An Executable Model for JFKr

An ACL2 approach to key-establishment protocol verification

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November 22, 2004

About ACL2

- J S Moore and Matt Kaufmann
- ACL2 - A Computational Logic for Applicative Common Lisp
- Applicative – functional
- Hierarchical
  - Prove lemmas to prove larger theorems
- Doubles as an executable model

Diffie-Helman

- Model based off a state containing a list of “knowledge”
- From “knowledge” compute diffie-helman components
- From diffie-helman components, show:
  - Forward secrecy - yes
  - Authentication - no
  - Replay Attack - yes
  - DoS - no
  - ID Protection - no

Basic DH Model Parts

1. If an actor has neither of the two nonces used in a DH computation, it can not derive the DH key.
2. An intruder does not begin with either of the two relevant nonces.
3. Nonces are not released during the communication (requires induction).
4. Since nonces are not released during communication and the intruder has neither of the two relevant nonces, the intruder can not obtain the DH key

- Should be easy

Knowledge-state Attempt #1

- Contained redundant data
- Should trim to basic building blocks

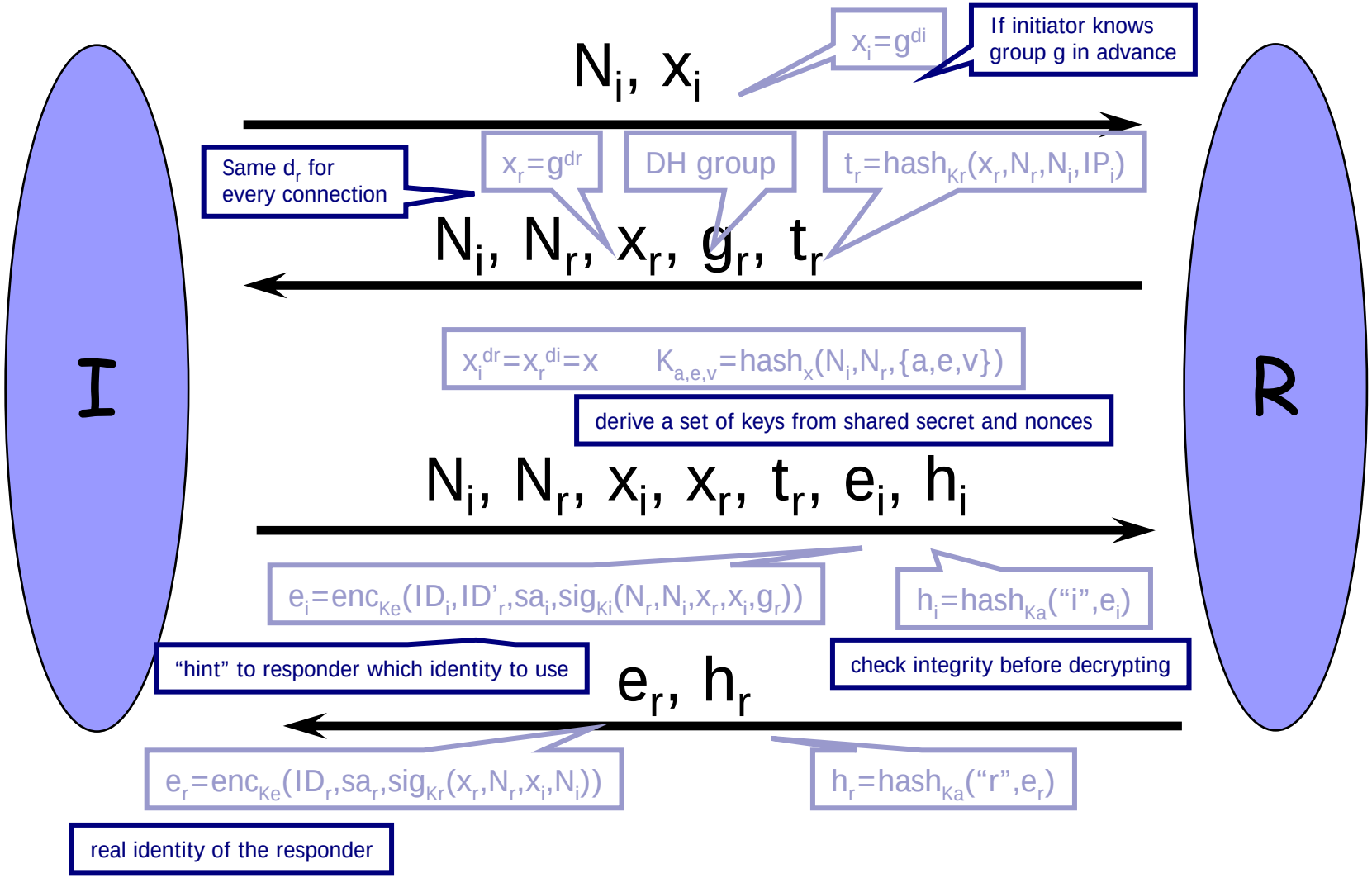
```
'((A (nonce a)
     (exp (nonce g) (nonce a))
     (exp (nonce g) (nonce b))
     (exp (nonce g) (mult (nonce a) (nonce b))))

  (B (nonce b)
     (exp (nonce g) (nonce a))
     (exp (nonce g) (nonce b))
     (exp (nonce g) (mult (nonce a) (nonce b))))

  (I (exp (nonce g) (nonce a))
     (exp (nonce g) (nonce b))))
```

Knowledge-state Attempt #2

```
‘( ;; I is for initiator
   (I (nonce x)
      (base g)
      (mod b)
      (term (mod (exp g y) b))))
   ;; R is for Responder
   (R (nonce y)
      (base g)
      (mod b)
      (term (mod (exp g x) b))))
   ;; N is for intruder
   (N (base g)
      (mod b)
      (term (mod (exp g x) b)))
      (term (mod (exp g y) b)))))
```

- The need to move forward preempted developing this more

Onto JFKr



[Aiello et al.] and Shmatikov

JFKr Properties

- Secrecy (via DH like key agreement)
- Prevention of DoS (via cookie)
- Forward secrecy (use of nonce for randomization)
- Authentication (public/private key signatures)
- ID Protection (ID not revealed until protocol nearing completion)

What I Did

- Executable model
- 1200 lines of ACL2 code
- Relatively low global constant usage

Capturing Perfect Cryptography

- First idea:
  - Make all knowledge broadcast in previous transmissions a constant > 100
  - Make all private knowledge < 100
  - Show that the attacker never gains something < 100

Capturing Perfect Cryptography

- Second idea:
  - Assign a probability threshold for what is acceptable
  - Requires tracking probability of a “crack” cumulatively
  - Could use to show mathematical weakness in encryption schemes

Capturing Perfect Cryptography

- Third idea:
  - Create generic functions “encapsulated” together with some other functions
  - These functions don’t begin with any definitions
  - Through instantiation of the function set, can prove that there exist functions that satisfy certain properties
  - Useful for specifying mysterious properties like keyed-hash and digital signatures
  - Can specify “perfect” encryption
- None of these ideas were actually used by me

Capturing Perfect Cryptography

- My Version:
  - Computed a hash of an integer list:

```
(defun compute-hash (int-list key acc)
  (if (atom int-list)
      acc
    (compute-hash (cdr int-list)
                  key
                  (* key (+ acc (car int-list))))))
```

  - Signatures similar
  - Symmetric keys modeled with one + key value
    - Encryption was an addition operation and decryption was a subtraction operation
  - Asymmetric keys modeled with +/- key values
    - Encryption and decryption were same
    - + for encryption
    - - for decryption

Main Function

- Uses “honest” participants
- Chose to make it an explicit calling of recursion instead of a case statement

```
(defun run-honest (network-s initiator-s responder-s)
  (mv-let
   (network-s-after-1 initiator-s-after-1)
   (step1-honest network-s initiator-s)

   (mv-let
    (network-s-after-2 responder-s-after-2)
    (step2-honest network-s-after-1 responder-s)

… left out part so it would fit …

      (mv-let
        (network-s-after-5 initiator-s-after-5)
        (step5-honest network-s-after-4 initiator-s-after-3)

        (mv-let
         (network-s-after-6 responder-s-after-6)
         (step6-honest network-s-after-5 responder-s-after-4)
         (mv network-s-after-6
             initiator-s-after-5
             responder-s-after-6))))))))
```

A Simple Honest Step Function

```
; doesn't matter who responder is
(defun step1-honest (network-s my-s); resp-s) ; doesn't matter who responder is
  (let* ((Ni (nonce-mine my-s))
         (Xi (compute-public-dh-value
              *g*
              (dh-exponent my-s)
              *b*))
         ;; updates are alists
         (network-update (list (cons 'Ni Ni)
                               (cons 'Xi Xi)
                               (cons 'Src-ip (ip my-s))))

         (my-update
          (list (cons 'cost-cpu (+ (cost-cpu my-s) 1))
                (cons 'cost-mem (+ (cost-mem my-s) 1))
                (cons 'public-dh-value-mine Xi)
                (cons 'role 'initiator))))

    (mv
     (acons 1 network-update network-s)
     (append my-update my-s))))
```

A Simple Dishonest Step Function

```
(defun step1-dishonest (network-s my-s) ; doesn't matter who responder is
  (let* ((Ni -1)
         (Xi -1)

         (Src-ip (ip my-s))

         ;; updates are alists
         (network-update (list (cons 'Ni Ni)
                               (cons 'Xi Xi)
                               (cons 'Src-ip Src-ip)))

         (my-update
          (list (cons 'cost-cpu (+ (cost-cpu my-s) 0))
                (cons 'cost-mem (+ (cost-mem my-s) 0)))))

    (mv
     (acons 1 network-update network-s)
     (append my-update my-s))))
```

A More Complex Step Function…

```
;; responder is processing and sending message
(defun step2-honest (network-s my-s)
  (let* ((Ni (ni-msg1 network-s))
         (Nr (nonce-mine my-s))
         (Src-ip (Src-ip-msg1 network-s))

         ;;(Xi (xi-msg1 network-s))

         (Xr (compute-public-dh-value *g* (dh-exponent my-s) *b*))

         (Gr *g*)

         (Tr (compute-hash (list Xr Nr Ni src-ip)
                           (private-key my-s)
                           0))
         (network-update
          (list (cons 'Ni Ni)
                (cons 'Nr Nr)
                (cons 'Xr Xr)
                (cons 'Gr Gr)
                (cons 'Tr Tr)
                (cons 'src-ip (ip my-s))))
         ;; no real update to my state, since I'm throwing it away - stateless
         (my-update
          (list (cons 'cost-cpu (+ (cost-cpu my-s) 2))
                (cons 'cost-mem (+ (cost-mem my-s) 0))
                (cons 'public-dh-value-mine Xr))))

         (mv
          (acons 2 network-update network-s)
          (append my-update my-s))))
```

Example

Script:

```
(defconst *initiator-beg-state*
  (list
   (cons 'nonce-mine *initiator-nonce*)
   (cons 'dh-exponent
         *initiator-dh-exponent*)
   (cons 'ip *initiator-ip*)
   (cons 'private-key *initiator-private-key*)
   (cons 'cost-cpu 0)
   (cons 'cost-mem 0)
   (cons 'id-mine *initiator-id*)
   (cons 'sa-mine *initiator-sa*)))

 (step1-honest nil *initiator-beg-state*)
```

RESULTS:

```
(((1 (NI . 200)
     (XI . 202942)
     (SRC-IP . 100001)))
 ((COST-CPU . 1)
  (COST-MEM . 1)
  (PUBLIC-DH-VALUE-MINE . 202942)
  (ROLE . INITIATOR)
  (NONCE-MINE . 200)
  (DH-EXPONENT . 5091)
  (IP . 100001)
  (PRIVATE-KEY . 12481)
  (COST-CPU . 0)
  (COST-MEM . 0)
  (ID-MINE . 50)
  (SA-MINE . 412)))
```

DOS Non-deterministic Function

```
(defun run-dos-interleaved (network-s initiator-s
                            responder-s)
  (mv-let
   (network-s-after-1 initiator-s-after-1)
   (if (evenp (random-int))
       (step1-dishonest network-s initiator-s)
     (step1-honest network-s initiator-s))

   (mv-let
    (network-s-after-2 responder-s-after-2)
    (step2-honest network-s-after-1 responder-s)
    (mv network-s-after-2 initiator-s-after-1
        responder-s-after-2))))
```

Mem DoS Thm

```
(defthm run-dos-interleaved-mem-safe-generic
  (implies (and (beginning-statep initiator-s)
                (beginning-statep responder-s))
           (mv-let (network init resp)
                   (run-dos-interleaved nil initiator-s responder-s)
                   (declare (ignore network))
                   (and (<= (cost-mem resp)
                            (cost-mem init)))))
  :hints (("Goal" :in-theory (disable
                              DH-EXPONENT
                              ID-MINE
                              IP
                              NONCE-MINE
                              PRIVATE-KEY
                              SA-MINE))))
```

Currently proves in 60 seconds.

Future Work

- Model man in the middle attack
- Form encapsulate functions for perfect encryption
- Prove termination of the protocol
- If JFKr terminates for both parties, then they agree on the key
- One party terminates iff the other party terminates

Conclusions

- Showed safety from memory DoS attacks
- Separation of actor states allows better inductive reasoning
- ACL2 proficiency increased

Resources

- Davis, Jared for ACL2 help.
- Kaufmann, Matt and Moore, J Strother. ACL2 FAQ. 2004.
- Levy, Benjamin (translator). Diffie-Helman Method for Key Agreement. 1997.
- Paulson, Lawrence C. Proving Properties by Induction. 1997.
- Shmatikov, Vitaly. Just Fast Keying. 2004.