Software Quality and Infrastructure Protection for Diffuse Computing

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OPTION STARTED IN MAY 2004
The SPYCE Team

- Joan Feigenbaum (Yale)
- Joseph Y. Halpern (Cornell)
- Patrick D. Lincoln
- John C. Mitchell (Stanford)
- Andre Scedrov (U Penn)
- Jonathan M. Smith (U Penn) (until December 2003)
External Collaborators

- Cynthia Dwork (Microsoft)
- Tim Griffin (U Cambridge)
- Vitaly Shmatikov (U Texas)
- Paul Syverson (NRL)
Postdocs

- Björn Knutsson, Penn (till Spring 2005)
- Ninghui Li, Stanford (until Summer 2003, now at Purdue Univ.)
- Michael Elkin, Yale (Fall 2003 - Summer 2004, now at Ben Gurion Univ., Israel)
- Gergei Bana, Penn (Fall 2004 - Summer 2005)
- Anupam Datta, Stanford (starting in Fall 2005)

- 22 Ph.D. Students
URI Objective
Algorithms to model, manage and maintain a computational infrastructure, distributed among many heterogeneous nodes that do not trust each other completely and may have incentives (needs, priorities).

DoD Capabilities
Reduced cost, improved performance, and higher reliability for networked operations across untrusted networks

Scientific/Technical Approaches
Computing and networking elements diffusing into the environment need:
- Local incentive-compatibility in global distributed computing
- Scalable authorization mechanisms
- Assured communication
- Experimental evidence
Diffuse Computing

- Paradigm developing rapidly as a result of:
  - commercial computing markets
  - now-recognized potential of peer-to-peer computing and grid computing
  - the need for distributed network-centric systems

- Raises challenges for:
  - system design
  - software production
  - the development of mechanisms ensuring stable equilibria of diffuse systems
Breaking and Fixing Public-Key Kerberos

- Part of ongoing formal analysis of Kerberos 5 suite
  - Previously studied core part of protocol and cross-realm authentication
  - Focus on PKINIT, public-key extension to Kerberos
- Attack on PKINIT found when using “public-key mode” (one of two possible modes)
  - Breaks binding client’s request and the response
  - Prevents full authentication and confidentiality
- Formal verification of fixes preventing attack
  - Close, ongoing interactions with IETF Working Group
  www.microsoft.com/technet/security/bulletin/MS05-042.mspx
Attack and Fixes (Overview)

- Protocol level attack on PKINIT-25
  - Not a problem with crypto or implementation
  - Kerberos server believes he is talking to the attacker
  - Client believes she is talking to the Kerberos server
  - Attacker knows the key shared by the client and Kerberos server
- Possible because the Kerberos server does not sign data identifying the client
  - Attacker constructs request based on client's request
  - Kerberos server signs data from client, sends in reply to attacker
  - Attacker forwards this to client after learning keys
  - Ran Canetti, consulted on details of spec., independently hypothesized the possibility of an “identity misbinding” attack
- PKINIT-27 is intended to defend against this attack
  - Kerberos server signs data derived from client's identity
Consequences of the Attack

- The attacker knows the keys $C$ uses; she may:
  - Impersonate servers (in later rounds) to the client $C$
  - Monitor $C$'s communications with the end server

- Other notes
  - Attacker must be a legal user
  - $C$ is authenticated to end server as attacker (not as $C$)
  - The second key generation mode (Diffie-Hellman) appears to avoid the attack
    - DH mode narrowly deployed
    - Still need to prove formally security for DH
Kerberos Review

● Protocol goals
  - Repeatedly authenticate a client to multiple servers
  - Does not guard against DOS attacks

● Kerberos 4 - 1989

● Kerberos 5
  - Extensions under development in IETF WG

● A widely deployed protocol
  - Windows, MIT, Linux, Unix and OS X use MIT, CableLabs implementation for cable TV
  - User login, file access, printing, etc.
Basic Kerberos 5

- Authentication
  - Repeatedly authenticate a client to multiple servers
- Client $C$ wants ticket for end server $S$
  - Tickets are encrypted – unreadable by $C$
- $C$ first obtains long term (e.g., 1 day) ticket from a Kerberos Authentication Server $K$
  - Makes use of $C$'s long-term shared symmetric key
- $C$ then obtains short term (e.g., 5 min.) ticket from a Ticket Granting Server $T$
  - Based on long term ticket from $K$
  - $C$ sends this ticket to $S$
Public-Key Kerberos

- Extend basic Kerberos 5 to use PKI
  - Change first round to avoid long-term shared keys
  - Originally motivated by security
    - If Kerberos server is compromised, don't need to regenerate shared keys
    - Avoid use of password-derived keys
  - Current emphasis on administrative convenience
    - Avoid the need to register in advance of using Kerberized services
- This extension is called PKINIT
  - Current version is PKINIT-28
  - We found attack in -25; -26 does not change the relevant design
  - Versions included in Windows and Linux (called Heimdal)
  - Implementation developed by CableLabs (for cable boxes)
  - Apparently not in MIT version
Two Modes

- In general, no key $k_c$ shared between $C$ and $K$
  - Credentials for $C$ instead encrypted under a temporary key $k$
    - How to generate and deliver $k$?
- Public-key encryption
  - $k$ is generated by $K$
  - $k$ encrypted under $C$'s public key and is signed by $K$
  - Attack is against this mode
- Diffie-Hellman
  - $k$ is generated by DH using data from $C$ and $K$
  - $C$ and $K$ each send signed data to contribute to DH key
    - Option for 'reuse' of the shared secret
  - CableLabs appears to be only implementation of this
  - Initial inspection did not turn up attacks against this mode
Public-Key Encryption Mode

1. \( t, n_2, \text{Cert}_C, [t, n_2]_{sk_C}, C, T, n_1 \)

2. \( \{\text{Cert}_K, k, n_2, [k, n_2]_{sk_K}\}_pk_C, C, \{k_{CT, C}\}_{k_T}, \{k_{CT, n_1, T}\}_k \)

3. \( \{k_{CT, C}\}_{k_T}, \{C\}_{k_{CT}}, C, S, n_3 \)

4. \( C, \{k_{CS, C}\}_{k_S}, \{k_{CS, n_3, S}\}_{k_{CT}} \)

5. \( \{k_{CS, C}\}_{k_S}, \{C, t\}_{k_{CS}} \)

6. \( \{t\}_{k_{CS}} \)
The Attack

At time $t_c$, client $C$ requests a ticket for ticket server $T$ (using nonces $n_1$ and $n_2$):

$C \xrightarrow{t_c, n_2, Cert_C, [t_c, n_2]_{skC}, C, T, n_1} I$

The attacker $I$ intercepts this, puts her name/signature in place of $C$'s:

$I \xrightarrow{t_c, n_2, Cert_I, [t_c, n_2]_{skI}, I, T, n_1} K$

Kerberos server $K$ replies with credentials for $I$, including: fresh keys $k$ and $AK$, a ticket-granting ticket $X$, and $K$'s signature over $k, n_2$:

(Ignore most of enc-part)

$I \xrightarrow{\{k, n_2, [k, n_2]_{skK}\}_{pkI}, I, X, \{AK, \ldots\}_{k}} K$

$I$ decrypts, re-encrypts with $C$'s public key, and replaces her name with $C$'s:

$C \xleftarrow{\{k, n_2, [k, n_2]_{skK}\}_{pkC}, C, X, \{AK, \ldots\}_{k}} I$

- $I$ knows fresh keys $k$ and $AK$
- $C$ receives $K$'s signature over $k, n_2$ and assumes $k, AK, \ldots$, were generated for $C$ (not $I$)
- Principal $P$ has secret key $sk_P$, public key $pk_P$
- $\{msg\}_{key}$ is encryption of $msg$ with key
- $[msg]_{key}$ is signature over $msg$ with key
Real-World Impact

- Our work cited in August 2005 Microsoft security bulletin
  www.microsoft.com/technet/security/bulletin/MS05-042.mspx

- Although other vulnerabilities viewed as more pressing for IT managers, this attack has real-world effects and highlights a design vulnerability
  - Remote code execution, privilege elevation seem to arise from coding errors, not design flaws
  - No known exploit using our attack
Interactions with IETF

- Close collaboration with IETF Kerberos WG
  - Discussed possible fixes we were considering
  - Attack announced on WG list in July 2005
  - We verified a fix the WG suggested
    - This was incorporated into PKINIT-27
  - Presented this work at IETF-63
    - Discussed possible fixes and our analysis of these
    - Useful discussions with WG participants on other areas for work
  - Participating in WG meetings in Sept. and Nov. 2005

- Impact of formal methods in IETF security area
  - At security-area level, they want to see more interaction with formal methods
Software Quality and Infrastructure Protection for Diffuse Computing
U Penn, Stanford, Cornell, Yale

URI, May 2001  Email: scedrov@math.upenn.edu  WWW:  http://www.cis.upenn.edu/spyce  Nov. 10, 2005

Scientific Accomplishments
• Interdomain routing
  Path vector protocols  [Penn-Yale-Intel]
  Local conditions for stable routes  [Yale]
• Analysis of cryptographic protocols
  Formal methods for cryptography  [Penn-Stanford]
  Kerberos 5 analysis  [Penn-NRL]
• Logic for reasoning about policies  [Cornell]
• SPAM reduction algorithms  [Microsoft-Stanford]
• Privacy in databases  [SRI-Microsoft]
• Anonymity and information hiding  [Cornell-NRL]
• Content transcoding for heterogeneous clients  [Penn]
• Flexible Lightweight Active Measuring Environment  [Penn]

Educational Accomplishments
• Enhanced the ability to educate and train students in science and engineering and perform CIP/SW relevant research
  • 14 refereed journal publications
  • 65 refereed conference proceedings
  • 5 prototypes
  • 14 PhD students graduated, 22 PhD students supported

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Spyce Interaction Graph

- Protocol Analysis
- Formal Methods for Cryptography
- Anonymity
- Privacy
- Algorithmic Mech Design
- Authorization
- Decision Theory
- Networking
- Digital Rights
Recent SPYCE Dissertations

- **Stanford**
  - Ajith Ramanathan, Anupam Datta, Vanessa Teague

- **Penn**
  - Kostas Anagnostakis, Gergei Bana
  - MA Thesis: Jennifer Strong

- **Yale**
  - Vijay Ramachandran, Jian Zhang

- **Cornell**
  - Riccardo Pucella, Vicky Weissman
Today

- Impossibility result in cryptography
  - Anupam Datta, Stanford

- Policy languages and reasoning about policies
  - Vicky Weissman, Cornell

- Networking
  - Vijay Ramachandran, Yale