Just Fast Keying ?

W. Aiello, S.M. Bellovin, M. Blaze, R. Canetti, J. Ionnidis, A.D Keromytis, and O. Reingold. Efficient, DoS Resistant, Secure Key Exchange for Internet Protocols. In *ACM Conference on Computer and Communications Security (CCS'02)*, November 2002.

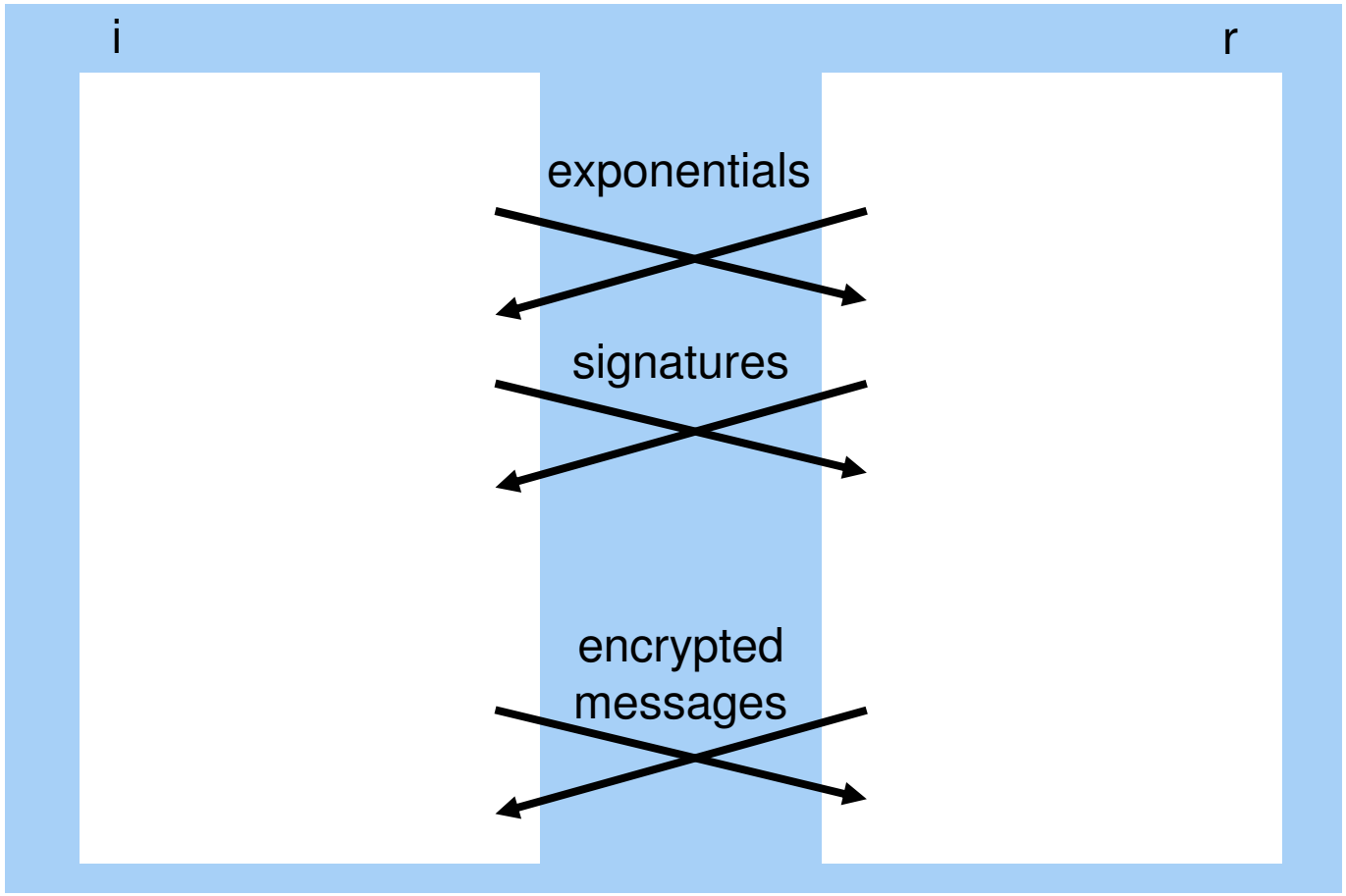
Session establishment (again)

- Two parties want to open a secure session
  - Telnet (SSH)
  - Web connection (SSL, TLS)
  - IP tunnel (VPN)
  - Wireless network
- They need to
  - Generate a shared secret (the "session key")
  - Agree on many parameters
  - Verify each other's identity
- Attackers might eavesdrop, delete, and insert messages, may impersonate principals,… in order to
  - gain information
  - confuse or hinder the participants

Building blocks

- Shared-key encryption
- Cryptographic hash (HMAC)
- Tokens (or cookies)
- Diffie-Hellman computation
- Public-key signature

Two-round Diffie-Hellman



- Against active attackers,
  first create a shared key, then authenticate

Complications

- Configuration
  - Different security needs according to the application
  - Many cryptographic algorithms to choose from
  - Many flavours of authentication (PKIs)
  - Different modes
- Concurrency
  - Parallel sessions
  - Various principals using several shared proxies
- Efficiency concerns
  - Round-trips are expensive
  - Cryptography can be expensive
- Session management
  - Key derivation
  - Rekeying
  - Dead peer detection

IKE and its successors

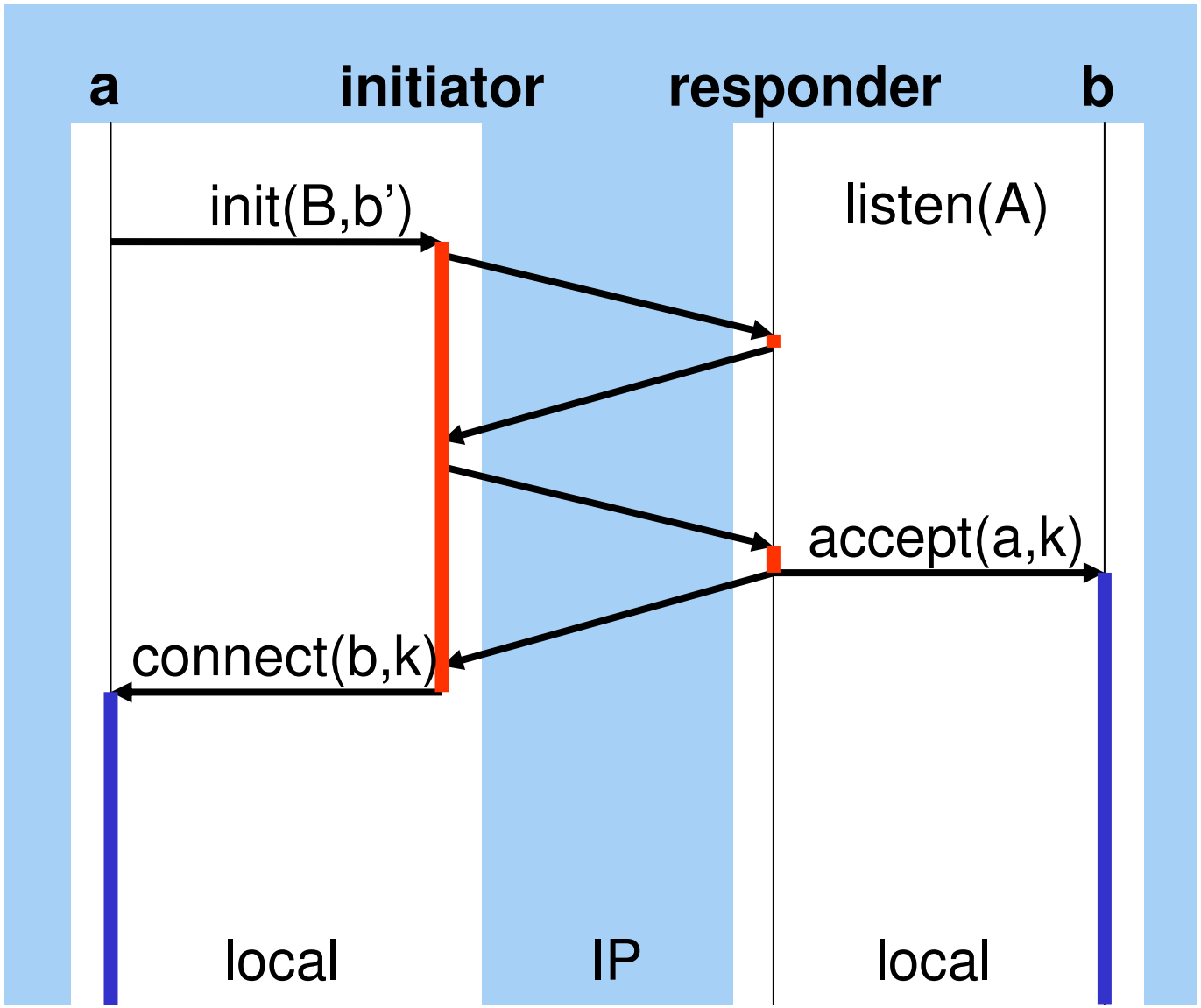
- IKE (Internet Key Exchange)
  - Session management for IPSEC
  - Quite secure
  - Some concerns
    - Too complicated
    - Inefficient (too many messages & expensive operations)
    - Poor resistance against denial of service
- The IETF is considering a successor for IKE, (now merging the different proposals into IKEv2)
- JFK (Just Fast Keying) is a simple proposal that incorporates several new mechanisms. http://www.ietf.org/internet-drafts/draft-ietf-ipsec-jfk-04.txt

Design goals for JFK

- Security
  - "The key should be cryptographically secure, according to standard measures of cryptographic security for key exchange"
- Simplicity
- Resistance to Memory DoS
- Resistance to CPU DoS
- Privacy
  - Identity protection for some parties, against some classes of attacks
- Efficiency
- Non-negotiated
- "Flexible" perfect forward secrecy
  - With reuse of exponentials
- Plausible deniability

These goals are (sometimes) contradictory.

Using JFK


a
initiator
responder
b
init(B,b')
listen(A)
accept(a,k)
connect(b,k)
local
IP
local

The JFKr protocol

Msg 1	$i \rightarrow r$:	$n_i, g\hat{}d_i$
Msg 2	$r \rightarrow i$:	$n_i, n_r, g\hat{}d_r, p_r, h_t$
Msg 3	$i \rightarrow r$:	$n_i, n_r, g\hat{}d_i, g\hat{}d_r, h_t, e_i, \mathsf{Hmac}\{k_a\}(\text{'i'}, e_i)$
Msg 4	$r \rightarrow i$:	$n_i, n_r, e_r, \mathsf{Hmac}\{k_a\}(\text{'r'}, e_r)$

where

$$h_t = \mathsf{Hmac}\{k_t\}(g\hat{}d_r, n_r, n_i, \mathsf{IP}_i)$$

$$e_i = \mathsf{Encrypt}\{k_e\}(\mathsf{id}_i, \mathsf{id}'_r, sa_i, s_i)$$
$$e_r = \mathsf{Encrypt}\{k_e\}(\mathsf{id}_r, sa', s_r)$$

$$s_i = \mathsf{Sign}\{i\}(n_i, n_r, g\hat{}d_i, g\hat{}d_r, p_r)$$
$$s_r = \mathsf{Sign}\{r\}(g\hat{}d_r, n_r, g\hat{}d_i, n_i)$$

$$k_u = \mathsf{Hmac}\{g\hat{}(d_i\, d_r)\}(n_i, n_r, \text{'u'}) \text{ for } u = a, e, v$$

The JFKr protocol: flexible PFS

Msg 1	$i \rightarrow r$:	$n_i, g\hat{}d_i$
Msg 2	$r \rightarrow i$:	$n_i, n_r, g\hat{}d_r, p_r, h_t$
Msg 3	$i \rightarrow r$:	$n_i, n_r, g\hat{}d_i, g\hat{}d_r, h_t, e_i, \mathsf{Hmac}\{k_a\}(\text{'i'}, e_i)$
Msg 4	$r \rightarrow i$:	$n_i, n_r, e_r, \mathsf{Hmac}\{k_a\}(\text{'r'}, e_r)$

where

$$\begin{aligned} & \ldots\}(g\hat{}d_r, n_r, n_i, \mathsf{IP}_i) \\ & \ldots(\mathsf{id}_i, \mathsf{id}'_r, sa_i, s_i) \\ e_r &= \mathsf{Encrypt}\{k_e\}(\mathsf{id}_r, \ldots \\ s_i &= \mathsf{Sign}\{i\}(n_i, n_r, g\hat{} \ldots \\ s_r &= \mathsf{Sign}\{r\}(g\hat{}d_r, n_r, g \ldots \\ k_u &= \mathsf{Hmac}\{g\hat{}(d_i\, d_r)\}(n_i, n_r, \text{'u'}) \text{ for } u = a, e, v \end{aligned}$$

The pair of nonces is unique to this session

Many keys can be derived from the same exponentials for different usages

The JFKr protocol: DoS

The responder uses an authenticator against DoS

Msg 1	$i \rightarrow r$:	$n_i, g\hat{}d_i$
Msg 2	$r \rightarrow i$:	$n_i, n_r, g\hat{}d_r, p_r, h_t$
Msg 3	$i \rightarrow r$:	$n_i, n_r, g\hat{}d_i, g\hat{}d_r, h_t, e_i, \mathsf{Hmac}\{k_a\}(\text{'i'}, e_i)$
Msg 4	$r \rightarrow i$:	$n_i, n_r, e_r, \mathsf{Hmac}\{k_a\}(\text{'r'}, e_r)$

where $h_t = \mathsf{Hmac}\{k_t\}(g\hat{}d_r, n_r, n_i, \mathsf{IP}_i)$

$e_i = \mathsf{Encrypt}\{k$ [illegible] $i, \mathsf{id}'_r, sa_i, s_i)$

[illegible] $sa', s_r)$

[illegible] $i, g\hat{}d_r, p_r)$

[illegible] $\hat{}d_i, n_i)$

The responder can check that the contents of msg 3 matches the contents of msg 1 & 2

$k_u = \mathsf{Hmac}\{g\hat{}(d_i\, d_r)\}(n_i, n_r, \text{'u'})$ for $u = a, e, v$

The JFKr protocol: Privacy

Msg 1 $i \rightarrow r: \; n_i, g\hat{}d_i$

Msg 2 $r \rightarrow i: \; n_i, n_r, g\hat{}d_r, p_r, h_t$

Msg 3 $i \rightarrow r: \; n_i, n_r, g\hat{}d_i, g\hat{}d_r, h_t, e_i, \mathsf{Hmac}\{k_a\}(\text{'i'}, e_i)$

Msg 4 $r \rightarrow i: \; n_i, n_r, e_r, \mathsf{Hma}$

where $h_t = \mathsf{Hmac}\{k_t\}(g\hat{}d_r, n_r, n_i, \mathsf{IP}_i)$

$e_i = \mathsf{Encrypt}\{k_e\}(\mathsf{id}_i, \mathsf{id}'_r, sa_i, s_i)$

$e_r = \mathsf{Encrypt}\{k_e\}(\mathsf{id}_r, sa', s_r)$

$s_i = \mathsf{Sign}\{i\}(n_i, n_r, g\hat{}d_i, g\hat{}d_r, p_r)$

$s_r = \mathsf{Sign}\{r\}(g\hat{}d_r, n_r, g\hat{}d_i, n_i)$

$k_u = \mathsf{Hmac}\{g\hat{}(d_i\, d_r)\}(n_i, n$

Identities are always encrypted

Identities are never signed

The JFKr protocol

Msg 1	$i \rightarrow r$:	$n_i, g\hat{}d_i$
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where

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$$s_i = \mathsf{Sign}\{i\}(n_i, n_r, g\hat{}d_i, g\hat{}d_r, p_r)$$
$$s_r = \mathsf{Sign}\{r\}(g\hat{}d_r, n_r, g\hat{}d_i, n_i)$$

$$k_u = \mathsf{Hmac}\{g\hat{}(d_i\, d_r)\}(n_i, n_r, \text{'u'}) \text{ for } u = a, e, v$$

Some minor problems

Identity protection?

- Two variants with different trade-offs
  - "JFKi protects id_i against active attacks"
  - "JFKr protects id_r against active attacks and protects id_i against passive attacks"
- What is guaranteed? Does it make sense for the responder? This depends on relations between principals and roles
- Various leaks:
  - An attacker can perform traffic analysis using nonces, IP addresses, and insider knowledge (cf. private authentication)
  - A passive attacker can observe shared exponentials
    - if exponentials are re-used by a single principal, all these sessions involve the same principal
    - an active attacker (or an insider) may obtain the identity for one of these sessions

…

Identity protection in JFKr ?

Msg 1	$i \rightarrow r$:	$n_i, g\hat{}d_i$
Msg 2	$r \rightarrow i$:	$n_i, n_r, g\hat{}d_r, p_r, h_t$
Msg 3	$i \rightarrow r$:	$n_i, n_r, g\hat{}d_i, g\hat{}d_r, h_t, e_i, \mathsf{Hmac}\{k_a\}(\text{'i'}, e_i)$
Msg 4	$r \rightarrow i$:	$n_i, n_r, e_r, \mathsf{Hmac}\{k_a\}(\text{'r'}, e_r)$

where $h_t = \mathsf{Hmac}\{k_t\}(g\hat{}d_r, n_r, n_i, \mathsf{IP}_i)$

An attacker E can

1. Intercept message 2
2. Initiate its own session with R with the same nonce n_i and its exponential
3. Swap the two messages 2
4. Guess id_r and proceed as usual
5. Observe messages 4

The responder accepts two sessions (I,R) and (E,R) only if E's guess is right

Fix: MAC the initiator exponential too

Non-negotiated?

- Usually, the cryptographic algorithms are negotiated:
  hash, encryption, certificates, compression, …
  Some algorithms are weak (legacy, legal…), or even nil.

- The protocol must (at least) authenticate the negotiation, and also relies on these operations for authentication! Cf. SSL

- "JFK is non-negotiated": the responder demands specific algorithms, the initiator takes it or leaves it. Still…
  - If the responder demands weak algorithms,
    there is no guarantees at all.
  - What if the attacker modifies the responder's demands?
  - Recent fix in JFKi: sign the algorithm demands

Caching message 3?

- "The responder caches answers to identical messages 3"
- More precisely, the responder should answer just once for every valid token received in a message 3.
- Otherwise, several attacks appear

Caching message 3?

Msg 1	$i \rightarrow r$:	$n_i, g\hat{}d_i$
Msg 2	$r \rightarrow i$:	$n_i, n_r, g\hat{}d_r, p_r, h_t$
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where $h_t = \mathsf{Hmac}\{k_t\}(g\hat{}d_r, n_r, n_i, \mathsf{IP}_i)$

$e_i =$

$e_r =$

$s_i =$

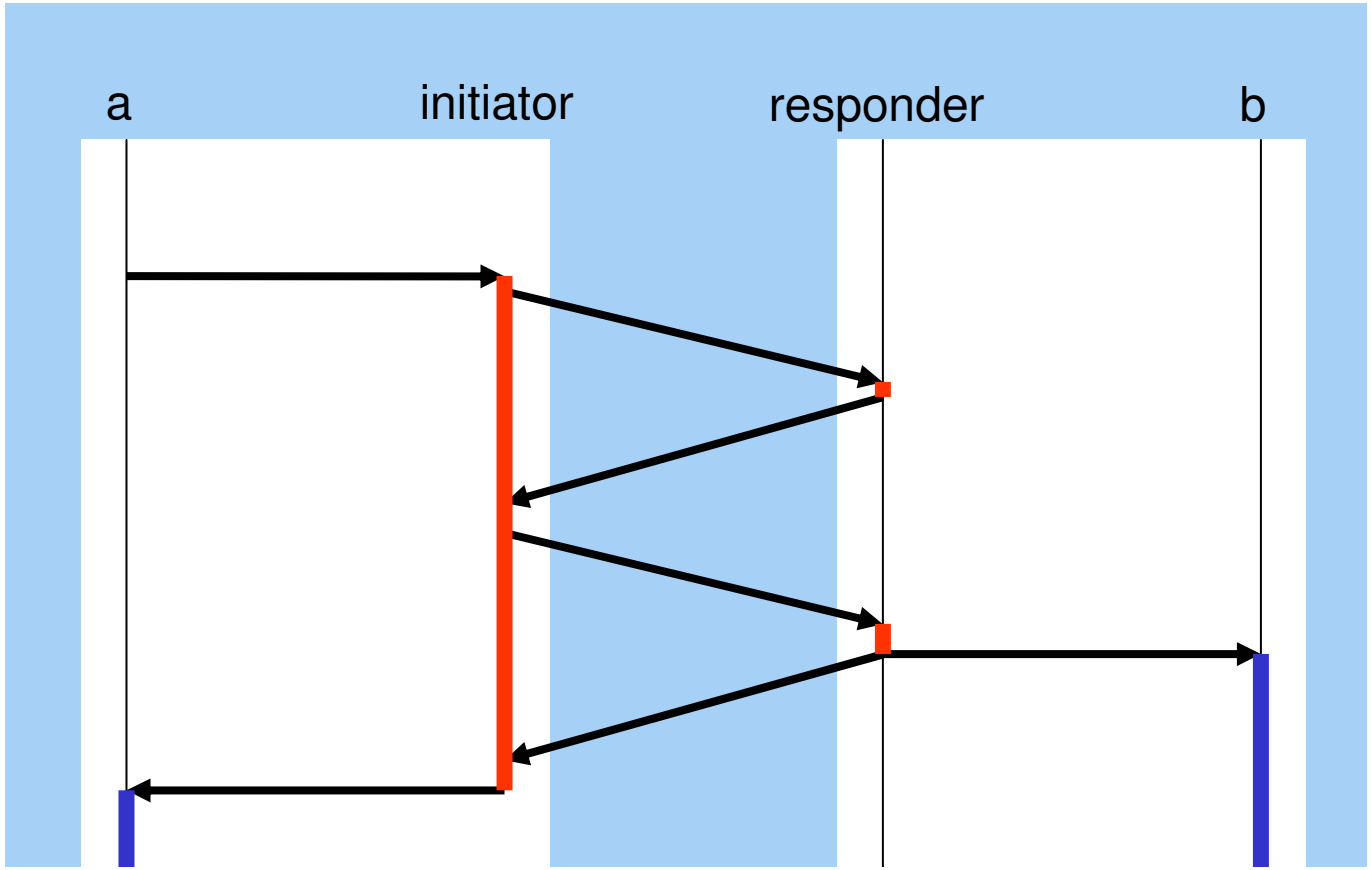
$s_r =$ Sign

$k_u =$ Hmac{

An active attac could trick R into accepting ssions with the same key

An attacker E could obtain a valid message 3 and modify eg the exponential
(an easy, "blind" DoS attack against R)

A model of JFK in applied pi



Public key signature

- To model public-key signature, we construct the public verification key form the private signing key:

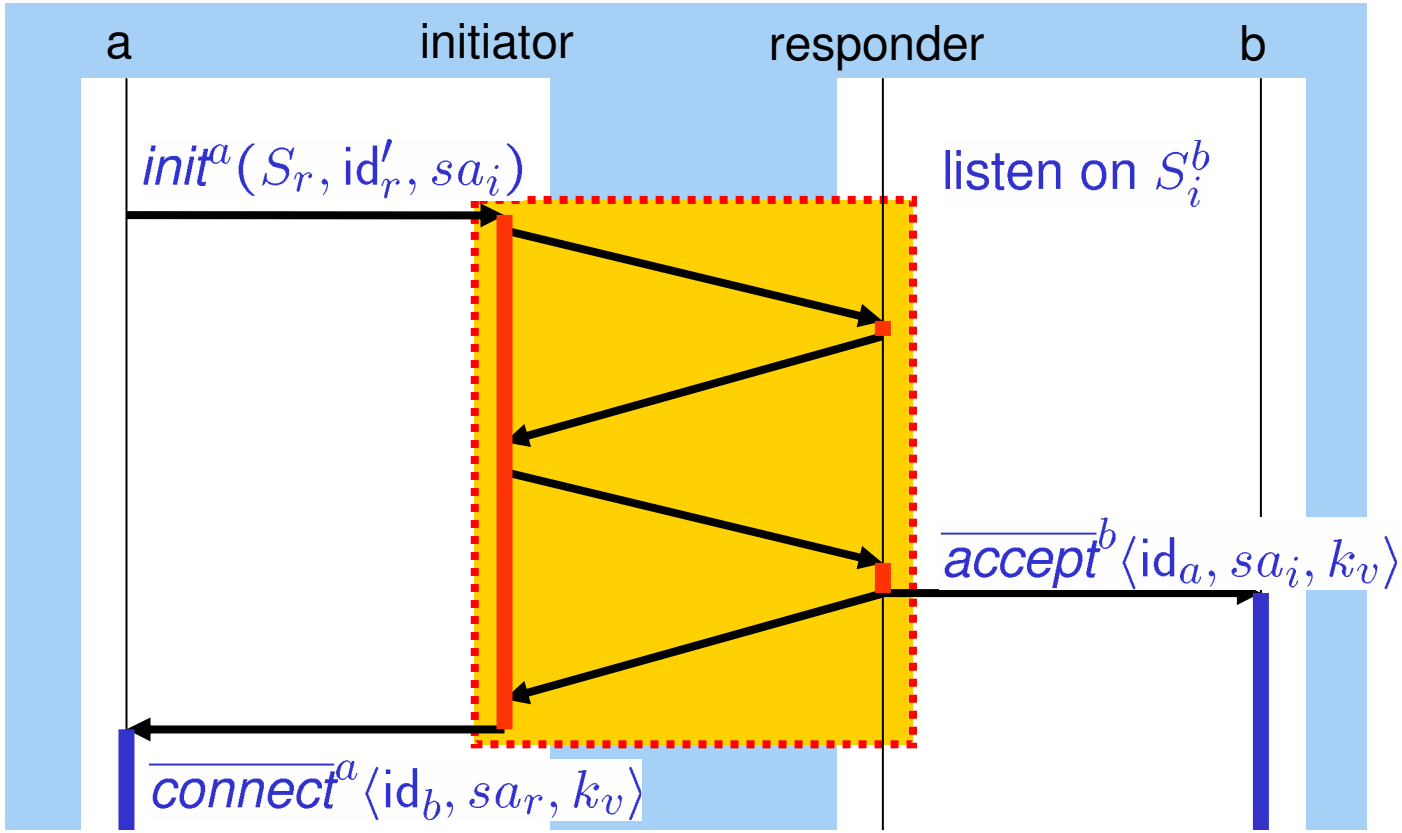
$$\mathsf{Verify}\{\mathsf{Pk}(k), \mathsf{Sign}\{k\}(v)\}(v) \quad = \quad \mathsf{True}$$

- Using active substitutions, we can write a process that exports the public key, and keeps the signing key secret.

$$\nu s.\Big(\{pk = \mathsf{Pk}(s)\} \mid \overline{a}\langle \mathsf{Sign}\{s\}(M)\rangle\Big)$$

Control actions

- We distinguish between
  - principals (signers)
  - JFK roles: initiator, responder (exponentials)
- We provide an API between applications & JFK



Grammar for terms

$M, N ::=$	terms
x, y, z	variable
m, n, s, t	name
$B\hat{}X$	exponential
$\mathsf{Pk}(K)$	public key (and identity)
$\mathsf{S}\{K\}(T)$	public-key signature
$\mathsf{V}\{K, S\}(D)$	public-key signature verification
$\mathsf{H}\{K\}(T)$	keyed crypto hash function
$\mathsf{E}\{K\}(T)$	shared-key encryption
$\mathsf{D}\{K\}(T)$	shared-key decryption
$\mathsf{T}_e, \mathsf{T}_a, \mathsf{T}_v$	constant tags for key derivation
$1(_, _), 2(_, _, _, _, _), \ldots$	constructors for JFK messages
$\mathsf{F}_1^1(_), \ldots, \mathsf{F}_4^2(_)$	selectors for JFK messages
$K \in S$	sets (for authorized identities)

Equations for terms

$(g\hat{}y)\hat{}z$	$=$	$(g\hat{}z)\hat{}y$	Diffie-Hellman exponentials
$\mathsf{V}\{\mathsf{Pk}(k), \mathsf{S}\{k\}(v)\}(v)$	$=$	True	Public key signature verification
$\mathsf{D}\{k\}(\mathsf{E}\{k\}(v))$	$=$	v	Shared-key decryption
$\mathsf{F}_n^i(n(v_1, \ldots, v_i, \ldots))$	$=$	v_i	Selection of message fields
$K \in \{\ldots, K, \ldots\}$	$=$	True	Set membership (authorization)
$\mathsf{RecoverKey}(\mathsf{S}\{k\}(v))$	$=$	$\mathsf{Pk}(k)$	Public key recovery *
$\mathsf{RecoverText}(\mathsf{S}\{k\}(v))$	$=$	v	Signed text recovery *

JFK configuration initiator responder

JFK	$=$	$\prod_{a \in \mathcal{L}} PK^a[I^a \mid R^a]$	JFK for principals $a \in \mathcal{L}$
$PK^a[_]$	$=$	$\nu a.\{id^a = \mathsf{Pk}(a)\} \mid [_]$	Signing key a and identity id^a
$D_z[_]$	$=$	$\nu d_z.\{x_z = g\hat{}d_z\} \mid [_]$	DH secret and exponential
C_z	$=$	$\nu h.\{h = x_{\overline{z}}\hat{}d_z\} \mid \prod_{u=a,e,v} K_u$	DH computation
K_u	$=$	$\{k_u = \mathsf{H}\{h\}(n_i, n_r, \mathsf{T}_u)\}$	derivation of key k_u

Only a specific subset of principals appear in $\mathcal{L}$

These are ”compliant principals”.

JFK configuration initiator responder

I	$=$	$\prod_{\widetilde{x_i}} D_i \left[!\mathit{init}^a(S_r, id'_r, sa_i).I_1 \right]$	init handler (for a)
I_1	$=$	$\nu n_i.\langle 1(n_i, x_i)\rangle \mid$	*send message 1*
		$(2(n'_i, n_r, x_r, p_r, h_t)).I_3$	*wait for message 2*
I_3	$=$	$\nu k_e\, k_a\, k_v.C_i \mid$	*compute the keys*
		$\nu s_i\, e_i\, h_i.$	*build message 3*
		$\{s_i = \mathsf{S}\{a\}(n_i, n_r, x_i, x_r, p_r)\} \mid$	
		$\{e_i = \mathsf{E}\{p_r, k_e\}(\mathit{id}_a, \mathit{id}'_r, sa_i, s_i)\} \mid$	
		$\{h_i = \mathsf{H}\{k_a\}(\mathsf{T}_i, e_i)\} \mid$	
		$\langle 3(n_i, n_r, x_i, x_r, h_t, e_i, h_i)\rangle$	*send message 3*
		$(4(e_r, h_r)).I_5$	*wait for message 4*
I_5	$=$	$\mathit{if}\ \mathsf{H}\{k_a\}(\mathsf{T}_r, e_r) = h_r\ \mathit{then}$	*check MAC*
		$\nu \mathit{id}_r\, sa_r\, s_r.\{\mathit{id}_r, sa_r, s_r = \mathsf{D}\{p_r, k_e\}(e_r)\} \mid$	*decrypt*
		$\mathit{if}\ id_r \in S_r\ \mathit{then}$	*authorize*
		$\mathit{if}\ \mathsf{V}\{s_r, id_r\}(n_i, n_r, x_i, x_r)\ \mathit{then}$	*authenticate*
		$\overline{\mathit{connect}}^a\langle \mathit{id}_r, sa_r, k_v\rangle$	*open session*

JFK configuration initiator responder

$$R = \prod_{\widetilde{x_r}} \nu c_t\, k_t.D_r \left[\begin{array}{l} !(1(n_i, x_i)).R_2 \mid \\ !(3(n_i, n_r, x_i, x_r, h_t, e_i, h_i)).R_4 \end{array} \right]$$ responder (for a)

$$R_2 = \nu n_r\, h_t.\{h_t = \mathsf{H}\{k_t\}(x_r, n_r, n_i)\} \mid \overline{c_t}\langle h_t \rangle \mid \langle 2(n_i, n_r, x_r, p_r, h_t)\rangle$$ *token* *send message 2*

$$\begin{array}{rcl} R_4 & = & \mathit{if}\ \mathsf{H}\{k_t\}(x_r, n_r, n_i) = h_t\ \mathit{then} \\ & & c_t(h'_t).\mathit{if}\ h'_t = h_t\ \mathit{then} \\ & & \nu k_e\, k_a\, k_v.C_r \mid \\ & & \mathit{if}\ \mathsf{H}\{k_a\}(\mathsf{T}_i, e_i) = h_i\ \mathit{then} \\ & & \nu id_i\, sa_i\, s_i.\{id_i, _, sa_i, s_i = \mathsf{D}\{k_e\}(e_i)\} \mid \\ & & \mathit{if}\ id_i \in S_i^a\ \mathit{then} \\ & & \mathit{if}\ \mathsf{V}\{s_i, id_i\}(n_i, n_r, x_i, x_r, p_r)\ \mathit{then} \\ & & \overline{\mathit{accept}}^a\langle id_i, sa_i, k_v\rangle. \\ & & \nu s_r\, e_r\, h_r. \\ & & \{s_r = \mathsf{S}\{a\}(n_i, n_r, x_i, x_r)\} \mid \\ & & \{e_r = \mathsf{E}\{k_e\}(id_a, sa_r, s_r)\} \mid \\ & & \{h_r = \mathsf{H}\{k_a\}(\mathsf{T}_r, e_r)\} \mid \\ & & \langle 4(e_r, h_r)\rangle \end{array}$$

verify token
accept token once
handle message 3
authorize
authenticate
complete keying
build message 4
send message 4

Security properties ?

- Main results:
  - In any state, the protocol can establish a secure session between compliant principals
  - There are causality relations between control actions (aka authentication)
  - When both protocols are compliant,
    the key is secure (aka perfect forward secrecy)

- Stated independently of low-level messages
- Compliant principals are also part of the “attacker”

- Additional results:
  - Some identity protection
  - Some DOS properties
  - Some plausible deniability

Operational correctness

Basic Operational Correctness

ocol configuration with compli-

$b \in$ s

with $id_b \in S_r$. *We have:*

$$S \xrightarrow{init^a(S_r, id_r, sa_i)} \rightarrow \approx$$

$$\xrightarrow{\nu k_v.\overline{accept}^b\langle id_a, sa_i, k_v\rangle} \xrightarrow{\overline{connect}^a\langle id_b, sa_r, k_v\rangle} S$$

The protocol uses internal steps:
- low-level communications
- tests after receiving messages

At the end of the protocol,
we can use an observational
equivalence to simplify the
established keys.

We start from any reachable
configuration of the p
(past & running sess

Each party gets the other's
identity & parameters,
shared key.

We end up exactly in the
original configuration !
In particular, *kv* is a perfect key.

Operational correctness with eavesdropping

Let S be a running protocol configuration with compliant principals $\mathcal{L}$. Let $a, b \in \mathcal{L}$ and S_r be a set of terms with $id_b \in S_r$. We have:

In addition, the environment can observe mostly-opaque messages, still unrelated to the session key.

$$
\begin{aligned}
S \quad & \xrightarrow{init^a(S_r, id_r', sa_i)} \\
& \xrightarrow{\nu n_i.[1(n_i, x_i^a)]} \\
& \xrightarrow{\nu n_r\, h_t.[2(n_i, n_r, x_r^b, p_r^b, h_t)]} \\
& \xrightarrow{\nu e_i\, h_i.[3(n_i, n_r, x_i^a, x_r^b, h_t, e_i, h_i)]} \\
& \xrightarrow{\nu e_r\, h_r.[4(e_r, h_r)]} \\
& \rightarrow^4 \approx \xrightarrow{\nu k_v.\overline{accept}^b\langle id_a, sa_i, k_v\rangle} \xrightarrow{\overline{connect}^a\langle id_b, sa_r, k_v\rangle} S
\end{aligned}
$$

where x_i^a is an exponential defined by I^a, x_r^b and p_r^b are an exponential and the preferences defined by R^b, and n_i, n_r, h_t, e_i, h_i, e_r, h_r, k_v are all fresh names.

Correspondence properties

Let S_0 *be an initial configuration with compliant principals* $\mathcal{L}$ *and labeled transitions* $S_0 \xrightarrow{\mu}^* S$ *with no immediate output on any channel* accept^b *in* S.

The actions occuring in μ *have the following properties:*

1. *For any* $\beta = \overline{\mathit{accept}}^b\langle \mathit{id}_a, sa_i, k_v\rangle$, *we have* $\mathit{id}_a \in S_i^b$.
2. *For any* β *with* $a \in \mathcal{L}$, *there is a distinct* $\alpha = \mathit{init}^a(S_r, \mathit{id}'_r, sa_i)$ *with* $\mathit{id}_b \in S_r$.
3. *For any* $\gamma = \overline{\mathit{connect}}^a\langle \mathit{id}_b, sa_r, k_v\rangle$ *there is a distinct* $\alpha = \mathit{init}^a(S_r, \mathit{id}'_r, sa_i)$ *with* $\mathit{id}_b \in S_r$.
4. *For any* γ *with* $b \in \mathcal{L}$, *there is a distinct* $\beta = \overline{\mathit{accept}}^b\langle \mathit{id}_a, sa_i, k_v\rangle$.
5. *For any two other control actions that output a session key (either* $\overline{\mathit{connect}}^a\langle _, _, k_v\rangle$ *or* $\overline{\mathit{accept}}^b\langle _, _, k_v\rangle$*), the keys are equationally different.*

Anti-DoS properties

- We characterize "round-trip communication" as a trace property:

  $\nu n_r\, h_t.(2(_, n_r, _, _, h_t)) \ldots \langle 3(_, n_r, _, _, h_t, _, _)\rangle$

  and show an injective correspondence property from (informally) expensive responder steps to round-trips.

- The use of a token is a refinement, modelled as an equivalence
  - The basic model uses local responder state after message 1 & 2
  - The refined model uses the token instead

  This is much like the parallel law for CCS

  $(!P \mid !Q) \approx !(P \mid !Q)$

Plausible deniability

- What gets signed ?
  - Authentication for an active party
  - Deniability from some (data) evidence
- Example:
  - a opens a session with e (which may not comply with JFK)
  - e tries to prove that a opened the session from his data.
  - a refutes e's evidence by exhibiting a trace where
    - a complies with JFK
    - a never tries to open a session with e
    - e produces the same evidence

  for instance, a plausible trace may be
    - a opens a session with a compliant b $\neq$ e
    - e is an active attacker that impersonates b

Summary on JFK

- JFK is a state-of-the-art protocol, well-written but message-centric and sometimes imprecise
  - We had to interpret the spec and invent a service API
  - Writing down a precise definition for the intended properties of the protocol is difficult (and reveals problems)
- We wrote a "formal implementation" of JFKr in applied pi
- We obtained a formal counterpart for each informal claim, against a large class of active attackers (=contexts)

Questions?

See also http://research.microsoft.com/~fournet/