The Perils of Unauthenticated Encryption: Kerberos Version 4

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- Unauthenticated encryption in Kerberos version 4 creates a critical vulnerability.

- We implemented highly efficient chosen-plaintext attack to impersonate arbitrary principals

- Practical demonstration of importance of authenticating encryption

- Version 5 also differently vulnerable

- Ongoing revisions to version 5 fix these too

Authentication is More Important Than Confidentiality

- Unauthenticated encryption known to be dangerous
- Forging authentic ciphertext more useful than recovering plaintext
- Becoming someone else is more useful than knowing what someone said

Kerberos Vulnerabilities

- Kerberos version 4 has a critical authentication vulnerability allowing impersonation of arbitrary principals
- Caused by multiple design errors
- First specification of Kerberos version 5 (RFC 1510) has related (less serious) weaknesses.
- Upcoming revision to version 5 in IETF fixes even these.
- Despite improvements, obsolete version 4 remains in widespread use — protocols live longer than anticipated

The Version 4 Vulnerability

- Unauthenticated encryption of security-critical information
- Can forge credentials impersonating arbitrary principals
- Encryption oracle using legitimate protocol transactions
- Very efficient attack: $O(n)$ oracle queries to forge n block-long ciphertext
- Successful attack may go completely unnoticed

Vulnerability is Symptom of Design Errors

- Designers of Kerberos version 4 failed to explicitly identify nonmalleability requirement
- Malleability in version 4 allows our attack
- Lack of good encryption abstraction contributed to problems
- Deterministic encryption scheme allows oracle
- Version 5 encryption thwarts oracle creation
- Make cryptographic assumptions explicit
- Create good encryption abstraction

RFC 1510 Flaws

- RFC 1510 uses encrypted plaintext checksums
- Message authentication can be subverted by using encryption oracle
- Designers should ensure that attackers can’t subvert message authentication by ciphertext surgery

Long-Lived Protocols

- Multiple application protocols built on top of Kerberos
- Deployment of security infrastructure expensive
- Resistance to change unless clear and present danger due to expense
- Use conservative design in security protocols
- Evaluate whether apparently theoretical weaknesses indicate more serious problems

Outline

- Kerberos History
- Design Shortcomings of Kerberos Version 4
- Kerberos Version 4 Protocol
- Block Encryption Oracle
- Ticket Ciphertext as Oracle
- Implementation Flaws
- Evolution of Kerberos Encryption

Kerberos History

Historical Overview

- Version 4 designed/deployed at MIT Project Athena (Miller *et al.* 1987; Steiner *et al.* 1988)
- Based on Needham-Schroeder (1978) symmetric-key
- Uses timestamps to mitigate replays (Denning 1981)
- Version 5, defined by RFC 1510
- Ongoing revision of version 5 in IETF

AFS leads to Widespread Deployment

- Andrew File System (AFS) developed at CMU
- AFS protocol uses Kerberos version 4
- Commerical AFS from Transarc/IBM
- Introduction of open-source version OpenAFS led to wider adoption of Kerberos version 4
- Reluctance to update AFS to use Kerberos version 5
- Our attack prompted rapid migration

Prior Work

- Formal correctness analyses (Bella and Riccobene 1997; Bella and Paulson 1998; Burrows *et al.* 1989)

- Deficiencies in encryption scheme (Bellovin and Merritt 1991; Stubblebine and Gligor 1992)

- Encryption oracle attacks against other protocols (Lowe 1996)

Evolution of Kerberos

- RFC 1510 fixes some flaws of version 4; still has some vulnerabilities

- Ongoing work (post-RFC 1510) in IETF
  - More explicit cryptographic abstraction
  - Strategies similar to recent work on SSH protocol (Bellare *et al.* 2002)
  - Fixes flaws in RFC 1510

Design Shortcomings of Kerberos Version 4

Abstract Design Flaws

- Failure to make cryptographic assumptions explicit
- Needham-Schroeder implicitly requires nonmalleable encryption (Dolev *et al.* 2000)
- Kerberos version 4 fails to provide nonmalleability
- Concept of malleability not well-developed at time of design

Concrete Design Flaws

- DES in nonstandard Propagating Cipher Block Chaining (PCBC) mode
- Assumption: error propagation properties of PCBC sufficient to scramble plaintext after manipulation
- Constant Initialization Vector (IV)
- Use of PCBC for integrity via known values at end of plaintext
- PCBC as integrity check fails spectacularly
- PCBC insufficient against encryption oracle

Lack of Abstraction

- Dependency between integrity and message layout indicates lack of sufficient abstraction of encryption
- Separation of encryption and message details previously emphasized (Bellovin and Merritt 1991)
- Security of encryption should not depend on packet layout details

Our Attack Nearly Discovered Earlier

- Version 4 security assumptions do not include encryption oracle
- Existing chosen-plaintext attack (Voydock and Kent 1983) against CBC mode with fixed IV.
- Designers of version 4 were unaware
- Designers of version 5 nearly uncovered our attack on version 4 during design discussions
- Dismissed by (incorrect!) argument that first plaintext block is randomized
- Again, indicative of insufficiently abstracted encryption

Kerberos Version 4 Protocol

Dramatis Personae

- Trusted third party: Key Distribution Center (KDC)
- Client
- Server

Keys and Other Elements

- Client A's long-term key: k_a
- Server B's long-term key: k_b
- Ticket: ciphertext encrypted with k_b
  - Identifies client
  - Contains session key
- Credential: ticket and session key k_{ab}
- Ticket alone insufficient; also must prove knowledge of session key

Obtaining Credentials

- Two conceptual services in KDC
  - Authentication Service (AS)
  - Ticket Granting Service (TGS)
- The AS issues credentials encrypted using client's long-term key k_a
- The TGS acts as a special application service for obtaining additional credentials
- Typically, client uses AS exchange to get ticket for TGS; permits single sign-on

AS Exchange

Here, client requests a ticket granting ticket (TGT) for later use with the TGS.

$$
\begin{aligned}
A \rightarrow S &: A, S \\
S \rightarrow A &: \{k_{as}, S, \{A, S, t_s, k_{as}\}k_s\}k_a
\end{aligned}
$$

t_s	KDC's timestamp
$\{M\}k_x$	M encrypted with key k_x
A	client name
S	TGS name
k_a	client long-term key
k_s	TGS long-term key
k_{as}	session key between client and TGS
$\{A, S, t_s, k_{as}\}k_s$	ticket

TGS Exchange

Here, client requests ticket for service B from the TGS.

$$\begin{aligned} A \rightarrow S &: \{A, S, t_s, k_{as}\}k_s, \{A, t_a\}k_{as}, B \\ S \rightarrow A &: \{k_{ab}, B, \{A, B, t'_s, k_{ab}\}k_b\}k_{as} \end{aligned}$$

t_a	client's timestamp
B	server name
k_b	server long-term key
k_{as}	session key between client and TGS
$\{A, S, t_s, k_{as}\}k_s$	TGT
$\{A, t_a\}k_{as}$	authenticator for TGS request
$\{A, S, t'_s, k_{ab}\}k_b$	service ticket

Authenticator assures TGS that client has recent knowledge of session key k_{as}.

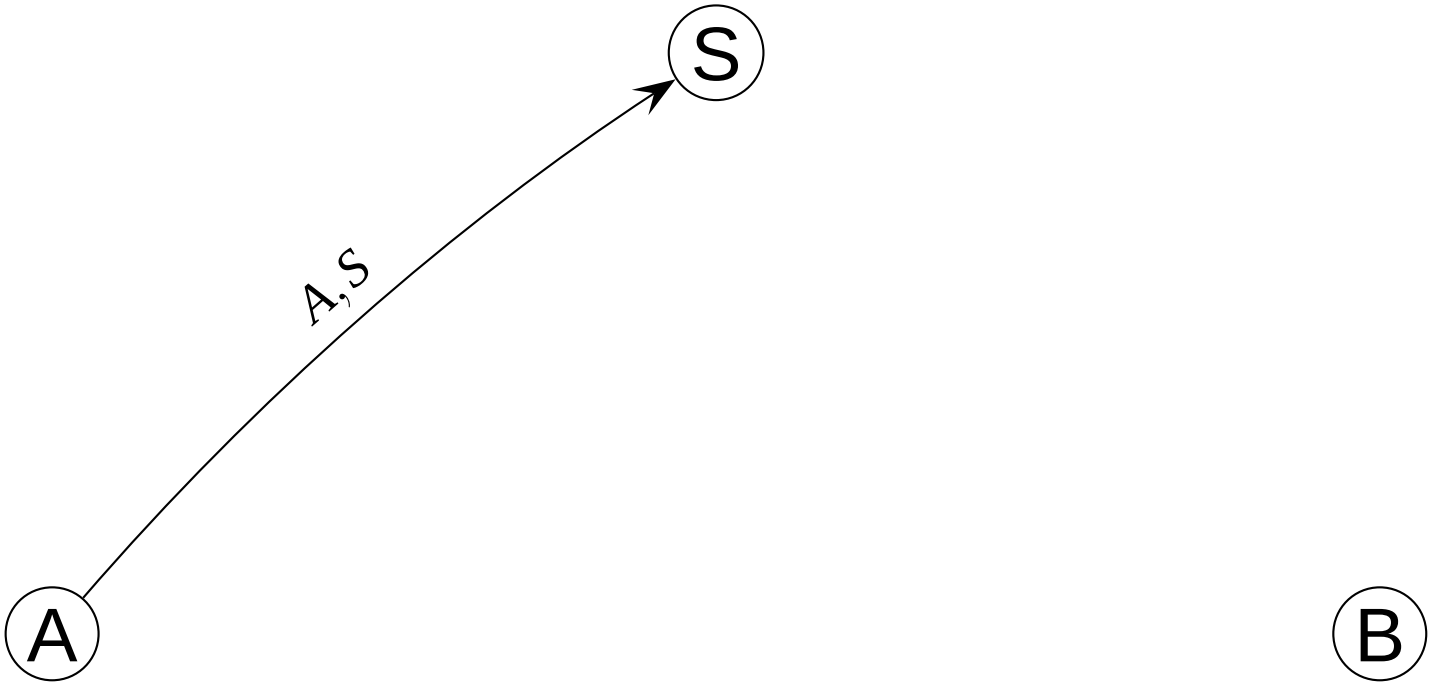
Using Credential

Client sends application request

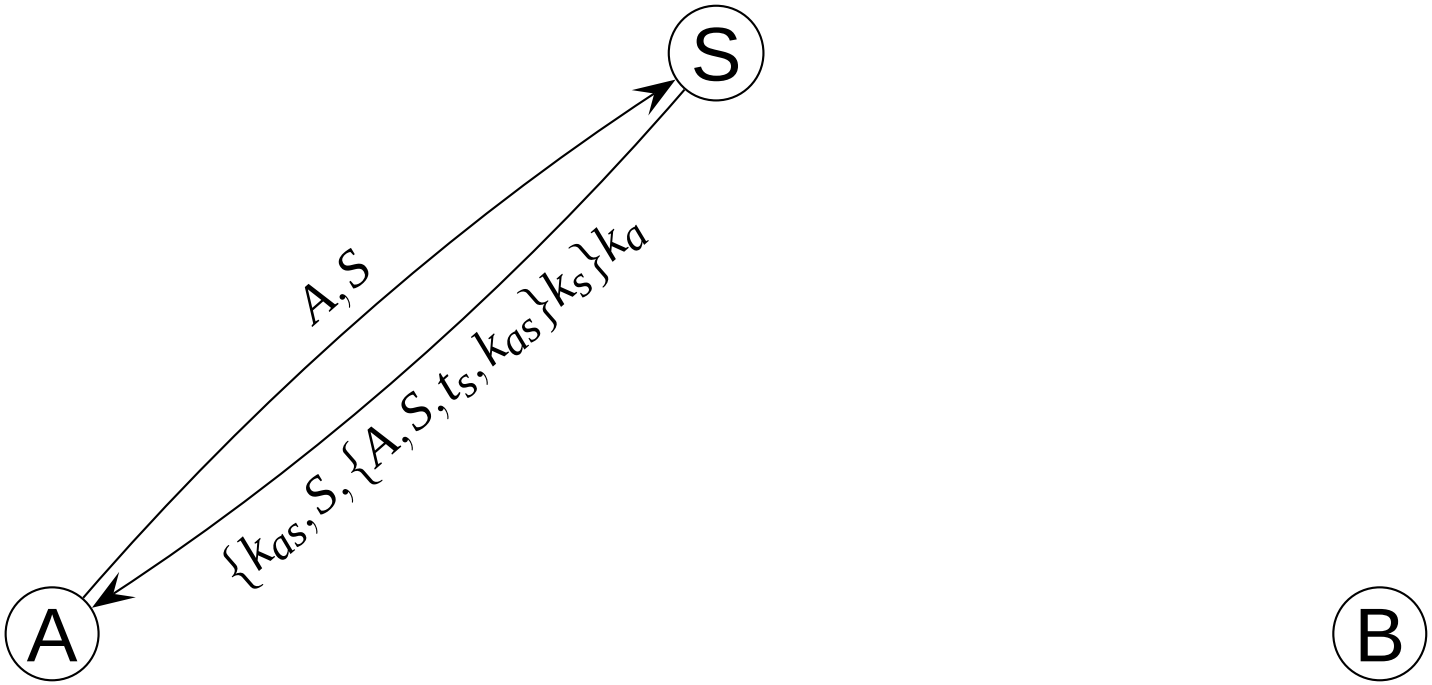
$$A \rightarrow B : \{A, B, t_s', k_{ab}\}k_b, \{A, t_a'\}k_{ab}$$

Authenticator $\{A, t_a'\}k_{ab}$ proves to service B that A has recent knowledge of session key k_{ab}.

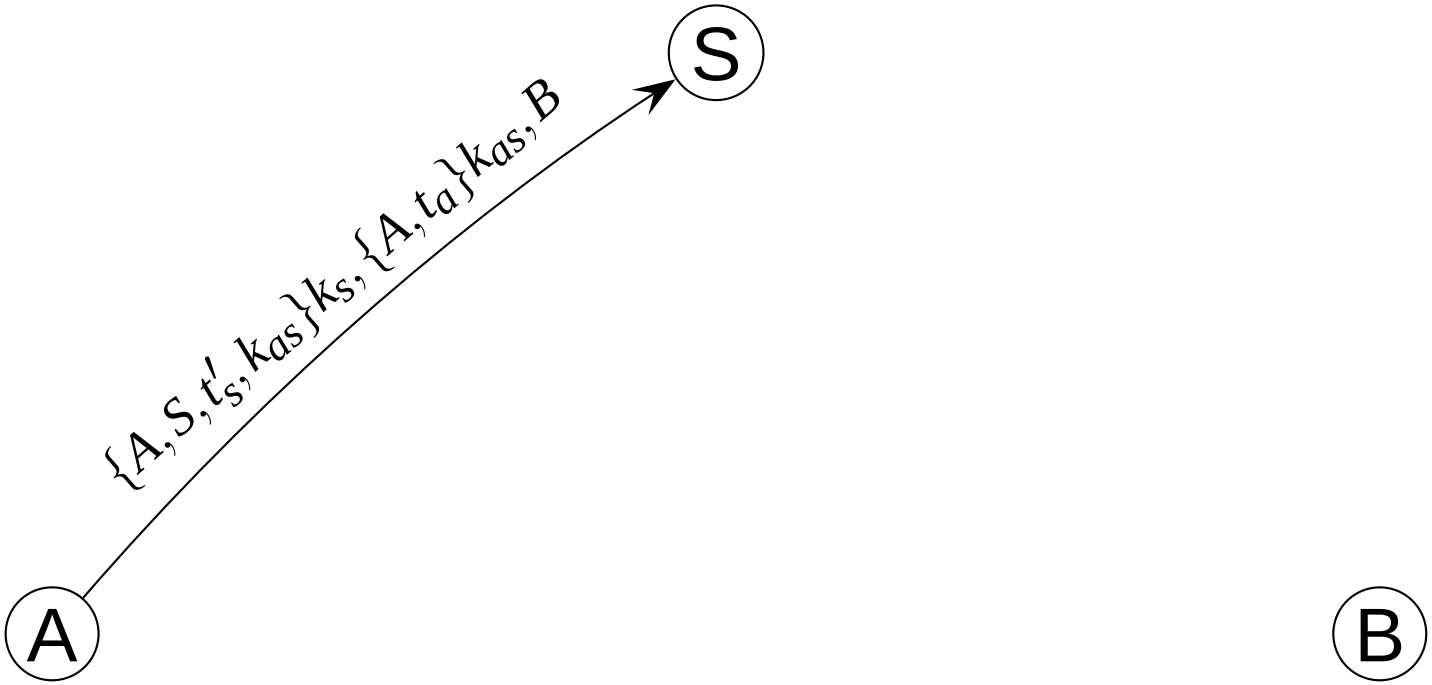
AS Request



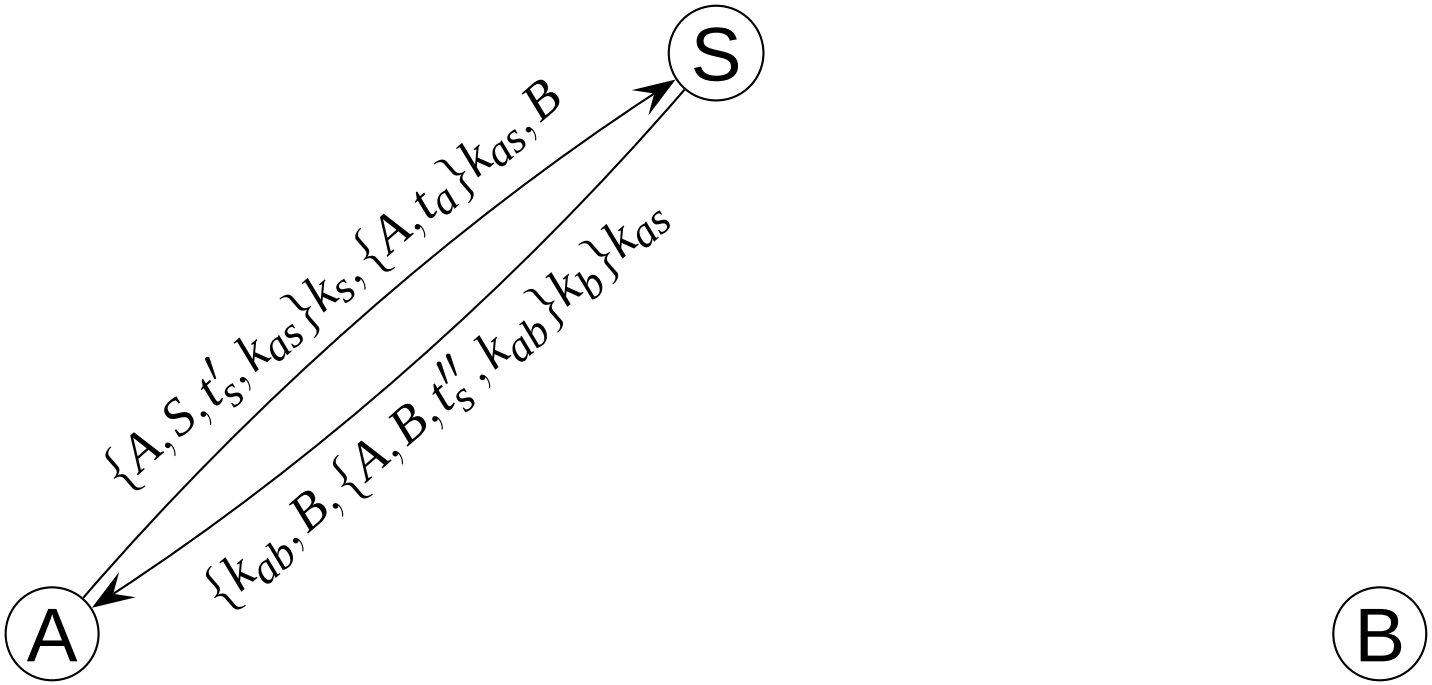
AS Reply



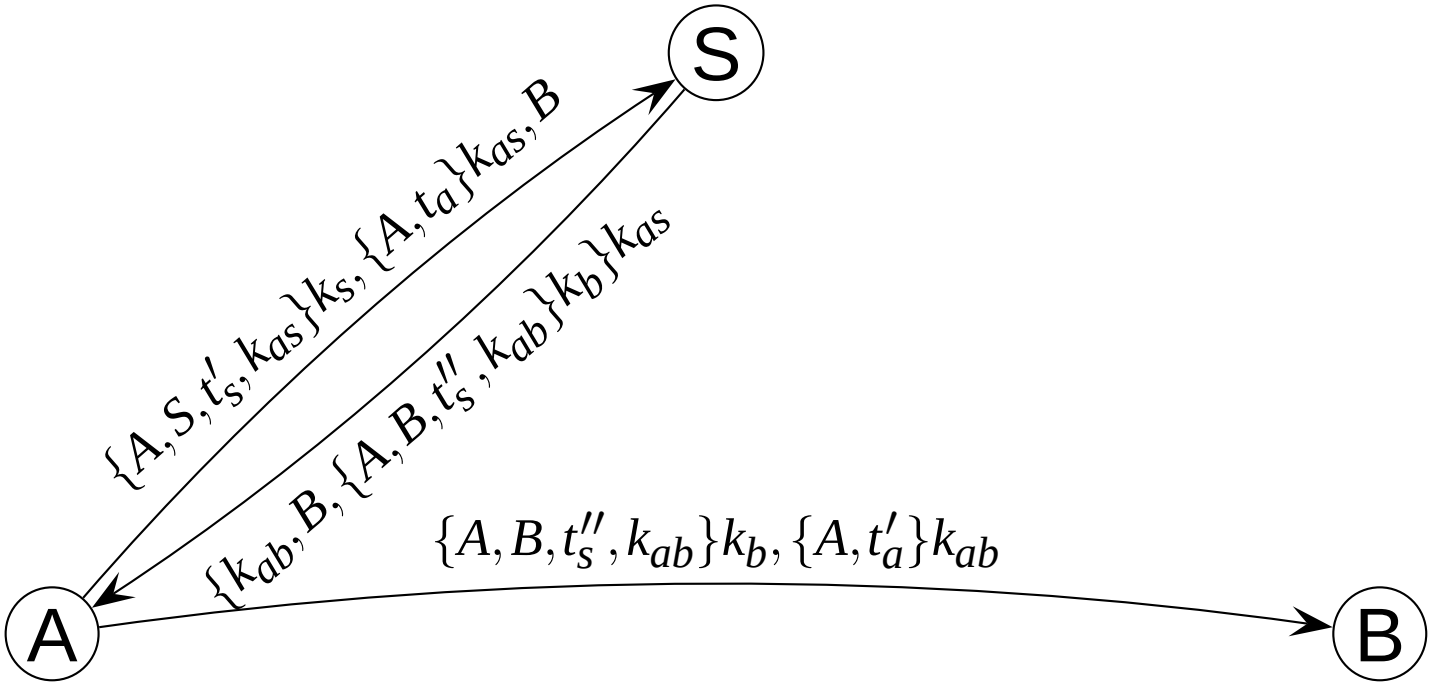
TGS Request



TGS Reply



Application Request



Kerberos Names

- Form of principal name has implications for attack
- Principal name is a triple

$$\{primaryname, instance, realm\}$$

- Usually displayed like

$$primaryname\texttt{.}instance@realm$$

- Normal TGS principal name

$$\texttt{krbtgt.}realm@realm$$

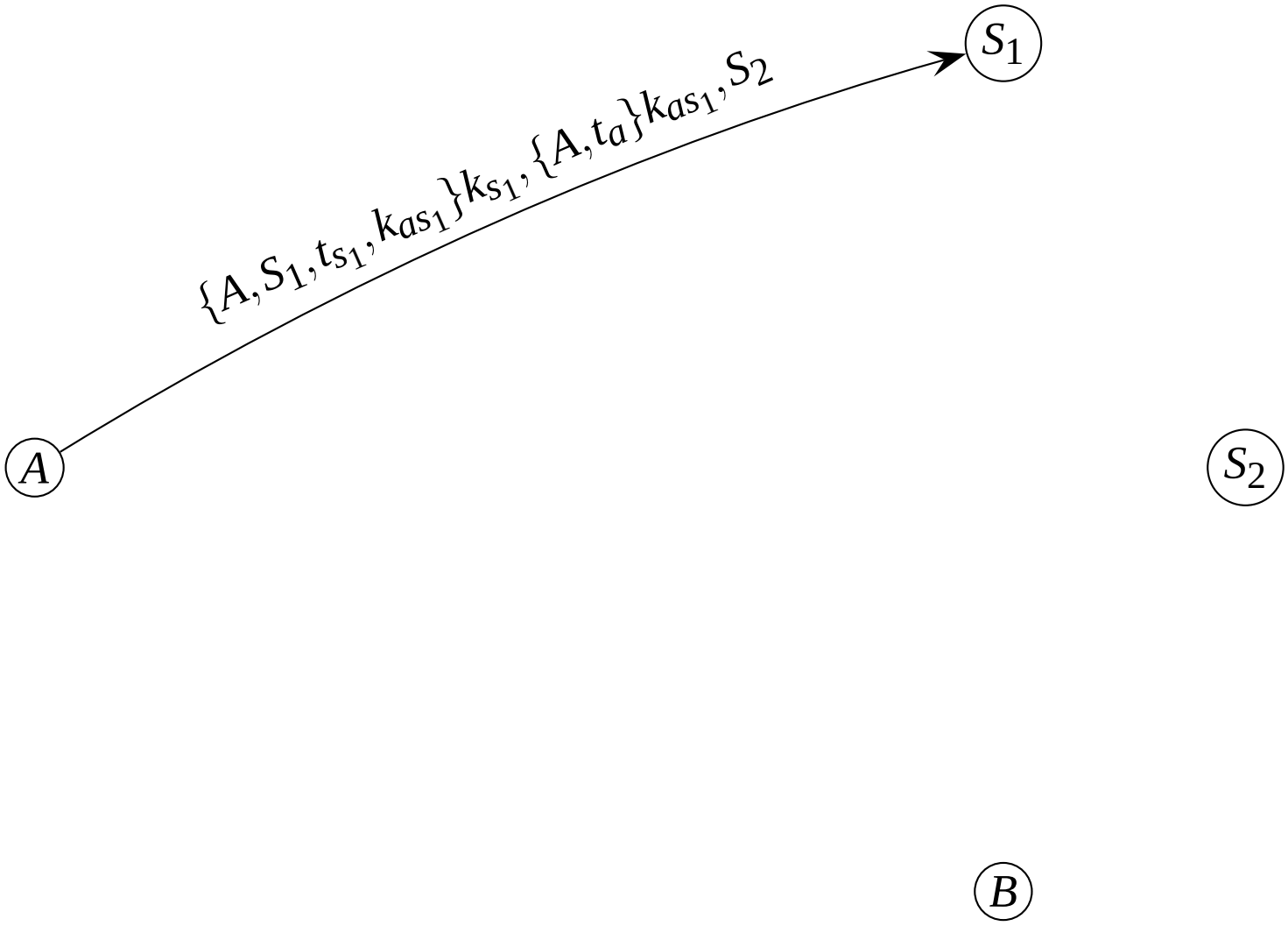
- Cross-realm TGS principal name

$$\texttt{krbtgt.}localrealm@foreignrealm$$

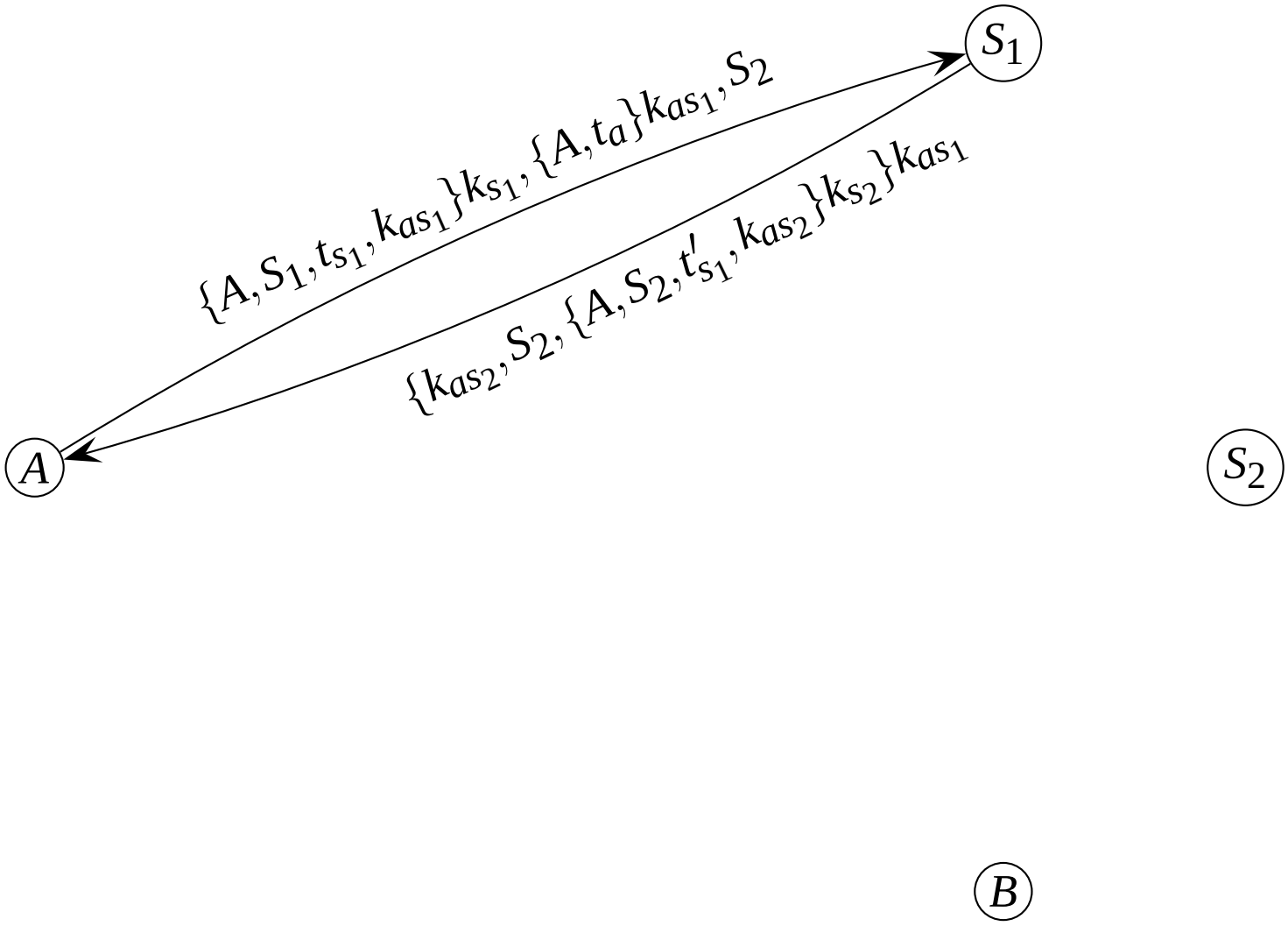
Cross-realm Authentication

- Local KDC checks cross-realm TGT for client principal realm matching foreign realm; local KDC can’t normally issue ticket certifying wrong client realm
- Implementation flaws allow for circumvention of this check
- As designed, sharing cross-realm keys only implies trust that foreign realm trustworthy for its own principals
- Compromise of foreign realm only renders that realm’s principals untrustworthy
- Cryptographic flaws invalidate these trust assumptions
- Cross-realm TGS requests useful for inserting known plaintext

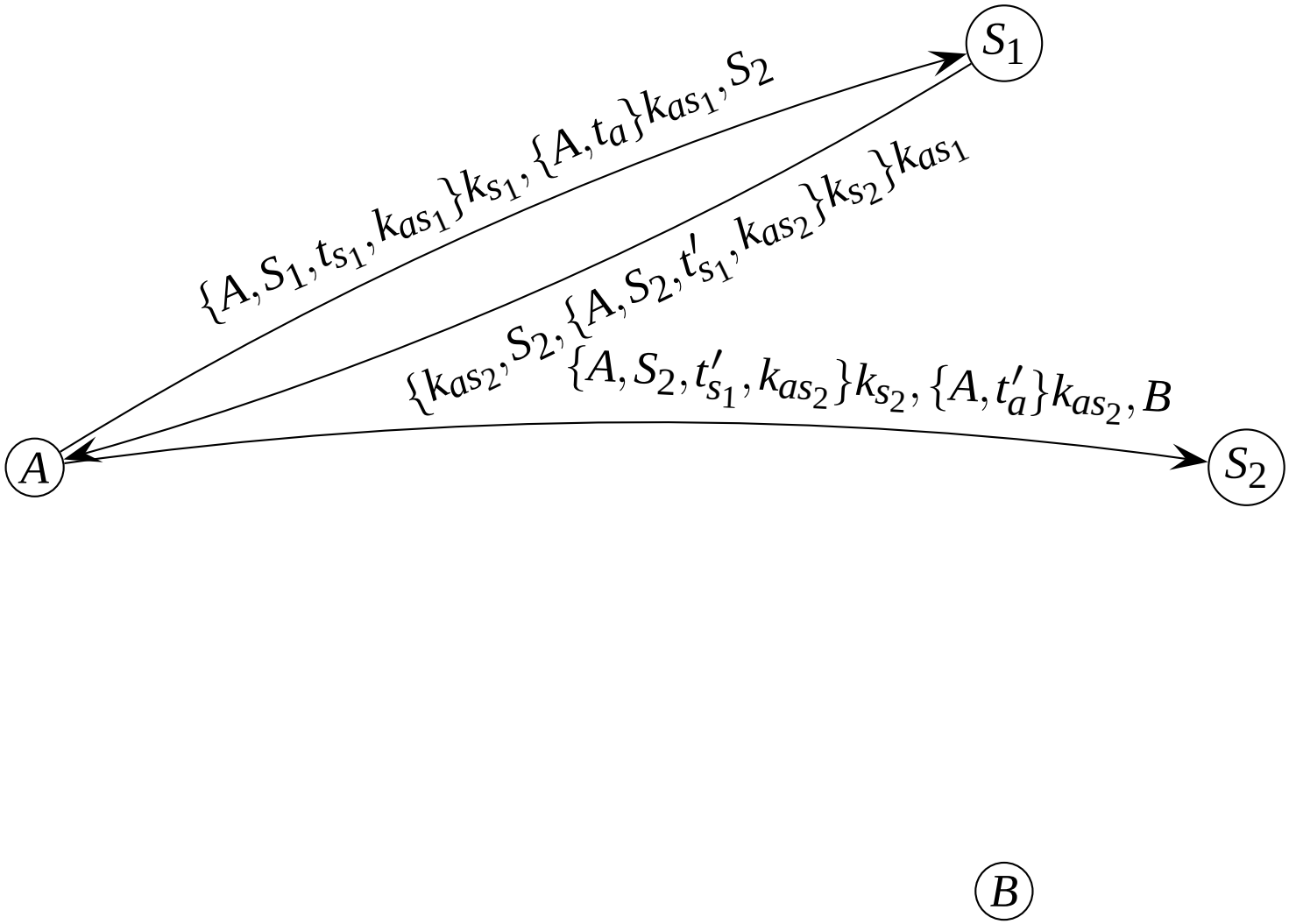
TGS Request for S_2



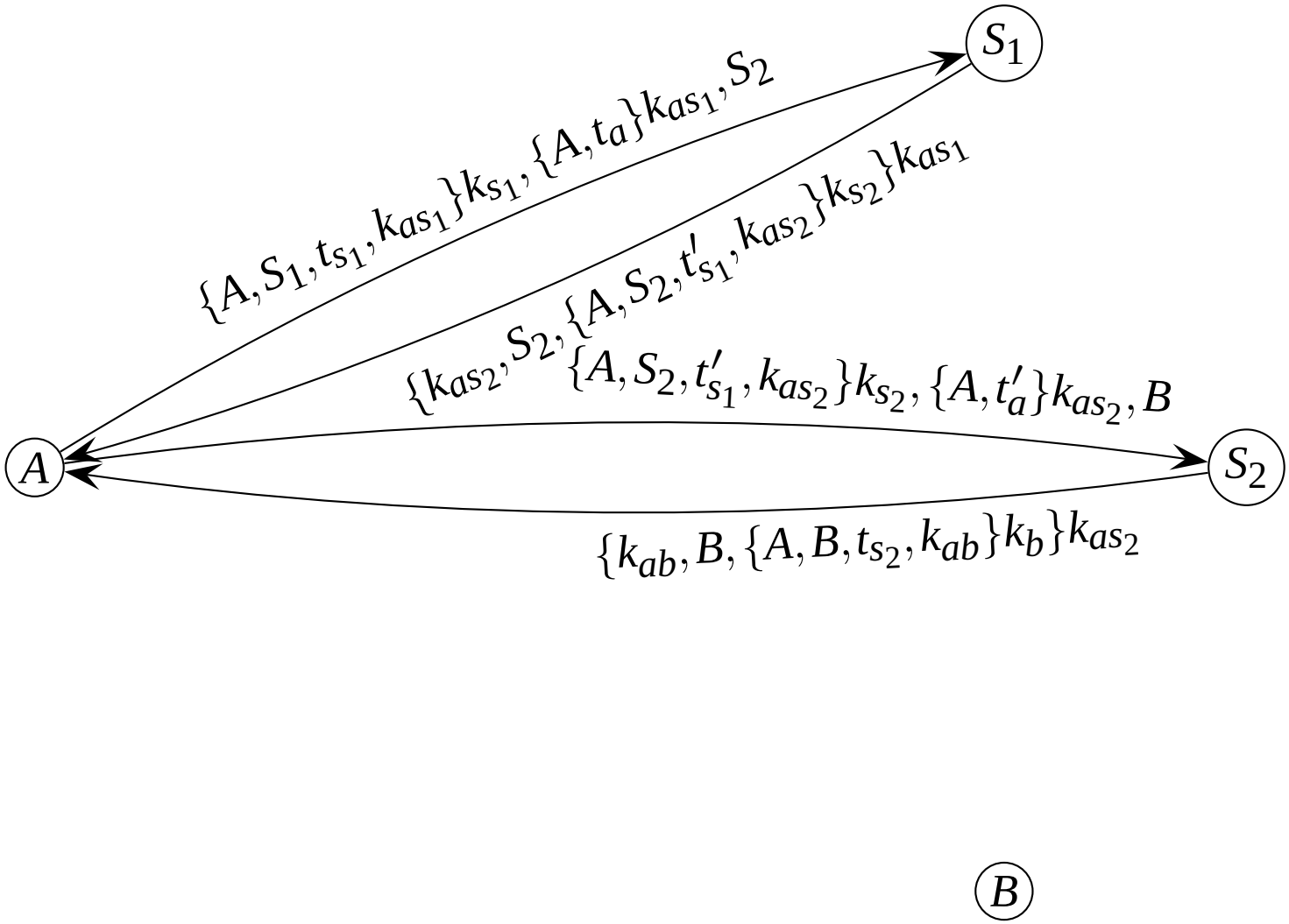
TGS Reply for S_2



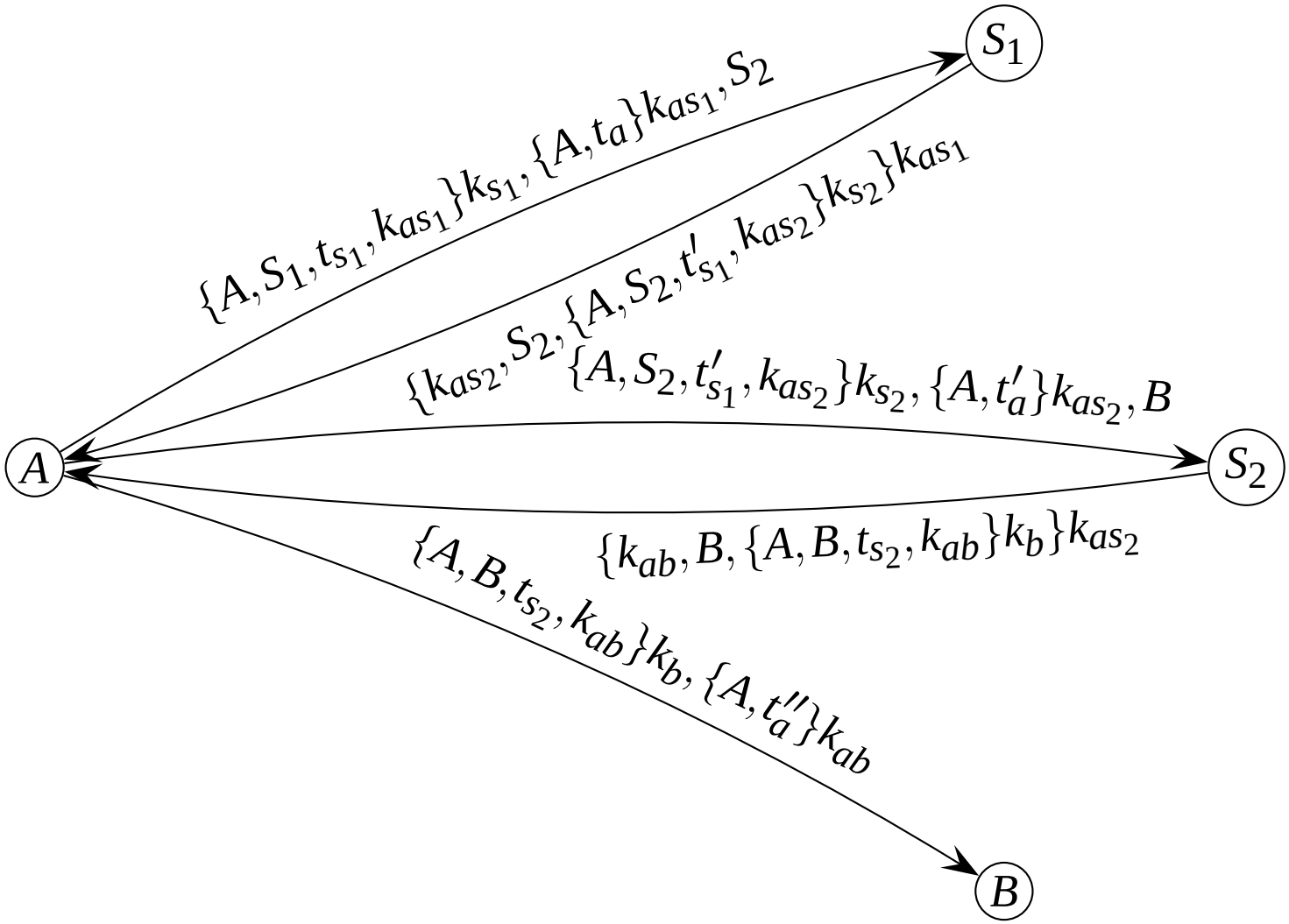
TGS Request for B



TGS Reply for B



Application Request to B



Block-Encryption Oracle

Block-Encryption Oracle

- Chosen plaintext allows block-encryption oracle in Kerberos version 4
- Oracle takes advantage of fixed or predictable IV
- Oracle uses structure of CBC or PCBC mode

Cipher Modes

- Cipher Block Chaining (CBC) mode

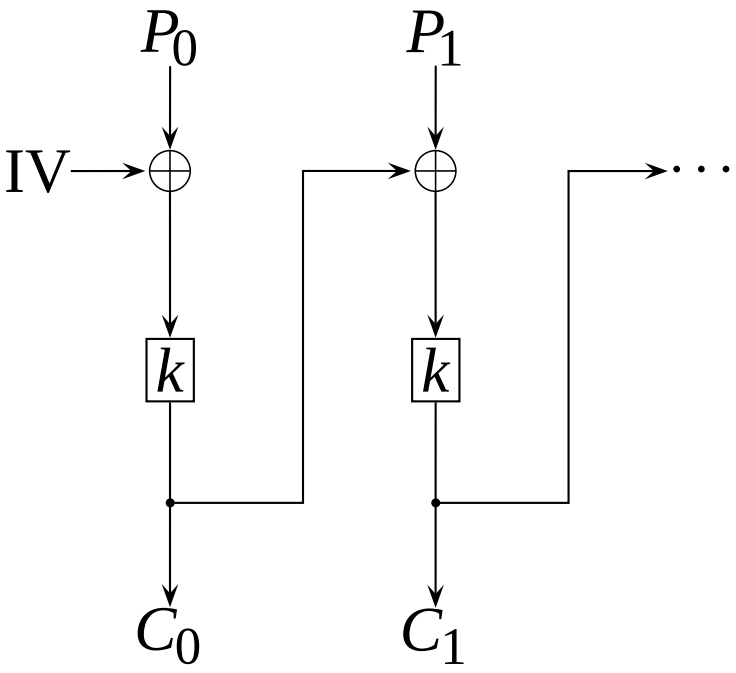
$$\begin{aligned} C_{i+1} &= k(P_{i+1} \oplus C_i) \\ P_{i+1} &= k^{-1}(C_{i+1}) \oplus C_i \end{aligned}$$

- Propagating Cipher Block Chaining (PCBC) mode

$$\begin{aligned} C_{i+1} &= k(P_{i+1} \oplus C_i \oplus P_i) \\ P_{i+1} &= k^{-1}(C_{i+1}) \oplus C_i \oplus P_i \end{aligned}$$

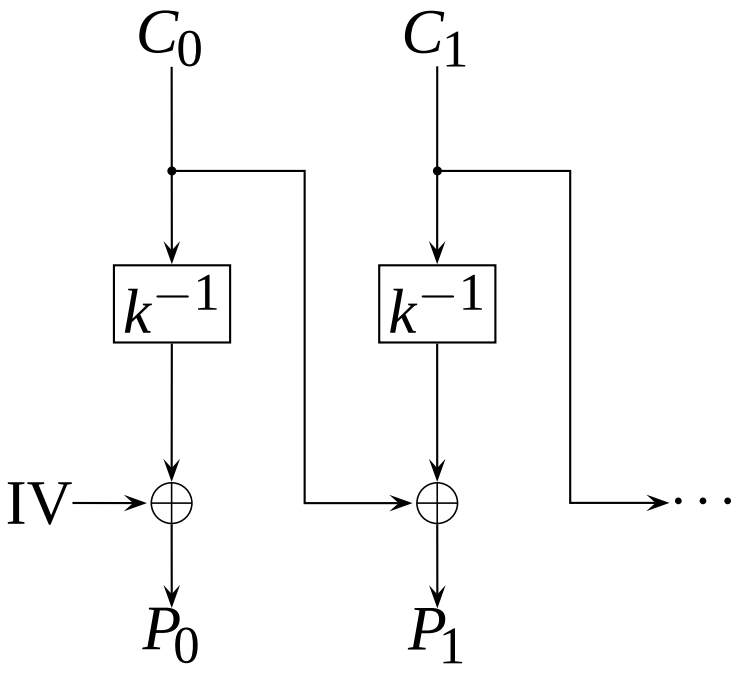
$C_0, C_1, \ldots, C_n$	ciphertext blocks
$P_0, P_1, \ldots, P_n$	plaintext blocks
$k(x)$	encryption of block x with key k
$k^{-1}(x)$	decryption of block x with key k
$x \oplus y$	bitwise exclusive-OR of x with y

CBC encrypt



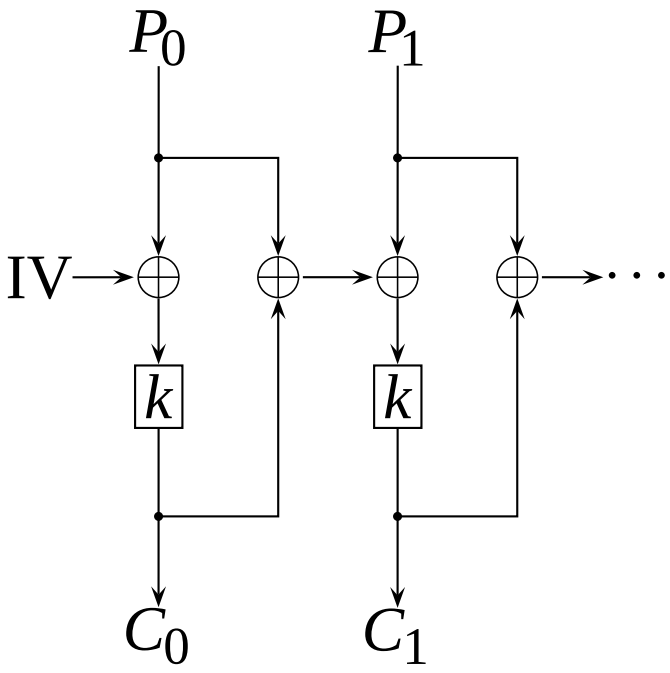
$$C_{i+1} = k(P_{i+1} \oplus C_i)$$

CBC decrypt



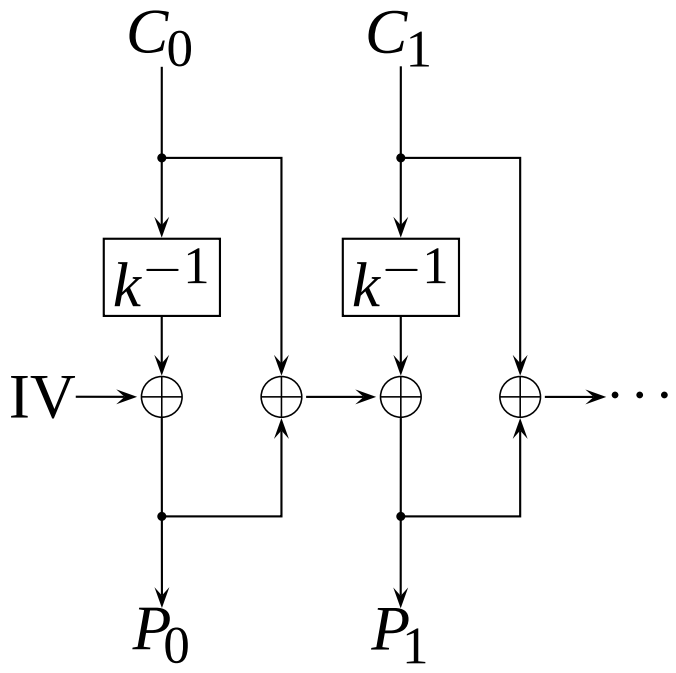
$$P_{i+1} = k^{-1}(C_{i+1}) \oplus C_i$$

PCBC encrypt



$$C_{i+1} = k(P_{i+1} \oplus C_i \oplus P_i)$$

PCBC decrypt



$$P_{i+1} = k^{-1}(C_{i+1}) \oplus C_i \oplus P_i$$

Generalized Feedback Modes

- CBC and PCBC can be generalized as feedback modes

$$\begin{aligned} C_i &= k(P_i \oplus F_i) \\ P_i &= k^{-1}(P_i) \oplus F_i, \end{aligned}$$

- F_i is i-th feedback block; not necessarily transmitted

- CBC mode: $F_{i+1} = C_i$

- PCBC mode: $F_{i+1} = C_i \oplus P_i$

Predictable Feedback Makes an Oracle

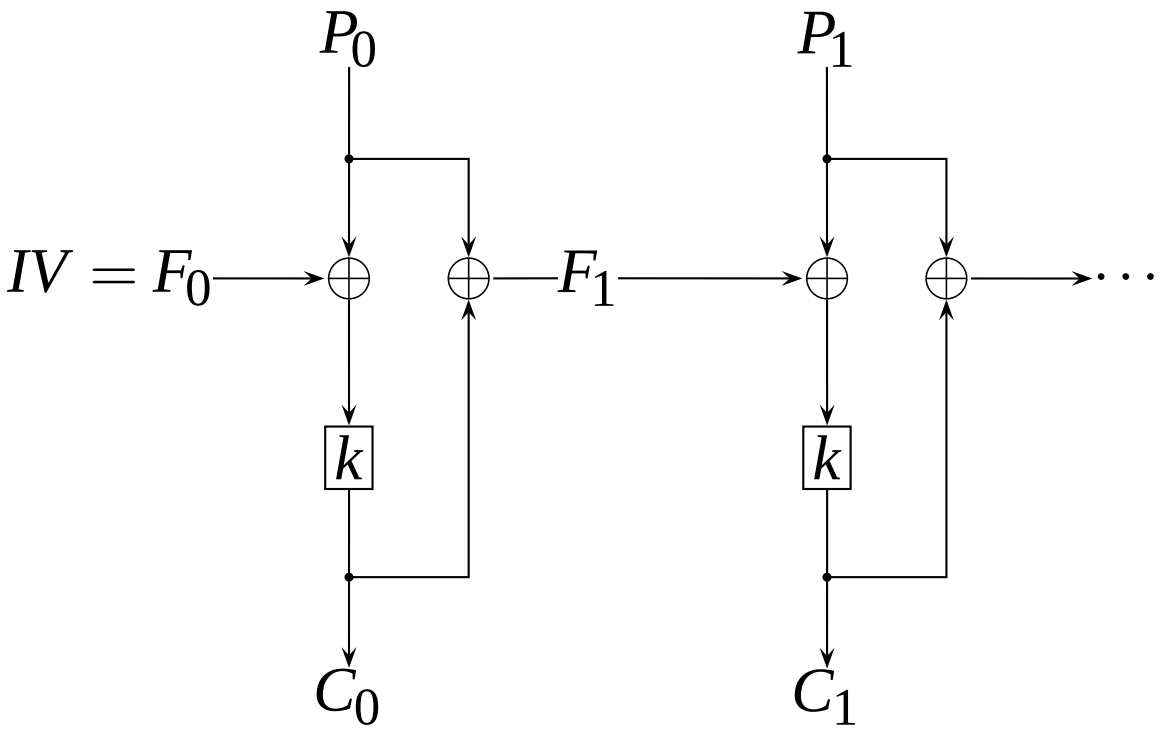
To get encryption $X = k(M)$ of block M

- Find an F_j that will remain the same when P_j replaced with P'_j
- Choose $P'_j = M \oplus F_j$
- Now, the new ciphertext block C'_j is the desired encryption of M

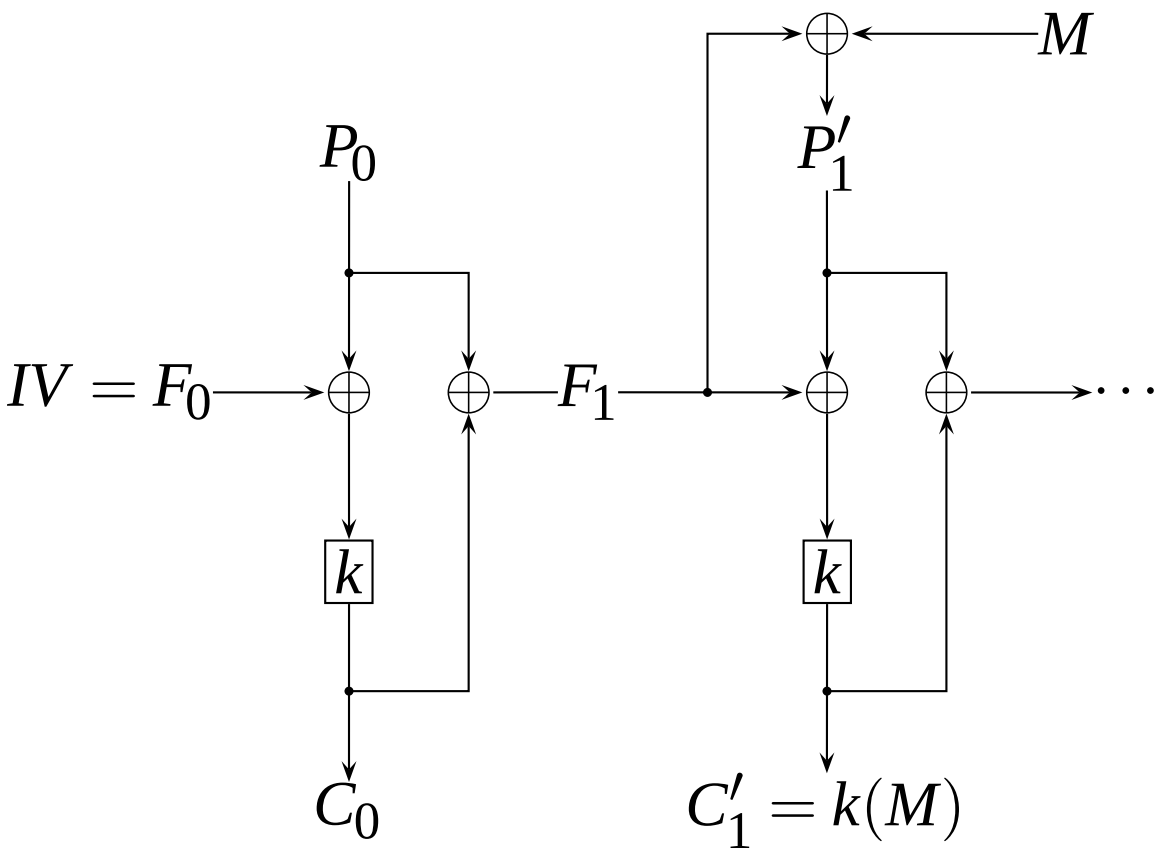
$$\begin{aligned} C'_j &= k(P'_j \oplus F_j) \\ &= k(M \oplus F_j \oplus F_j) \\ &= k(M) = X. \end{aligned}$$

- In well-designed protocol, attacker can't create this oracle, since F_j should not be predictable

Original Plaintext



Chosen Plaintext



Constructing Desired Ciphertext

To get ciphertext blocks $\{X_i\}$, whose plaintext blocks are $\{M_i\}$, for each M_i

- Use oracle to perform block encryption $X_i = k(M_i \oplus \Phi_i)$
- Φ_i is the feedback block, *e.g.*, $\Phi_{i+1} = M_i \oplus X_i$ in PCBC mode
- Choose plaintext block $P'_j = M_i \oplus \Phi_i \oplus F_j$
- This gives $C'_j = k(M_i \oplus \Phi_i)$

Ticket Ciphertext as Oracle

Kerberos Version 4 Ticket (pre-encryption)

1 byte	flags	namely, HOST_BYTE_ORDER
string	pname	client's name
string	pinstance	client's instance
string	prealm	client's realm
4 bytes	paddress	client's address
8 bytes	session	session key
1 byte	life	ticket lifetime
4 bytes	time_sec	KDC timestamp
string	sname	service's name
string	sinstance	service's instance
$\leq$ 7 bytes	null	null pad to 8 byte multiple

- *flags* has only one meaningful bit (HOST_BYTE_ORDER — KDC's byte order)

- "string" fields are NUL-terminated ASCII, max 40 chars

Chosing Plaintext in Ticket

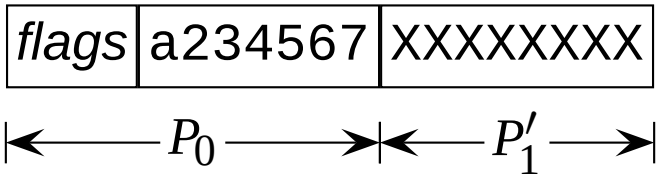
- Hold one aligned block of client name constant
- Vary the following block as chosen plaintext for oracle
- First byte (*flags*) usually constant
- IV is constant, but unknown (it’s the key)
- Client name and instance easily controlled

TGS Attack Scenario

- Attacker controls realm `A`
- Target realm `B`
- Attacker knows key of TGS principal `krbtgt.B@A`, which has same key as `krbtgt.A@B`
- Attacker creates cross-realm ticket with client principal `a234567XXXXXXXX@A`
  - "`a234567`" arbitrary and held constant
  - "XXXXXXXX" is the P_1' varied to produce desired ciphertext block
- Attacker uses cross-realm ticket to get ticket for target service

TGS Attack Scenario (cont'd)

Resulting initial two blocks of plaintext of ticket issued by realm B KDC are



- C_0 remains constant, due to constant IV and constant P_0
- F_1 also remains constant
- C_1' contains desired ciphertext block when P_1' is varied
- Choose $P_1' = M_i \oplus \Phi_i \oplus F_1$ to get $C_1' = X_i$

TGS Attack Scenario Limitations

- May need to choose different P_0 if P_1' needs to contain too many NUL characters

- First ciphertext block can be problematic
  - Can sniff initial ciphertext block
  - Can submit initial substring of target principal, with restrictions due to NUL characters
  - Cross-protocol attack

Alternate Attack Scenario

- Knowledge of sufficient number of keys in target realm allows using AS exchange as oracle
- Particularly effective if attacker can create principals in target realm
- MIT implementation allows less-privileged administrators to create/change keys for host-based service
- Typically of form `rcmd.`*hostname@realm*
- Used for authenticating remote logins
- May need to create as few as n principals for n blocks of ciphertext

Alternate Attack Scenario Limitations

- Not very useful in version 4-only environment
- Few interesting client principals begin with "`rcmd`"
- Cross-protocol attack can work, though
- Can also get initial ciphertext block by sniffing

Implementation Flaws

Implementation flaws make certain additional attacks possible

- MIT implementation of version 4 has lax checking for cross-realm TGT issuance, allowing “hopping” between realms, which is normally not permitted

- MIT implementation of version 5 shares keys with its version 4 backwards-compatibility mode, allowing cross-protocol attack

Realm Hopping

- MIT implementation of version 4 will issue “useless” tickets that would be rejected by the target realm’s KDC

client	using TGS	requested service	
`clienta@A`	`krbtgt.A@A`	`krbtgt.B@A`	issued
`clienta@A`	`krbtgt.B@A`	`krbtgt.C@B`	issued
`clienta@A`	`krbtgt.C@B`	`krbtgt.D@C`	rejected
`clienta@A`	`krbtgt.B@A`	`krbtgt.B@B`	issued
`clienta@A`	`krbtgt.B@B`	`anything@B`	rejected

- Normally harmless, this allows use of forged tickets for `krbtgt.B@A` to run an oracle on key for `krbtgt.C@B`

- Recursive realm compromise possible; must forge $O(c^n)$ tickets to compromise a realm n hops away

Realm Hopping (cont'd)

- Can shortcut by forging tickets of a realm administrator
- Can also use forged tickets for `krbtgt.B@A` to run an oracle on key for `krbtgt.B@B`.

Cross-Protocol Attack

- Using a key for multiple cryptographic purposes can be a vulnerability
- MIT implementation of version 5 can allow KDC to issue version 4 tickets for backwards compatibility
- Same key used for version 4 and version 5 tickets for a principal
- Can use version 4 ticket oracle to forge ciphertext for version 5 ticket

Cross-Protocol Attack (cont'd)

- RFC 1510 uses single-DES
- Encoded plaintext of version 5 ticket prior to encryption is

confounder	*checksum*	*. . . data. . .*	*pad*

- *confounder* is a block of random bits
- *checksum* is not keyed
- For checksums MD4 and MD5, IV is block of zeros
- For CRC-32 checksum, key used as IV

Cross-Protocol Attack (cont'd)

- Forge complete encoded plaintext of version 5 ticket, including checksum
- Use version 4 oracle to encrypt
- CRC-32 checksum makes first block slightly tricky; can use *any* initial ciphertext block whose plaintext is known, as receiver doesn't know what random confounder value to expect

Evolution of Kerberos Encryption

RFC 1510

- Improvement over version 4
- No more PCBC
- Confounder prevents using ciphertext as oracle
- Plaintext checksum allows use of version 4 block-encryption oracle to forge ciphertext
- Confounder also prevents cut-and-paste attacks (Bellovin and Atkins, private communication, 1999)

Ongoing Revision to Kerberos Version 5

- Repairs many flaws in RFC 1510
- Increases encryption abstraction; moves encryption specification to separate document
- Stronger ciphers (triple-DES, AES, etc.)
- Uses HMAC for integrity checking — can’t be forged with encryption oracle

Revised Ciphertext (post-RFC 1510)

- Ciphertext output

$encrypt(k_e, plaintext)$	$HMAC(k_c, plaintext)$

- Encoded plaintext

confounder	*data*	*pad*

- k_e: derived key exclusively for encrypting
- k_c: derived key exclusively for HMAC
- Both derived via one-way function from key exchanged in protocol

Conclusions

- Critical vulnerabilities in Kerberos version 4 provide examples of errors in cryptographic protocol design
- Clearly identify role of encryption in protocols
- Use good abstraction of encryption to avoid cross-dependencies between message layout and encryption
- Avoid deterministic encryption
- Avoid using one key for multiple purposes
- Protocols live longer than expected