Protocol Security

Protocol Design

Why Protocol Security?

- Expectation on ICT systems: **Dependability**
  - More and more mission-critical tasks are moved to ICT
- Problem: Bugs, Crashes, Failures, Malfunctions
- Problem: **Malice**
  - Protection against Malice may also help against bad coincidences

How much security?

Some terminology

- A **system** is designed with ***security objectives*** in mind
- Real systems have ***weaknesses***
- ***Vulnerabilities*** allow circumvention (or misuse!) of security mechanisms

- A ***threat*** is the potential for an ***attack***
- Attacks may create ***damage***
- ***Risk*** = p(attack) × cost(damage)

Security systems

- Security systems control attacks by:
  - *prevention*
  - *detection*
  - *containment*
- This is based on an underlying ***security policy***
  - Rules and regulations, training of employees
  - Emergency planning, training
  - Management support (including protection of security personnel)

Who are the attackers?

- **Insiders** (lazy, frustrated, criminal)
  - Possibly implicated in **Social Engineering**
- **„Hackers“** (Crackers), „script kiddies“
  - Pure curiosity, Fun/Suspense/Addiction, Craving for recognition!
- **Professional** Attackers (espionage, secret services)
- Organized **Crime**
  - E.g., blackmail
  - E.g., damaging a competitor

Security Objectives

- Confidentiality, access control (read), Privacy
  - Special case: Anonymity
- Integrity/Authenticity, access control (write)
- Accountability/Non-repudiability
- Availability

Confidentiality, access control (read), Privacy

- ***secrecy***: restricting (read) access to authorized principals
- ***confidentiality***: (often used in the sense of secrecy) obligation to keep secret
- ***privacy***: right to secrecy of personal information

- Special case: The fact that communication occurred at all is often also a subject of confidentiality (vs. ***traffic analysis***)
- Special case:
  Anonymity: Principal can act without giving away **identity**
  - Possibly giving away a **pseudonym**

Integrity/Authenticity, access control (write)

- ***Integrity*** of data: protection against **unauthorized** and **unnoticed** modification

  (cf. integrity in databases)

- ***Authenticity***: Information is **integrity-protected** and **fresh**; clearly associated to the **identity** of a principal

Accountability/Non-repudiability

- ***Accountability***: An action can be reliably associated with the identity of the principal responsible for the action

- ***Non-repudiability***: An action cannot be denied after the fact
  Necessary for:
  - Digital contracts
  - Digital interaction with government authorities

Availability

- ***Availability***: protect the system against unauthorized impairment of function
  - vs. Denial of Service (DoS) attacks
- Availability + Correctness:
  dependability: soundness; ***reliability*** in providing the service

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Where are the weaknesses?

- Bad **Design**
  - E.g., missing security mechanisms, bad security model
- Bad **Implementation**
  - E.g., buffer overflows, avenues for circumvention
- Bad **Administration**
  - E.g., leaving accounts with standard password, open ports in firewalls, using inappropriate systems and tools
- Bad **Management**
  - E.g., leaving the security policy less than well-defined, not investing in training, no funds for security audits, no management support for the organizational cost of security measures

Design principles for secure systems (1)

- **Principle of Economy of Mechanism**
  The protection mechanism should have a simple and small design.
- **Principle of Fail-safe Defaults**
  The protection mechanism should deny access by default, and grant access only when explicit permission exists.
- **Principle of Complete Mediation**
  The protection mechanism should check every access to every object.

[Saltzer/Schroeder 1975]

Design principles for secure systems (2)

- **Principle of Open Design**
  The protection mechanism should not depend on attackers being ignorant of its design to succeed
  (no ***security by obscurity***).
  It may however be based on the attacker's ignorance of specific information such as passwords or cipher keys.
- **Principle of Separation of Privilege**
  The protection mechanism should grant access only based on more than one piece of information.

Design principles for secure systems (3)

- **Principle of Least Privilege**
  The protection mechanism should force every process to operate with the minimum privileges needed to perform its task.
- **Principle of Least Common Mechanism**
  The protection mechanism should be shared as little as possible among users.
- **Principle of Psychological Acceptability**
  The protection mechanism should be easy to use (at least as easy as not using it).

Design principles for secure systems (4)

- **Principle of Defense in Depth**
  There should be multiple layers of defense before a high-value target is compromised. (No Maginot lines.)
- **Principle of Securing the Weakest Link**
  The protection mechanism should not have weak spots that allow circumventing the well-secured parts. (Security often is a chain.)
- **Principle of Reluctance to Trust**
  The protection mechanism should not give unwarranted trust to any mechanism or entity. (Healthy skepticism.)

(Beyond the 8 principles listed by Saltzer/Schroeder)

Examples: Layer 1 attacks

- Ethernet Repeaters, most kinds of communication lines:
  - Eavesdropping (attacking confidentiality)
  - Data Modification, Injection
    - (usually simpler on higher layers)
- Countermeasure: Quantum cryptography
  - Observation changes phenomena
    - Eavesdropping attack can be reliably detected
  - Low bitrate: mainly useful for transferring keying material

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Examples: Layer 2 attacks

- Ethernet Switches: Poisoning the Switch database
  - E.g., make the switch send traffic to all ports
- ARP Spoofing
  - Eavesdropping (attacking confidentiality), data modification/suppression
  - Tools: Dsniff, Ettercap
- Spoofing MAC Adresses
  - E.g., to circumvent WLAN access control
  - Tools: ifconfig … ether …

Examples: Layer 3 attacks

- Router: Poisoning Routing Protocols
  - Traffic is diverted
  - Eavesdropping (attacking confidentiality)
  - Traffic suppression (creating black holes so victim cannot be heard)

- Spoofing IP addresses
  - E.g., to circumvent NFS access control
  - Injection of data (e.g., for Session Hijacking)

- Loose Source Routing
  - Packets are returned via reversed source route
  - Circumvents TCP Handshake
  - ➔ Loose Source Route is heavily filtered throughout the Internet

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Finding victims: Scanning

- Reconnaissance: Finding potentially vulnerable Hosts
- IPv4 address space is densely populated
  - Of ~ 4.3E9 IPv4 addresses, ~ 3.7E9 can be used as unicast addresses; of these ~ 2.5E9 are allocated (66 %)
  - Of these, ~ 1.7E9 are routed globally (44 % of the usable, 68 % of the allocated address space)
  - > 0.3E9 of these have a web server (netcraft.com), which is nearly 10 %!
- IPv6 makes scanning much harder
  - 4E33 addresses are allocated (0.01 % of the currently usable space)
  - Enumerating these at 1 Gbit/s takes ~ 4E19 years
  - However, there are other ways to collect IPv6 addresses, e.g.
    - DNS analysis
    - Snooping traffic

Internet Background Radiation

- Worms such as SQL-Slammer are always active somewhere
- There is also backscatter from random spoofed source addresses
- „Background radiation“: ~ 0.1–4 Bytes/s/IP-Address
- Connecting an unpatched Windows-System to the Internet?
  - Infections within minutes (seconds?)
  - Usually crashes completely after ~ 30 minutes
- Add the intentionally targeted attacks
- Corporate networks may not need full Internet connectivity
  - Firewalls ➔ next segment

Examples: Layer 4 attacks

- RST-Attacks
  - Aborting a TCP connection between victim hosts
  - Can seriously damage Routing System (BGP) ➔ DoS
- SYN-Flooding
  - Create state
  - Overload prevents the creation of normal connections (DoS)

Examples: Layer 7 attacks

- DNS Spoofing
    - Poison the Caches of DNS Servers
- Email Spoofing
- Web Spoofing, Phishing
- Attacking programs: Buffer Overflows etc.

Commonalities

- On-Path attackers can eavesdrop
    - Certain active attacks can divert the path to make the attacker “on-path”
    - Countermeasure: Encryption (Cryptography)
- Identity assertions (e.g., source addresses) can be faked
    - Countermeasure: Authentication
    - Must be resistant against eavesdropping and replay
        - Cryptographic authentication

The Internet threat model

- Assumption: The end-systems are not compromised
  - There are ways to minimize damage even in this case, e.g., perfect forward secrecy
- However, the communications channel is completely compromised, i.e., attacker can:
- Read any PDU
- Undetectably remove, modify, inject any PDU
  - Including PDUs that appear to be from a “trusted” machine

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Types of attacks

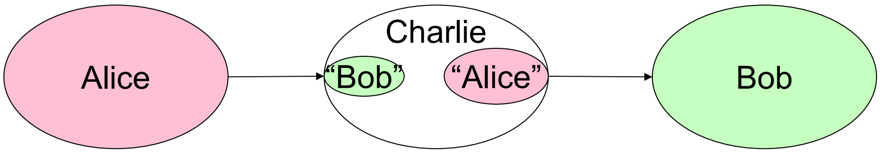
- Passive attacks:
  - Attacker only reads packets (“sniffing”)
  - Extremely easy on wireless
  - Relatively easy on shared media such as Ethernet
  - Can only really be excluded by quantum cryptography
- Active attacks:
  - Attacker also injects new packets into the network
  - Source address can be spoofed
    - Egress/ingress filtering can make this harder
  - Blind attacks: can only write, not read
  - Replay attacks: inject copy of previous good packet (“launch rocket now”)

Combinations

- Passive followed by active attack:
  - Password sniffing (passive) + login using sniffed password (active)
  - Can be supported by an offline attack, e.g. dictionary attack
    - If sniffed information can be used offline to determine whether guessed password is correct
- Active attack to facilitate passive attack:
  - Subvert forwarding/routing system to divert traffic via attacker
  - Quite easy at layer 2 (tools: dsniff, ettercap)
  - Subverting routing at layer 3 may be harder
  - Compromised router/switch can be used as tool

Man-in-the-middle (middleperson) attack

- Special form of active attack:
- Man-in-the-middle creates the illusion for each communicating partner to be the other communicating partner:
  - Messages can be copied and modified



- Countermeasure: Cryptography (Authentication/Encryption)

On-path vs. off-path attacks

- On-path attacker can easily eavesdrop, spoof, suppress, inject
- Off-path attacker typically is limited to blind attacks
  - Unless topology can be subverted to convert off-path into on-path situation
- Many protocols protect well against off-path attackers, not so well against on-path
  - E.g., TCP random sequence numbers are worthless if overheard by on-path attackers
- (Note that real Internet paths are often asymmetric.)

Special case: link-local attacks

- Link-local peers may enjoy special trust (e.g., home network)
- Packets with TTL 1 will only reach link-local peers
- Packets with TTL 255 can only have been originated by link-local peers
- Warning: Some tunneling systems don’t decrement TTL

Key Management

- Keys “wear off”
  - Each usage increases amount of material available for cryptanalysis
  - The longer (in time) a key is in use, the more time an attacker has for cryptanalysis
  - Some modes of operation only allow limited number of uses before IV repeats
- Rekeying
  - After some time / some amount of data exchanged, rerun key management
  - **Key derivation**: Use “master key” to derive the actual keys in use
    - Needs cryptographically secure derivation function
    - Per-application keys: compromise in one application does not affect other application

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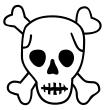
Case Study: IEEE 802.11 WEP

- “Wired Equivalent Privacy”: Encryption designed under serious fear of export control problems
- Key too short (40 bits, this one remedied in products)
- Bad crypto usage (24-bit IV, RC4 problems)
  - Product flaws often made IV reuse even more likely
- No replay protection
- Ridiculous integrity check (CRC32 allows bit flipping attacks)
- The really bad problem:
  - There is only one key for each WLAN
  - The long-term key is directly used as encryption key
  - Once cracked, there is no security left



Case Study: IEEE 802.11i (“WPA”)

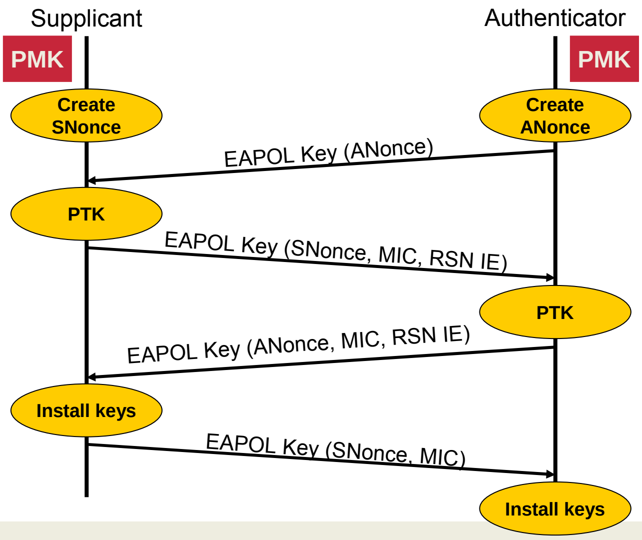
- 802.11i: Completely redesigned security algorithms
- Pairwise master key (PMK)
  - Derived from secure authentication protocol (e.g., EAP-TLS, EAP-TTLS)
  - PMK is not used directly for encryption/authentication of data
- PMK can alternatively be per-WLAN shared secret (“Pre-shared key”, WAP-PSK)
  - Intended for SOHO use (no EAP authentication server available)
  - Well-defined Password-based Key Derivation Function (PBKDF2, RFC2898) to convert passphrase into fixed-size key (**usability**!)
  - Unfortunately, still vulnerable to passive offline dictionary attack
    - But passphrase can be long and hard to guess, thwarting dictionary attacks
    - I.e., need to choose passphrase wisely

WPA: 4-Way-Handshake and PTK

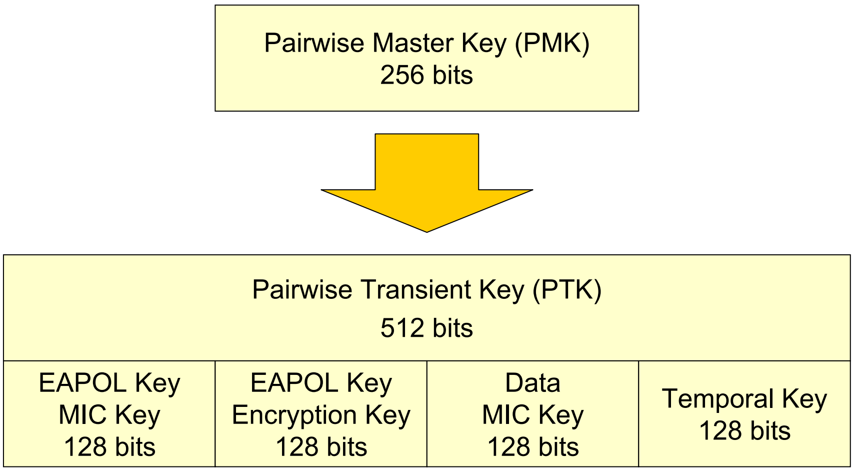
- Do not use PMK for actual data transfer
- Instead:
  create Pairwise Transient Key PTK (512 bits) from the PMK and two Nonces
  - ANonce (*authenticator nonce*) and SNonce (*supplicant nonce*) ensure freshness of PTK
  - Principle: **Joint Key Control** (both parties contribute to key)
- This is then divided up into 4 parts of 128 bit each:
  - Encryption key, Integrity protection key
  - EAPOL-Key Encryption, EAPOL-Key Integrity
- I.e., a part of the PTK is used for protecting rekeying

- The four-way handshake also establishes that both Station and AP know PMK
  - Principle: **Mutual Authentication**

4 Way Handshake und PTK



4 Way Handshake und PTK



Group Keys

- So far, all keys are pairwise (except PSK)
- Problem: Broadcasts (AP to Station) cannot use pairwise key
  - (Exception: Broadcast packets from the Stations are unicast to APs first)
  - For unicast Station→AP, the normal PTK is used

- Separate Group Transient Key (GTK)
- Sent from AP to each Station
  - via pairwise security association, once this has been established
- Needs to be recreated after each disassociation!
  - The old WEP Key-ID field is used to indicate a key serial
  - Allows seamless transition from old to new GTK

Generalizing the Terminology: Multicast Data Confidentiality

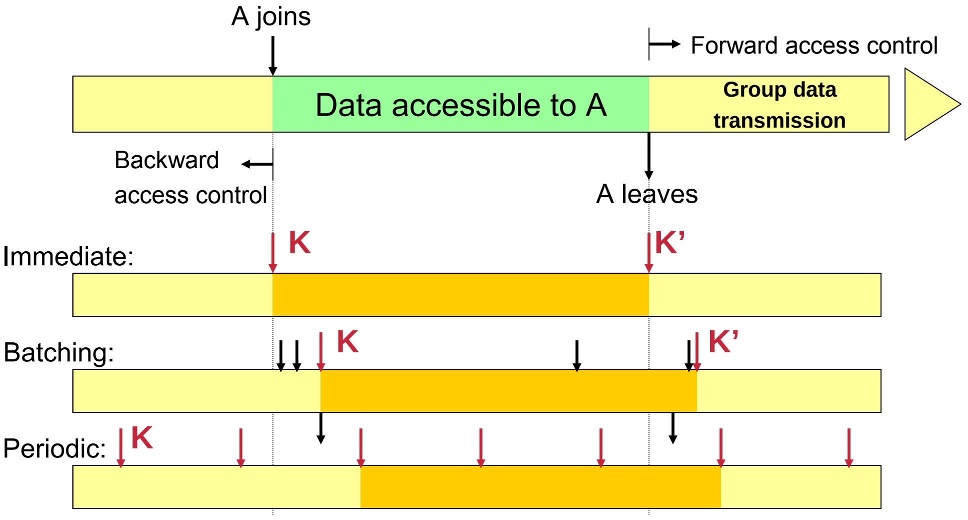
- GTK == use a shared session key in the group:
  Traffic Encryption Key (TEK)

- To be deployed with a symmetric encryption algorithm
- Straightforward

- In addition:
  - Initial key distribution
  - Rekeying due to membership changes

- PTK == one or more Key Encryption Keys (KEK)

Data Confidentiality and Re-Keying



Group Authentication

- Apply shared group key also to authentication
- Calculate hashed message authentication code (HMAC)
  - Hash over the message + key + nonce (e.g. timestamp)
  - E.g. Message Digest 5 (MD5, RFC 1321),
    better: SHA1 (RFC 3174), SHA256/384/512 (RFC 4634)
- Allows to identify the originator of a message as one of the group
  - But: does not provide source authentication
  - And does not support integrity protection
    - Message may have been altered by another group member
- Different for point-to-point communications
  - There are only two peers sharing a secret

Source Authentication (1)

- Prove the origination of a message / packet
- Must work for multicasting

- Digital signatures?
  - Public-key cryptography too expensive
  - Would require PKI

- Possibly operate on blocks of packets
  - Hash over a group of packets, then sign
  - Application-specific authentication support
    - E.g. file transfer: Calculate signatures only once over the entire contents
    - Entire transmission is lost if only a single packet is faked
  - Delays verification of contents!

Source Authentication (2)

- Authenticating individual packets
  - Tree hashing / hash chaining
  - Hash a sequence of packets
  - e.g. Packet P1 validates the hash of P2, P2 that of P3, etc.
  - Only one packet (e.g. P1) is signed per run of packets

- Issues with packet losses: verification may get impossible
  - Multi-chaining: include a hash in several other packets
  - Still may lead to extra packet drops of unauthenticated packets

- MAC-based authentication of unreliable streams: TESLA
  Timed Efficient Stream Loss-tolerant Authentication

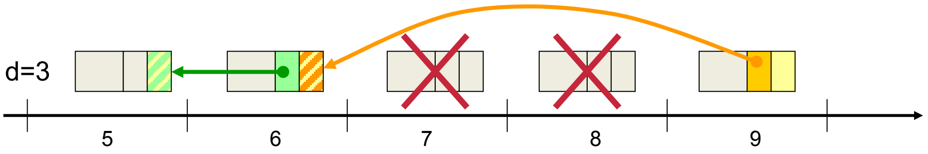
TESLA (1)

- Basic idea: Hash key chain
  - Select an initial key
  - Then calculate derived keys using a one-way function f
  - Generate keys $k_0, \ldots, k_t$ – starting with k_t as initial random key
    $k_{t-1} = f(k_t)$
  - Use another hash function to derive k'_j from k_j: $k'_j = g(k_j)$
  - Use keys in backwards order, starting with k_0

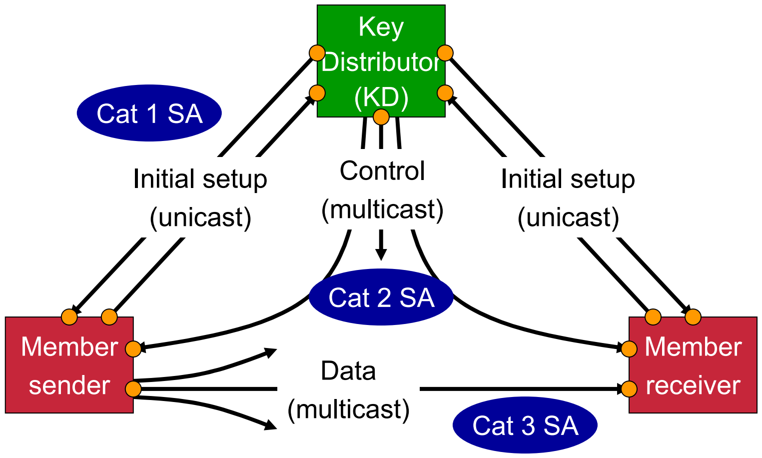
$$\begin{tikzcd}
 & \boxed{k'_1} & \boxed{k'_2} & & \boxed{k'_{t-1}} & \boxed{k'_t} \\
\boxed{k_0} & \boxed{k_1} \arrow[l, "f"'] \arrow[u, "g"'] & \boxed{k_2} \arrow[l, "f"'] \arrow[u, "g"'] & \cdots \arrow[l, "f"'] & \boxed{k_{t-1}} \arrow[l, "f"'] \arrow[u, "g"'] & \boxed{k_t} \arrow[l, "f"'] \arrow[u, "g"']
\end{tikzcd}$$

TESLA (2)

- Requirement: rough time synchronization of senders & receivers
- Subdivide time axis into t intervals
  - All data packets per interval i = [1, …, t] are authenticated with k'_i
  - Choose a disclosure interval d (equals authentication / processing delay)
- Sender transmits a digitally signed packet to initialize
  - Include “commitment to key chain” by means of signed k_0
- Sender transmits data packet P_j in interval i containing
  - Data D_j, the revealed key k_{j-d} of interval j-d, auth MAC using k'_j



Group Security Association (GSA)



Group Management

- Initial setup of a Category 1 SA to the KD
  - (Several KDs may operate in a distributed fashion)
  - Point for access control policy enforcement
    - Authenticate the new group member
    - Verify its authorization to participate in the group
  - Configure member
  - Bootstrap Category 2 SA
  - Initialize Category 3 SA(s)

- Group management involves rekeying
  - Via push mechanisms using Category 2 SA
  - Via pull mechanisms through Category 1 SA

Group Key Management

- Provide a shared group key to all members: TEK
- Update group key during the group's lifetime
  - Periodically to "defeat" cryptoanalysis
  - For membership changes
- Group key management architectures
  - E.g. IKAM
  - Hierarchical approach to key management and distribution
- Group key distribution protocols
  - GKMP, GSAKMP (derived from ISAKMP), GDOI
  - MIKEY (Multimedia Internet Keying; used for RTP)

Group Key Management Algorithms

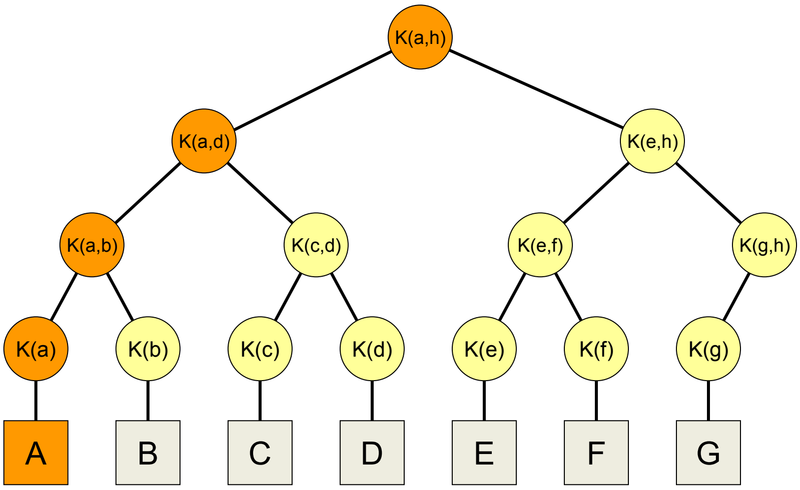
- Initialization and re-keying
- Re-keying: immediate, periodic, batching
- Simplest variant for group changes
  - Re-key each group member individually using Cat 1 SA
  - O(n) for rekeying
  - Does not really scale to large groups
- Periodic re-keying: use a different group key from Cat 2 SA
  - Helps for stable membership
- Use hierarchical schemes to achieve better scalability

Example: Logical Key Trees (LKH)

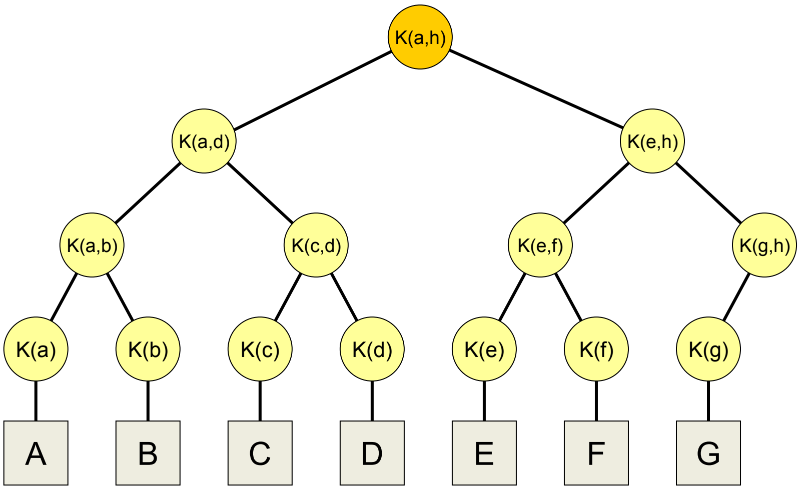
- Create a (balanced) binary tree
  - As many leafs as group members (each leaf represents a member)
  - Adjusted dynamically by adding nodes (possibly splitting existing ones) and removing nodes
- Each node (including leafs) represents a KEK
- KEKs are used to distribute TEKs and new KEK when membership changes

- A group member A knows all the keys (KEKs) on the path from its corresponding leaf node up to the root
- Rekeying is done by distributing new keys (TEKs, KEKs) using the KEKs that are known to as many members possible
- Complexity O(2 log n) for join and leave group operations

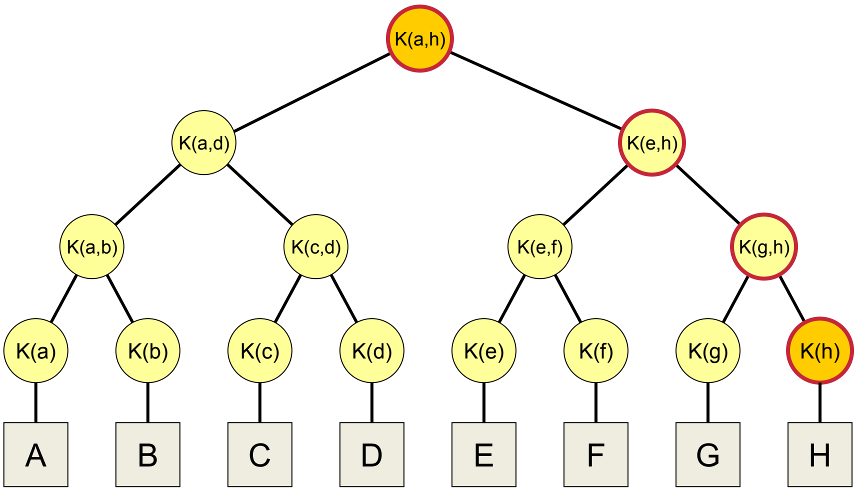
LKH Example



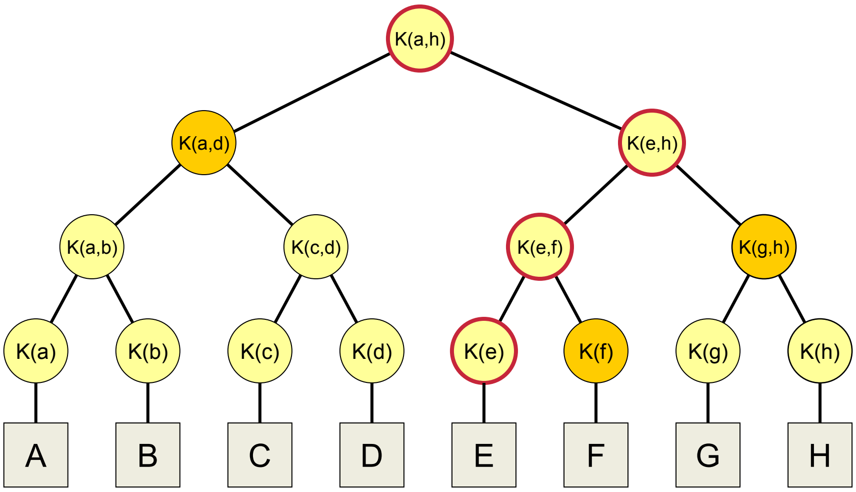
LKH Example: Periodic Re-keying



LKH Example: H joining



LKH Example: E leaving



Multicast Security Review

- No surprise: Adding Multicast makes life harder
  - Multicast Key Management = Security + Multicast
  - In practice, needs to interact with membership management
- LKH: Adding (even artificial) structure to a group can reduce effort required for state management algorithms significantly
- Scalable, efficient source authentication is really hard
  - TESLA is a nice “out of the box” idea with a limited field of application

Security: Take-away message

- Study security best practices
  - Key management usually is the complex part
  - Most security algorithms have a **limited field of applicability**
  - Often, security mechanisms need to be combined to hold water
    - But, in combinations, one algorithm can be used to attack another in surprising ways
- Reuse existing protocols, frameworks, algorithms as much as possible
  - But make sure you are using them **within** their field of applicability!
  - Communication security vs. object security
- Most important:
  Submit security protocols to early review (open design!)