Security Principles (continued) and x86 Assembly

CS 161 Spring 2022 - Lecture 2

Heads up: These slides won't exactly match the recording, sorry, but the differences are all fairly minor, and both have the exact same content.

Announcements

- HW1 to be released after lecture
- Project 1 will be released next week
- Discussion sections start next week
  - Attend any one you want

Next: Security Principles (continued)

- Security principles
  - Know your threat model
  - Consider human factors
  - Security is economics
  - Detect if you can’t prevent
  - Defense in depth
  - Least privilege
  - Separation of responsibility
  - Ensure complete mediation
  - Don’t rely on security through obscurity
  - Use fail-safe defaults
  - Design in security from the start

Defense in Depth

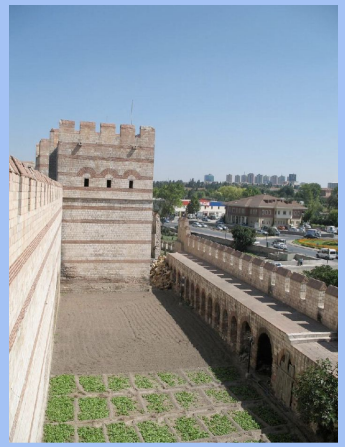
Textbook Chapter 1.5

Defense in Depth

- Multiple types of defenses should be layered together
- An attacker should have to breach all defenses to successfully attack a system
  - Ideally the strength of the defenses compounds somehow
- However, remember: security is economics
  - Defenses are not free.
  - Diminishing returns: Defenses are often less than the sum of their parts
    - 2 walls is much better than 1 wall
    - 101 walls is not much better than 100 walls

The Theodosian Walls of Constantinople

- The ancient capital of the Byzantine empire had a wall…
  - Well, they had a moat…
  - then a wall…
  - then a depression…
  - … and then an even bigger wall
- It also had towers to rain fire and arrows upon the enemy…
- Lasted until the Ottoman empire came along with cannons in 1453…
  - And now it's Istanbul not Constantinople
- **Takeaway**: Defense in depth: An attacker needed to breach all the walls
- **Takeaway**: Changing attacker technology changes defensive requirements



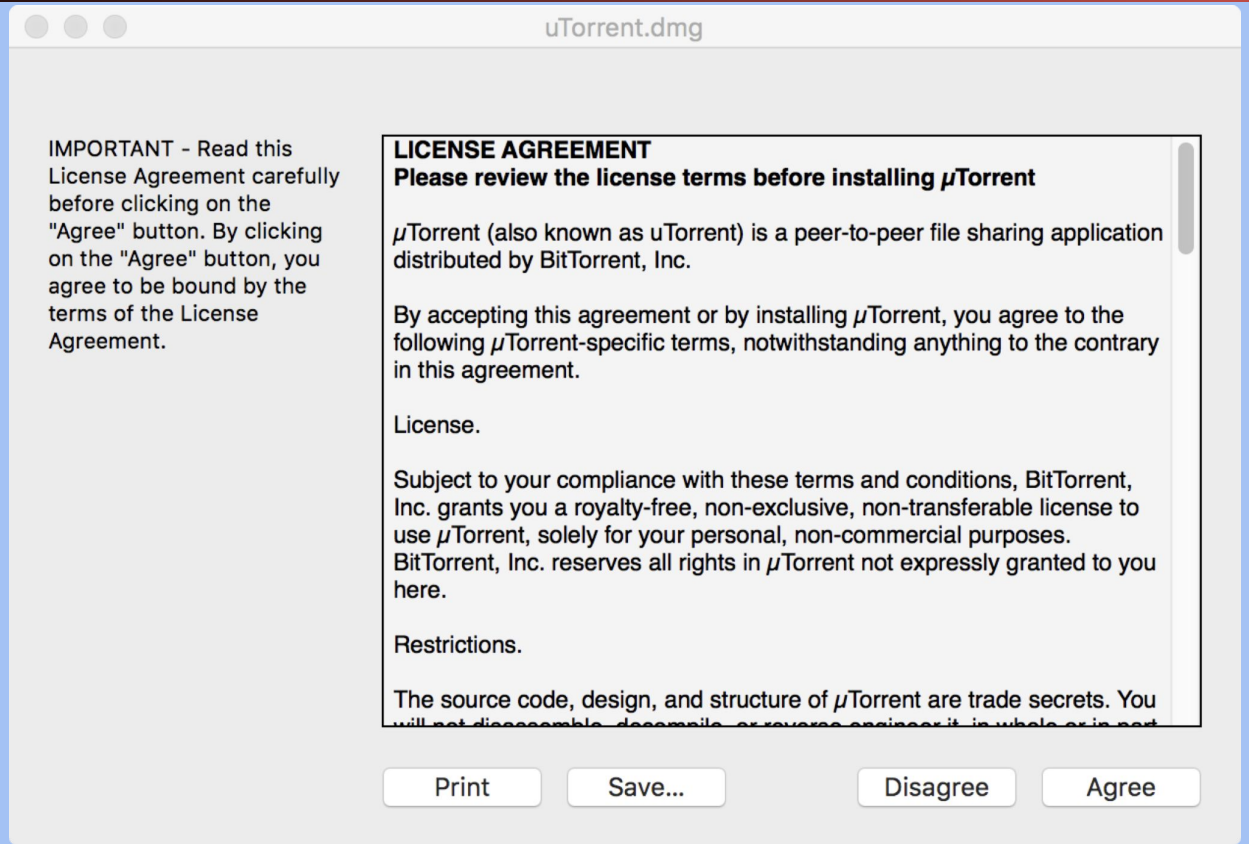
Least Privilege

Textbook Chapter 1.6

Least Privilege

- Consider the minimum permissions an entity or program *needs* to be able to do its job correctly, and grant only those permissions
  - If you grant unnecessary permissions, a malicious or hacked program could use those permissions against you

uTorrent


uTorrent.dmg
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Save...
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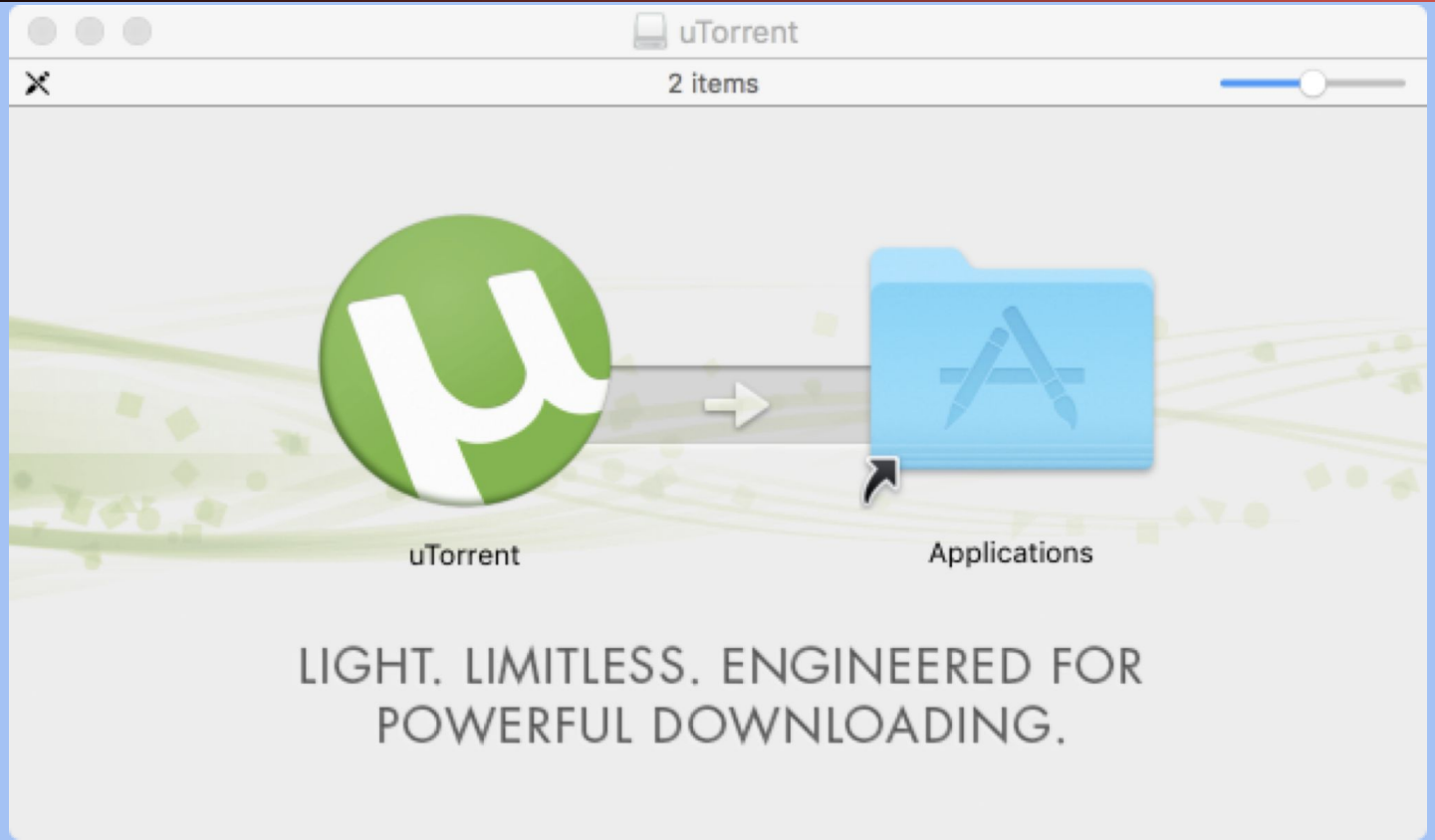
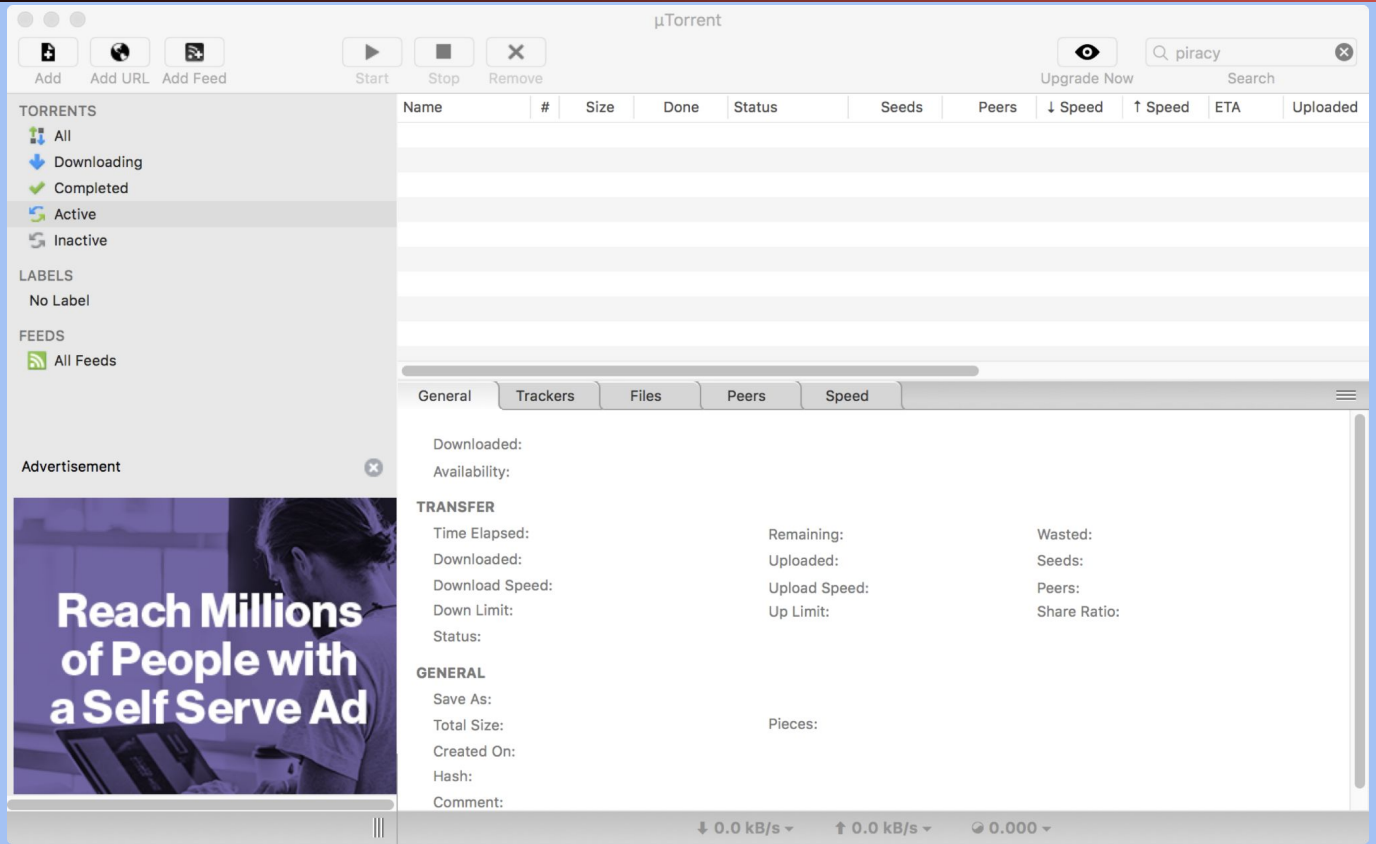
uTorrent


uTorrent
2 items
uTorrent
Applications
LIGHT. LIMITLESS. ENGINEERED FOR
POWERFUL DOWNLOADING.

uTorrent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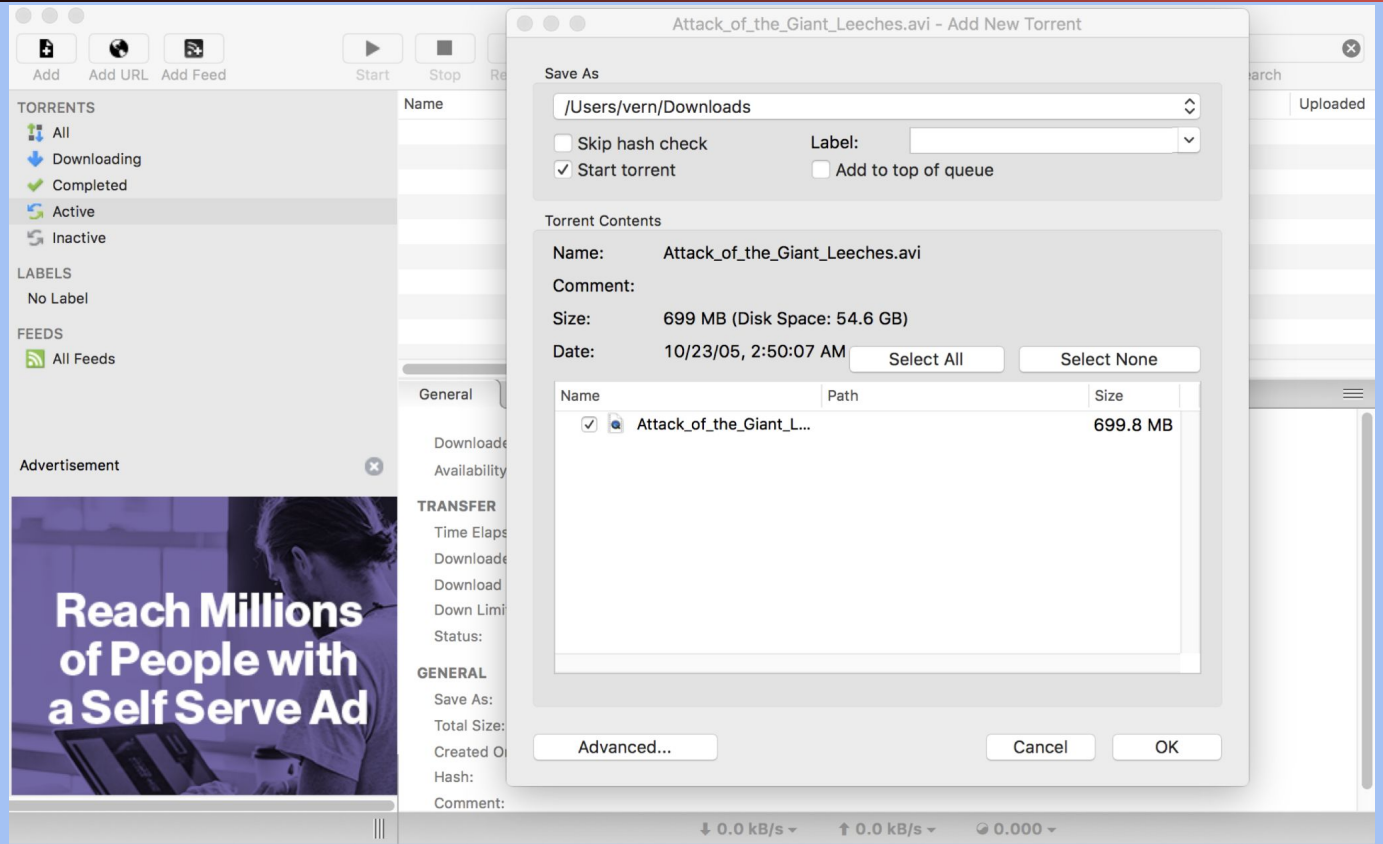
uTorrent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Reach Millions of People with a Self Serve Ad
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Label:
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Torrent Contents
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Comment:
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Cancel
OK
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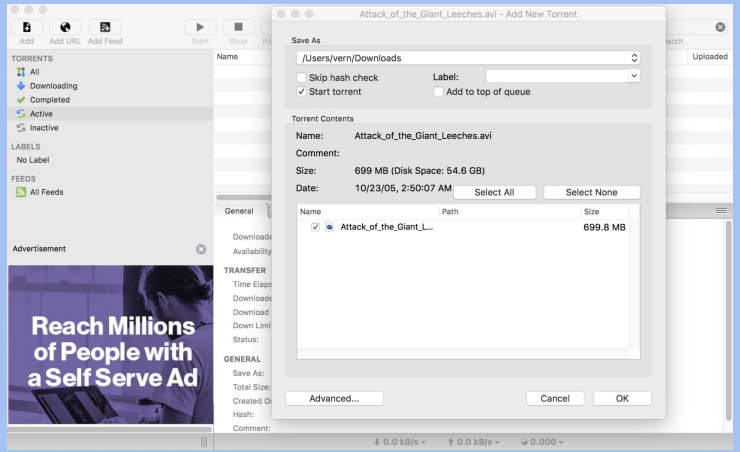
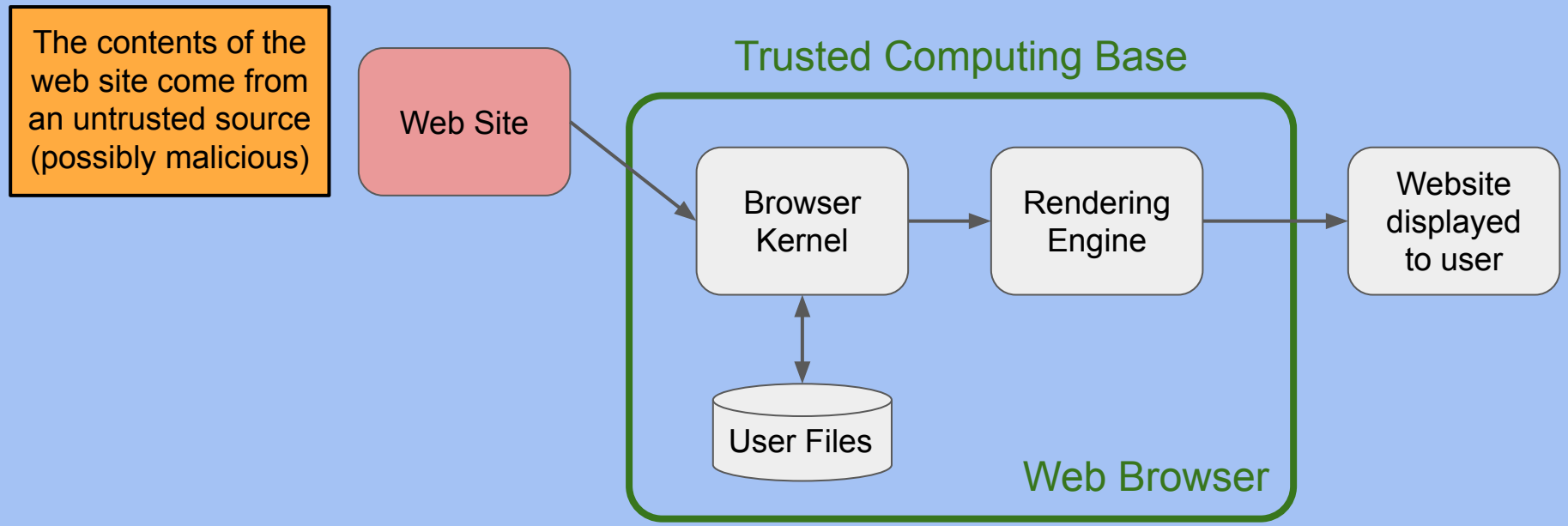
uTorrent

- What was this program able to do?
  - Leak your files
  - Delete your files
  - Send spam
  - Run another malicious program
- What does this program need to be able to do?
  - Access the screen
  - Manage some files (but not all files)
  - Make some Internet connections (but not all Internet connections)
- **Takeaway**: Least privilege

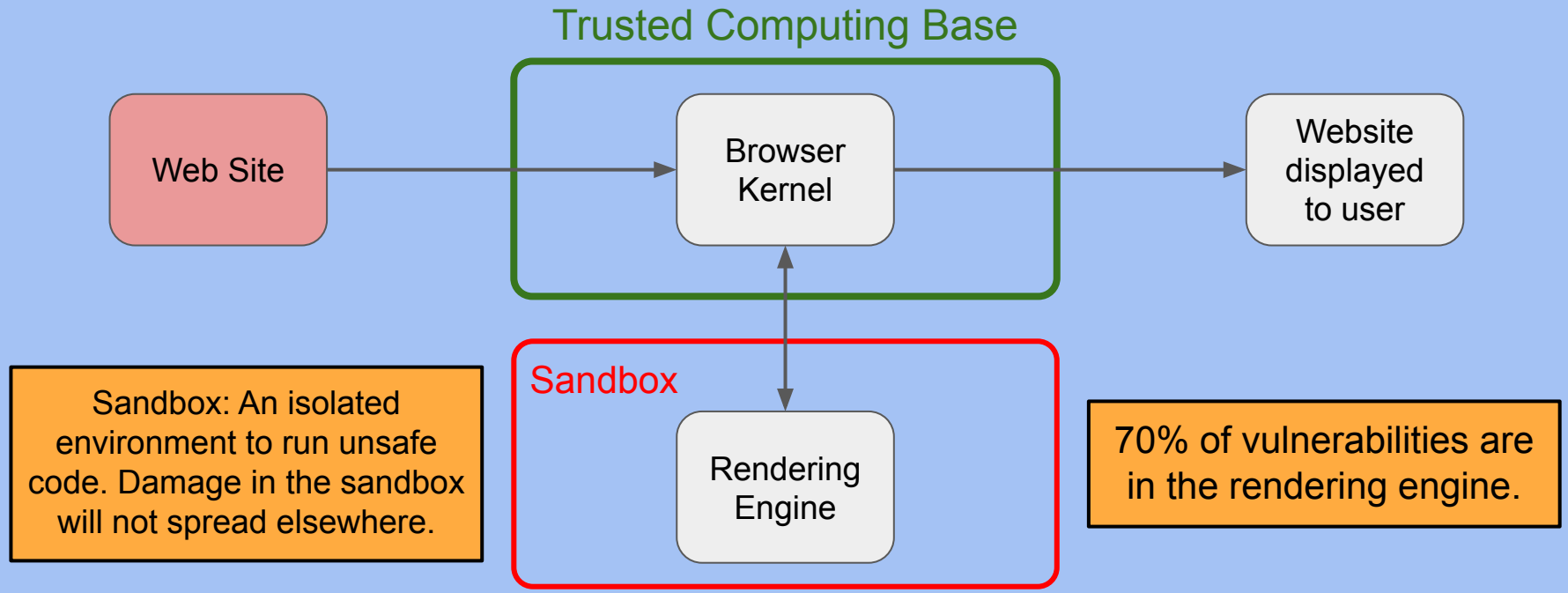


Browser Design with Poor Least Privilege



"Drive-by malware": A malicious web page exploits a browser bug to infect local files

Google Chrome Design: Apply Least Privilege



Prevent "drive-by malware," where a malicious webpage exploits a browser bug to infect local files

Enabling Least Privilege: Access Control

- How to control who has access to particular data
  - Access needs to be *necessary* to accomplish the tasks
  - Least privilege: Excessive access can be a problem
- Example: Access control for DSP data in CS 161
  - Separate Google shared Drive from the main Drive
    - This allows independent access control *defaults*
  - *Limit* access to that Drive to those who have a need to know
    - Nick, head TAs, DSP TAs, course manager

Access Control for Systems: The Operating System

- The OS is the TCB of most modern systems, and it provides access controls to restrict the privileges of user programs
- The OS provides the following “guarantees”:
  - **Isolation**: A process can’t read or write the memory of any other process
  - **Permissions**: A process can only change files, interact with devices, etc. if it has permission to

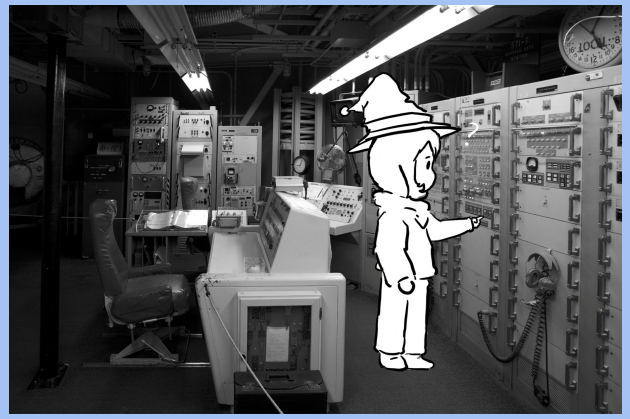
Separation of Responsibility

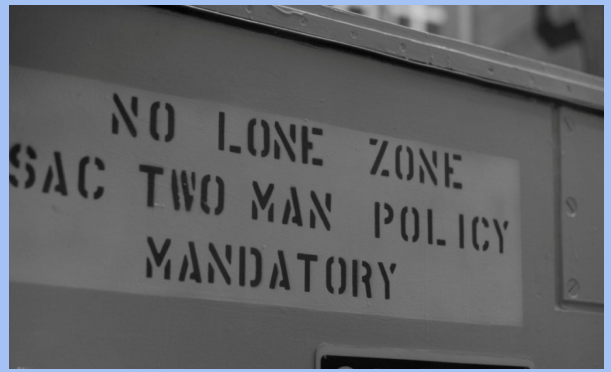
Textbook Chapter 1.7

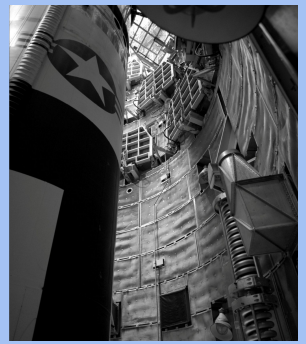
Separation of Responsibility

- Also known as distributed trust
- If you need to have a privilege, consider requiring multiple parties to work together (collude) to exercise it
  - It's much more likely for a single party to be malicious than for all multiple parties to be malicious and collude with one another

Welcome to a Nuclear Bunker







Welcome to a Movie Theater

Ensure Complete Mediation

Textbook Chapter 1.8 & 1.13

Security Principle: Ensure Complete Mediation

- Ensure that every access point is monitored and protected
- **Reference monitor**: Single point through which all access must occur
  - Example: A network firewall, airport security, the doors to the dorms
- Desired properties of reference monitors:
  - Correctness
  - Completeness (can't be bypassed)
  - Security (can't be tampered with)
  - Should be part of the TCB

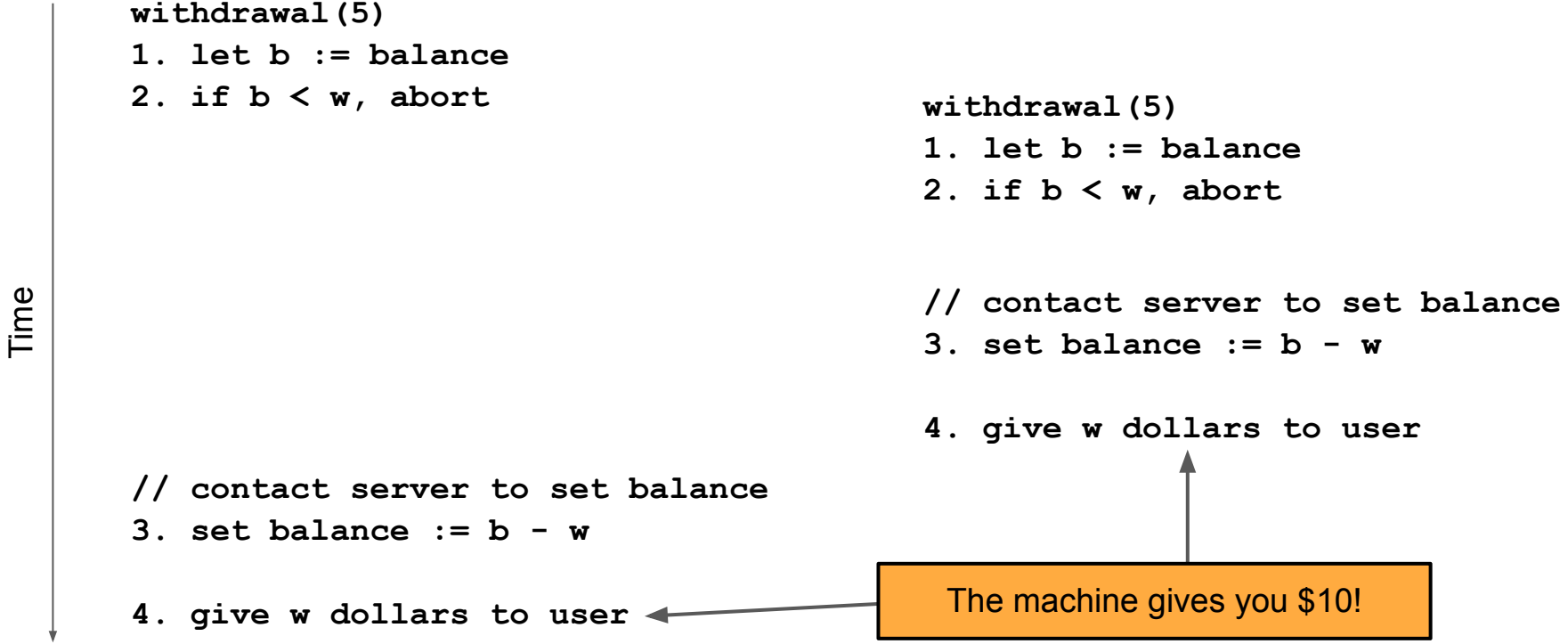
Time-of-Check to Time-of-Use

- A common failure of ensuring complete mediation involving race conditions
- Consider the following code:

```
procedure withdrawal(w)
    // contact central server to get balance
    1. let b := balance

    2. if b < w, abort

    // contact server to set balance
    3. set balance := b - w

    4. give w dollars to user
```

Suppose you have $5 in your account. How can you trick this system into giving you more than $5?

Time-of-Check to Time-of-Use



Don’t Rely on Security Through Obscurity

Textbook Chapter 1.9

Don’t Rely on Security Through Obscurity

- Also known as **Shannon’s Maxim**
  - “The enemy knows the system”
- Also known as **Kerckhoff’s Principle**
  - “The only part of a cryptographic system unknown to the adversary is the cryptographic keys”

Highway Signs

Here's a highway sign.

Here's the hidden computer inside the sign.

Here's the control panel. Most signs use the default password, **DOTS**.

Highway Signs

Note/Takeaway: Do not **ever** do this. Yes, some former CS 161 students did it once.

Highway Signs

Takeaway: Don’t rely on security through obscurity

Don’t Rely on Security Through Obscurity

- Always assume that the attacker knows every detail about the system you are working with (algorithms, hardware, defenses, etc.)
  - Sometimes, obscurity *can help*
    - Example: We don’t tell you how we detect academic dishonesty
  - However, systems that *rely* on obscurity are brittle, since the attacker may find out!
- Don’t do security through obscurity!

Assume the attacker knows where the “secret” control panel is located, and knows the default password.

Use Fail-Safe Defaults

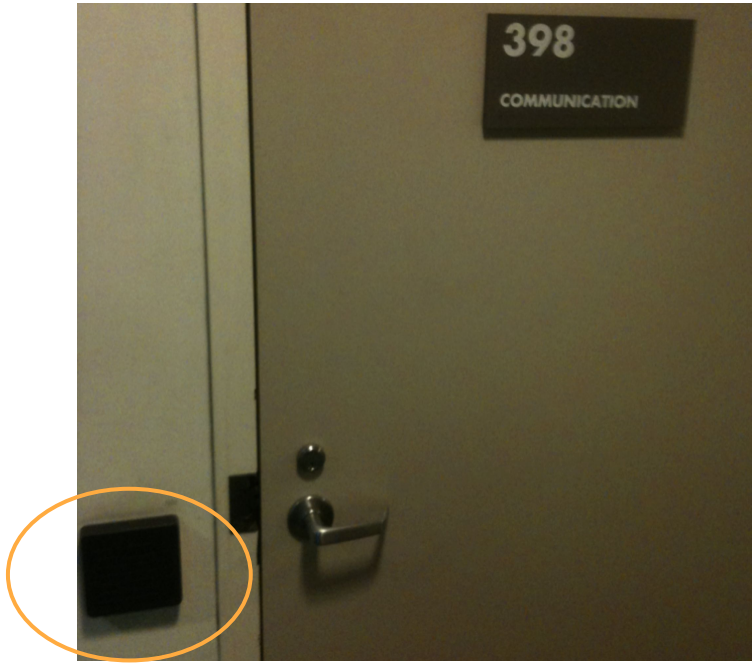
Textbook Chapter 1.10

Soda Hall

- Rooms in Berkeley's Soda Hall are guarded by electronic card keys
- What do you do if the power goes out?
  - Fail closed: No one can get in if the power is out
  - Fail open: Anyone can get in if the power goes out
- What's the best option to choose for closets with expensive equipment? What about emergency exit doors?
- **Takeaway**: Use fail-safe defaults… (if you can come up with one!)

Use Fail-Safe Defaults

- Choose default settings that “fail safe,” balancing security with usability when a system goes down
  - This can be hard to determine
- In the end, the right “default” often depends on context
  - Default open?
  - Default locked?



Design in Security from the Start

Textbook Chapter 1.11

Design in Security from the Start

- When building a new system, include security as part of the design considerations rather than patching it after the fact
  - A lot of systems today were not designed with security from the start, resulting in patches that don’t fully fix the problem!
- Keep these security principles in mind whenever you write code!

Summary: Security Principles

- **Know your threat model**: Understand your attacker and their resources and motivation
- **Consider human factors**: If your system is unusable, it will be unused
- **Security is economics**: Balance the expected cost of security with the expected benefit
- **Detect if you can't prevent**: Security requires not just preventing attacks but detecting and responding to them
- **Defense in depth**: Layer multiple types of defenses
- **Least privilege**: Only grant privileges that are needed for correct functioning, and no more
- **Separation of responsibility**: Consider requiring multiple parties to work together to exercise a privilege
- **Ensure complete mediation**: All access must be monitored and protected, unbypassable
- **Don't rely on security through obscurity**: Assume the enemy knows the system
- **Use fail-safe defaults**: Construct systems that fail in a safe state, balancing security and usability.
- **Design in security from the start**: Consider all of these security principles when designing a new system, rather than patching it afterwards

Next: x86 Assembly and Call Stack

- Part CS 61C review
  - How do computers represent numbers as bits and bytes?
  - How do computers interpret and run the programs we write?
  - How do computers organize segments of memory?
- Part new content
  - How does x86 assembly work?
  - How do you call a function in x86?

Number Representation

Textbook Chapter 2.1

Units of Measurement

- In computers, all data is represented as bits
  - **Bit**: a binary digit, 0 or 1
- Names for groups of bits
  - 4 bits = 1 **nibble**
  - 8 bits = 1 **byte**
- How many bits/nibbles/bytes in `0b 1000 1000 1000 1000`?
  - 16 bits, or 4 nibbles, or 2 bytes

Hexadecimal

- 4 bits can be represented as 1 hexadecimal digit (base 16)
- How would you write `0b11000110` in hex?
  - `0xC6`
  - Note: For clarity, we add `0b` in front of bits and `0x` in front of hex

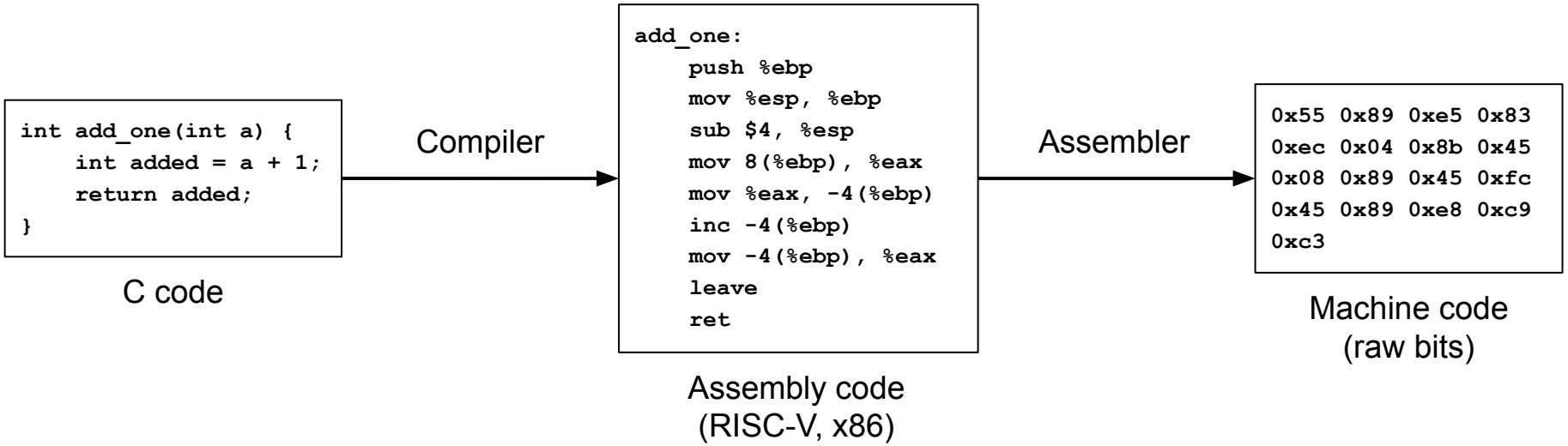
Binary	Hexadecimal
0000	0
0001	1
0010	2
0011	3
0100	4
0101	5
0110	6
0111	7

Binary	Hexadecimal
1000	8
1001	9
1010	A
1011	B
1100	C
1101	D
1110	E
1111	F

Running C Programs

Textbook Chapter 2.2

CALL (Compiler, Assembler, Linker, Loader)



CALL (Compiler, Assembler, Linker, Loader)

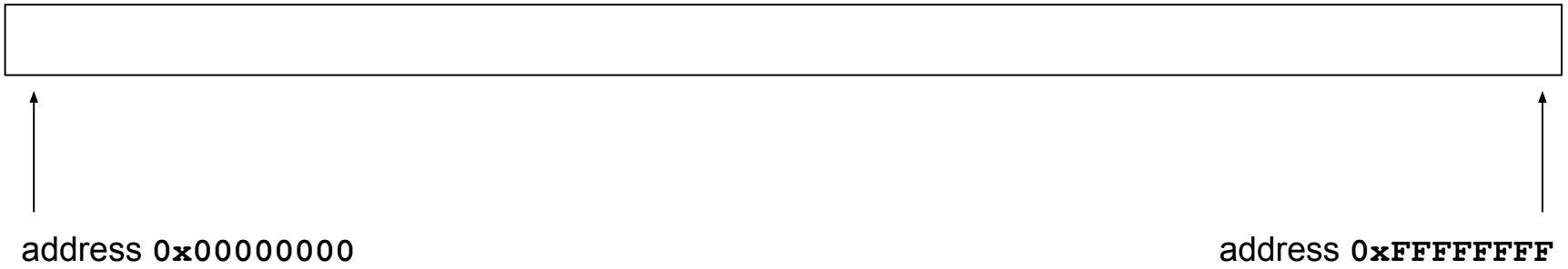
- Compiler: Converts C code into assembly code (RISC-V, x86)
- Assembler: Converts assembly code into machine code (raw bits)
  - Think 61C's RISC-V "green sheet"
- Linker: Deals with dependencies and libraries
  - You can ignore this part for 161
- Loader: Sets up memory space and jumps into the machine code
  - Sometimes, there is an additional linking step right before loading, called dynamic loading
    - Result: The executable doesn't need to contain all the dependencies
    - This also provides additional mitigations, as we'll see later
- After these steps, execution begins, and C runtime library calls **`main`**!

Memory Layout

Textbook Chapter 2.3 & 2.5

C Memory Layout

- At runtime, the loader tells your OS to give your program a big blob of memory
- On a 32-bit system, the memory has 32-bit addresses
  - On a 64-bit system, memory has 64-bit addresses
  - We use 32-bit systems in this class
- Each address refers to one byte, which means you have 2^{32} bytes of memory

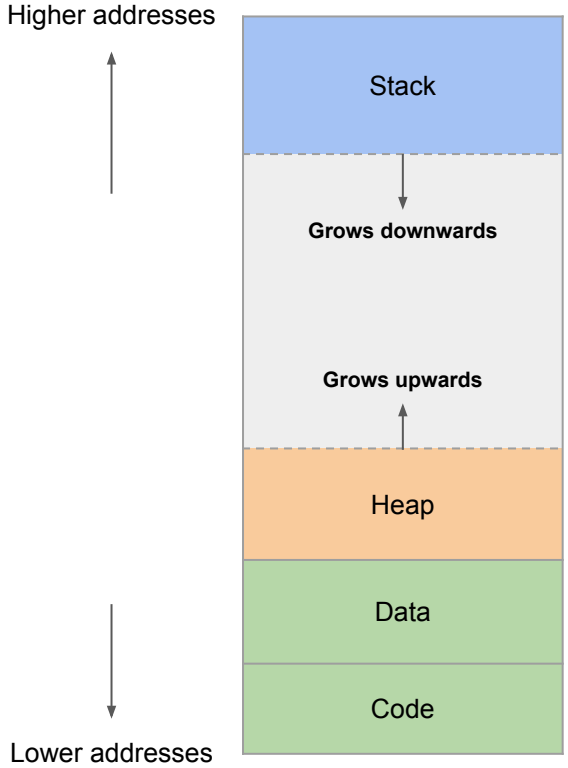


C Memory Layout

- Often drawn vertically for ease of viewing
  - But memory is still just a long array of bytes
- Each process has its own address space (virtual memory)
  - Isolation: Two processes can read and write the same address but access different pieces of physical memory
  - Least privilege: Virtual memory also enables the OS to control what memory a process can “see”

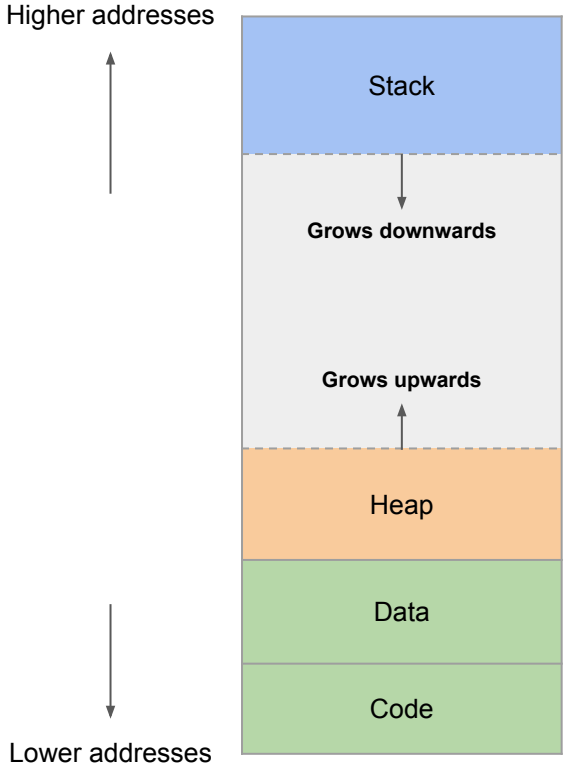
x86 Memory Layout

- Code
  - The program code itself (also called “text”)
- Data
  - Static variables, allocated when the program is started
- Heap
  - Dynamically allocated memory using **`malloc`** and **`free`**
  - As more and more memory is allocated, it grows *upwards*
- Stack:
  - Local variables and stack frames
  - As you make deeper and deeper function calls, it grows *downwards*



Registers

- Recall registers from CS 61C
  - Examples of RISC-V registers: **`a0`**, **`t0`**, **`ra`**, **`sp`**
- Registers are located on the CPU
  - This is different from the memory layout
  - Memory: addresses are 32-bit numbers
  - Registers: addresses are names (**`ebp`**, **`esp`**, **`eip`**)



x86 Architecture

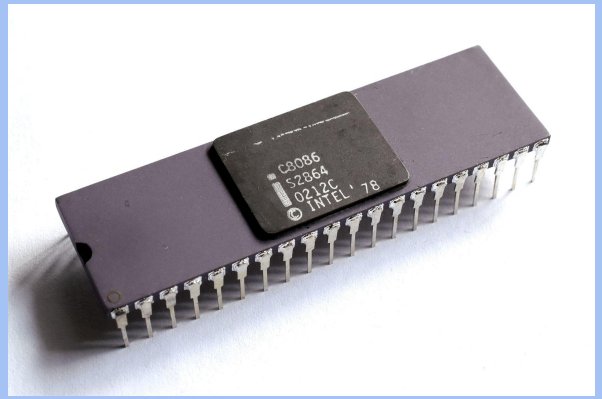
Textbook Chapter 2.4 & 2.7

Why x86?

- It’s the most commonly used instruction set architecture in consumer computers!
  - You are probably using an x86 computer right now… unless you’re on a phone, tablet, or M1 Mac
- You only need enough to be able to read it and know what is going on
  - We will make comparisons to RISC-V, but it’s okay if you haven’t taken 61C and don’t know RISC-V; you don’t need to understand the comparisons to understand x86
- However, if you have a choice, choose ARM
  - Significantly higher performance for the same cost
  - 64b ARM has some unique security features we will discuss later

What is x86?

- Complex instruction set computer (CISC) architecture
  - The opposite of reduced instruction set computer (RISC) architecture
  - There are a lot of instructions… The full ISA manual is over **5,000 pages long**!
  - We will not be teaching the full instruction set (obviously), just enough of the calling convention to be able to do Project 1
- Launched in 1978 with the Intel 8086 processor and eventually took over much of computing
  - Over 40 years ago! The ISA is very bloated because of this…
- 64-bit variant x86-64 launched in 1999 (but we won't study it)



x86 Fact Sheet

- Little-endian
  - The least-significant byte of multi-byte numbers is placed at the first/lowest memory address
  - Same as RISC-V
- Variable-length instructions
  - When assembled into machine code, instructions can be anywhere from 1 to 16 bytes long
  - Contrast with RISC-V, which has fixed-length, 4-byte instructions (or, optionally, 2-byte instructions)

```
int main(void) {
    uint32_t num = 0xdeadbeef;

    // This prints "deadbeef".
    printf("%x", num);

    // This prints "ef be ad de".
    uint8_t *bytes = (uint8_t *) &num;
    for (size_t i = 0; i < 4; i++) {
        printf("%x ", bytes[i]);
    }
}
```

x86 Registers

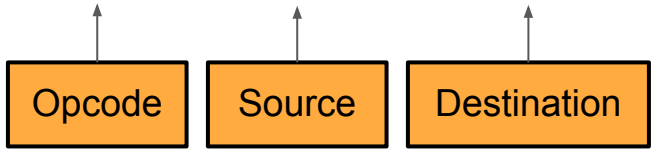
- Storage units as part of the CPU architecture (not part of memory)
- Only 8 main general-purpose registers:
  - EAX, EBX, ECX, EDX, ESI, EDI: General-purpose
  - ESP: Stack pointer (similar to **`sp`** in RISC-V)
  - EBP: Base pointer (similar to **`fp`** in RISC-V)
  - We will discuss ESP and EBP in more detail later
- Instruction pointer register: EIP
  - Similar to PC in RISC-V

x86 Syntax

- Register references are preceded with a percent sign `%`
  - Example: **`%eax`**, **`%esp`**, **`%edi`**
- Immediates are preceded with a dollar sign **`$`**
  - Example: **`$1`**, **`$161`**, **`$0x4`**
- Memory references use parentheses and can have immediate offsets
  - Example: **`8(%esp)`** dereferences memory 8 bytes above the address contained in ESP

x86 Assembly

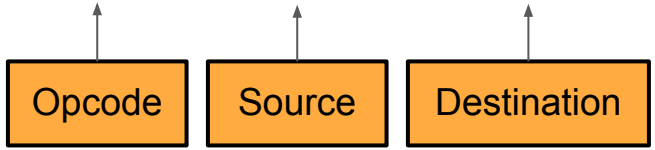
- Instructions are composed of an opcode and zero or more operands.
- `add $0x8, %ebx`



- Pseudocode: **`EBX = EBX + 0x8`**
- The destination comes last
  - Contrast with RISC-V assembly, where the destination (RD) is first
- The **`add`** instruction only has two operands; and the destination is an input
  - Contrast with RISC-V, where the two source operands are separate (RS1 and RS2)
- This instruction uses a register and an immediate

x86 Assembly

- `xor 4(%esi), %eax`



- Pseudocode: **`EAX = EAX ^ *(ESI + 4)`**
- This is a memory reference, where the value at 4 bytes above the address in ESI is dereferenced, XOR'd with EAX, and stored back into EAX
  - Most instructions can be register-register, register-immediate, register-memory, or memory-immediate (but not memory-memory)
    - How can you achieve a memory-memory operation?

Stack Layout

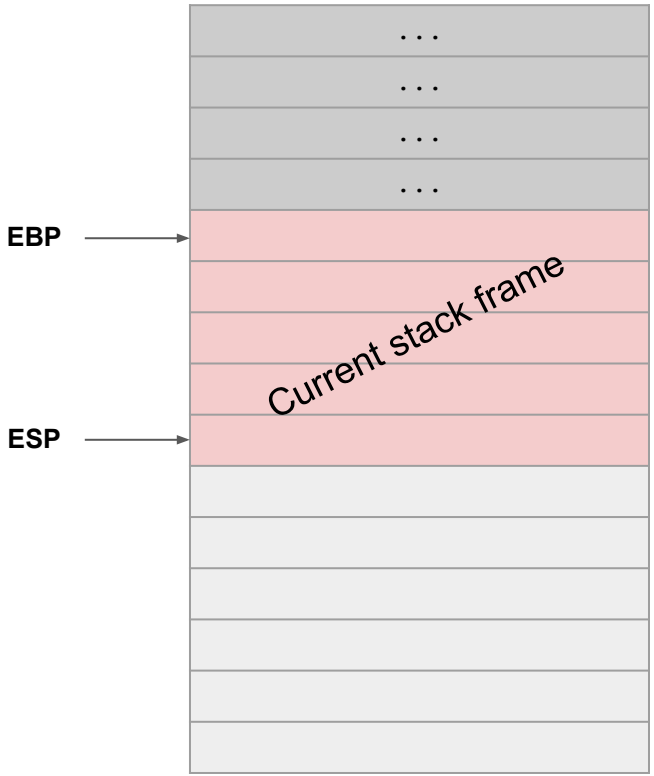
Textbook Chapter 2.6

Stack Frames

- When your code calls a function, space is made on the stack for local variables
  - This space is known as the **stack frame** for the function
  - The stack frame goes away once the function returns
- The stack starts at higher addresses. Every time your code calls a function, the stack makes extra space by growing down
  - Note: Data on the stack, such as a string, is still stored from lowest address to highest address. “Growing down” only happens when extra memory needs to be allocated.

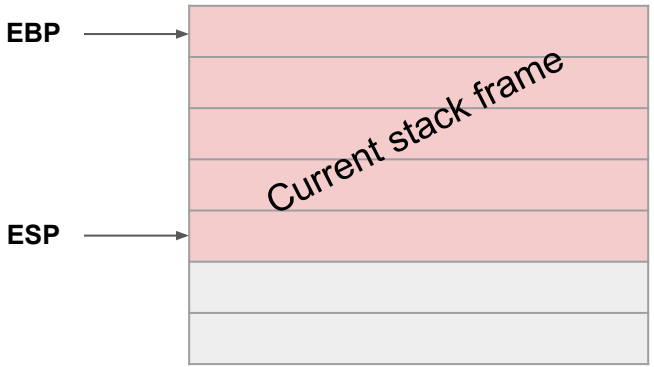
Stack Frames

- To keep track of the current stack frame, we store two pointers in registers
  - The EBP (base pointer) register points to the top of the current stack frame
    - Equivalent to RISC-V **`fp`**
  - The ESP (stack pointer) register points to the bottom of the current stack frame
    - Equivalent to RISC-V **`sp`** (but x86 moves the stack pointer up and down a lot more than RISC-V does)



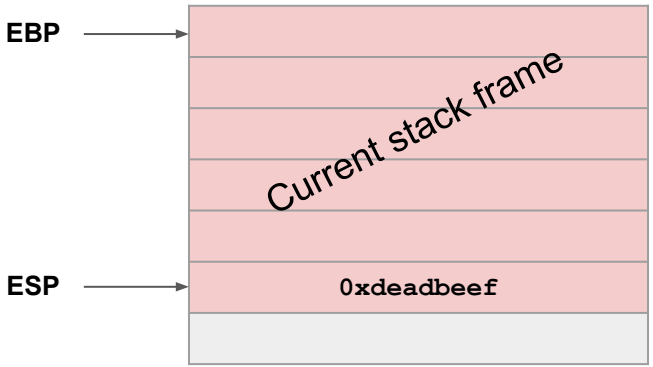
Pushing and Popping

- The **`push`** instruction adds an element to the stack
  - Decrement ESP to allocate more memory on the stack
  - Save the new value on the lowest value of the stack



EAX = `0xdeadbeef`
EBX = ...

Before **`push %eax`**

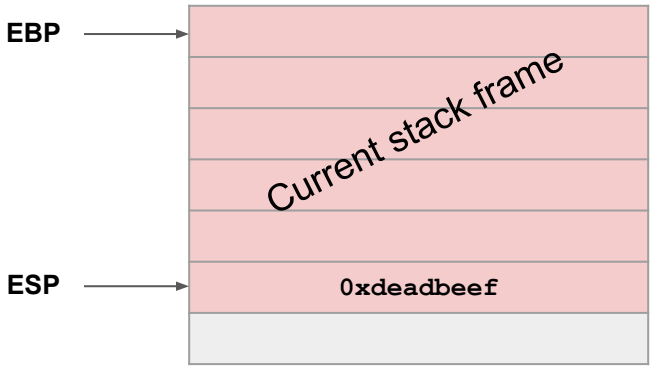


EAX = `0xdeadbeef`
EBX = ...

After **`push %eax`**

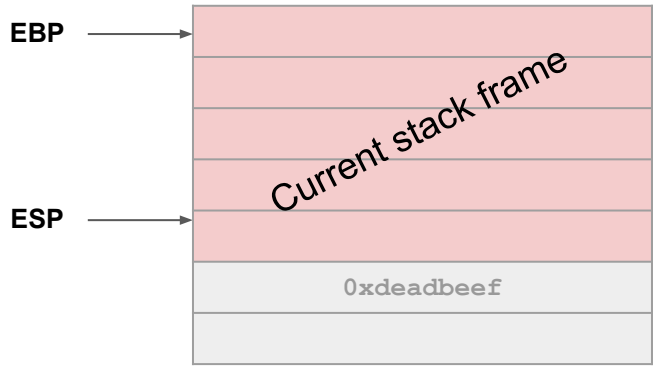
Pushing and Popping

- The **`pop`** instruction removes an element from the stack
  - Load the value from the lowest value on the stack and store it in a register
  - Increment ESP to deallocate the memory on the stack



EAX = `0x00000000`
EBX = ...

Before **`pop %eax`**



EAX = `0xdeadbeef`
EBX = ...

After **`pop %eax`**

Why `push` and `pop`?

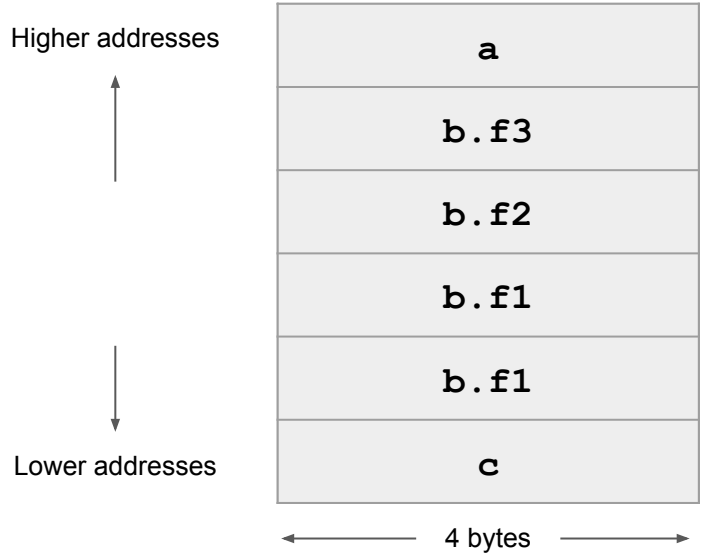
- This allows x86 to use “stack-machine”-style logic
  - Operations always operate on the top items on the stack and push the result back onto the stack
  - Example: *a* + *b* * *c* + *d*
    - `PUSH a // a`
    - `PUSH b // a, b`
    - `PUSH c // a, b, c`
    - `MUL  // a, (b*c)`
    - `ADD  // (a+(b*c))`
    - `PUSH  // (a+(b*c)), d`
    - `ADD  // (a+(b*c))+d`
    - Result is the last remaining item on the stack!
- Used to think this allowed for smaller code and simpler code generation
  - Reality? Not so much. RISC logic is equally efficient in code size in practice, especially with the compressed instructions for RISC-V.
  - But this misconception is why the Java VM is a stack machine too…
- (Not really a) Takeaway: Take 164 if you want to learn more about this

x86 Stack Layout

- Local variables are always allocated on the stack
  - Contrast with RISC-V, which has plenty of registers that can be used for variables
- Individual variables within a stack frame are stored with the first variable at the *highest* address
- Members of a struct are stored with the first member at the *lowest* address
- Global variables are stored with the first variable at the *lowest* address

Stack Layout


```
struct foo {
    long long f1; // 8 bytes
    int f2;       // 4 bytes
    int f3;       // 4 bytes
};

void func(void) {
    int a;        // 4 bytes
    struct foo b;
    int c;        // 4 bytes
}
```



How would you fill out the boxes in this stack diagram?
Options:
a **b.f1** **b.f2** **b.f3** **c**