Authentication Tests: Analyzing and Designing Cryptographic Protocols

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Cryptographic Protocols

- For instance, Secure Sockets Layer (SSL)
  - Creates secure channel, browser to server
  - Agree on new shared secret
  - Use secret for encryption, integrity
- What is a cryptographic protocol?
  - Short, conventional sequence of messages
  - Uses cryptography
  - Goals: key distribution, authentication
- Frequently wrong
  - Even if the crypto is fine
  - May also amplify issues in crypto

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Trust Infrastructure

- Authenticate via cryptography
  - Principal demonstrates knowledge of
    - A private (asymmetric) key matching a certified public key, or
    - A shared secret key
  - Establishes identity
- Create new shared secrets
  - Entwined with authentication
  - Basis for secure conversation
  - Allows easy repeated authentication
- Preserve confidentiality or control access

Today's Goals

- Focus on one class of protocols, one type of flaw
  - Structural rather than cryptographic
- Explain how to prove correctness
- Illustrate how same ideas provide a protocol design method

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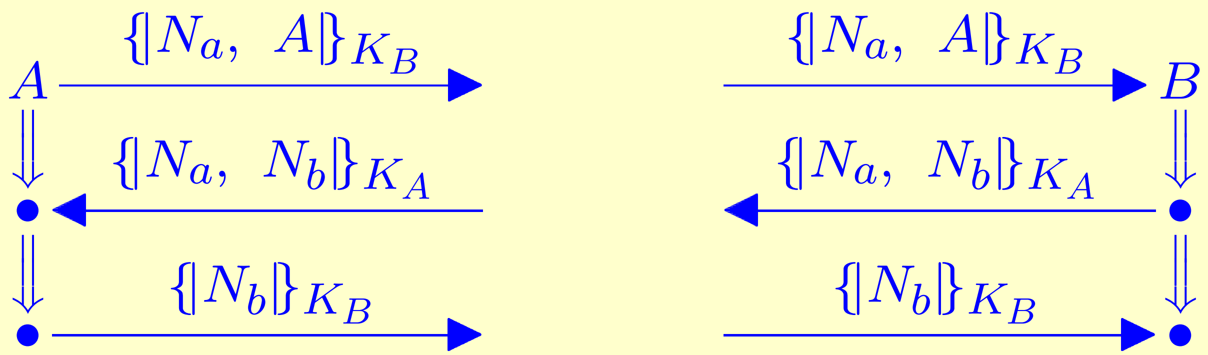
Example: Needham-Schroeder



K_A, K_B	Public keys of A, B
N_a, N_b	Nonces, one-time random bitstrings
$\{\|t\|\}_K$	Encryption of t with K
$N_a \oplus N_b$	New shared secret

Why are Crypto Protocols Hard?

- Attacker chooses pattern of communication
- Attacker may also be a player
  - May hold keys
  - Will misuse them freely
- Attacker manipulates honest players
  - They play by the rules
  - Forced to serve as oracles
  - Protocol creates "unintended services"

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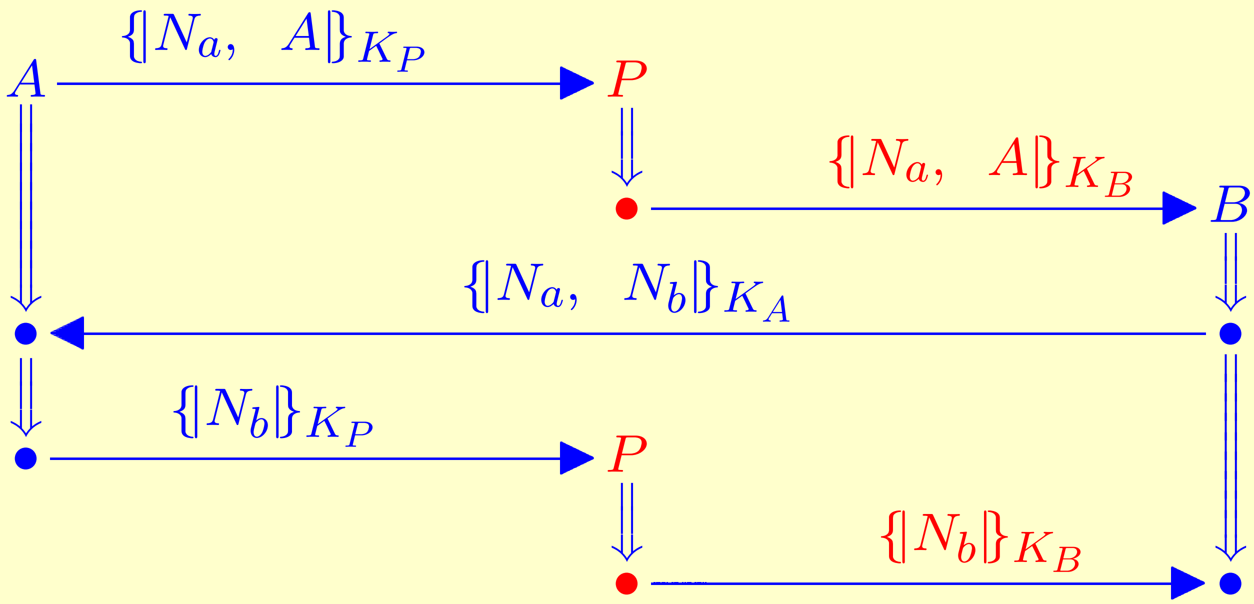
Needham-Schroeder Failure



Due to Gavin Lowe, 1995

Diagnosis of a Failure

- Who was duped?
- Not A: Meant to share N_a, N_b with P
- B: Thinks he shares N_a, N_b only with A
  - Secrecy failed: P knows N_a, N_b
  - Authentication failed:
    - A had no run with B
    - B thinks A did

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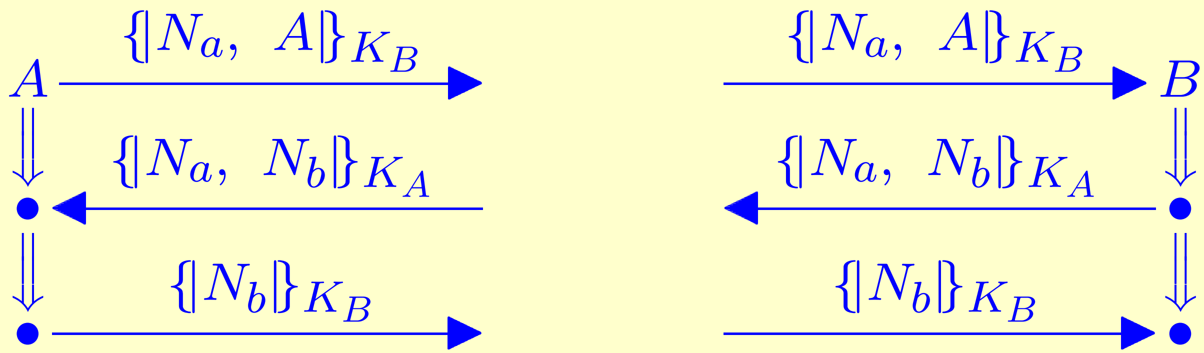
Regular strands



NSInit$[A, B, N_a, N_b]$

NSResp$[A, B, N_a, N_b]$

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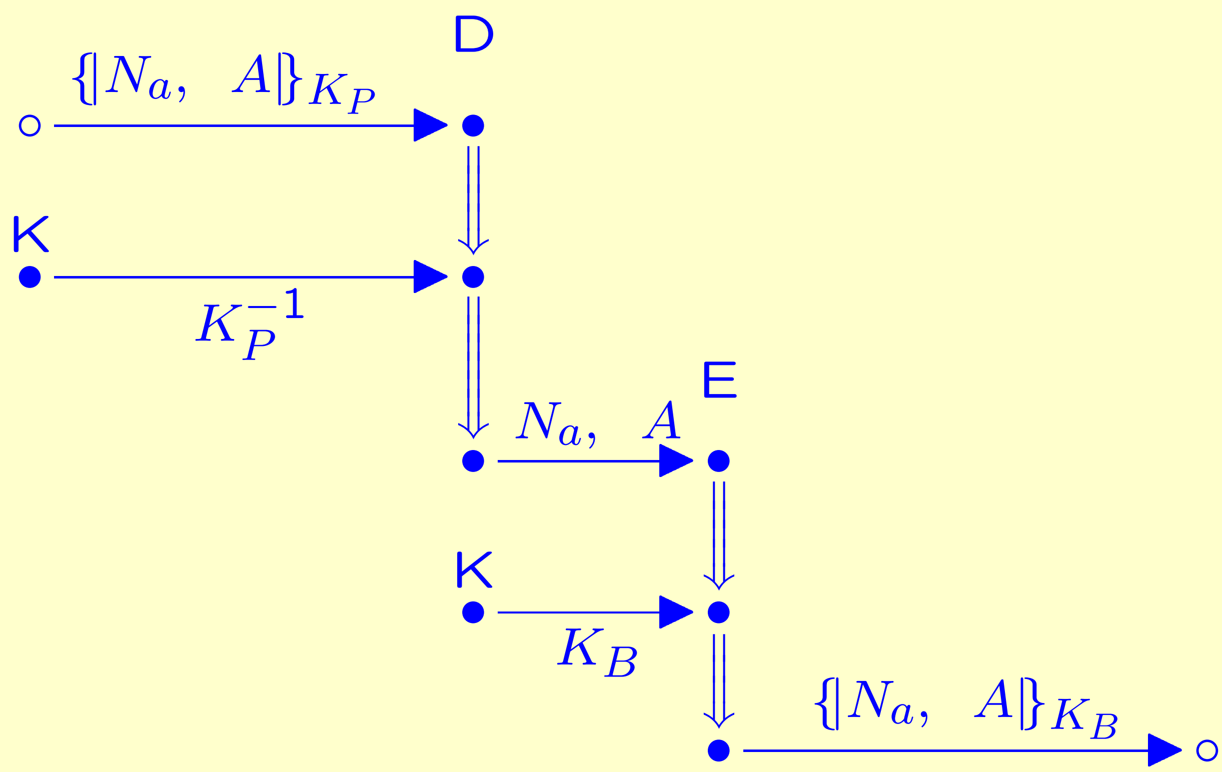
NS Attack: Penetrator Activity



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Protocol Executions are Bundles

- Send, receive events on strands called “nodes”
  - Positive for send
  - Negative for receive
- Bundle $\mathcal{B}$: Finite 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

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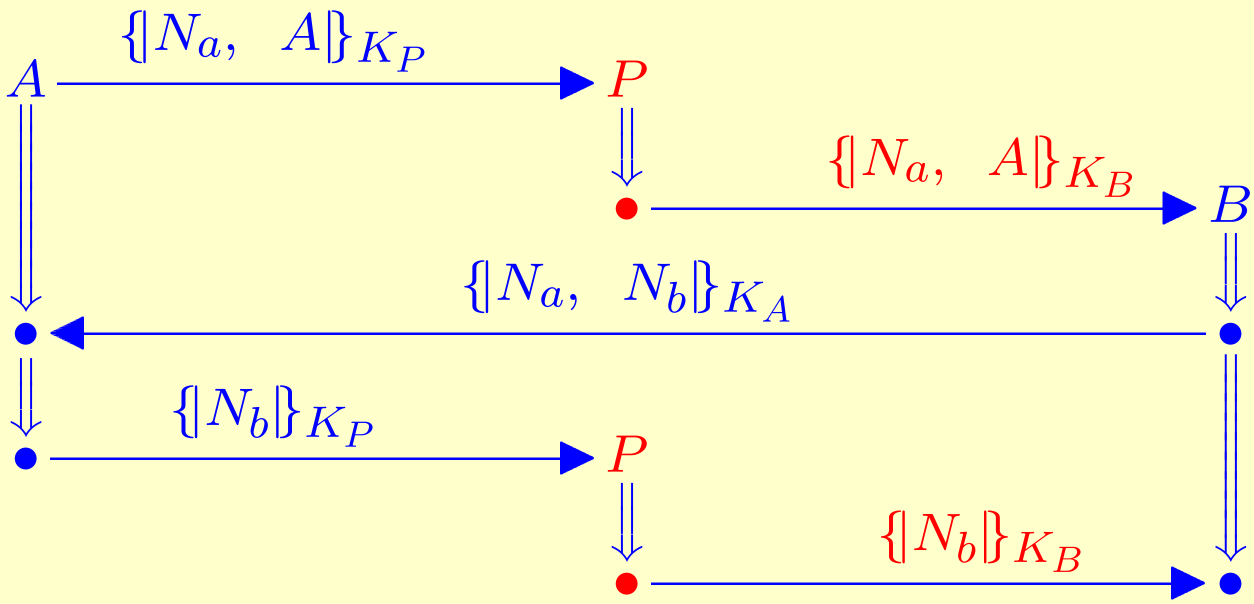
A Bundle



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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 m

  $\preceq_{\mathcal{B}}$ 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

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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

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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. $K \sqsubset \{\!|h|\!\}_K$ implies $K \sqsubset h$
- Represents *contents* of message, not how it's constructed
- t **originates** at n_1 means

  n_1 is a transmission $(+)$
  $t \sqsubset \text{term}(n_1)$
  if $n_0 \Rightarrow \cdots \Rightarrow n_1$, then $t \not\sqsubset \text{term}(n_0)$
- Unique origination, non-origination formalize
  a probabilistic assumption

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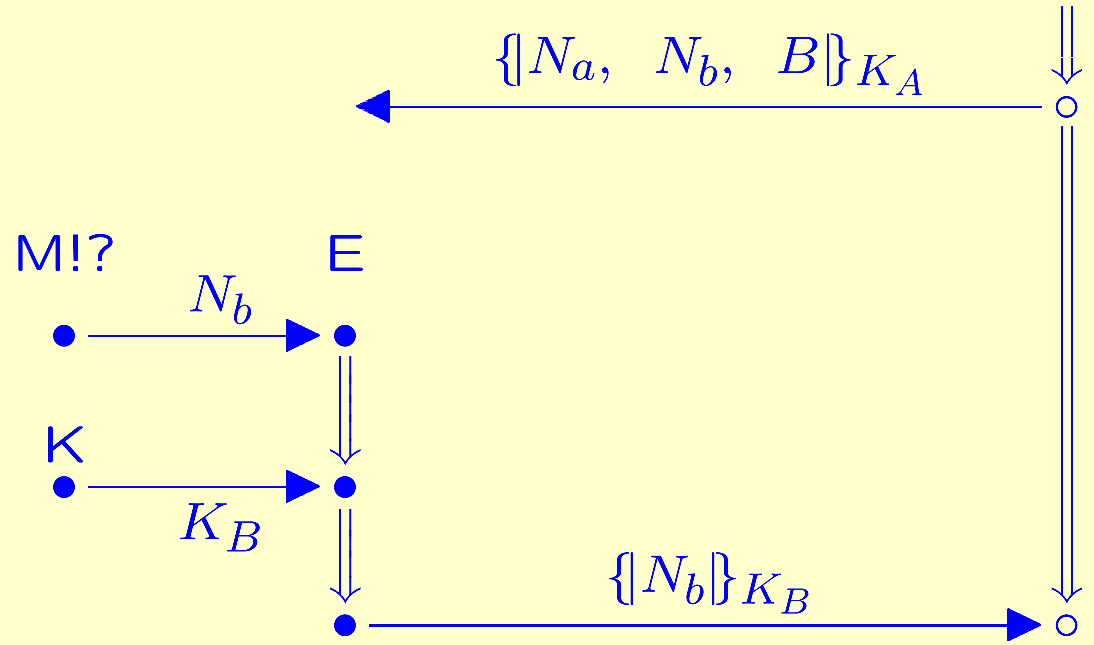
Guessing a Nonce



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

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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 $\mathcal{B}$
- 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

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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

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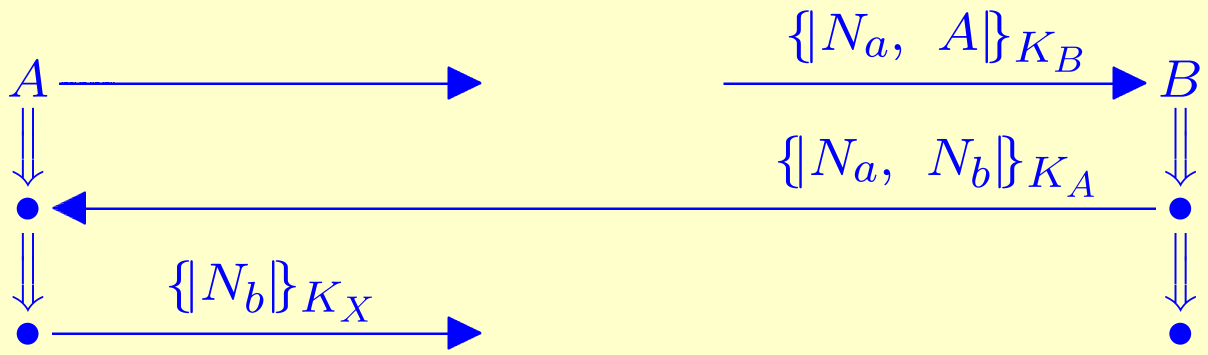
Why NS Fails



NSInit$[A, X, N_a, N_b]$ NSResp$[A, B, N_a, N_b]$

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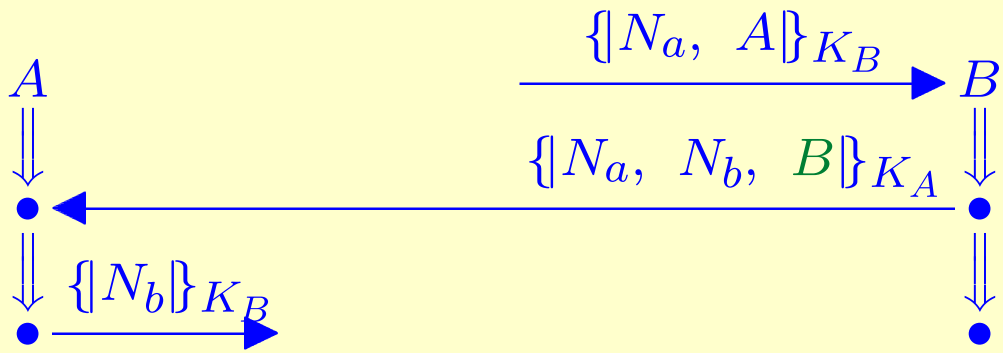
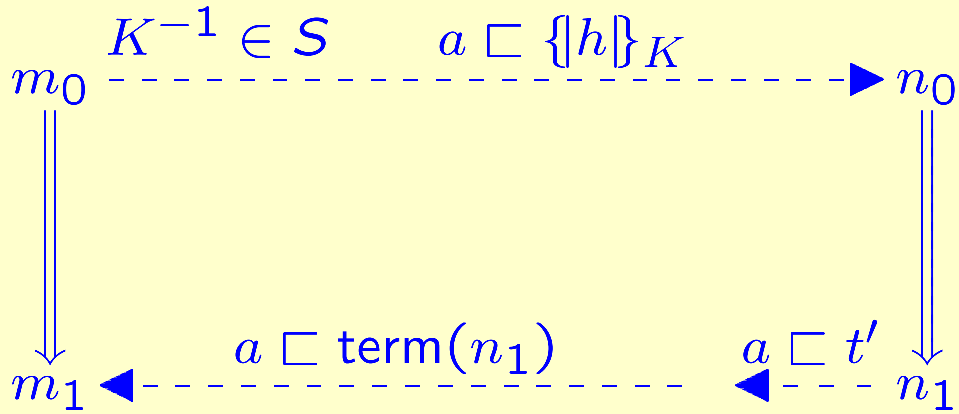
Lowe's Fix



$\mathsf{NSInit}[A, B, N_a, N_b]$ $\mathsf{NSResp}[A, B, N_a, N_b]$

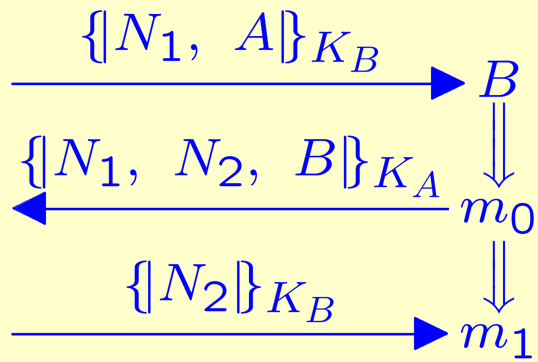
Outgoing Authentication Test



Assume $\{\!|h|\!\}_K \not\sqsubset \mathsf{term}(m_1)$
a originates uniquely at m_0,
a contained only in $\{\!|h|\!\}_K$

Conclude nodes n_0, n_1 exist in $\mathcal{B}$ and are regular
$\{\!|h|\!\}_K \not\sqsubset t'$
$m_0 \prec n_0 \prec n_1 \prec m_1$

NSL: Responder's Outgoing Test



This is an outgoing test

What regular strand can transform $\{\!|N_1,\ N_2,\ B|\!\}_{K_A}$?

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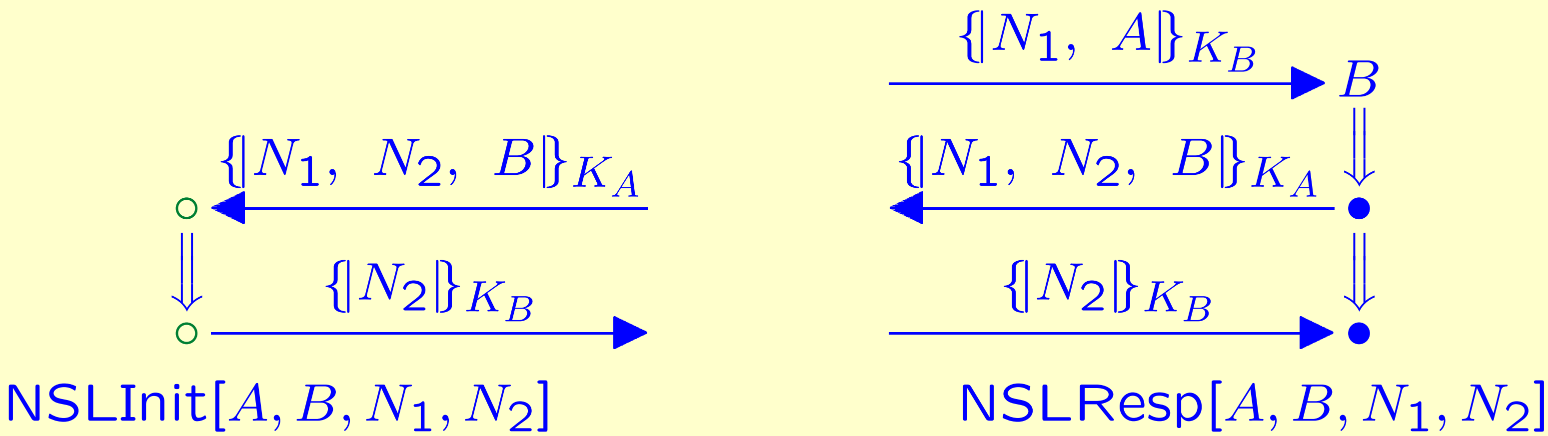
Outgoing Test Conclusion



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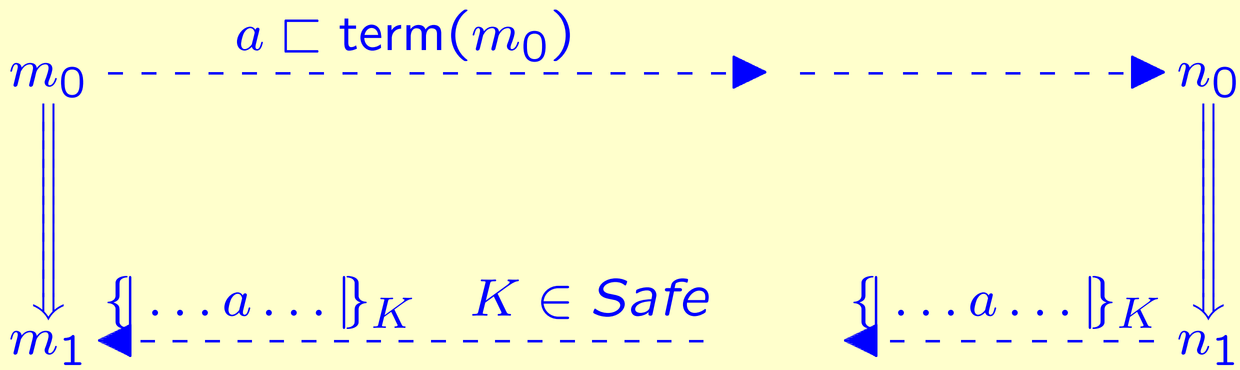
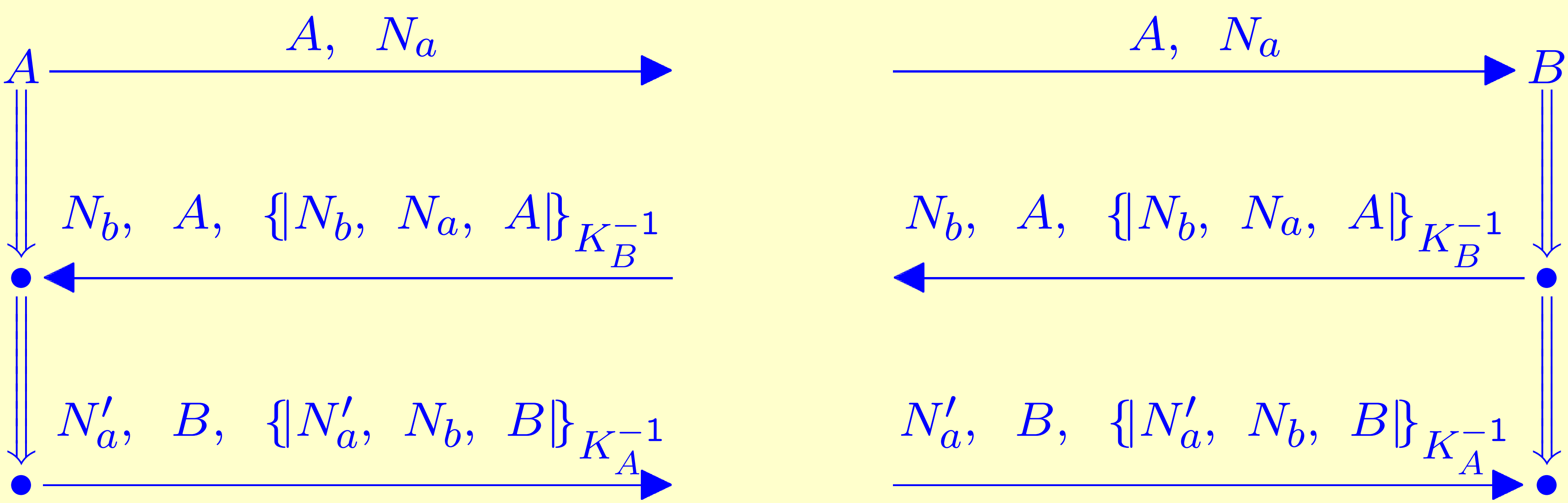
Incoming Tests



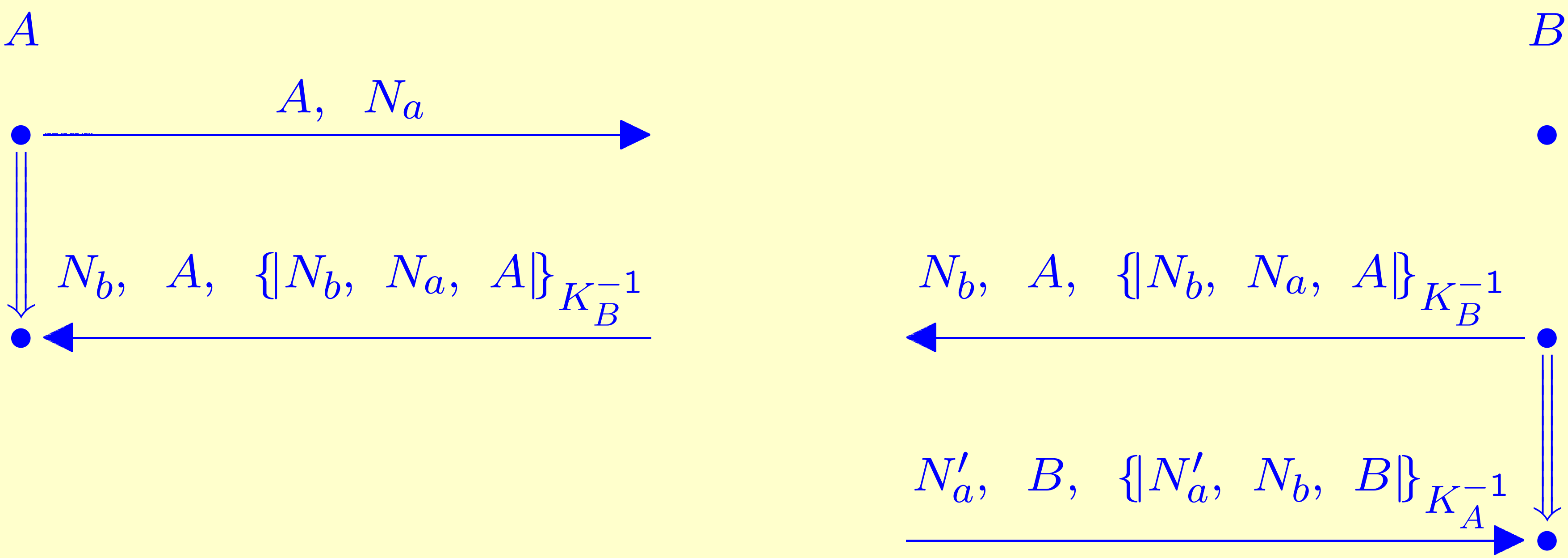
Assume	a originates uniquely at m_0
	$\{\!|\ldots a \ldots|\!\}_K \not\sqsubset \mathsf{term}(m_0)$
Conclude	nodes n_0, n_1 exist in $\mathcal{B}$ and are regular
	$m_0 \prec n_0 \prec n_1 \prec m_1$

Another Protocol (ISO reject)



Mere authentication, using incoming tests

The Incoming Tests



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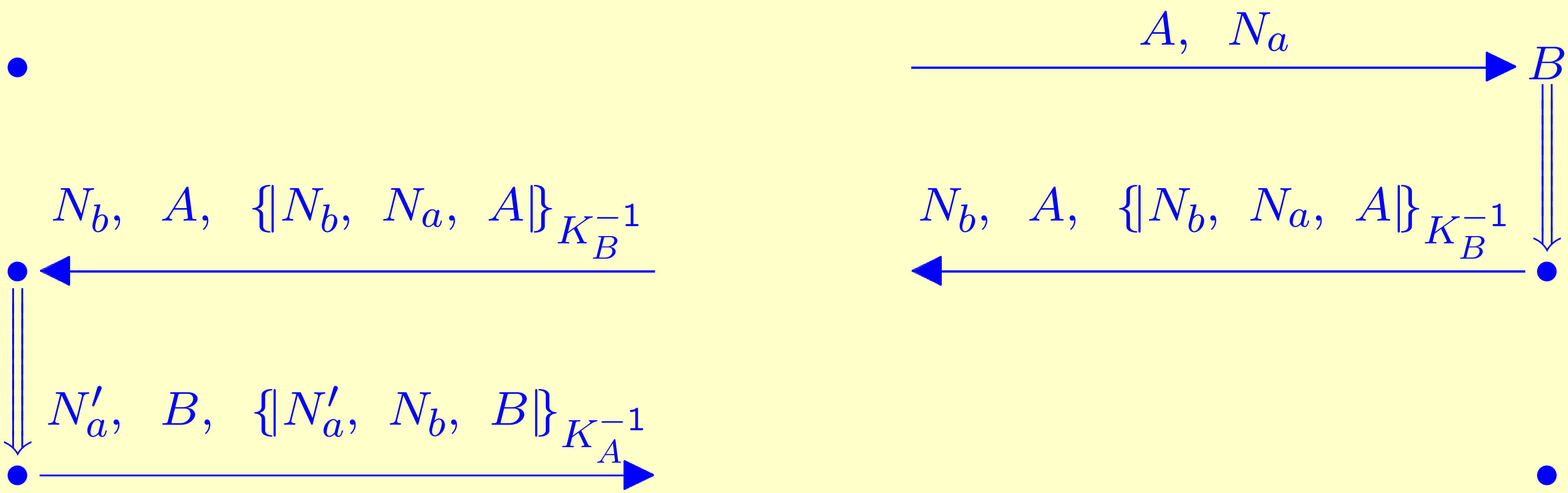
The Transforming Edges



Produce same term
(just rename free variables)

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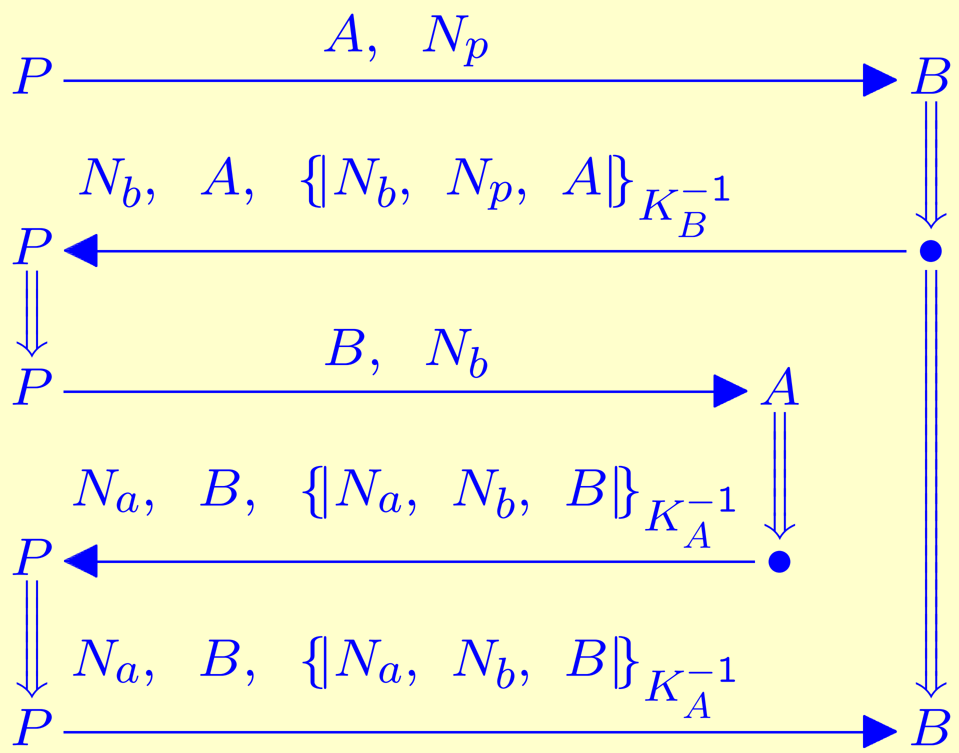
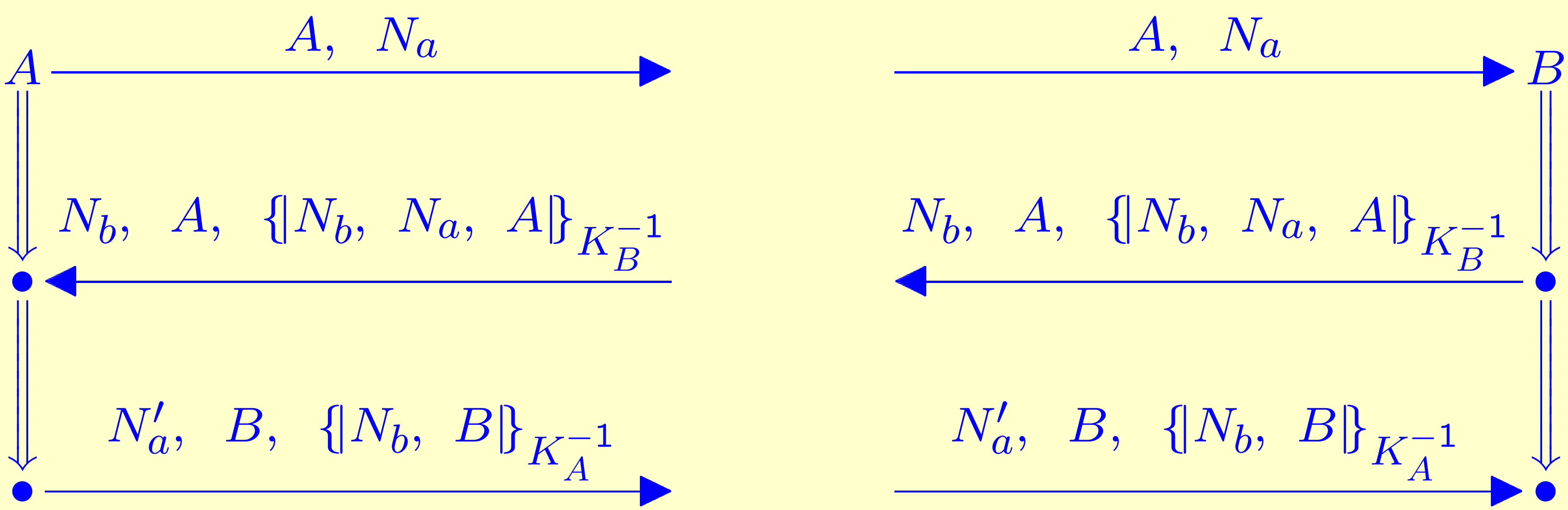
Counterexample to One Security Goal



ISO Reject: Corrected Version



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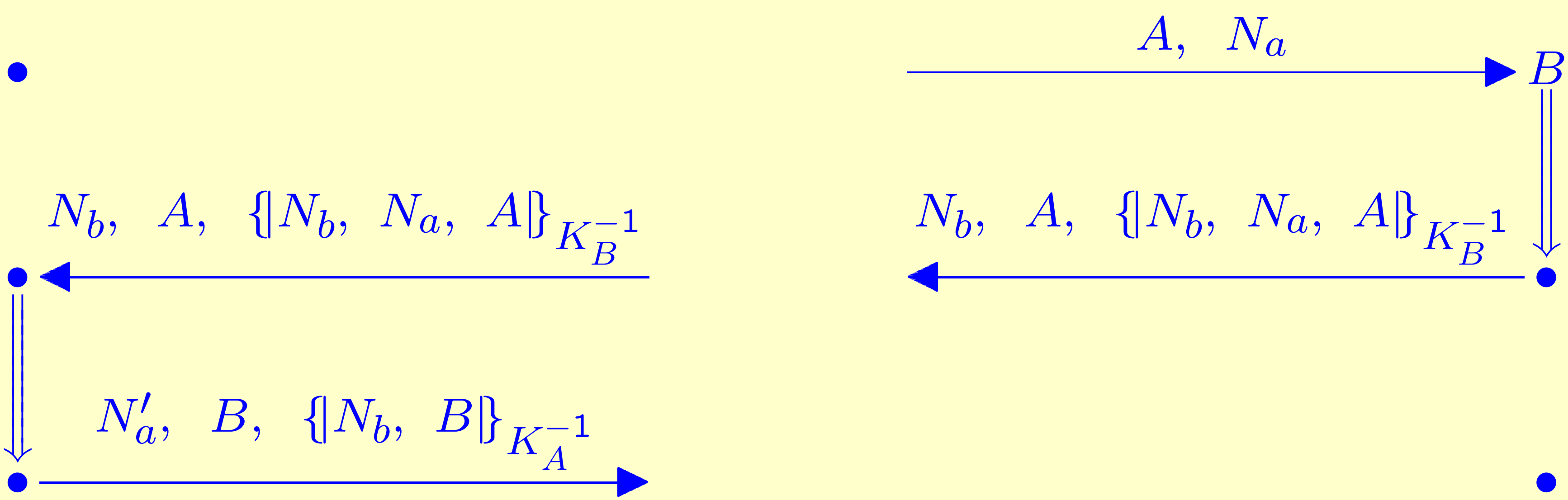
The Transforming Edges



Each test now requires a single, explicit transforming edge

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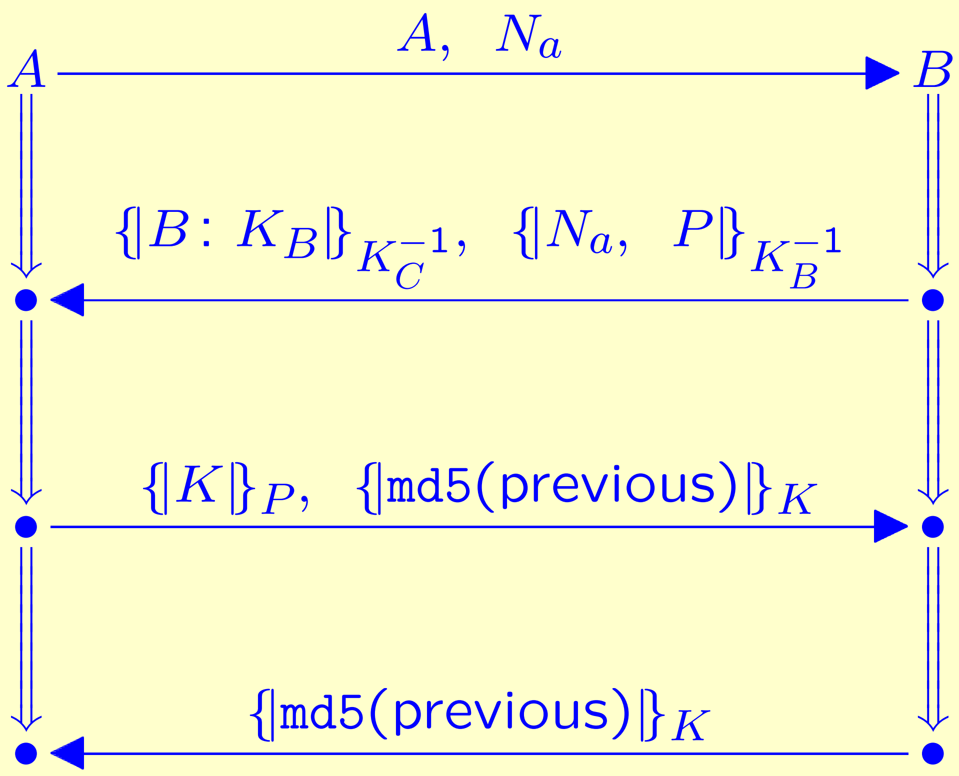
SSSL, a Simplified SSL



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Protocol Design

- Largely a matter of
  - selecting incoming, outgoing tests
  - inserting a single, explicit transforming edge for each
- Choosing an example: comparison with SSL
  - Provides good secrecy and authentication
  - Requires customer to trust merchant
  - Frequently undesirable
- Better: three-party protocol for customer, merchant, and bank
  - Credit card number goes to bank only
  - Item purchased shared with merchant only
  - All three must agree on price

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Secure Electronic Transaction

- SET protocol:
  - Visa, MasterCard, bank alliance
  - Protocol complete in 1997
  - In use nowhere
- Spectacularly complex
  - Hard to analyze
  - Hard to implement
  - Creates risk
- Our goal:
  simple, correct by design alternative

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Protocol Goals

Participants: Customer C, Merchant M, Bank B

Confidentiality All data to remain secret
Data for a pair not to be disclosed to third participant

Authentication, I Each P receives guarantee:
Q received and accepted P's data

Non-Repudiation P can prove its **Authentication, I** guarantee to a third party

Authentication, II Each Q receives guarantee:
data purportedly from P originated with P, in a recent run

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Assumptions

- Uncompromised public/private keypairs:
  - Private signature key
    (Public part for verification)
  - Private decryption key
    (Public part for encryption)

  We write $[\![h]\!]_P$, $\{\!| h |\!\}_P$
- Good hash function h

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Two Party Subprotocols

- Goals are essentially pair-wise
  (except confidentiality for shared data)
- Hence, design set of six two-party subprotocols
  - $C.M$, $C.B$, $M.B$, etc.
  - Each $P.Q$ achieves goals for role P
- Piece them together, later

Confidentiality Send data as $\{\!|\ \ldots,\ \ \mathsf{sec}_{P.Q},\ \ \mathsf{shared}_P |\!\}_Q$

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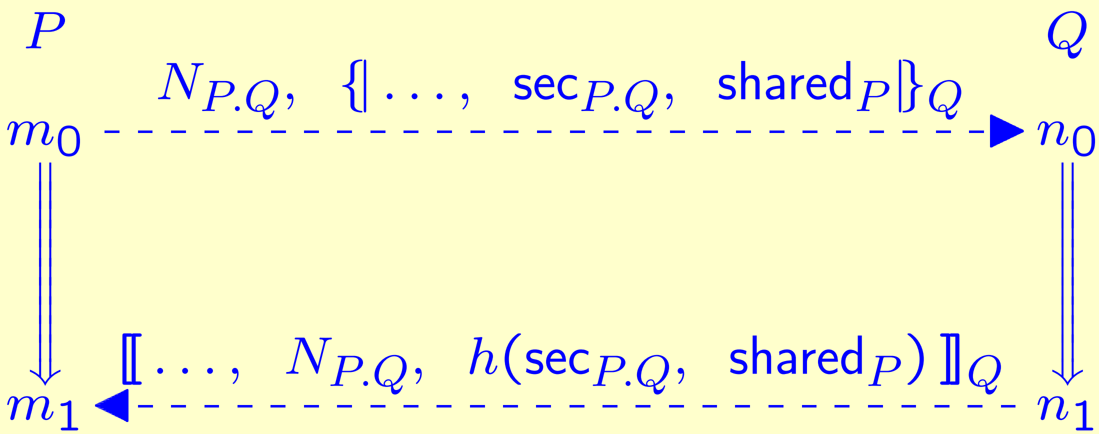
Authentication, I

Each P receives guarantee: Q received and accepted P's data

- Use incoming test:



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Non-Repudiation

P can prove its **Authentication, I** guarantee to a third party

- No additional protocol contents needed
  - P discloses $N_{P.Q}, \ \ldots, \ \mathsf{sec}_{P.Q}, \ \mathsf{shared}_P$
  - Third party verifies signature

    $[\![\ldots, \ N_{P.Q}, \ h(\mathsf{sec}_{P.Q}, \ \mathsf{shared}_P)]\!]_Q$

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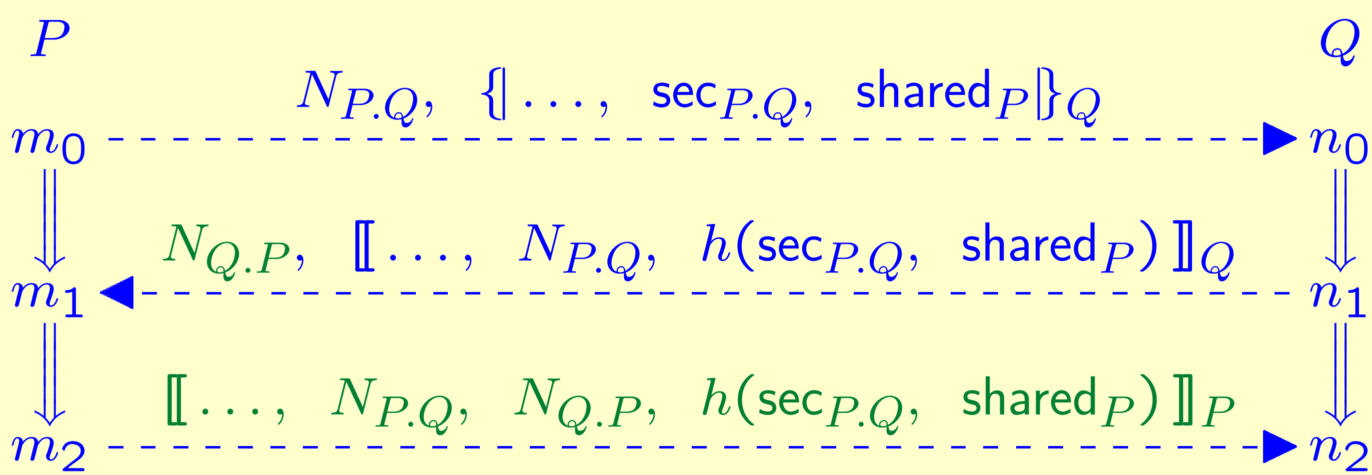
Authentication, II

Each Q receives guarantee:
data purportedly from P originated with P, in a recent run

- Again, use incoming test (right-to-left)



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Preventing Confusion among Subprotocols

- Multiple protocols on same network lead to failures
  - New transforming edges
  - Undermine authentication tests
- We have just designed six protocols
  - Are they still right if executed together?
  - Safer to tag each message with protocol name
    $C.M$, $C.B$, $M.B$, etc
- General theorem:
  disjoint encryption guarantees protocol independence
  (CSFW 2000)

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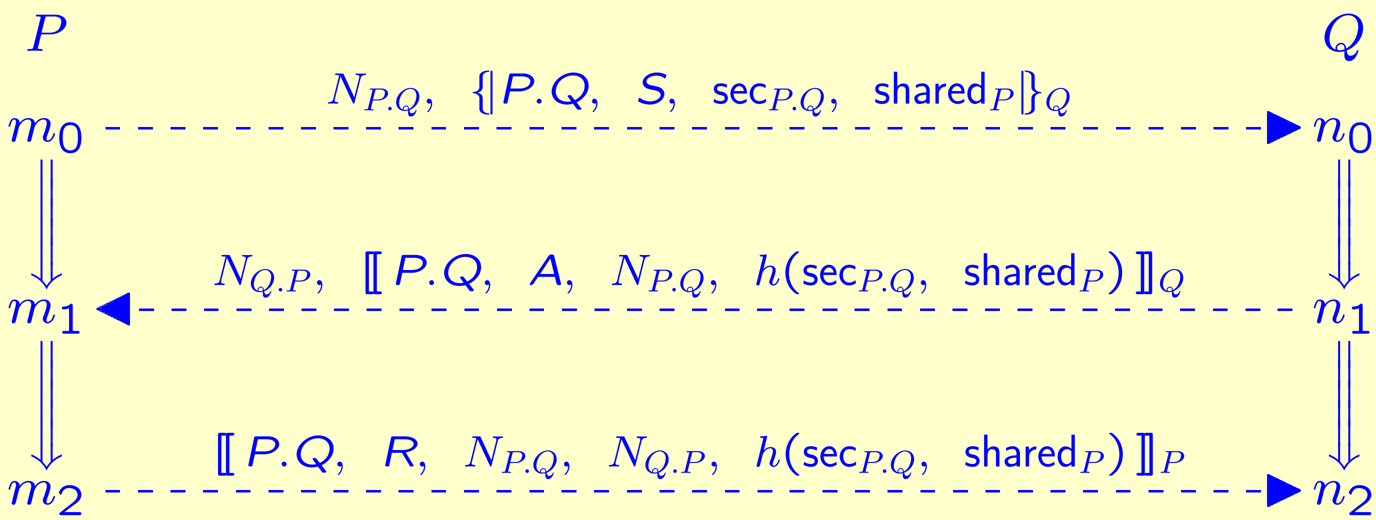
Final Two-Party Protocol



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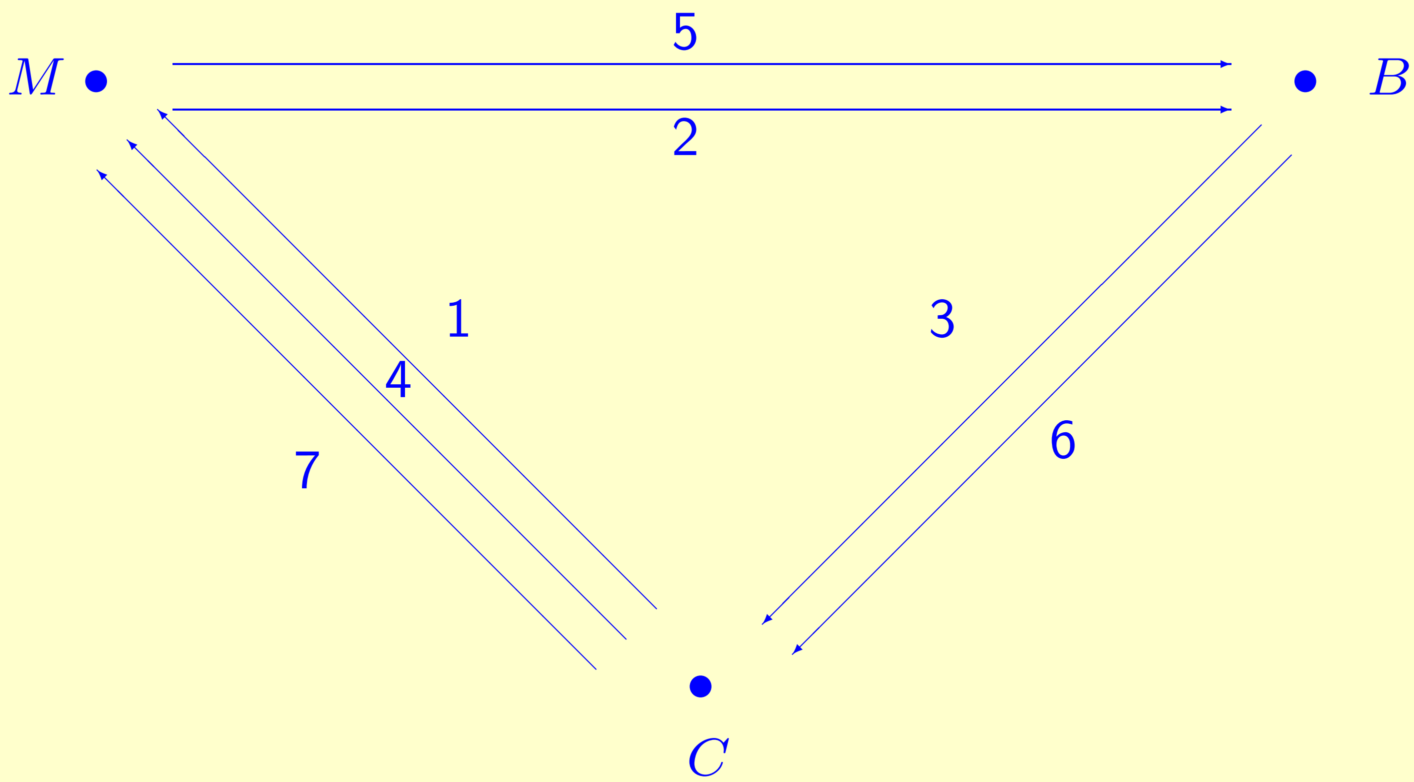
Piecing together the Three Party Protocol



Coordinating the subprotocols

- When to start:
  - C starts when ready
  - M starts on receipt of $C.M$ messages
  - B starts on receipt of $C.B$ messages
- When to emit new messages
  - On receipt of a $P.Q$ message
    P or Q follows the subprotocol
- When to forward message
  - On receipt of a $P.Q$ message
    forward it if neither P nor Q

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Protocol Design via Authentication Tests

- Designed new electronic commerce protocol
  - Trust relations in electronic transactions
  - Uniform, correct-by-design protocol
- Authentication tests:
  - Strong protocol proof method
  - Strong heuristic for design
- But:
  - Purely structural
  - Assume crypto perfect
  - Additional issues if crypto imperfect
- Cryptographic protocols:
  trust infrastructure for distributed systems

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