Preview question
What is the return type of `getchar()`?
A. signed char
B. int
C. unsigned char
D. char
E. float

Outline
Control-flow integrity (CFI), cont’d
More modern exploit techniques
Saltzer & Schroeder’s principles
Announcements + BCECHO intermission
More secure design principles
Software engineering for security
Secure use of the OS

Basic CFI principle
- Each indirect jump should only go to a programmer-intended (or compiler-intended) target
- I.e., enforce call graph
- Often: identify disjoint target sets

Target checking: classic
- Identifier is a unique 32-bit value
- Can embed in effectively-nop instruction
- Check value at target before jump
- Optionally add shadow stack

Challenge 1: performance
- In CCS’05 paper: 16% avg., 45% max.
  - Widely varying by program
  - Probably too much for on-by-default
  - Improved in later research
    - Common alternative: use tables of legal targets

Challenge 2: compatibility
- Compilation information required
- Must transform entire program together
- Can’t inter-operate with untransformed code

Target checking: classic
- `cmp [ecx], 12345678h`
- `jne error_label`
- `lea ecx, [ecx+4]`
- `jmp ecx`
Recent advances: COTS

- Commercial off-the-shelf binaries
- CCFIR (Berkeley+PKU, Oakland'13): Windows
- CFI for COTS Binaries (Stony Brook, USENIX'13): Linux

COTS techniques

- CCFIR: use Windows ASLR information to find targets
- Linux paper: keep copy of original binary, build translation table

Control-Flow Guard

- CFI-style defense now in latest Windows systems
- Compiler generates tables of legal targets
- At runtime, table managed by kernel, read-only to user-space

Coarse-grained counter-attack

- "Out of Control" paper, Oakland'14
- Limit to gadgets allowed by coarse policy
  - Indirect call to function entry
  - Return to point after call site ("call-preceded")
- Use existing direct calls to VirtualProtect
- Also used against kBouncer

Control-flow bending counter-attack

- Control-flow attacks that still respect the CFG
- Especially easy without a shadow stack
- Printf-oriented programming generalizes format-string attacks

Target #1: web browsers

- Widely used on desktop and mobile platforms
- Easily exposed to malicious code
- JavaScript is useful for constructing fancy attacks

Heap spraying

- How to take advantage of uncontrolled jump?
- Maximize proportion of memory that is a target
- Generalize NOP sled idea, using benign allocator
- Under W\textsuperscript{X}, can't be code directly

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**JIT spraying**

- Can we use a JIT compiler to make our sleds?
- Exploit unaligned execution:
  - Benign but weird high-level code (bitwise ops. with constants)
  - Benign but predictable JITted code
  - Becomes sled + exploit when entered unaligned

**JIT spray example**

```
25 90 90 90 3c and $0x3c909090,%eax
```

**Use-after-free**

- Low-level memory error of choice in web browsers
- Not as easily audited as buffer overflows
- Can lurk in attacker-controlled corner cases
- JavaScript and Document Object Model (DOM)

**Sandbox and escape**

- Chrome NaCl: run untrusted native code with SFI
- Extra instruction-level checks somewhat like CFI
- Each web page rendered in own, less-trusted process
- But not easy to make sandboxes secure
- While allowing functionality

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**Chained bugs in Pwnium 1**

- Google-run contest for complete Chrome exploits
  - First edition in spring 2012
  - Winner 1: 6 vulnerabilities
  - Winner 2: 14 bugs and “missed hardening opportunities”
  - Each got $60k, bugs promptly fixed

**Economy of mechanism**

- Security mechanisms should be as simple as possible
- Good for all software, but security software needs special scrutiny
Fail-safe defaults
- When in doubt, don’t give permission
- Whitelist, don’t blacklist
- Obvious reason: if you must fail, fail safe
- More subtle reason: incentives

Complete mediation
- Every mode of access must be checked
  - Not just regular accesses: startup, maintenance, etc.
- Checks cannot be bypassed
  - E.g., web app must validate on server, not just client

Open design
- Security must not depend on the design being secret
- If anything is secret, a minimal key
  - Design is hard to keep secret anyway
  - Key must be easily changeable if revealed
  - Design cannot be easily changed

Open design: strong version
- "The design should not be secret"
- If the design is fixed, keeping it secret can’t help attackers
- But an unscrutinized design is less likely to be secure

Separation of privilege
- Real world: two-person principle
- Direct implementation: separation of duty
- Multiple mechanisms can help if they are both required
  - Password and wheel group in Unix

Least privilege
- Programs and users should have the most limited set of powers needed to do their job
- Presupposes that privileges are suitably divisible
  - Contrast: Unix root

Least privilege: privilege separation
- Programs must also be divisible to avoid excess privilege
- Classic example: multi-process OpenSSH server
- N.B.: Separation of privilege ≠ privilege separation

Least common mechanism
- Minimize the code that all users must depend on for security
- Related term: minimize the Trusted Computing Base (TCB)
- E.g.: prefer library to system call; microkernel OS
Psychological acceptability

- A system must be easy to use, if users are to apply it correctly
- Make the system's model similar to the user's mental model to minimize mistakes

Sometimes: work factor

- Cost of circumvention should match attacker and resource protected
- E.g., length of password
- But, many attacks are easy when you know the bug

Sometimes: compromise recording

- Recording a security failure can be almost as good as preventing it
- But, few things in software can't be erased by root

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ROP defense question

Which of these defense techniques would completely prevent a ROP attack from returning from an intended return instruction to an unintended gadget?

A. ASLR
B. A non-executable stack
C. Adjacent stack canaries
D. A shadow stack
E. A and C, but only if used together

Project meetings

- Starting tomorrow, run through next Wednesday
- Invitations sent yesterday

Deadlines reminder

- Exercise set 1: tonight night
- HAI week 2: Friday night

Alternative Saltzer & Schroeder

- Not a replacement for reading the real thing, but:
  - Security Principles of Saltzer and Schroeder, illustrated with scenes from Star Wars (Adam Shostack)
More BCECHO attacker techniques

- Modifying a system file
- 0-free shellcoding
- Shellcode in an environment variable

Shellcode concept

```c
fd = open("/etc/passwd",
        O_WRONLY|O_APPEND);
write(fd, "pwned\n", 6);
```

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Back to the preview question

- Asked before: what's the type of the return value of `getchar`?
- Why?

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
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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

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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 user 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)

Whitelist 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

Next time

- Recommendations from the author of `qmail`
- A variety of isolation mechanisms