Midterm Exam

- **March 25 – Don't miss it!**
- **Open book, open note**
  - Bring copies of all the papers, you will need them
  - Don't count on reading the papers during the exam
- **Covers first six lectures**
  - There will be at least one question on protocols
- **See me after lecture if you have any questions**
  - It's my office hours (I have to sit around anyway)
  - If it seems like a stupid question, all the more reason to get it answered
  - I can meet other times, just send me mail

SPKI/SDSI naming

- **Every *public key* has a local name space**
  - No global names
- **A *local name* is an expression of the form $K\ A$**
  - K is a public key
  - A is an *identifier*, such as “Alice” or “faculty”
- **An *extended name* is a key K followed by two or more identifiers**
  - E.g., K NYU faculty, or K David Security-class-TA
- **A *term* is a public key or local or extended name**

Name certificates

- **A *name certificate* is a signed 4-tuple** (K, A, S, V)
  - K is the *issuer* that signed the certificate
  - A is an identifier (e.g., faculty, David)
  - S, a term, is the *subject* (the "meaning" of local name $K\ A$)
  - V is a *validity specification*
- **Given set C of certificates, the *value* $\mathcal{V}_C(T)$ of term T is a set of certificates defined as follows:**
  - $\mathcal{V}_C(K) = \{K\}$ for any key K
  - If $(K, A, S, V) \in C$, then $\mathcal{V}_C(K\ A) \supseteq \mathcal{V}_C(S)$.
  - $\mathcal{V}_C(K\ A_1\ A_2\ \ldots\ A_n) = \bigcup_{K' \in \mathcal{V}_C(K\ A_1)} \mathcal{V}_C(K'\ A_2\ \ldots\ A_n)$
- **Alternate interpretation as re-write rule:** $K\ A \rightarrow S$

Example

- **Some hypothetical certificates for NYU:**
  - K_{NYU} David $\rightarrow K_D$
  - K_{NYU} faculty $\rightarrow K_{\text{NYU}}$ David
  - K_{NYU} Margaret $\rightarrow K_M$
  - K_{NYU} faculty $\rightarrow K_{\text{NYU}}$ Margaret
  - K_{NYU} comp-sci-chair $\rightarrow K_{\text{NYU}}$ Margaret
  - K_{NYU} faculty $\rightarrow K_{\text{NYU}}$ comp-sci-chair adjunct-faculty
- $\mathcal{V}_C(K_{\text{NYU}}\text{ faculty})$ **includes:**
  - K_D, K_M
  - Keys of anyone Margaret has designated adjunct-faculty

Evaluating terms

- **With only local names, evaluate by creating graph**
  - Every key and local name is a vertex
  - Edges go from local name to subjects in certificates
  - $\mathcal{V}(T)$ is all K such that $T \xrightarrow{*} K$
- **With extended names, must define composition:**
  - If $C = L \rightarrow R$ and $S = LX$, then $S \circ C = RX$
  - If $C_1 = L_1 \rightarrow R_1$, $C_2 = L_2 \rightarrow R_2$, and $R_1 = L_2X$, then $C_1 \circ C_2 = L_1 \rightarrow R_2X$
- **The *closure* $\mathcal{C}^+$ of a set of certificates $\mathcal{C}$ is smallest superset of $\mathcal{C}$ closed under composition.**
  - Can use same graph algorithm to evaluate
  - Problem: Infinite $\mathcal{C}^+$: $K\ A \rightarrow K\ A\ A$

Solution: Name-reduction closures

- **A cert** $C = L \rightarrow R$ **is** ***reducing*** **if** $|L| > |R|$
  - All reducing certs are of form $K\ A \rightarrow K'$
- **Compute** ***name-reduction closure*** $\mathcal{C}^{\#}$ **as follows:**
  - Initialize $\mathcal{C}' \leftarrow \mathcal{C}$
  - If $C_1, C_2 \in \mathcal{C}'$, $C_1 \circ C_2$ is defined, and C_2 is reducing, add $C_1 \circ C_2$ to $\mathcal{C}'$
  - Repeat previous step until no new certificates can be added
- **Theorem: If** $L \rightarrow R \in \mathcal{C}$**, then** $\forall K \in V_{\mathcal{C}}(R),\ L \rightarrow K \in \mathcal{C}^{\#}$
- **Converse: If** $L \rightarrow K \in \mathcal{C}^{\#}$**, then** $\exists L \rightarrow R \in \mathcal{C}$ **s.t.** $K \in \mathcal{V}_{\mathcal{C}}(R)$

Authorization certificates

- **Auth certs are signed 5-tuples** (K, S, d, T, V)
  - K is the *issuer*
  - S, a term, is the *subject* ($\mathcal{V}(S)$ are keys getting permission)
  - d is *delegation bit* (if true, $\mathcal{V}(S)$ can further delegate)
  - T is the *authorization tag*—what is being authorized
  - V is the *validity specification* an in name certs
- **Example: Access control lists**
  - Owner of protected resource issues one or more auth certs
  - In this common case, K can just be written Self
  - E.g., Web server key signs $(\mathrm{Self}, K_{\mathrm{NYU}}\ \mathrm{students}, 0, T, V)$, where $T =$`(tag (* prefix http://www.nyu.edu/))`

Authorization tags

- **Mostly opaque to certification machinery**
  - Must be able to intersect two tags
- **Represented as S-expressions, some special forms**
  - `(*)` – is a wild card matching anything
  - `(* set id1 id2...)` – is a set of tag expressions
  - `(* prefix string)` – is anything with prefix string
  - `(* range ordering lower-lim upper-lim)` – is a range
- **Can be intersected. Example:**
  - `(tag (pkpfs (* prefix //www.nyu.edu/) read))`
  - `(tag (pkpfs (* prefix //www.nyu.edu/G22.3033-001/) (* set read write))`

Auth certs as rewrite rules

- (K, S, d, T, V) **can be written** $K\,\boxed{\mathbf{1}} \rightarrow S\,\boxed{\mathbf{d}}$
  - $\boxed{\text{z}}$ is a *ticket symbol* representing delegation
  - $\boxed{1}$ means further delegation is permitted, $\boxed{0}$ not
- **Use the same rules as before for** $C_3 = C_1 \circ C_2$
  - If $C_1 = L_1 \rightarrow L_2X$, $C_2 = L_2 \rightarrow R_2$, $C_1 \circ C_2 = L_1 \rightarrow R_2X$
  - Note L_2 cannot end $\boxed{0}$, so neither can X
    (this restricts further delegation as desired)
  - C_1 can be a name or auth cert, C_3 will be same type
  - C_2 cannot be auth cert if C_1 is not also an auth cert
  - If C_2 is an auth cert, X must be empty

The Kerberos authentication system

- **Goal: Authentication in "open environment"**
  - Not all hardware under centralized control
    (e.g., users have "root" on their workstations)
  - Users require services from many different computers
    (mail, printing, file service, etc.)
- **Model: Central authority manages all resources**
  - Effectivaly manages human-readable names
  - User names: dm, waldman, ...
  - Machine names: class1, class2, ...
  - Must be assigned a name to use the system

Kerberos principals

- *Principal*: **Any entity that can make a statement**
  - Users and servers sending messages on network
  - "Services" that might run on multiple servers
- **Every kerberos principal has a key (password)**
- **Central key distribution server (KDC) knows all keys**
  - Coordinates authentication between other principals

Kerberos protocol

- **Goal: Mutually authenticated communication**
  - Two principals wish to communicate
  - Principals know each other by KDC-assigned name
  - Kerberos establishes shared secret between the two
  - Can use shared secret to encrypt or MAC communication (but most services don't encrypt, none MAC)
- **Approach: Leverage keys shared with KDC**
  - KDC has keys to communicate with any principal

Protocol detail

- **To talk to server s, client c needs key & ticket:**
  - Session key: $K_{s,c}$ (randomly generated key KDC)
  - Ticket: $T = \{s, c, \text{addr}, \text{expire}, K_{s,c}\}_{K_s}$
    (K_S is key s shares with KDC)
  - Only server can decrypt T
- **Given ticket, client creates authenticator:**
  - Authenticator: $T, \{c, \text{addr}, \text{time}\}_{K_{s,c}}$
  - Client must know $K_{s,c}$ to create authenticator
  - T convinces server that $K_{s,c}$ was given to c
- **"Kerberized" protocols begin with authenticator**
  - Replaces passwords, etc.

Getting tickets in Kerberos

- **Upon login, user fetches "ticket-granting ticket"**
  - $c \to t$: c, t (t is name of TG service)
  - $t \to c$: $\{K_{c,t}, T_{c,t} = \{s, t, \text{addr}, \text{expire}, K_{c,t}\}_{K_t}\}_{K_c}$
  - Client decrypts with password ($K_c = H(\text{pwd})$)
- **To fetch ticket for server s**
  - $c \to t$: $s, T_{c,t}, \{c, \text{addr}, \text{time}\}_{K_{c,t}}$
  - $t \to c$: $\{T_{s,c}, K_{s,c}\}_{K_{c,t}}$
- **Applications can use Kerberos as follows:**
  - $c \to s$: $T_{s,c}, \{c, \text{addr}, \text{time}, K_1, K_2, K_3, K_4\}_{K_{s,c}}$
  - Then c and s use $K_1 \ldots K_4$ as encryption and MAC keys to communicate securely in each direction.

Security issues with kerberos

- **Protocol weaknesses:**
  - Kinit could act as oracle
  - Replay attacks
  - Off-line password guessing
  - Can't securely change compromised password
- **General design problems:**
  - KDC vulnerability
  - Hard to upgrade system (everyone relies on KDC)

Authentication in AFS

- **User logs in, fetches kerberos ticket for AFS server**
- **Hands ticket and session key to file system**
- **Requests/replies accompanied by an authenticator**
  - Authenticator includes CRC checksum of packets
  - Note: CRC is not a valid MAC!
- **What about anonymous access to AFS servers?**
  - User w/o account may want universe-readable files

AFS permissions

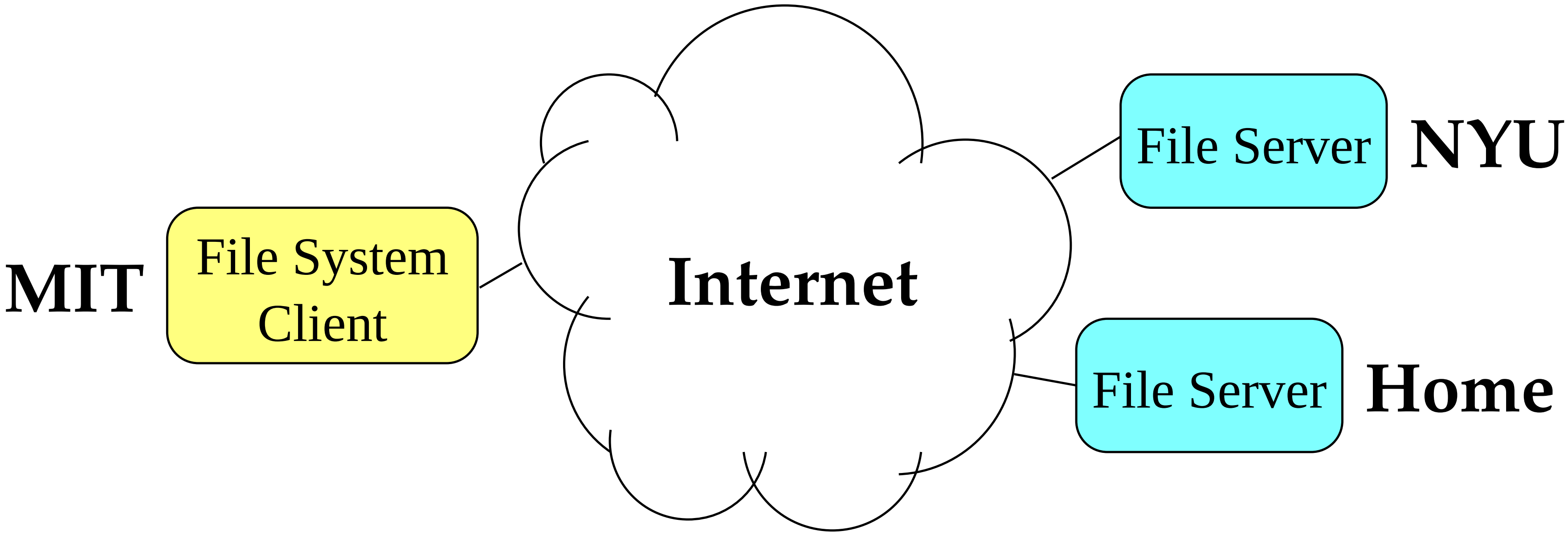
- **Each directory has ACL for all its files**
  - Precludes cross-directory links
- **ACL lists principals and permissions**
  - Both “positive” and “negative” access lists
- **Principals: Just kerberos names**
  - Extra principles, system:anyuser, system:authuser
- **Permissions: rwlidak**
  - read, write, lookup, insert, delete, administer, lock

Kerberos inconvenience

- **Large (e.g., university-wide) administrative realms**
  - University-wide administrators often on the critical path
  - Departments can't add users or set up new servers
  - Can't develop new services without central admins
  - Can't upgrade software/protocols without central admins
  - Central admins have monopoly servers/services
    (Can't set up your own without a principal)
- **Crossing administrative realms a pain**
- **Ticket expirations**
  - Must renew tickets every 12–23 hours
  - Hard to have long-running backround jobs

Stretch break

SFS goal: A secure global file system



`/sfs/nyu.edu:···/dm/lec4.pdf`

- One namespace for all files
- Global deployment (anyone can set up a server)
- Security over untrusted networks

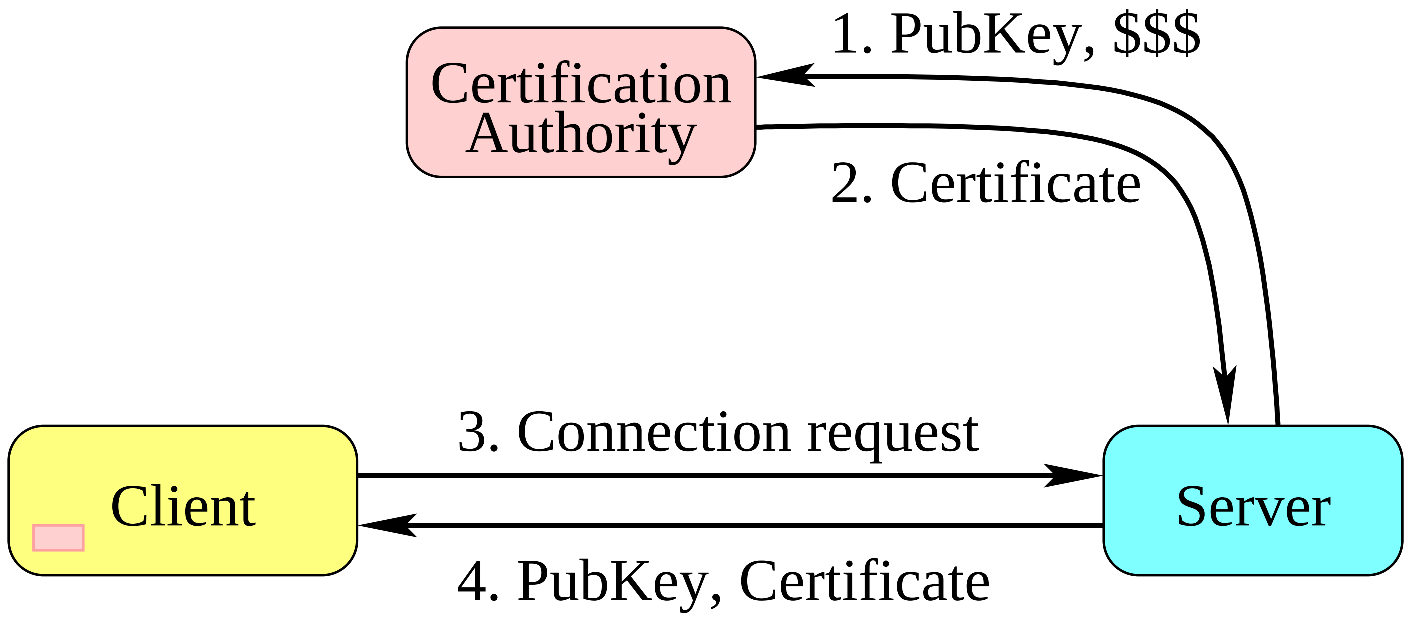
The security problem

- **Secure client–server communications**
  - Solution: Encrypt and MAC all network traffic
- **Authenticate users to servers**
  - Servers know what classes of users to expect in advance
  - Solution: Store users' passwords or public keys
- **Authenticate servers to clients**
  - Would be solved if client had server's public key
  - Clients don't know about servers in advance
  - A user can potentially access any server in the world
  - Solution: ?

Typical systems

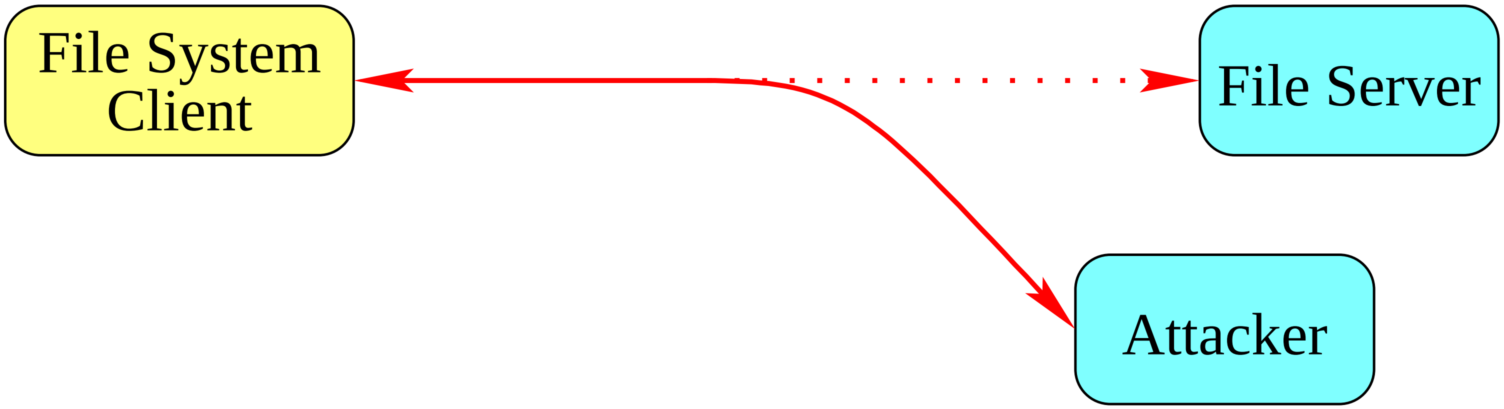
- **Presume hypothetical cooperation of third parties**
  - Echo: Assume DNS admins will manage keys
- **Lack security across administrative boundaries**
  - AFS provides no security to unknown users
- **Penalize the creation of new administrative realms**
  - Kerberos and AFS lead to inconveniently large realms
- **Provide inappropriate security procedures or guarantees**
  - SSL takes “one size fits all” approach to key management

SSL approach in detail



- **Everybody trusts some certification authority**
- **Trade-off between ease of certification and security**
- **Precludes other models (passwords, Kerberos, . . .)**

Server key management



- **How to get a server's public key?**
  - Use password in conjunction with SRP
  - A CA whose key you know certified the server
  - Another server in the same realm gives you the key
  - Bootstrap using another system's key management
  - The CD-ROM for your OS contained the key
  - Correct answer: All of the above in different situations

Self-certifying File System

- **Idea: Make file system security independent of key management**
- **Specify server keys in *self-certifying pathnames*:**
  `/sfs/sfs.mit.edu:bzcc5hder7cuc86kf6qswyx6yuemnw69/dm/`
  - File name itself certifies server's public key
- **Push key management out of the file system**
  - Problem reduces to finding correct file name

Different approach to key management

- **Provide security without key management**
- **Let multiple key management schemes coexist**
- **Make it easy to implement new schemes**
  - *Self-certifying pathnames* managed with standard file utilities
  - *SFS Agents* let external programs manage keys
  - *Secure symbolic links* like web links but secure
  - *SFS itself* allows secure sharing key management data

User's view of SFS

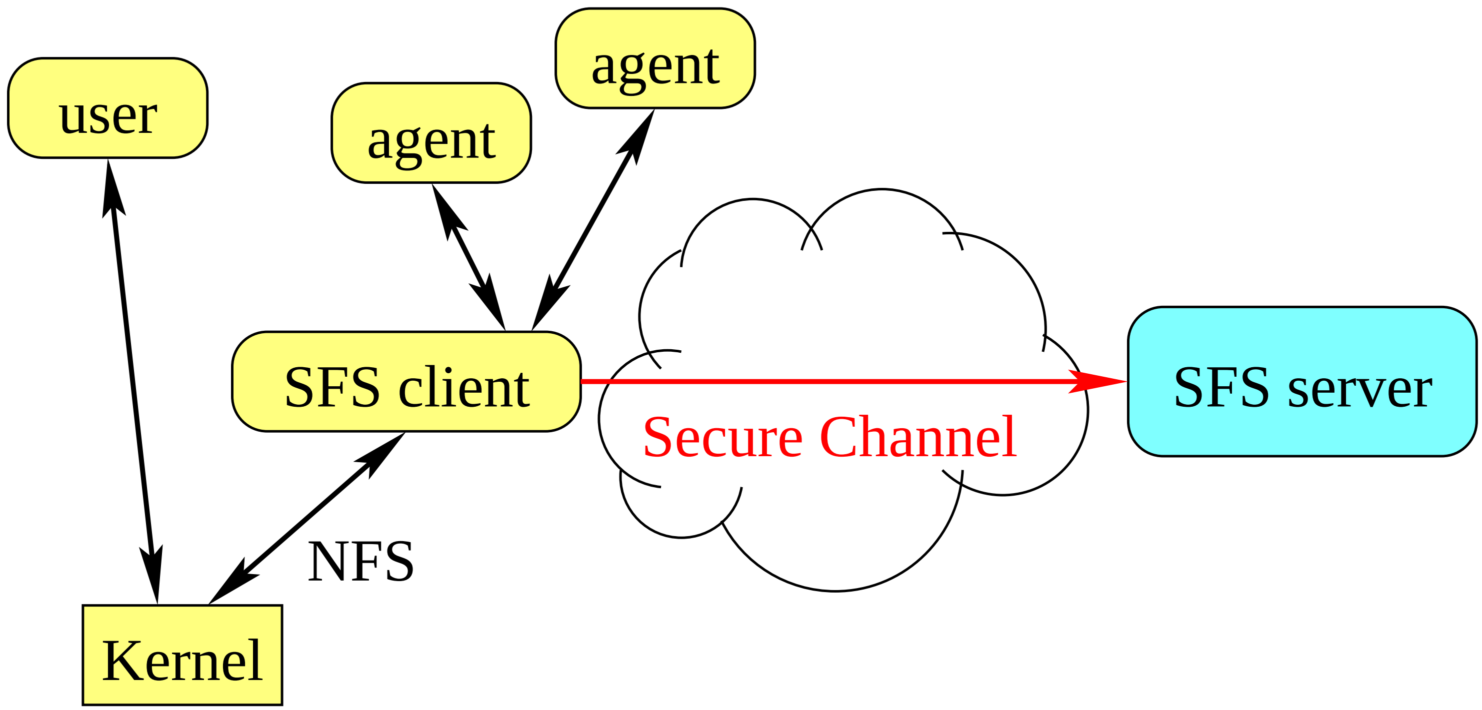
- **New directory `/sfs` contains global files**
- **Subdirectories of `/sfs` are self-certifying**

  `/sfs/sfs.nyu.edu:bzcc5hder7cuc86kf6qswyx6yuemnw69/`
- **Human-readable aliases give names to public keys**

  `/sfs/NYU` $\longrightarrow$ `/sfs/sfs.nyu.edu:bzcc···nw69`
- **Ordinary naming under self-certifying pathnames**

  `/sfs/sfs.nyu.edu:bzcc···nw69/usr/dm/mbox`

System's view of SFS



- **Client appears to system as NFS server for `/sfs`**
- **Interprets requests for self-certifying pathnames**
- **Agents interpret non-self-certifying pathnames**

Self-certifying pathnames

- **File systems lie under `/sfs/`*Location*:*HostID***

$$\textbf{\textit{HostID}} = \mathrm{SHA\text{-}1}\,(K_S, \ldots)$$

  - *Location* is DNS name or IP address
  - K_S is the server's public key

- ***HostID* effectively equivalent to public key**
  - SHA-1 is collision-resistant
  - Client can ask server for key and check against *HostID*

Self-certifying pathname details

$$/\texttt{sfs}/\underbrace{\texttt{sfs.fs.net}}_{\textit{Location}}:\overbrace{\texttt{eu4cvv6wcnzscer98yn4qjpjnn9iv6pi}}^{\textit{HostID}\text{ (specifies public key)}}/\underbrace{\texttt{sfswww/index.html}}_{\text{path on remote server}}$$

- **Pathnames transparently created when referenced**
  - Anyone can create a server
  - New servers instantly accessible from any client
- **Client requires server to have *HostID*'s private key**
- **Pathname implies nothing about name of server**
  - e.g., server may not actually be the real `sfs.fs.net`
  - Need key management to produce the correct file name

Key management through symbolic links

- **Symbolic links assign additional names to paths**
  - *link* → *dest* makes *link* another name for *dest*
  - Always interpreted locally on a file system client
- **Link human-readable to self-certifying pathnames**
- **Example: manual key distribution**
  - Install central server's path in root directory of all clients:

    `/nyu → /sfs/sfs.nyu.edu:bzcc5hder7cuc86kf6qswyx6yuemnw69`
  - `/nyu/README` designates the pathname:

    `/sfs/sfs.nyu.edu:bzcc5hder7cuc86kf6qswyx6yuemnw69/README`

    "The file `README` on the server my administrator calls `/nyu`"
    In SDSI terminology, "`nyu`'s `README`"

Certification authorities

- **Are simply SFS file systems**
  - Can be named by local symbolic links:

    `/verisign` → `/sfs/sfs.verisign.com:r6ui9gwucpkz85uvb95cq9hdhpfbz4pe`
  - Name other file systems with symbolic links, e.g.

    `/verisign/NYU` → `/sfs/sfs.nyu.edu:bzcc5hder7cuc86kf6qswyx6yuemnw69`
  - Servers reachable from `/verisign` can name other servers

    `/verisign/NYU/cs` might name server for `cs.nyu.edu`
  - Read-only protocol keeps private key off-line
- **Pathnames reflect trust relationships:**

  `/verisign/NYU/README` – "File `README` on the server Verisign calls NYU"
- **This is just like SDSI naming!**
  - Let file namespace double as "local key namespace"

Example: Getting *HostID* with a password

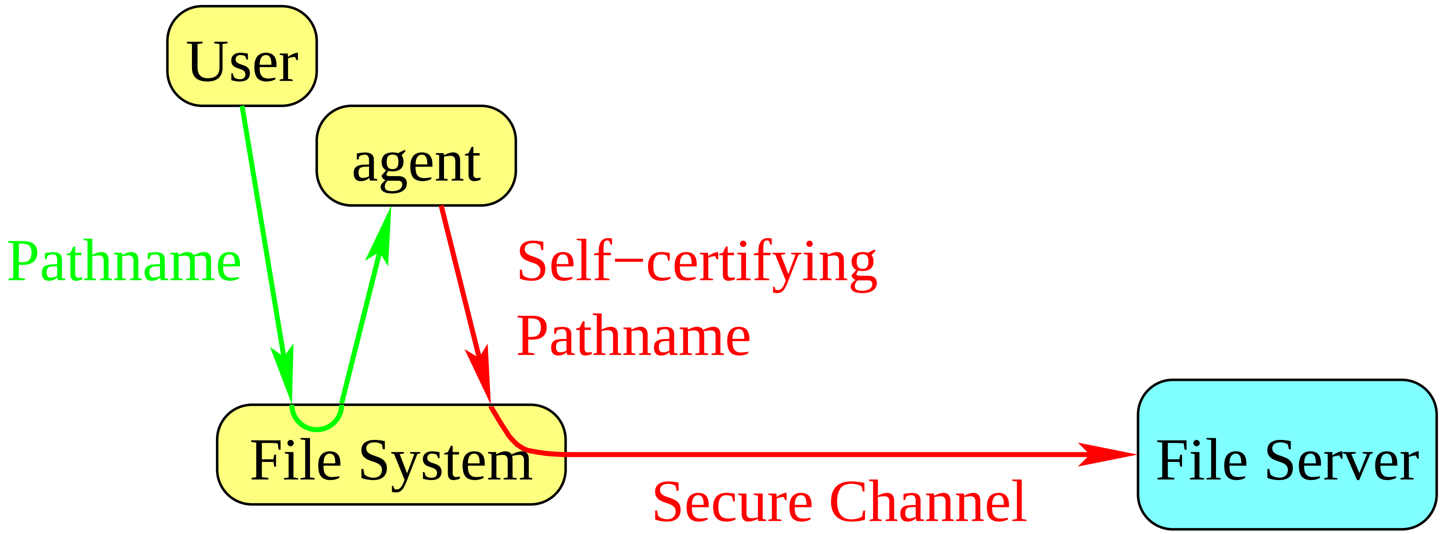
- **Use password to authenticate server (SRP)**
  - Force server to prove possession of secret password
- **Downloading my server's *HostID* from Lucent:**

```
% sfskey add dm@scs.cs.nyu.edu
Passphrase for dm@scs.cs.nyu.edu:
% ls -al /sfs/scs.cs.nyu.edu
lr--r--r--  1 root  sfs  512 May 28 04:16 /sfs/scs.cs.nyu.edu ->
scs.cs.nyu.edu:85xq6pznt4mgfvj4mb23x6b8adak55ue
```

[*sfskey* also simultaneously handles user authentication.]

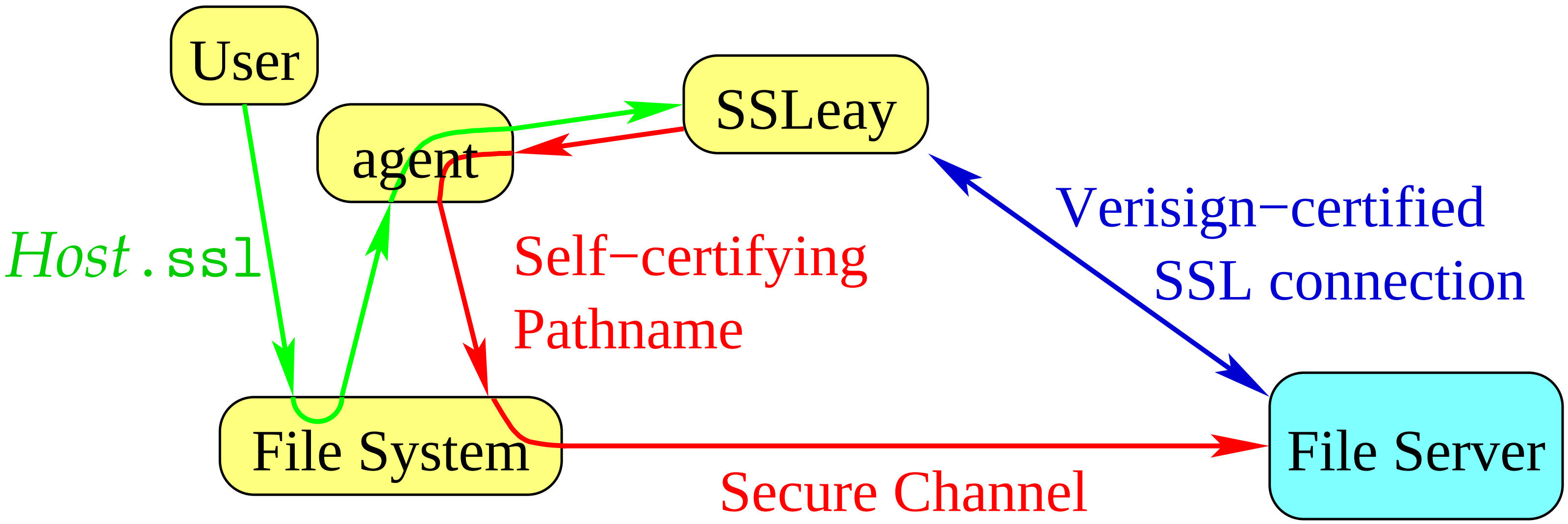
- **Bootstrap security using links on `scs.cs.nyu.edu`**

Dynamic server authentication



- **Each user runs an *agent* program to control `/sfs`**
- **Agents can create symbolic links in `/sfs` on-demand**
  - Agent maps names to self-certifying pathnames with arbitrary external programs

Example: Getting *HostID*s through SSL



- **User references `/sfs/`*Host*`.ssl`**
- **Agent spawns SSL client to get *HostID* securely**
- **Agent links `/sfs/`*Host*`.ssl` → *Host*:*HostID***
  - User's file access transparently redirected

Implementing key management is trivial!

- **SSL example implemented in two lines**
  - Distribute pathnames from URL `https://`*Host*`/sfspath.txt`
  - Map `/sfs/`*Location*`.ssl` to path retrieved with SSL:

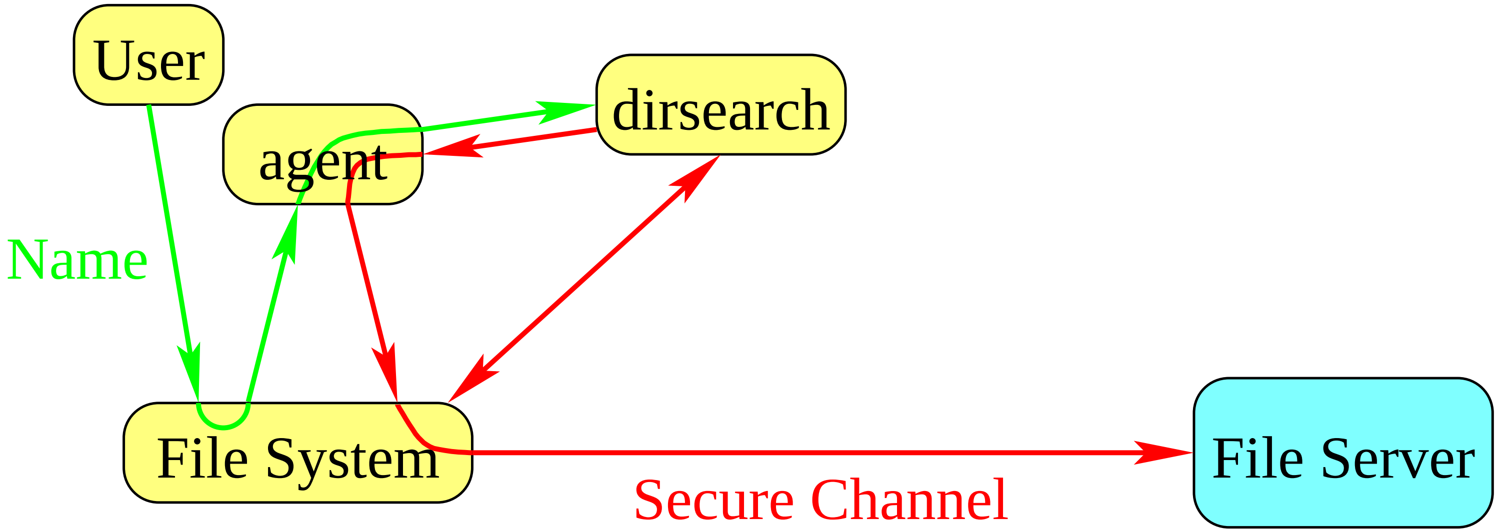
```
% sfskey certprog -s ssl \
    sh -c 'lynx -source https://$0/sfspath.txt'
```

- **Don't like SSL? How about Kerberos?**
  - Map `/sfs/`*Location*`.krb` to path retrieved with Kerberos:

```
% sfskey certprog -s krb \
    sh -c 'rsh -x $0 sfskey hostid -'
```

  - Similar command works for SSH

Certification paths



- **Combine multiple certification authorities**
  - Merge your own names with those assigned by third parties
- **Make agent search multiple directories for links:**

  `~/.sfs/known_hosts`, `/nyu/links`, `/verisign`, `/thawte`
- **Dirsearch implementation easy given file system**

Revocation

- **Many links may exist to a compromised *HostID***
- **Separate key revocation from key distribution**
  - Announce revocation with self-authenticating certificates

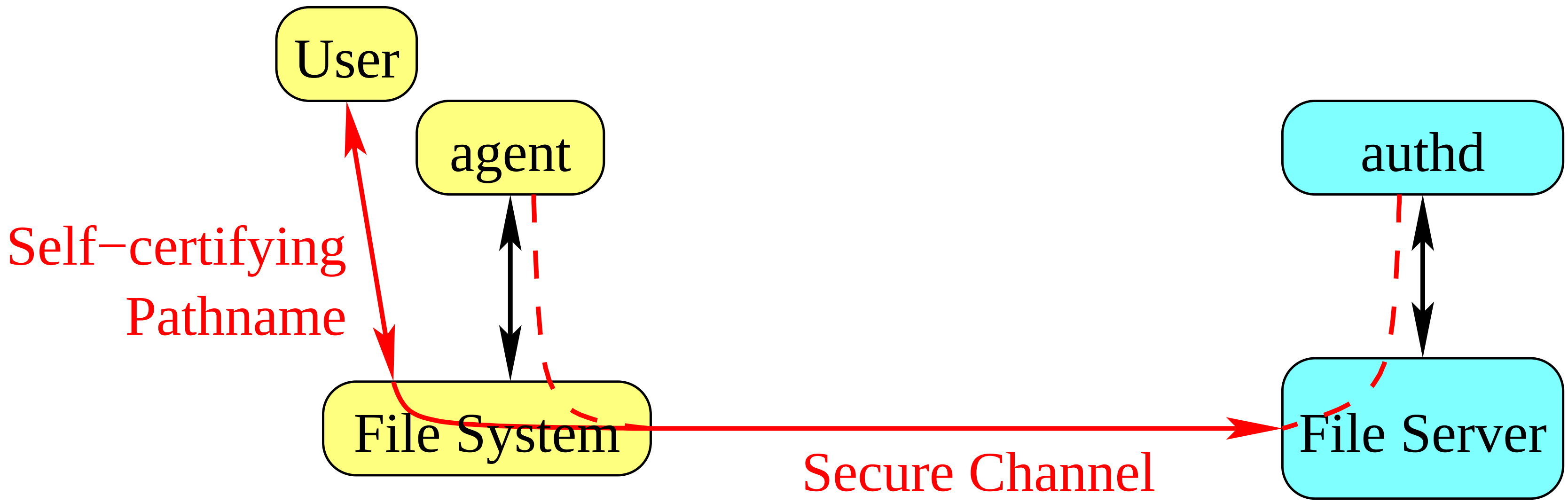
$$\{\text{“Path Revoke”}, \mathit{Location}, K_S, \ldots\}_{K_S^{-1}}$$

  - Let agents search for certificates on-the-fly

Distributing revocation certificates

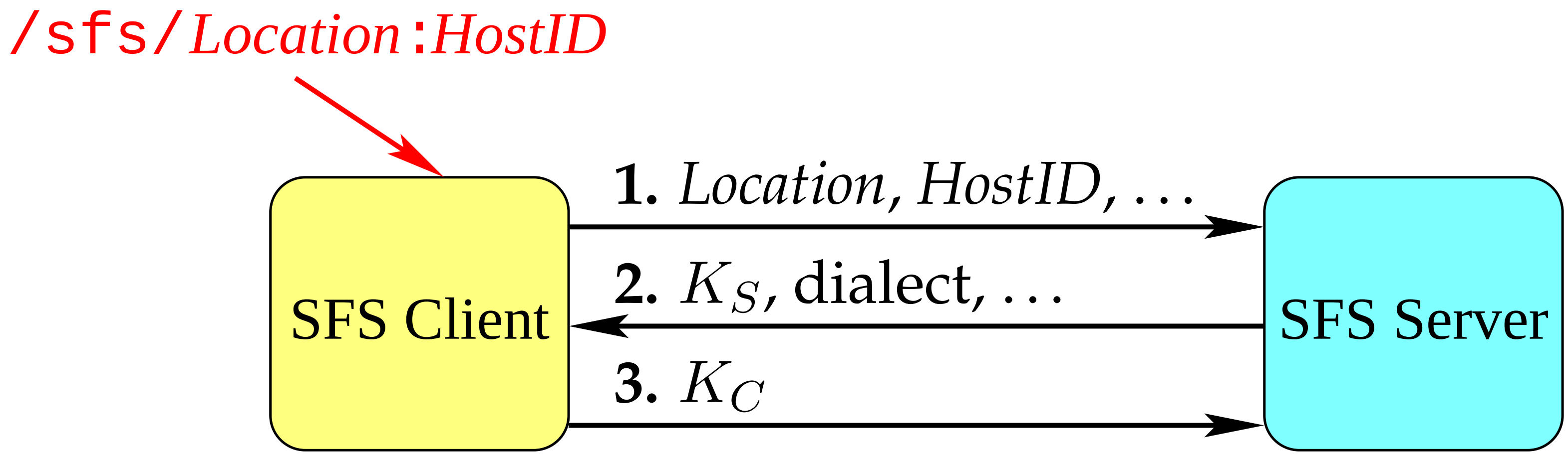
- **Use the file system!**
  - Publish revocation certificates as `/verisign/revoked/`*HostID*
  - *dirsearch* fetches certificates, as with certification paths
- **Benefits of separating revocation from certification:**
  - Revocation certificates require no out-of-band verification
  - No authority necessary to submit a revocation certificate
  - Revocation certificates as secure as *best* CA, not weakest

User authentication



- **Separate programs handle authentication**
  - User-authentication protocols opaque to file system proper
- **Current authd has simple public-key protocol**
  - No penalty for accessing many administrative realms
  - Use the file system to distribute user keys

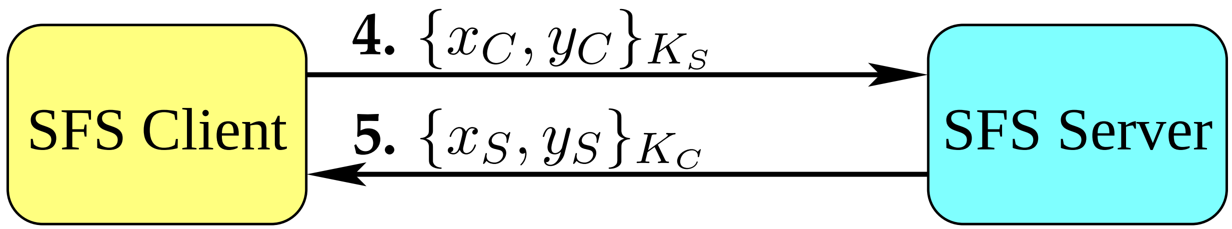
Connection protocol



Goal: A secure channel to the server for *HostID*

1. **Client connects to server**
2. **Server returns its public key,** K_S
   - Client hashes K_S and verifies it matches *HostID*
   - Client passes connection to appropriate daemon for dialect
3. **Client sends short-lived, anonymous public key,** K_C

Session key negotiation



$$
\begin{aligned}
\textbf{6. } k_{CS} &= \text{SHA-1}(\text{dialect}, K_S, x_S, K_C, x_C, \ldots) \\
k_{SC} &= \text{SHA-1}(\text{dialect}, K_S, y_S, K_C, y_C, \ldots)
\end{aligned}
$$

4. Client encrypts two random key halves with K_S

5. Server encrypts two random key halves with K_C

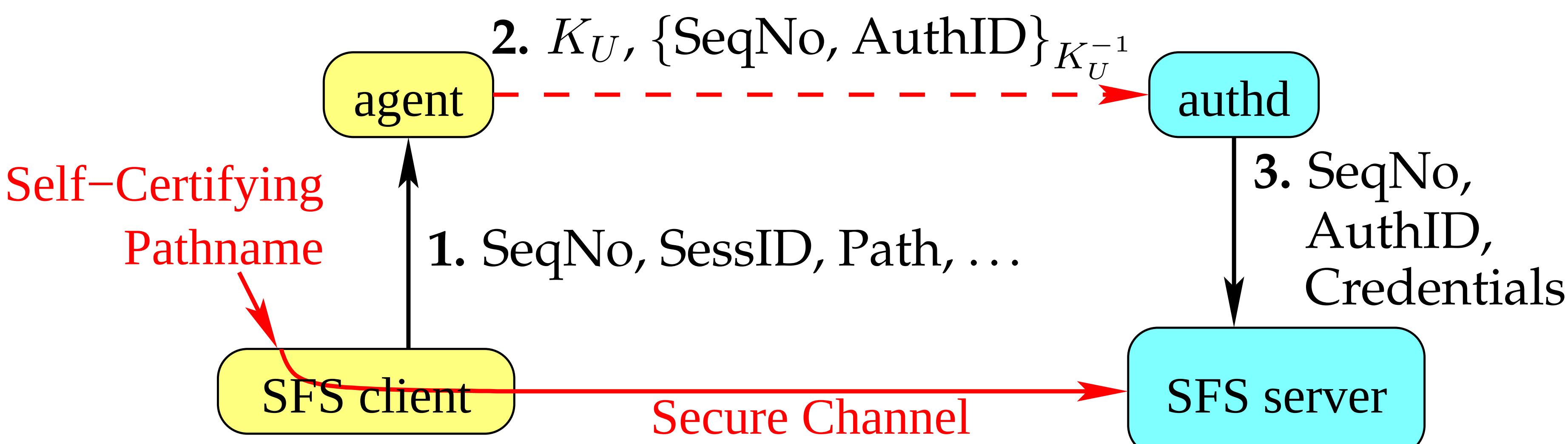
6. Client and server compute shared session keys

Important properties of protocol:

- Efficient: Minimizes server computation, overlaps with client
- Simple: No options, always secure

User authentication protocol

$$\text{SessID} = \text{SHA-1}(k_{CS}, k_{SC}, \ldots)$$
$$\text{AuthID} = \text{SHA-1}(\text{SessID, Path}, \ldots)$$



1. **Client notifies agent, assigns it SeqNo**
2. **Agent authorizes secure channel to represent user**
3. ***authd* informs file server of user's credentials**

Attacking SFS

- **Inherent dangers of a global file system**
  - Attacker's own files visible everywhere—facilitates exploits
  - Symbolic links on bad servers can point to unexpected places
- **SFS may further expose bugs in existing software**
  - Running NFS at all can cause security holes
  - Bugs in NFS may let attackers crash machines (or worse)
- **Attacks on SFS itself**
  - Cause resource exhaustion (e.g. use up all file descriptors)
  - Cut network during non-idempotent operations

Lessons learned

- **Challenge of global security is key management**
- **Global public key management not the answer**
  - Even in a global system, key management often a local issue
- **Don't base system security on key management**
  …base key management on secure systems
- **Strip clients of any notion of administrative realm**

Conclusions

- **SFS is first web-like system with global security**
  - Provides strong file system security
  - Realistically deployable on a global scale
    (anyone can create a server, any client can access any server)
- **SFS takes a new approach to key management**
  - Provide global security without any key management
  - Let arbitrary key management schemes coexist externally
  - Make it easy to implement new schemes
- **New key management mechanisms**
  - Self-certifying pathnames, Agents, Secure links
- **SFS is its own key management infrastructure**