CS 259

Security Analysis of Network Protocols

John Mitchell
Stanford

Vitaly Shmatikov
SRI

http://www.stanford.edu/class/cs259/

Course organization

- Lectures
  - Tues, Thurs for approx first six weeks of quarter
  - Project presentations last three weeks
- This is a project course
  - There may be one or two short homeworks
  - Most of your work will be project and presentation

Please enroll!

Computer Security

- Cryptography
  - Encryption, signatures, cryptographic hash, …
- Security mechanisms
  - Access control policy
  - Network protocols
- Implementation
  - Cryptographic library
  - Code implementing mechanisms
    - Reference monitor and TCB
    - Protocol
  - Runs under OS, uses program library, network protocol stack

Analyze protocols, assuming crypto, implementation, OS correct

Cryptographic Protocols

- Two or more parties
- Communication over insecure network
- Cryptography used to achieve goal
  - Exchange secret keys
  - Verify identity (authentication)

Class poll:
Public-key encryption, symmetric-key encryption, CBC, hash, signature, key generation, random-number generators

Correctness vs Security

- Program or System Correctness
  - Program satisfies specification
    - For reasonable input, get reasonable output
- Program or System Security
  - Program properties preserved in face of attack
    - For unreasonable input, output not completely disastrous
- Main differences
  - Active interference from adversary
  - Refinement techniques may fail

Security Analysis

- Model system
- Model adversary
- Identify security properties
- See if properties preserved under attack
- Result
  - No "absolute security"
  - Security means: under given assumptions about system, no attack of a certain form will destroy specified properties.

Important Modeling Decisions

- How powerful is the adversary?
  - Simple replay of previous messages
  - Block messages; Decompose, reassemble and resend
  - Statistical analysis, partial info from network traffic
  - Timing attacks
- How much detail in underlying data types?
  - Plaintext, ciphertext and keys
    - atomic data or bit sequences
  - Encryption and hash functions
    - "perfect" cryptography
    - algebraic properties: encr(x*y) = encr(x) * encr(y) for RSA encrypt(k,msg) = msg^k mod N

This has been our research area

- Automated nondeterministic finite-state analysis
  - General paper, Oakland conference, 1997 [JM, …]
  - Efficiency for large state spaces, 1998 [VS, …]
  - Analysis of SSL, 1998-99 [VS, JM, …]
  - Analysis of fair exchange protocols, 2000 [VS, JM, …]
- Automated probabilistic analysis
  - Analysis of probabilistic contract signing, 2004 [VS, …]
  - Analysis of an anonymity system, 2004 [VS, …]
- Beyond finite-state analysis
  - Decision procedures for unbounded # of runs
  - Proof methods, assuming idealized cryptography
  - Beyond idealized cryptography

Many others have worked on these topics too …

Some other projects and tools

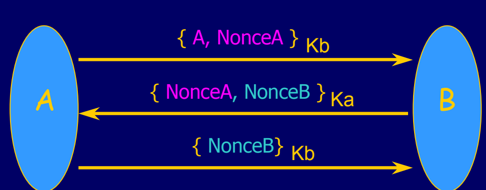
- Exhaustive finite-state analysis
  - FDR, based on CSP [Lowe, Roscoe, Schneider, …]
- Search using symbolic representation of states
  - Meadows: NRL Analyzer, Millen: Interrogator
- Prove protocol correct
  - Paulson's "Inductive method", others in HOL, PVS, …
  - MITRE -- Strand spaces
  - Process calculus approach: Abadi-Gordon spi-calculus, applied pi-calculus, …
  - Type-checking method: Gordon and Jeffreys, …

Many more – this is just a small sample

Example: Needham-Schroeder

- Famous simple example
  - Protocol published and known for 10 years
  - Gavin Lowe discovered unintended property while preparing formal analysis using FDR system
- Background: Public-key cryptography
  - Every agent A has
    - Public encryption key Ka
    - Private decryption key Ka^{-1}
  - Main properties
    - Everyone can encrypt message to A
    - Only A can decrypt these messages

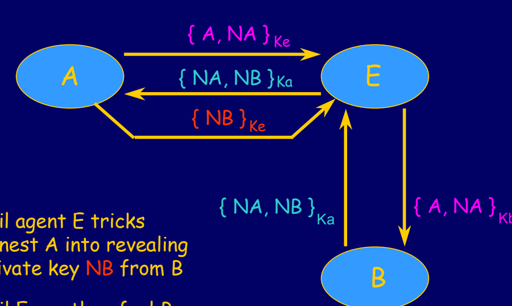
Needham-Schroeder Key Exchange



Result: A and B share two private numbers not known to any observer without Ka^{-1}, Kb^{-1}

Anomaly in Needham-Schroeder

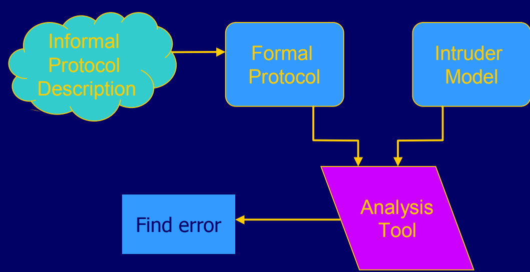
[Lowe]



Evil agent E tricks honest A into revealing private key NB from B

Evil E can then fool B

Explicit Intruder Method



Murφ [Dill et al.]

- Describe finite-state system
  - State variables with initial values
  - Transition rules
  - Communication by shared variables
- Scalable: choose system size parameters
- Automatic exhaustive state enumeration
  - Space limit: hash table to avoid repeating states
- Research and industrial protocol verification

Finite-state methods

- Two sources of infinite behavior
  - Many instances of participants, multiple runs
  - Message space or data space may be infinite
- Finite approximation
  - Assume finite participants
    - Example: 2 clients, 2 servers
  - Assume finite message space
    - Represent random numbers by r1, r2, r3, …
    - Do not allow encrypt(encrypt(encrypt(…)))

Verification vs Error Detection

- Verification
  - Model system and attacker
  - Prove security properties
- Error detection
  - Model system and attacker
  - Find attacks

Applying Murφ to security protocols

- Formulate protocol
- Add adversary
  - Control over "network" (shared variables)
  - Possible actions
    - Intercept any message
    - Remember parts of messages
    - Generate new messages, using observed data and initial knowledge (e.g. public keys)

Needham-Schroeder in Murφ (1)

```
const
  NumInitiators:  1;   -- number of initiators
  NumResponders:  1;   -- number of responders
  NumIntruders:   1;   -- number of intruders
  NetworkSize:    1;   -- max. outstanding msgs in network
  MaxKnowledge:  10;   -- number msgs intruder can remember

type
  InitiatorId:  scalarset (NumInitiators);
  ResponderId:  scalarset (NumResponders);
  IntruderId:   scalarset (NumIntruders);

  AgentId:   union {InitiatorId, ResponderId, IntruderId};
```

Needham-Schroeder in Murφ (2)

```
MessageType : enum {        -- types of messages
  M_NonceAddress,           --  {Na, A}Kb  nonce and addr
  M_NonceNonce,             --  {Na,Nb}Ka  two nonces
  M_Nonce                   --  {Nb}Kb     one nonce
};

Message : record
    source:   AgentId;       -- source of message
    dest:     AgentId;       -- intended destination of msg
    key:      AgentId;       -- key used for encryption
    mType:    MessageType;   -- type of message
    nonce1:   AgentId;       -- nonce1
    nonce2:   AgentId;       -- nonce2 OR sender id OR empty
end;
```

Needham-Schroeder in Murφ (3)

```
-- intruder i sends recorded message
ruleset i: IntruderId do            -- arbitrary choice of
  choose j: int[i].messages do        --  recorded message
    ruleset k: AgentId do             --  destination
      rule "intruder sends recorded message"
        !ismember(k, IntruderId) &     -- not to intruders
        multisetcount (l:net, true) < NetworkSize
      ==>
       var  outM: Message;
       begin
          outM        := int[i].messages[j];
          outM.source := i;
          outM.dest   := k;
          multisetadd (outM,net);
end; end; end; end;
```

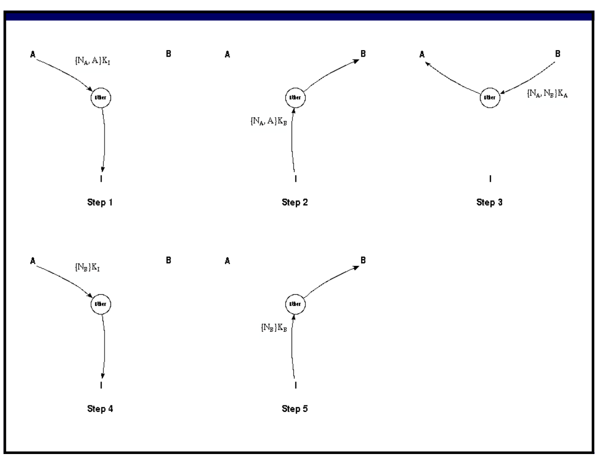
Adversary Model

- Formalize "knowledge"
  - initial data
  - observed message fields
  - results of simple computations
- Optimization
  - only generate messages that others read
  - time-consuming to hand simplify
- Possibility: automatic generation

Run of Needham-Schroeder

- Find error after 1.7 seconds exploration
- Output: trace leading to error state
- Murφ times after correcting error:

number of			size of		
ini.	res.	int.	network	states	time
1	1	1	1	1706	3.1s
1	1	1	2	40 207	82.2s
2	1	1	1	17 277	43.1s
2	2	1	1	514 550	5761.1s



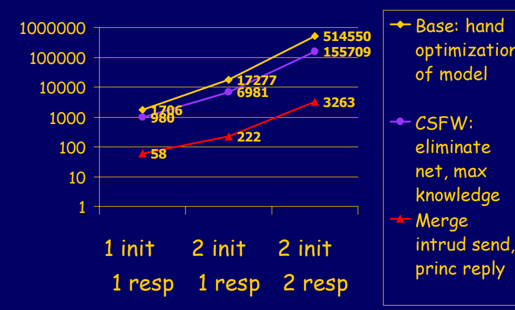
Limitations

- System size with current methods
  - 2-6 participants
    - Kerberos: 2 clients, 2 servers, 1 KDC, 1 TGS
  - 3-6 steps in protocol
  - May need to optimize adversary
- Adversary model
  - Cannot model randomized attack
  - Do not model adversary running time

Security Protocols in Murφ

- Standard "benchmark" protocols
  - Needham-Schroeder, TMN, …
  - Kerberos
- Study of Secure Sockets Layer (SSL)
  - Versions 2.0 and 3.0 of handshake protocol
  - Include protocol resumption
- Tool optimization
- Additional protocols
  - Contract-signing
  - Wireless networking
  - … ADD YOUR PROJECT HERE …

State Reduction on N-S Protocol



Plan for this course

- Protocols
  - Authentication, key establishment, assembling protocols together (TLS ?), fairness exchange, …
- Tools
  - Finite-state and probabilistic model checking, constraint-solving, process calculus, temporal logic, proof systems, game theory, polynomial time …
- Projects
  - Choose a protocol or other security mechanism
  - Choose a tool or method and carry out analysis
  - Hard part: formulating security requirements

Reference Material (CS259 web site)

- Protocols
  - Clarke-Jacob survey
  - Use Google; learn to read an RFC
- Tools
  - Murphi
    - Finite-state tool developed by David Dill's group at Stanford
  - PRISM
    - Probabilistic model checker, University of Birmingham
  - MOCHA
    - Alur and Henzinger; now consortium
  - Constraint solver using prolog
    - Shmatikov and Millen
  - Isabelle
    - Theorem prover developed by Larry Paulson in Cambridge, UK
    - A number of case studies available on line

Hope you enjoy the course

- We'll lecture for a few weeks to get started
  - Case studies are the best way to learn this topic
  - Cathy Meadows guest lecture next Thursday
- Choose a project that interests you !!!
  - If you have another idea, come talk with us
  - Can build or extend a tool, or paper study if you prefer

Protocols and other mechanisms

- Secure electronic transactions (SET) or other e-commerce protocols
- Onion routing or other privacy mechanism
- Firewall policies
- Electronic voting protocols
- Publius: censorship-resistant Web publishing
- Group key distribution protocols
- Census protocols
- Stream signing protocols:
- Analysis/verification/defense against MCI's network routing scam
  - Apparently, MCI routed long-distance phone calls through small local companies and Canada to avoid paying access charges to local carriers)
- Wireless networking protocols