How to Break a Protocol

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Thanks to support from: National Security Agency

What is a cryptographic protocol?

For instance, the Secure Socket Layer protocol (SSL)

- Short, conventional sequence of messages
- Uses cryptography
- Goals: authentication, key distribution

Establish trust

- E-commerce
- Remote access
- Secure networking

Cryptographic protocols are often wrong

- Active attacker can subvert goals
- May fail even if cryptography ideal
- Hard to predict which protocols achieve which goals

How to Break a Protocol

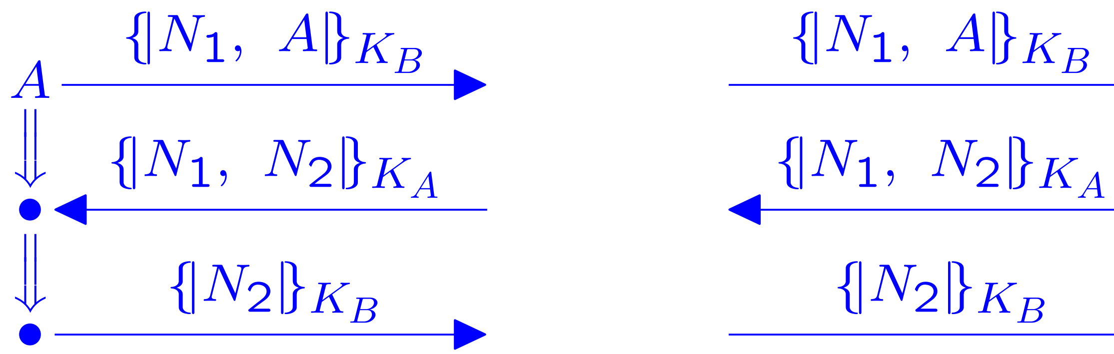
Try to prove it correct

- Where you get stuck
  that's where the flaw is

Focus on services provided by protocol

- Actions the protocol requires regular principals to pe
- Produce values useful to penetrator

Needham-Schroeder



K_A, K_B	Public (asymmetric) keys of A, B
N_1, N_2	Nonces, one-time random bitstrings
$\{\!|t|\!\}_K$	Encryption of t with K
$N_1 \oplus N_2$	New shared secret
	(whitespace)

Essence of Cryptography (for today's lecture)

Symmetric key cryptography: algorithm using a single value, shared as a secret between sender, receive

- Same key makes ciphertext, extracts plaintext

Public key cryptography: algorithm using two related values, one private, the other public

- Encryption: Public key makes ciphertext, only private key owner can decrypt
- Signature: Private key makes ciphertext, anyone can verify signature with public key

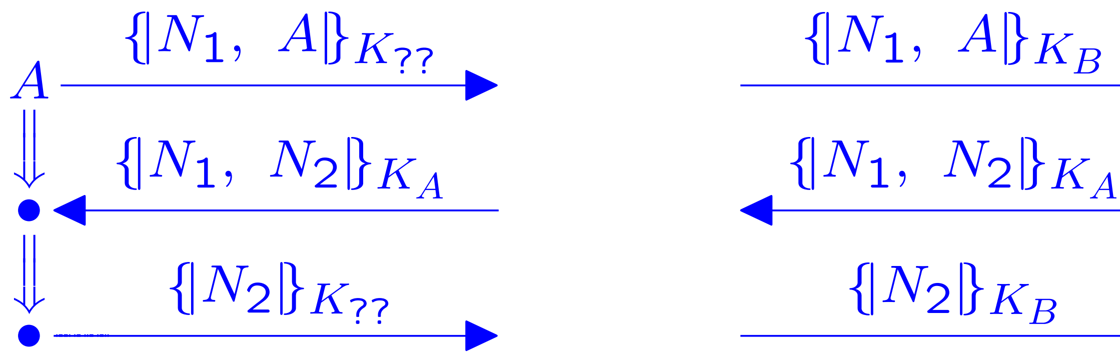
Terminology: A's public key: K_A A's private ke

In symmetric crypto, $K = K^{-1}$

Uncompromised key:

- Key used only in accordance with protocol

Needham-Schroeder: How does it work?



	Assume A's private key K_A^{-1} uncompromi
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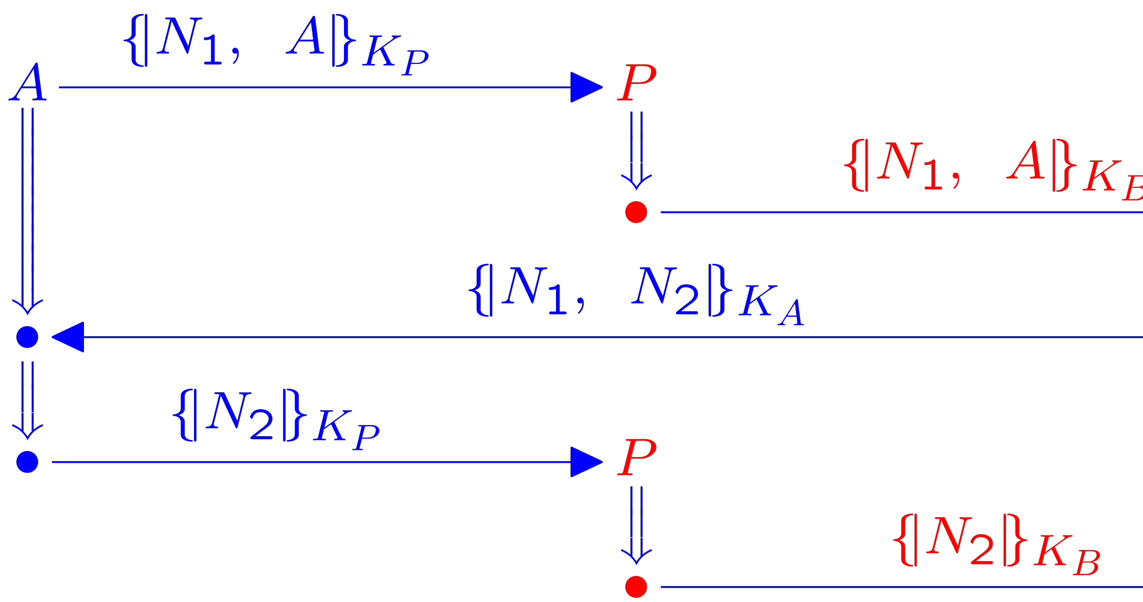
Whoops

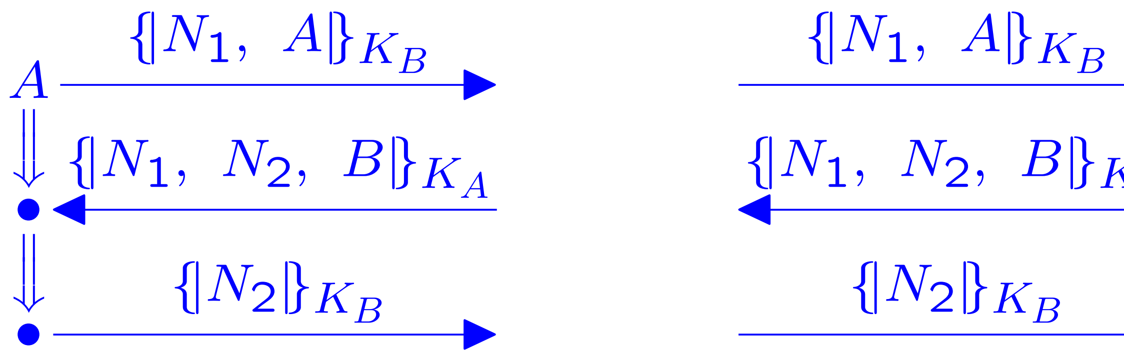
Needham-Schroeder Failure

If $?? = P$,



(Gavin Lowe)

Needham-Schroeder-Lowe



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How to Break Protocols:

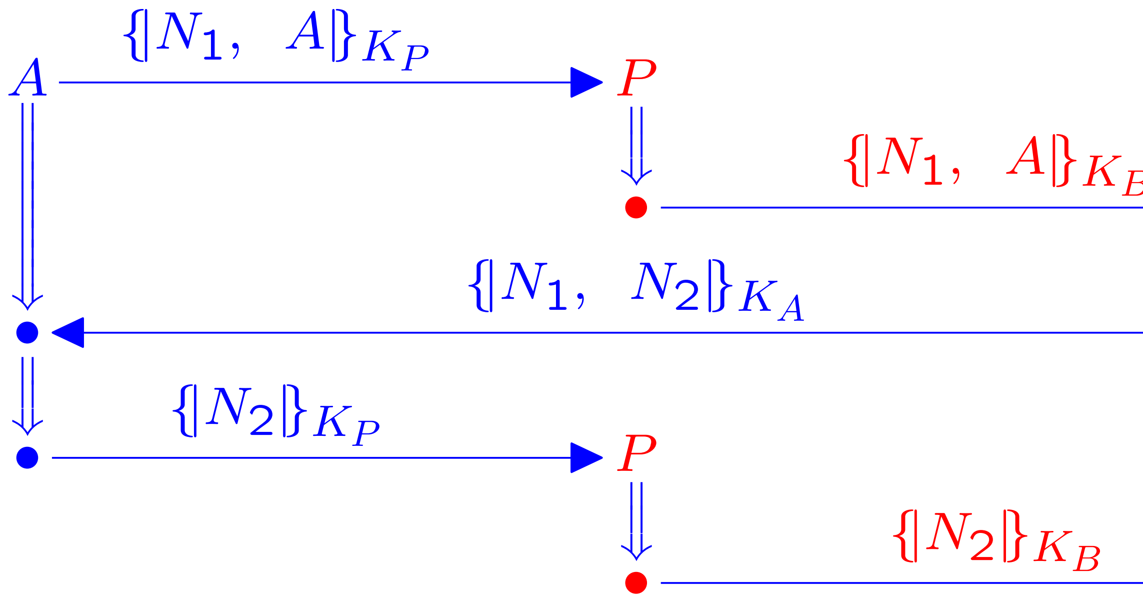
Unintended Services

and

Junk Terms

Needham-Schroeder Failure

If $?? = P$,



(Gavin Lowe)

Diagnosis of a Failure

Who was duped?

- Not A: Meant to share N_1, N_2 with P
- B: Thinks he shares N_1, N_2 only with A
  - Secrecy failed: P knows values
  - Authentication failed: A had no run with B

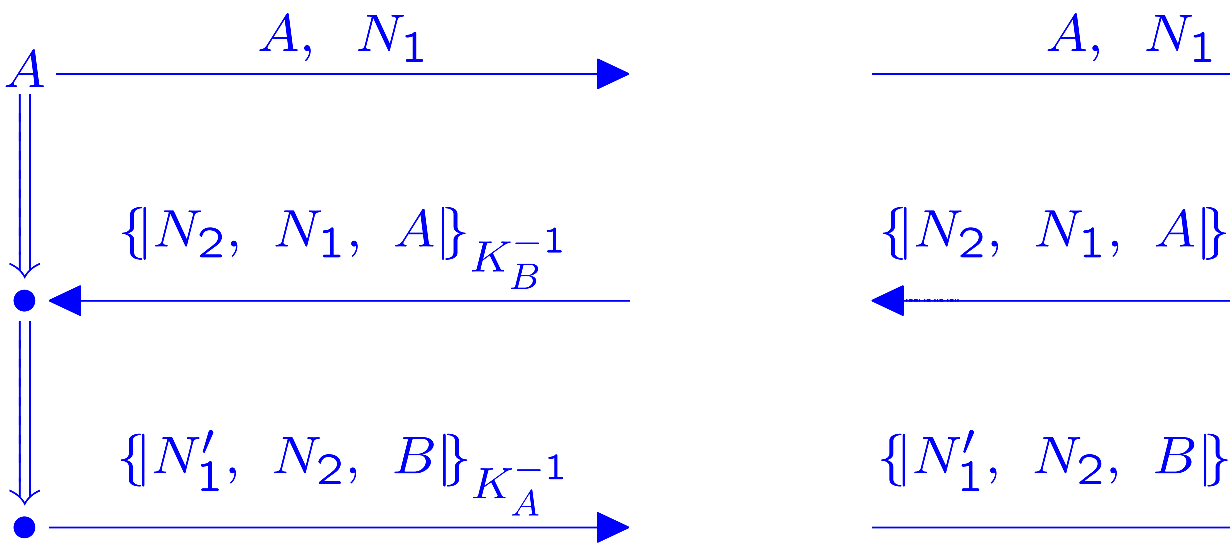
How? A offered P a service:

- Gave P nonce N_1
- Promised to translate $\{\!|N_1, N|\!\}_{K_A}$ to $\{\!|N|\!\}_{K_P}$

An "unintended service"

- Attacker needs to compute some value
  - N_2 in this case
- But legitimate party creates such a value

Another Example: ISO Reject



Signatures only

Mere authentication

Diagnosis of ISO

Respondent B gets only two messages

- Clearly $A, \; N_1$ is "junk"
  - It has no authenticating force
- Other term received is the only challenge

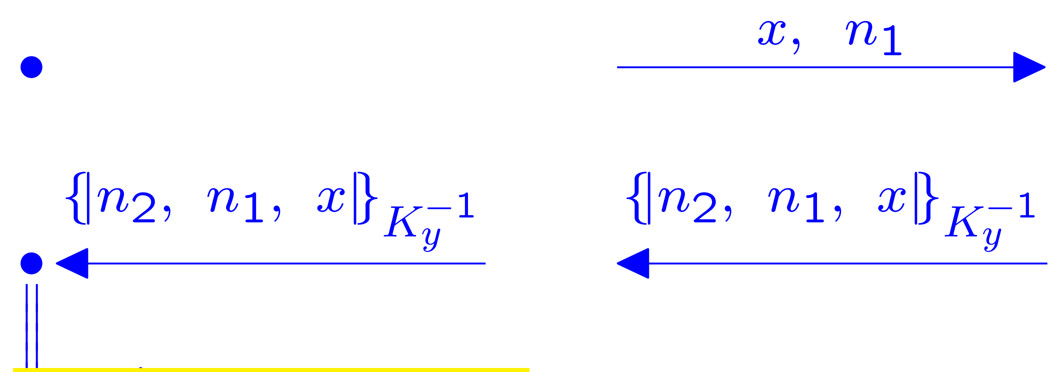
Attacker needs to create

$$\{\!|N_1', \; N_2, \; B|\!\}_{K_A^{-1}}$$

Only $\{\!|N_1', \; N_2, \; B|\!\}_{K_A^{-1}}$ requires work

What services are useful?

The Available Services



Shown in lower case to emphasize status as variables

May rename in-bound variables

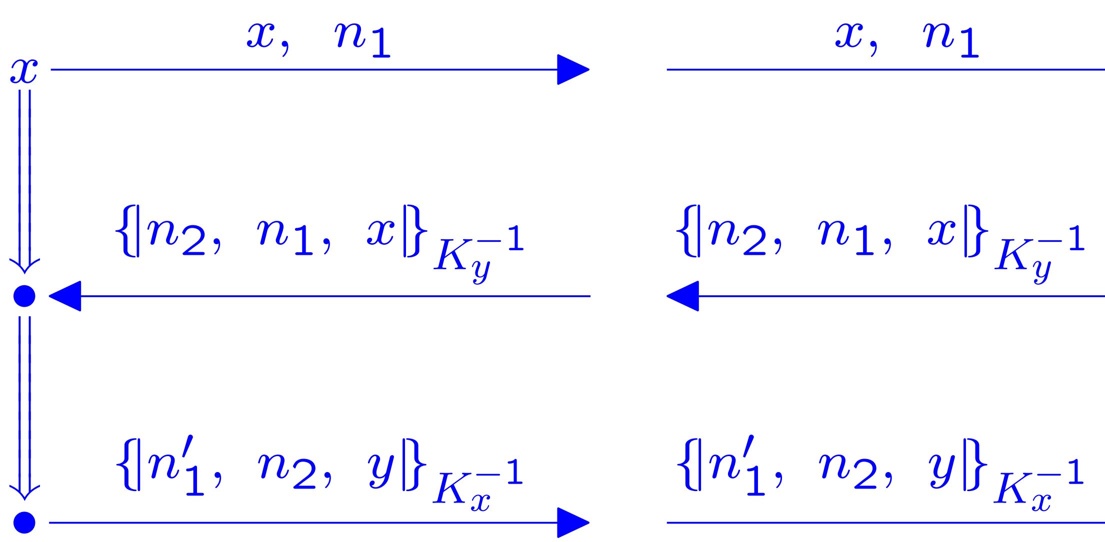
Want to produce $\{\!|N_1', \ N_2, \ B|\!\}_{K_A^{-1}}$

for some N_1'

Can use A as respondent, B, N_2 in-bound

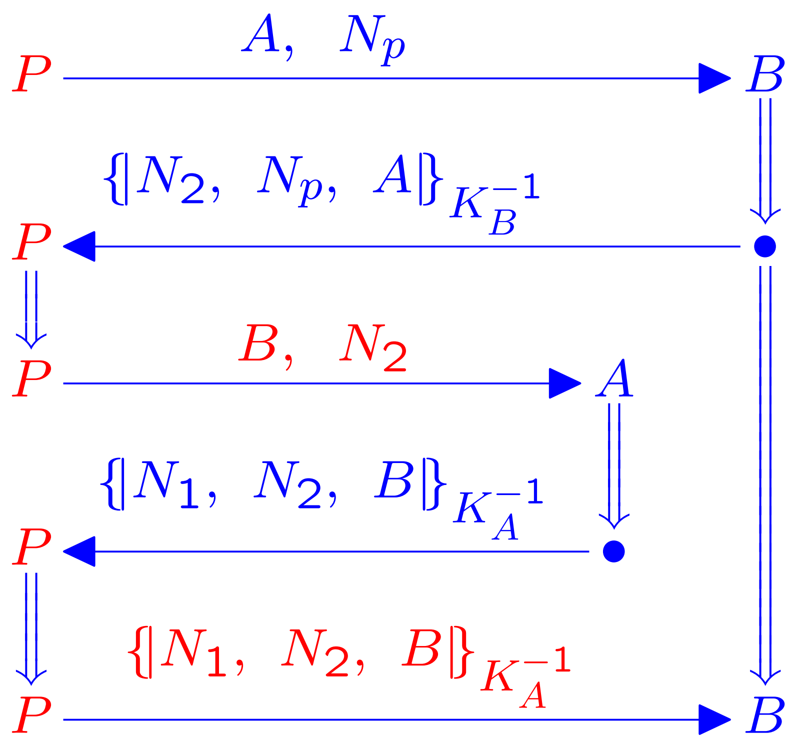
i.e. use substitution $[A/y, \ B/x, \ N_2/n_1]$

Behaviors are Parametric



x, y, n_1, n_2, n_1' are variables
Possible behaviors are all substitution instances

Counterexample to One Security Goal



What Goal is Refuted?

A executed a signature

– "Entity authentication" for A may hold depending what that means

But A was not initiator
in any run with B

Dolev-Yao Attacks: A Recipe

Identify and discard "junk" messages

- They don't contribute to authentication
- Remaining incoming messages: "Challenge"
- Adversary needs to synthesize them

Look for unintended services

- Criterion: Can they build challenge messages?

Combine unintended services

What Unintended Services Occur?

Signature:	N_a	$\mapsto$	$\{\ N_a\ \}_{K^{-1}}$
Encryption:	N_a	$\mapsto$	$\{\ N_a\ \}_{K}$
Decryption:	$\{\ N_a\ \}_{K}$	$\mapsto$	N_a
Translation:	$\{\ N_a\ \}_{K}$	$\mapsto$	$\{\ N_a\ \}_{K'}$

Examples:

- Signature service: ISO reject protocol
- Encryption service: Woo-Lam
- Decryption service: None
  (too obvious?)
- Key-translation service: NS PK

The Dolev-Yao Problem

Given a protocol, and assuming all cryptography perfect,

- What secrecy properties
- What authentication properties

the protocol achieves

Find counterexamples to other properties

- Unintended services useful

What does perfect cryptography mean?

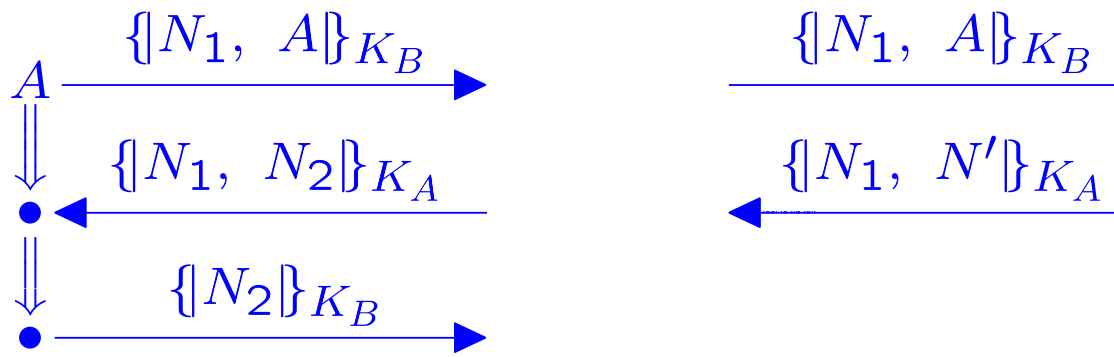
- No collisions
- Need key to make encrypted value
- Need key to decrypt and recover plaintext

How to Prove a Protocol Correct

Try to break it

- When you get stuck
  you'll see why it's right

Needham-Schroeder: Initiator's View



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Does $N' = N_2$? Yes, there are no available services!

Breaking and Proving

How to break a protocol

- Try to prove it correct
- Where you get stuck, look for trouble
- Specifically, look for unintended services to produce non-junk terms expected by regular principals

How to prove a protocol correct

- Try to break it
- See what unintended services must be used
- “Read off” authentication properties

Strand spaces: make these ideas precise,
justify method

Strand Spaces

work done jointly with
Javier Thayer and Jonathan Herzog

Protocol Executions are Bundles

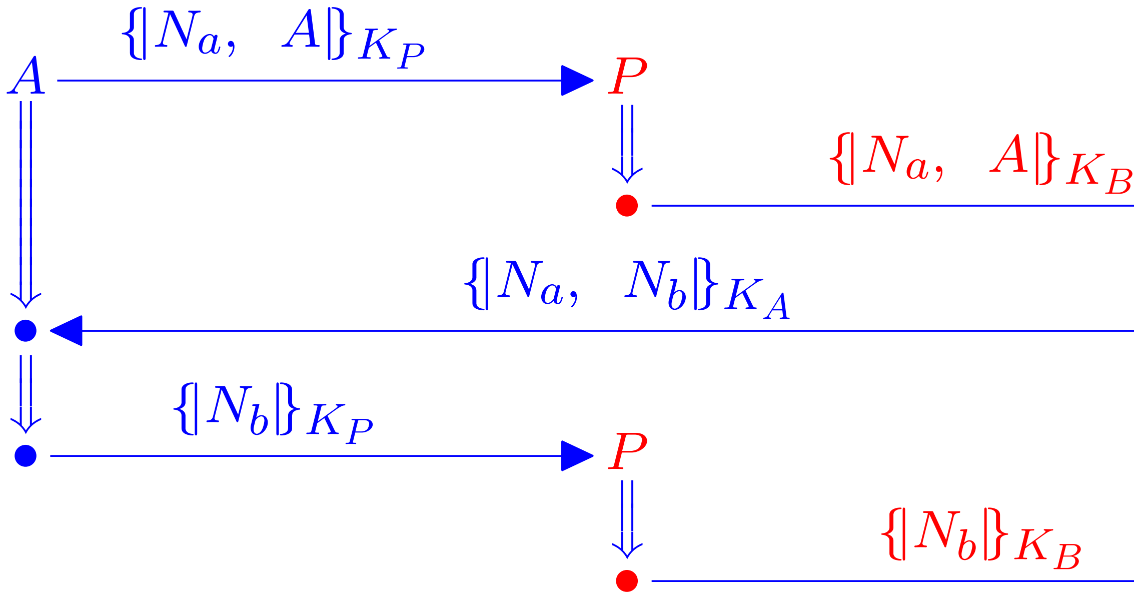
Send, receive events on strands called "nodes"

- Positive for send
- Negative for receive

Bundle $\mathcal{B}$: Finite directed graph of nodes and edges representing causally well-founded execution;
Edges are arrows $\rightarrow$, $\Rightarrow$

- For every reception $-t$ in $\mathcal{B}$, there's a unique transmission $+t$ where
  $+t \rightarrow -t$
- When nodes $n_i \Rightarrow n_{i+1}$ on same strand,
  if n_{i+1} in $\mathcal{B}$, then n_i in $\mathcal{B}$
- $\mathcal{B}$ is acyclic

A Bundle



Precedence within a Bundle

Bundle precedence ordering $\preceq_{\mathcal{B}}$

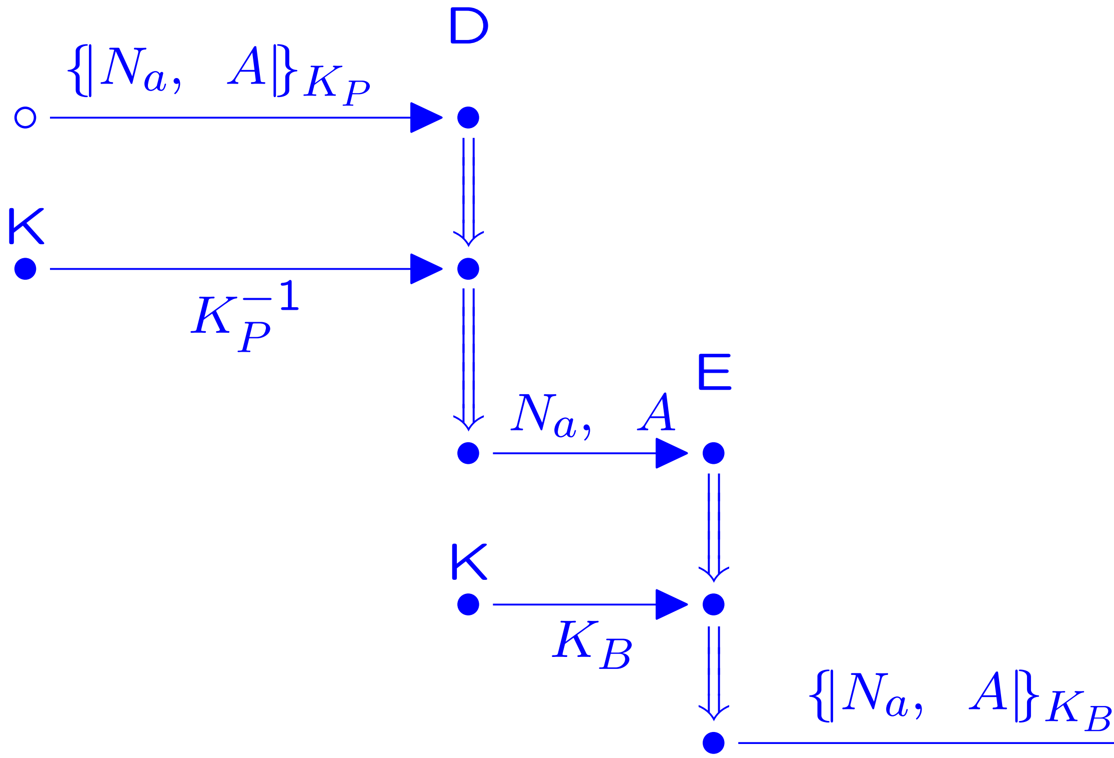
$n \preceq_{\mathcal{B}} n'$	means sequence of 0 or more arrows $\rightarrow$, $\Rightarrow$ lead from n to n'
$\preceq_{\mathcal{B}}$	is a partial order by acyclicity
$\preceq_{\mathcal{B}}$	is well-founded by finiteness

Bundle induction: Every non-empty subset of $\mathcal{B}$ has $\preceq_{\mathcal{B}}$-minimal members

Reasoning about protocols combines

- Bundle induction
- Induction on message structure

NS Attack: Adversary Activity



Messages

Terms freely generated from

- Names, texts
- Nonces
- Keys

using the operators:

- Concatenation $t_0,\ t_1$
- Encryption with a key $\{\!|t_0|\!\}_K$

Other algebras also interesting
but today we'll use the free one

Subterms and Origination

Subterm relation $\sqsubset$
least transitive, reflexive relation with

$g \sqsubset g, \;\; h$
$h \sqsubset g, \;\; h$
$h \sqsubset \{\!|h|\!\}_K$

N.B. $\quad K \sqsubset \{\!|h|\!\}_K$ implies $K \sqsubset h$

Represents *contents* of message, not how it's construct

t **originates** at n_1 means

n_1 is a transmission $(+)$
$t \sqsubset \mathrm{term}(n_1)$
if $n_0 \Rightarrow \cdots \Rightarrow n_1$, then $t \not\sqsubset \mathrm{term}(n_0)$

Unique origination, non-origination formalize
a probabilistic assumption

An Authentication Goal

Suppose:

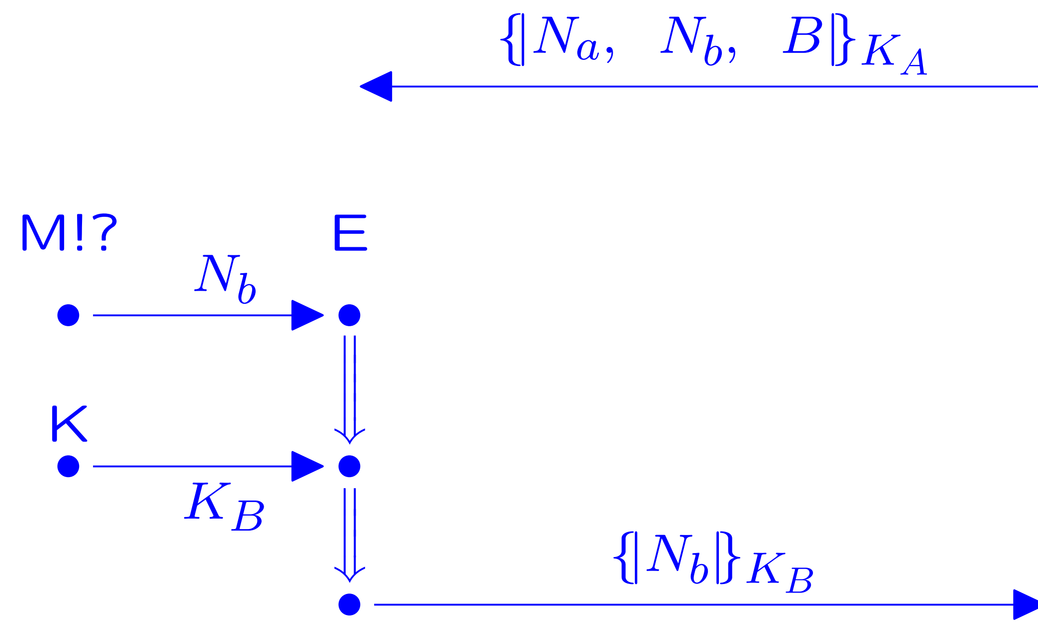
- Bundle $\mathcal{B}$ contains a strand Resp$[A, B, N_a, N_b]$
- K_A^{-1} non-originating
- N_b originates uniquely in $\mathcal{B}$
- $N_b \neq N_a$

Then:

- There is a strand Init$[A, B, N_a, N_b]$ in $\mathcal{B}$

Authentication: correspondence assertions (of form $\forall\exists$)
(This is false for NS)

Guessing a Nonce



Guessing a private key (e.g. K_A^{-1})
similarly improbable

A Secrecy Goal

Suppose:

- Bundle $\mathcal{B}$ contains a strand Resp$[A, B, N_a, N_b]$
- K_A^{-1}, K_B^{-1} non-originating
- N_b originates uniquely in $\mathcal{B}$

Then:

- There is no node $n \in \mathcal{B}$ with term$(n) = N_b$

Form: $\forall$

This also is false for NS

Summary: Breaking Protocols, Strand Spac

To break a protocol, you

- Discard junk terms
- Identify unintended services
- Match services against non-junk goals

Core strand space ideas:

- Behaviors (regular or adversary) are strands
- Executions are bundles
- Unique origination and non-origination

Security goals:

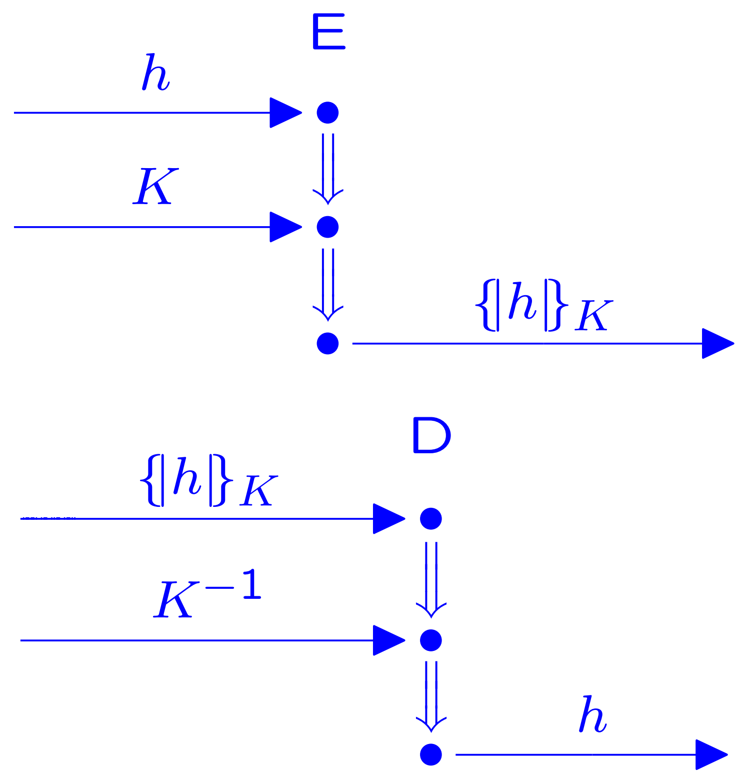
- Authentication asserts existence of matching strand
- Secrecy asserts non-existence of "disclosing" nodes
- Premises concern n.o., u.o., existence of strands, ine

A further question:

- How would you prove these goals?

Adversary Strands, I: Initiating Values

Adversary Strands, II: Encrypt, Decrypt



Formalizes notion of ideal cryptography

Adversary Strands, III: Concatenate, Separa