Computationally Sound Mechanized Proof of PKINIT for Kerberos

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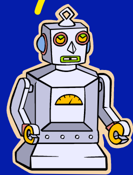
Context

Analysis of Cryptographic Protocols

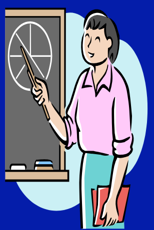


Mechanized Proofs

Symbolic/ Dolev-Yao

- Algebra of terms
- Good for checking protocol structure
- Limited adversary capabilities

Using strong Crypto



Academic Protocols

e.g.
- NSL
- Otway-Rees
- Yahalom

Computational

- Complexity theory
- Probability theory
- Strong security guarantees

Commercial Protocols

PKINIT

e.g.
- TLS
- Kerberos
- IKE

Hand proofs in Computational model prone to human error, and even in Dolev-Yao model highly time consuming for more complex protocols

Overview

- Formalization and Analysis of Kerberos 5 with and without its public-key extension (PKINIT) in "Public-Key mode" using the CryptoVerif tool
- First computationally sound mechanized proof of an industrial-sized protocol
  - PKINIT in particular is complex, involving both asymmetric and symmetric cryptographic primitives
  - Kerberos and PKINIT are available for all major operating systems, *e.g.*, implemented in Microsoft Windows (Vista/XP/2000) and Windows Server 2003.
- CryptoVerif tool works directly in the computational model
  - Previously tested only on *academic* protocols, *e.g.*, NSL, Otway-Rees, Yahalom
  - Our work provides evidence for the suitability of CryptoVerif for *industrial* protocols

Overview

- Authentication and security results proved using CryptoVerif
- Key usability
  - Define stronger version of IND-CCA2 usability that we can prove for Kerberos using CryptoVerif
  - Now exploring how to define INT-CTXT usability; what's the right approach?
- Part of an ongoing analysis of Kerberos 5 suite
  - Previously discovered a flaw in a draft version of PKINIT used in Windows (XP/2000) and Windows Server 2003
    - Joint work with Cervesato and Walstad
  - Previously conducted by-hand computational proofs of PKINIT and Kerberos
    - Joint work with Cervesato and Backes using the *Backes-Pfitzmann-Waidner model (BPW)*

Related Protocol Work

- [Butler, Cervesato, Jaggard, Scedrov,Walstad '02, '03, '06], [Cervesato, Jaggard, Scedrov, Tsay, Walstad '06]: Symbolic analysis of Kerberos (basic and public-key) using Multi Set Rewriting (Includes the attack on PKINIT draft version)
- [Backes, Cervesato, Jaggard, Scedrov, Tsay '06]: Computational Sound by-hand Proofs using the BPW model
- [He, Sundararajan, Datta, Derek, Mitchell '05]: By-hand symbolic correctness proof of IEEE 802.11i and TLS using Protocol Composition Logic
- [Roy, Datta, Derek, Mitchell '07]: By-hand correctness proof of Diffie-Hellman mode of PKINIT using Computational Protocol Composition Logic
- [Meadows '99] : Symbolic analysis of IETF IKE with NRL protocol analyzer
- [Bella, Paulson '97] / [Paulson '97]: Symbolic analysis with Isabelle theorem prover of Kerberos 4 / TLS

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Mechanized Prover Background

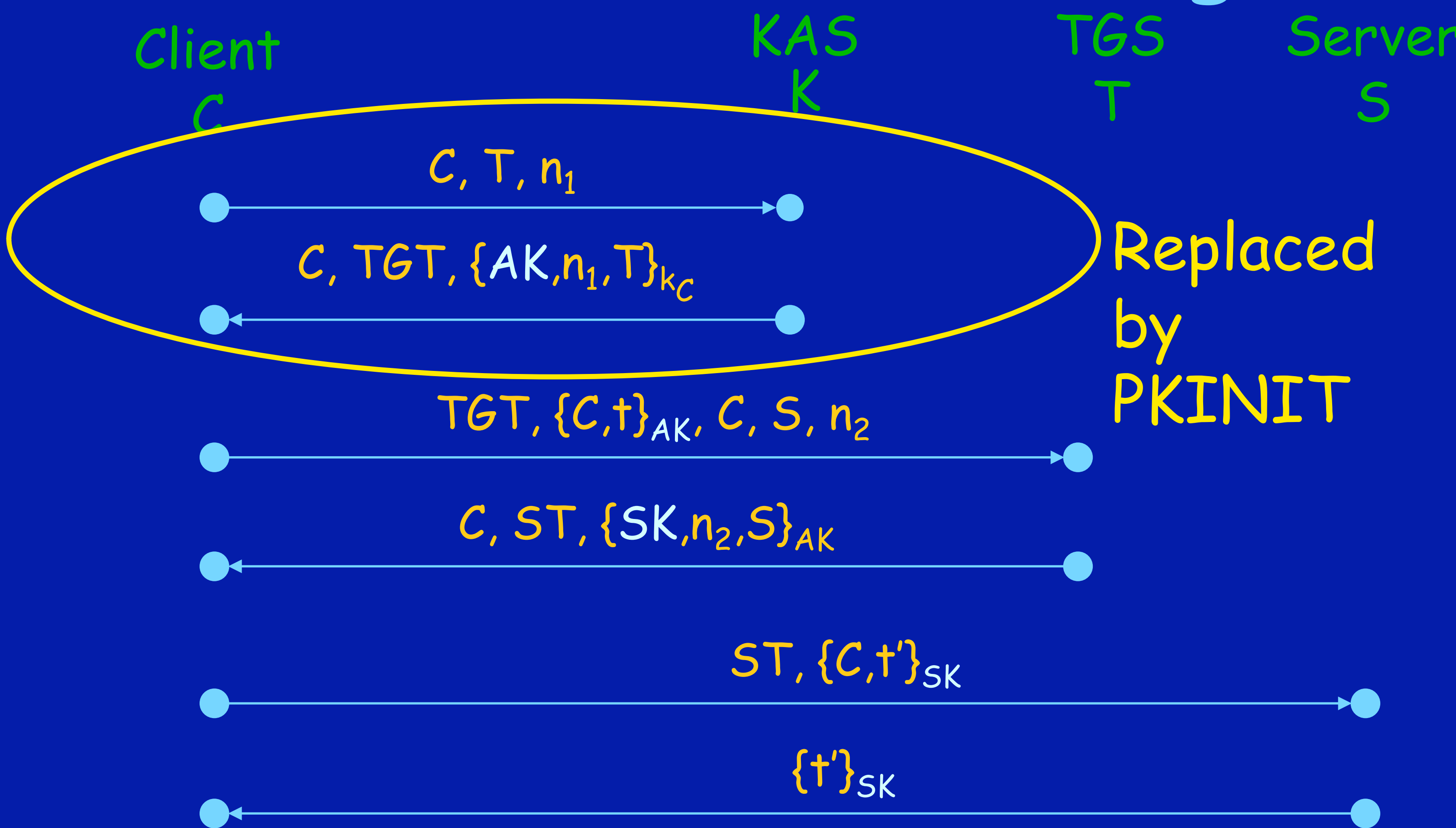
- [Blanchet'06,'07], [Blanchet, Pointcheval '06]: CryptoVerif; computationally sound mechanized prover
- [Backes, Basin, Pfitzmann, Sprenger, Waidner '06]: Beginnings of automation of BPW using Isabelle theorem prover
- [Armando,Basin,Boichut,Chevalier,Compagna,Cuellar,Hankes Drielsma,Heám,Kouchnarenko,Mantovani,Mödersheim, von Oheimb,Rusinowitch,Santiago,Turuani,Viganò,Vigneron '05]: AVISPA tool for automated symbolic validation of protocols and applications
- [Blanchet '04]: ProVerif; automatic Dolev-Yao verification tool
- [Cremers '06]: Scyther; automatic Dolev-Yao verification tool
- [Cortier, Warinschi '05]: Computationally sound, automated symbolic analysis using Casrul tool

…

Kerberos

- Goals
  - Repeatedly authenticate a client to multiple servers on single log-on
    - Remote login, file access, print spooler, email, directory, …
- A real world protocol
  - Part of Windows, Linux, Unix, Mac OS, …
  - Cable TV boxes, high availability server systems, …
  - Standardization and ongoing extension/refinement by IETF (very active --- 9 current RFCs, 8 drafts)
  - RFC 4120 (Kerberos 5), 4556 (PKINIT), …

Abstract Kerberos Messages



$TGT = \{AK, C, t_K\}_{k_T}$

$ST = \{SK, C, t_T\}_{k_S}$

Public-Key Kerberos

Client C → KAS K: $CertC, [t_C, n_2]_{skC}, C, T, n_1$

KAS K → Client C: $\{\{Cert_K, [k, ck]_{skK}\}\}_{pkC}, C, TGT, \{AK, n_1, T\}_k$

$TGT = \{AK, C, t_K\}_{k_T}$, $ck = Hash_k(CertC, [t_C, n_2]_{skC}, C, T, n_1)$

- Extend basic Kerberos 5 to use Public Keys
  - Change first round to avoid long-term shared keys (k_c)
- Motivations
  - Administrative convenience: Avoid the need to register shared key to use Kerberized services
  - Security: Avoid use of password-derived keys
    - Smartcard authentication support

Cryptographic Assumptions

- Public-key encryption assumed to be IND-CCA2, signature scheme assumed to be UF-CMA
- Symmetric encryption implemented as *encrypt-then-MAC*, with IND-CPA and INT-CTXT encryption and (W)UF-CMA message authentication code
  - This implies IND-CCA2 and INT-PTXT [Bellare, Namprempre'00]
- Hash function is collision resistant

Authentication (1, 2)

- Authentication in PKINIT
  - Whenever an honest client C finishes a PKINIT exchange with KAS K, after sending a request m1 and receiving a response $\{\{Cert_K, [k,ck]_{skCC}\}\}_{pkC}$, C, $\{AK,n_1,T\}_k$, (disregarding the MACS), the KAS K must have received m1 and sent $\{\{Cert_K, [k,ck]_{skCC}\}\}_{pkC}$, C, TGT, $\{AK,n_1,T\}_k$, (disregarding the MACS) with overwhelming probability
  - CryptoVerif proves authentication of K to C by proving the query:

```
query x:bitstring,y: bitstring, k:key;
event inj:fullC(K,k,x,y) ==> inj:fullK(C,k,x,y).
```

where x=m1, y= $\{\{Cert_K, [k,ck]_{skCC}\}\}_{pkC}$, C, $\{AK,n_1,T\}_k$ (without macs), and k=AK

Authentication

- We can show with CryptoVerif that the following hold with overwhelming probability for basic and public-key Kerberos:
  - Authentication (injective) of the KAS to the client
    - If an honest client receives what appears to be a valid reply from the KAS, then the KAS generated a reply for the client.
    - CryptoVerif proves the query:

```
query x:bitstring,y: bitstring, k:key;
 event inj:fullC(K,k,x,y) ==> inj:fullK(C,k,x,y).
```

where x=m1, y= $\{\{Cert_K, [k,ck]_{skCC}\}\}_{pkC}$, C, $\{AK,n_1,T\}_k$ (without macs), and k=AK

  - Authentication of request for ST
    - If an honest TGS processes a valid request for a service ticket ST, then the ticket in the request was generated by the KAS and the authenticator included in the request was generated by the client (modulo the MACs).

Authentication

- Again, with overwhelming probability for basic and public-key Kerberos:
  - Authentication (injective) of TGS to client
    - If an honest client sees what appears to be a valid reply to a request for a service ticket for an honest server S from an honest TGS, then the TGS generated a reply for the client.
  - Authentication of request to server
    - If an honest server S processes a valid request, ostensibly from an honest client C, that contains a service ticket ST and a session key pair (SK, mSK), then some honest TGS generated (SK, mSK) for C to use with S and also created ST (modulo the MAC). Furthermore, C created the authenticator (modulo the MAC).
  - Authentication of server to client
    - If an honest client C sees a valid reply from an honest server S, then this reply was generated by S (modulo the MAC).

Key Secrecy

- In both basic and public-key Kerberos, we have:
  - Secrecy of AK
    - If an honest client *C* finishes an AS exchange with the KAS, which generated the authentication key pair (AK, mAK) for use between *C* and an honest TGS, then AK and mAK are secret w.r.t. the *real-or-random* definition of secrecy.
  - Secrecy of SK
    - If an honest client finishes a TG exchange with an honest TGS, which generated the service key pair (SK, mSK) for use between *C* and an honest server *S*, then SK and mSK are secret with respect to the *real-or-random* definition of secrecy.

- These keys will be distinguishable from random once they are used for encryption in the subsequent requests

Subsession Key Secrecy

- The final round of Kerberos can be used by C and S to agree on a subsession key for further use
  - This key can be generated by either the client or the server
- CryptoVerif proves that both basic and public-key Kerberos preserve:
  - Secrecy of the key possessed by the party that generated the subsession key
  - One-session secrecy of the key possessed by the other party (of C, S)
  - Difference from possibility of replays
    - Party accepting (not generating) key might accept same key multiple times, allowing it to be distinguished from random
    - Current formalization lacks replay cache

Key Usability

- Notion of *key usability* introduced by Datta, Derek, Mitchell, and Warinschi [2006]
- Weaker than indistinguishability from random
  - Captures whether a key is still 'good' for future cryptographic operations
- Important for protocols that perform operations with a key during a run and allow future use of the key
- Definition parallels definition of key indistinguishability
  - Two-phase attacker (Ae, Ac): Ae interacts with protocol sessions, then Ac tries to win an attack game that uses the exchanged keys, *e.g.*, IND-CCA2 against an encryption scheme
  - During the second phase, Ac cannot interact with protocol sessions

Key Usability with CryptoVerif

- Stronger version of key usability (w.r.t. IND-CCA2 encryption), where adversary can still interact with uncompleted protocol sessions during the attack game:
  - Adversary A first interacts with polynomially many protocol sessions
  - A requests a session id to be drawn at random; let k be the key locally output in that session
  - A is given access to LR-encryption oracle Ek and a decryption oracle Dk corresponding to k
  - A plays a variant of the IND-CCA2 game where
    - A may interact with uncompleted protocol sessions
    - But all sessions do not accept ciphertexts output by Ek when they reach a point of the protocol at which at least one session expects to receive a message encrypted under k

Key Usability in Kerberos

- We can use CryptoVerif to prove
  - Usability of AK
    - If an honest client C finishes a session of basic or public-key Kerberos involving the KAS and an honest TGS, then the authentication key pair (AK, mAK) is (strongly) usable for IND-CCA2 secure encryption
  - Usability of SK
    - If an honest client C finishes a session of basic or public-key Kerberos involving the KAS, an honest TGS, and an honest server, then the session key pair (SK, mSK) is (strongly) usable for IND-CCA2 secure encryption

(Strong) INT-CTXT Usability

- Not previously defined
- How to define?
  - In standard INT-CTXT game, attacker tries to produce a valid ciphertext that was not generated by the encryption oracle
  - In the game for key usability, the attacker interacts with protocol sessions
    - If these include encryptions by protocol participants, the attacker can trivially win the game
    - This possibility highlighted by use of CryptoVerif
  - Currently check (strong) INT-CTXT usability of a session key k by having the decryption oracle refuse:
    - Ciphertexts produced by the encryption oracle
    - Ciphertexts produced by participants (using *any* session key)

(Strong) INT-CTXT Usability

- CryptoVerif can handle this definition
  - Is it the right one? (Seems reasonable)
- Proofs of INT-CTXT usability
  - Proofs of usability of AK and SK
  - These currently require some manual analysis
    - CryptoVerif produces games that include branches in which the attacker wins
    - Show that these branches can never be taken

Weakening Crypto

- Leak content of authenticators
  - $\{C,t\}_{AK}$, C, t instead of just $\{C,t\}_{AK}$
  - $\{C,t'\}_{SK}$, C, t' instead of just $\{C,t'\}_{SK}$
  - Suggested by examining by-hand proofs in Dolev-Yao model
- The authentication results still hold for both basic and public-key Kerberos
- The secrecy of the subsession key also still holds for both basic and public-key Kerberos
- Advantage of CryptoVerif---very fine control over crypto assumptions

CryptoVerif (1)

- Developed by Blanchet
- CryptoVerif (CV) can prove secrecy properties and correspondence asssertions for cryptographic protocols, and also cryptographic primitives
  - Secrecy w.r.t. real-or-random definition
  - Authentication through [injective] correspondence assertions [inj:] φ ==> [inj:] ψ
  - Proof of cryptographic primitives in the random oracle model
- CV works directly in the Computational Model
  - Protocols represented as processes in calculus inspired by pi-calculus, the calculi by [Lincoln,Mitchell,Ramanathan,Scedrov,Teague '98, '99, '02] and [Laud '05]; with probabilistic semantics
  - Processes Q and Q' are *observationally equivalent* (Q≈ Q') if, intuitively, an adversary has negligible probability of distinguishing Q from Q'

CryptoVerif (2)

- Proofs as sequences of games
  - Construct sequence Q_0, Q_1, … , Q_{n-1}, Q_n, where Q_0 formalizes the investigated protocol and desired security properties are obvious in Q_n
  - CV uses cryptographic and syntactic transformations to reach Q_j from Q_{j-1} and such that the new game is negligibly different from the old one
- Subtleties with crypto assumptions
- Note: CryptoVerif is sound but not complete
  - Properties it cannot prove are not necessarily invalid
  - CV operates in different modes:
    - Automatic mode (if only symmetric crypto is used)
    - Interactive mode (if public-key crypto is used)
      - Requires user to type in commands that determine the next game transformation

Summary

- Proof of authentication and secrecy properties of PKINIT using the tool CryptoVerif
  - Extended our Kerberos analysis project to include mechanized proofs
- First mechanized proof of authentication and secrecy for a commercial/real-life protocol directly in the computational model
  - CryptoVerif seems suitable for industrial protocols
- Stronger notions of usability
  - Working on right definition of INT-CTXT usability

Future work

- Finalize INT-CTXT key usability definitions and proofs
- Using weaker crypto
- Add more details from Kerberos RFCs
  - Adding lots of detail to key generation may cause games to explode
  - Diffie-Hellman mode of PKINIT
    - Mechanized proof in the computational model
      - Hand Proof exists in Computational PCL [Roy,Datta,Derek,Mitchell '07]
- Look for general results about usability and composability

Context (1)

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Computational

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Context (2)

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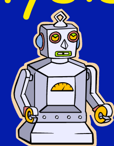

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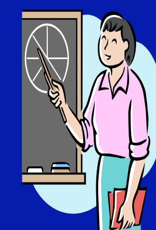

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- NSL
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Commercial Protocols

PKINIT

e.g.
- TLS
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Computational

- Complexity Theory
- Probability Theory