CSci 5271
Introduction to Computer Security
Day 8: Defensive programming and design, part 2

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Preview question

What is the return type of `getchar()`?

A. `signed char`
B. `int`
C. `unsigned char`
D. `char`
E. `float`

Outline

Separate the control plane

- Keep metadata and code separate from untrusted data
- Bad: format string vulnerability
- Bad: old telephone systems

Defense in depth

- Multiple levels of protection can be better than one
- Especially if none is perfect
- But, many weak security mechanisms don't add up

Canonicalize names

- Use unique representations of objects
- E.g. in paths, remove `.`, `..`, extra slashes, symlinks
- E.g., use IP address instead of DNS name

Fail-safe / fail-stop

- If something goes wrong, behave in a way that's safe
- Often better to stop execution than continue in corrupted state
- E.g., better segfault than code injection

Outline

Modularity

- Divide software into pieces with well-defined functionality
- Isolate security-critical code
  - Minimize TCB, facilitate privilege separation
  - Improve auditability

Minimize interfaces

- Hallmark of good modularity: clean interface
- Particularly difficult:
  - Safely implementing an interface for malicious users
  - Safely using an interface with a malicious implementation

Appropriate paranoia

- Many security problems come down to missing checks
- But, it isn't possible to check everything continuously
- How do you know when to check what?

Invariant

- A fact about the state of a program that should always be maintained
- Assumed in one place to guarantee in another
- Compare: proof by induction

Pre- and postconditions

- Invariants before and after execution of a function
- Precondition: should be true before call
- Postcondition: should be true after return

Dividing responsibility

- Program must ensure nothing unsafe happens
- Pre- and postconditions help divide that responsibility without gaps

When to check

- At least once before any unsafe operation
- If the check is fast
- If you know what to do when the check fails
- If you don't trust
  - your caller to obey a precondition
  - your callee to satisfy a postcondition
  - yourself to maintain an invariant

Sometimes you can't check

- Check that `p` points to a null-terminated string
- Check that `fp` is a valid function pointer
- Check that `x` was not chosen by an attacker

Error handling

- Every error must be handled
  - I.e, program must take an appropriate response action
- Errors can indicate bugs, precondition violations, or situations in the environment

Error codes

- Commonly, return value indicates error if any
- Bad: may overlap with regular result
- Bad: goes away if ignored

Exceptions

- Separate from data, triggers jump to handler
- Good: avoid need for manual copying, not dropped
- May support: automatic cleanup (`finally`)
- Bad: non-local control flow can be surprising

Testing and security

- "Testing shows the presence, not the absence of bugs" – Dijkstra
- Easy versions of some bugs can be found by targeted tests:
  - Buffer overflows: long strings
  - Integer overflows: large numbers
  - Format string vulnerabilities: `%x`

Fuzz testing

- Random testing can also sometimes reveal bugs
- Original 'fuzz' (Miller): `program </dev/urandom`
- Even this was surprisingly effective

Modern fuzz testing

- Mutation fuzzing: small random changes to a benign *seed* input
  - Complex benign inputs help cover interesting functionality
- Grammar-based fuzzing: randomly select valid inputs
- Coverage-driven fuzzing: build off of tests that cause new parts of the program to execute
  - Automatically learns what inputs are "interesting"
  - Pioneered in the open-source AFL tool

Outline

Project meetings

- Starting tomorrow, run through Friday
- Invitations for Tuesday and Wednesday sent before class
- Look for Thursday and Friday invitations this evening
- This week only, my Zoom office hour will be Wednesday 10–11am

Outline

More secure design principles
Software engineering for security
Announcements intermission
Secure use of the OS
Some debugging with BCECHO
Bernstein's perspective
Techniques for privilege separation

Avoid special privileges

- Require users to have appropriate permissions
  - Rather than putting trust in programs
- Anti-pattern 1: setuid/setgid program
- Anti-pattern 2: privileged daemon
- But, sometimes unavoidable (e.g., email)

One slide on setuid/setgid

- Unix users and process have a user id number (UID) as well as one or more group IDs
- Normally, process has the IDs of the use who starts it
- A setuid program instead takes the UID of the program binary

Don't use shells or Tcl

- . . . in security-sensitive applications
- String interpretation and re-parsing are very hard to do safely
- Eternal Unix code bug: path names with spaces

Prefer file descriptors

- Maintain references to files by keeping them open and using file descriptors, rather than by name
- References same contents despite file system changes
- Use `openat`, etc., variants to use FD instead of directory paths

Prefer absolute paths

- Use full paths (starting with `/`) for programs and files
- `$PATH` under local user control
- Initial working directory under local user control
  - But FD-like, so can be used in place of `openat` if missing

Prefer fully trusted paths

- Each directory component in a path must be write protected
- Read-only file in read-only directory can be changed if a parent directory is modified

Don't separate check from use

- Avoid pattern of e.g., `access` then `open`
- Instead, just handle failure of open
  - You have to do this anyway
- Multiple references allow races
  - And `access` also has a history of bugs

Be careful with temporary files

- Create files exclusively with tight permissions and never reopen them
  - See detailed recommendations in Wheeler
- Not quite good enough: reopen and check matching device and inode
  - Fails with sufficiently patient attack

Give up privileges

- Using appropriate combinations of `set*id` functions
  - Alas, details differ between Unix variants
- Best: give up permanently
- Second best: give up temporarily
- Detailed recommendations: Setuid Demystified (USENIX'02)

Allow-list environment variables

- Can change the behavior of called program in unexpected ways
- Decide which ones are necessary
  - As few as possible
- Save these, remove any others

Outline

`print_arg` stack layout

Return address
Saved `%rbp`
Saved `%rbx`
8 unused bytes
8 unused bytes
`buf[16 .. 19]`, 4 unused bytes
`buf[8 .. 15]`
`buf[0 .. 7]`

Outline

Historical background

- Traditional Unix MTA: Sendmail (BSD)
  - Monolithic setuid root program
  - Designed for a more trusting era
  - In mid-90s, bugs seemed endless
- Spurred development of new, security-oriented replacements
  - Bernstein's qmail
  - Venema et al.'s Postfix

Distinctive qmail features

- Single, security-oriented developer
- Architecture with separate programs and UIDs
- Replacements for standard libraries
- Deliveries into directories rather than large files

Ineffective privilege separation

- Example: prevent Netscape DNS helper from accessing local file system
- Before: bug in DNS code
  - → read user's private files
- After: bug in DNS code
  - → inject bogus DNS results
  - → man-in-the-middle attack
  - → read user's private web data

Effective privilege separation

- Transformations with constrained I/O
- General argument: worst adversary can do is control output
  - Which is just the benign functionality
- MTA header parsing (Sendmail bug)
- `jpegtopnm` inside `xloadimage`

Eliminating bugs

- Enforce explicit data flow
- Simplify integer semantics
- Avoid parsing
- Generalize from errors to inputs

Eliminating code

- Identify common functions
- Automatically handle errors
- Reuse network tools
- Reuse access controls
- Reuse the filesystem

The "qmail security guarantee"

- $500, later $1000 offered for security bug
- Never paid out
- Issues proposed:
  - Memory exhaustion DoS
  - Overflow of signed integer indexes
- Defensiveness does not encourage more submissions

qmail today

- Originally had terms that prohibited modified redistribution
  - Now true public domain
- Latest release from Bernstein: 1998; netqmail: 2007
- Does not have large market share
- All MTAs, even Sendmail, are more secure now

Outline

Restricted languages

- Main application: code provided by untrusted parties
- Packet filters in the kernel
- JavaScript in web browsers
  - Also Java, Flash ActionScript, etc.

SFI

- Software-based Fault Isolation
- Instruction-level rewriting like (but predates) CFI
- Limit memory stores and sometimes loads
- Can't jump out except to designated points
- E.g., Google Native Client

Separate processes

- OS (and hardware) isolate one process from another
- Pay overhead for creation and communication
- System call interface allows many possibilities for mischief

System-call interposition

- Trusted process examines syscalls made by untrusted
- Implement via `ptrace` (like strace, gdb) or via kernel change
- Easy policy: deny

Interposition challenges

- Argument values can change in memory (TOCTTOU)
- OS objects can change (TOCTTOU)
- How to get canonical object identifiers?
- Interposer must accurately model kernel behavior
- Details: Garfinkel (NDSS'03)

Separate users

- Reuse OS facilities for access control
- Unit of trust: program or application
- Older example: qmail
- Newer example: Android
- Limitation: lots of things available to any user

`chroot`

- Unix system call to change root directory
- Restrict/virtualize file system access
- Only available to root
- Does not isolate other namespaces

OS-enabled containers

- One kernel, but virtualizes all namespaces
- FreeBSD jails, Linux LXC, Solaris zones, etc.
- Quite robust, but the full, fixed, kernel is in the TCB

(System) virtual machines

- Presents hardware-like interface to an untrusted kernel
- Strong isolation, full administrative complexity
- I/O interface looks like a network, etc.

Virtual machine designs

- (Type 1) hypervisor: 'superkernel' underneath VMs
- Hosted: regular OS underneath VMs
- Paravirtualizaion: modify kernels in VMs for ease of virtualization

Virtual machine technologies

- Hardware based: fastest, now common
- Partial translation: e.g., original VMware
- Full emulation: e.g. QEMU proper
  - Slowest, but can be a different CPU architecture

Modern example: Chrom(ium)

- Separates "browser kernel" from less-trusted "rendering engine"
  - Pragmatic, keeps high-risk components together
- Experimented with various Windows and Linux sandboxing techniques
- Blocked 70% of historic vulnerabilities, not all new ones
- `http://seclab.stanford.edu/websec/chromium/`

Next time

- Protection and isolation
- Basic (e.g., classic Unix) access control