keys. Analogous rewriting rules for other keys aren't needed.

```

lemma parts_image_priEK:
  "[|Key (priEK C) ∈ parts (Key'KK Un (knows Spy evs));
    evs ∈ set_cr|] ==> priEK C ∈ KK | C ∈ bad"
<proof>

```

trivial proof because (priEK C) never appears even in (parts evs)

```

lemma analz_image_priEK:
  "evs ∈ set_cr ==>
    (Key (priEK C) ∈ analz (Key'KK Un (knows Spy evs))) =

```

(priEK C ∈ KK | C ∈ bad)"
 <proof>

4.8 Secrecy of Session Keys

4.8.1 Lemmas about the predicate KeyCryptKey

A fresh DK cannot be associated with any other (with respect to a given trace).

lemma DK_fresh_not_KeyCryptKey:
 "[| Key DK ∉ used evs; evs ∈ set_cr |] ==> ~ KeyCryptKey DK K evs"
 <proof>

A fresh K cannot be associated with any other. The assumption that DK isn't a private encryption key may be an artifact of the particular definition of KeyCryptKey.

lemma K_fresh_not_KeyCryptKey:
 "[| ∀ C. DK ≠ priEK C; Key K ∉ used evs |] ==> ~ KeyCryptKey DK K evs"
 <proof>

This holds because if (priEK (CA i)) appears in any traffic then it must be known to the Spy, by *Spy_see_private_Key*

lemma cardSK_neq_priEK:
 "[| Key cardSK ∉ analz (knows Spy evs);
 Key cardSK : parts (knows Spy evs);
 evs ∈ set_cr |] ==> cardSK ≠ priEK C"
 <proof>

lemma not_KeyCryptKey_cardSK [rule_format (no_asm)]:
 "[| cardSK ∉ symKeys; ∀ C. cardSK ≠ priEK C; evs ∈ set_cr |] ==>
 Key cardSK ∉ analz (knows Spy evs) --> ~ KeyCryptKey cardSK K evs"
 <proof>

Lemma for message 5: pubSK C is never used to encrypt Keys.

lemma pubSK_not_KeyCryptKey [simp]: "~ KeyCryptKey (pubSK C) K evs"
 <proof>

Lemma for message 6: either cardSK is compromised (when we don't care) or else cardSK hasn't been used to encrypt K. Previously we treated message 5 in the same way, but the current model assumes that rule *SET_CR5* is executed only by honest agents.

lemma msg6_KeyCryptKey_disj:
 "[| Gets B {|Crypt KC3 {|Agent C, Nonce N, Key KC2, Key cardSK, X|}, Y|}
 ∈ set evs;
 cardSK ∉ symKeys; evs ∈ set_cr |]
 ==> Key cardSK ∈ analz (knows Spy evs) |
 (∀ K. ~ KeyCryptKey cardSK K evs)"
 <proof>

As usual: we express the property as a logical equivalence

lemma Key_analz_image_Key_lemma:
 "P --> (Key K ∈ analz (Key'KK Un H)) --> (K ∈ KK | Key K ∈ analz H)
 ==>

$P \rightarrow (Key\ K \in \text{analz}\ (Key'KK\ Un\ H)) = (K \in KK \mid Key\ K \in \text{analz}\ H)$ "

<proof>

<ML>

The *(no_asm)* attribute is essential, since it retains the quantifier and allows the simplifier's condition to itself be simplified.

lemma *symKey_compromise* [rule_format (no_asm)]:

"*evs* \in *set_cr* ==>

$(\forall SK\ KK. SK \in \text{symKeys} \rightarrow (\forall K \in KK. \sim \text{KeyCryptKey}\ K\ SK\ \text{evs}) \rightarrow$

$(Key\ SK \in \text{analz}\ (Key'KK\ Un\ (\text{knows}\ Spy\ \text{evs}))) =$

$(SK \in KK \mid Key\ SK \in \text{analz}\ (\text{knows}\ Spy\ \text{evs})))$ "

<proof>

The remaining quantifiers seem to be essential. NO NEED to assume the cardholder's OK: bad cardholders don't do anything wrong!!

lemma *symKey_secrecy* [rule_format]:

"[CA *i* \notin *bad*; *K* \in *symKeys*; *evs* \in *set_cr*]

==> $\forall X\ c. \text{Says}\ (\text{Cardholder}\ c)\ (CA\ i)\ X \in \text{set}\ \text{evs} \rightarrow$

$Key\ K \in \text{parts}\ \{X\} \rightarrow$

$\text{Cardholder}\ c \notin \text{bad} \rightarrow$

$Key\ K \notin \text{analz}\ (\text{knows}\ Spy\ \text{evs})$ "

<proof>

4.9 Primary Goals of Cardholder Registration

The cardholder's certificate really was created by the CA, provided the CA is uncompromised

Lemma concerning the actual signed message digest

lemma *cert_valid_lemma*:

"[Crypt (*priSK* (CA *i*)) {Hash {Nonce *N*, Pan(*pan* *C*)}, Key *cardSK*, *N1*} \in *parts* (*knows* *Spy* *evs*);

CA *i* \notin *bad*; *evs* \in *set_cr*]

==> $\exists KC2\ X\ Y. \text{Says}\ (CA\ i)\ C$

$(Crypt\ KC2$

$\{X, \text{certC}\ (\text{pan}\ C)\ \text{cardSK}\ N\ \text{onlySig}\ (\text{priSK}\ (CA\ i)),$

Y})

$\in \text{set}\ \text{evs}$ "

<proof>

Pre-packaged version for cardholder. We don't try to confirm the values of KC2, X and Y, since they are not important.

lemma *certificate_valid_cardSK*:

"[Gets *C* (Crypt KC2 {X, certC (*pan* *C*) cardSK *N* onlySig (*invKey* *SKi*),

cert (CA *i*) *SKi* onlySig (*priSK* *RCA*)}) \in *set*

evs;

CA *i* \notin *bad*; *evs* \in *set_cr*]

==> $\exists KC2\ X\ Y. \text{Says}\ (CA\ i)\ C$

$(Crypt\ KC2$

$\{X, \text{certC}\ (\text{pan}\ C)\ \text{cardSK}\ N\ \text{onlySig}\ (\text{priSK}\ (CA\ i)),$

Y})

$\in \text{set evs}$ "

<proof>

lemma *Hash_imp_parts* [rule_format]:
 "evs \in set_cr
 $\implies \text{Hash}\{X, \text{Nonce } N\} \in \text{parts } (\text{knows Spy evs}) \implies$
 $\text{Nonce } N \in \text{parts } (\text{knows Spy evs})$ "

<proof>

lemma *Hash_imp_parts2* [rule_format]:
 "evs \in set_cr
 $\implies \text{Hash}\{X, \text{Nonce } M, Y, \text{Nonce } N\} \in \text{parts } (\text{knows Spy evs}) \implies$
 $\text{Nonce } M \in \text{parts } (\text{knows Spy evs}) \ \& \ \text{Nonce } N \in \text{parts } (\text{knows Spy evs})$ "

<proof>

4.10 Secrecy of Nonces

4.10.1 Lemmas about the predicate KeyCryptNonce

A fresh DK cannot be associated with any other (with respect to a given trace).

lemma *DK_fresh_not_KeyCryptNonce*:
 "[| DK \in symKeys; Key DK \notin used evs; evs \in set_cr |]
 $\implies \sim \text{KeyCryptNonce DK K evs}$ "

<proof>

A fresh N cannot be associated with any other (with respect to a given trace).

lemma *N_fresh_not_KeyCryptNonce*:
 " $\forall C. \text{DK} \neq \text{priEK } C \implies \text{Nonce } N \notin \text{used evs} \implies \sim \text{KeyCryptNonce DK N evs}$ "

<proof>

lemma *not_KeyCryptNonce_cardSK* [rule_format (no_asm)]:
 "[| cardSK \notin symKeys; $\forall C. \text{cardSK} \neq \text{priEK } C$; evs \in set_cr |] \implies
 $\text{Key cardSK} \notin \text{analz } (\text{knows Spy evs}) \implies \sim \text{KeyCryptNonce cardSK N evs}$ "

<proof>

4.10.2 Lemmas for message 5 and 6: either cardSK is compromised (when we don't care) or else cardSK hasn't been used to encrypt K.

Lemma for message 5: pubSK C is never used to encrypt Nonces.

lemma *pubSK_not_KeyCryptNonce* [simp]: " $\sim \text{KeyCryptNonce } (\text{pubSK } C) N \text{ evs}$ "

<proof>

Lemma for message 6: either cardSK is compromised (when we don't care) or else cardSK hasn't been used to encrypt K.

lemma *msg6_KeyCryptNonce_disj*:
 "[| Gets B {|Crypt KC3 {|Agent C, Nonce N, Key KC2, Key cardSK, X|}, Y|}
 \in set evs;
 $\text{cardSK} \notin \text{symKeys}$; evs \in set_cr |]
 $\implies \text{Key cardSK} \in \text{analz } (\text{knows Spy evs}) \mid$
 $((\forall K. \sim \text{KeyCryptKey cardSK K evs}) \ \&$

$(\forall N. \sim \text{KeyCryptNonce cardSK } N \text{ evs}))"$
 $\langle \text{proof} \rangle$

As usual: we express the property as a logical equivalence

lemma *Nonce_analz_image_Key_lemma*:
 $"P \rightarrow (\text{Nonce } N \in \text{analz } (\text{Key}'KK \text{ Un } H)) \rightarrow (\text{Nonce } N \in \text{analz } H)$
 $\implies P \rightarrow (\text{Nonce } N \in \text{analz } (\text{Key}'KK \text{ Un } H)) = (\text{Nonce } N \in \text{analz } H)"$
 $\langle \text{proof} \rangle$

The *(no_asm)* attribute is essential, since it retains the quantifier and allows the *simp* rule's condition to itself be simplified.

lemma *Nonce_compromise [rule_format (no_asm)]*:
 $"\text{evs} \in \text{set_cr} \implies$
 $(\forall N \text{ KK}. (\forall K \in \text{KK}. \sim \text{KeyCryptNonce } K \text{ N evs}) \rightarrow$
 $(\text{Nonce } N \in \text{analz } (\text{Key}'KK \text{ Un } (\text{knows Spy evs}))) =$
 $(\text{Nonce } N \in \text{analz } (\text{knows Spy evs})))"$
 $\langle \text{proof} \rangle$

4.11 Secrecy of CardSecret: the Cardholder's secret

lemma *NC2_not_CardSecret*:
 $"[| \text{Crypt EKj } \{| \text{Key } K, \text{Pan } p, \text{Hash } \{| \text{Agent } D, \text{Nonce } N | \} | \}$
 $\in \text{parts } (\text{knows Spy evs});$
 $\text{Key } K \notin \text{analz } (\text{knows Spy evs});$
 $\text{Nonce } N \notin \text{analz } (\text{knows Spy evs});$
 $\text{evs} \in \text{set_cr}|]$
 $\implies \text{Crypt EKj } \{| \text{Key } K', \text{Pan } p', \text{Nonce } N | \} \notin \text{parts } (\text{knows Spy evs})"$
 $\langle \text{proof} \rangle$

lemma *KC2_secure_lemma [rule_format]*:
 $"[| U = \text{Crypt KC3 } \{| \text{Agent } C, \text{Nonce } N, \text{Key } KC2, X | \};$
 $U \in \text{parts } (\text{knows Spy evs});$
 $\text{evs} \in \text{set_cr}|]$
 $\implies \text{Nonce } N \notin \text{analz } (\text{knows Spy evs}) \rightarrow$
 $(\exists k \text{ i } W. \text{Says } (\text{Cardholder } k) (\text{CA } i) \{| U, W | \} \in \text{set evs} \ \&$
 $\text{Cardholder } k \notin \text{bad} \ \& \text{CA } i \notin \text{bad})"$
 $\langle \text{proof} \rangle$

lemma *KC2_secrecy*:
 $"[| \text{Gets } B \{| \text{Crypt } K \{| \text{Agent } C, \text{Nonce } N, \text{Key } KC2, X | \}, Y | \} \in \text{set evs};$
 $\text{Nonce } N \notin \text{analz } (\text{knows Spy evs}); \text{KC2} \in \text{symKeys};$
 $\text{evs} \in \text{set_cr}|]$
 $\implies \text{Key } KC2 \notin \text{analz } (\text{knows Spy evs})"$
 $\langle \text{proof} \rangle$

Inductive version

lemma *CardSecret_secrecy_lemma [rule_format]*:
 $"[| \text{CA } i \notin \text{bad}; \text{evs} \in \text{set_cr}|]$
 $\implies \text{Key } K \notin \text{analz } (\text{knows Spy evs}) \rightarrow$
 $\text{Crypt } (\text{pubEK } (\text{CA } i)) \{| \text{Key } K, \text{Pan } p, \text{Nonce CardSecret} | \}$
 $\in \text{parts } (\text{knows Spy evs}) \rightarrow$
 $\text{Nonce CardSecret} \notin \text{analz } (\text{knows Spy evs})"$
 $\langle \text{proof} \rangle$

Packaged version for cardholder

```

lemma CardSecret_secretcy:
  "[/Cardholder k  $\notin$  bad; CA i  $\notin$  bad;
   Says (Cardholder k) (CA i)
    {/X, Crypt EK i {/Key KC3, Pan p, Nonce CardSecret/}/}  $\in$  set evs;
   Gets A {/Z, cert (CA i) EK i onlyEnc (priSK RCA),
            cert (CA i) SK i onlySig (priSK RCA)/}  $\in$  set evs;
   KC3  $\in$  symKeys; evs  $\in$  set_cr/]
  ==> Nonce CardSecret  $\notin$  analz (knows Spy evs)"
<proof>

```

4.12 Secrecy of NonceCCA [the CA's secret]

```

lemma NC2_not_NonceCCA:
  "[/Hash {/Agent C', Nonce N', Agent C, Nonce N/}
    $\in$  parts (knows Spy evs);
   Nonce N  $\notin$  analz (knows Spy evs);
   evs  $\in$  set_cr/]
  ==> Crypt KC1 {/Agent B, Nonce N/}, Hash p/}  $\notin$  parts (knows Spy evs)"
<proof>

```

Inductive version

```

lemma NonceCCA_secretcy_lemma [rule_format]:
  "[/CA i  $\notin$  bad; evs  $\in$  set_cr/]
  ==> Key K  $\notin$  analz (knows Spy evs) -->
    Crypt K
      {/sign (priSK (CA i))
       {/Agent C, Nonce N, Agent(CA i), Nonce NonceCCA/},
       X, Y/}
       $\in$  parts (knows Spy evs) -->
        Nonce NonceCCA  $\notin$  analz (knows Spy evs)"
<proof>

```

Packaged version for cardholder

```

lemma NonceCCA_secretcy:
  "[/Cardholder k  $\notin$  bad; CA i  $\notin$  bad;
   Gets (Cardholder k)
     (Crypt KC2
       {/sign (priSK (CA i)) {/Agent C, Nonce N, Agent(CA i), Nonce NonceCCA/},
        X, Y/})  $\in$  set evs;
   Says (Cardholder k) (CA i)
     {/Crypt KC3 {/Agent C, Nonce NC3, Key KC2, X'/}, Y'/}  $\in$  set evs;
   Gets A {/Z, cert (CA i) EK i onlyEnc (priSK RCA),
            cert (CA i) SK i onlySig (priSK RCA)/}  $\in$  set evs;
   KC2  $\in$  symKeys; evs  $\in$  set_cr/]
  ==> Nonce NonceCCA  $\notin$  analz (knows Spy evs)"
<proof>

```

We don't bother to prove guarantees for the CA. He doesn't care about the PANSecret: it isn't his credit card!

4.13 Rewriting Rule for PANs

Lemma for message 6: either cardSK isn't a CA's private encryption key, or if it is then (because it appears in traffic) that CA is bad, and so the Spy knows that key already. Either way, we can simplify the expression $\text{analz } (\text{insert } (\text{Key cardSK}) X)$.

```
lemma msg6_cardSK_disj:
  "[|Gets A {|Crypt K {|c, n, k', Key cardSK, X|}, Y|}
   ∈ set evs; evs ∈ set_cr |]
   ==> cardSK ∉ range(invKey o pubEK o CA) | Key cardSK ∈ knows Spy evs"
<proof>
```

```
lemma analz_image_pan_lemma:
  "(Pan P ∈ analz (Key'nE Un H)) --> (Pan P ∈ analz H) ==>
   (Pan P ∈ analz (Key'nE Un H)) = (Pan P ∈ analz H)"
<proof>
```

```
lemma analz_image_pan [rule_format]:
  "evs ∈ set_cr ==>
   ∀KK. KK <= - invKey ' pubEK ' range CA -->
     (Pan P ∈ analz (Key'KK Un (knows Spy evs))) =
     (Pan P ∈ analz (knows Spy evs))"
<proof>
```

```
lemma analz_insert_pan:
  "[| evs ∈ set_cr; K ∉ invKey ' pubEK ' range CA |] ==>
   (Pan P ∈ analz (insert (Key K) (knows Spy evs))) =
   (Pan P ∈ analz (knows Spy evs))"
<proof>
```

Confidentiality of the PAN. Maybe we could combine the statements of this theorem with analz_image_pan , requiring a single induction but a much more difficult proof.

```
lemma pan_confidentiality:
  "[| Pan (pan C) ∈ analz(knows Spy evs); C ≠ Spy; evs :set_cr|]
   ==> ∃ i X K HN.
     Says C (CA i) {|X, Crypt (pubEK (CA i)) {|Key K, Pan (pan C), HN|}
   |}
     ∈ set evs
     & (CA i) ∈ bad"
<proof>
```

4.14 Unicity

```
lemma CR6_Says_imp_Notes:
  "[|Says (CA i) C (Crypt KC2
    {|sign (priSK (CA i)) {|Agent C, Nonce NC3, Agent (CA i), Nonce Y|},
    certC (pan C) cardSK X onlySig (priSK (CA i)),
    cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)|}) ∈ set evs;
   evs ∈ set_cr |]
   ==> Notes (CA i) (Key cardSK) ∈ set evs"
<proof>
```

Unicity of cardSK: it uniquely identifies the other components. This holds because a CA accepts a cardSK at most once.

```

lemma cardholder_key_unicity:
  "[|Says (CA i) C (Crypt KC2
    {/sign (priSK (CA i)) {/Agent C, Nonce NC3, Agent (CA i), Nonce Y/},
    certC (pan C) cardSK X onlySig (priSK (CA i)),
    cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)/})
   ∈ set evs;
   Says (CA i) C' (Crypt KC2'
    {/sign (priSK (CA i)) {/Agent C', Nonce NC3', Agent (CA i), Nonce
Y'/},
    certC (pan C') cardSK X' onlySig (priSK (CA i)),
    cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)/})
   ∈ set evs;
   evs ∈ set_cr |] ==> C=C' & NC3=NC3' & X=X' & KC2=KC2' & Y=Y'"
<proof><proof><proof>

```

Cannot show cardSK to be secret because it isn't assumed to be fresh it could be a previously compromised cardSK [e.g. involving a bad CA]

end

5 The SET Merchant Registration Protocol

theory Merchant_Registration **imports** PublicSET **begin**

Copmpared with Cardholder Reigstration, *KeyCryptKey* is not needed: no session key encrypts another. Instead we prove the "key compromise" theorems for sets KK that contain no private encryption keys (*priEK C*).

consts set_mr :: "event list set"

inductive set_mr

intros

Nil: — Initial trace is empty
 "[|] ∈ set_mr"

Fake: — The spy MAY say anything he CAN say.
 "[| evsf ∈ set_mr; X ∈ synth (analz (knows Spy evsf)) |]
 ==> Says Spy B X # evsf ∈ set_mr"

Reception: — If A sends a message X to B, then B might receive it
 "[| evsr ∈ set_mr; Says A B X ∈ set evsr |]
 ==> Gets B X # evsr ∈ set_mr"

SET_MR1: — RegFormReq: M requires a registration form to a CA
 "[| evs1 ∈ set_mr; M = Merchant k; Nonce NM1 ∉ used evs1 |]
 ==> Says M (CA i) {/Agent M, Nonce NM1/} # evs1 ∈ set_mr"

SET_MR2: — RegFormRes: CA replies with the registration form and the certificates for her keys

```
"[| evs2 ∈ set_mr; Nonce NCA ∉ used evs2;
  Gets (CA i) {|Agent M, Nonce NM1|} ∈ set evs2 |]
==> Says (CA i) M {|sign (priSK (CA i)) {|Agent M, Nonce NM1, Nonce NCA|},
  cert (CA i) (pubEK (CA i)) onlyEnc (priSK RCA),
  cert (CA i) (pubSK (CA i)) onlySig (priSK RCA) |}
  # evs2 ∈ set_mr"
```

SET_MR3:

— CertReq: M submits the key pair to be certified. The Notes event allows KM1 to be lost if M is compromised. Piero remarks that the agent mentioned inside the signature is not verified to correspond to M. As in CR, each Merchant has fixed key pairs. M is only optionally required to send NCA back, so M doesn't do so in the model

```
"[| evs3 ∈ set_mr; M = Merchant k; Nonce NM2 ∉ used evs3;
  Key KM1 ∉ used evs3; KM1 ∈ symKeys;
  Gets M {|sign (invKey SKi) {|Agent X, Nonce NM1, Nonce NCA|},
  cert (CA i) EKi onlyEnc (priSK RCA),
  cert (CA i) SKi onlySig (priSK RCA) |}
  ∈ set evs3;
  Says M (CA i) {|Agent M, Nonce NM1|} ∈ set evs3 |]
==> Says M (CA i)
  {|Crypt KM1 (sign (priSK M) {|Agent M, Nonce NM2,
    Key (pubSK M), Key (pubEK M)|}),
  Crypt EKi (Key KM1)|}
  # Notes M {|Key KM1, Agent (CA i)|}
  # evs3 ∈ set_mr"
```

SET_MR4:

— CertRes: CA issues the certificates for merSK and merEK, while checking never to have certified the m even separately. NOTE: In Cardholder Registration the corresponding rule (6) doesn't use the "sign" primitive. "The CertRes shall be signed but not encrypted if the EE is a Merchant or Payment Gateway."— Programmer's Guide, page 191.

```
"[| evs4 ∈ set_mr; M = Merchant k;
  merSK ∉ symKeys; merEK ∉ symKeys;
  Notes (CA i) (Key merSK) ∉ set evs4;
  Notes (CA i) (Key merEK) ∉ set evs4;
  Gets (CA i) {|Crypt KM1 (sign (invKey merSK)
    {|Agent M, Nonce NM2, Key merSK, Key merEK|}),
  Crypt (pubEK (CA i)) (Key KM1) |}
  ∈ set evs4 |]
==> Says (CA i) M {|sign (priSK(CA i)) {|Agent M, Nonce NM2, Agent(CA i)|},
  cert M merSK onlySig (priSK (CA i)),
  cert M merEK onlyEnc (priSK (CA i)),
  cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)|}
  # Notes (CA i) (Key merSK)
  # Notes (CA i) (Key merEK)
  # evs4 ∈ set_mr"
```

Note possibility proofs are missing.

```
declare Says_imp_knows_Spy [THEN parts.Inj, dest]
declare parts.Body [dest]
```

```

declare analz_into_parts [dest]
declare Fake_parts_insert_in_Un [dest]

```

General facts about message reception

```

lemma Gets_imp_Says:
  "[| Gets B X ∈ set evs; evs ∈ set_mr |] ==> ∃ A. Says A B X ∈ set evs"
⟨proof⟩

```

```

lemma Gets_imp_knows_Spy:
  "[| Gets B X ∈ set evs; evs ∈ set_mr |] ==> X ∈ knows Spy evs"
⟨proof⟩

```

```

declare Gets_imp_knows_Spy [THEN parts.Inj, dest]

```

5.0.1 Proofs on keys

Spy never sees an agent's private keys! (unless it's bad at start)

```

lemma Spy_see_private_Key [simp]:
  "evs ∈ set_mr
  ==> (Key(invKey (publicKey b A)) ∈ parts(knows Spy evs)) = (A ∈ bad)"
⟨proof⟩

```

```

lemma Spy_analz_private_Key [simp]:
  "evs ∈ set_mr ==>
  (Key(invKey (publicKey b A)) ∈ analz(knows Spy evs)) = (A ∈ bad)"
⟨proof⟩

```

```

declare Spy_see_private_Key [THEN [2] rev_iffD1, dest!]
declare Spy_analz_private_Key [THEN [2] rev_iffD1, dest!]

```

Proofs on certificates - they hold, as in CR, because RCA's keys are secure

```

lemma Crypt_valid_pubEK:
  "[| Crypt (priSK RCA) {|Agent (CA i), Key EKi, onlyEnc|}
    ∈ parts (knows Spy evs);
    evs ∈ set_mr |] ==> EKi = pubEK (CA i)"
⟨proof⟩

```

```

lemma certificate_valid_pubEK:
  "[| cert (CA i) EKi onlyEnc (priSK RCA) ∈ parts (knows Spy evs);
    evs ∈ set_mr |]
  ==> EKi = pubEK (CA i)"
⟨proof⟩

```

```

lemma Crypt_valid_pubSK:
  "[| Crypt (priSK RCA) {|Agent (CA i), Key SKi, onlySig|}
    ∈ parts (knows Spy evs);
    evs ∈ set_mr |] ==> SKi = pubSK (CA i)"
⟨proof⟩

```

```

lemma certificate_valid_pubSK:
  "[| cert (CA i) SKi onlySig (priSK RCA) ∈ parts (knows Spy evs);
    evs ∈ set_mr |] ==> SKi = pubSK (CA i)"

```

<proof>

lemma *Gets_certificate_valid:*

```
"[| Gets A {| X, cert (CA i) EKi onlyEnc (priSK RCA),
              cert (CA i) SKi onlySig (priSK RCA)|} ∈ set evs;
  evs ∈ set_mr |]
==> EKi = pubEK (CA i) & SKi = pubSK (CA i)"
```

<proof>

Nobody can have used non-existent keys!

lemma *new_keys_not_used [rule_format,simp]:*

```
"evs ∈ set_mr
==> Key K ∉ used evs --> K ∈ symKeys -->
    K ∉ keysFor (parts (knows Spy evs))"
```

<proof>

5.0.2 New Versions: As Above, but Generalized with the Kk Argument

lemma *gen_new_keys_not_used [rule_format]:*

```
"evs ∈ set_mr
==> Key K ∉ used evs --> K ∈ symKeys -->
    K ∉ keysFor (parts (Key'KK Un knows Spy evs))"
```

<proof>

lemma *gen_new_keys_not_analz:*

```
"[|Key K ∉ used evs; K ∈ symKeys; evs ∈ set_mr |]
==> K ∉ keysFor (analz (Key'KK Un knows Spy evs))"
```

<proof>

lemma *analz_Key_image_insert_eq:*

```
"[|Key K ∉ used evs; K ∈ symKeys; evs ∈ set_mr |]
==> analz (Key ' (insert K KK) ∪ knows Spy evs) =
    insert (Key K) (analz (Key ' KK ∪ knows Spy evs))"
```

<proof>

lemma *Crypt_parts_imp_used:*

```
"[|Crypt K X ∈ parts (knows Spy evs);
  K ∈ symKeys; evs ∈ set_mr |] ==> Key K ∈ used evs"
```

<proof>

lemma *Crypt_analz_imp_used:*

```
"[|Crypt K X ∈ analz (knows Spy evs);
  K ∈ symKeys; evs ∈ set_mr |] ==> Key K ∈ used evs"
```

<proof>

Rewriting rule for private encryption keys. Analogous rewriting rules for other keys aren't needed.

lemma *parts_image_priEK:*

```
"[|Key (priEK (CA i)) ∈ parts (Key'KK Un (knows Spy evs));
  evs ∈ set_mr|] ==> priEK (CA i) ∈ KK | CA i ∈ bad"
```

<proof>

trivial proof because $(\text{priEK } (CA \ i))$ never appears even in $(\text{parts } \text{evs})$

```
lemma analz_image_priEK:
  "evs ∈ set_mr ==>
    (Key (priEK (CA i)) ∈ analz (Key'KK Un (knows Spy evs))) =
    (priEK (CA i) ∈ KK | CA i ∈ bad)"
  <proof>
```

5.1 Secrecy of Session Keys

This holds because if $(\text{priEK } (CA \ i))$ appears in any traffic then it must be known to the Spy, by *Spy_see_private_Key*

```
lemma merK_neq_priEK:
  "[|Key merK ∉ analz (knows Spy evs);
    Key merK ∈ parts (knows Spy evs);
    evs ∈ set_mr|] ==> merK ≠ priEK C"
  <proof>
```

Lemma for message 4: either merK is compromised (when we don't care) or else merK hasn't been used to encrypt K .

```
lemma msg4_priEK_disj:
  "[|Gets B {|Crypt KM1
    (sign K {|Agent M, Nonce NM2, Key merSK, Key merEK|}),
    Y|} ∈ set evs;
    evs ∈ set_mr|]
  ==> (Key merSK ∈ analz (knows Spy evs) | merSK ∉ range(λC. priEK C))
    & (Key merEK ∈ analz (knows Spy evs) | merEK ∉ range(λC. priEK C))"
  <proof>
```

```
lemma Key_analz_image_Key_lemma:
  "P --> (Key K ∈ analz (Key'KK Un H)) --> (K ∈ KK | Key K ∈ analz H)
  ==>
  P --> (Key K ∈ analz (Key'KK Un H)) = (K ∈ KK | Key K ∈ analz H)"
  <proof>
```

```
lemma symKey_compromise:
  "evs ∈ set_mr ==>
    (∀ SK KK. SK ∈ symKeys → (∀ K ∈ KK. K ∉ range(λC. priEK C)) -->
      (Key SK ∈ analz (Key'KK Un (knows Spy evs))) =
      (SK ∈ KK | Key SK ∈ analz (knows Spy evs)))"
  <proof>
```

```
lemma symKey_secrecy [rule_format]:
  "[|CA i ∉ bad; K ∈ symKeys; evs ∈ set_mr|]
  ==> ∀ X m. Says (Merchant m) (CA i) X ∈ set evs -->
    Key K ∈ parts{X} -->
    Merchant m ∉ bad -->
    Key K ∉ analz (knows Spy evs)"
  <proof>
```

5.2 Unicity

```
lemma msg4_Says_imp_Notes:
```

```

"/[Says (CA i) M {|sign (priSK (CA i)) {|Agent M, Nonce NM2, Agent (CA i)|},
  cert M      merSK    onlySig (priSK (CA i)),
  cert M      merEK    onlyEnc (priSK (CA i)),
  cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)|}] ∈ set
evs;
  evs ∈ set_mr |]
==> Notes (CA i) (Key merSK) ∈ set evs
  & Notes (CA i) (Key merEK) ∈ set evs"
<proof>

```

Unicity of merSK wrt a given CA: merSK uniquely identifies the other components, including merEK

lemma merSK_unicity:

```

"/[Says (CA i) M {|sign (priSK(CA i)) {|Agent M, Nonce NM2, Agent (CA i)|},
  cert M      merSK    onlySig (priSK (CA i)),
  cert M      merEK    onlyEnc (priSK (CA i)),
  cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)|}] ∈ set
evs;
  Says (CA i) M' {|sign (priSK(CA i)) {|Agent M', Nonce NM2', Agent (CA i)|},
  cert M'      merSK    onlySig (priSK (CA i)),
  cert M'      merEK'   onlyEnc (priSK (CA i)),
  cert (CA i) (pubSK(CA i)) onlySig (priSK RCA)|}] ∈ set
evs;
  evs ∈ set_mr |] ==> M=M' & NM2=NM2' & merEK=merEK'"
<proof>

```

Unicity of merEK wrt a given CA: merEK uniquely identifies the other components, including merSK

lemma merEK_unicity:

```

"/[Says (CA i) M {|sign (priSK(CA i)) {|Agent M, Nonce NM2, Agent (CA i)|},
  cert M      merSK    onlySig (priSK (CA i)),
  cert M      merEK    onlyEnc (priSK (CA i)),
  cert (CA i) (pubSK (CA i)) onlySig (priSK RCA)|}] ∈ set
evs;
  Says (CA i) M' {|sign (priSK(CA i)) {|Agent M', Nonce NM2', Agent (CA i)|},
  cert M'      merSK'   onlySig (priSK (CA i)),
  cert M'      merEK    onlyEnc (priSK (CA i)),
  cert (CA i) (pubSK(CA i)) onlySig (priSK RCA)|}] ∈ set
evs;
  evs ∈ set_mr |]
==> M=M' & NM2=NM2' & merSK=merSK'"
<proof>

```

-No interest on secrecy of nonces: they appear to be used only for freshness.
 -No interest on secrecy of merSK or merEK, as in CR. -There's no equivalent of the PAN

5.3 Primary Goals of Merchant Registration

5.3.1 The merchant's certificates really were created by the CA, provided the CA is uncompromised

The assumption $CA\ i \neq RCA$ is required: step 2 uses certificates of the same form.

```

lemma certificate_merSK_valid_lemma [intro]:
  "[/Crypt (priSK (CA i)) {/Agent M, Key merSK, onlySig/}
    ∈ parts (knows Spy evs);
    CA i ∉ bad; CA i ≠ RCA; evs ∈ set_mr/]
  ==> ∃ X Y Z. Says (CA i) M
    {/X, cert M merSK onlySig (priSK (CA i)), Y, Z/} ∈ set evs"
⟨proof⟩

lemma certificate_merSK_valid:
  "[/ cert M merSK onlySig (priSK (CA i)) ∈ parts (knows Spy evs);
    CA i ∉ bad; CA i ≠ RCA; evs ∈ set_mr/]
  ==> ∃ X Y Z. Says (CA i) M
    {/X, cert M merSK onlySig (priSK (CA i)), Y, Z/} ∈ set evs"
⟨proof⟩

lemma certificate_merEK_valid_lemma [intro]:
  "[/Crypt (priSK (CA i)) {/Agent M, Key merEK, onlyEnc/}
    ∈ parts (knows Spy evs);
    CA i ∉ bad; CA i ≠ RCA; evs ∈ set_mr/]
  ==> ∃ X Y Z. Says (CA i) M
    {/X, Y, cert M merEK onlyEnc (priSK (CA i)), Z/} ∈ set evs"
⟨proof⟩

lemma certificate_merEK_valid:
  "[/ cert M merEK onlyEnc (priSK (CA i)) ∈ parts (knows Spy evs);
    CA i ∉ bad; CA i ≠ RCA; evs ∈ set_mr/]
  ==> ∃ X Y Z. Says (CA i) M
    {/X, Y, cert M merEK onlyEnc (priSK (CA i)), Z/} ∈ set evs"
⟨proof⟩

```

The two certificates - for merSK and for merEK - cannot be proved to have originated together

end

6 Purchase Phase of SET

theory Purchase **imports** PublicSET **begin**

Note: nonces seem to consist of 20 bytes. That includes both freshness challenges (Chall-EE, etc.) and important secrets (CardSecret, PANsecret)

This version omits *LID_C* but retains *LID_M*. At first glance (Programmer's Guide page 267) it seems that both numbers are just introduced for the respective convenience of the Cardholder's and Merchant's system. However, omitting both of them would create a problem of identification: how can the Merchant's system know what transaction is it supposed to process?

Further reading (Programmer's guide page 309) suggest that there is an outside bootstrapping message (SET initiation message) which is used by the Merchant and the Cardholder to agree on the actual transaction. This bootstrapping message is described in the SET External Interface Guide and ought to generate *LID_M*. According SET Extern Interface Guide, this number might be a cookie, an invoice number etc. The Programmer's Guide on page 310, states that

in absence of *LID_M* the protocol must somehow ("outside SET") identify the transaction from OrderDesc, which is assumed to be a searchable text only field. Thus, it is assumed that the Merchant or the Cardholder somehow agreed out-of-band on the value of *LID_M* (for instance a cookie in a web transaction etc.). This out-of-band agreement is expressed with a preliminary start action in which the merchant and the Cardholder agree on the appropriate values. Agreed values are stored with a suitable notes action.

"XID is a transaction ID that is usually generated by the Merchant system, unless there is no PInitRes, in which case it is generated by the Cardholder system. It is a randomly generated 20 byte variable that is globally unique (statistically). Merchant and Cardholder systems shall use appropriate random number generators to ensure the global uniqueness of XID." –Programmer's Guide, page 267.

PI (Payment Instruction) is the most central and sensitive data structure in SET. It is used to pass the data required to authorize a payment card payment from the Cardholder to the Payment Gateway, which will use the data to initiate a payment card transaction through the traditional payment card financial network. The data is encrypted by the Cardholder and sent via the Merchant, such that the data is hidden from the Merchant unless the Acquirer passes the data back to the Merchant. –Programmer's Guide, page 271.

consts

CardSecret :: "nat => nat"

— Maps Cardholders to CardSecrets. A CardSecret of 0 means no certificate, must use unsigned format.

PANSecret :: "nat => nat"

— Maps Cardholders to PANSecrets.

set_pur :: "event list set"

inductive set_pur

intros

Nil: — Initial trace is empty
"[] ∈ set_pur"

Fake: — The spy MAY say anything he CAN say.
"[| evsf ∈ set_pur; X ∈ synth(anzl(knowns Spy evsf)) |]
==> Says Spy B X # evsf ∈ set_pur"

Reception: — If A sends a message X to B, then B might receive it
"[| evsr ∈ set_pur; Says A B X ∈ set evsr |]
==> Gets B X # evsr ∈ set_pur"

Start:

— Added start event which is out-of-band for SET: the Cardholder and the merchant agree on the amounts and uses *LID_M* as an identifier. This is suggested by the External Interface Guide. The Programmer's Guide, in absence of *LID_M*, states that the merchant uniquely identifies the order out of some data contained in

OrderDesc.

```
"[/evsStart ∈ set_pur;
  Number LID_M ∉ used evsStart;
  C = Cardholder k; M = Merchant i; P = PG j;
  Transaction = {/Agent M, Agent C, Number OrderDesc, Number PurchAmt/};
  LID_M ∉ range CardSecret;
  LID_M ∉ range PANSecret []
==> Notes C {/Number LID_M, Transaction/}
      # Notes M {/Number LID_M, Agent P, Transaction/}
      # evsStart ∈ set_pur"
```

PInitReq:

— Purchase initialization, page 72 of Formal Protocol Desc.

```
"[/evsPIReq ∈ set_pur;
  Transaction = {/Agent M, Agent C, Number OrderDesc, Number PurchAmt/};
  Nonce Chall_C ∉ used evsPIReq;
  Chall_C ∉ range CardSecret; Chall_C ∉ range PANSecret;
  Notes C {/Number LID_M, Transaction []} ∈ set evsPIReq []
==> Says C M {/Number LID_M, Nonce Chall_C/} # evsPIReq ∈ set_pur"
```

PInitRes:

— Merchant replies with his own label XID and the encryption key certificate of his chosen Payment Gateway. Page 74 of Formal Protocol Desc. We use *LID_M* to identify Cardholder

```
"[/evsPIRes ∈ set_pur;
  Gets M {/Number LID_M, Nonce Chall_C/} ∈ set evsPIRes;
  Transaction = {/Agent M, Agent C, Number OrderDesc, Number PurchAmt/};
  Notes M {/Number LID_M, Agent P, Transaction/} ∈ set evsPIRes;
  Nonce Chall_M ∉ used evsPIRes;
  Chall_M ∉ range CardSecret; Chall_M ∉ range PANSecret;
  Number XID ∉ used evsPIRes;
  XID ∉ range CardSecret; XID ∉ range PANSecret[]
==> Says M C (sign (priSK M)
              {/Number LID_M, Number XID,
               Nonce Chall_C, Nonce Chall_M,
               cert P (pubEK P) onlyEnc (priSK RCA)/})
      # evsPIRes ∈ set_pur"
```

PReqUns:

— UNSIGNED Purchase request (*CardSecret* = 0). Page 79 of Formal Protocol Desc. Merchant never sees the amount in clear. This holds of the real protocol, where XID identifies the transaction. We omit Hash—Number XID, Nonce (*CardSecret* k)—from *PIHead* because the *CardSecret* is 0 and because *AuthReq* treated the unsigned case very differently from the signed one anyway.

```
"[/evsPReqU ∈ set_pur;
  C = Cardholder k; CardSecret k = 0;
  Key KC1 ∉ used evsPReqU; KC1 ∈ symKeys;
  Transaction = {/Agent M, Agent C, Number OrderDesc, Number PurchAmt/};
  HOD = Hash{/Number OrderDesc, Number PurchAmt/};
  OIData = {/Number LID_M, Number XID, Nonce Chall_C, HOD, Nonce Chall_M/};
  PIHead = {/Number LID_M, Number XID, HOD, Number PurchAmt, Agent M/};
  Gets C (sign (priSK M)
          {/Number LID_M, Number XID,
           Nonce Chall_C, Nonce Chall_M,
```



```

      cert P EKj onlyEnc (priSK RCA)|})
    ∈ set evsPReqU;
  Says C M {|Number LID_M, Nonce Chall_C|} ∈ set evsPReqU;
  Notes C {|Number LID_M, Transaction|} ∈ set evsPReqU |]
==> Says C M
      {|EXHcrypt KC1 EKj {|PIHead, Hash OIData|} (Pan (pan C)),
        OIData, Hash{|PIHead, Pan (pan C)|} |}
      # Notes C {|Key KC1, Agent M|}
      # evsPReqU ∈ set_pur"

```

PReqS:

— SIGNED Purchase request. Page 77 of Formal Protocol Desc. We could specify the equation $PIReqSigned = \{PIDualSigned, OIdualSigned\}$, since the Formal Desc. gives PIHead the same format in the unsigned case. However, there's little point, as P treats the signed and unsigned cases differently.

```

"/[evsPReqS ∈ set_pur;
  C = Cardholder k;
  CardSecret k ≠ 0; Key KC2 ∉ used evsPReqS; KC2 ∈ symKeys;
  Transaction = {|Agent M, Agent C, Number OrderDesc, Number PurchAmt|};
  HOD = Hash{|Number OrderDesc, Number PurchAmt|};
  OIData = {|Number LID_M, Number XID, Nonce Chall_C, HOD, Nonce Chall_M|};
  PIHead = {|Number LID_M, Number XID, HOD, Number PurchAmt, Agent M,
    Hash{|Number XID, Nonce (CardSecret k)|}|};
  PANData = {|Pan (pan C), Nonce (PANSecret k)|};
  PIData = {|PIHead, PANData|};
  PIDualSigned = {|sign (priSK C) {|Hash PIData, Hash OIData|},
    EXcrypt KC2 EKj {|PIHead, Hash OIData|} PANData|};
  OIdualSigned = {|OIData, Hash PIData|};
  Gets C (sign (priSK M)
    {|Number LID_M, Number XID,
      Nonce Chall_C, Nonce Chall_M,
      cert P EKj onlyEnc (priSK RCA)|})
    ∈ set evsPReqS;
  Says C M {|Number LID_M, Nonce Chall_C|} ∈ set evsPReqS;
  Notes C {|Number LID_M, Transaction|} ∈ set evsPReqS |]
==> Says C M {|PIDualSigned, OIdualSigned|}
      # Notes C {|Key KC2, Agent M|}
      # evsPReqS ∈ set_pur"

```

— Authorization Request. Page 92 of Formal Protocol Desc. Sent in response to Purchase Request.

AuthReq:

```

"/[ evsAReq ∈ set_pur;
  Key KM ∉ used evsAReq; KM ∈ symKeys;
  Transaction = {|Agent M, Agent C, Number OrderDesc, Number PurchAmt|};
  HOD = Hash{|Number OrderDesc, Number PurchAmt|};
  OIData = {|Number LID_M, Number XID, Nonce Chall_C, HOD,
    Nonce Chall_M|};
  CardSecret k ≠ 0 -->
    P_I = {|sign (priSK C) {|HPIData, Hash OIData|}, encPANData|};
  Gets M {|P_I, OIData, HPIData|} ∈ set evsAReq;
  Says M C (sign (priSK M) {|Number LID_M, Number XID,
    Nonce Chall_C, Nonce Chall_M,
    cert P EKj onlyEnc (priSK RCA)|})

```

```

    ∈ set evsAReq;
    Notes M {|Number LID_M, Agent P, Transaction|}
    ∈ set evsAReq []
==> Says M P
      (EncB (priSK M) KM (pubEK P)
        {|Number LID_M, Number XID, Hash OIData, HOD|} P_I)
      # evsAReq ∈ set_pur"

```

— Authorization Response has two forms: for UNSIGNED and SIGNED PIs. Page 99 of Formal Protocol Desc. PI is a keyword (product!), so we call it P_I . The hashes HOD and HOIData occur independently in P_I and in M's message. The authCode in AuthRes represents the baggage of EncB, which in the full protocol is [CapToken], [AcqCardMsg], [AuthToken]: optional items for split shipments, recurring payments, etc.

AuthResUns:

— Authorization Response, UNSIGNED

```

"[] evsAResU ∈ set_pur;
  C = Cardholder k; M = Merchant i;
  Key KP ∉ used evsAResU; KP ∈ symKeys;
  CardSecret k = 0; KC1 ∈ symKeys; KM ∈ symKeys;
  PIHead = {|Number LID_M, Number XID, HOD, Number PurchAmt, Agent M|};
  P_I = EXHcrypt KC1 EKj {|PIHead, HOIData|} (Pan (pan C));
  Gets P (EncB (priSK M) KM (pubEK P)
    {|Number LID_M, Number XID, HOIData, HOD|} P_I)
    ∈ set evsAResU []
==> Says P M
      (EncB (priSK P) KP (pubEK M)
        {|Number LID_M, Number XID, Number PurchAmt|}
        authCode)
      # evsAResU ∈ set_pur"

```

AuthResS:

— Authorization Response, SIGNED

```

"[] evsAResS ∈ set_pur;
  C = Cardholder k;
  Key KP ∉ used evsAResS; KP ∈ symKeys;
  CardSecret k ≠ 0; KC2 ∈ symKeys; KM ∈ symKeys;
  P_I = {|sign (priSK C) {|Hash PIData, HOIData|},
    EXcrypt KC2 (pubEK P) {|PIHead, HOIData|} PANData|};
  PANData = {|Pan (pan C), Nonce (PANSecret k)|};
  PIData = {|PIHead, PANData|};
  PIHead = {|Number LID_M, Number XID, HOD, Number PurchAmt, Agent M,
    Hash{|Number XID, Nonce (CardSecret k)|}|};
  Gets P (EncB (priSK M) KM (pubEK P)
    {|Number LID_M, Number XID, HOIData, HOD|}
    P_I)
    ∈ set evsAResS []
==> Says P M
      (EncB (priSK P) KP (pubEK M)
        {|Number LID_M, Number XID, Number PurchAmt|}
        authCode)
      # evsAResS ∈ set_pur"

```

```

PRes:
— Purchase response.
"/| evsPRes ∈ set_pur; KP ∈ symKeys; M = Merchant i;
Transaction = {|Agent M, Agent C, Number OrderDesc, Number PurchAmt|};
Gets M (EncB (priSK P) KP (pubEK M)
          {|Number LID_M, Number XID, Number PurchAmt|}
          authCode)
  ∈ set evsPRes;
Gets M {|Number LID_M, Nonce Chall_C|} ∈ set evsPRes;
Says M P
  (EncB (priSK M) KM (pubEK P)
   {|Number LID_M, Number XID, Hash OIDData, HOD|} P_I)
  ∈ set evsPRes;
Notes M {|Number LID_M, Agent P, Transaction|}
  ∈ set evsPRes
/]
==> Says M C
  (sign (priSK M) {|Number LID_M, Number XID, Nonce Chall_C,
                  Hash (Number PurchAmt)|})
  # evsPRes ∈ set_pur"

```

```

specification (CardSecret PANSecret)
inj_CardSecret: "inj CardSecret"
inj_PANSecret: "inj PANSecret"
CardSecret_neq_PANSecret: "CardSecret k ≠ PANSecret k'"
— No CardSecret equals any PANSecret
⟨proof⟩

```

```

declare Says_imp_knows_Spy [THEN parts.Inj, dest]
declare parts.Body [dest]
declare analz_into_parts [dest]
declare Fake_parts_insert_in_Un [dest]

declare CardSecret_neq_PANSecret [iff]
CardSecret_neq_PANSecret [THEN not_sym, iff]
declare inj_CardSecret [THEN inj_eq, iff]
inj_PANSecret [THEN inj_eq, iff]

```

6.1 Possibility Properties

```

lemma Says_to_Gets:
  "Says A B X # evs ∈ set_pur ==> Gets B X # Says A B X # evs ∈ set_pur"
⟨proof⟩

```

Possibility for UNSIGNED purchases. Note that we need to ensure that XID differs from OrderDesc and PurchAmt, since it is supposed to be a unique number!

```

lemma possibility_Uns:
  "/| CardSecret k = 0;
    C = Cardholder k; M = Merchant i;
    Key KC ∉ used []; Key KM ∉ used []; Key KP ∉ used [];
    KC ∈ symKeys; KM ∈ symKeys; KP ∈ symKeys;
    KC < KM; KM < KP;

```

```

Nonce Chall_C  $\notin$  used []; Chall_C  $\notin$  range CardSecret  $\cup$  range PANSecret;
Nonce Chall_M  $\notin$  used []; Chall_M  $\notin$  range CardSecret  $\cup$  range PANSecret;
Chall_C < Chall_M;
Number LID_M  $\notin$  used []; LID_M  $\notin$  range CardSecret  $\cup$  range PANSecret;
Number XID  $\notin$  used []; XID  $\notin$  range CardSecret  $\cup$  range PANSecret;
LID_M < XID; XID < OrderDesc; OrderDesc < PurchAmt []
==>  $\exists$  evs  $\in$  set_pur.
      Says M C
        (sign (priSK M)
          {|Number LID_M, Number XID, Nonce Chall_C,
            Hash (Number PurchAmt)|})
           $\in$  set evs"
<proof>

```

lemma possibility_S:

```

"[] CardSecret k  $\neq$  0;
  C = Cardholder k; M = Merchant i;
  Key KC  $\notin$  used []; Key KM  $\notin$  used []; Key KP  $\notin$  used [];
  KC  $\in$  symKeys; KM  $\in$  symKeys; KP  $\in$  symKeys;
  KC < KM; KM < KP;
  Nonce Chall_C  $\notin$  used []; Chall_C  $\notin$  range CardSecret  $\cup$  range PANSecret;
  Nonce Chall_M  $\notin$  used []; Chall_M  $\notin$  range CardSecret  $\cup$  range PANSecret;
  Chall_C < Chall_M;
  Number LID_M  $\notin$  used []; LID_M  $\notin$  range CardSecret  $\cup$  range PANSecret;
  Number XID  $\notin$  used []; XID  $\notin$  range CardSecret  $\cup$  range PANSecret;
  LID_M < XID; XID < OrderDesc; OrderDesc < PurchAmt []
==>  $\exists$  evs  $\in$  set_pur.
      Says M C
        (sign (priSK M) {|Number LID_M, Number XID, Nonce Chall_C,
                          Hash (Number PurchAmt)|})
           $\in$  set evs"
<proof>

```

General facts about message reception

lemma Gets_imp_Says:

```

"[] Gets B X  $\in$  set evs; evs  $\in$  set_pur []
==>  $\exists$  A. Says A B X  $\in$  set evs"
<proof>

```

lemma Gets_imp_knows_Spy:

```

"[] Gets B X  $\in$  set evs; evs  $\in$  set_pur [] ==> X  $\in$  knows Spy evs"
<proof>

```

declare Gets_imp_knows_Spy [THEN parts.Inj, dest]

Forwarding lemmas, to aid simplification

lemma AuthReq_msg_in_parts_spies:

```

"[] Gets M {|P_I, OIData, HPIDData|}  $\in$  set evs;
  evs  $\in$  set_pur[] ==> P_I  $\in$  parts (knows Spy evs)"
<proof>

```

lemma AuthReq_msg_in_analz_spies:

```

"[] Gets M {|P_I, OIData, HPIDData|}  $\in$  set evs;

```

```

    evs ∈ set_pur[] ==> P_I ∈ analz (knows Spy evs)"
  <proof>

```

6.2 Proofs on Asymmetric Keys

Private Keys are Secret

Spy never sees an agent's private keys! (unless it's bad at start)

```

lemma Spy_see_private_Key [simp]:
  "evs ∈ set_pur
   ==> (Key(invKey (publicKey b A)) ∈ parts(knows Spy evs)) = (A ∈ bad)"
  <proof>
declare Spy_see_private_Key [THEN [2] rev_iffD1, dest!]

```

```

lemma Spy_analz_private_Key [simp]:
  "evs ∈ set_pur ==>
   (Key(invKey (publicKey b A)) ∈ analz(knows Spy evs)) = (A ∈ bad)"
  <proof>
declare Spy_analz_private_Key [THEN [2] rev_iffD1, dest!]

```

rewriting rule for priEK's

```

lemma parts_image_priEK:
  "[|Key (priEK C) ∈ parts (Key'KK Un (knows Spy evs));
   evs ∈ set_pur|] ==> priEK C ∈ KK | C ∈ bad"
  <proof>

```

trivial proof because priEK C never appears even in parts evs.

```

lemma analz_image_priEK:
  "evs ∈ set_pur ==>
   (Key (priEK C) ∈ analz (Key'KK Un (knows Spy evs))) =
   (priEK C ∈ KK | C ∈ bad)"
  <proof>

```

6.3 Public Keys in Certificates are Correct

```

lemma Crypt_valid_pubEK [dest!]:
  "[| Crypt (priSK RCA) {|Agent C, Key EKi, onlyEnc|}
   ∈ parts (knows Spy evs);
   evs ∈ set_pur |] ==> EKi = pubEK C"
  <proof>

```

```

lemma Crypt_valid_pubSK [dest!]:
  "[| Crypt (priSK RCA) {|Agent C, Key SKi, onlySig|}
   ∈ parts (knows Spy evs);
   evs ∈ set_pur |] ==> SKi = pubSK C"
  <proof>

```

```

lemma certificate_valid_pubEK:
  "[| cert C EKi onlyEnc (priSK RCA) ∈ parts (knows Spy evs);
   evs ∈ set_pur |]
   ==> EKi = pubEK C"
  <proof>

```

```

lemma certificate_valid_pubSK:
  "[| cert C SKi onlySig (priSK RCA) ∈ parts (knows Spy evs);
    evs ∈ set_pur |] ==> SKi = pubSK C"
  <proof>

lemma Says_certificate_valid [simp]:
  "[| Says A B (sign SK {|lid, xid, cc, cm,
    cert C EK onlyEnc (priSK RCA)|}) ∈ set evs;
    evs ∈ set_pur |]
    ==> EK = pubEK C"
  <proof>

lemma Gets_certificate_valid [simp]:
  "[| Gets A (sign SK {|lid, xid, cc, cm,
    cert C EK onlyEnc (priSK RCA)|}) ∈ set evs;
    evs ∈ set_pur |]
    ==> EK = pubEK C"
  <proof>

  <ML>

```

6.4 Proofs on Symmetric Keys

Nobody can have used non-existent keys!

```

lemma new_keys_not_used [rule_format,simp]:
  "evs ∈ set_pur
    ==> Key K ∉ used evs --> K ∈ symKeys -->
      K ∉ keysFor (parts (knows Spy evs))"
  <proof>

lemma new_keys_not_analz:
  "[|Key K ∉ used evs; K ∈ symKeys; evs ∈ set_pur |]
    ==> K ∉ keysFor (analz (knows Spy evs))"
  <proof>

lemma Crypt_parts_imp_used:
  "[|Crypt K X ∈ parts (knows Spy evs);
    K ∈ symKeys; evs ∈ set_pur |] ==> Key K ∈ used evs"
  <proof>

lemma Crypt_analz_imp_used:
  "[|Crypt K X ∈ analz (knows Spy evs);
    K ∈ symKeys; evs ∈ set_pur |] ==> Key K ∈ used evs"
  <proof>

New versions: as above, but generalized to have the KK argument

lemma gen_new_keys_not_used:
  "[|Key K ∉ used evs; K ∈ symKeys; evs ∈ set_pur |]
    ==> Key K ∉ used evs --> K ∈ symKeys -->
      K ∉ keysFor (parts (Key'KK Un knows Spy evs))"
  <proof>

lemma gen_new_keys_not_analz:

```

```

"[/Key K  $\notin$  used evs; K  $\in$  symKeys; evs  $\in$  set_pur /]
==> K  $\notin$  keysFor (analz (Key'KK Un knows Spy evs))"
<proof>

lemma analz_Key_image_insert_eq:
"[/Key K  $\notin$  used evs; K  $\in$  symKeys; evs  $\in$  set_pur /]
==> analz (Key ' (insert K KK)  $\cup$  knows Spy evs) =
      insert (Key K) (analz (Key ' KK  $\cup$  knows Spy evs))"
<proof>

```

6.5 Secrecy of Symmetric Keys

```

lemma Key_analz_image_Key_lemma:
"P --> (Key K  $\in$  analz (Key'KK Un H)) --> (K $\in$ KK | Key K  $\in$  analz H)
==>
P --> (Key K  $\in$  analz (Key'KK Un H)) = (K $\in$ KK | Key K  $\in$  analz H)"
<proof>

```

```

lemma symKey_compromise:
"evs  $\in$  set_pur ==>
  ( $\forall$  SK KK. SK  $\in$  symKeys  $\longrightarrow$ 
    ( $\forall$  K  $\in$  KK. K  $\notin$  range( $\lambda$ C. priEK C))  $\longrightarrow$ 
      (Key SK  $\in$  analz (Key'KK  $\cup$  (knows Spy evs))) =
      (SK  $\in$  KK  $\vee$  Key SK  $\in$  analz (knows Spy evs)))"
<proof>

```

6.6 Secrecy of Nonces

As usual: we express the property as a logical equivalence

```

lemma Nonce_analz_image_Key_lemma:
"P --> (Nonce N  $\in$  analz (Key'KK Un H)) --> (Nonce N  $\in$  analz H)
==> P --> (Nonce N  $\in$  analz (Key'KK Un H)) = (Nonce N  $\in$  analz H)"
<proof>

```

The (no_asm) attribute is essential, since it retains the quantifier and allows the simp rule's condition to itself be simplified.

```

lemma Nonce_compromise [rule_format (no_asm)]:
"evs  $\in$  set_pur ==>
  ( $\forall$  N KK. ( $\forall$  K  $\in$  KK. K  $\notin$  range( $\lambda$ C. priEK C)) -->
    (Nonce N  $\in$  analz (Key'KK  $\cup$  (knows Spy evs))) =
    (Nonce N  $\in$  analz (knows Spy evs)))"
<proof>

```

```

lemma PANSecret_notin_spies:
"[/Nonce (PANSecret k)  $\in$  analz (knows Spy evs); evs  $\in$  set_pur/]
==>
  ( $\exists$  V W X Y KC2 M.  $\exists$  P  $\in$  bad.
    Says (Cardholder k) M
      {/|W, EXcrypt KC2 (pubEK P) X {/Y, Nonce (PANSecret k)|}/|},
    V/}  $\in$  set evs)"
<proof>

```

This theorem is a bit silly, in that many CardSecrets are 0! But then we don't care. NOT USED

```
lemma CardSecret_notin_spies:
  "evs ∈ set_pur ==> Nonce (CardSecret i) ∉ parts (knows Spy evs)"
<proof>
```

6.7 Confidentiality of PAN

```
lemma analz_image_pan_lemma:
  "(Pan P ∈ analz (Key'nE Un H)) --> (Pan P ∈ analz H) ==>
   (Pan P ∈ analz (Key'nE Un H)) = (Pan P ∈ analz H)"
<proof>
```

The (*no_asm*) attribute is essential, since it retains the quantifier and allows the simp rule's condition to itself be simplified.

```
lemma analz_image_pan [rule_format (no_asm)]:
  "evs ∈ set_pur ==>
   ∀ KK. (∀ K ∈ KK. K ∉ range(λC. priEK C)) -->
   (Pan P ∈ analz (Key'KK Un (knows Spy evs))) =
   (Pan P ∈ analz (knows Spy evs))"
<proof>
```

```
lemma analz_insert_pan:
  "[| evs ∈ set_pur; K ∉ range(λC. priEK C) |] ==>
   (Pan P ∈ analz (insert (Key K) (knows Spy evs))) =
   (Pan P ∈ analz (knows Spy evs))"
<proof>
```

Confidentiality of the PAN, unsigned case.

```
theorem pan_confidentiality_unsigned:
  "[| Pan (pan C) ∈ analz(knows Spy evs); C = Cardholder k;
   CardSecret k = 0; evs ∈ set_pur |]
 ==> ∃ P M KC1 K X Y.
   Says C M {|EXHcrypt KC1 (pubEK P) X (Pan (pan C)), Y|}
   ∈ set evs &
   P ∈ bad"
<proof>
```

Confidentiality of the PAN, signed case.

```
theorem pan_confidentiality_signed:
  "[| Pan (pan C) ∈ analz(knows Spy evs); C = Cardholder k;
   CardSecret k ≠ 0; evs ∈ set_pur |]
 ==> ∃ P M KC2 PIDualSign_1 PIDualSign_2 other OIDualSign.
   Says C M {|PIDualSign_1,
   EXcrypt KC2 (pubEK P) PIDualSign_2 {|Pan (pan C), other|}|},
   OIDualSign|} ∈ set evs & P ∈ bad"
<proof>
```

General goal: that C, M and PG agree on those details of the transaction that they are allowed to know about. PG knows about price and account details. M knows about the order description and price. C knows both.

6.8 Proofs Common to Signed and Unsigned Versions

lemma *M_Notes_PG*:

```
"[|Notes M {|Number LID_M, Agent P, Agent M, Agent C, etc|} ∈ set evs;
  evs ∈ set_pur|] ==> ∃ j. P = PG j"
```

<proof>

If we trust M, then *LID_M* determines his choice of P (Payment Gateway)

lemma *goodM_gives_correct_PG*:

```
"[| MsgPInitRes =
  {|Number LID_M, xid, cc, cm, cert P EKj onlyEnc (priSK RCA)|};
  Crypt (priSK M) (Hash MsgPInitRes) ∈ parts (knows Spy evs);
  evs ∈ set_pur; M ∉ bad |]
==> ∃ j trans.
  P = PG j &
  Notes M {|Number LID_M, Agent P, trans|} ∈ set evs"
```

<proof>

lemma *C_gets_correct_PG*:

```
"[| Gets A (sign (priSK M) {|Number LID_M, xid, cc, cm,
  cert P EKj onlyEnc (priSK RCA)|}) ∈ set evs;
  evs ∈ set_pur; M ∉ bad |]
==> ∃ j trans.
  P = PG j &
  Notes M {|Number LID_M, Agent P, trans|} ∈ set evs &
  EKj = pubEK P"
```

<proof>

When C receives PInitRes, he learns M's choice of P

lemma *C_verifies_PInitRes*:

```
"[| MsgPInitRes = {|Number LID_M, Number XID, Nonce Chall_C, Nonce Chall_M,
  cert P EKj onlyEnc (priSK RCA)|};
  Crypt (priSK M) (Hash MsgPInitRes) ∈ parts (knows Spy evs);
  evs ∈ set_pur; M ∉ bad |]
==> ∃ j trans.
  Notes M {|Number LID_M, Agent P, trans|} ∈ set evs &
  P = PG j &
  EKj = pubEK P"
```

<proof>

Corollary of previous one

lemma *Says_C_PInitRes*:

```
"[| Says A C (sign (priSK M)
  {|Number LID_M, Number XID,
  Nonce Chall_C, Nonce Chall_M,
  cert P EKj onlyEnc (priSK RCA)|})
  ∈ set evs; M ∉ bad; evs ∈ set_pur |]
==> ∃ j trans.
  Notes M {|Number LID_M, Agent P, trans|} ∈ set evs &
  P = PG j &
  EKj = pubEK (PG j)"
```

<proof>

When P receives an AuthReq, he knows that the signed part originated with M. PIRes also has a signed message from M....

lemma *P_verifies_AuthReq*:

```

  "[| AuthReqData = {|Number LID_M, Number XID, HOIData, HOD|};
    Crypt (priSK M) (Hash {|AuthReqData, Hash P_I|})
      ∈ parts (knows Spy evs);
    evs ∈ set_pur; M ∉ bad|]
  ==> ∃ j trans KM OIData HPIData.
    Notes M {|Number LID_M, Agent (PG j), trans|} ∈ set evs &
    Gets M {|P_I, OIData, HPIData|} ∈ set evs &
    Says M (PG j) (EncB (priSK M) KM (pubEK (PG j)) AuthReqData P_I)
      ∈ set evs"

```

<proof>

When M receives AuthRes, he knows that P signed it, including the identifying tags and the purchase amount, which he can verify. (Although the spec has SIGNED and UNSIGNED forms of AuthRes, they send the same message to M.) The conclusion is weak: M is existentially quantified! That is because Authorization Response does not refer to M, while the digital envelope weakens the link between *MsgAuthRes* and *priSK M*. Changing the precondition to refer to *Crypt K (sign SK M)* requires assuming K to be secure, since otherwise the Spy could create that message.

theorem *M_verifies_AuthRes*:

```

  "[| MsgAuthRes = {|{|Number LID_M, Number XID, Number PurchAmt|},
    Hash authCode|};
    Crypt (priSK (PG j)) (Hash MsgAuthRes) ∈ parts (knows Spy evs);
    PG j ∉ bad; evs ∈ set_pur|]
  ==> ∃ M KM KP HOIData HOD P_I.
    Gets (PG j)
      (EncB (priSK M) KM (pubEK (PG j))
        {|Number LID_M, Number XID, HOIData, HOD|}
        P_I) ∈ set evs &
    Says (PG j) M
      (EncB (priSK (PG j)) KP (pubEK M)
        {|Number LID_M, Number XID, Number PurchAmt|}
        authCode) ∈ set evs"

```

<proof>

6.9 Proofs for Unsigned Purchases

What we can derive from the ASSUMPTION that C issued a purchase request. In the unsigned case, we must trust "C": there's no authentication.

lemma *C_determines_EKj*:

```

  "[| Says C M {|EXHcrypt KC1 EKj {|PIHead, Hash OIData|} (Pan (pan C)),
    OIData, Hash{|PIHead, Pan (pan C)|} |} ∈ set evs;
    PIHead = {|Number LID_M, Trans_details|};
    evs ∈ set_pur; C = Cardholder k; M ∉ bad|]
  ==> ∃ trans j.
    Notes M {|Number LID_M, Agent (PG j), trans |} ∈ set evs &
    EKj = pubEK (PG j)"

```

<proof>

Unicity of *LID_M* between Merchant and Cardholder notes

lemma *unique_LID_M*:

```

    "[|Notes (Merchant i) {|Number LID_M, Agent P, Trans|} ∈ set evs;
      Notes C {|Number LID_M, Agent M, Agent C, Number OD,
        Number PA|} ∈ set evs;
      evs ∈ set_pur|]
    ==> M = Merchant i & Trans = {|Agent M, Agent C, Number OD, Number PA|}"
  <proof>

```

Unicity of *LID_M*, for two Merchant Notes events

```

lemma unique_LID_M2:
  "[|Notes M {|Number LID_M, Trans|} ∈ set evs;
    Notes M' {|Number LID_M, Trans'|} ∈ set evs;
    evs ∈ set_pur|] ==> Trans' = Trans"
  <proof>

```

Lemma needed below: for the case that if PRes is present, then *LID_M* has been used.

```

lemma signed_imp_used:
  "[| Crypt (priSK M) (Hash X) ∈ parts (knows Spy evs);
    M ∉ bad; evs ∈ set_pur|] ==> parts {X} ⊆ used evs"
  <proof>

```

Similar, with nested Hash

```

lemma signed_Hash_imp_used:
  "[| Crypt (priSK C) (Hash {|H, Hash X|}) ∈ parts (knows Spy evs);
    C ∉ bad; evs ∈ set_pur|] ==> parts {X} ⊆ used evs"
  <proof>

```

Lemma needed below: for the case that if PRes is present, then *LID_M* has been used.

```

lemma PRes_imp_LID_used:
  "[| Crypt (priSK M) (Hash {|N, X|}) ∈ parts (knows Spy evs);
    M ∉ bad; evs ∈ set_pur|] ==> N ∈ used evs"
  <proof>

```

When C receives PRes, he knows that M and P agreed to the purchase details. He also knows that P is the same PG as before

```

lemma C_verifies_PRes_lemma:
  "[| Crypt (priSK M) (Hash MsgPres) ∈ parts (knows Spy evs);
    Notes C {|Number LID_M, Trans |} ∈ set evs;
    Trans = {| Agent M, Agent C, Number OrderDesc, Number PurchAmt |};
    MsgPres = {|Number LID_M, Number XID, Nonce Chall_C,
      Hash (Number PurchAmt)|};
    evs ∈ set_pur; M ∉ bad|]
  ==> ∃ j KP.
    Notes M {|Number LID_M, Agent (PG j), Trans |}
      ∈ set evs &
    Gets M (EncB (priSK (PG j)) KP (pubEK M)
      {|Number LID_M, Number XID, Number PurchAmt|}
      authCode)
      ∈ set evs &
    Says M C (sign (priSK M) MsgPres) ∈ set evs"
  <proof>

```

When the Cardholder receives Purchase Response from an uncompromised Merchant, he knows that M sent it. He also knows that M received a message signed by a Payment Gateway chosen by M to authorize the purchase.

theorem *C_verifies_PRes*:

```
"[| MsgPRes = {|Number LID_M, Number XID, Nonce Chall_C,
              Hash (Number PurchAmt)|};
  Gets C (sign (priSK M) MsgPRes) ∈ set evs;
  Notes C {|Number LID_M, Agent M, Agent C, Number OrderDesc,
            Number PurchAmt|} ∈ set evs;
  evs ∈ set_pur; M ∉ bad|]
==> ∃ P KP trans.
  Notes M {|Number LID_M, Agent P, trans|} ∈ set evs &
  Gets M (EncB (priSK P) KP (pubEK M)
          {|Number LID_M, Number XID, Number PurchAmt|}
          authCode) ∈ set evs &
  Says M C (sign (priSK M) MsgPRes) ∈ set evs"
⟨proof⟩
```

6.10 Proofs for Signed Purchases

Some Useful Lemmas: the cardholder knows what he is doing

lemma *Crypt_imp_Says_Cardholder*:

```
"[| Crypt K {|{|{|Number LID_M, others|}, Hash OIData|}, Hash PANData|}
  ∈ parts (knows Spy evs);
  PANData = {|Pan (pan (Cardholder k)), Nonce (PANSecret k)|};
  Key K ∉ analz (knows Spy evs);
  evs ∈ set_pur|]
==> ∃ M shash EK HPIData.
  Says (Cardholder k) M {|{|shash,
    Crypt K
      {|{|{|Number LID_M, others|}, Hash OIData|}, Hash PANData|},
    Crypt EK {|Key K, PANData|}|},
    OIData, HPIData|} ∈ set evs"
⟨proof⟩
```

lemma *Says_PReqS_imp_trans_details_C*:

```
"[| MsgPReqS = {|{|shash,
  Crypt K
    {|{|{|Number LID_M, PIREst|}, Hash OIData|}, hashpd|},
    cryptek|}, data|};
  Says (Cardholder k) M MsgPReqS ∈ set evs;
  evs ∈ set_pur |]
==> ∃ trans.
  Notes (Cardholder k)
    {|Number LID_M, Agent M, Agent (Cardholder k), trans|}
    ∈ set evs"
⟨proof⟩
```

Can't happen: only Merchants create this type of Note

lemma *Notes_Cardholder_self_False*:

```
"[|Notes (Cardholder k)
  {|Number n, Agent P, Agent (Cardholder k), Agent C, etc|} ∈ set
  evs;
```

```

    evs ∈ set_pur[] ==> False"
  <proof>

```

When M sees a dual signature, he knows that it originated with C. Using XID he knows it was intended for him. This guarantee isn't useful to P, who never gets OIData.

```

theorem M_verifies_Signed_PReq:
  "[| MsgDualSign = {|HPIData, Hash OIData|};
    OIData = {|Number LID_M, etc|};
    Crypt (priSK C) (Hash MsgDualSign) ∈ parts (knows Spy evs);
    Notes M {|Number LID_M, Agent P, extras|} ∈ set evs;
    M = Merchant i; C = Cardholder k; C ∉ bad; evs ∈ set_pur|]
  ==> ∃ PIData PICrypt.
    HPIData = Hash PIData &
    Says C M {|sign (priSK C) MsgDualSign, PICrypt|}, OIData, Hash PIData|}
    ∈ set evs"
  <proof>

```

When P sees a dual signature, he knows that it originated with C. and was intended for M. This guarantee isn't useful to M, who never gets PIData. I don't see how to link PG j and LID_M without assuming M ∉ bad.

```

theorem P_verifies_Signed_PReq:
  "[| MsgDualSign = {|Hash PIData, HOIData|};
    PIData = {|PIHead, PANData|};
    PIHead = {|Number LID_M, Number XID, HOD, Number PurchAmt, Agent M,
      TransStain|};
    Crypt (priSK C) (Hash MsgDualSign) ∈ parts (knows Spy evs);
    evs ∈ set_pur; C ∉ bad; M ∉ bad|]
  ==> ∃ OIData OrderDesc K j trans.
    HOD = Hash{|Number OrderDesc, Number PurchAmt|} &
    HOIData = Hash OIData &
    Notes M {|Number LID_M, Agent (PG j), trans|} ∈ set evs &
    Says C M {|sign (priSK C) MsgDualSign,
      EXcrypt K (pubEK (PG j))
        {|PIHead, Hash OIData|} PANData|},
      OIData, Hash PIData|}
    ∈ set evs"
  <proof>

```

```

lemma C_determines_EKj_signed:
  "[| Says C M {|sign (priSK C) text,
    EXcrypt K EKj {|PIHead, X|} Y|}, Z|} ∈ set evs;
    PIHead = {|Number LID_M, Number XID, W|};
    C = Cardholder k; evs ∈ set_pur; M ∉ bad|]
  ==> ∃ trans j.
    Notes M {|Number LID_M, Agent (PG j), trans|} ∈ set evs &
    EKj = pubEK (PG j)"
  <proof>

```

```

lemma M_Says_AuthReq:
  "[| AuthReqData = {|Number LID_M, Number XID, HOIData, HOD|};
    sign (priSK M) {|AuthReqData, Hash P_I|} ∈ parts (knows Spy evs);
    evs ∈ set_pur; M ∉ bad|]

```

```

==> ∃ j trans KM.
      Notes M {|Number LID_M, Agent (PG j), trans |} ∈ set evs &
      Says M (PG j)
        (EncB (priSK M) KM (pubEK (PG j)) AuthReqData P_I)
        ∈ set evs"
<proof>

```

A variant of *M_verifies_Signed_PReq* with explicit PI information. Even here we cannot be certain about what C sent to M, since a bad PG could have replaced the two key fields. (NOT USED)

lemma *Signed_PReq_imp_Says_Cardholder*:

```

"[| MsgDualSign = {|Hash PIData, Hash OIData|};
   OIData = {|Number LID_M, Number XID, Nonce Chall_C, HOD, etc|};
   PIHead = {|Number LID_M, Number XID, HOD, Number PurchAmt, Agent M,
             TransStain|};
   PIData = {|PIHead, PANData|};
   Crypt (priSK C) (Hash MsgDualSign) ∈ parts (knows Spy evs);
   M = Merchant i; C = Cardholder k; C ∉ bad; evs ∈ set_pur/]
==> ∃ KC EKj.
      Says C M {|{|sign (priSK C) MsgDualSign,
                    EXcrypt KC EKj {|PIHead, Hash OIData|} PANData|},
                OIData, Hash PIData|}
        ∈ set evs"
<proof>

```

When P receives an AuthReq and a dual signature, he knows that C and M agree on the essential details. PurchAmt however is never sent by M to P; instead C and M both send $HOD = Hash \{Number\ OrderDesc, Number\ PurchAmt\}$ and P compares the two copies of HOD.

Agreement can't be proved for some things, including the symmetric keys used in the digital envelopes. On the other hand, M knows the true identity of PG (namely j'), and sends AReq there; he can't, however, check that the EXcrypt involves the correct PG's key.

theorem *P_sees_CM_agreement*:

```

"[| AuthReqData = {|Number LID_M, Number XID, HOIData, HOD|};
   KC ∈ symKeys;
   Gets (PG j) (EncB (priSK M) KM (pubEK (PG j)) AuthReqData P_I)
   ∈ set evs;
   C = Cardholder k;
   PI_sign = sign (priSK C) {|Hash PIData, HOIData|};
   P_I = {|PI_sign,
           EXcrypt KC (pubEK (PG j)) {|PIHead, HOIData|} PANData|};
   PANData = {|Pan (pan C), Nonce (PANSecret k)|};
   PIData = {|PIHead, PANData|};
   PIHead = {|Number LID_M, Number XID, HOD, Number PurchAmt, Agent M,
             TransStain|};

   evs ∈ set_pur; C ∉ bad; M ∉ bad/]
==> ∃ OIData OrderDesc KM' trans j' KC' KC'' P_I' P_I''.
      HOD = Hash{|Number OrderDesc, Number PurchAmt|} &
      HOIData = Hash OIData &
      Notes M {|Number LID_M, Agent (PG j'), trans|} ∈ set evs &
      Says C M {|P_I', OIData, Hash PIData|} ∈ set evs &
      Says M (PG j') (EncB (priSK M) KM' (pubEK (PG j'))

```

```

                                AuthReqData P_I'') ∈ set evs &
P_I' = {|PI_sign,
        EXcrypt KC' (pubEK (PG j')) {|PIHead, Hash OIData|} PANData|}
&
P_I'' = {|PI_sign,
        EXcrypt KC'' (pubEK (PG j)) {|PIHead, Hash OIData|} PANData|}"
⟨proof⟩
end

```