



Breaking and Fixing Public-Key Kerberos

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Outline

- This work in context
- Kerberos 5
 - PKINIT
- Breaking PKINIT
- Fixing PKINIT
- Developments



Security Protocols

- 
- Protect sensitive network communications
 - Authentication
 - Confidentiality
 - (... and more)
 - Extremely hard to get right
 - What we do
 - Design frameworks to describe
 - Protocols
 - Intended security properties
 - Design verification methodologies
 - Apply them to protocols

What makes a good protocol?

What is security?

MSR

- Simple model of distributed computing
- Executable protocol specification language
 - Theoretical results
 - Undecidability
 - Most powerful intruder, ...
 - Practice
 - Bridge to other models
 - Kerberos V, ...
 - Maude implementation
- 3 generations already
 - MSR 1: designed in 1999
 - MSR 2: 1 + strong typing
 - MSR 3: 2 + ω -multisets
- Based on MultiSet Rewriting
 - Foundations in (linear) logic
 - Ties to Petri nets and process algebra



The Kerberos Verification Project

- Started in 2001
 - Test MSR on a **real** protocol
 - Kerberos 5 was gaining popularity
- 2002-03: detailed analysis of main protocol
 - Kerberos 5 behaves as expected
 - Authentication and confidentiality properties hold
 - Some anomalous behavior, but not attacks
 - One still under review in the IETF Working Group
- 2004: cross-realm authentication
 - Detailed analysis of what can go wrong if uncheckable hypothesis not met
- 2005: public-key extension of Kerberos - PKINIT
 - **Serious attack**
- Close, ongoing interactions with IETF WG






Verification

- MSR is methodology-neutral
 - Supports any proposed approach
- Developed new methodology for Kerberos
 - Doubly-inductive proof technique
 - Verify authentication using “rank function”
 - Verify confidentiality using “corank function”
 - Generalized in recent work with C. Meadows and D. Pavlovic
 - Authentication logic
 - Secrecy logic
 - Current work on automation

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Kerberos



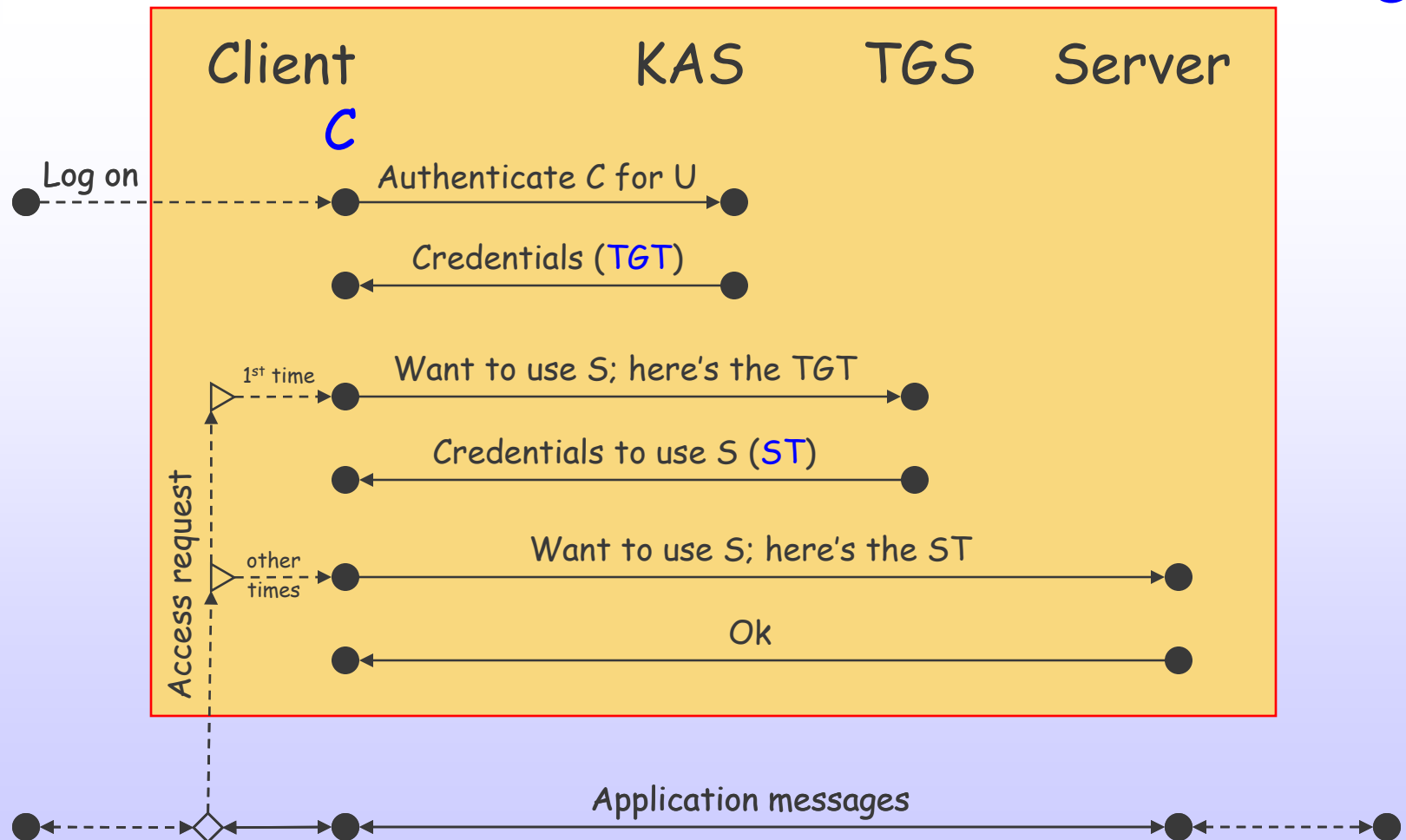
- Goals
 - Repeatedly authenticate a client to multiple servers
 - Remote login, file access, print spooler, email, directory, ...
 - Transparent to user
- History
 - Kerberos 4: 1989 - now (less and less)
 - Kerberos 5: 1993 - now (more and more)
 - Developed by IETF
 - Members from across industry
 - Define interoperability standards
 - 10 active documents, over 350 pages
 - This is a live protocol
 - New extensions under development in IETF WG
- A real world protocol
 - Part of Windows, Linux, Unix, Mac OS, ...
 - Microsoft will phase out all other authentication technology
 - Cable TV boxes, high availability server systems, ...

Basic Kerberos Operation

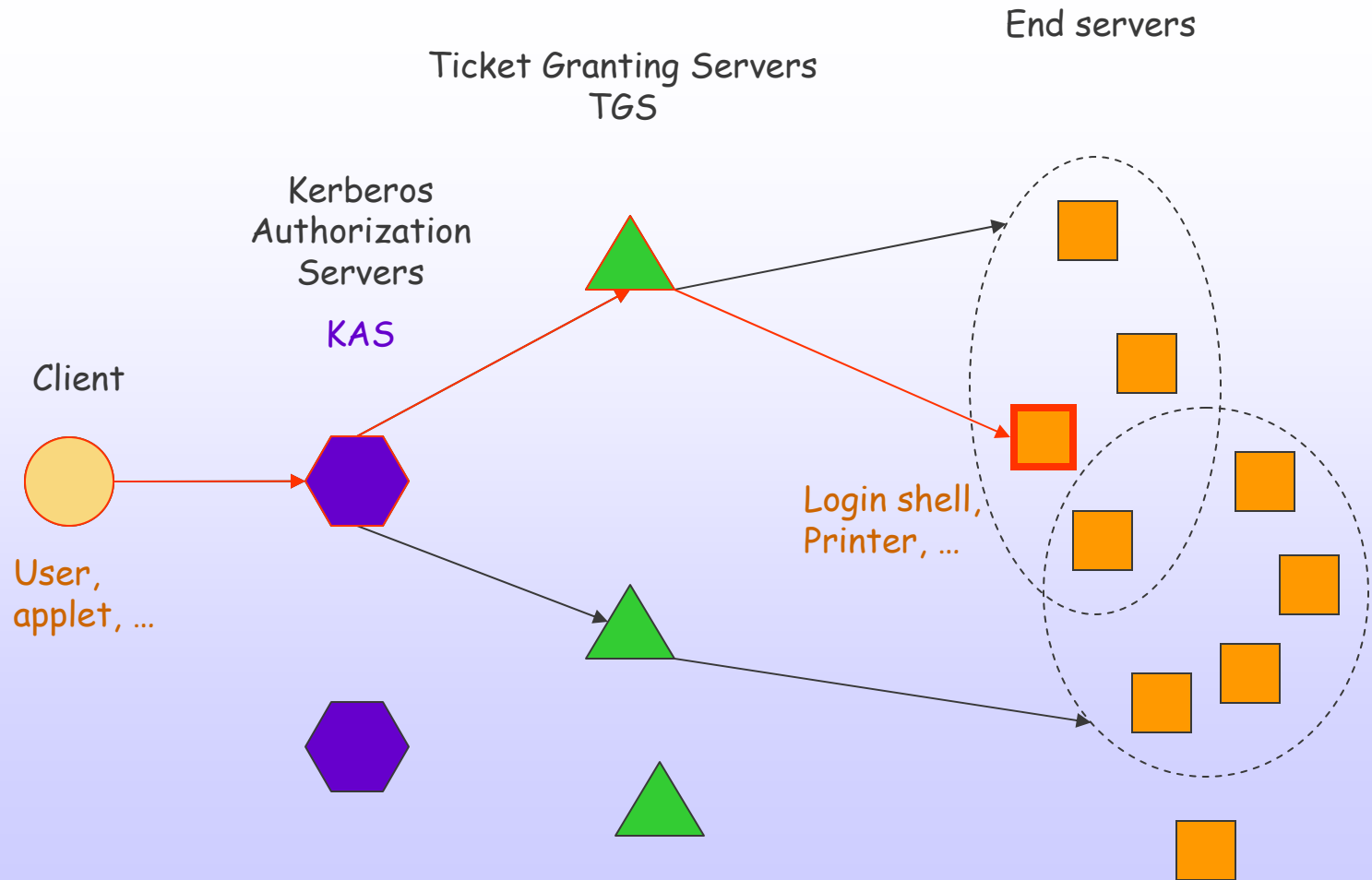
User
U

Kerberos

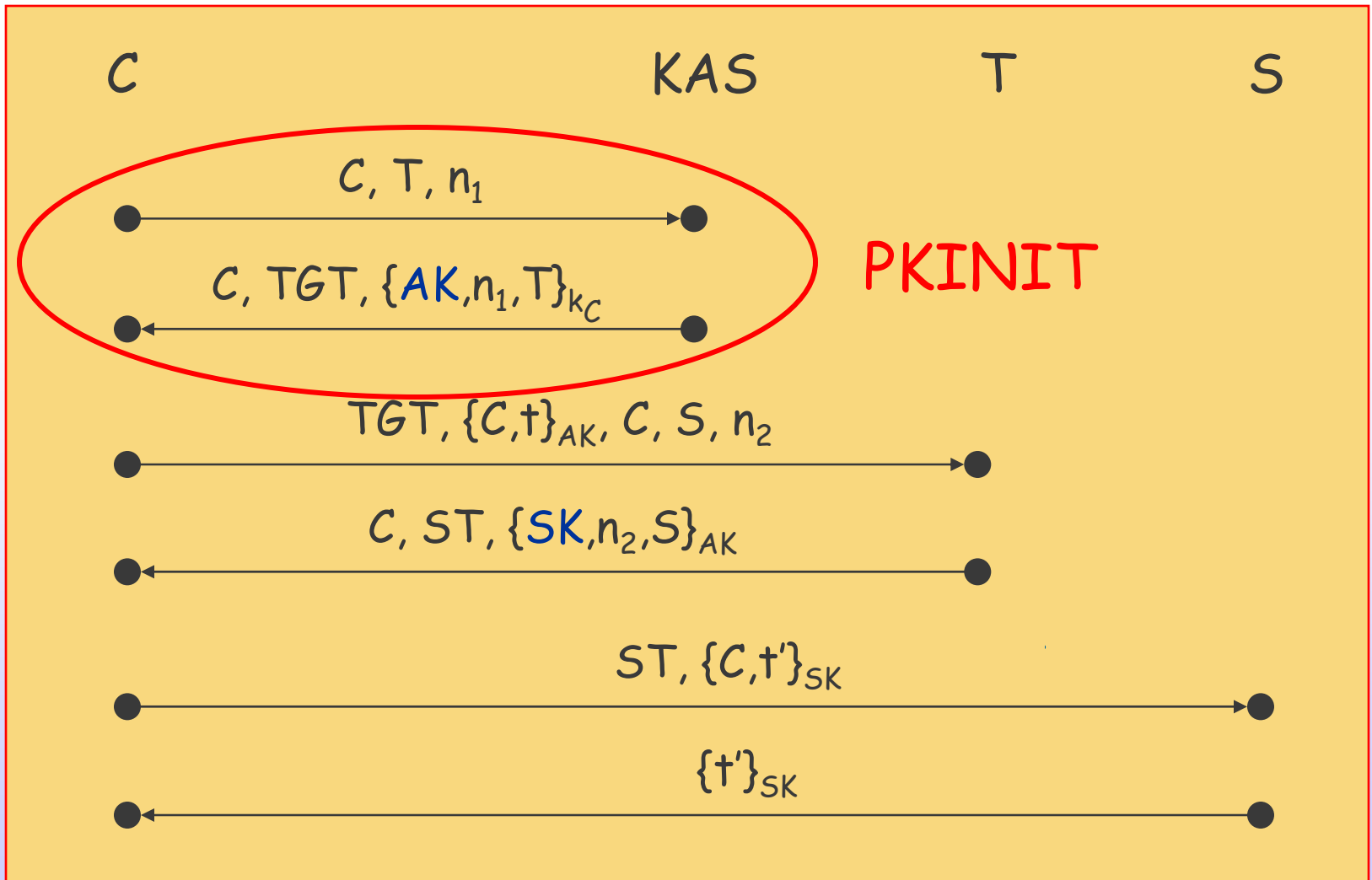
Service
S



Kerberos Principals

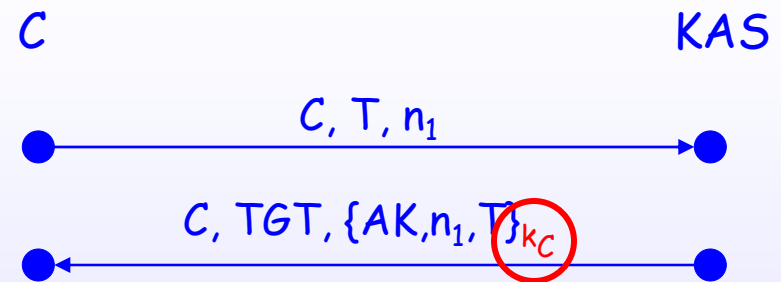


Abstract Messages

$$\text{TGT} = \{AK, C\}_{k_T}$$
$$\text{ST} = \{SK, C\}_{k_S}$$


Public-Key Kerberos

- Extend basic Kerberos 5 to use Public Keys
 - Change first round to avoid long-term shared keys (k_C)



- Motivations
 - Security
 - Avoid use of password-derived keys
 - Smartcard authentication support
 - If KAS is compromised, don't need to regenerate shared keys
 - Administrative convenience
 - Avoid the need to register in advance of using Kerberized services
 - Delegate management of keys to external PKI

PKINIT Revisions

- Now RFC 4556
- Then, a series of IETF Drafts
 - Last, -34
 - We found attack in -25 (May 2005)
 - We analyzed -26
 - Traced back to -00 (1996)
 - Attack fixed in -27 (July 2005)
- Widely deployed
 - All versions of Windows since Win2K
 - Linux since 2003 (Heimdal implementation)
 - Domain specific systems
 - CableLabs implementation for TV cable boxes, ...
 - Under development for MIT reference implementation
 - Unix, Mac OS, ...





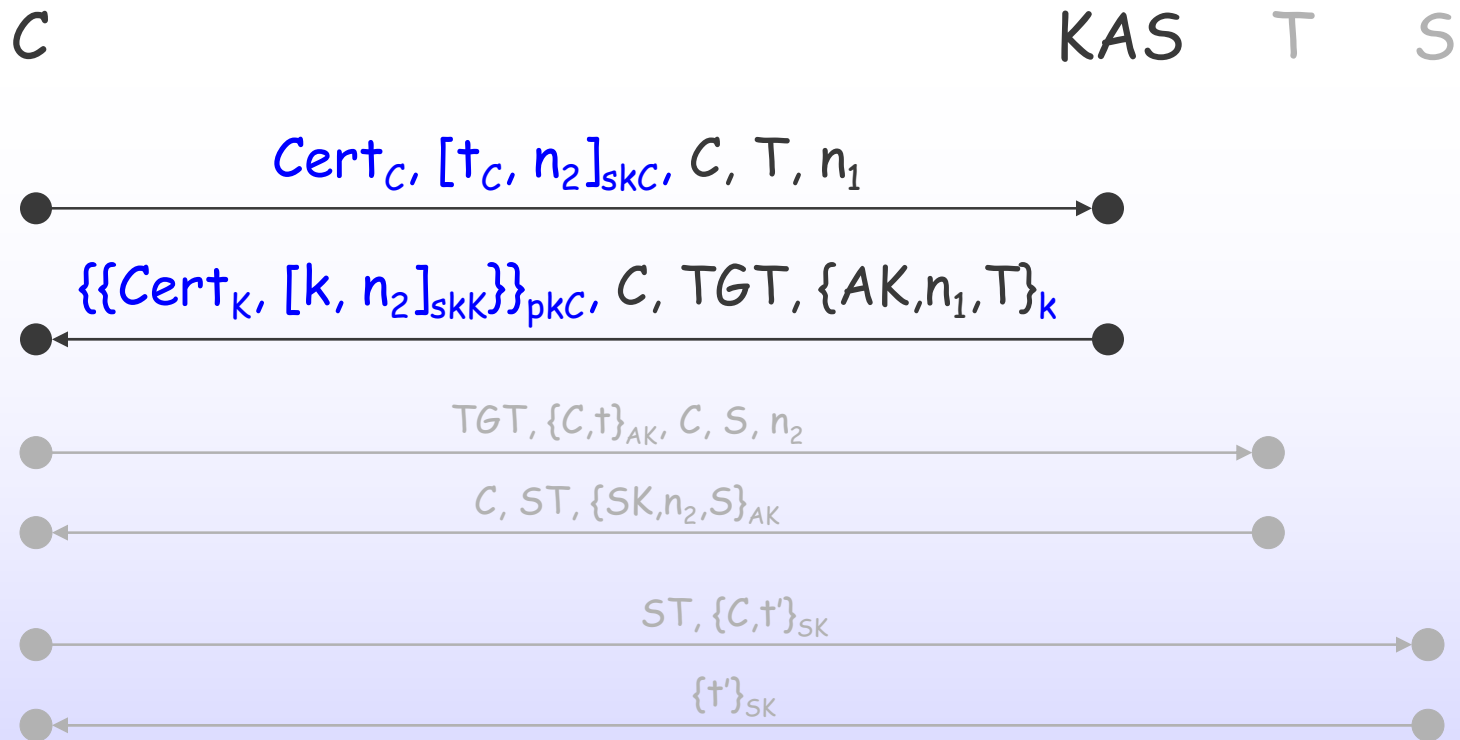
Two Modes

No more key k_c shared between C and KAS

- Credentials for C encrypted under a temporary key k
 - How to generate and deliver k ?
- Public-key encryption
 - k is generated by KAS
 - k encrypted under C's public key and signed by KAS
 - Attack is against this mode
- Diffie-Hellman
 - k is derived from DH exchange between C and KAS
 - C and KAS each send signed data contributing to DH key
 - Option for 'reuse' of the shared secret
 - Not widely implemented
 - CableLabs appears to be only implementation of DH mode
 - Initial inspection did not turn up attacks against this mode

PKINIT in PKE-mode

$$\begin{aligned} \text{TGT} &= \{AK, C\}_{k_T} \\ \text{ST} &= \{SK, C\}_{k_S} \end{aligned}$$



- $\{m\}_k$: shared-key encryption
- $\{\{m\}\}_{pk}$: public-key encryption
- $[m]_{sk}$: digital signature

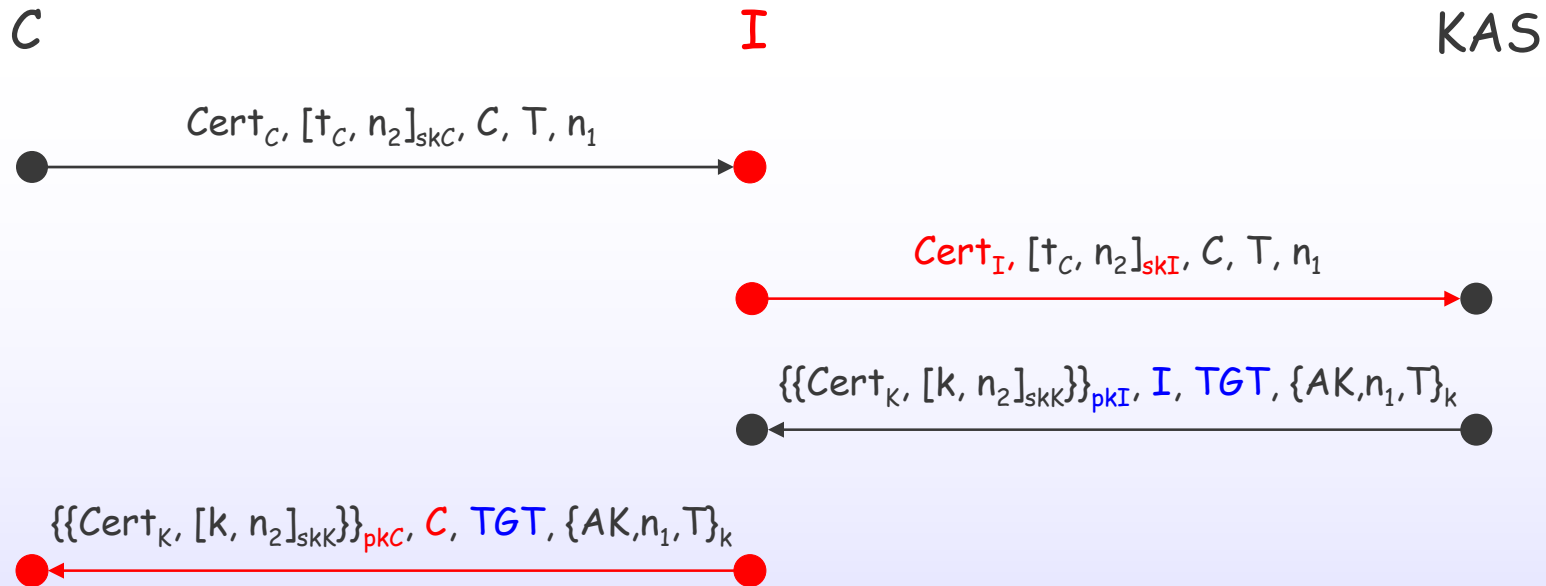
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$$TGT = \{AK, I\}_{k_T}$$

The Attack



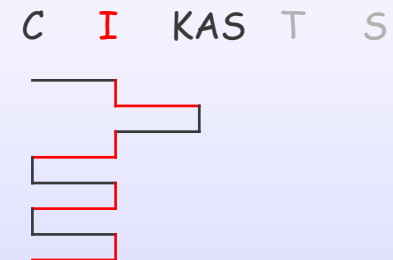
- Failure of authentication
 - C believes to be talking to KAS, is talking to I instead
- Failure of confidentiality
 - I knows AK (and k)
 - C believes KAS produced AK and k just for her

After the First Round ...

- **I** repeats attack on follow up exchanges
 - Monitors communications
 - Learns keys in replies



- **I** impersonates servers
 - Forge reply messages
 - T, S not involved



- Mixed strategy



Notes about this Attack

- This is a deterministic attack
 - Conducted at symbolic Dolev-Yao level
 - Man-in-the-middle attack
- **I** must be a legal user
 - Otherwise, KAS would not talk to him
- **C** is authenticated to **S** as **I** (not as **C**)
 - **I** does not trick **S** to believe he is **C**
 - **I** can observe all communications between **C** and **S**
 - **I** can pretend to be **S** to **C**
- DH mode appears to avoid this attack
 - Still need to formally prove security for DH



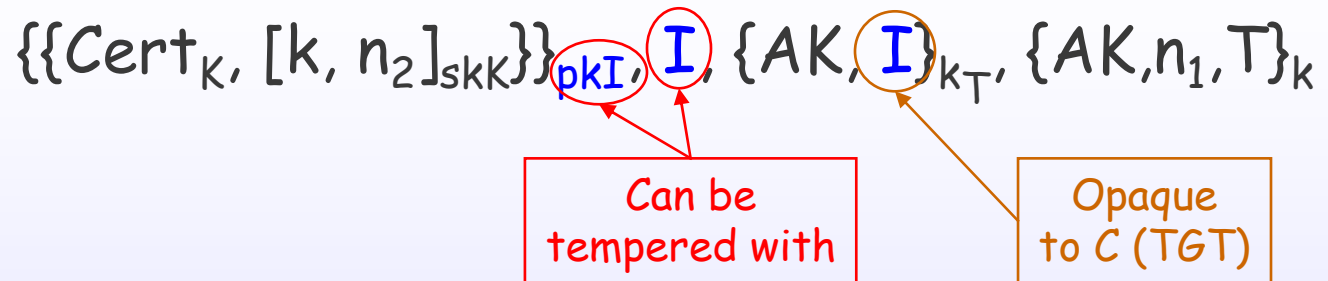
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What Went Wrong?

- C cannot tell the reply was not for her



➤ Misbinding of request and reply

- I can
 - Tamper with signature in request
 - Tamper with encryption in reply



A Familiar Attack ...

- Tampering with signatures
 - 1992: Signature-based variant of StS [Diffie, van Oorschot, Wiener]
 - 2003: basic authenticated DH mode in IKE [Canetti, Krawczyk]
- Tampering with encryption
 - 1996: Needham-Schroeder public key protocol [Lowe]
- Tampering with both
 - 1995: SPLICE/AS [Hwang, Chen] [Clark, Jacob]
- Our attack is the first instance in a widely deployed real-world protocol



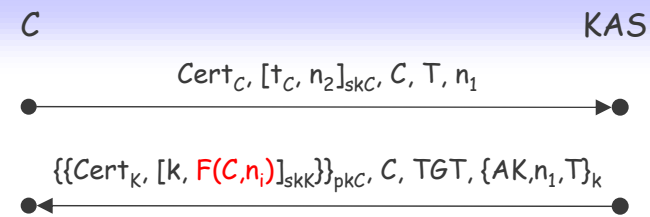
Desired Authentication Property

If a client **C** processes a message containing KAS-generated public-key credentials, then the KAS produced such credentials **for C**

- The attack shows this property does not hold in PKINIT-00/-26
- What are the necessary conditions for the property to hold?

General Fix

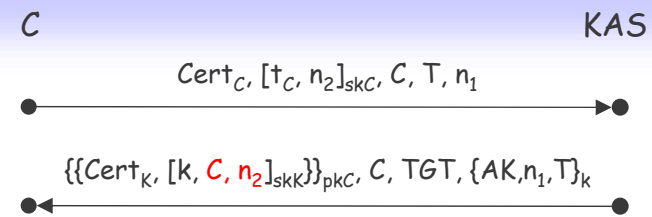
- Sign data identifying client
 - The KAS signs $k, F(C, n_i)$
 - Either n_1 or n_2 (or both)
 - Assume $F(C, n) = F(C', n')$ implies $C = C'$ and $n = n'$
- We have formally proved that this guarantees authentication
 - n_2 is redundant
- Further questions
 - Does cname/crealm uniquely identify client?
 - Added secrecy properties if $F(C, n_i)$ identifies pkC?



Initial Proposal

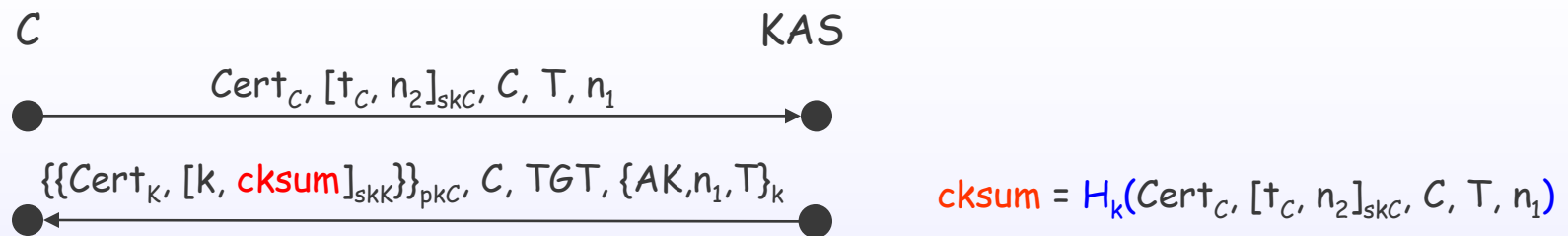
- Traditional approach

$$F(C, n_i) = C, n_2$$



Fix Adopted by Kerberos WG

$F(C, n_i) = \text{Keyed hash of request}$




- E.g., $H = \text{hmac-sha1-96-aes128}$
- Why??
 - Easier to implement than signing k, C, n_2
- Included in PKINIT-27
- Formal assumptions
 - H is preimage resistant
 - KAS's signature key is secret

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Timeline

- 
- **Early May '05:** Top Kerb. WG members notified
 - Request to hold off full disclosure
 - **Late May:** fixes proposed
 - **June:** Microsoft reproduces attack
 - Hold off any disclosure
 - **July:** Kerberos WG notified
 - **July:** IETF adopts fix
 - **July:** PKINIT-27 incorporates it
 - **Aug.:** Attack reported in MS Security Bulletin
 - **Oct.:** Patch available for Heimdal (Linux)

Real-World Impact

- Design vulnerability on widely deployed protocol
- Immediate responses
 - IETF fix to specification
 - Microsoft patch
<http://www.microsoft.com/technet/security/bulletin/MS05-042.msp>
 - Linux patch
 - CERT entry
<http://www.kb.cert.org/vuls/id/477341>
- Request to IETF developers to seek formal validation of protocols




Interactions with IETF

- Close collaboration with IETF Kerberos WG
 - Discussed possible fixes we were considering
 - Attack announced on WG list in July
 - We verified a fix the WG suggested
 - This was incorporated into PKINIT-27
 - Presented this work at IETF-63
 - Discussed possible fixes and our analysis of these
 - Useful discussions with WG participants on other areas for work
 - Now regular participants at IETF / krb-wg meetings
- Impact of formal methods in IETF security area
 - At security-area level, they want to see more interaction with formal methods



Conclusions

- 
- Extended formalization of Kerberos 5 to PKINIT
 - Serious attack against public-key encryption mode in PKINIT-00/-26
 - Protocol-level attack with real-world effects
 - General fix defending against this
 - Close collaboration with IETF WG
 - Discussion and analysis of possible fixes
 - We've analyzed the fix employed in PKINIT-27

Future Work

- Fully analyze and verify PKINIT
 - Computational proofs
 - *E.g.*, signature strength
 - Look at DH mode
- Other parts of Kerberos suite
 - Password changing subprotocol
- Continue interactions with WG
- Timed analysis

