

Computer Science Fundamentals:

From Logic to Algorithms & Data Structures

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Contents

Contents	1
1 Memory Management	5
1.1 CPU Architecture	5
1.2 Code Security	10
1.3 Stack Data Structures	11
1.4 Heap Data Structures	15
1.5 Hashing & Collisions	22
Open Addressing	23
Searching: Insertion & Deletion	26
Separate Chaining & Linked Lists	27
Load Factor & Performance Metrics	32
Bibliography	33

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Preface

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Please note: These are my personal notes, and while I strive for accuracy, there may be errors. I encourage you to refer to the original slides for precise information. Comments and suggestions for improvement are always welcome.

Prerequisites

Memory Management

1.1 CPU Architecture

This section provides a high-level overview of the CPU to provide context/motivation for the following algorithms and data structures.

Definition 1.1: Central Processing Unit (CPU)

The **CPU (Central Processing Unit)**, is a hardware component that *computes* instructions within a computer. Abstract models that define interfaces between hardware and software for a CPU are called **instruction set architectures (ISA)**.

Possible operations are detailed as **opcodes** (operation codes), which are numeric identifiers for each instruction. Moreover, the ISA defines supported data types, **registers (temporary storage locations)**, and addressing modes (ways to access memory).

ISA's are defines the instruction set, which allows for flexibility in hardware performance needs. This various categories:

- **CISC (Complex Instruction Set Computing)**: Large number of complex instructions (multiple operations per instruction).
- **RISC (Reduced Instruction Set Computing)**: Small set of simple/efficient instructions.
- **VLIW (Very Long Instruction Word)**: Enables instruction parallelism (simultaneous execution).
- **EPIC (Explicitly Parallel Instruction Computing)**: More explicit control over parallel execution.

Smaller more theoretical architectures exists such as **MISC (Minimal Instruction Set Computing)** and **OISC (One Instruction Set Computing)**, which are not used in practice. Popular CPU architectures include x86_64, and ARM64 (64-bit), originating from x86 and ARM (32-bit).

The implementation of a CPU on a circuit board is called a **microprocessor**. Multiple CPUs on a single circuit board are **multi-core processors**, where each *core* is a fully functional CPU.

Definition 1.2: CPU Anatomy

The CPU is comprised of three main components:

- **ALU (Arithmetic Logic Unit):** Performs arithmetic and logical operations (e.g., addition, subtraction, AND, OR).
- **Control Unit (CU):** Directs the operation of the CPU, fetching and decoding instructions, and controlling the flow of data.
- **Memory Unit (MU):** Manages data storage and retrieval, including registers and cache memory.

All these components have volatile memory, lost when the computer is turned off.

Definition 1.3: CPU Execution Flow

The **CPU execution flow** is the sequence of operations that the CPU performs to execute a program. It typically follows these steps:

1. **Fetch:** Fetches the next instruction from memory.
2. **Decode:** Decodes the fetched instruction to associated opcode and operands.
3. **Execute:** Perform decoded operation using the ALU or other components.
4. **Store:** Save results of the operation back into memory or registers.

This cycle is repeated until the program completes or an interrupt occurs.

Definition 1.4: Registers

Registers are small, high-speed storage locations within the CPU that hold data temporarily during execution. Common types of registers include:

- **General-Purpose Registers (GPR):** Hold general data storage and manipulation.
- **Special-Purpose Registers:** For specific functions, such as a reference to the current line of code.
- **Floating-Point Registers:** Floating-point arithmetic (e.g., decimal numbers).

Registers are faster than main memory (RAM) and are used to store frequently accessed data during program execution.

The following is an example of the primary registers in the x86-32 (IA-32) architecture, which is a CISC architecture.

Register	Size	Purpose
EAX	32-bit	Accumulator (arithmetic / return value)
EBX	32-bit	Base register (data pointer)
ECX	32-bit	Counter (loops, shifts)
EDX	32-bit	Data register (I/O, multiply/divide)
ESI	32-bit	Source index (string / memory ops)
EDI	32-bit	Destination index (string / memory ops)
EBP	32-bit	Base/frame pointer (stack-frame anchor)
ESP	32-bit	Stack pointer
EIP	32-bit	Instruction pointer (program counter)
EFLAGS	32-bit	Flags / status register (ZF, CF, OF...)

Table 1.1: Primary registers of the x86-32 (IA-32) architecture. **Note:** Registers are prefixed with ‘E’ for 32-bit, ‘R’ for 64-bit in x86-64.

Definition 1.5: Machine Code & Compilation

Code is separated into two main areas of memory management, the program itself, and the data in transit during execution. The program itself is broken up such as follows:

- **Text Segment:** The part of the program which contains the executable code.
- **Data Segment:** The part of the program which contains global and static variables.
- **Machine Code:** The compiled code of the program, which is executed by the CPU.

Once the code compiles, our data segment is further divided into two parts in memory:

- **Initialized Data:** Data given a value before the program starts (global variables).
- **Uninitialized Data:** Data yet to be assigned (local variables), which are zeroed at program start.

By memory we mean the **RAM (Random Access Memory)** hardware component, which stores temporary data, constantly communicating with the CPU or external storage (e.g., hard drive, SSD). Each memory cell is IDed by a unique monotonic **address**, often in hexadecimal format(e.g., 0xF00, 0xF01, etc).

Definition 1.6: Operating System (OS)

Implemented ISAs only provide an interface to the CPU; Programmers must design how their systems utilize the CPU (e.g., file and memory management), such software is called an **operating system (OS)**.

Tip: In an analogous sense, say we have a train riding service. The ISA would be the specifications of the trains, rails, routes, and stations needed. The physical implementation of trains, rails, and stations would be the CPU. The OS would be the train schedule system, managing external factors such as workers and other tasks effecting the train service.

Definition 1.7: The Kernel

The **kernel** is a **process** (a program) vital for OS operation, always running with the highest priority. It is the only program that can directly interact with the CPU and various hardware components.

Other processes running on the system are called **user processes**. This is where applications and other user-level programs run. If a user wishes to perform a task that requires hardware access (e.g., writing/reading files), they must request the kernel called a **system call (syscall)**. System calls provide an **Application Programming Interface (API)** for user processes to interact with the kernel.

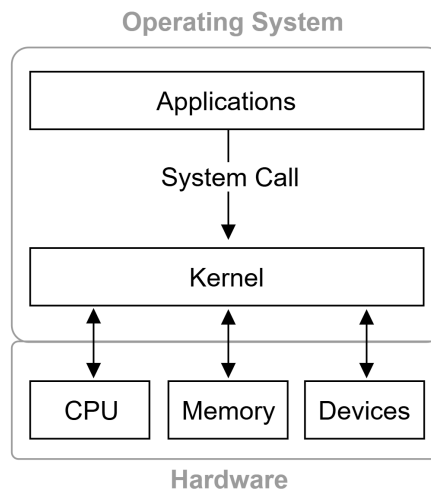


Figure 1.1: User-level applications make syscalls to the kernel to access hardware resources.

Definition 1.8: Bus

A **bus** is a collection of physical signal lines (wires or pins) and protocols that carry data, addresses, and control signals between components inside a computer (e.g. CPU, memory, I/O devices) or between multiple boards and peripherals. There are two main types of buses:

- **Serial Bus:** Transfers data one bit at a time over a single channel (e.g., USB).
- **Parallel Bus:** Transfers multiple bits simultaneously over multiple channels (e.g., PCI).

Definition 1.9: Device Drivers

The kernel exposes generic interfaces to various sub-systems (e.g., file system) that user processes can use to perform tasks; **Device drivers** implement such interfaces, translating generic system calls into hardware-specific operations for specific devices (e.g., disk drives, network cards, etc.). Drivers must be loaded into kernel space.

This text does not concern assembly code, so **do not** get caught in the specifics of this Example:

Example 1.1: Assembly Code

An assembly example demonstrating initialized (.data) and uninitialized (.bss) data sections:

```
section .data                ; Initialized data section
    num1    dd    7          ; num1 is initialized to 7
    num2    dd    3          ; num2 is initialized to 3

section .bss                 ; Uninitialized data section
    temp    resd 1           ; temp is reserved (uninitialized)
    result  resd 1           ; result is reserved (uninitialized)

section .text                ; Code section
    global _start

_start:
    mov eax, [num1]          ; Load num1 into eax
    mov [temp], eax          ; Store num1 in temp
    mov ebx, [num2]          ; Load num2 into ebx
    add eax, ebx             ; Add num2 to eax (eax = num1 + num2)
    mov [result], eax        ; Store the sum in result
    ; Exit syscall removed for simplicity
```

In this example, ‘num1’ and ‘num2’ are initialized before execution, while ‘temp’ and ‘result’ are uninitialized and only receive values during program execution. ■

1.2 Code Security

At a *very* high-level, vulnerabilities exploited by hackers stem from flaws that the programmer forgot to consider (i.e., bugs). To learn more on cybersecurity, consider our other text [here](#).

Definition 2.1: Proper Encapsulation

Proper encapsulation is the practice of hiding implementation details and exposing only necessary interfaces to prevent unauthorized access or modification.

Example 2.1: Student Class

Consider a simple ‘Student’ class in an object-oriented programming language:

```
public class Student {  
    private String name; // Private field, not accessible outside  
                        // the class  
    private int age;    // Private field, not accessible outside  
                        // the class  
  
    public Student(String name, int age) {  
        this.name = name;  
        this.age = age;  
    }  
  
    public String getName() { // Public method to access name  
        return name;  
    }  
    // Other methods...  
}
```

Upon creating a new student instance `new Student("Alice", 20)`, the name and age are private, preventing direct access via **dot notation** (e.g., `student.name`). The only way to access the name is through the public method `getName()`. Here we do not have a method for accessing age. ■

Definition 2.2: Risks of Accessing Main Memory

Programs access main memory (RAM) to read and write data; **It’s critical** that such references to RAM are abstracted to avoid malicious or accidental access of data.

For example, in Java when users print objects, instead of printing the object’s memory address, it prints the `toString()` method, which **by default** prints the class name and hash code of the object.

In conclusion, there are significant risks when dealing with memory management.

1.3 Stack Data Structures

Let's talk about our first data structure, the stack:

Definition 3.1: Stack

A **stack data structure** is a collection of elements that follows a **Last In, First Out (LIFO)** principle. I.e., in a stack of plates, the last added plate is the first one to be removed, not the middle or bottom/first plate. Each *plate* in the stack is called a **stack frame**.

A **call stack** is a stack which keeps track of function calls in a program as well as any local variables within such functions.

This is why we say a variable is in **scope**, as when a function is taken off the stack, or a new stack frame is placed on top, the variables in the previous or discarded stack frame are **no longer accessible**.

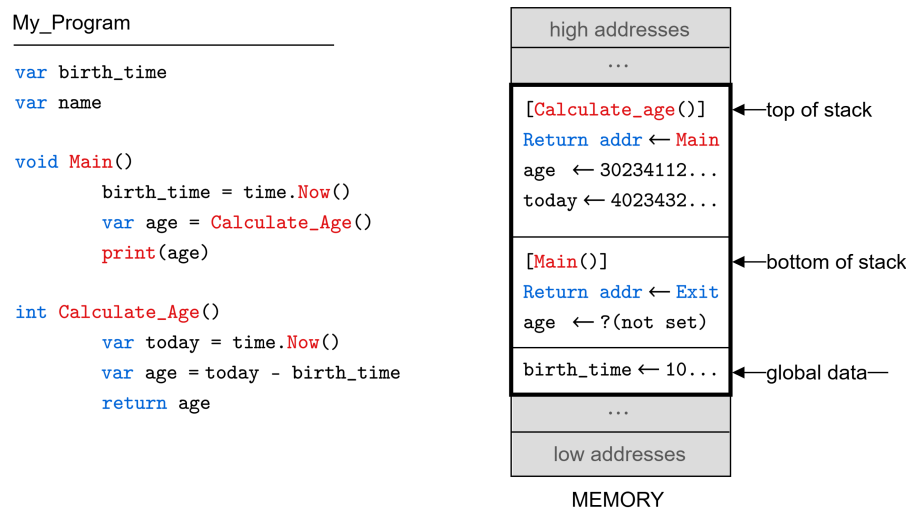


Figure 1.2: Here is a simplified look at how memory manages the stack. On the left is our program written in some abstract language, and on the right is the call stack in memory (simplified). The program has a global 'birth_time' variable, which is initialized in the **Main** function. The **Main** function then calls the **Calculate_Age** function which uses the 'birth_time' variable to calculate the 'age' via the difference of the current time and the 'birth_time.' Looking at the memory, we see at the bottom of our memory contains global variables accessible to any frame. Next, is the bottom of the stack, containing a return address to exit the program, while awaiting the result of the function call for 'age'. The top of our stack contains another frame that we will return the value a new 'age' (not the same as the one before) not accessible from the main function. This new frame also contains a new local variable 'today.' Once this function returns, **Main** will have the result of its local variable 'age.'. Concretely, the 'age' variable in both the **Main** and **Calculate_Age** function are completely separate despite sharing the same *name*.

Please Note: The above figure is a simplified version; This presentation derivatives from what actually happens for teaching sake. In the following pages we define the stack frame in more detail.

Tip: A lot of demonstrations (including this text) will show the stack growing **upwards**; This is strictly because it's easier to visualize and does not accurately portray what a stack really does or looks like. In the following pages we will clear this up, and show how the stack actually grows from top-to-bottom. Of course, there is always room for deviation if a developer wishes to implement a stack in some other arbitrary way. Nonetheless, the following is what one might typically expect in a stack implementation.

Definition 3.2: Stack Frame Anatomy

Under the x86-32 calling convention Two registers keep track our place in the stack:

- **Base Pointer (BP/EBP):** Points to the base (i.e. “bottom”) of the current function’s stack frame.
- **Stack Pointer (SP/ESP):** Points to the “top” of the current function’s stack frame, i.e., the next free byte where a push would land.

When the program starts, the operating system *reserves* a contiguous region of memory for the stack. By convention, the *bottom* of that region lies at a higher address, and the stack “grows downward” toward lower addresses as data is pushed. If the stack pointer ever moves past the reserved limit—a **stack overflow** occurs.

A single **stack frame** itself is a contiguous block of memory in which the function stores:

- **Parameters:** The arguments passed in by the caller,
- **Return Address:** The address of the next instruction to execute after the function returns,
- **Old Base Pointer:** The caller’s ‘EBP’, saved so that on return we can restore the previous frame,
- **Local Variables:** Space for any locals or temporaries that the function needs.

This is why variables in previous or new functions calls become “**out of scope**” (no longer accessible), as they belong to some other stack frame; When it comes to **Global Variables**, they live in a separate region of memory, defined by the **data segment** (1.5).

Moreover, a call to a new function invokes the call instruction, this automatically pushes the return address to the current frame onto the stack. Additionally, the CPU reserves the **EAX** register for the return value (number or address) of a function. When the function returns, it can place its result in ‘EAX’, and the caller can retrieve it from there. During constant use the ‘EAX’ register may contain garbage data from previous use, unless explicitly set to zero or some other value.

High Addresses		
Contents	Offset	Notes
(Parameters 3, 4, ...)	$EBP + 16, +20, \dots$	Third-and-onward arguments, if any.
Parameter 2	$EBP + 12$	Second argument passed on stack.
Parameter 1	$EBP + 8$	First argument passed on stack.
Return Address	$EBP + 4$	Auto-pushed by the <code>call</code> instruction.
Old EBP (Saved BP)	$EBP + 0$	The caller's base pointer
Current Frame (locals/temporaries)		
Local Variable 1	$EBP - 4$	First 4-byte local (or smallest slot).
Local Variable 2	$EBP - 8$	Next 4-byte local or part of a larger object.
...	\vdots	(additional locals at $EBP - 12, -16, \dots$)
Low Addresses		

Table 1.2: Typical x86-32 Stack-Frame Layout, where offsets are typically a multiple of 4 bytes.

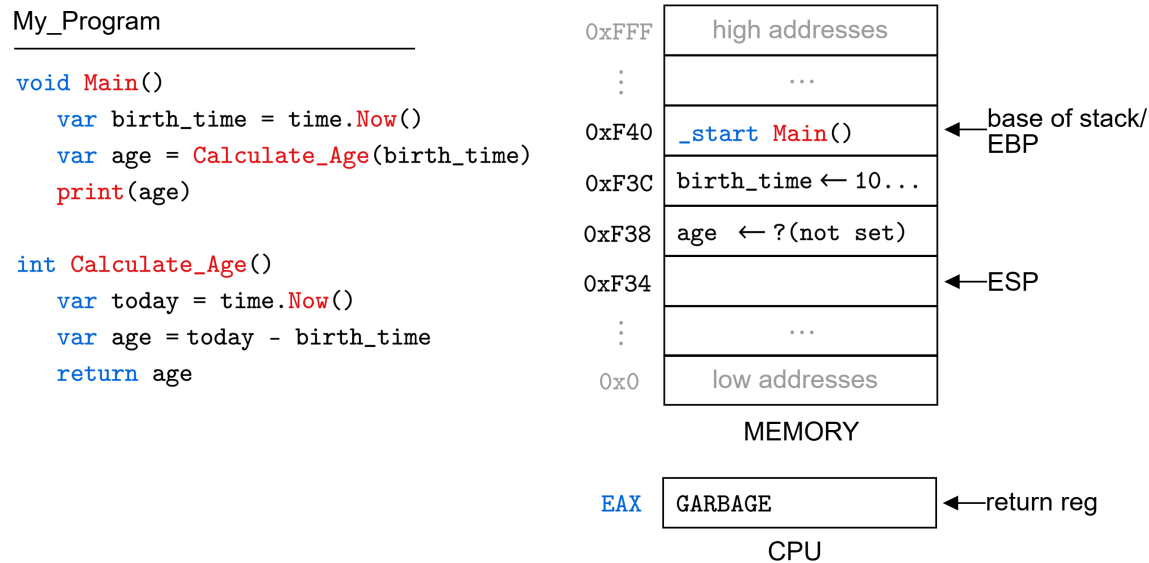


Figure 1.3: Revisiting Figure (1.2) with slight alterations to the code: This is a snapshot of the code executing right before `CalculateAge(birth_time)` is called. For simplicity sake, let's say the stack begins at address `0xF40` (Hexadecimal), growing downwards. Here the base of the stack and the EBP are one and the same. We include the CPU's EAX (return register), which contains garbage. Address `0xF38` is currently just reserved space for 'age'.

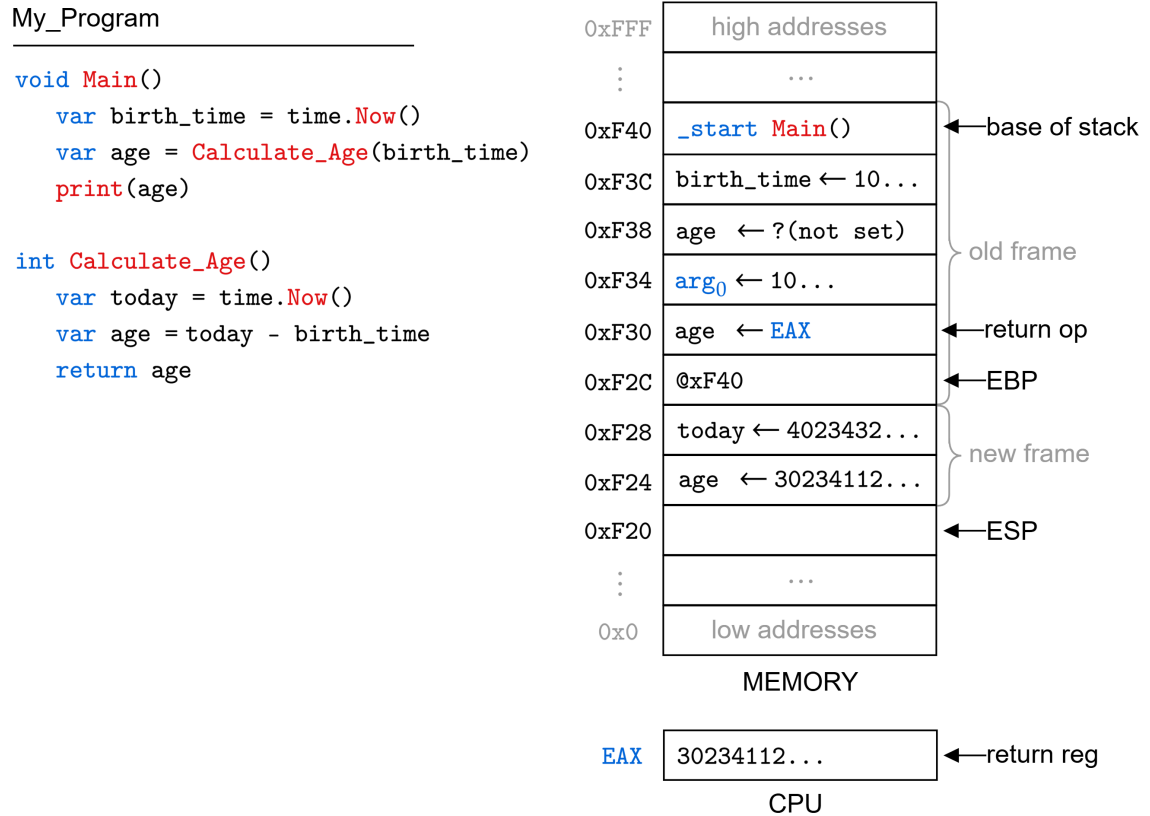


Figure 1.4: Revisiting Figure (1.3) at the moment the function `CalculateAge(birth_time)` has supplied its return value to the `EAX` register, and is about to return. We see that before calling `CalculateAge(birth_time)`: The old frame pushed its arguments (`birth_time`) onto the stack, then the return address (IP/Next Instruction) onto the stack, and finally the old `EBP` (Base Pointer) onto the stack. The ‘new frame’ then sets the saved `EBP` address to the current `EBP`, concluding the old frame into the ‘new frame’. Moreover, since the offset looks for local variables below `0xF40`, the above ‘`birth_time`’ and ‘`age`’ are **out of scope** for the ‘new frame’, vice-versa. **Note:** This is still a high-level abstraction of what actually happens sequentially with opcodes; Nonetheless, this is the fundamental idea of how a stack works.

This concludes our discussion on stack structures; We continue with the heap structure next.

1.4 Heap Data Structures

So far we have simply said global data is declared in the **data segment** of memory. There is a second segment of memory that builds ontop of this called the **heap**:

Definition 4.1: Heap – Dynamic vs. Static Memory

When a program runs there is a **static** (fixed) region reserved for the program's data segment (local/global variables). During execution, more objects may be created, needing additional memory; A new region of memory is reserved **dynamically**, building upwards from the top of the data segment, called the **heap**.

Language protocols either **manually** (e.g., Assembly, C) or **automatically** (e.g., Python, Java) manage this memory:

- **Manual Memory Management:** The programmer must explicitly allocate and deallocate memory using functions like 'malloc' and 'free' in C.
- **Automatic Memory Management:** The language runtime automatically allocates and deallocates memory, often using a **garbage collector** to reclaim unused memory (no variables pointing to it).

Unlike the stack, this allows values to be accessed from anywhere in the program, regardless of the function call or scope.

We discuss hash tables more in-depth in the following section, for now we provide a high-level idea:

Definition 4.2: Hash Table

A **hash table** uses a **hash function**, taking a **key** (e.g., number or string) and producing a fixed-sized **hash** value (index), creating a table of mappings (key→hash). At such indices lies data associated with the key, enabling fast data retrievals.

A **universal hash function** is a hash function that uniformly distributes hashes across the hash table.

Note: The input in many context (typically cryptographic), may be called 'data' or 'message'; The output: hash, checksum, fingerprint, or digest.

Definition 4.3: Arrays in Memory

Arrays list elements sequentially in memory. A reference to an array is a pointer to the first element. To terminate reading an array, we must either know the size of said array or have some **sentinel value** (e.g., 'null' or '0') to indicate the end of the array.

Consider the following examples:

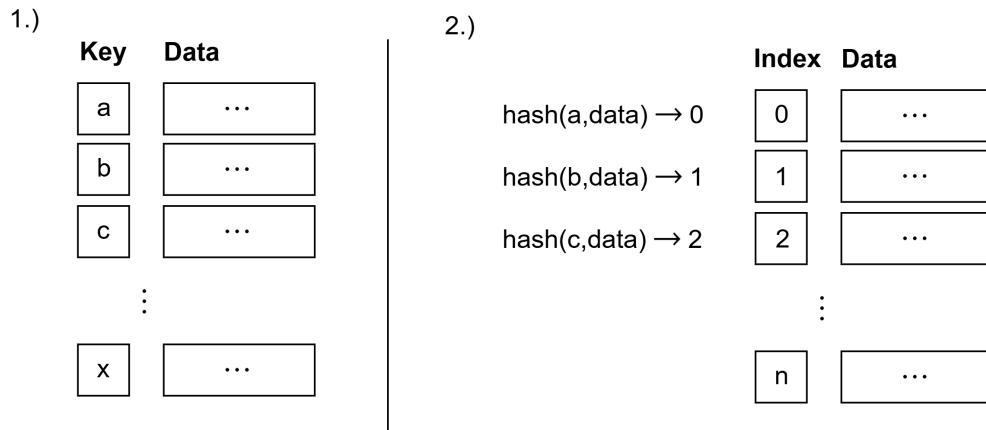


Figure 1.5: On the left (1) demonstrates a typical diagram one might find when learning about hash tables. Here a through x are the keys, which house some type of data. On the right (2) shows a slightly more detailed version, which emphasizes that keys a – x are hashed to indices 0 – n in the hash table. The data could be any other value (e.g., number, string, or object). Moreover, hash tables under the hood are arrays, with each index pointing to whatever data is associated with the key.

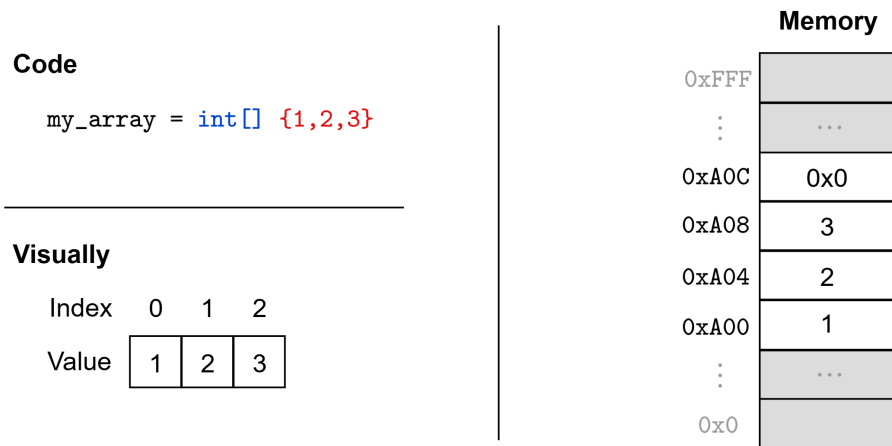


Figure 1.6: Here there are three sections breaking down how arrays look: In code, typical diagram depictions (Visually), and in memory. The code depiction illustrates a toy language creating an array of numbers ($[1, 2, 3]$). The visual depiction shows how indices relate to values. The memory depiction shows how the array is laid out in contiguous memory locations, where $0x0$ is the sentinel value (a bit-pattern of all zeros). In code, `my_array` holds the address `0xA00`.

Objects behave very similarly to arrays, but with a few key differences:

Definition 4.4: Objects in Memory

An **Object** (or **struct**), is a collection of key-value pairs, where each key is called a **field** or **attribute** and each value can be any data type (e.g., number, string, or address).

Attributes are stored in array like fashion, where each element is a fixed-offset from the head (start) of the object. The object itself is a pointer to the first element. Accessing attributes works differently in compiled (e.g., C) vs. interpreted (e.g., Python) languages:

- **Compiled Languages:** There is no lookup, as the compiler has *hardcoded* the offsets of each attribute interaction (e.g., 'object.attribute' is translated to a direct memory access).
- **Interpreted Languages:** The interpreter looks up a hash table lookup for the attribute name.

Depending on the use case, objects may be stored in the heap or stack:

- **Static Objects:** An objects whose size is known at compile time can be allocated on the stack. I.e., no changes to the object are made after creation (e.g., Math and Time objects, which purely exist to compute).
- **Dynamic Objects:** Often just called **objects**, are allocated on the heap, allowing for dynamic resizing and modification (e.g., a student object with attributes like 'name', 'age', and 'grades' that can change over time).

Languages like Java push this even further by allowing both static (shared) and dynamic (personal) fields within a class.

Definition 4.5: Object-oriented – Classes, Interfaces, & Polymorphism

Object-oriented programming is a paradigm where objects are the main building blocks of the program. A **class** is a blueprint for defining how an object will behave once **instantiated** (created). In this paradigm, functions are called **methods**, as they are defined and used within the class (i.e., globally does not exist in independence).

Some languages (e.g., Java, C++) support **interfaces** (or protocols), which specify a set of methods that implementing classes must provide. Although the terminology varies (abstract classes, traits, protocols, etc.), they all ultimately describe capabilities an object must fulfill.

Inheritance is the main motivation behind classes and interfaces, enabling a **child** (sub) class to reuse or extend the functionality of a **parent** (super) class. To further reduce redundancy, **Polymorphism** allows objects to **override** (redefine) methods of the same signature (variable name) to accept different types of data or behave differently based on their context.

Example 4.1: Java – Classes, Interfaces, Abstracts, Inheritance, & Polymorphism

Consider the following Java code:

```
public interface Animal { // Rough blueprint
    void eat(); void sleep(); void sound();
}

public abstract class Cat implements Animal { // Partial blueprint
    @Override
    public void eat() {
        System.out.println("Cat eats fish");
    }

    @Override
    public void sound() {
        System.out.println("Meow");
    }

    // Abstract method to demonstrate subclass-specific behavior
    public abstract void run();
}

public class Cheetah extends Cat { // Inheritance from parent Cat class
    @Override
    public void run() {
        System.out.println("Cheetah runs at 120 km/h");
    }

    @Override
    public void sound() {
        System.out.println("Chirp");
    }
}

public class Main {
    public static void main(String[] args) {
        // Polymorphism: reference is Animal, instance is Cheetah
        Animal anim = new Cheetah();
        anim.eat(); // calls Cat.eat()
        anim.sound(); // calls Cheetah.sound()
    }
}
```

Java polymorphism allows parent types to host children instances as seen with `Animal anim = new Cheetah();`, but `Cheetah chet = new Cheetah();` also works. This allows us to create arrays of different animal types:

E.g., `Animal[] zoo = {new Cheetah(), new Lion(), new Elephant()};`, assuming they all implement the `Animal` interface. ■

Strings are not what they seem:

Definition 4.6: Strings & Characters in Memory

A **character** is represented by a numeric code unit:

- In C, a single **char** (1 byte) typically holds an ASCII code (0–127). Characters beyond U+FFFF use two **char** values, a **surrogate pair**.
- In Java, **char** is a 16-bit UTF-16 code unit (U+0000..U+FFFF). ASCII values (0–127) map directly to the same Unicode code points. We can take advantage of the encoding:

```
1 char c = 'A';
2 System.out.println((int)c); // prints 65, since 'A' is U+0041
```

This allows us to do things like checking for valid characters:

```
1 if ((c >= 'a' && c <= 'z') || (c >= 'A' && c <= 'Z')) {
2     // c is in 'a'..'z' or 'A'..'Z'
3 }
```

We can also perform arithmetic on **char**:

```
1 char c = 'A'; // U+0041 (65)
2 char next = (char)(c + 1); // 'B' (66)
```

Typically, a **string** is stored as a contiguous array of **characters**. In low-level languages (e.g. C), that array ends with a null terminator (`\0`) and literal strings reside in the data segment. In higher-level languages (e.g. Java, Python), strings are full objects with methods. For e.g.,

C:

- String literals (e.g. "Hello") are placed in the (often read-only) data segment.
- Runtime-constructed strings (via `malloc`, `strcpy`, etc.) live on the heap.

Java:

- Compile-time literals are **interned** (stored as a single shared copy) into the **String Constant Pool** section (specially reserved on the heap).
- Any other **String** (e.g. via `new String(...)`, concatenation, or user input) also resides on the heap but outside the pool.
- Because Java strings are immutable, interning lets multiple references share the same character data.

With slight alterations to our code in Figure (1.5), we illustrate heaps and arrays:

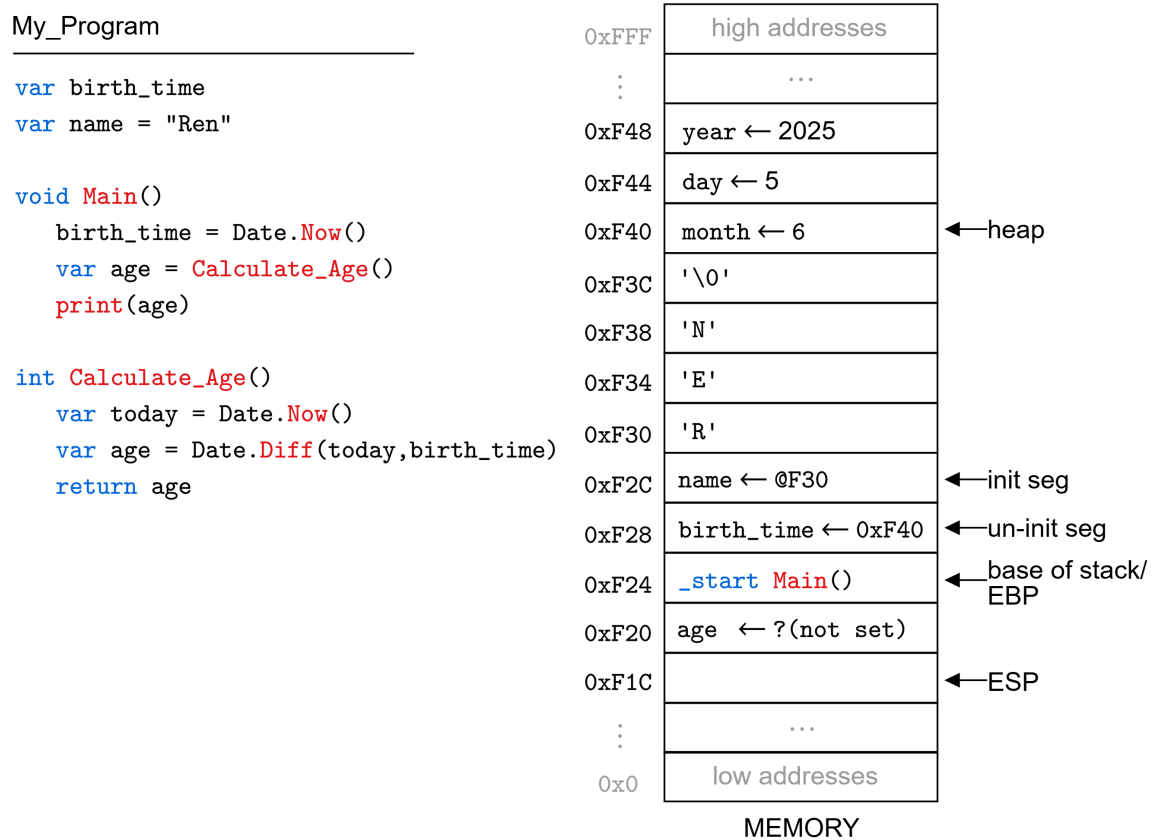


Figure 1.7: Here `birth_time` and `name` are global variables. Following the C convention, `birth_time` is placed in the uninitialized data segment, while `name` is placed in the initialized data segment. Since `name` is a string, it holds a reference to the first character in the string, which is stored contiguously in the initialized data segment ending with a null terminator (`'\0'`). During execution, `Date.Now()` a method call from a `Date` object is called; This method returns a new object, which is placed on the heap with its attributes (`month`, `day`, `year`) stored contiguously in memory. **Note:** Methods such as `Date.Diff()` are code (not data), which do not live in the heap or stack.

Definition 4.7: Factory Method

A **factory method** is a function that creates and returns an object, often initializing it with default values or parameters. In Figure (1.7), the method `Date.Now()` is a factory method that creates a new `Date` object with the current date and time.

The below illustration summarizes the heap and stack in memory:

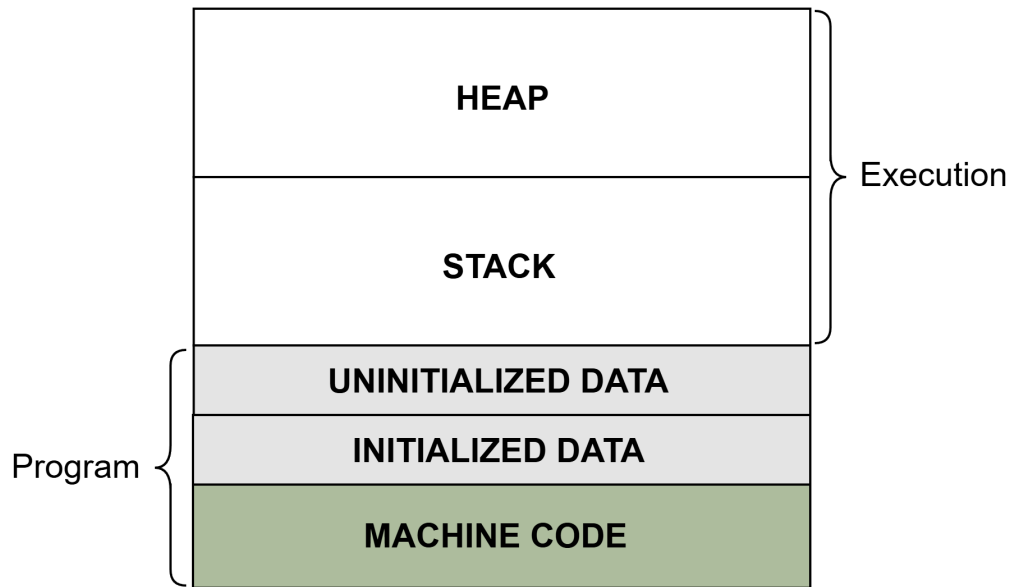


Figure 1.8: The above figure demonstrates the relationship from bottom-to-top the order at which data is loaded into memory. First the program compiles to machine code and loaded by the OS into memory. From there, provisions to the data segment (static memory: uninitialized and initialized) are made. Depending on the OS, some objects may have already been loaded into the heap, which are referenced by initialized data segment variables. Then as functions are called, the stack grows downwards within its allotted memory space. During execution of each stack frame, new objects may be placed on the heap, referenced by variables in the stack or data segment. Then depending on the language, a garbage collector periodically checks for objects with no references (i.e., no variables pointing to them) and deallocates them; Alternatively, the program explicitly deallocates memory using functions like ‘free’ in C.

1.5 Hashing & Collisions

In the previous section we lightly touched on the topic of hashing in Definition (4.2). This section will dive into more detail and difficulties collisions in hashing.

Definition 5.1: Collisions

A **collision** occurs when two different keys hash to the same index in a hash table. This is an unavoidable issue in hashing when keys begin to exceed the available indices.

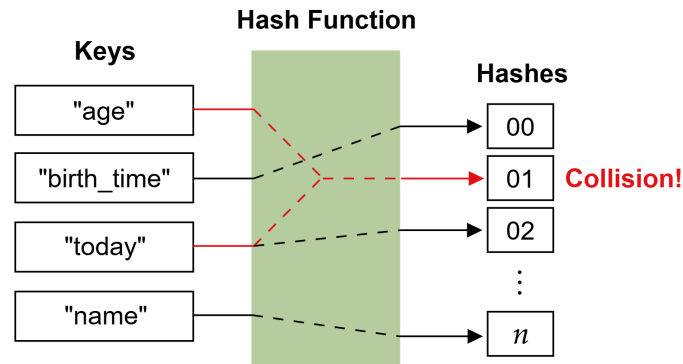


Figure 1.9: Four keys ('age', 'birth_time', 'today', 'name') go through a hash function to n possible indices. Keys, 'birth_time' and 'name', find a unique one-to-one mapping; However, 'age' and 'today' both hash to the same index, causing a collision.

Example 5.1: Simple Hashing Algorithm

Consider the hashing algorithm H , it takes the first ASCII value modulo the size of the table. Concretely, $H(k) := \text{ASCII}(k[0]) \% n$, where n is the size of the table.

Given the function H , we consider the following keys under a hash table of size 10:

- **Key:** 'apple' \rightarrow ASCII value = 97 $\rightarrow H(\text{apple}) = 97 \% 10 = 7$
- **Key:** 'banana' \rightarrow ASCII value = 98 $\rightarrow H(\text{banana}) = 98 \% 10 = 8$
- **Key:** 'bread' \rightarrow ASCII value = 98 $\rightarrow H(\text{bread}) = 98 \% 10 = 8$

Here, we see that 'banana' and 'bread' both hash to index 8, causing a collision. ■

One could have a superb hashing algorithm, but when space is tight, collisions are inevitable. We'll look at two particular methods for dealing with this issue.

Open Addressing

Our first method:

Definition 5.2: Open Addressing

Open addressing is a collision resolution method where, upon a collision, the algorithm searches for the next available slot via a probing sequence.

Wrap Around: the algorithm uses a modulo operation (e.g., Given a table size of 10 and request for index 12, the algorithm would use $12 \% 10 = 2$).

Time Complexity: $O(n)$, where n is the number of elements in the hash table. For example, say the only free index is at 0 with all other indices occupied. If we hash to index 1, the algorithm will have to walk all n indices to find the free index at 0. Changing the probe method only switches order of indices checked, not the worst case.

Space Complexity: $O(n)$, where n is the size of the hash table (no additional space).

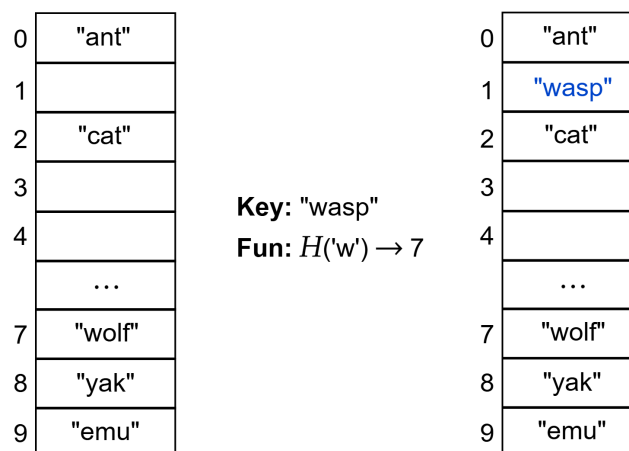


Figure 1.10: On the left is an existing hash table of 10 elements filled with various keys. The middle shows the insertion of a new key, 'wasp', which the function H hashes to index 7; However, index 7 already occupied. The algorithm walks through the table, wrapping around to the beginning, finding a free index at 1. The right shows the final state of the hash table with 'wasp' inserted at index 1.

Definition 5.3: Linear Probing

Linear Probing in open addressing refers to sequentially checking each index for an available slot (e.g., Figure 1.10).

Definition 5.4: Quadratic Probing

Given a universal hashing function $H(x)$, a **quadratic probing** resolves collisions by defining,

$$h(x, k) := (H(x) + k^2) \% n$$

Where k defines the number of collisions, and n hash table size. The algorithm may **never discover** particular cells due to its even probing style. We **terminate execution** once n indices have been checked, avoiding an infinite loop.

So why even use quadratic probing?

Definition 5.5: Clustering

Clustering is a phenomenon in open addressing where multiple keys form contiguous *runs* of occupied indices. This degrades linear probing performance; Such is the main motivation behind quadratic probing.

0	"ant"	Key: "wasp" Fun: $H('w') \rightarrow 4$
1		1.) $(4 + 0^2) \% 8 = 4$ (COLLISION)
2	"cat"	2.) $(4 + 1^2) \% 8 = 5$ (COLLISION)
3		3.) $(4 + 2^2) \% 8 = 0$ (COLLISION)
4	"wolf"	4.) $(4 + 3^2) \% 8 = 5$ (COLLISION)
5	"yak"	5.) $(4 + 4^2) \% 8 = 4$ (COLLISION)
6		6.) $(4 + 5^2) \% 8 = 5$ (COLLISION)
7		7.) $(4 + 6^2) \% 8 = 0$ (COLLISION)
8	"emu"	8.) $(4 + 7^2) \% 8 = 5$ (COLLISION)

Figure 1.11: On the left is an existing hash table of 8 elements. We attempt to insert a new key, 'wasp', which hashes to index 4; Though, 4 is occupied. The algorithm continues with $(4 + 1^2) \% 8 = 5$, which is also occupied. After some probing, it appears only indices 4, 5, 0 are appearing, from which are all occupied. The algorithm terminates at its n -th attempt with $(4 + 7^2) \% 8 = 5$. No spaces were found. One could imagine that if the table were larger or 0, 4, 5 were free, the algorithm would have had better success.

Definition 5.6: Double Hashing

Double hashing resolves collisions by using two hash functions; Given, $H_1(x)$ and $H_2(x)$ uniform hashing functions, we define the probe sequence $h(x, k)$ as:

$$h(x, k) := (H_1(x) + k \cdot H_2(x)) \% n,$$

Where k is the collision count, and n is the hash table size. $H_2(x)$ is chosen such that:

- The hash satisfies $0 < H_2(x) < n$ (i.e., The result is likely taken by modulo n).
- It is pair-wise independent from $H_1(x)$ (i.e., not a transformation of/related to $H_1(x)$).
- Computationally inexpensive to evaluate.
- All outputs of $H_2(x)$ are relatively prime to n (does not share any common factors other than 1), ensuring all entries are probed.

We elaborate on the need for relatively prime numbers:

Theorem 5.1: Probing Period

A **period** defines the number of unique elements before the sequence begins to repeat. This cycle length is defined as the ratio:

$$\frac{n}{\gcd(n, H_2(x))}$$

Where n is the hash table size, and $H_2(x)$ is each hash output on an arbitrary x input. We ideally want $\gcd(n, H_2(x)) = 1$ for each x to achieve a full period of n . Hence, if n is a power of 2, $H_2(x)$ may uniformly provide odd numbers; Otherwise, for that particular key, it will only partially probe the table.

Without too much number theory, we attempt to intuitively understand the theorem:

Proof 5.1: Length of Probing Period

In terms of modulo, n defines a cycle of n elements, $0, 1, \dots, n-1$; Each element is called a **residue class** (i.e., all possible remainders). E.g., 8 has residue classes 0–7. Given a finite set of integers \mathcal{H} (i.e., our hash function), all \mathcal{H}_i need be co-prime to n to exhaust all residue classes. We exclude all $\mathcal{H}_i \geq n$, as n 's cycle is definitively over (also by Definition 5.6). E.g., $1 \% 8 = 1$, $9 \% 8 = 1$. We pick a fixed-hash $h := \mathcal{H}_i$ such that $\gcd(n, h) = d > 1$. Recall that we calculate $(k \cdot h) \% n$ for each k collision. Hence if h and n factors intersect at d , then the $k = n/d_{th}$ collision will produce a multiple of n , terminating prematurely at 0. ■

Let's try an example to see how this works:

Example 5.2: Double Hashing without co-primes

Consider a $H_1(x)$ function which always causes collisions, forcing the use the $H_2(x)$ function:

$$H_1(x) := x^0 \quad H_2(x) := x^2 \% (n - 1)$$

Giving us the full function:

$$h(x, k) := (x^0 + k \cdot (x^2 \% (n - 1))) \% n$$

Observe when $n = 12$, with key $x = 3$, while increasing k collisions:

$k \cdot (3^2 \% 11) \% 12$	$h(x, k)$
$0 \cdot 9 \% 12$	0
$1 \cdot 9 \% 12$	9
$2 \cdot 9 \% 12$	6
$3 \cdot 9 \% 12$	3
$4 \cdot 9 \% 12$	0
$5 \cdot 9 \% 12$	9
$6 \cdot 9 \% 12$	6
$7 \cdot 9 \% 12$	3
$8 \cdot 9 \% 12$	0
$9 \cdot 9 \% 12$	9
$10 \cdot 9 \% 12$	6

Since $\gcd(12, 9) = 3$, the probing period is $12/3 = 4$, only touching indices $\{0, 3, 9, 6\}$. ■

Searching: Insertion & Deletion

Things become trickier with a populated hash table with previous deletions:

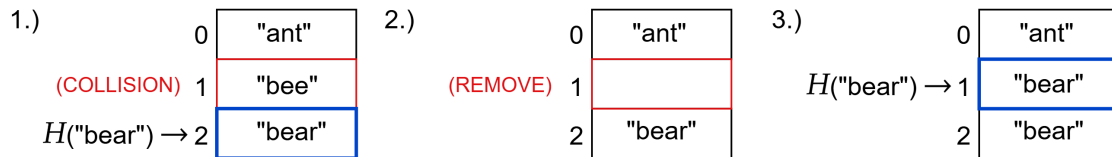


Figure 1.12: Demonstrates complications when inserting into a table blindly. 3.) naively inserts “bear” at index 1 despite it already existing in the table. This is caused by a previous collision (1) and removal of the collider (2).

Theorem 5.2: Safe Insertion

To safely insert a key into a hash table, we create three distinctions for each cell:

- **Empty:** The index is empty, and a key can be inserted.
- **Occupied:** The index is occupied (blocked) by another key.
- **Deleted:** This index was previously occupied but free.

We may proceed as normal for events Empty and Occupied, but Deleted requires special handling; First, take note of the first **deleted index** then probe the table:

- **Empty:** If an empty index is found, insert at the first deleted index.
- **Occupied/Deleted:** Continue probing.
- **Duplicate** If the same key is found, insert any data, otherwise terminate.

Insertion at the first deleted index is safe, as if the key already existed in the table, it would have been inserted at any found empty index.

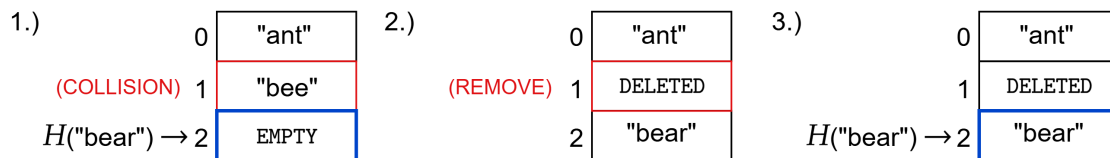


Figure 1.13: Revisiting Figure 1.12 at (3) we continue to probe after finding a deleted index. This leads us to find the already inserted key, “bear”, at index 2.

Separate Chaining & Linked Lists

A problem we have with open addressing is that it requires a lot of array space; If we run out of space, we have to resize the table, which is costly:

Theorem 5.3: Resizing a Hash Table

Resizing a hash table requires rehashing all keys, which is $O(n)$, where n is the number of elements in the table, excluding the computation cost of hashing each key again.

This brings us to the motivation for our second method of collision resolution:

Definition 5.7: Separate Chaining

Separate chaining is a collision resolution method where each index contains a **bucket**, which contains all keys that hash to such index. This saves contiguous memory space, as the array can stay a fixed size while holding object references living in the heap.

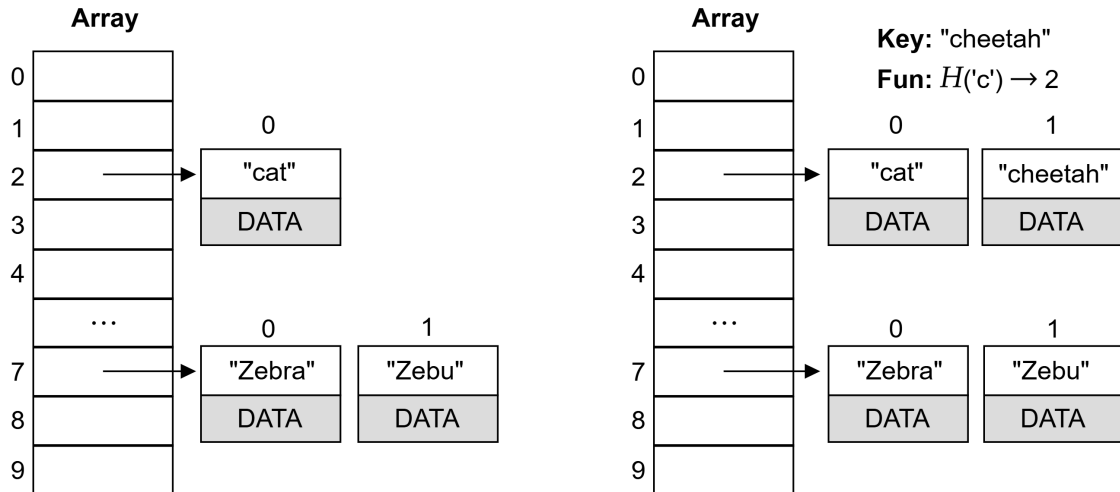


Figure 1.14: The left an array which points to another array (the bucket). The right shows the insertion of “cheetah” into the table, indexing at 2, adding to the end of the bucket. Here it’s unclear how the data for each element is stored (perhaps a nested array). Additionally, the **same problem** of resizing occurs, as if a bucket is another array, we still have to resize it (there is no need to rehash the keys in buckets).

Definition 5.8: Resizing an Array

Many languages provide a method for resizing an array; However, this is costly as perhaps the next contiguous memory cell for the array is not available in memory. Hence, a new memory region is found and all elements are copied to a new array of larger size, typically $O(n)$, where n is the number of elements in the array.

Tip: In languages like Java or GO, resizing an array (ArrayList or Slice) is done by creating a new array of double the size and copying all elements over.

We introduce a new data structure to solve this problem:

Definition 5.9: Linked List

A **linked list** is a data structure consisting of single objects called **nodes**. Nodes are *linked* together via a reference to the next node in the list. This means there are no indices, and the next node can live anywhere in memory. The first element is called the **head**, and the last element is called the **tail**.

Each node at the very least contains a **value** and a **next** pointer to the next node in the list. Since a node is an object, an indefinite number of fields can be added to its class definition.

Definition 5.10: Common Types of Linked Lists

- **Singly Linked List:** Each node contains a reference to the next node.
- **Doubly Linked List:** Each node contains a reference to both the next and previous nodes.
- **Circular Linked List:** The last node points back to the first node, creating a cycle.

Time Complexity: Search is $O(n)$, as we may need to traverse the entire list.

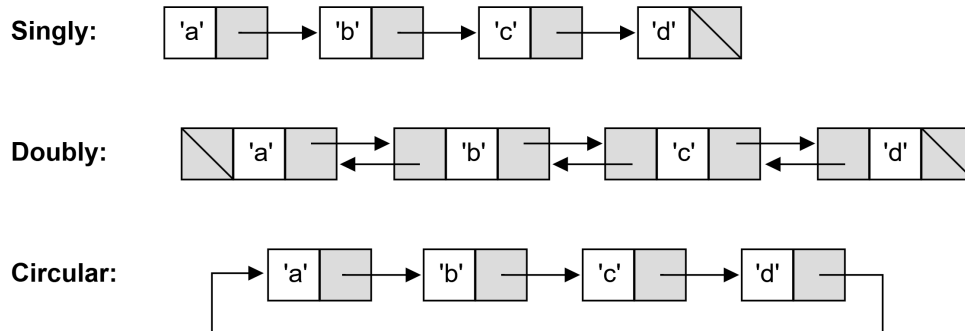


Figure 1.15: A visual representation of a singly, doubly, and circular linked lists.

Theorem 5.4: Open Addressing vs. Separate Chaining

If updates to the table are **rare** (rehashing on resize), choose open addressing. If updates are **frequent**, consider separate chaining.

It's worth noting that, separate chaining with linked lists requires **more memory** overhead for each node object.

We revisit Figure 1.14 with a linked list implementation:

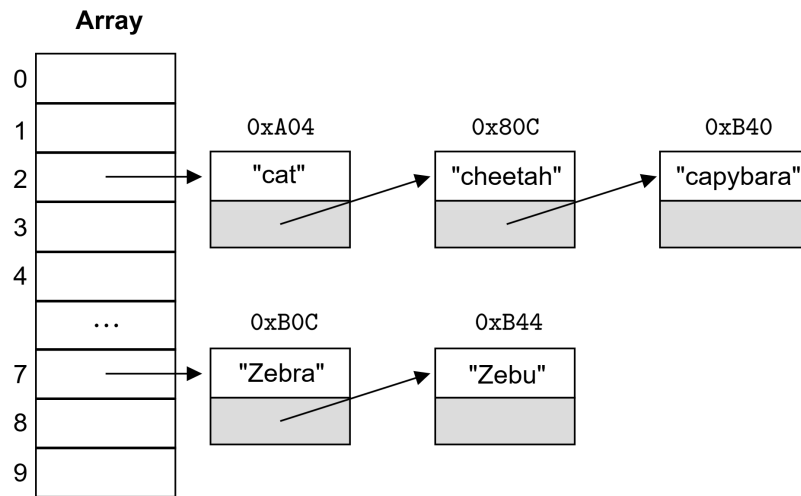


Figure 1.16: Here we see an array with two buckets, each bucket is a linked list. Each node points to the next node in the list. In particular, each node lives in at an ambiguous memory location.

Definition 5.11: Insertion & Deletion in Linked Lists

Inserting or deleting relies on shifting pointers around. To make sure references aren't lost to the linked list, we always point to a **dummy head** node, which holds no data and always points to the first actual node.

Say we have two nodes, A and B sequentially in a singly linked list referenced by `my_llist` (points to dummy head). It has one dot operator, `my_llist.next` (the next node in the list).

- **Inserting:** We attempt to add a new node C ,
 - **At the head:** Set `my_llist.next = C` and `C.next = A`, $O(1)$.
 - **At the tail:** Traverse the list until via `my_llist.next` until a null `.next` is found, set the previous node's `.next` to C and `C.next = null`, $O(n)$.
 - **In the middle:** Traverse the list until node A is found, set `C.next = A.next`, then `A.next = C.next`, $O(n)$.
- **Deleting:** Now we have three sequential nodes, A , B , and C .
 - **The head:** Set `my_llist.next = A.next`, discards references to A , $O(1)$.
 - **The tail:** Traverse and set `B.next = null`, $O(n)$ (discards C).
 - **In the middle:** Traverse and set `A.next = B.next`, $O(n)$ (discards B).

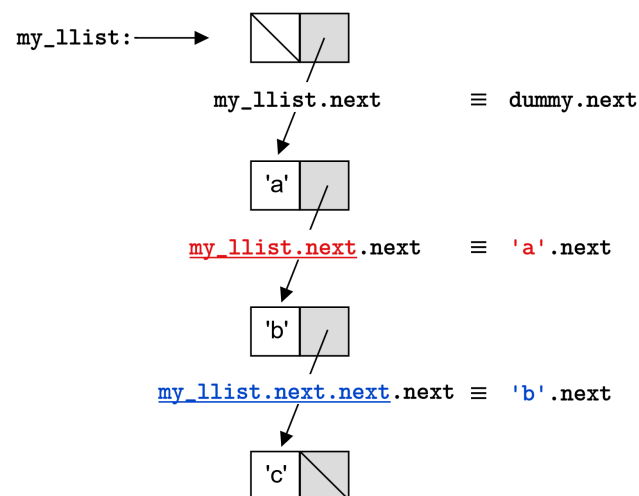
Visualizations on the next page.

Example 5.3: Insertion & Deletion in Linked Lists – Corollary

If we know the position of the node to be inserted or deleted, we can directly access it via a pointer. Revisiting Definition 5.11, we can insert or delete in constant time $O(1)$, instead of traversing the list. To demonstrate deletion, we have three sequential nodes, A , B , and C :

- **The head:** Set `my_llist.next = my_llist.next.next`, discards references to A .
- **The tail:** Set `my_llist.next.next.next = null`, discards C .
- **In the middle:** Set `my_llist.next.next = my_llist.next.next.next`, discards B .

This is a bit hard to read, we visualize it as follows:



In other words, `my_llist` is the dummy head node, `my_llist.next` returns the dummy node's `next` pointer (an address). If we *act* on such address, we access the address's fields. Hence, `my_llist.next.next ≡ A.next`. Again, `A.next ≡ B` (the address). So,

$$\begin{aligned}
 \text{my_llist.next.next.next} &\equiv A.\text{next.next} \\
 &\equiv B.\text{next} \\
 &\equiv C \quad (\text{the address})
 \end{aligned}$$

Still, it's not advisable to code like this, primarily because of readability. ■

Load Factor & Performance Metrics

We want to be pre-emptive at avoiding collisions and resizing the table. The following measurement tracks this:

Definition 5.12: Load Factor

The **load factor** α of a hash table is defined as the ratio of the number of elements n to the size of the table m :

$$\alpha := \frac{n}{m}$$

- **Open Addressing:** $\alpha < 0.5$.
- **Separate Chaining:** $\alpha < 1$.

Once α exceeds the optimal threshold, we should **consider resizing** the table. Upon good load conditions, we generally expect $\Theta(1)$ and $\Theta(1 + \alpha)$ time complexity for insertion and deletion, respectively with open addressing and separate chaining.

Method	Insertion	Deletion
Open Addressing	$\Theta(1)$ average, $O(n)$ worst	$\Theta(1)$ average, $O(n)$ worst
Separate Chaining	$\Theta(1 + \alpha)$ average, $O(n)$ worst	$\Theta(1 + \alpha)$ average, $O(n)$ worst

Table 1.3: Time-complexity comparison of insertion and deletion in open addressing vs. separate chaining (where α is the load factor).

Operation	Dynamic Array	Singly Linked List
Insert at head	$O(n)$ (shift all elements)	$O(1)$
Insert at tail	$O(1)$	$O(n)$
Insert in middle	$O(n)$	$O(n)$
Delete at head	$O(n)$	$O(1)$
Delete at tail	$O(1)$	$O(n)$
Delete in middle	$O(n)$	$O(n)$
Search for element	$O(n)$	$O(n)$
Random access	$O(1)$	$O(n)$ (traversal)

Table 1.4: Inserting or deleting elements in dynamic arrays (growing) versus singly linked lists. In particular, maintaining order within a dynamic array forces shifting of elements upon insertion or deletion.

Bibliography