APPLYING FORMAL METHODS TO CRYPTOGRAPHIC PROTOCOL ANALYSIS

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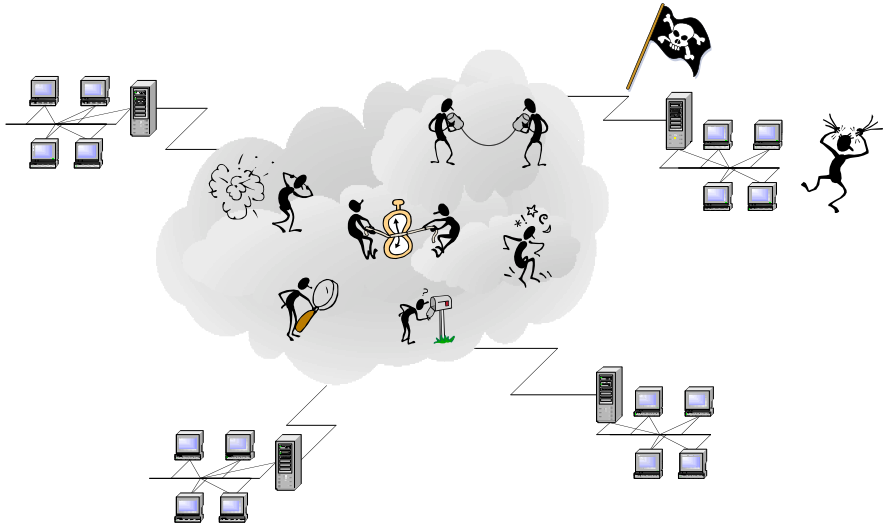
OVERVIEW OF TALKS

- **Background: What are cryptographic protocols, and why should we be interested in them?**
- **Short history of application of formal methods to cryptographic protocol analysis**
- **In-depth look at**
  - **Use of invariants in crypto protocol analysis**
  - **Formulation of requirements for crypto protocols**
- **Discussion of what I see as emerging issues**
  - **Will concentrate on issues raised by applications rather than the theoretical issues**

WHAT IS A CRYPTOGRAPHIC PROTOCOL?

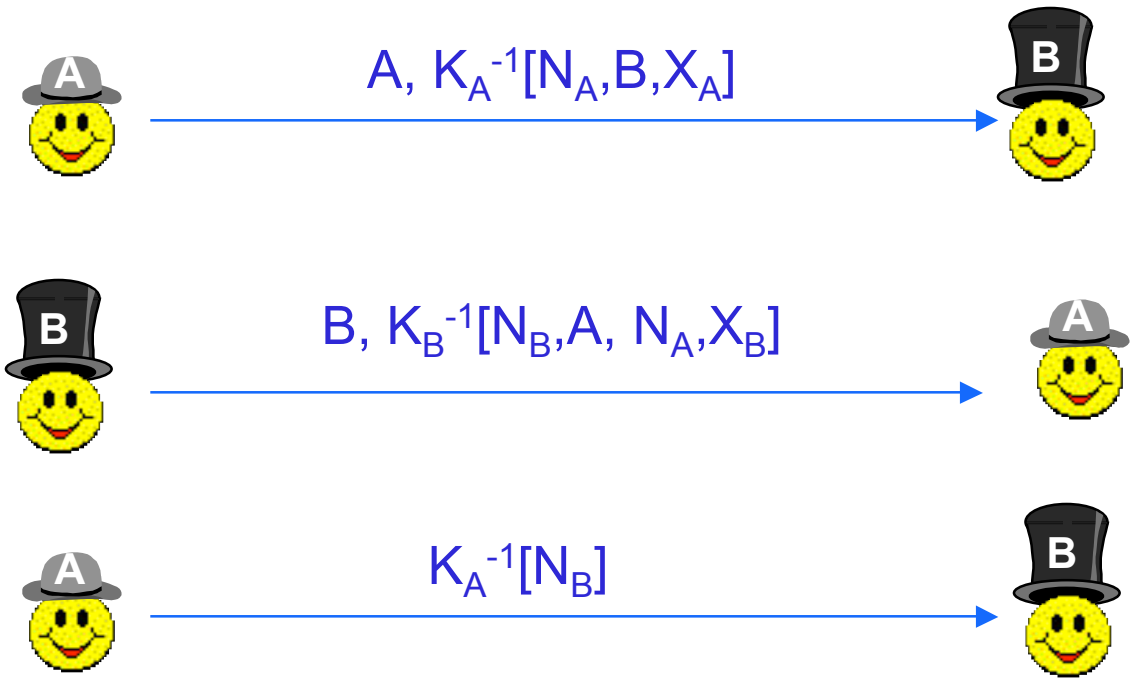


- Communication protocol that uses encryption to:
  - **Distribute keys**
  - **Authenticate principals**
  - **Process transactions securely**
- Must operate in hostile environment in which traffic may be intercepted, altered or destroyed

EXAMPLE: CCITT DRAFT STANDARD X.509 (1987)

- A and B want to verify origin and recency of messages
- Protocol uses public key crypto
  - A and B possess public keys K_A and K_B, private keys K_A^{-1} and K_B^{-1}
  - Anyone can send $K_A[X]$ to A, only A can read X
  - If A sends $K_A^{-1}[X]$, anyone can compute $K_A[K_A^{-1}[X]] = X$ and verify X came from A
- A and B both have the capacity to generate nonces
  - If B receives $K_A^{-1}[X,N]$, where N is a nonce previously sent by B, B knows A sent message after B sent nonce

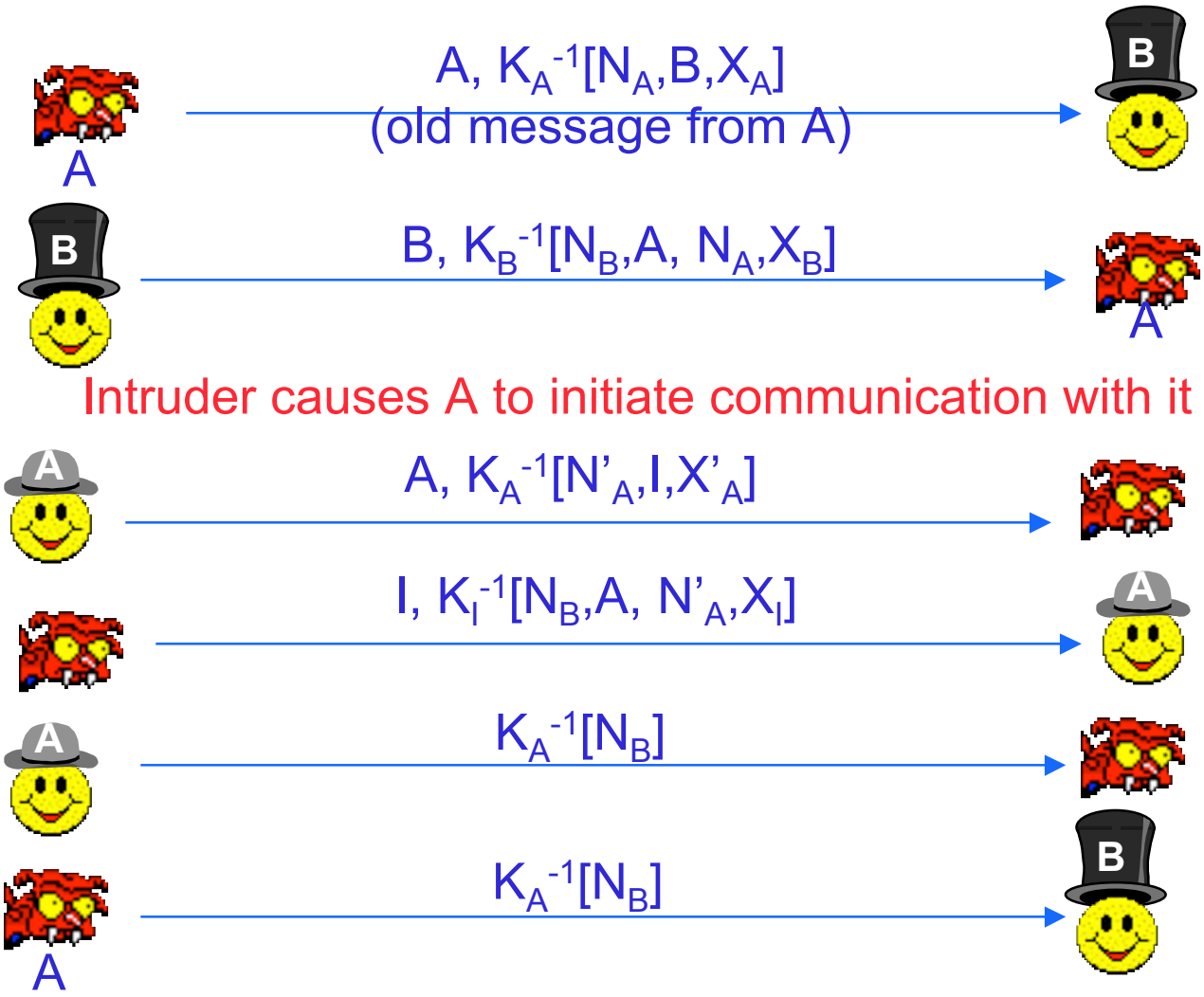
THE PROTOCOL (simplified)



Third message appears to be linked to second by N_B
Second message appears to be linked to first by N_A

Is this enough?

NO! (Burrows, Abadi, Needham, 1989)



A HIERARCHY OF CRYPTO PROTOCOL MODELS

Logics of knowledge and belief

- No concrete model of intruder
- Describes what can be deduced by honest principals from a successful protocol run

"Dolev-Yao" model

- Concrete model of adversary
  - Adversary restricted to (possibly arbitrary set of) fixed set of operations
  - Adversary able to intercept traffic, etc.

Complexity-theoretic models

- Reduce breaking the protocol to solving a computationally hard problem
  - May or may not be able to intercept traffic, etc.
- Adversary restricted to computations done in polynomial time
- Random oracle model special case - appears to integrate well with Dolev-Yao model

Information-theoretic models

- Adversary assumed to have infinite computational power
  - May or may not be able to intercept traffic, etc.

FIRST MENTION OF FORMAL METHODS FOR CRYPTO PROTOCOL ANALYSIS - 1978

- **Needham & Schroeder -- "Using encryption for authentication in large networks of computers," CACM, 1978**
  - **Early protocols for key distribution and authentication**
  - **Mention as an aside that formal methods could be useful for assuring correctness**

DOLEV-YAO (IEEE Trans Info Theory, 1983)
DOLEV-EVEN & KARP (Info & Control, 1982)

- Assume that cryptoalgorithms obey a certain set of algebraic identities
- Assume an intruder who can
  - read all traffic
  - modify, delete and create traffic
  - perform cryptographic operations available to legitimate users of the system
  - is in league with a subset of "corrupt" nodes
- Assume an arbitrary number of nodes
- Assume an arbitrary number of protocol executions
- Assume that protocol executions may be interleaved
- Allows us to consider the protocol as an algebraic system operated by the intruder

With some modifications, this is the most commonly used model today for formal methods analyses of crypto protocols

PING-PONG PROTOCOLS

- Small number of operations
  - Public key encryption and decryption
  - Namestamps
- Action of a party on receiving a message is to apply some sequence of operations to it and send it back out
- Message sent back and forth like a ping-pong ball, hence the name
- Dolev-Yao, Dolev, Even & Karp, and later others, found algorithms for determining whether a protocol would reveal secrets to an intruder
  - Found to be related to problem of finding intersection of two formal languages
  - Freshness issues (e.g. replay) were not considered

EXAMPLES OF INSECURE PING-PONG PROTOCOLS

- A -> B: $E_B(M)$
- B -> A: EA(M)

Z intercepts message as passes it off as own

- B -> Z : EZ(M) Z leans M

Introduce namestamps:

- A -> B: EB(MA)
- B -> A: EA(M)

Possible to show that this protocol secure in the sense that Z does not learn M unless A wants it to

A SIMILAR, BUT INSECURE PROTOCOL

- A -> B: $E_B(E_B(M)A)$
- B -> A: $E_A(M)$

Attack

- A -> B: $E_B(E_B(M)A)$
- Z -> B : $E_B(E_B(E_B(M)A)Z)$
- B -> Z: $E_Z(E_B(M)A)$
- Z -> B: $E_B(E_B(M)Z)$
- B -> Z: $E_Z(M)$
- Z decrypts M

MODEL AND ASSUMPTIONS

- For every legitimate user X of the network, 4 ops
  - E_X (pk encryption)
  - D_X (pk decryption)
  - I_X (attach name)
  - R_X (reading and removing name)
- Anyone can perform, E_X, I_X,R_X, only X can do D_X
- Operators obey reduction rules:
  - $E_X D_X = D_X E_X = I_X R_X = R_X I_X$ = identity
- Operators, together with cancellation rules, obey Church-Rosser property
  - No matter which order the cancellations performed, always get the same answer

DEFINITION OF A PING-PONG PROTOCOL

- **Abstract away from original message: only deal with operators**
- **A ping-pong protocol P(S,R) is a sequence of operator words a1, …, an such that**
  - **If i odd ai is in vocabulary of S**
  - **If i even ai is in vocabulary of R**
- **EXAMPLE: Protocol 2**
  - **A -> B: $E_B(M_A)$ becomes a1(A,B) = $E_B I_A$**
  - **B -> A: $E_A(M)$ becomes a2(A,B) = $E_A R_A D_B$**

CAPABILITIES OF INTRUDER

- Think of protocol as machine operated by Z
  - Z sees all traffic
  - Any message honest user receives is from Z
    - Even if Z only passed message along from another honest user
- What is Z's vocabulary?
  - Operations available to Z
  - EX, IX, RX, for any X, and DZ
  - ai(X,Y) for i > 1 and any two different X,Y
    - Wait for principal to be ready to execute ai, and feed it word already known by Z as message to operate on
- Can now reason about protocol in terms of algebra manipulated by Z

WHAT HAVE WE LEARNED HERE?

- **Possible to abstract away from original protocol model to one that treats protocol as maching operated by intruder**
- **Possible to reason about machine in exhaustive way so that even nonintuitive attacks ruled out**

WHAT'S MISSING FROM THE MODEL

- Other operators, such as
  - Concatenation
  - single-key encryption
  - Digital signatures
- Other data types, such as
  - Nonces
  - timestamps
- Requirements other than secrecy, such as
  - Authentication
  - Replay prevention
- Other intruder capabilities, such as
  - Compromise of keys, etc.
- Unfortunately, difficult to keep problem from becoming undecideable

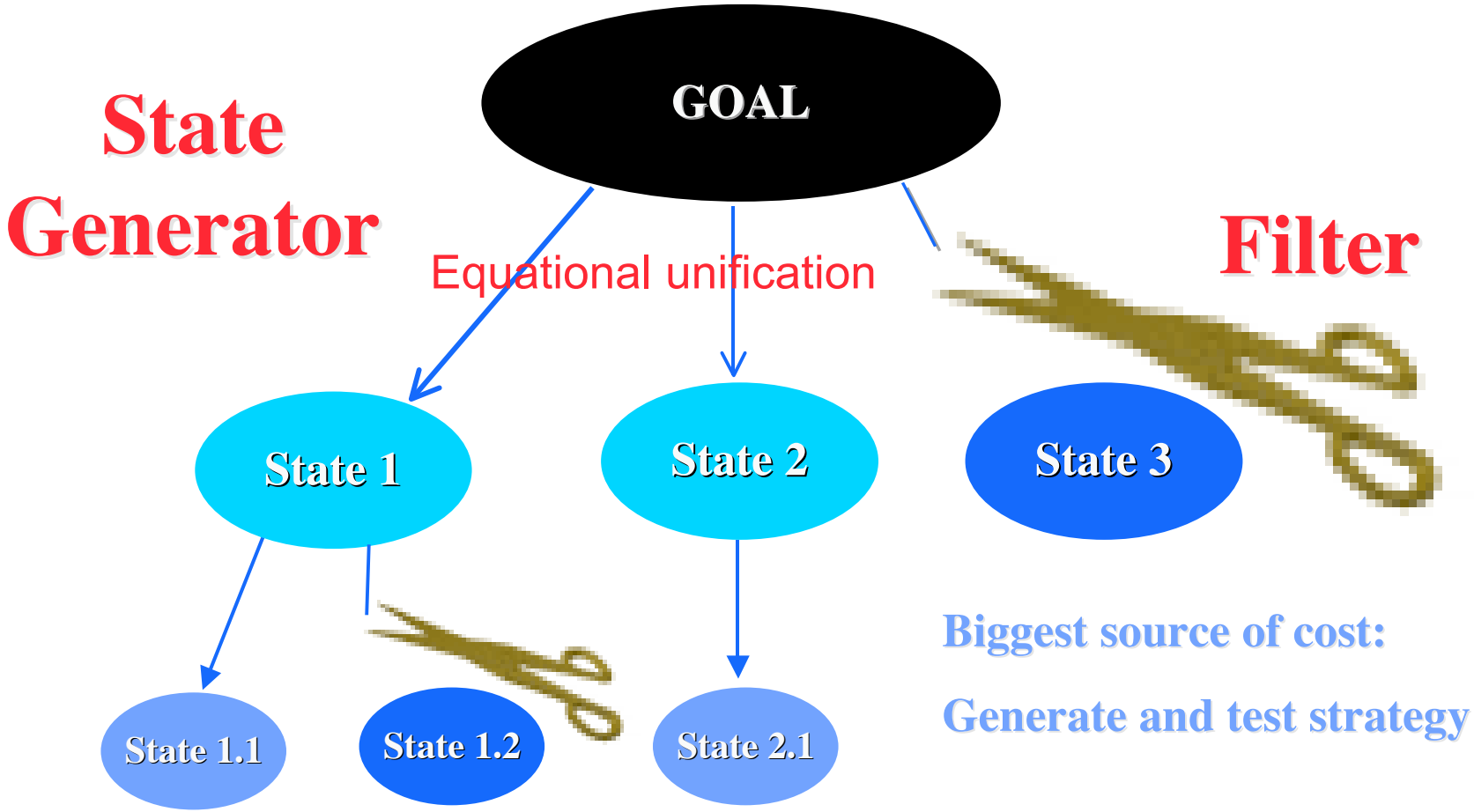
EARLY STATE EXPLORATION TOOLS

- **Interrogator (Millen, earliest version 1984)**
  - **First to automate intruder**
  - **Earliest version similar to a finite state model-checker**
    - **Searched finite number of rounds to find attack**
- **Ina Test (Kemmerer, 1987)**
  - **General-purpose symbolic execution tool, could be used to reproduce attacks**
- **NRL Protocol Analyzer (Meadows, earliest version 1989)**
  - **Automated intruder in a way similar to Interrogator**
    - **Implemented full Dolev-Yao model**
  - **Used symbolic representation of states, and supported use of lemmas to reduce infinite state space to finite one**
  - **In earliest version, lemmas proved by hand, later offered automated support**

NRL PROTOCOL ANALYZER

- A formal methods tool for the analysis of crypto protocols
- Uses standard Dolev-Yao model of intruder
- User specifies insecure state using a combination of constants and existentially quantified variables
  - NPA works backwards from state to determine if there is a path to it
  - May make substitutions to the variables as it goes
- Uses rewrite rules to specify properties of cryptosystems
  - Narrowing to match up rule outputs with state description
- Search space is initially infinite
  - User may prove a set of lemmas to cut down search space size
  - When a state is generated, lemmas are used to determine whether it should be kept or discarded

HOW NPA EXPLORES STATE SPACE



EXAMPLE

- **Rewrite rules:**

  pke(pubkey(U),pke(privkey(U),X)) --> X

  pke(privkey(U),pke(pubkey(U),X)) --> X

- **Rule for signing**

  If receive message X, then produce message pke(privkey(server),X)

- **Try and find state in which intruder knows word Y**
- **First result: Y = pke(privkey(server),X), intruder needs to know X**
- **Second result:**

  X = pke(pubkey(server),W),

  Y = pke(privkey(server,pke(pubkey(server),W)) = W

  Intruder needs to know X = pke(pubkey(server),W)

- **Can use rule as oracle for decrypting encrypted messages**

EXAMPLE OF LEMMA GENERATION

- **Consider protocol with only one rule:**
  - **IF a rcvs X THEN a sends d(k,X)**
- **Suppose you want to know if the intruder can learn m, not known initially**
  - **If you want to know word m, system tells you that you need to know e(k,m)**
  - **If you want to know e(K,m) system tells you that you need to know e(k,e(k,m)), and so on**
  - **Try to show the unobtainability of the formal language A defined by**

1. A -> m

2. A -> e(k,A)

PROVING THE LEMMA

- **Try to show the unobtainability of the formal language A defined by**
  - **1. A -> m**
  - **2. A -> e(k,A)**
  - **Already tried Analyzer on first production**
  - **Try it on second, find that you need to know d(k,d(k,A)), which is also in A**
- **Have proved that, in order to learn a word from A, need to already know a word from A**
- **Analyzer can show automatically that languages are unreachable**

THE AGE OF BELIEF LOGICS

- **Burrows, Abadi, and Needham (BAN) logic for analyzing authentication protocols, 1989**
  - **Codified common-sense reasoning about cryptographic properties into a set of rules about beliefs that could be inferred during operation of a crypto protocol**
  - **Easy to use and intuitively appealing**
- **A host of descendants, GNY, AT, SvO, AAPA (automated and augmented GNY)**
- **Trade-off high level of abstraction with efficiency and ease of use**
- **However, have been shown to be effective at flagging a large number of protocol errors [Brackin - 1998,99]**

BURROWS, ABADI, AND NEEDHAM (BAN) LOGIC 1989

- **Builds upon statements about beliefs in messages sent through the course of a protocol**
- **Example: "If I've received a message encrypted with key K, and I believe that only Alice and I know K, then I believe that the message was originated by either Alice or me."**
- **In the analysis of a protocol, an initial set of beliefs is assumed.**
- **Each message received is mapped to another set of beliefs.**
- **Inference rules used to determine what beliefs can be derived from initial beliefs and beliefs gained from participating in the protocol**
- **If resulting set of beliefs adequate, the protocol is assumed to be correct**
- **If set of beliefs not adequate, this observation can lead to the discovery of a security flaw**

SOME BAN INFERENCE RULES

1. **(message-meaning) If P believes that K is a key shared with Q AND P sees K[X] THEN P believes that Q said X**

2. **(nonce-verification) If P believes that X is fresh AND P believes that Q said X THEN P believes that Q believes X**

3. **(freshness) If P believes that X is fresh, then P believes that <X,Y> is fresh**

4. **(jurisdiction) If P believes that Q believes X AND P believes that Q controls X THEN P believes X**

EXAMPLE BAN ANALYSIS (SKETCH)

1. **A --> S: B, N_A**
2. **S --> A: $K_A[N_A,B,K_{AB}]$**

- **Initial beliefs: A believes N_A is fresh, A believes , for all K, S controls the fact that K is a good key for A and B, A believes that K_A is a good key for A and S**
- **From message 2 and message meaning rule, conclude that A believes S once said <N_A,K_{AB} key for A and B>**
- **From A believes that NA is fresh, and freshness rule, conclude that A believes that <N_A,K_{AB} key for A and B> is fresh**
- **From A believes that <N_A,K_{AB} key A and B> is fresh, and A believes S once said <N_A,K_{AB} key forA and B>, and nonce-verification, conclude that A believes S believes <N_A,K_{AB} key for A and B>**
- **From A believes S believes <N_A,K_{AB} key for A and B>, conclude A believes S believes K_{AB} key for A and B**
- **From A believes S controls K for A and B, and A believes S believes K_{AB} key for A and B, and jurisdiction rule, conclude A believes K_{AB} key for A and B**

THE AGE OF MODEL CHECKERS

- Goal of a model checker: to verify system properties by exhaustive search of a finite set of states
- How a model checker is used
  - Specify your system
  - Specify the behavior of your system, usually using a temporal logic
  - Use the model checker to exhaustively generate possible behaviors of the system that can violate the desired behavior
    - For example, generate all paths possible starting from an initial state
  - Can only search finite space, but with suitable abstractions, can also use on infinite systems

LOWE'S USE OF FDR

- Lowe first to use a model checker (FDR) to demonstrate a protocol failure (Needham-Schroeder public key protocol)
- FDR: model checker based on Hoare's communication sequental processes
- User can specify size of search space in terms of number of participants, protocol executions, etc.
- Some work since then
  - Developed high-level specification language, Casper
  - Conditions that will guarantee that, if a protocol is secure for a finite search space, then it is secure for an infinite space

NEEDHAM-SCHROEDER PUBLIC-KEY PROTOCOL

1. A --> B: $[R_A,A]K_B$

2. B --> A $[R_A,R_B]K_A$

3. A --> B: $[R_B]K_B$

THE ATTACK

1. A --> I: $[R_A,A]K_I$

1': IA -> B: $[R_A,A]K_B$

2': B --> A: $[R_A,R_B]K_A$

3: A --> I : $[R_B]K_I$

3': IA --> B: $[R_B]K_B$

CHALLENGES IN MODEL-CHECKING CRYPTO PROTOCOLS

- **Sources of infinity**
  - **unbounded number of actions by intruder**
  - **unbounded number of concurrent sessions that could interact**
  - **unbounded number of data items such as keys, nonces, etc.**
    - **Roscoe et al. have shown that, if you bound the number of concurrent sessions, can also bound nonces, etc.**
- **Undecidability of secrecy problem**
  - **easy to show that this also implies undecidability of authentication problem**

SOME OTHER MODEL CHECKERS

- **Mitchell, et al. Mur**
- **Special purpose model checkers**
  - **Clarke/Marrero: BRUTUS**
  - **Song: Athena**
  - **Huima**

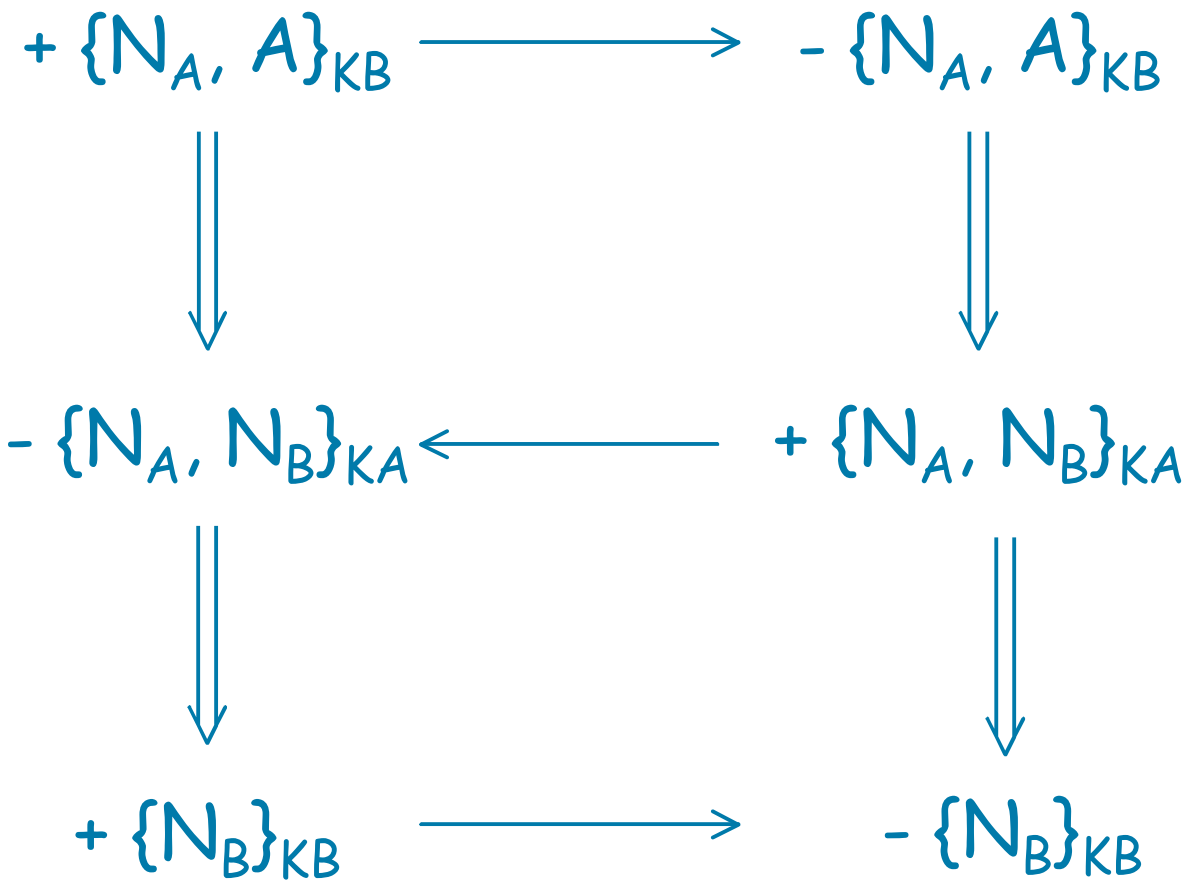
THEOREM PROVERS

- **Paulson's inductive approach**
  - **Uses Isabelle theorem prover to inductively define invariants**
  - **Has developed library of techniques which have been taken up by others**
- **Some special-purpose tools**
  - **TAPS (Cohen)**
  - **Cryptyc Type Checker (Gordon and Jeffries)**

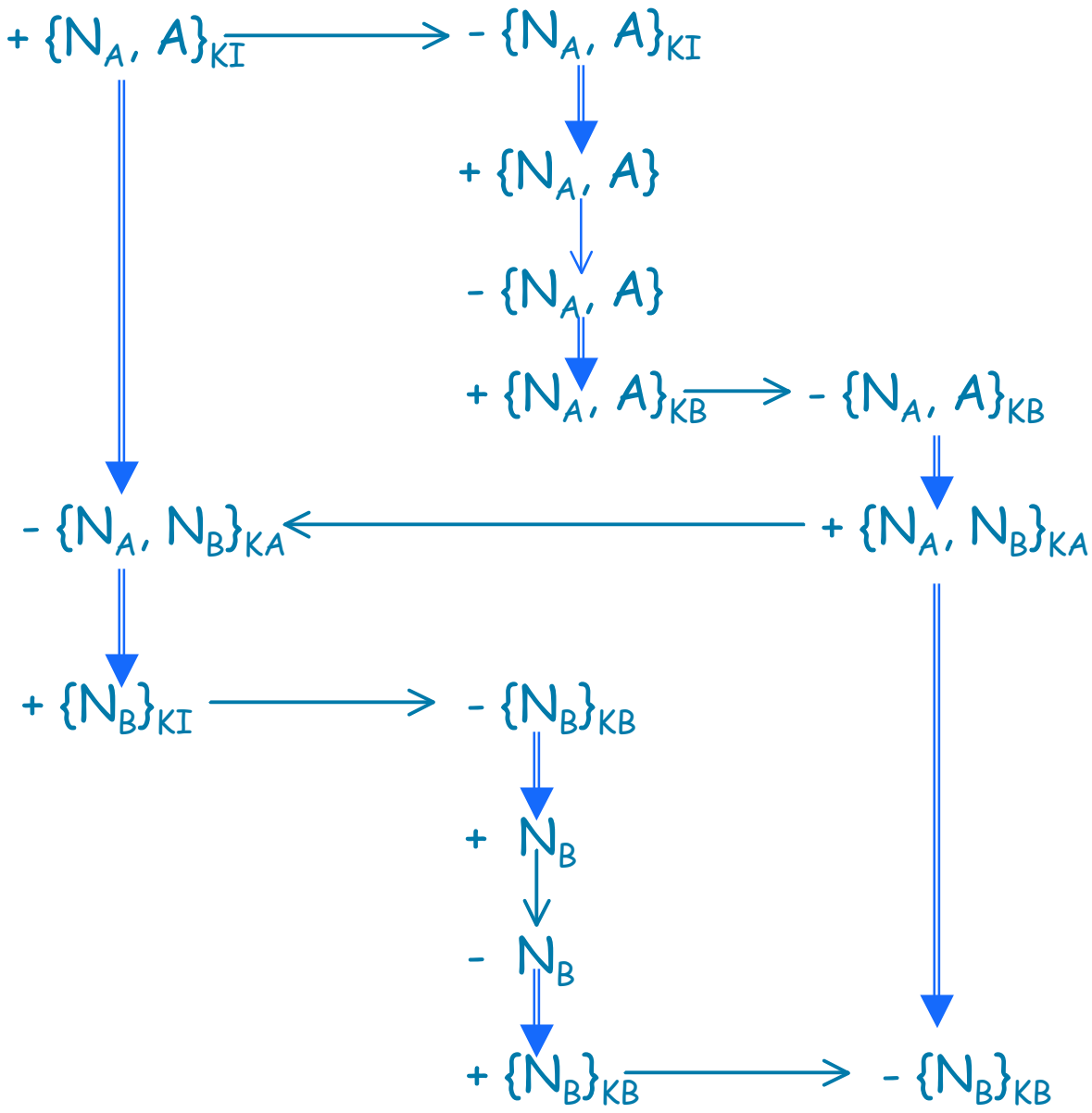
STRAND SPACES (THAYER, HERZOG,GUTMANN)

- Graph-theoretic model for crypto-protocol analysis
  - Similar to Lamport's theory of causality
- Strands (linear graphs) represent local executions
  - Protocol strands: local execution of protocol participant in one protocol instance
  - Penetrator strands: describe actions such as concatenation, encryption, decryption, etc.
- Strands contain both positive (output) and negative (input) nodes
- Can glue up strands along positive and negative nodes to obtain a bundle

EXAMPLE BUNDLE - NS PUBLIC KEY



ATTACK ON NS PUBLIC KEY



ADVANTAGES OF STRAND SPACES

- **Simple, easy to work with model**
- **Graph-theoretic approach easy to visualize**
- **Can use as basis of comparison with other models**
- **We'll meet up with strand spaces again**

USE OF INDUCTION IN CRYPTOGRAPHIC PROTOCOL ANALYSIS

USES OF INDUCTION IN CRYPTOGRAPHIC PROTOCOL ANALYSIS

- Mathematical induction gives a way to get around finite-state limitations of model checkers
  - Cryptosystems have often have regular behavior that is amenable to inductive definition of invariants
- Some tools and methodologies that incorporate this use of induction
  - NRL Protocol Analyzer (model checker with theorem-proving capabilities)
  - Strand Space model
    - Athena model checker, based on strand space model
  - Paulson's inductive method
    - Methodology for using induction with Isabelle theorem prover
    - Has been applied in other contexts as well
  - Schneider's rank functions
  - Cohen's TAPS (special-purpose theorem prover)

ANALYSIS TECHNIQUES

- **Belief logics -- usually doesn't require inductive reasoning or invariants, so not considered here**
- **Theorem-proving techniques**

  Forwards search - show that if invariant holds in a given state, then invariant still holds after any state transition

  Backwards search -- show that if invariant doesn't hold in a state, then it doesn't hold in previous state

- **Model checking**

  Forwards search - start from initial state, produce all protocol exeuctions leading to final states, subject to limits on numbers of principals, number of concurrent runs, etc.

  Backwards search - start from final state (usually an insecure state) and work backwards to initial states

  May use invariants (as does NRL Protocol Analyzer, Athena) to limit size of the search space

WHAT WE WANT TO PROVE

- **Backwards search**

  May produce a state that requires an intruder to know a term that may be impossible to learn

  Need a way of characterizing these and proving them unlearnable

  Often, can do this by producing set of terms such that the property of their not being known remains invariant under protocol execution

- **Forwards search**

  May produce state in which intruder or other principal generates term which will never be accepted as a legitimate message by an honest principal

  Want to characterize these terms and avoid states that produce them

TERMS NOT KNOWN BY THE INTRUDER-STRAND SPACE IDEALS

- **Strand spaces**
  - Uses free cryptoalgebra and strong typing
  - Only operations are encryption and concatenation
  - Only types are keys, nonces, names
- **Let T be a set of terms that we want to show are not known by the intruder**
  - If (X,T) or (T,X), where T ∈ T, is known by the intruder, then intruder can learn T
  - If $e_K(T)$ where T ∈ T and K ∈ K (set of keys known by the intruder), is known by the intruder, then intruder can learn T
  - Define $I_K(T)$ to be the smallest set containing T closed under concatenation with any term and encryption by keys from K
  - This is exactly the ideal defined by the strand space model

NRL PROTOCOL ANALYZER LANGUAGES

- **Uses identities that form set of Noetherian, confluent rewrite rules**

  e.g., d(X,e(X,Y)) -> Y

- **Languages are automatically generated invariants produced as follows**

  Give single term G as goal ("seedword")

  Search backwards from goal, produce all paths to goal of a predefined depth

  For each path, find terms that intruder must learn to execute that path

  Generate new language rules that imply that these terms are in the path

  Iterate process with terms defined by language rules produced, continue until no new language rules need to be generated

RELATIONSHIP BETWEEN LANGUAGES AND IDEALS

- **Will always have a path corresponding to intruder deconcatenation**

  That is, intruder could have learned X if knew (X,T) or (T,X)

  So need rules saying that if T in language, then so is (X,T) & (T,X) for any X

- **Will always have a path corresponding to intruder decryption**

  Analyzer generates rule saying if T in language then so is $e_K(T)$ for any K

- **Have produced something similar to $I_K(\{G\})$, where K is all keys**

RANK FUNCTIONS

- **Define function from set of terms to integers**
- **Show that a principal does not send a message of rank 0 or less unless it has already seen them**
- **Numerous examples in Schneider's analysis of NSPK**

  Rank of concatenation minimum of ranks of two terms

  Encryption generally rank-preserving

  A few exceptions: if M is a message we are trying to prove secret (so it is of nonpositive rank), and $e_K(M)$ may appear in the protocol, then encryption must be rank-increasing in this case
- **Conclusion: non-positive rank terms very close to ideal, with a few exceptions**

HOW IDEALS USED FOR SECRECY

- **In all three systems**
  - **Find term we want to prove secret**
  - **Use it to generate ideal-like object**
  - **Use induction to prove intruder can't learn any element in ideal-like object**

HOW IDEALS USED FOR AUTHENTICATION

- **NRL Protocol Analyzer and Strand Spaces**

  Attempt to show that intruder can't fool principal into accepting a fake message M as genuine

  Use messages M acceptable by principal to generate an ideal-like object

  Use induction to show intruder can't learn words in ideal-like object except for some exceptions

  Show that exceptions could only have been generated by honest principals

- **Schneider**

  Construct new protocol in which sending of message by legitimate principal blocked

  Use same technique as for secrecy to show that forged message can't be generated in blocked protocol

SUBALGEBRAS AND SETS OF TERMS KNOWN BY THE INTRUDER

- **Let T1, ..., Tn be a set of terms known by the intruder, and let op be an operation**
  - **Then op(T1,...,Tn) also be learnable by the intruder**
- **Clearly, set of terms learnable by the intruder closed under any intruder operation**
- **GIven any set of terms T, and set of operations O, let S(O,T) be the smallest set containing T closed under the operations in O**

  Call S(O,T) the subalgebra generated by T over O
- **If can find good way of characterizing S(O,T), may be able to use this prove results about protocol**

PAULSON'S INDUCTIVE METHOD

- **Based completely on induction, using Isabelle theorem prover**
  - **Each theorem and lemma stated as an invariant**
  - **Use Isabelle to show each invariant holds under each state transition**
- **No general algorithm for proving secrecy results, but makes use of two subalgebra constructs**

  Analyz(X) = S({deconcatenation, decryption},K U X)

  Synth(X) = S({concatenation, encryption},I U X) (where I = set of agent names and guessable nonces)
- **Uses Isabelle to prove 101 theorems involving Analyz, Synth, and a related concept, parts (all the subterms of a message)**

COHEN'S TAPS

- **Automates Paulson's inductive method**
  - **Defines several types of general invariants, which can be proved automatically**
  - **The one of interest to us is the secrecy invariant**
- **Secrecy invariant defined in terms of :**

  prime(X) -- describes certain types of basic messages that it is permissable for the intruder to know

  pub(X) -- set of messages published at a particular state

  ok(X) -- set of all messages permissible to know

  prime(X) => ok(X)

  ok(X) ∧ ok(Y) => ok((X,Y))

  pub(X) ∧ pub(Y) => ok(eX,Y))
- **Invariant to be proved is pub(X) => ok(X)**

CONCLUSIONS - SUGGESTIONS FOR FURTHER RESEARCH

- **Can we mix and match techniques?**
- **How closely is the connection between ideals and backwards search and subalgebras and forward search?**
- **What is the relationship between these techniques and decidability results?**
- **How well will these techniques work for more expressive models?**

OPEN PROBLEMS

Emerging Properties of Protocols

- **Greater interoperation**
  - **Meta protocols to negotiate agreement upon protocols, eg. ISAKMP-IKE**
- **Negotiation of policy**
  - **Security associations**
  - **Certificate hierarchies**
- **Greater complexity**
  - **Especially for electronic commerce**
- **Group-oriented protocols**
- **Emerging security threats**
  - **Denial of service**
  - **Traffic analysis**

ISSUE 1:
Composability

- A crypto protocol does not exist in isolation
- Usually part of a suite of protocols
  - Members of the suite will use similar mechanisms, syntax, etc.
  - Need to be sure protocols will not interact in harmful ways
  - Eventually, will become impractical to evaluate all in one go
  - Work becomes even harder when applied to evaluating composition of protocols from different sources
- Guttman and Thayer have general approach for verifying composability (CSFW 13, June 2000)
  - Basic idea: look at all authenticated messages, see which ones can be confused with each other
  - Questions:
    - What if you allow key compromise?
    - What is number of possible authenticated messages is infinite?

ISSUE 2: Incremental Analysis

- Many protocols part of a family of protocols that differ only slightly
  - Would be helpful to be able to reuse proofs
- When integrating formal analysis in design, necessary to be able to redo proofs rapidly as design changes
  - Again, would be helpful to be able to reuse parts of proofs that are still valid
- But -- analysis of crypto protocols requires checking for unsafe interaction of all parts
  - How can we tell if any of our proofs are still valid
- Closely related to modular evaluation problem

ISSUE 3: PROBABILISTIC AND GAME-THEORETIC ANALYSIS

- Many attacks on protocols are probabilistic
  - Traffic Analysis
    - Can an attacker increase the accuracy of its picture of the network?
  - Protocols Using Lightweight Authentication
    - How much do they reduce the likelihood for a successful attack?
- Many protocol properties can be modeled in terms of games
  - Electronic commerce protocols
  - Denial of service
    - Trading off effort of attacker against cost to defender

ISSUE 4:
High Fidelity

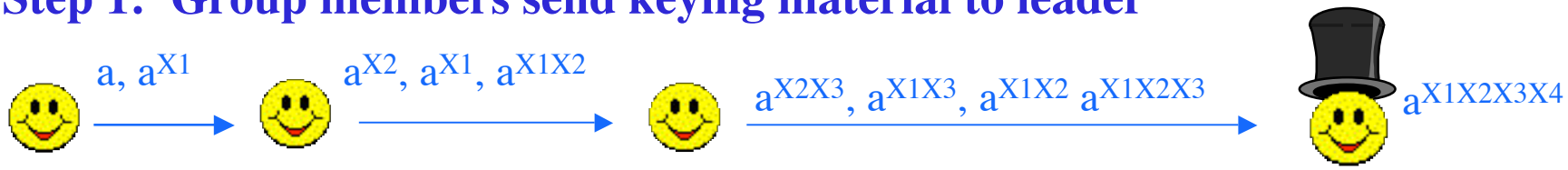
- There are a number of protocol problems that occur below the level at which most formal methods work operates, but above the cryptoalgorithm level
  - Modes of encryption
  - Integrity checks
    - Bellovin (Usenix 96) describes a cut-and-paste attack on an earlier version of ESP relying on ESP's use of CBC mode and TCP's not checking length of packets
  - Malleable cryptosystems
    - Some techniques (e.g. Chaum's blinded signatures, actually make use of malleability)
- Some work exists on formal models for properties at this level
  - Stubblebine-Gligor (Security and Privacy '92, '93)
  - Can automated tools be extended to deal with these properties?

ISSUE 5:
Open-Ended and Group Protocols

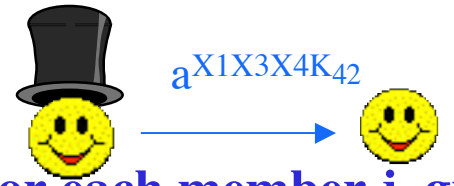
- Many of the newer protocols use open-ended data structures
- Examples
  - Protocols for negotiating choices from an open-ended set of algorithms
  - Group-oriented protocols
    - Group authentication
    - Secure auction, voting, etc.
    - Anonymity: Chaum mixes
- Some work done on this (Paulson, Schneider,Zakiudin)
  - Could use a lot more

CLIQUES GROUP KEY DISTRIBUTION PROTOCOL

- Group leader n shares common secret exponent Knj with each principal j
- Step 1: Group members send keying material to leader



- Group leader raises each value received to the Xn.
- At the end, for each group member j, group leader has a $\hat{a}^{X1...Xj...Xn}$.
- Group leader also has group key a $^{X1...Xn}$.
- Step 2: Leader sends key info to members, encrypted w. shared secret exponents



- For each member j, group leader sends a $\hat{a}^{X1...Xj...XnKnj}$ to j.
- Group member j computes a $\hat{a}^{X1...Xj...XnKnjXj(Knj^{-1})}$ = group key

ISSUE 6: TRANSACTION PROCESSING

- E-commerce protocols such as SET allow parties to agree on complex data structures
  - Need to assure integrity and consistency of the structure
  - Different parts of the structure introduced by different principals
  - Some parts of the structure kept secret from some of the principals
- Protocols such as ISAKMP-IKE agree on somewhat less complex, but open-ended data structures
- Otway-Rees protocol (1987) tried to agree on a two-part data structure (key and key id)
  - Thayer, Herzog, and Guttman (1998) showed protocol didn't achieve that
- This is a problem that could use some close attention

ISSUE 7:
Getting it into the Real World

- Protocol developers are aware that assurance is a problem
  - If you care enough about security to use cryptography, you probably care enough to worry about whether you're using it correctly
- But -- formal methods are seen as an arcane field only accessible to a few experts
  - Seen as a barrier to integration of formal methods into the design process
  - Promotes adversarial relationship between developers and verifiers
  - Leads to inflexibility in application of formal methods
- How can we make formal methods more accessible and more flexible?
- What is the best way of introducing them into the design process?

BIBLIOGRAPHY

These talks based on the following papers:

Meadows, C., "Invariant Generation Techniques in Cryptographic Protocol Analysis", Proceedings of the 13th Computer Security Foundations Workshop, IEEE Computer Society Press, July, 2000.

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Meadows, C. "Formal Verification of Cryptographic Protocols: A Survey," Advances in Cryptology - Asiacrypt '94, LNSC 917, Springer-Verlag, 1995, pp. 133-150.

All of the above available at

http://chacs.nrl.navy.mil/projects/crypto.html