Chapter 9: Security

Security

- The security environment
- Basics of cryptography
- User authentication
- Attacks from inside the system
- Attacks from outside the system
- Protection mechanisms
- Trusted systems

Security environment: threats

Goal	Threat
Data confidentiality	Exposure of data
Data integrity	Tampering with data
System availability	Denial of service

- Operating systems have goals
  - Confidentiality
  - Integrity
  - Availability
- Someone attempts to subvert the goals
  - Fun
  - Commercial gain

What kinds of intruders are there?

- Casual prying by nontechnical users
  - Curiosity
- Snooping by insiders
  - Often motivated by curiosity or money
- Determined attempt to make money
  - May not even be an insider
- Commercial or military espionage
  - This is very big business!

Accidents cause problems, too…

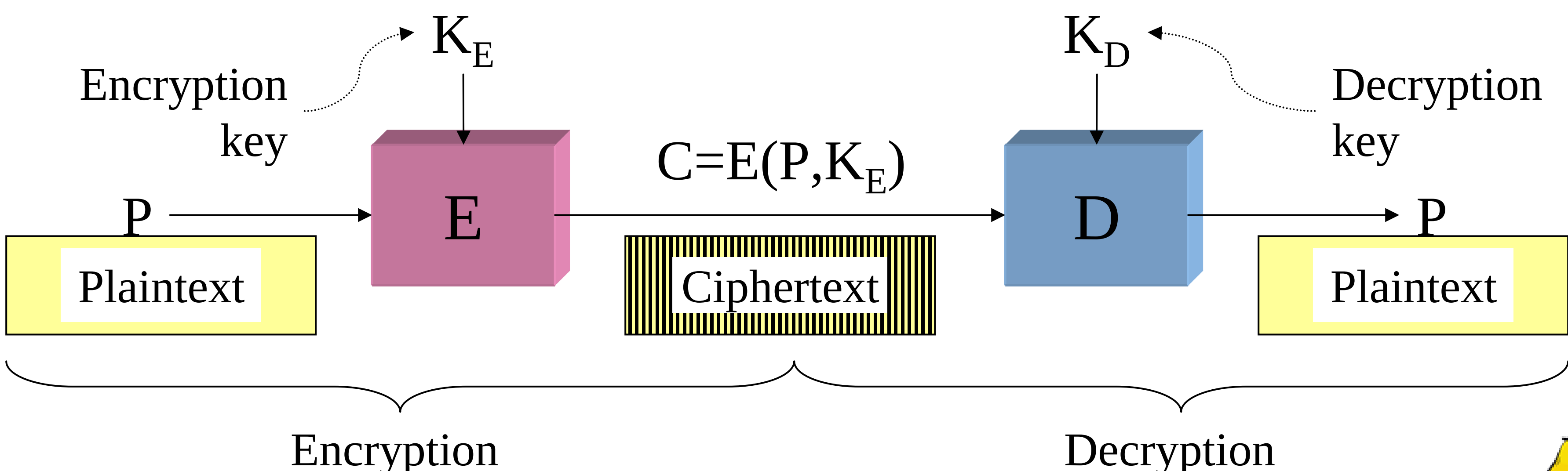
- Acts of God
  - Fires
  - Earthquakes
  - Wars (is this really an “act of God”?)
- Hardware or software error
  - CPU malfunction
  - Disk crash
  - Program bugs (hundreds of bugs found in the most recent Linux kernel)
- Human errors
  - Data entry
  - Wrong tape mounted
  - rm * .o

Cryptography

- Goal: keep information from those who aren't supposed to see it
  - Do this by "scrambling" the data
- Use a well-known algorithm to scramble data
  - Algorithm has two inputs: data & key
  - Key is known only to "authorized" users
  - Relying upon the secrecy of the algorithm is a *very* bad idea (see WW2 Enigma for an example…)
- Cracking codes is ***very*** difficult, *Sneakers* and other movies notwithstanding

Cryptography basics

- Algorithms (E, D) are widely known
- Keys (K_E, K_D) may be less widely distributed
- For this to be effective, the ciphertext should be the only information that's available to the world
- Plaintext is known only to the people with the keys (in an ideal world…)



Secret-key encryption

- Also called symmetric-key encryption
- Monoalphabetic substitution
  - Each letter replaced by different letter
- Vignere cipher
  - Use a multi-character key

    THEMESSAGE

    ELMELMELME

    XSQQPEWLSI
- Both are easy to break!
- Given the encryption key, easy to generate the decryption key
- Alternatively, use different (but similar) algorithms for encryption and decryption

Modern encryption algorithms

- Data Encryption Standard (DES)
  - Uses 56-bit keys
  - Same key is used to encrypt & decrypt
  - Keys used to be difficult to guess
    - Needed to try 2^{55} different keys, on average
    - Modern computers can try millions of keys per second with special hardware
    - For $250K, EFF built a machine that broke DES quickly
- Current algorithms (AES, Blowfish) use 128 bit keys
  - Adding one bit to the key makes it twice as hard to guess
  - Must try 2^{127} keys, on average, to find the right one
  - At 10^{15} keys per second, this would require over 10^{21} seconds, or 1000 billion years!
  - Modern encryption isn't usually broken by brute force…

Unbreakable codes

- There ***is*** such a thing as an unbreakable code: one-time pad
  - Use a truly random key as long as the message to be encoded
  - XOR the message with the key a bit at a time
- Code is unbreakable because
  - Key could be anything
  - Without knowing key, message could be anything with the correct number of bits in it
- Difficulty: distributing key is as hard as distributing message
- Difficulty: generating truly random bits
  - Can’t use computer random number generator!
  - May use physical processes
    - Radioactive decay
    - Leaky diode
    - Lava lamp (!) [http://www.sciencenews.org/20010505/mathtrek.asp]

Public-key cryptography

- Instead of using a single shared secret, keys come in pairs
  - One key of each pair distributed widely (*public key*), K_p
  - One key of each pair kept secret (*private or secret key*), K_s
  - Two keys are inverses of one another, but not identical
  - Encryption & decryption are the same algorithm, so $E(K_p,E(K_s,M)) = E(K_s,E(K_p,M)) = M$
- Currently, most popular method involves primes and exponentiation
  - Difficult to crack unless large numbers can be factored
  - Very slow for large messages

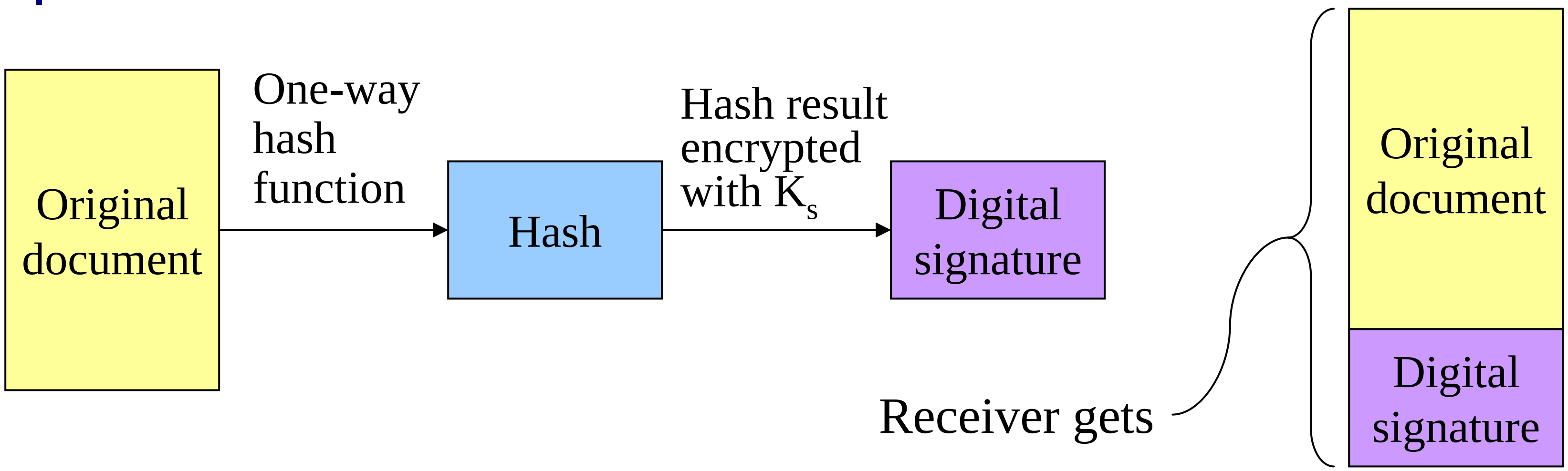
The RSA algorithm for public key encryption

- Public, private key pair consists of $K_p = (d,n)$ $K_s = (e,n)$
  - n = p x q (p and q are large primes)
  - d is a randomly chosen integer with GCD (d, (p-1) x (q-1)) = 1
  - e is an integer such that (e x d) MOD (p-1) x (q-1) = 1
- p & q aren't published, and it's hard to find them: factoring large numbers is thought to be NP-hard
- Public key is published, and can be used by anyone to send a message to the private key's owner
- Encryption & decryption are the same algorithm: $E(K_p,M) = M^d$ MOD n (similar for K_s)
  - Methods exist for doing the above calculation quickly, but...
  - Exponentiation is still very slow
  - Public key encryption not usually done with large messages

One-way functions

- Function such that
  - Given formula for f(x), easy to evaluate y = f(x)
  - Given y, computationally infeasible to find any x such that y = f(x)
- Often, operate similar to encryption algorithms
  - Produce fixed-length output rather than variable length output
  - Similar to XOR-ing blocks of ciphertext together
- Common algorithms include
  - MD5: 128-bit result
  - SHA-1: 160-bit result

Digital signatures



- Digital signature computed by
  - Applying one-way hash function to original document
  - Encrypting result with sender's *private* key
- Receiver can verify by
  - Applying one-way hash function to received document
  - Decrypting signature using sender's public key
  - Comparing the two results: equality means document unmodified

Pretty Good Privacy (PGP)

- Uses public key encryption
  - Facilitates key distribution
  - Allows messages to be sent encrypted to a person (encrypt with person’s public key)
  - Allows person to send message that must have come from her (encrypt with person’s private key)
- Problem: public key encryption is very slow
- Solution: use public key encryption to exchange a shared key
  - Shared key is relatively short (~128 bits)
  - Message encrypted using symmetric key encryption
- PGP can also be used to authenticate sender
  - Use digital signature and send message as plaintext

User authentication

- Problem: how does the computer know who you are?
- Solution: use *authentication* to identify
  - Something the user knows
  - Something the user has
  - Something the user is
- This must be done before user can use the system
- Important: from the computer's point of view…
  - Anyone who can duplicate your ID *is* you
  - Fooling a computer isn't all that hard…

Authentication using passwords

Login: **elm** Password: **foobar** Welcome to Linux!	Login: **jimp** User not found! Login:	Login: **elm** Password: **barfle** Invalid password! Login:

- Successful login lets the user in
- If things don't go so well…
  - Login rejected after name entered
  - Login rejected after name and incorrect password entered
- Don't notify the user of incorrect user name until *after* the password is entered!
  - Early notification can make it easier to guess valid user names

Dealing with passwords

- Passwords should be memorable
  - Users shouldn't need to write them down!
  - Users should be able to recall them easily
- Passwords shouldn't be stored "in the clear"
  - Password file is often readable by all system users!
  - Password must be checked against entry in this file
- Solution: use hashing to hide "real" password
  - One-way function converting password to meaningless string of digits (Unix password hash, MD5, SHA-1)
  - Difficult to find another password that hashes to the same random-looking string
  - Knowing the hashed value and hash function gives no clue to the original password

Salting the passwords

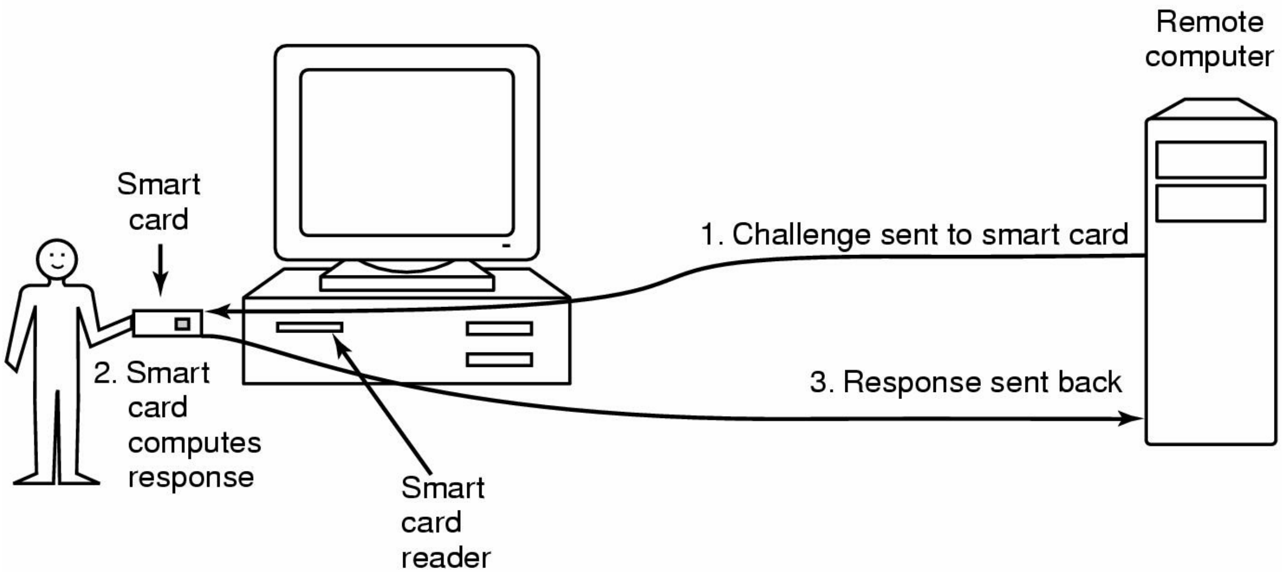
- Passwords can be guessed
  - Hackers can get a copy of the password file
  - Run through dictionary words and names
    - Hash each name
    - Look for a match in the file
- Solution: use “salt”
  - Random characters added to the password before hashing
  - Salt characters stored “in the clear”
  - Increase the number of possible hash values for a given password
    - Actual password is “pass”
    - Salt = “aa” => hash “passaa”
    - Salt = “bb” => hash “passbb”
  - Result: cracker has to try many more combinations
- Mmmm, salted passwords!

Sample breakin (from LBL)

LBL> **telnet elxsi**
ELXSI AT LBL
LOGIN: **root**
PASSWORD: **root**
INCORRECT PASSWORD, TRY AGAIN
LOGIN: **guest**
PASSWORD: **guest**
INCORRECT PASSWORD, TRY AGAIN
LOGIN: **uucp**
PASSWORD: **uucp**
WELCOME TO THE ELXSI COMPUTER AT LBL

Moral: change all the default system passwords!

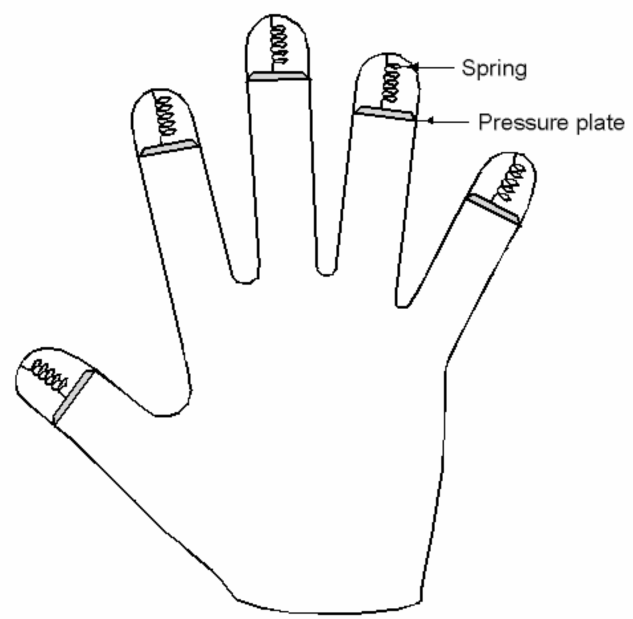
Authentication using a physical object



- Magnetic card
  - Stores a password encoded in the magnetic strip
  - Allows for longer, harder to memorize passwords
- Smart card
  - Card has secret encoded on it, but not externally readable
  - Remote computer issues challenge to the smart card
  - Smart card computes the response and proves it knows the secret

Authentication using biometrics

- Use basic body properties to prove identity
- Examples include
  - Fingerprints
  - Voice
  - Hand size
  - Retina patterns
  - Iris patterns
  - Facial features
- Potential problems
  - Duplicating the measurement
  - Stealing it from its original owner?



Countermeasures

- Limiting times when someone can log in
- Automatic callback at number prespecified
  - Can be hard to use unless there's a modem involved
- Limited number of login tries
  - Prevents attackers from trying lots of combinations quickly
- A database of all logins
- Simple login name/password as a trap
  - Security personnel notified when attacker bites
  - Variation: allow anyone to "log in," but don't let intruders do anything useful

Attacks on computer systems

- Trojan horses
- Logic bombs
- Trap doors
- Viruses
- Exploiting bugs in OS code

Trojan horses

- Free program made available to unsuspecting user
  - Actually contains code to do harm
  - May do something useful as well…
- Altered version of utility program on victim's computer
  - Trick user into running that program
- Example (getting superuser access on CATS?)
  - Place a file called **ls** in your home directory
    - File creates a shell in /tmp with privileges of whoever ran it
    - File then actually runs the real ls
  - Complain to your sysadmin that you can’t see any files in your directory
  - Sysadmin runs ls in your directory
    - Hopefully, he runs *your* ls rather than the real one (depends on his search path)

Login spoofing

Real login screen

Phony login screen

- No difference between real & phony login screens
- Intruder sets up phony login, walks away
- User logs into phony screen
  - Phony screen records user name, password
  - Phony screen prints "login incorrect" and starts real screen
  - User retypes password, thinking there was an error
- Solution: don't allow certain characters to be "caught"

Logic bombs

- Programmer writes (complex) program
  - Wants to ensure that he's treated well
  - Embeds logic "flaws" that are triggered if certain things aren't done
    - Enters a password daily (weekly, or whatever)
    - Adds a bit of code to fix things up
    - Provides a certain set of inputs
    - Programmer's name appears on payroll (really!)
- If conditions aren't met
  - Program simply stops working
  - Program may even do damage
    - Overwriting data
    - Failing to process new data (and not notifying anyone)
- Programmer can blackmail employer
- Needless to say, this is highly unethical!

Trap doors

```
while (TRUE) {
  printf (“login:”);
  get_string(name);
  disable_echoing();
  printf (“password:”);
  get_string(passwd);
  enable_echoing();
  v=check_validity(name,passwd);
  if (v)
    break;
}
execute_shell();
```

Normal code

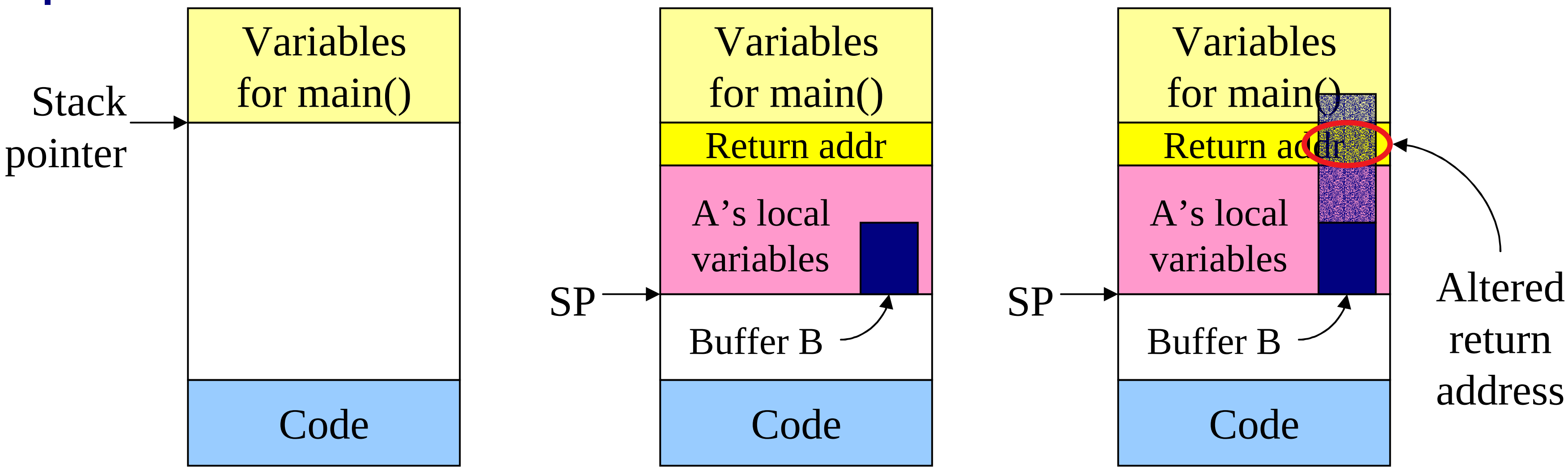
```
while (TRUE) {
  printf (“login:”);
  get_string(name);
  disable_echoing();
  printf (“password:”);
  get_string(passwd);
  enable_echoing();
  v=check_validity(name,passwd);
  if (v || !strcmp(name, “elm”))
    break;
}
execute_shell();
```

Code with trapdoor

Trap door: user’s access privileges coded into program

Example: “joshua” from *Wargames*

Buffer overflow

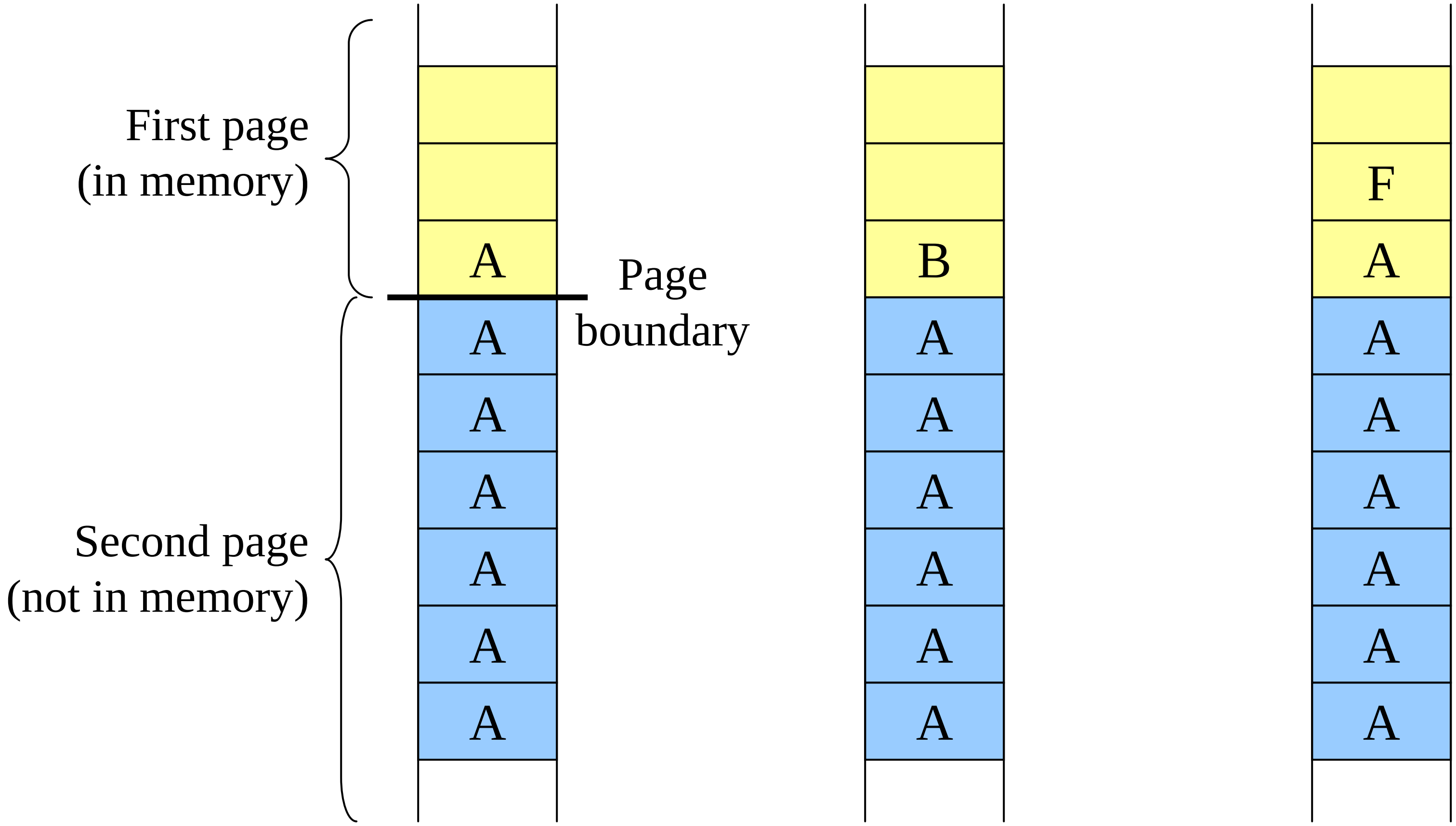


- Buffer overflow is a big source of bugs in operating systems
  - Most common in user-level programs that help the OS do something
  - May appear in "trusted" daemons
- Exploited by modifying the stack to
  - Return to a different address than that intended
  - Include code that does something malicious
- Accomplished by writing past the end of a buffer on the stack

Generic security attacks

- Request memory, disk space, tapes and just read
- Try illegal system calls
- Start a login and hit DEL, RUBOUT, or BREAK
- Try modifying complex OS structures
- Try to do specified DO NOTs
- Social engineering
  - Convince a system programmer to add a trap door
  - Beg admin's secretary (or other people) to help a poor user who forgot password
  - Pretend you're tech support and ask random users for their help in debugging a problem

Security flaws: TENEX password problem



Design principles for security

- System design should be public
- Default should be no access
- Check for current authority
- Give each process least privilege possible
- Protection mechanism should be
  - Simple
  - Uniform
  - In the lowest layers of system
- Scheme should be psychologically acceptable
- Biggest thing: **keep it simple!**

Security in a networked world

- External threat
  - Code transmitted to target machine
  - Code executed there, doing damage
- Goals of virus writer
  - Quickly spreading virus
  - Difficult to detect
  - Hard to get rid of
  - Optional: does something malicious
- Virus: embeds itself into other (legitimate) code to reproduce and do its job
  - Attach its code to another program
  - Additionally, may do harm

Virus damage scenarios

- Blackmail
- Denial of service as long as virus runs
- Permanently damage hardware
- Target a competitor's computer
  - Do harm
  - Espionage
- Intra-corporate dirty tricks
  - Practical joke
  - Sabotage another corporate officer's files

How viruses work

- Virus language
  - Assembly language: infects programs
  - “Macro” language: infects email and other documents
    - Runs when email reader / browser program opens message
    - Program “runs” virus (as message attachment) automatically
- Inserted into another program
  - Use tool called a “dropper”
  - May also infect system code (boot block, etc.)
- Virus dormant until program executed
  - Then infects other programs
  - Eventually executes its “payload”

How viruses find executable files

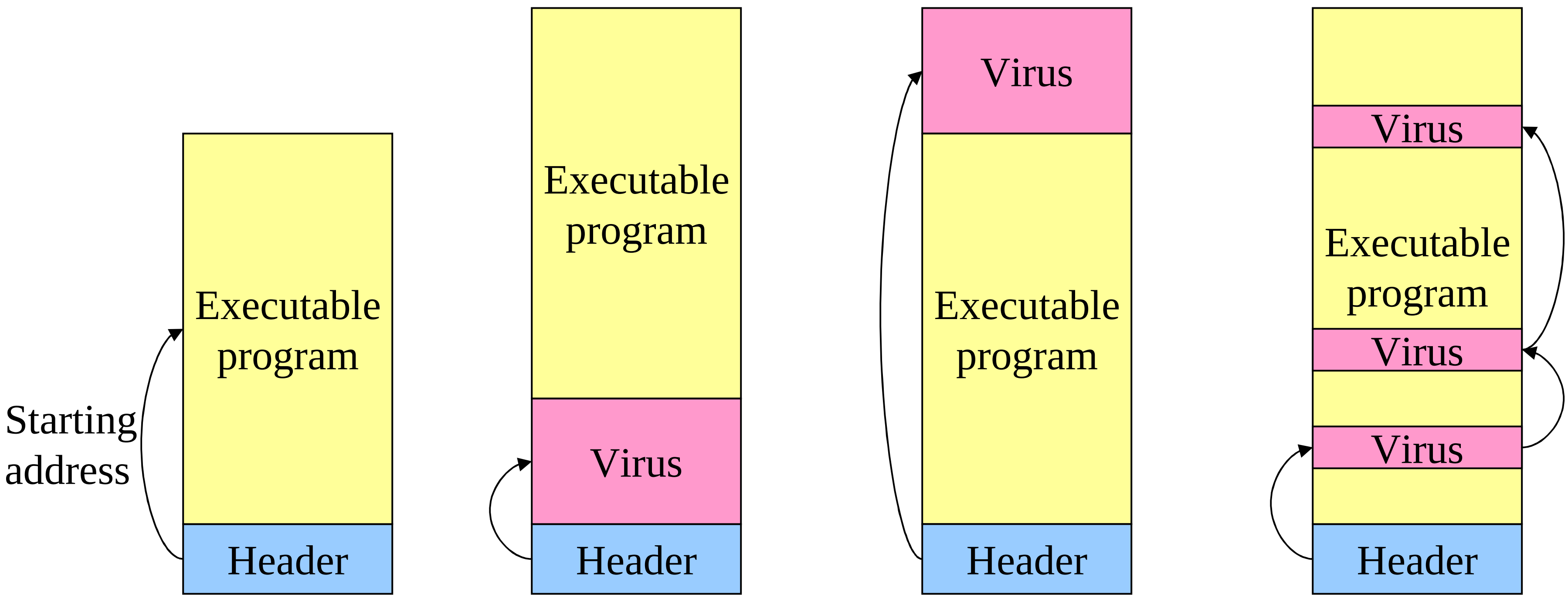
```
#include <sys/types.h>                       /* standard POSIX headers */
#include <sys/stat.h>
#include <dirent.h>
#include <fcntl.h>
#include <unistd.h>
struct stat sbuf;                            /* for lstat call to see if file is sym link */

search(char *dir_name)
{                                            /* recursively search for executables */
    DIR *dirp;                               /* pointer to an open directory stream */
    struct dirent *dp;                       /* pointer to a directory entry */

    dirp = opendir(dir_name);                /* open this directory */
    if (dirp == NULL) return;                /* dir could not be opened; forget it */
    while (TRUE) {
        dp = readdir(dirp);                  /* read next directory entry */
        if (dp == NULL) {                    /* NULL means we are done */
            chdir ("..");                    /* go back to parent directory */
            break;                           /* exit loop */
        }
    if (dp->d_name[0] == '.') continue;      /* skip the . and .. directories */
    lstat(dp->d_name, &sbuf);                /* is entry a symbolic link? */
    if (S_ISLNK(sbuf.st_mode)) continue; /* skip symbolic links */
    if (chdir(dp->d_name) == 0) {            /* if chdir succeeds, it must be a dir */
        search(".");                         /* yes, enter and search it */
    } else {                                     /* no (file), infect it */
        if (access(dp->d_name,X_OK) == 0) /* if executable, infect it */
            infect(dp->d_name);
    }
    closedir(dirp);                          /* dir processed; close and return */
}
```

- Recursive procedure that finds executable files on a UNIX system
- Virus can infect some or all of the files it finds
  - Infect all: possibly wider spread
  - Infect some: harder to find?

Where viruses live in the program



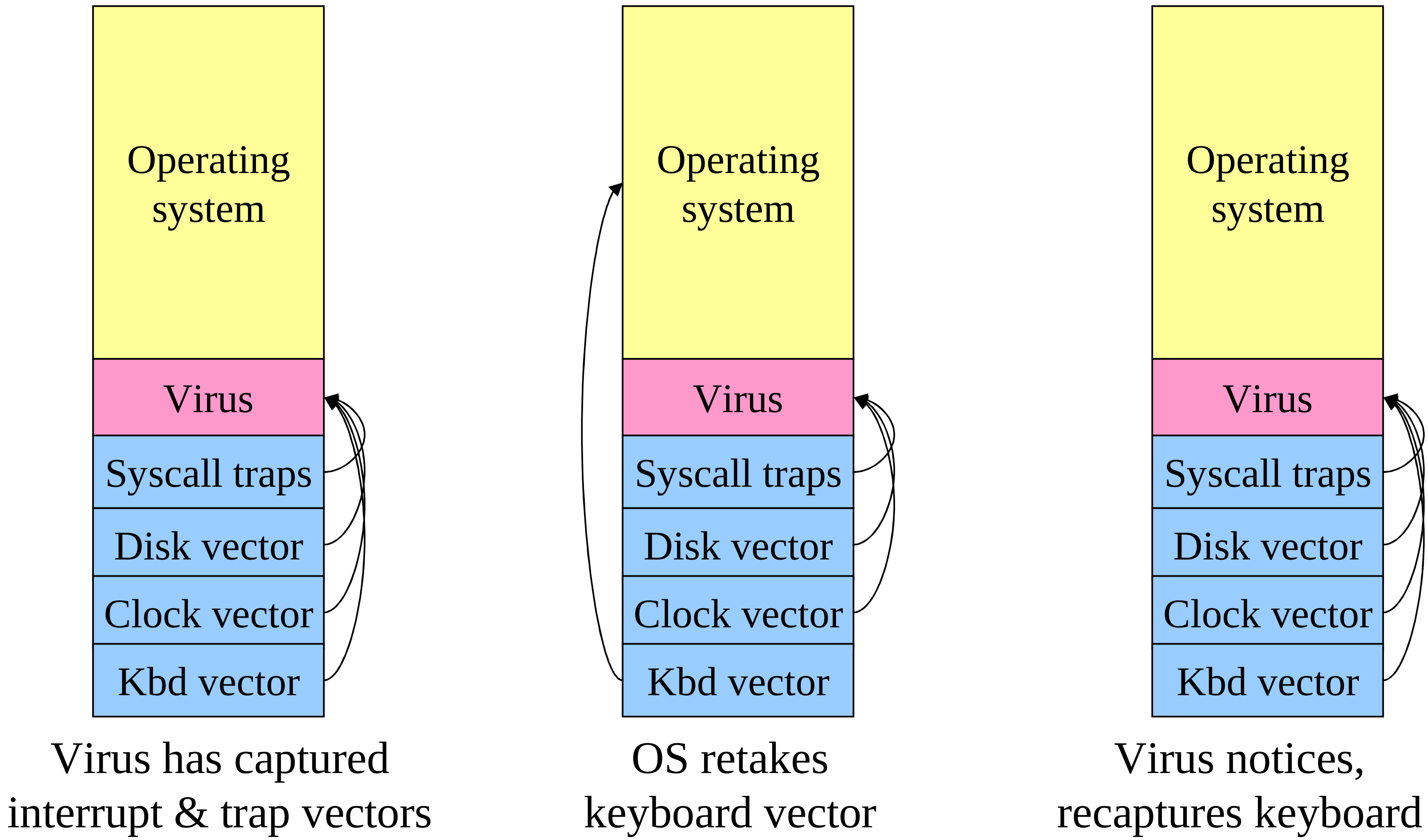
Uninfected program

Virus at start of program

Virus at end of program

Virus in program's free spaces

Viruses infecting the operating system

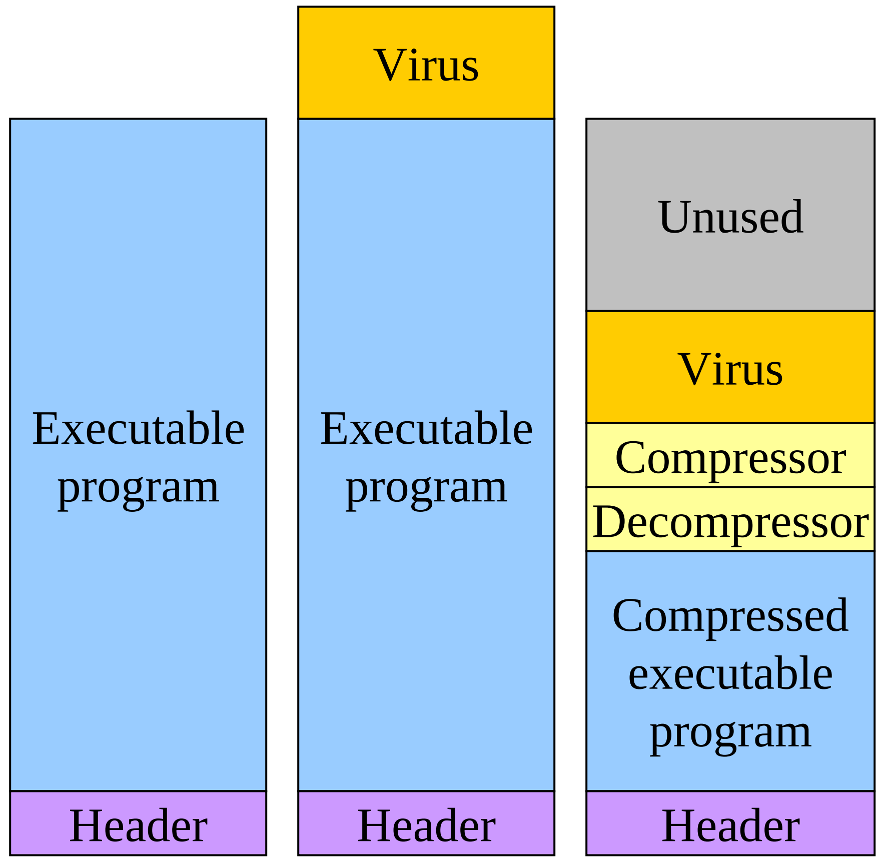


How do viruses spread?

- Virus placed where likely to be copied
  - Popular download site
  - Photo site
- When copied
  - Infects programs on hard drive, floppy
  - May try to spread over LAN or WAN
- Attach to innocent looking email
  - When it runs, use mailing list to replicate
  - May mutate slightly so recipients don't get suspicious

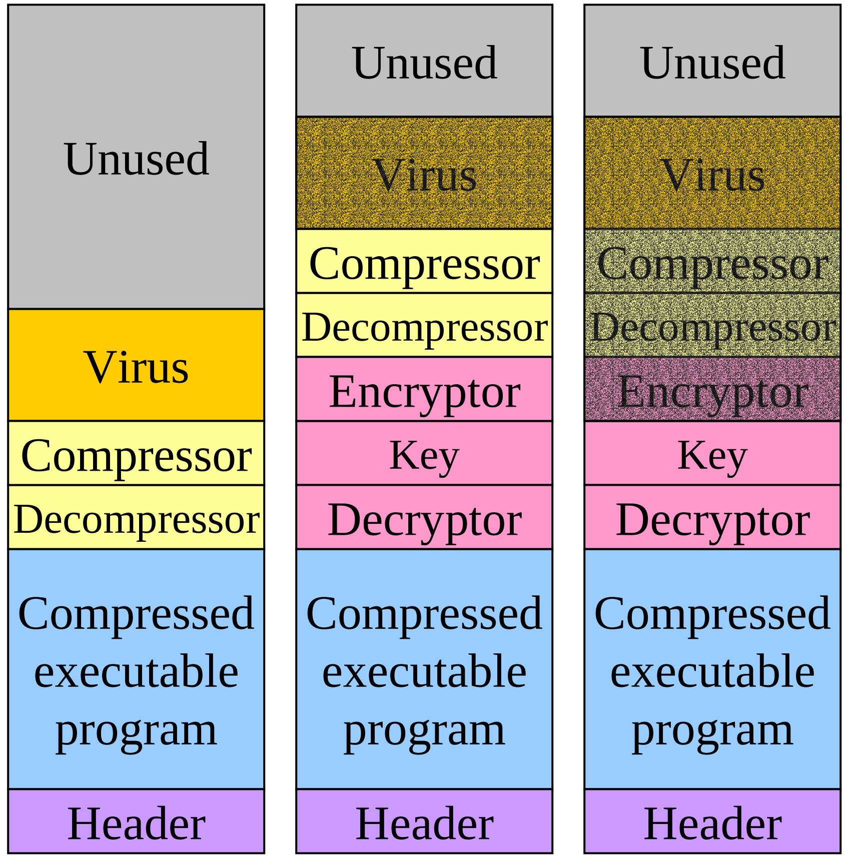
Hiding a virus in a file

- Start with an uninfected program
- Add the virus to the end of the program
  - Problem: file size changes
  - Solution: compression
- Compressed infected program
  - Decompressor: for running executable
  - Compressor: for compressing newly infected binaries
  - Lots of free space (if needed)
- Problem (for virus writer): virus easy to recognize



Using encryption to hide a virus

- Hide virus by encrypting it
  - Vary the key in each file
  - Virus “code” varies in each infected file
  - Problem: lots of common code still in the clear
    - Compress / decompress
    - Encrypt / decrypt
- Even better: leave only decryptor and key in the clear
  - Less constant per virus
  - Use polymorphic code (more in a bit) to hide even this



Polymorphic viruses

- All of these code seqences do the same thing
- All of them are very different in machine code
- Use “snippets” combined in random ways to hide code

(a)	(b)	(c)	(d)	(e)
MOV A,R1	MOV A,R1	MOV A,R1	MOV A,R1	MOV A,R1
ADD B,R1	NOP	ADD #0,R1	OR R1,R1	TST R1
ADD C,R1	ADD B,R1	ADD B,R1	ADD B,R1	ADD C,R1
SUB #4,R1	NOP	OR R1,R1	MOV R1,R5	MOV R1,R5
MOV R1,X	ADD C,R1	ADD C,R1	ADD C,R1	ADD B,R1
	NOP	SHL #0,R1	SHL R1,0	CMP R2,R5
	SUB #4,R1	SUB #4,R1	SUB #4,R1	SUB #4,R1
	NOP	JMP .+1	ADD R5,R5	JMP .+1
	MOV R1,X	MOV R1,X	MOV R1,X	MOV R1,X
			MOV R5,Y	MOV R5,Y

How can viruses be foiled?

- Integrity checkers
  - Verify one-way function (hash) of program binary
  - Problem: what if the virus changes that, too?
- Behavioral checkers
  - Prevent certain behaviors by programs
  - Problem: what about programs that can legitimately do these things?
- Avoid viruses by
  - Having a good (secure) OS
  - Installing only shrink-wrapped software (just hope that the shrink-wrapped software isn't infected!)
  - Using antivirus software
  - Not opening email attachments
- Recovery from virus attack
  - Hope you made a recent backup!
  - Recover by halting computer, rebooting from safe disk (CD-ROM?), using an antivirus program

Worms vs. viruses

- Viruses require other programs to run
- Worms are self-running (separate process)
- The 1988 Internet Worm
  - Consisted of two programs
    - Bootstrap to upload worm
    - The worm itself
  - Exploited bugs in sendmail and finger
  - Worm first hid its existence
  - Next replicated itself on new machines
  - Brought the Internet (1988 version) to a screeching halt

Mobile code

- Goal: run (untrusted) code on my machine
- Problem: how can untrusted code be prevented from damaging my resources?
- One solution: sandboxing
  - Memory divided into 1 MB sandboxes
  - Accesses may not cross sandbox boundaries
  - Sensitive system calls not in the sandbox
- Another solution: interpreted code
  - Run the interpreter rather than the untrusted code
  - Interpreter doesn't allow unsafe operations
- Third solution: signed code
  - Use cryptographic techniques to sign code
  - Check to ensure that mobile code signed by reputable organization

Security in Java

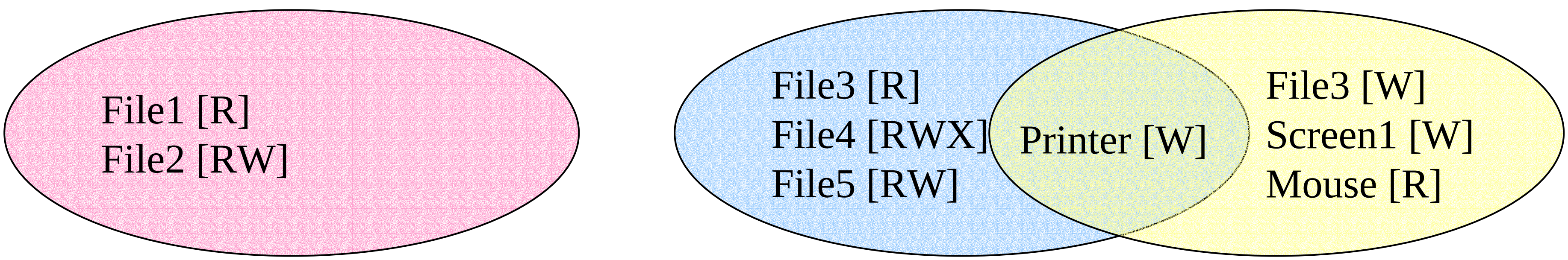
- Java is a type safe language
  - Compiler rejects attempts to misuse variable
- No “real” pointers
  - Can’t simply create a pointer and dereference it as in C
- Checks include …
  - Attempts to forge pointers
  - Violation of access restrictions on private class members
  - Misuse of variables by type
  - Generation of stack over/underflows
  - Illegal conversion of variables to another type
- Applets can have specific operations restricted
  - Example: don’t allow untrusted code access to the whole file system

Protection

- Security is mostly about *mechanism*
  - How to enforce policies
  - Policies largely independent of mechanism
- Protection is about specifying policies
  - How to decide who can access what?
- Specifications must be
  - Correct
  - Efficient
  - Easy to use (or nobody will use them!)

Protection domains

- Three protection domains
  - Each lists objects with permitted operations
- Domains can share objects & permissions
  - Objects can have different permissions in different domains
  - There need be no overlap between object permissions in different domains
- How can this arrangement be specified more formally?



Domain 1 Domain 2 Domain 3

Protection matrix

Domain	File1	File2	File3	File4	File5	Printer1	Mouse
1	Read	Read Write					
2			Read	Read Write Execute	Read Write	Write	
3			Write			Write	Read

- Each domain has a row in the matrix
- Each object has a column in the matrix
- Entry for <object,column> has the permissions
- Who’s allowed to modify the protection matrix?
  - What changes can they make?
- How is this implemented efficiently?

Domains as objects in the protection matrix

Domain	File1	File2	File3	File4	File5	Printer1	Mouse	Dom1	Dom2	Dom3
1	Read	Read Write						Modify		
2			Read	Read Write Execute	Read Write	Write		Modify		
3			Write			Write	Read		Enter	

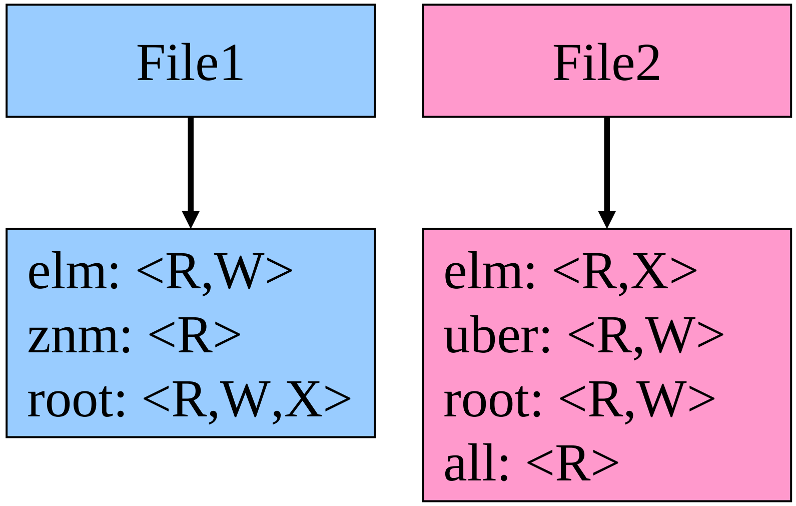
- Specify permitted operations on domains in the matrix
  - Domains may (or may not) be able to modify themselves
  - Domains can modify other domains
  - Some domain transfers permitted, others not
- Doing this allows flexibility in specifying domain permissions
  - Retains ability to restrict modification of domain policies

Representing the protection matrix

- Need to find an efficient representation of the protection matrix (also called the *access matrix*)
- Most entries in the matrix are empty!
- Compress the matrix by:
  - Associating permissions with each object: *access control list*
  - Associating permissions with each domain: *capabilities*
- How is this done, and what are the tradeoffs?

Access control lists

- Each object has a list attached to it
- List has
  - Protection domain
    - User name
    - Group of users
    - Other
  - Access rights
    - Read
    - Write
    - Execute (?)
    - Others?
- No entry for domain => no rights for that domain
- Operating system checks permissions when access is needed

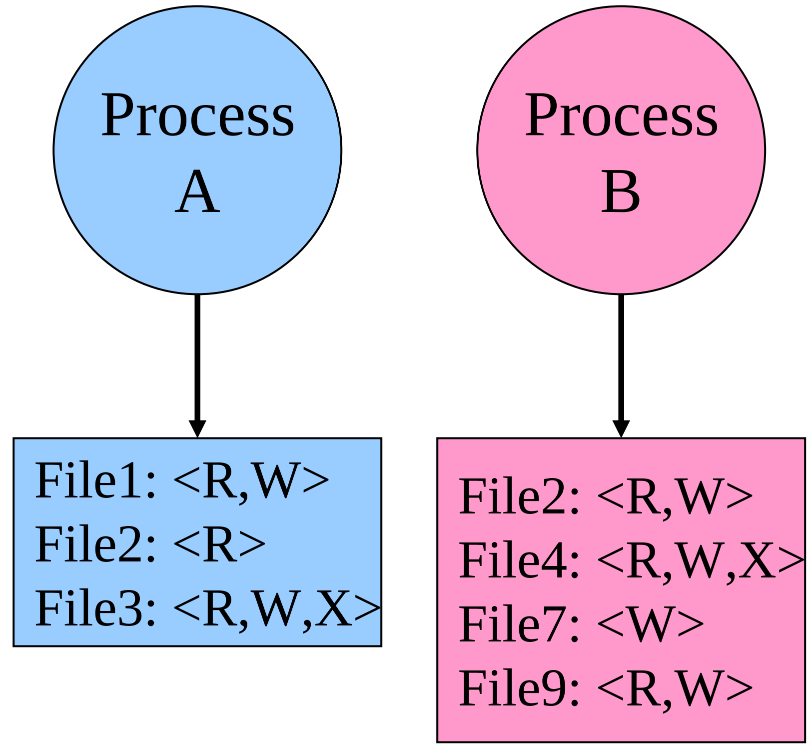


Access control lists in the real world

- Unix file system
  - Access list for each file has exactly three domains on it
    - User (owner)
    - Group
    - Others
  - Rights include read, write, execute: interpreted differently for directories and files
- AFS
  - Access lists only apply to directories: files inherit rights from the directory they're in
  - Access list may have many entries on it with possible rights:
    - read, write, lock (for files in the directory)
    - lookup, insert, delete (for the directories themselves),
    - administer (ability to add or remove rights from the ACL)

Capabilities

- Each process has a capability list
- List has one entry per object the process can access
  - Object name
  - Object permissions
- Objects not listed are not accessible
- How are these secured?
  - Kept in kernel
  - Cryptographically secured



Cryptographically protected capability

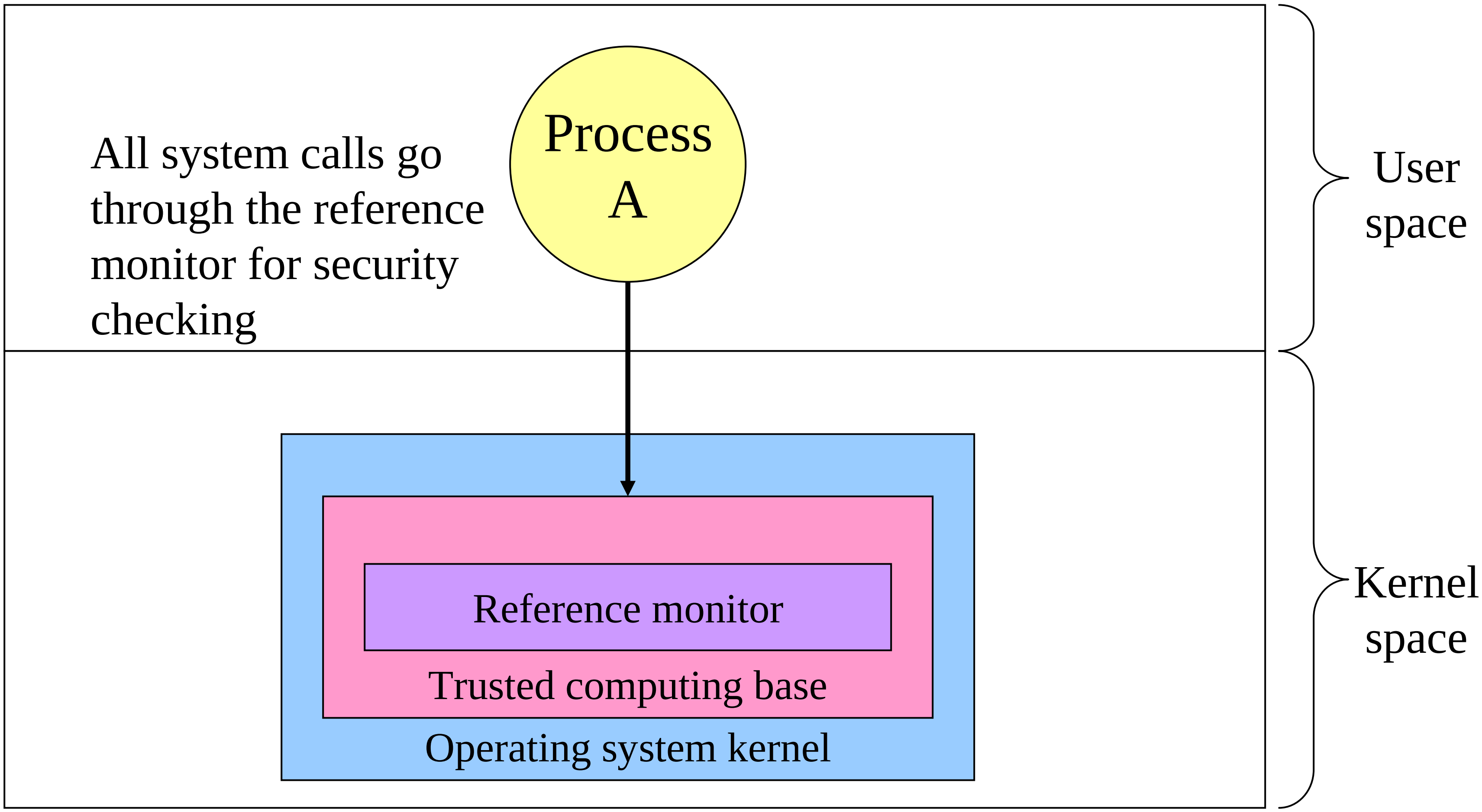
Server	Object	Rights	F(Objects,Rights,Check)

- Rights include generic rights (read, write, execute) and
  - Copy capability
  - Copy object
  - Remove capability
  - Destroy object
- Server has a secret (*Check*) and uses it to verify capabilities presented to it
  - Alternatively, use public-key signature techniques

Protecting the access matrix: summary

- OS must ensure that the access matrix isn't modified (or even accessed) in an unauthorized way
- Access control lists
  - Reading or modifying the ACL is a system call
  - OS makes sure the desired operation is allowed
- Capability lists
  - Can be handled the same way as ACLs: reading and modification done by OS
  - Can be handed to processes and verified cryptographically later on
  - May be better for widely distributed systems where capabilities can't be centrally checked

Reference monitor

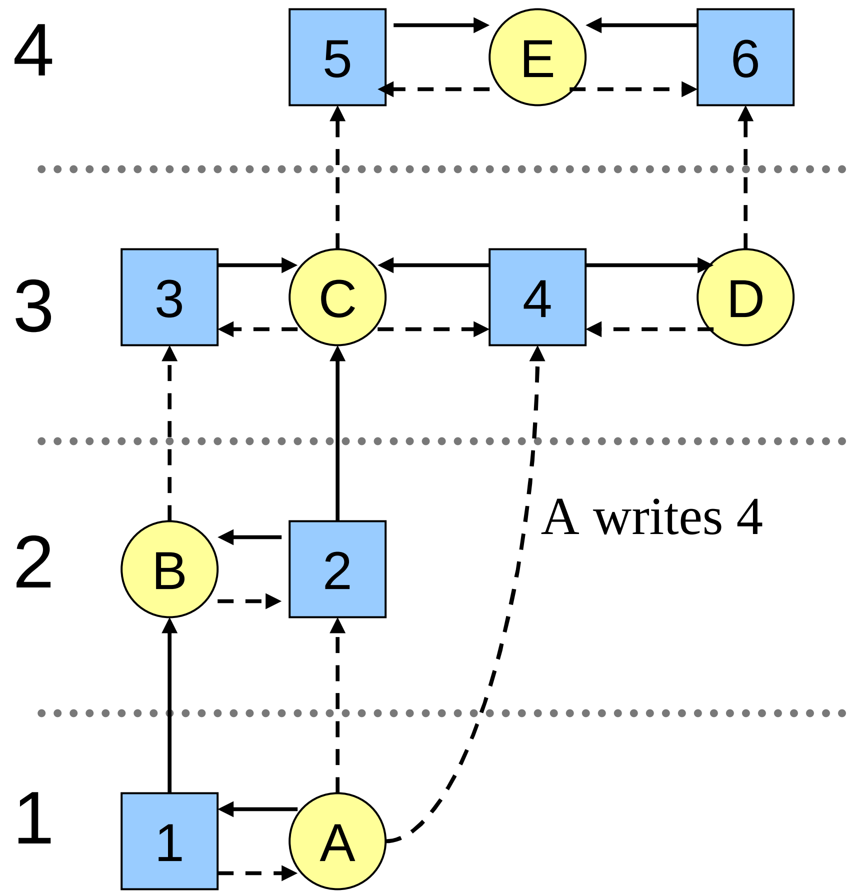


Formal models of secure systems

- Limited set of primitive operations on access matrix
  - Create/delete object
  - Create/delete domain
  - Insert/remove right
- Primitives can be combined into *protection commands*
  - May not be combined arbitrarily!
- OS can enforce policies, but can't decide what policies are appropriate
- Question: is it possible to go from an "authorized" matrix to an "unauthorized" one?
  - In general, undecidable
  - May be provable for limited cases

Bell-La Padula multilevel security model

- Processes, objects have security level
- Simple security property
  - Process at level *k* can only read objects at levels *k* or lower
- * property
  - Process at level *k* can only write objects at levels *k* or **higher**
- These prevent information from leaking from higher levels to lower levels



Biba multilevel integrity model

- Principles to guarantee integrity of data
- Simple integrity principle
  - A process can write only objects at its security level or lower
  - No way to plant fake information at a higher level
- The integrity * property
  - A process can read only objects at its security level or higher
  - Prevent someone from getting information from above and planting it at their level
- Biba is in direct conflict with Bell-La Padula
  - Difficult to implement both at the same time!

Orange Book security requirements

Criterion	D	C1	C2	B1	B2	B3	A1
Security policy							
Discretionary access control		X	X	→	→	X	→
Object reuse			X	→	→	→	→
Labels				X	X	→	→
Label integrity				X	→	→	→
Exportation of labeled information				X	→	→	→
Labeling human readable output				X	→	→	→
Mandatory access control				X	X	→	→
Subject sensitivity labels					X	→	→
Device labels					X	→	→
Accountability							
Identification and authentication		X	X	X	→	→	→
Audit			X	X	X	X	→
Trusted path					X	X	→

Orange Book security requirements, cont'd

Assurance							
System architecture		X	X	X	X	X	→
System integrity		X	→	→	→	→	→
Security testing		X	X	X	X	X	X
Design specification and verification				X	X	X	X
Covert channel analysis					X	X	X
Trusted facility management					X	X	→
Configuration management					X	→	X
Trusted recovery						X	→
Trusted distribution							X
Documentation							
Security features user's guide		X	→	→	→	→	→
Trusted facility manual		X	X	X	X	X	→
Test documentation		X	→	→	X	→	X
Design documentation		X	→	X	X	X	X

Covert channels

- Circumvent security model by using more subtle ways of passing information
- Can’t directly send data against system’s wishes
- Send data using “side effects”
  - Allocating resources
  - Using the CPU
  - Locking a file
  - Making small changes in legal data exchange
- *Very* difficult to plug leaks in covert channels!

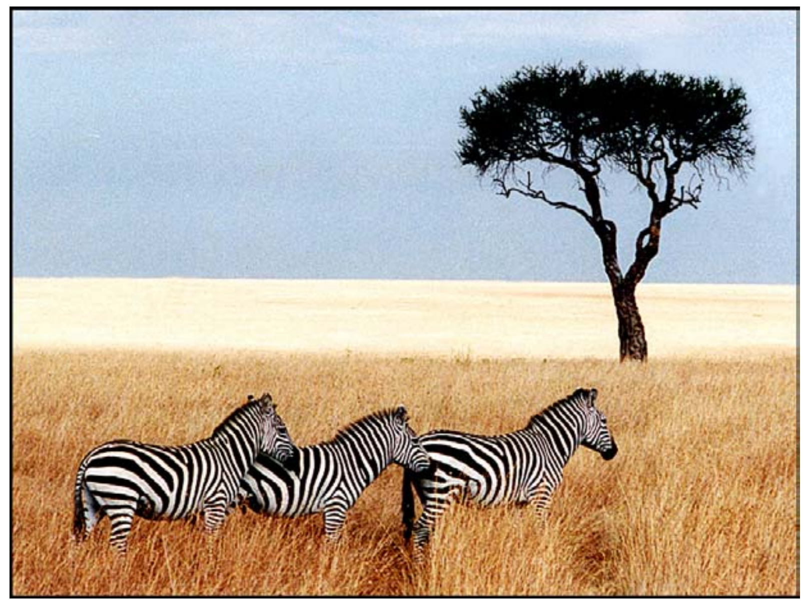
Covert channel using file locking

- Exchange information using file locking
- Assume *n*+1 files accessible to both A and B
- A sends information by
  - Locking files 0..*n*-1 according to an *n*-bit quantity to be conveyed to B
  - Locking file *n* to indicate that information is available
- B gets information by
  - Reading the lock state of files 0..*n*+1
  - Unlocking file *n* to show that the information was received
- May not even need access to the files (on some systems) to detect lock status!

Steganography

- Hide information in other data
- Picture on right has text of 5 Shakespeare plays
  - Encrypted, inserted into low order bits of color values

Zebras



Hamlet, Macbeth, Julius Caesar
Merchant of Venice, King Lear