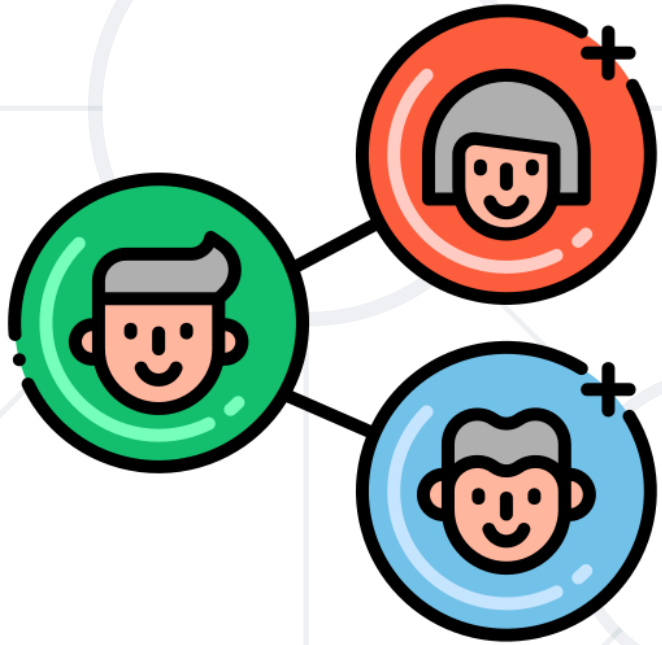
Computer Memory, Pointers and References

References, Computer Memory, Pointers, Pointer Arithmetic



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References

Creation, Usages, Limitations

References

- Identifiers assigned to the same memory as other identifiers
  - **Type& name**
  - Sometimes called "pseudonyms"

```
int original = 42;
int& reference = original;
original++; // original == 43; reference == 43
reference++; // original == 44; reference == 44
```

- Assigned on declaration with a **variable** of the **same type**

```
int& reference; // compilation error
int original = 42;
double& reference = original; // compilation error
```

Common Reference Usages

- Re-assigning caller variables

```
void swap(int& a, int& b) {
  int oldA = a;
  a = b;
  b = oldA;
}
```

```
int main() {
  int x = 13, y = 42;
  swap(x, y); // x == 42, y == 13
  return 0;
}
```

- Providing additional "return" values

```
int minValue(vector<int> numbers, int& foundAtIndex) {
  foundAtIndex = 0;
  for (int i = 1; i < numbers.size(); i++) {
    if (numbers[foundAtIndex] > numbers[i]) {
      foundAtIndex = i;
    }
  }
  return numbers[foundAtIndex]; // the second parameter now contains the min index
}
```

Common Reference Usages

- Modifying caller's objects
  - Changing the object's fields (not re-assigning it)

```
void removeNegative(std::list<int>& numbers) {
  auto i = numbers.begin();
  while (i != numbers.end()) {
    if (*i < 0) {
      i = numbers.erase(i);
    }
    else i++;
  }
}
```

```
list<int> values { 1, -69, -4, 42, -2, 13, -9 };

removeNegative(values); // values { 1, 42, 13 }
```

const References

- const references can only be read, not written
  - const Type& name

```
int original = 42;
const int& reference = original;
original++; // original == 43; reference == 43
reference++; // compilation error
```

- Used to improve performance for object parameters:
  - Using a reference avoids copying the entire object
  - Using const prevents function from modifying the original

const Reference Parameters – Example

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- Using reference prevents copying the vector

```
void printZeroIndices(const std::vector<int>& numbers) {
  for (int i = 0; i < numbers.size(); i++) {
    if (numbers[i] == 0) {
      std::cout << i << " ";
    }
  }
}
```

- Marking it const prevents accidental editing

```
void printZeroIndices(const std::vector<int>& numbers) {
  ...
  if (numbers[i] = 0) { // accidental "=" gives
compilation error
  ...
}
```

Reference Limitations

- If original variable goes out of scope, reference is undefined
- Can't change to reference other variable
- Initialized on creation – in class, must be set in initializer list

References

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Quick Quiz

- What will the following code do?

```
vector<int>& generateRoots(int toNumber) {
  std::vector<int> roots;
  for (int i = 0; i < toNumber; i++) {
    roots.push_back(sqrt(i));
  }
  return roots;
}
```

```
int main() {
  cout << generateRoots(100)[4] << endl;
}
```

a) cause a compile-time error

b) cause a runtime error due to index being out of bounds

c) summon demons

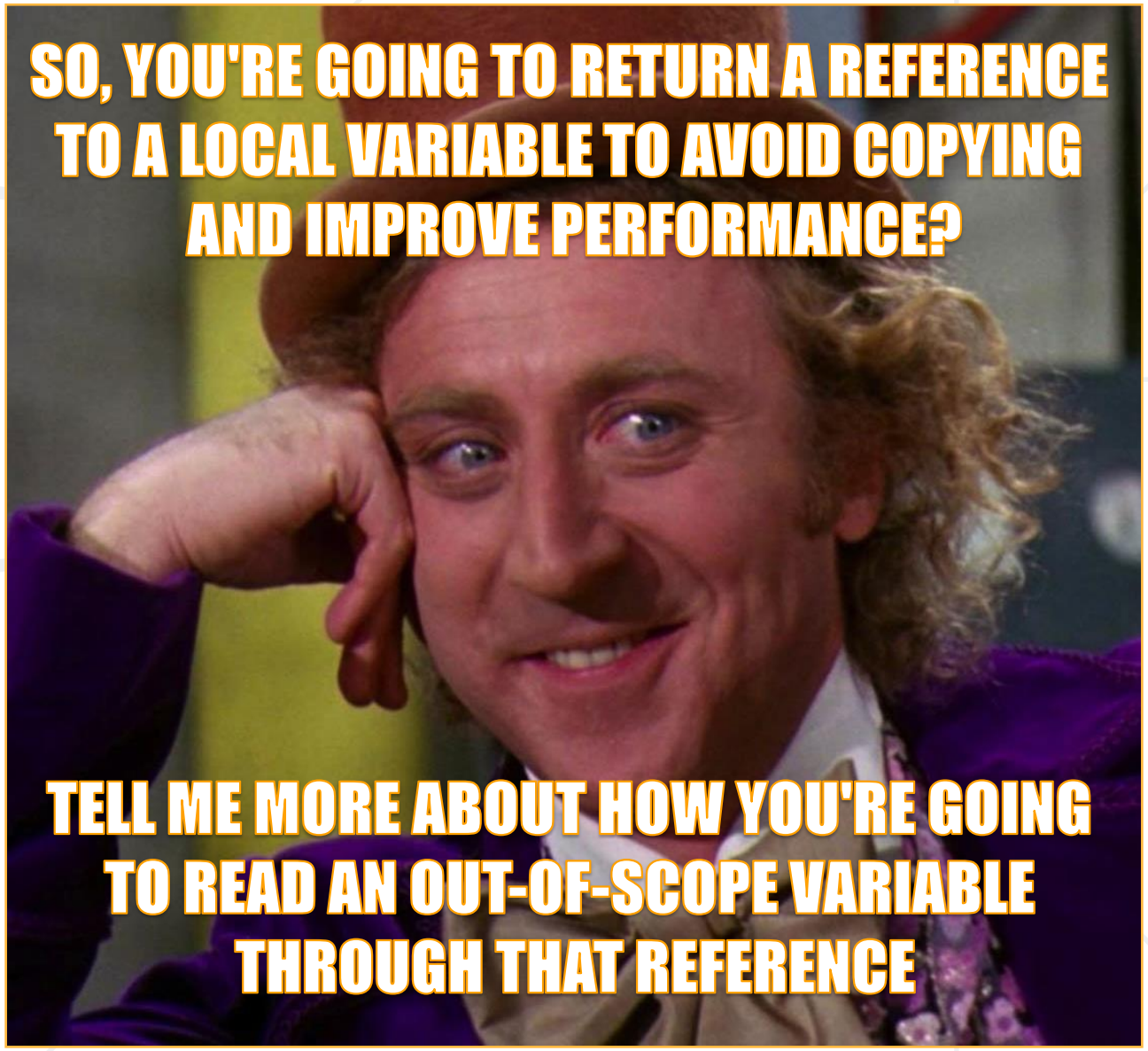
d) behavior is undefined

C++ PITFALL: REFERENCES TO VARIABLES THAT WERE FREED FROM MEMORY

If a variable goes out of scope, its memory is returned to the system.

References to it are invalidated.

Hence, we can't use a reference to a function's local variable outside the function.



Computer Memory

Memory Structure, Variables in Memory

What Do We Call Memory?

- In computer science, memory usually is:
  - A continuous, numbered (addressed) sequence of bytes
  - Storage for variables and functions created in programs
  - Random-access – equally fast accessing any byte
  - Addresses numbered in hexadecimal, prefixed with `0x`

Address	0x0	0x1	0x2	…	0x6afe4c	…
Byte	00001101	00101010	01000101	…	00000011	…

Memory Usage by Variables

- A primitive data type takes up a sequence of bytes
  - `char` is 1 byte, 1 address – often used for reading byte by byte

```
char alpha = 'A'; // let's assume alpha is at address 0x6afe4c
```

Address	…	0x6afe4b	0x6afe4c	…	…	…	…
Byte	…	…	01000001	…	…	…	…

  - Other types & arrays use consecutive bytes, e.g. 4-byte `int`:

```
int year = 2018; // let's assume year is at address 0x6afe4c
```

Address	…	0x6afe4b	0x6afe4c	0x6afe4d	0x6afe4e	0x6afe4f	…
Byte	…	…	11100010	00000111	00000000	00000000	…

Getting Addresses of Variables

- Prefix **operator&** returns a variable's address
  - Functions also have addresses – location in the memory

```
void f() {}

int main() {
  int x = 42;
  auto addressX = &x;
  cout << x << " at " << addressX << endl;
  cout << "f()" << " code at " << &f << endl;
  return 0;
}
```

Array Address Values

- C++ Array – a Type, a start address and a length
  - Index **i** is at address: **start** + **i** * sizeof(Type)

We can store an address in `size_t position`

```
int arr[] = { 2018, 310 }; // assume &arr[0] == 0x6afe4c
```

Address	…	0x6afe4b	0x6afe4c…0x6afe4f				0x6afe50…0x6afe53				0x6afe554
Byte	…	…	11100010	00000111	00000000	00000000	00110110	00000001	00000000	00000000	…
Value	…	…	2018				310				…

  - array, it's address, and first element address are the same

```
cout << arr << " " << &arr << " " << &arr[0]; // 006AFE4C 006AFE4C 006AFE4C
cout << &arr[1]; // 006AFE50
```

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Pointers

Using and Representing Memory Addresses

Pointers

- A Memory-Address Type – store and can access a memory address
  - `Type* name`
  - `Type` – the type of value the pointer "points to„

```
char a = 'A';
char* addressA = &a;
```

```
int x = 42;
int* addressX = &x;
```

  - A pointer to memory is what an index is to an array

Referencing and Dereferencing

- **Referencing** – setting what a pointer points to

```
int a = 42, b = 13; // let's assume &b == 0x69fef4
int* ptr = &a; // points to a
ptr = &b; // points to b
```

- **Dereferencing** – **operator*** – accesses memory, not a pointer

```
int a = 42; int* ptr = &a;
*ptr = 7 // a is now 7
cout << *ptr; // prints 7
```

- **operator->** – access member of pointed object

```
string s = "world"; string* ptr = &s;
ptr->insert(0, "hello "); // makes s == "hello world"
```

Pointers

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Quick Quiz

- What will the following code print?

```
int number = 42;
int* ptr = &number;
*ptr++;
std::cout << *ptr << std::endl;
```

a) 43

b) 42

c) there will be a runtime error

d) behavior is undefined`

C++ PITFALL: INCREMENTING POINTER INSTEAD OF POINTED OBJECT

`operator++` has higher precedence, and is applied to the pointer, then the dereference operator executes on the old pointer value.

On the next dereference, we could get an error, or a "random" value – undefined behavior

Use brackets to apply **`operator++`** over the pointed memory: **`(*number)++`**

The NULL Pointer

- Special pointer value of `0`, `NULL` or `nullptr`
  - Indicates a lack of value
  - `nullptr` requires C++11 or greater, otherwise the code won't compile

The NULL Pointer

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```
int* findFirstNegativePtr(int numbers[], int length) {
  for (int i = 0; i < length; i++) {
    if (numbers[i] < 0) {
      return &numbers[i];
    }
  }
  return nullptr;
}
```

"find" functions returning `nullptr` when no result found

```
int* negativePtr = findFirstNegativePtr(numbers, 4);
if (negativePtr != nullptr) {
  cout << *negativePtr;
}
else cout << "no negative numbers" << endl;
```

Pointers and const

Constant Pointers and Constant Data

Pointers and const

- Two things can change for a pointer
  - Where it is pointing at
  - The data of the address

Pointer	Memory editable?	Address editable?
`Type * ptr`	YES	YES
`const Type * ptr`	NO	YES
`Type * const ptr`	YES	NO
`const Type * const ptr`	NO	NO

- *What do the last 2 in the table match logically?*

Pointers to const Data

- Used similarly to `const` references
  - Pointer usage avoids object copy – only the address is copied
  - `const` on the `Type` prevents changing the pointed data

```
void printZeroIndices(const std::vector<int>* numbers) {
  for (int i = 0; i < numbers->size(); i++) {
    if (numbers->at(i) == 0) { std::cout << i << " "; }
  }
}

int main() {
vector<int> numbers{ 1, 0, -2, 7, 0, 10, -100, 42 };
printZeroIndices(&numbers);
return 0;
}
```

Pointers and const

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Pointer Arithmetic and Arrays

Type-Defined Pointer Calculations

Pointer Type Significance

- Pointer operations are based on their **Type**
  - Reading accesses exactly **sizeof(Type)** bytes
  - Writing sets exactly **sizeof(Type)** bytes

```
int year = 2018; // let's assume year is at address 0x6afe4c
int* intPtr = &year;
char* charPtr = (char*)&year;
```

Address	...	0x6afe4b	0x6afe4c	0x6afe4d	0x6afe4e	0x6afe4f	...
Byte	...	...	11100010	00000111	00000000	00000000	...

Pointer Arithmetic with Integers

- Typed pointers support integer addition/subtraction
- For a `Type* pointer` with address `x`
  - `pointer + value` calculates `x + sizeof(Type) * value`
  - `pointer - value` calculates `x - sizeof(Type) * value`

```
int number = 42; // assume &number == 0x6afe4c
int * intPtr = &number; char * charPtr = (char*)&number;

// NOTE: casting the char* to int* to avoid printing as a string
cout << intPtr << " " << (int*)charPtr << endl; // 0x6afe4c 0x6afe4c
intPtr++; charPtr++;
cout << intPtr << " " << (int*)charPtr << endl; // 0x6afe50 0x6afe4d
```

Pointers as Arrays

- Array `operator[]` is actually defined with pointer arithmetic
- `arr[i]` compiles to `*(arr + i)`

```
int arr[3]{ 13, 42, 69 };
int* p = arr;
p[1] = -42;
cout << arr[1]; // -42
cout << *(p + 1); // -42
cout << p[1]; // -42
```

- Array parameters in functions "degenerate" into pointers
  - `void f(int arr[], int length)` is the same as `void f(int* arr, int length)`

Pointer Arithmetic and Arrays

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Quick Quiz

- What will the following code print?

```
int arr[3] = { 13, 42, 69 };
cout << 1[arr] << endl;
```

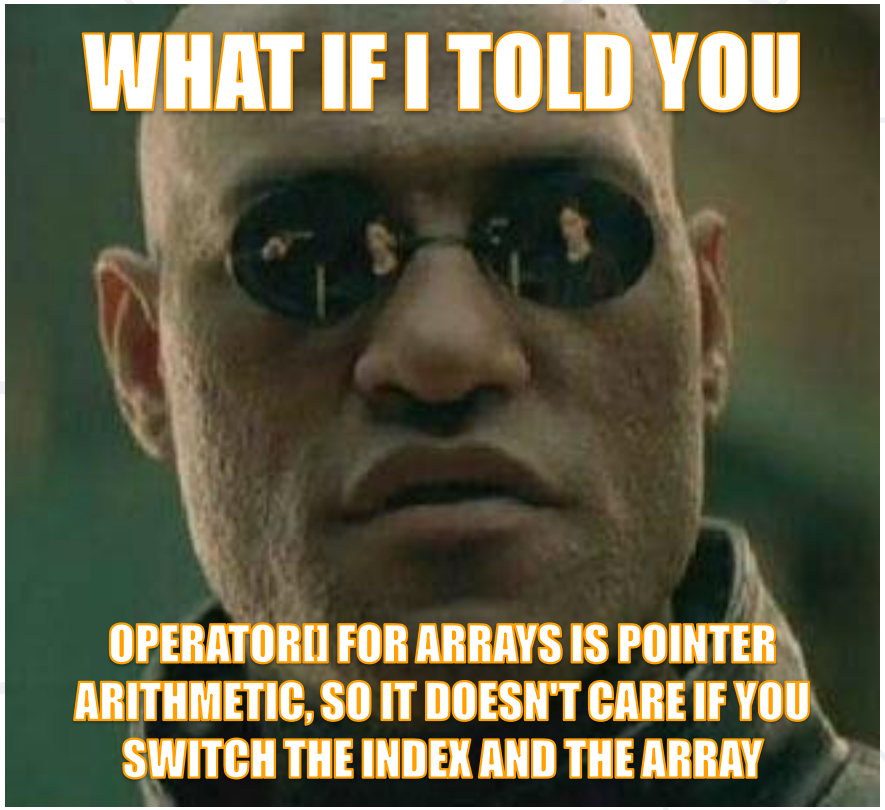
a) 42

b) there will be a compilation error

c) there will be a runtime error

d) behavior is undefined

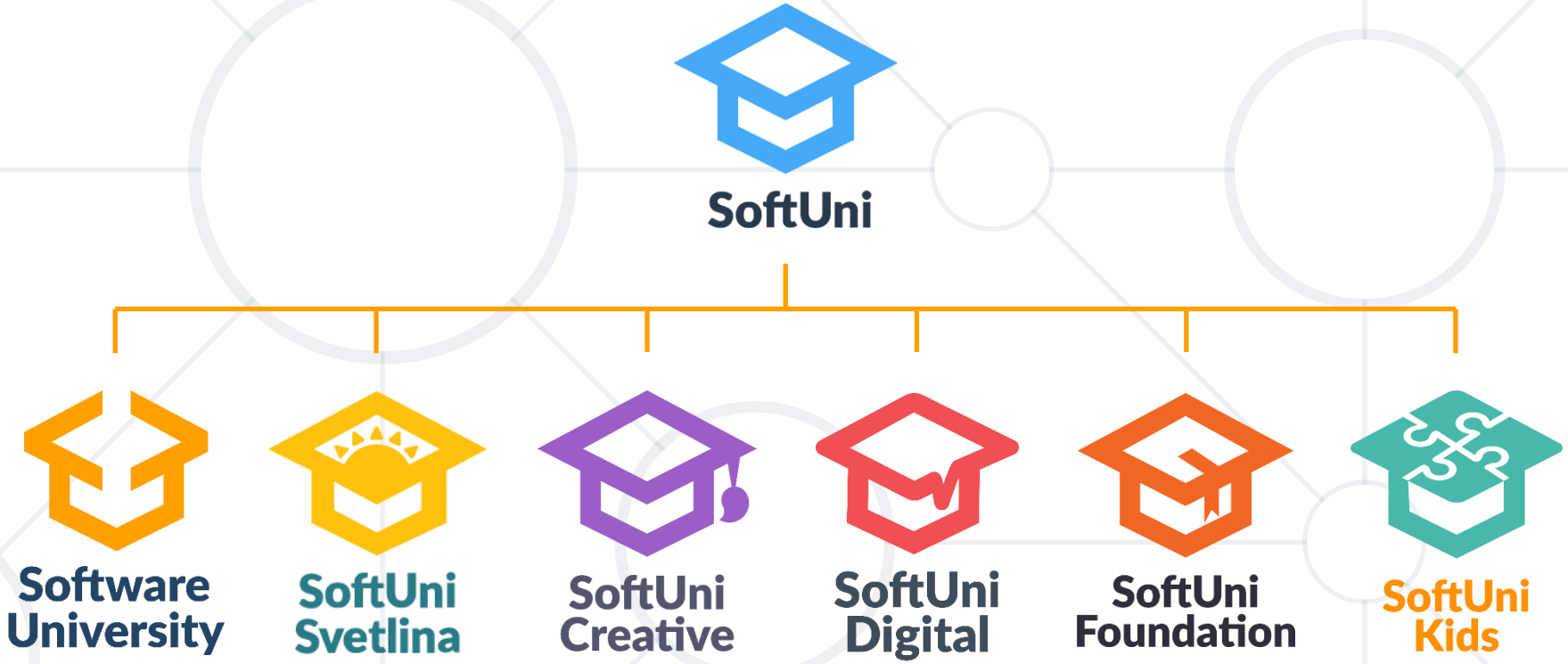
Array `operator[]` is just pointer arithmetic. `*(a + b)` is the same as `*(b + a)`, so `operator[]` works even if you switch the index and array.



Summary

- **References** allow setting new identifiers for existing variables
- **Computer memory** is essentially an **array** of **bytes**
- Variables occupy consecutive bytes of memory
- **Pointers** are to memory what indices are to arrays
  - Used to read/write memory
  - Can change to point to other memory
- Pointer arithmetic allows pointers to work like arrays

Questions?



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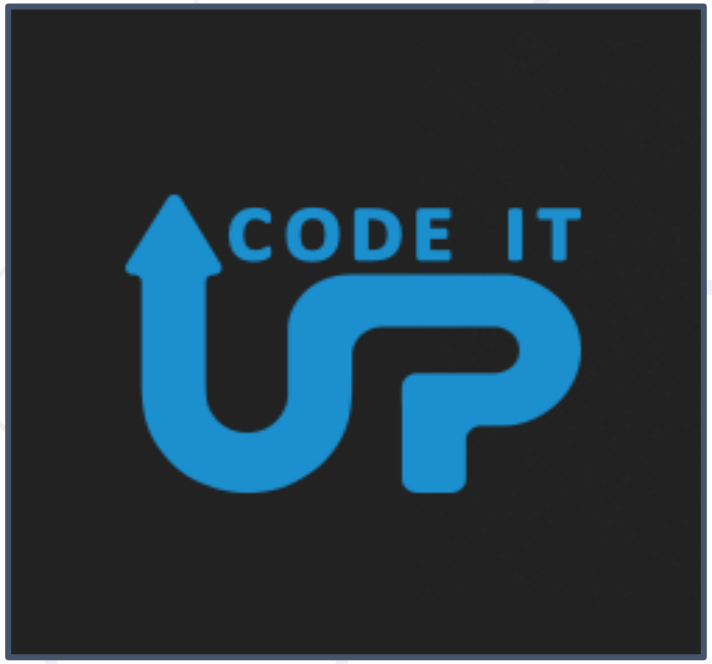

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