Programming paradigms

Based on Stanford CS107 Programming paradigms

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I dedicate these notes to Helena, my newborn daughter

Memory fundamentals

Recap on bits and bytes

A Bit is a contraction of the word *binary unit* and is a fundamental unit of information, it is binary in the sense that every bit represents two possible states (e.g 1 or 0)

- It is commonly used in digital systems because electronic circuits can easily distinguish between two states (on/off, high/low voltage)

- 1 bit can represent $2^1 = 2$ values e.g {0,1}
- 2 bits can represent $2^2 = 4$ values e.g {00, 01, 10, 11} or {0, 1, 2, 3}
- n bits can represent 2^n values e.g {$000\ldots0_n$, $100\ldots0_n$, …, $111\ldots1_n$} or $[0, 2^n[$

- The binary number system is also a positional number system, just like decimal, therefore:

  $101_{binary} = 0b101 = 1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 = 5 = 5 \cdot 10^0 = 0d5$

  $123_{decimal} = 0d123 =$

  $1 \cdot 10^2 + 2 \cdot 10^1 + 3 \cdot 10^0 =$

  $0 \cdot 2^7 + 1 \cdot 2^6 + 1 \cdot 2^5 + \ldots + 1 \cdot 2^3 + 0 \cdot 2^2 + 1 \cdot 2^1 + 1 \cdot 2^0 =$

  $0b01111011$

  => $(1, 2, 3)_{10} = (0, 1, 1, 1, 1, 0, 1, 1)_2$

- 1 byte is equal to 8 bits

Recap on memory addresses

- A 32 bit flat-memory model architecture is said to have 2^{32} distinct memory addresses, usually each can hold 1 byte of information → up to 2^{32} bytes of memory available
- A 64 bit architecture → up to 2^{64} bytes of memory available

- The addresses are usually shown in hexadecimal (i.e. 0x00000000 to 0xFFFFFFFF)

0x7FFE4A71	1010 0001
0x7FFE4A72	1101 1010
0x7FFE4A73	0101 0100
0x7FFE4A74	1001 1000
0x7FFE4A75	1010 0101
0x7FFE4A76	0101 0101
0x7FFE4A77	1110 0111

Further reading: https://elec2645.github.io/104/pointers.html

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Meaning of a "word"

Word Size

- **1 Byte (8 bits)**: A word could be as small as 1 byte on some early computers and microcontrollers. However, this is less common in modern computing.
- **2 Bytes (16 bits)**: Some older and embedded systems might use 16-bit words. This was common in 16-bit architectures.
- **4 Bytes (32 bits)**: On 32-bit architectures, a word is typically 4 bytes (32 bits).
- **8 Bytes (64 bits)**: On 64-bit architectures, a word is usually 8 bytes (64 bits).

General Usage

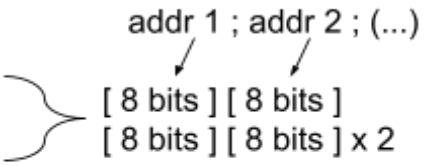
- **Word**: Generally refers to the natural data unit used by a particular processor design. This is typically 4 bytes (32 bits) on 32-bit systems and 8 bytes (64 bits) on 64-bit systems.

- **Half-Word**: Often refers to half the size of the word. On a 32-bit system, this would be 2 bytes (16 bits).
- **Double-Word**: Often refers to twice the size of the word. On a 32-bit system, this would be 8 bytes (64 bits).

The size of a word has an intrinsic relationship with the operation step at the register level within the assembly code.

Basic data types

bool	1 byte
char	1 byte
short	2 bytes
int	4 bytes
long	4 bytes
float	4 bytes
double	8 bytes



Signed magnitude

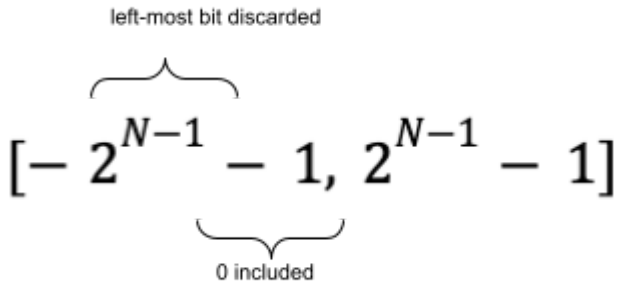
- Represents negative numbers with a leftmost 1 bit and positive numbers with a leftmost 0 bit

One's complement

- Represents negative numbers as the bit flip inverse of a positive integer

- The leftmost bit is used to determine the sign of the number, when it is 0 the number is positive and when it is 1 the number is negative

- It can map up to



non-zero integers

N: amount of bits available

e.g

- left-most bit 0 → (+)

0b	0d
0111 1110	126
0111 1111	127

- left-most bit 1 → (-)

0b	0d
1000 0001	-126
1000 0000	-127

Note that 0 can be represented in two ways

`short 0` *in one's complement*

0	00000000 00000000	11111111 11111111	-0

Two's complement

- Used in most systems
- Represents 0 without ambiguity

- Starts from one's complement and adds 1 bit **to the negative counterpart only**

e.g

`short 0` *on* `-0` *form in one's complement*

0	00000000 00000000	11111111 11111111 + 00000000 00000001	-0

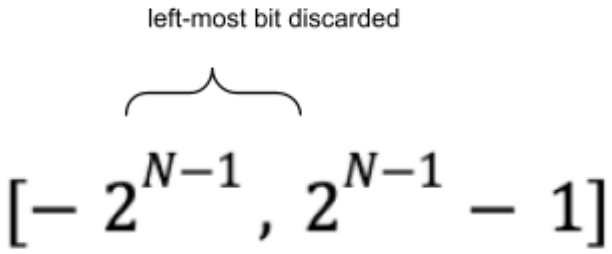
overflows to …

=

`short 0` in two's complement

0	00000000 00000000	00000000 00000000	0

- Which ends up giving more space to represent one additional negative integer, therefore two's complement maps up to:



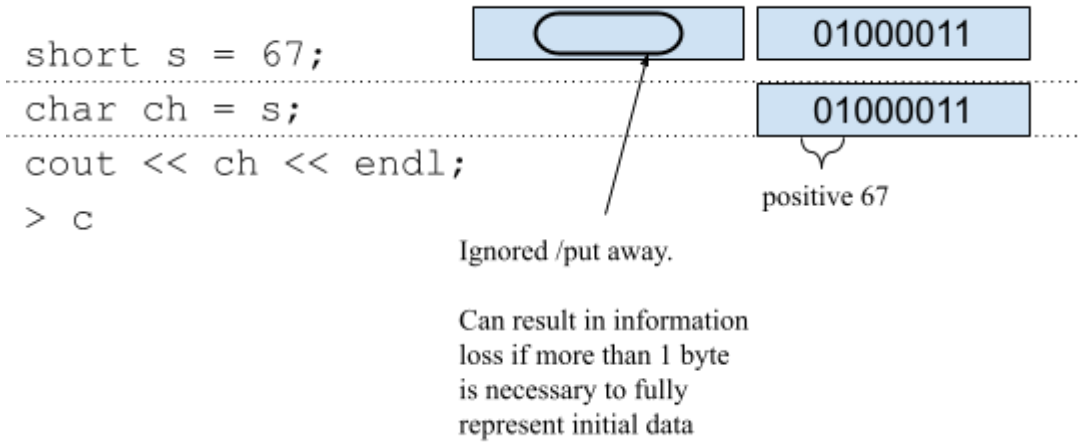
non-zero integers, which is one more than one's complement

N: amount of bits available

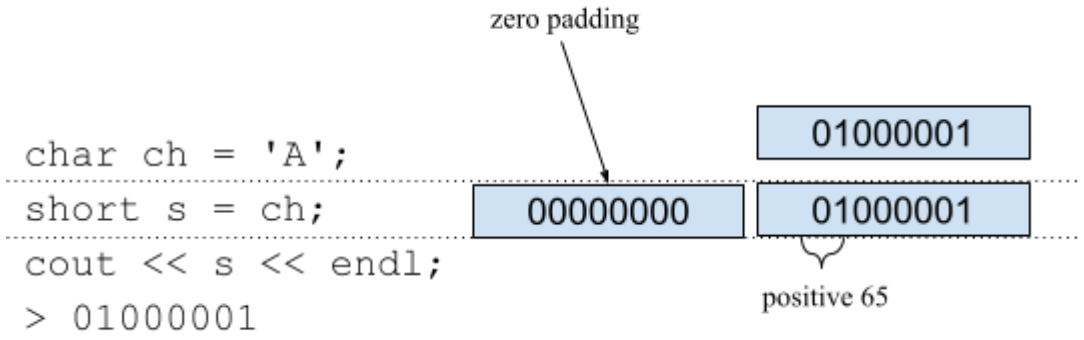
- Further reading on signed magnitude vs one's complement vs two's complement: https://www.electronics-tutorials.ws/binary/signed-binary-numbers.html

Type casting

Largest to smallest

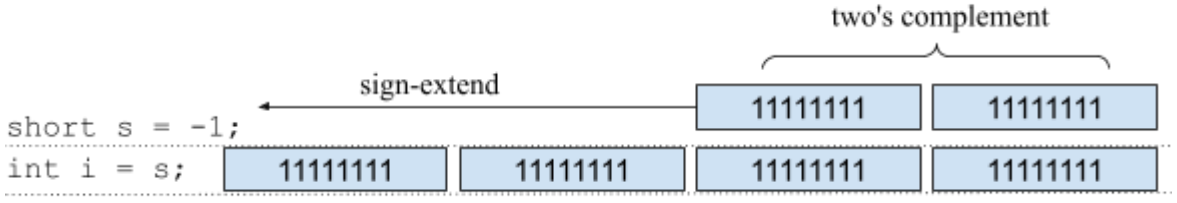


Smallest to largest



Casting signal preservation

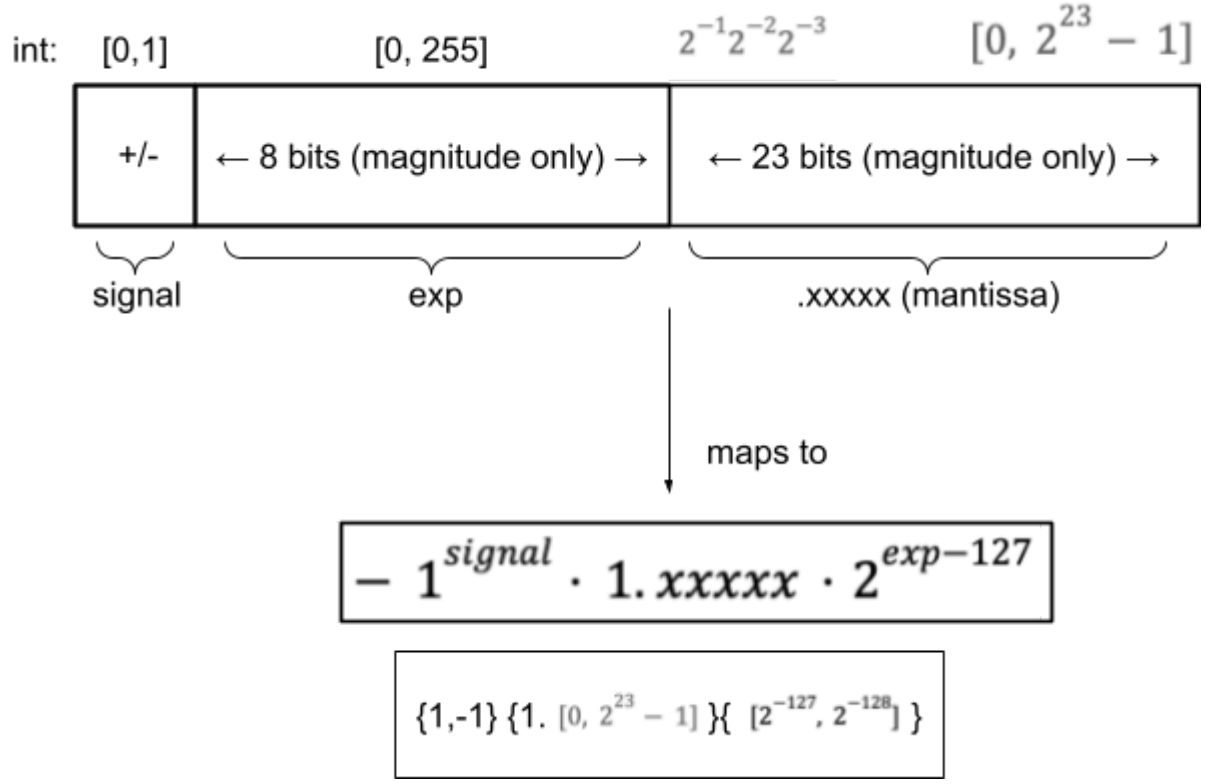
- Casting smallest to largest preserves signal through sign-extension



So that 2'C(-1 + 1) = 0 = 00000000 00000000 00000000 00000000

Floats

Memory representation (IEE 754)



e.g:

$$7.0$$
$$\Leftrightarrow 7.0 \cdot 2^{0}$$
$$\Leftrightarrow 3.5 \cdot 2^{1}$$
$$\Leftrightarrow 1.75 \cdot 2^{2}$$
$$\Leftrightarrow (-1^{0}) \cdot (1.75) \cdot (2^{2})$$

$\therefore$

→ signal = 0

→ .xxxxx = 75

→ exp = 129

Integer conversion

int → float

```
int i = 5;
float f = i;
cout << f << endl;
> 5.0
```

Machine operates in `int` to find **signal, exponent** and **mantissa** to calculate the IEE 754 float representation.

---

float → int

> Machine calculates the effective `float` value according to **signal**, **exponent** and **mantissa** and then truncate or round the value. According to ISO/IEC 9899:2018 (C18 Standard) on float → int conversion C truncates discarding everything after the decimal point.
>
> See https://cplusplus.com/forum/beginner/60827

Floating-point arithmetic

Floating-point arithmetic operations, such as addition and division, approximate the corresponding real number arithmetic operations by rounding any result that is not a floating-point number itself to a nearby floating-point number. For example, in floating-point arithmetic with five base-ten digits of precision, the sum 12.345 + 1.0001 = 13.3451 might be rounded to 13.345.

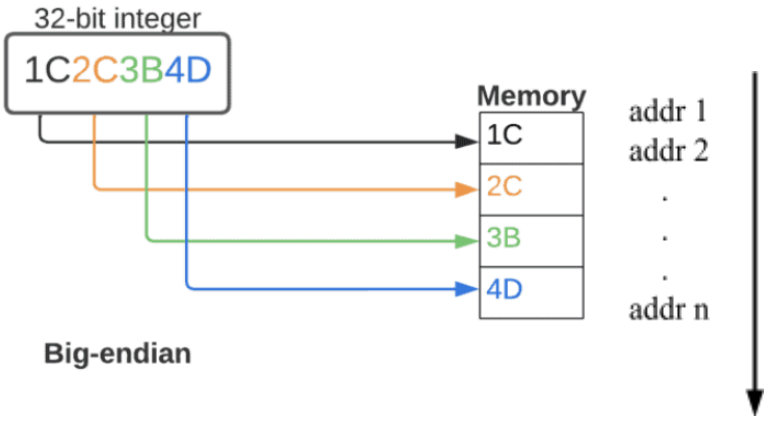
Pointers

Big endian vs little endian

Big-endian and little-endian are the two main ways to represent endianness.

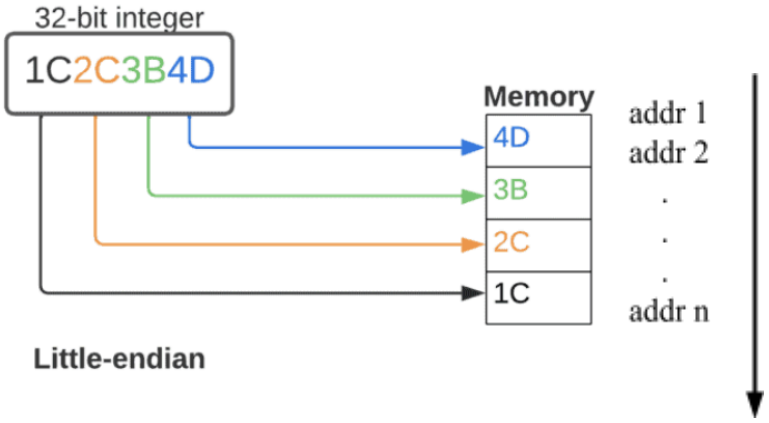
- Big-endian keeps the **most significant byte** of a word at the **smallest memory location** and the **least significant byte** at the **largest**.

`left → right`



- Little-endian keeps the **least significant** address at the **smallest memory location**.

`left ← right`

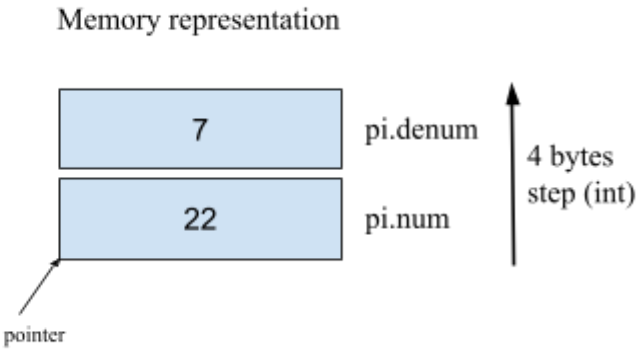


Further reading: baeldung.com/cs/big-endian-vs-little-endian; en.wikipedia.org/wiki/Endianness

C structs

```
struct fraction {
    int num;
    int denum;
};

fraction pi;
pi.num = 22;
pi.denum = 7;
```



Order of memory allocation

- **Variable Allocation Order**: The order in which variables are allocated in memory can depend on the compiler and its optimizations. Generally, variables are allocated in the order they are declared (left→right; top→down), but this is not strictly guaranteed as the compiler may reorder for optimization purposes.

  e.g

```
char sentence[] = "Hello";

| Memory Address | Data  |
|----------------|-------|
| ...            | ...   |
| 0x2000         | 'H'   |
| 0x2001         | 'e'   |
| 0x2002         | 'l'   |
| 0x2003         | 'l'   |
| 0x2004         | 'o'   |
| 0x2005         | '\0'  |
| ...            | ...   |
```

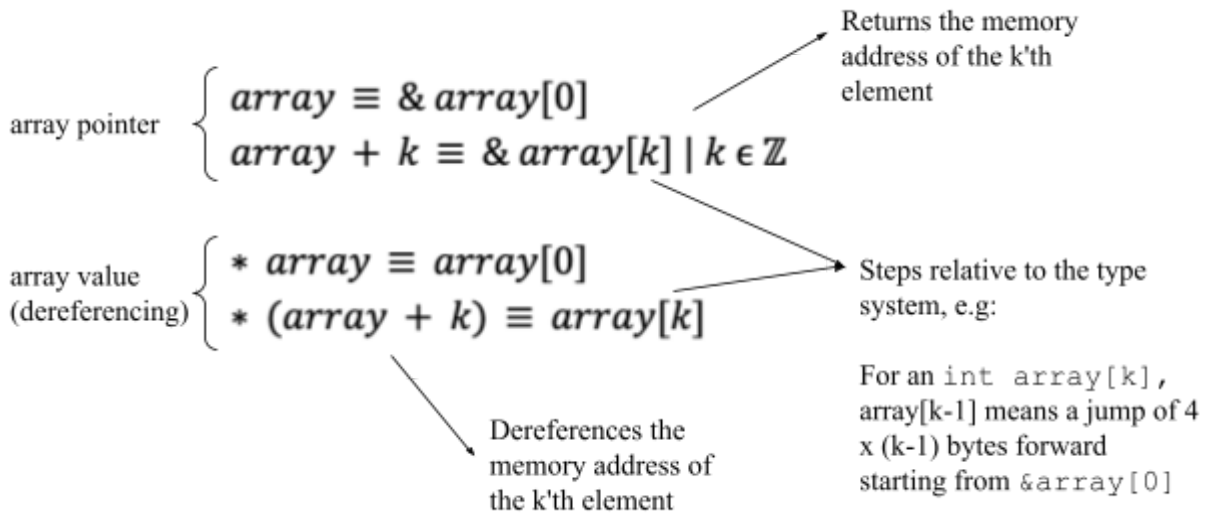
```
int x;
float y;

| Memory Address | Data    |
|----------------|---------|
| ...            | ...     |
| 0x1000         | x       |
| 0x1004         | y       |
| ...            | ...     |
```

- **Endianness**: Endianness (big-endian or little-endian) is determined by the machine architecture, not by the C code itself. But usually it is little-endian.

Pointer arithmetic

- Pointer is an object that stores a memory address. As an object, it has its own memory address as well.



e.g

```
int ar[2];
ar[0] = 1
ar[1] = 2

printf("%d\n", ar[0])
> 1

printf("%d\n", ar[1])
> 2

printf("%p\n", &ar[0])
> 0x10e374000

printf("%p\n", &ar[1])
> 0x10e374004
```

```
printf("%p\n", &ar[1] + 1)
>  0x10e374008
```

When working on a 32-bit system of a [flat memory model](#) a pointer address costs 32 bits of information, hence 8 different memory addresses are needed to store the pointer address itself.

To clarify:

- **Pointer Size**: On a 32-bit system, the size of a pointer is 4 bytes (32 bits).

  - Each byte in memory has its own unique address.
  - The 4 bytes required to store a pointer are contiguous, meaning they occupy 4 consecutive memory addresses.
  - It only takes one pointer to reference any address within the 4 GB addressable memory space of a 32-bit flat-model system.

Further reading: https://stackoverflow.com/questions/20763616/how-many-bytes-do-pointers-take-up

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Dereferencing

- Dereferencing is a technique for accessing or manipulating data stored in a memory location pointed to by a pointer. We use the * symbol with the pointer variable when dereferencing the pointer variable. Using dereferencing, we can get the value inside the variable.

- When you want to access the data/value in the memory that the pointer points to - the contents of the address with that numerical index - then you dereference the pointer.

Further reading:
https://stackoverflow.com/questions/4955198/what-does-dereferencing-a-pointer-mean-in-c-c

Dereferencing a null pointer

```
int c;
int *pi;
pi = NULL;
c = *pi;
```

- This operation will crash the application
- Never do this
- https://en.wikipedia.org/wiki/2024_CrowdStrike_incident

Further reading:
https://stackoverflow.com/questions/4007268/what-exactly-is-meant-by-de-referencing-a-null-pointer

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Void pointer

A void pointer is a pointer that has no associated data type with it.

```
int a = 10;
void *p = &a;
```

- Can hold an address of any data type
- Can be cast into any data type
- Has an undefined type system and thus cannot be dereferenced

Void pointer arithmetic

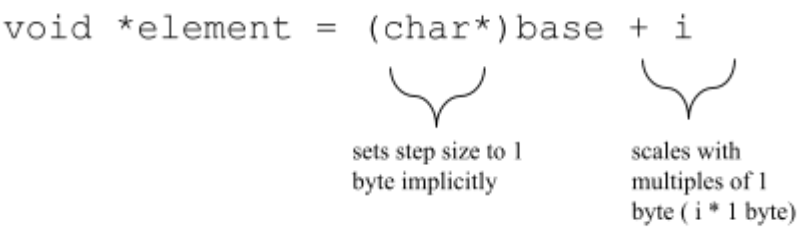
In C, pointer arithmetic is based on the size of the type that the pointer points to. When you perform an addition operation on a pointer, the compiler scales the integer by the size of the type that the pointer points to. Therefore, the compiler doesn't know how to handle the following code:

```
int i = 5;
void *base;
void *element = base + i;
```

Because behind the scenes, it would be trying to do `` `base + 5 * sizeof(void)` ``, and `` `void` `` has no predefined size. Although standard C does not allow arithmetic on void pointers, GNU C (GCC) does allow it and assumes the step size within a void pointer type system is 1 byte.

In an expression such as `` `*(array+i)` `` or `` `*(array-i)` `` the compiler is implicitly scaling `` `i` `` to the size of the type the array is deferred, so it also doesn't know what to do in an array of `` `void` ``.

But we can trick it to perform basic math and pointer arithmetic at the same time by using a 1:1 base for both domains (works the same for subtraction and addition):



Generics

Motivational:

```
void swap(int *ap, int *bp)
    {
        int temp = *ap;
        *ap = *bp;
        *bp = temp;
    }
```

What if we wanted to swap content from `float`, `char`, `short`, or any other type-system pointer?

Well, for that we can use generics.

```
void swap(void *vp1, void *vp2, int size)
    {
        char buffer[size];
        memcpy(buffer, vp1, size);
        memcpy(vp1, vp2, size);
        memcpy(vp2, buffer, size);
    }
```

Obs: `memcpy` copies the values of num bytes from the location pointed to by source directly to the memory block pointed to by destination.

Advantage of using this approach over using templates:

- Single assembly for many data types → avoids inflating the binary with compiler-specific code

Disadvantage:

- Requires client to comply with code;
- Loose of safety (non-compliance of client can lead to hidden bugs)

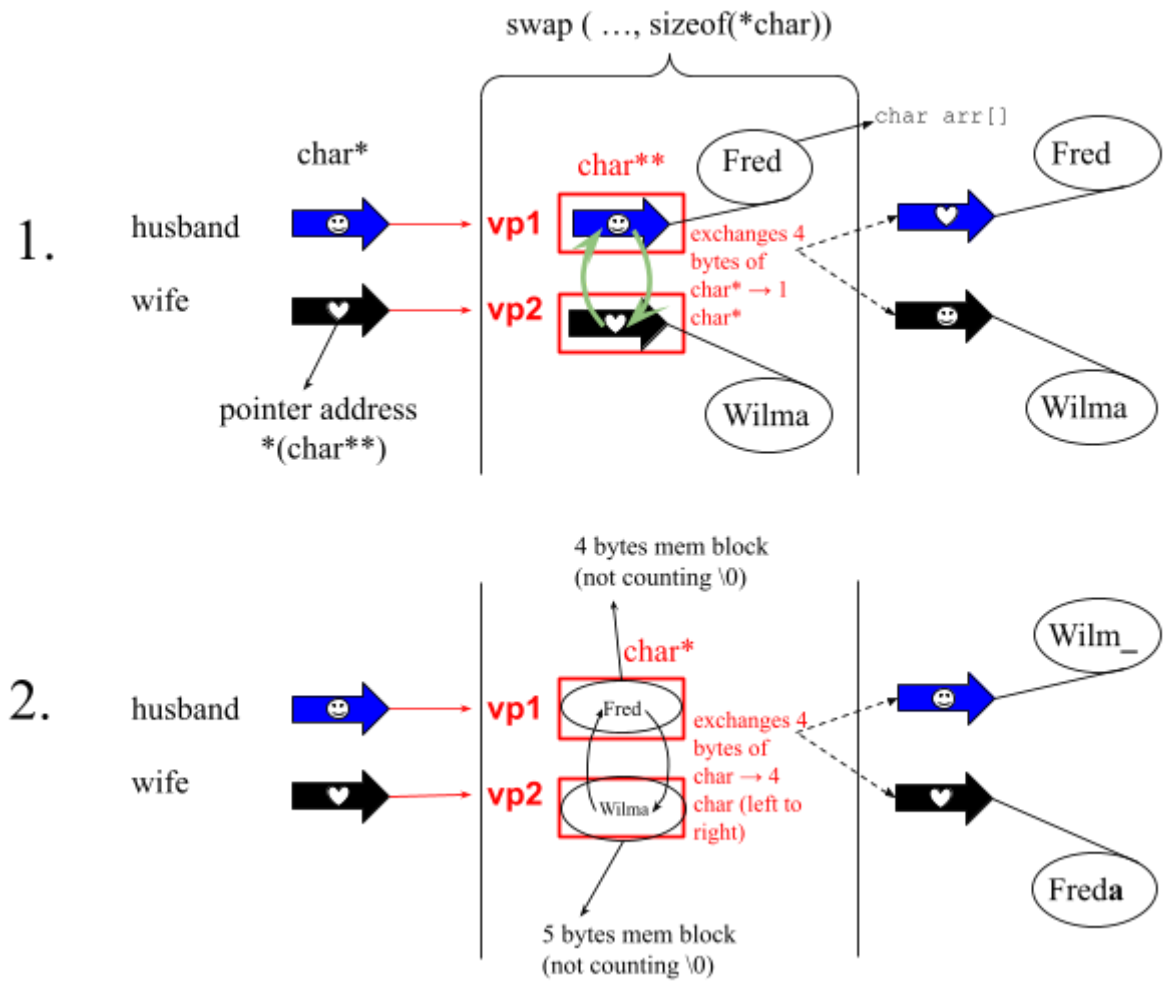
Swapping chars

Now suppose we have:

```
char *husband = strdup("Fred");
char *wife = strdup("Wilma");
```

And using the `swap` implementation above we perform:

```
1. swap(&husband, &wife, sizeof(char*));
2. swap(husband, wife, sizeof(char*));
```



obs: `sizeof(char*)` → 4 bytes in 32 bits flat-memory model

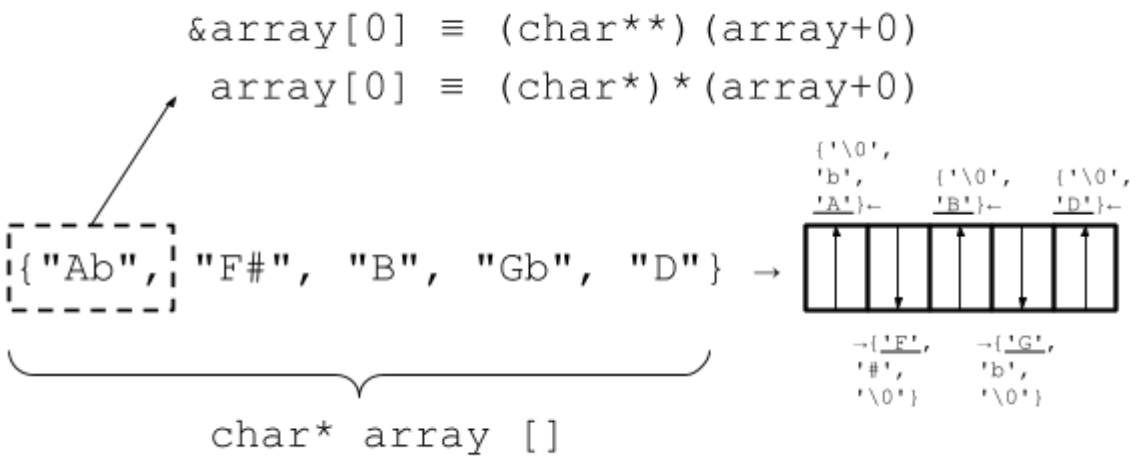
Pointers to pointers

There is no guarantee that `sizeof(n*) == sizeof(m*)` $\forall\, m, n \in \{type\ system\};$ The size of a pointer is architecture-specific, hence we should always emphasize memory address types.

Recap on C strings

- Each char in C represents one byte (8 bits) of information;
- A single memory address can hold 1 byte of information (on a byte-wide flat-memory model). Thus, each memory address can hold one char;
- **Strings are array of chars;**
  e.g: `` `char array[] = "abc"` ``
  which is equivalent to `` `char array[] = {'a', 'b', 'c', '\0'}` ``
  thus `` `sizeof(array) == strlen(array)+1` ``

Array of pointers to pointers



informally:

```
char* array[] = {
                    →char array_1[], →char array_2[],
                    →char array_3[], …
                }
```

For most compilers both `` `char array[] = "AbF#BGbD"` `` and `` `char* array[] = {"Ab", "F#", "B", "Gb", "D"}` `` allocate memory contiguously from the first char to the last, the difference is that the `` `char* array[]` `` approach will have a null character `` `\0` `` for each substring while `` `char array[]` `` will have only one. Think of `` `char* array[]` `` as chopping a string into distinct and "pointable" slices (substrings) located one after the other in memory. But be careful, there is no reason for that to be always true, it just happens to be that way in most cases, for more information see
https://stackoverflow.com/questions/51697188/in-array-of-pointers-to-string-will-all-the-strings-be-stored-in-contiguous-mem

Single dereferencing of a char **

```
int strcmp(void *vp1, void *vp2) {
    char *s1 = *(char**)vp1;
    char *s2 = *(char**)vp2;
    return strcmp(s1,s2);
}
```

(i) (ii) (iii)

(i) → Receives generic (void) pointer.

(ii) → Casts pointers to known type `char**` and dereferences it once, evaluating the amount of bytes equal the size of a pointer in the system architecture (4 bytes for 32 bits or 8 bytes for 64 in a flat-memory model), which in this case is an address assumed to be a `char*` pointer.

(iii) → Uses `strcmp` built-in function to compare each `char` inside `char array[]`. Here *strcmp* assumes input pointers are a `char*` address pointing to the first element of a string.

Recap on function pointers

Function Pointers provide an extremely interesting, efficient, and elegant programming technique. You can use them to replace switch/if-statements and to realize late-binding. Late binding is deciding the proper function during runtime instead of compiling time. They are less error-prone than normal pointers because you will never allocate or deallocate memory with them.

More info at:
https://www.cs.cmu.edu/~ab/15-123N09/lectures/Lecture%2008%20-%20Function%20Pointers.pdf

Functions like variables, can be associated with an address in the memory. We call this a function pointer. A specific function pointer variable can be defined as follows:

```
int (*fn)(int,int) ;
```

Here we define a function pointer `fn`, which can be initialized to any function that takes two integer arguments and returns an integer. Here is an example of such a function:

```
int sum(int x, int y) {
      return (x+y);
}
```

Now to initialize `fn` to the address of the sum, we can do the following:

- Make `fn` points to the address of sum

```
fn = &sum;
```

- Simply ignore the `&` as function names are just like array names, namely: they are pointers to the structure they are referring to.

```
fn = sum;
```

In the end, we can use the sum function in two ways.

```
int x = sum(10,12); /* direct call to the function */
int x = (*fn)(12,10); /* call to the function through a pointer */
```

Using Typedef's

The syntax of function pointers can sometimes be confusing. So we can use a typedef statement to make things simpler:

```
typedef (* fpointer)(argument list);
```

so we can define a variable of type `fpointer` as follows:

```
fpointer fp;
```

Now imagine you have a function that returns another function based on some conditions:

```
int (*Convert(const char code)) (int, int) {
     if (code = = '+') return &Sum;
     if (code = = '-') return &Difference;
}
```

The above function takes a `char` as an argument and returns a specific function pointer based on whether the char is + or – .

Both `Sum` and `Difference` are functions that essentially receive two numbers and return a single number, in this context we are working with ints, so we can do something like:

```
typedef int (*Ptr)(int,int);
```

And then simplify the Convert definition as follows:

output signature
input signature
function name

Without typedef	`int (*Convert(const char code)) (int, int) {`
	`  if (code == '+') return &Sum;`
	`  if (code == '-') return &Difference;`
	`}`

With typedef	`Ptr Convert(const char code) {`
	`  if (code == '+') return &Sum;`
	`  if (code == '-') return &Difference;`
	`}`

Linear search in C

Recap on linear search

In computer science, linear search or sequential search is a method for finding an element within a list. It sequentially checks each element of the list until a match is found or the whole list has been searched.

A linear search runs in linear time in the worst case, and makes at most n comparisons, where n is the length of the list

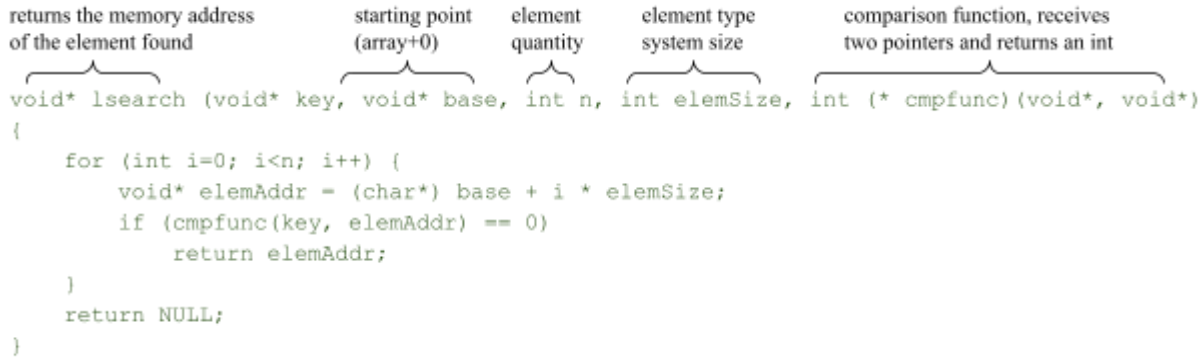
Basic algorithm

Given a list L of n elements with values or records L_0 .... L_{n-1}, and target value T, the following subroutine uses linear search to find the index of the target T in L.

1. Set i to 0.
2. If $L_i = T$, the search terminates successfully; return i.
3. Increase i by 1.
4. If $i < n$, go to step 2. Otherwise, the search terminates unsuccessfully.

More info at: https://en.wikipedia.org/wiki/Linear_search

Implementing a generic linear search



Applying it over known `int` space requires us to write our comparing function for integers:

```
int intcmp (void* elem1, void* elem2)
{
    int* ip1 = (int*) elem1;
    int* ip2 = (int*) elem2;
    return *ip1 - *ip2;
}
```

Now putting everything together:

int_lsearch.c
```
#include <stdio.h>

void* lsearch (void* key, void* base, int n, int elemSize, int (*
cmpfunc)(void*, void*))
{
    for (int i=0; i<n; i++) {
        void* elemAddr = (char*) base + i * elemSize;
        if (cmpfunc(key, elemAddr) == 0)
            return elemAddr;
    }
    return NULL;
}

int intcmp (void* elem1, void* elem2)
{
```

```
    int* ip1 = (int*) elem1;
    int* ip2 = (int*) elem2;
    return *ip1 - *ip2;
}

int main()
{
    int arr[] = {1, 2, 3, 4, 5};
    int key = 3;
    int size = sizeof(arr) / sizeof(arr[0]);
    int elemSize = sizeof(arr[0]);
    int* found = (int*) lsearch(&key, arr, size, elemSize,
intcmp);
    if (found != NULL)
        printf("Found: %d\n", *found); //remember to never
dereference a NULL pointer
    else
        printf("Not found\n");
    return 0;
}
```

> Found: 3

In case we want to search for a specific string in an array of strings (array of pointers to pointers), we can borrow the `*Strcmp*` function we implemented in part 1 and do something like:

```
char* note = "Eb";
char* notes[] = { "Ab", "F#", "B", "Gb", "D" };
char** found = lsearch(&note, notes, 5, sizeof(char**), Strcmp);
```

Approaching C++

The idea of a class

First, let us establish that **`Structs`** in C and **`Classes`** in C++ are identical in all ways except for the default access modifier: for a `struct` the default is **public**, whereas for a class it is **private**. There's no other difference as far as the language is concerned.

The arrow operator (->) vs the dot (.) operator

dot (.)

The dot operator is used to access the content of a member of a struct (or class in C++) directly when you have an instance of the struct or class.

Example: struct_instance.member

arrow (->)

The arrow operator is used to access the content of a member of a struct (or class) when you have a pointer to the struct (or class).

The arrow operator is syntactic sugar for dereferencing the pointer before accessing the member content via the dot operator.

Example: ptr->member is equivalent to (*ptr).member

Implementing a stack data structure for ints

Before we begin, we need to know that in C it is a common practice to aggressively separate implementation from behavior. This means that we should first create a `.h` file to store the implementation (interface) of the stack structure and then a `.c` file with the actual behavior.

`stack.h`
```
typedef struct {
    int *elems;
    int logicLen;
    int allocLen;
} Stack;

void StackNew(Stack* s);
void StackDispose(Stack* s);
void StackPush(Stack* s, int value);
int StackPop(Stack* s);
```

```

`stack.c`
```
```
#include <assert.h>
#include <stdlib.h>
#include <stdio.h>
#include "stack.h" //assuming stack.h is in the
same directory of stack.c


void StackNew(Stack* s) {
    s->logicLen = 0;
    s->allocLen = 4;
    s->elems = malloc(4 * sizeof(int));
    assert(s->elems != NULL);
}

void StackDispose(Stack* s) {
    free(s->elems); //returns memory to the heap
}

void StackPush(Stack* s, int value) {
    if(s->logicLen == s->allocLen) {
        s->allocLen *= 2;
        s->elems = realloc(s->elems,
s->allocLen*sizeof(int));
        assert(s->elems != NULL);
    }
    s->elems[s->logicLen] = value;
    s->logicLen++;
}

int StackPop(Stack* s) {
    assert(s->logicLen > 0);
    s->logicLen--;
    return s->elems[s->logicLen];
}

int main() {
    Stack s;
    StackNew(&s);
    StackPush(&s, 1);
    StackPush(&s, 2);
    StackPush(&s, 3);
    assert(StackPop(&s) == 3);
    assert(StackPop(&s) == 2);
    assert(StackPop(&s) == 1);
```

```
    StackDispose(&s);
    printf("All Good\n");
    return 0;
}
```

Note that `assert()` is just a macro we use here to ensure we get the *memblock* pointer in the end.

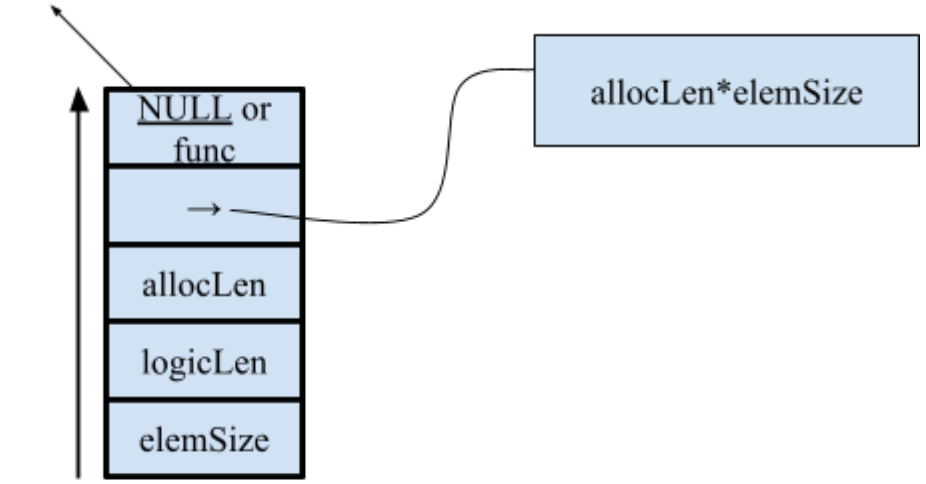
Quick words about realloc()

- Deallocate old array and returns a resized array;
- Has the advantage of checking if there is available space to contiguously extend the memory in the heap for `s->elems`;
- There is no similar function in c++;
- Fun fact: `malloc(size) ≡ realloc(Null, size)`

Implementing a generic stack data structure

`stack.h`
```
typedef struct {
    void* elems;
    int elemSize;
    int logicLen;
    int allocLen;
    void (*freefunc)(void*);
} Stack;

void StackNew(Stack* s, int elemSize, void (*freefunc)(void*));
void StackDispose(Stack* s);
void StackPush(Stack* s, void* elemAddr);
void StackPop(Stack* s, void* elemAddr);
```

If the stack is implemented for one of the basic types there is no need for a custom free function



memory allocation for Stack struct

`stack.c`
```
#include <assert.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include "stack.h" //assuming stack.h is in the same directory of stack.c


void StackNew(Stack* s, int elemSize, void(*freefunc)(void*)) {
    if(elemSize <= 0) {
        assert(0);
    }
    s->elemSize = elemSize;
    s->logicLen = 0;
    s->allocLen = 4;
    s->elems = malloc(4*elemSize);
    s->freefunc = freefunc;
    assert(s->elems != NULL);
}

/* `static` is analogous to `private` in c++; in C it marks the file as internal linkage */
static void StackGrow(Stack* s) {
    s->allocLen *= 2;
    s->elems = realloc(s->elems, s->allocLen * s->elemSize);
}
```

```
void StackPush(Stack* s, void* elemAddr) {
    if(s->logicLen == s->allocLen)
        StackGrow(s);
    void* target = (char*)s->elems + (s->logicLen * s->elemSize);
    memcpy(target, elemAddr, s->elemSize);
    s->logicLen++; //sets next available index
}

/* note that elemAddr gets modified externally via StackPop
internal operations */
void StackPop(Stack* s, void* elemAddr) {
    s->logicLen--;
    void* source = (char*)s->elems + (s->logicLen * s->elemSize);
    memcpy(elemAddr, source, s->elemSize);
}

/* we have to make sure to clear all structures whenever
applicable */
void StackDispose(Stack* s) {
    if(s->freefunc != NULL) {
        for(int i=0; i<s->logicLen; i++) {
            s->freefunc((char*)s->elems + (i * s->elemSize));
        }

    }
    free(s->elems);
}

void StringFree(void* elem) {
    free(*(char**)elem);
}

int main(){
    const char* friends[] = {"Al", "Bob", "Carl"};
    Stack stringStack;
    StackNew(&stringStack, sizeof(char**), StringFree);
    for(int i=0; i<3; i++) {
        char* copy = strdup(friends[i]);
        StackPush(&stringStack, &copy); //push the pointer to the
string copy (char**) onto the stack
    }
    char* name;
    printf("Popping elements:\n");
    for(int i=0; i<3; i++) {
        StackPop(&stringStack, &name);
        printf("%s\n", name);
        free(name);
    }
```

```
    StackDispose(&stringStack); //agnostic of stack content by
time of execution
}
```

Pause a bit to ponder on the above implementation, make sure you understand and agree with what each line is doing, and don't hesitate to go back to part 1 if you need to review something.

Quick words on memory disposal

Disposing basic types

If you dynamically allocate memory for basic types (***e.g int, float, char, etc)***, `free()` will correctly deallocate the memory without any additional steps needed:

```
int *p = malloc(sizeof(int));
// Use p...
free(p);  // No additional action needed
```

Disposing structures

For simple structures, like a fraction struct or any struct that only contains basic types, `free()` will deallocate the memory for the structure itself, but if the structure contains pointers to dynamically allocated memory (*e.g char**, pointers to structs, structs with pointers, etc*), you'll need to manually `free()` those inner allocations before freeing the structure:

```
typedef struct {
    char* name;
    int age;
} Person;

Person *p = malloc(sizeof(Person));
p->name = malloc(100 * sizeof(char));  // Dynamically allocate
memory for name

// Use p...

free(p->name);  // Free the inner allocation first
free(p);        // Then free the structure itself
```

In this case, failing to free `p->name` before freeing `p` would lead to a memory leak. C doesn't automatically traverse the structure to free any internal pointers, so you have to handle that manually.

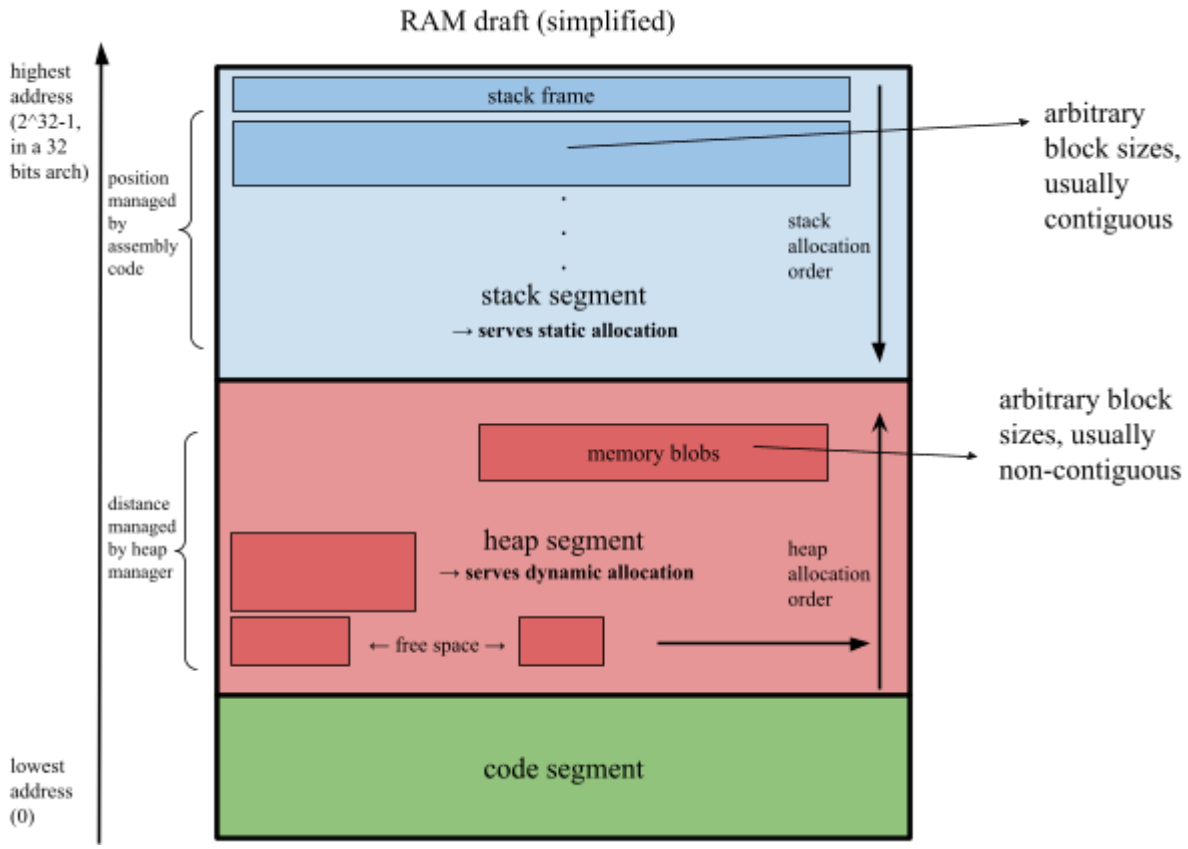
That is why we had to create a custom `StringFree()` function for our `stringStack` use case

.

The RAM memory

RAM is a common computing acronym that stands for random-access memory. It is often referred to as PC memory or simply memory. In essence, RAM is your computer's short-term memory, where data needed by the CPU to run applications and open files is stored for quick access.

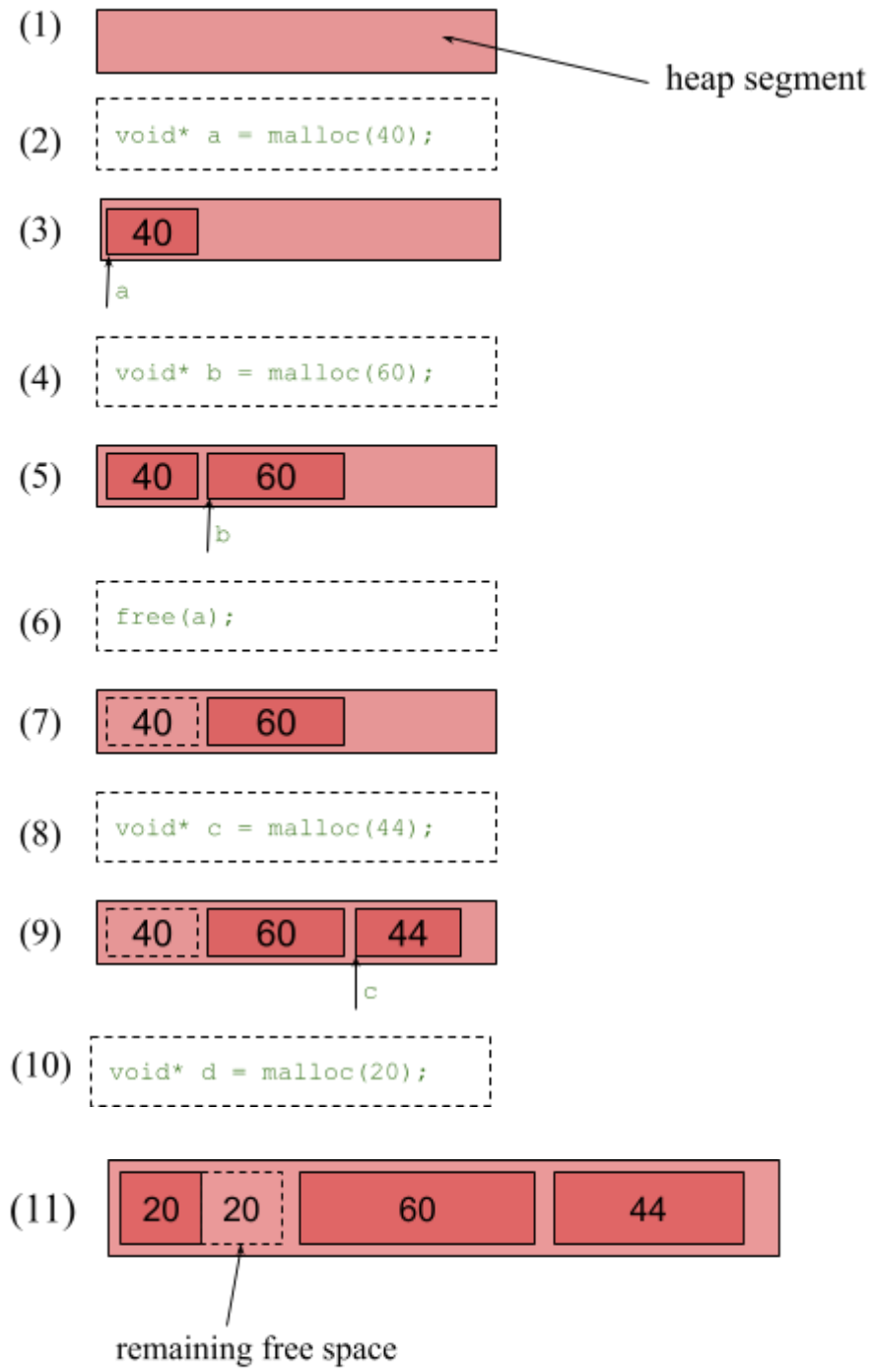
When memory is allocated—either statically on the stack via stack frames or dynamically on the heap—we are utilizing RAM. It is also referred to as primary storage.



Despite the lack of formal constraints, stack frames allocation are usually contiguous, and even if not contiguous in physical memory they are usually contiguous in virtual memory, more info at https://stackoverflow.com/questions/5086577/is-stack-memory-contiguous

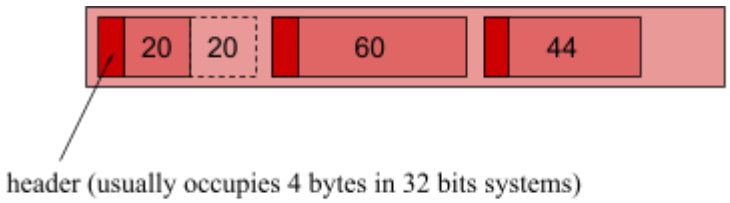
Unlike stack frames, heap allocations are typically not contiguous. Heap memory is often fragmented and can consist of blocks that are scattered throughout both physical and virtual memory, depending on the allocation and deallocation patterns.

Zeroing in the heap segment with malloc()



Zeroing a bit more

When `` `int *arr = malloc(40*sizeof(int))` `` is executed, the heap manager actually accommodates more than 160 bytes of memory. Along with the reserved memory blob lies a header that stores additional information, like memory footprint, etc.



General header information

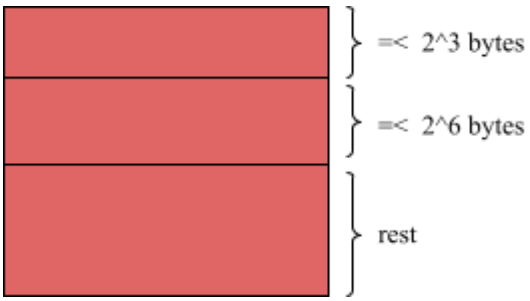
- **Block size**: The header usually stores the size of the allocated block;
- **Status**: It may include a flag indicating whether the block is free or in use;
- **Pointers to neighboring blocks**: In some memory allocators (especially those implementing a free list), the header might include pointers to the next and previous blocks in the list.

When `malloc()` runs, the memory management system stores the leading address of that memory blob and the address to its header in a symbol table which `free()` eventually relies on in order to know how much memory to deallocate. Hence, one cannot simply give any pointer to `free()`, it needs to be the same pointer that was handed back from `malloc()` in the first place.

e.g: `free(arr+1)` will not work as only the leading address of the array `(arr+0)` is kept at the symbol table by `malloc()` with a header reference that holds how much memory was allocated to the whole blob. The same is true for string arrays.

Two examples of heap segmentation are:

1. divided by groups of block sizes



2. big heap (basically the one shown in the RAM draft)

Important reminder: since there are many different heuristics on memory management and heap segmentation per OS, memory-specific interactions shouldn't be relied upon by the client. The way the heap is traversed when searching for available space is also arbitrary to implementation trade-offs

memcopy() vs memove() and the overlapping issue

Prototype: `void *memcpy(void *dest, const void *src, size_t n);`

- dest: Pointer to the destination memory location;
- src: Pointer to the source memory location;
- n: Number of bytes to copy from the source to the destination.

`memcpy()` assumes that the source (`src`) and destination (`dest`) memory areas do not overlap. The function directly copies n bytes from `src` to `dest` without performing any checks to see if these two memory regions might overlap.

If `src` and `dest` overlap, using `memcpy()` can lead to undefined behavior. This means that the outcome of the copy operation is unpredictable—data corruption or other unexpected issues might occur because the source data might be overwritten before it is fully copied.

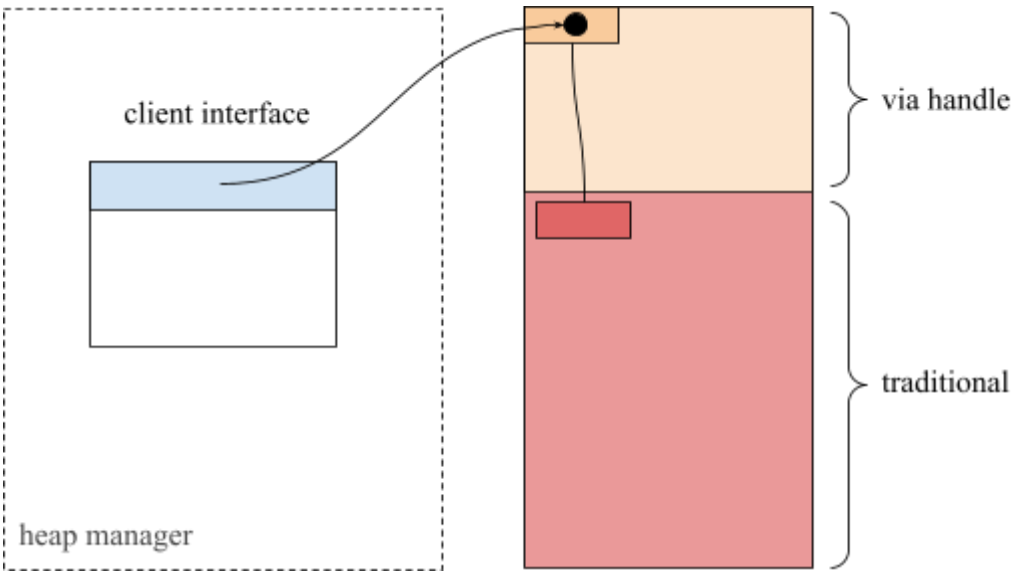
If there is a possibility that the memory regions might overlap, the `memmove()` function should be used instead. Unlike `memcpy()`, `memmove()` is designed to handle overlapping memory areas safely and does so with a slightly higher performance cost than *memcpy()*.

Handles and heap compaction

Indirect approaches, like using "handles" or "indirect pointers," can allow for heap compaction, which is a process where fragmented blocks of memory are consolidated to make larger contiguous blocks available.

Handles

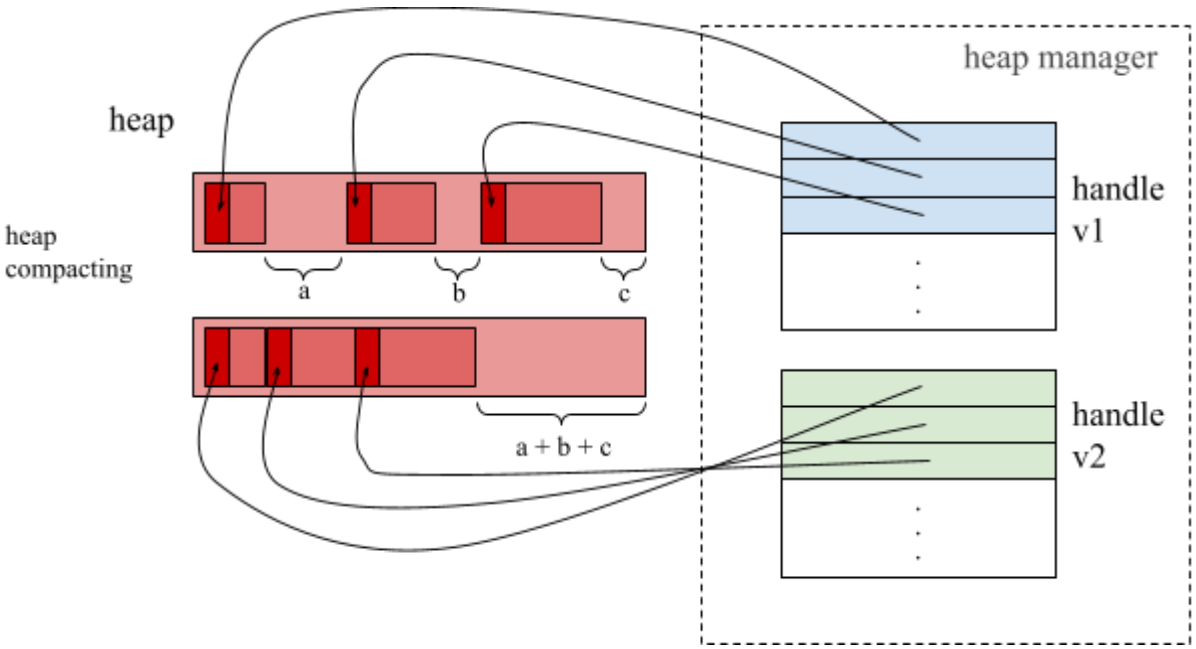
A handle is essentially a level of indirection where a pointer (or reference) does not directly point to the memory location of the data but instead points to a handle (a fixed location). This handle, in turn, points to the actual data. Therefore, the pointers handed to the client are two hops away from the actual data.



In other words, the handle serves as a lookup table for client reference that points to the header of a memory segment and can be updated during heap optimization processes.

Heap Compaction

When heap memory becomes fragmented due to allocations and deallocations, the memory manager can move the actual data to a new location in order to create larger contiguous blocks of free memory. Since the application code only references the handle and not the direct memory address, the memory manager can update the handle to point to the new location of the data, without requiring the application code to change.



The STACK memory

The stack pointer

The stack pointer is a special CPU register that holds the memory address of the top of the stack. it essentially moves step-by-step along with every piece of data that is allocated on the stack during the function call and execution process.

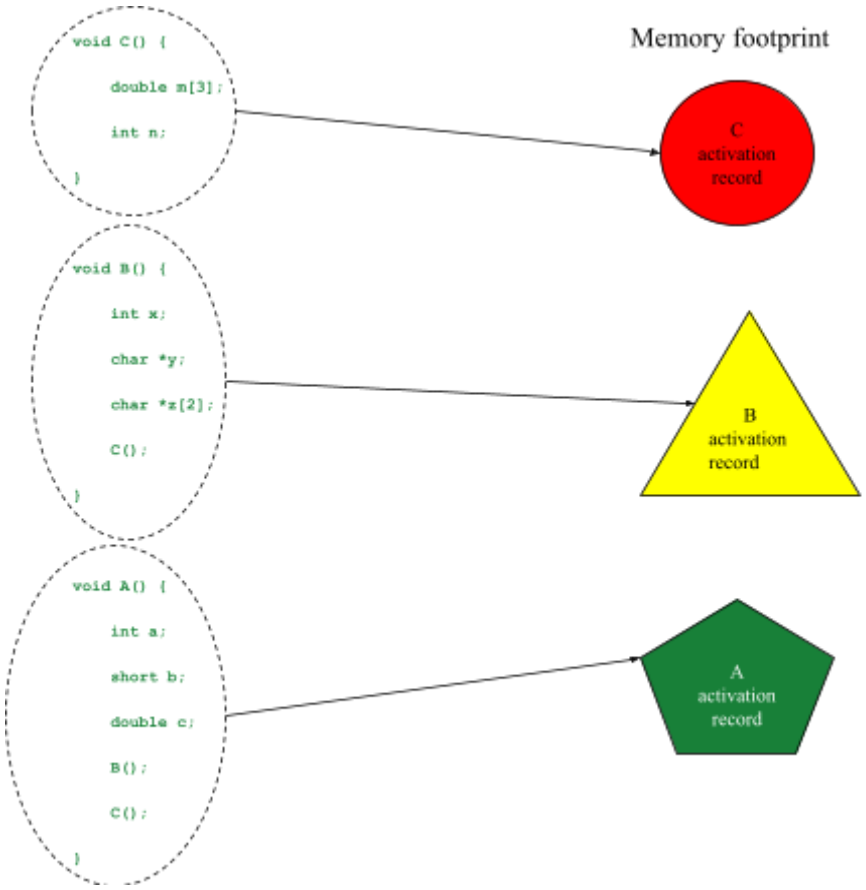
Naming conventions

- **SP (Stack Pointer)**: Used in 16-bit architectures.
- **ESP (Extended Stack Pointer)**: Used in 32-bit architectures.
- **RSP (Register Stack Pointer)**: Used in 64-bit architectures.

Activation record

An activation record is a logical concept used to describe the data structure that holds all the information necessary to execute a function. It's the formal name for the information held in a stack frame. Mind that the exact contents and layout of the stack vary by processor architecture and function call convention (more info at: https://manybutfinite.com/post/journey-to-the-stack/)

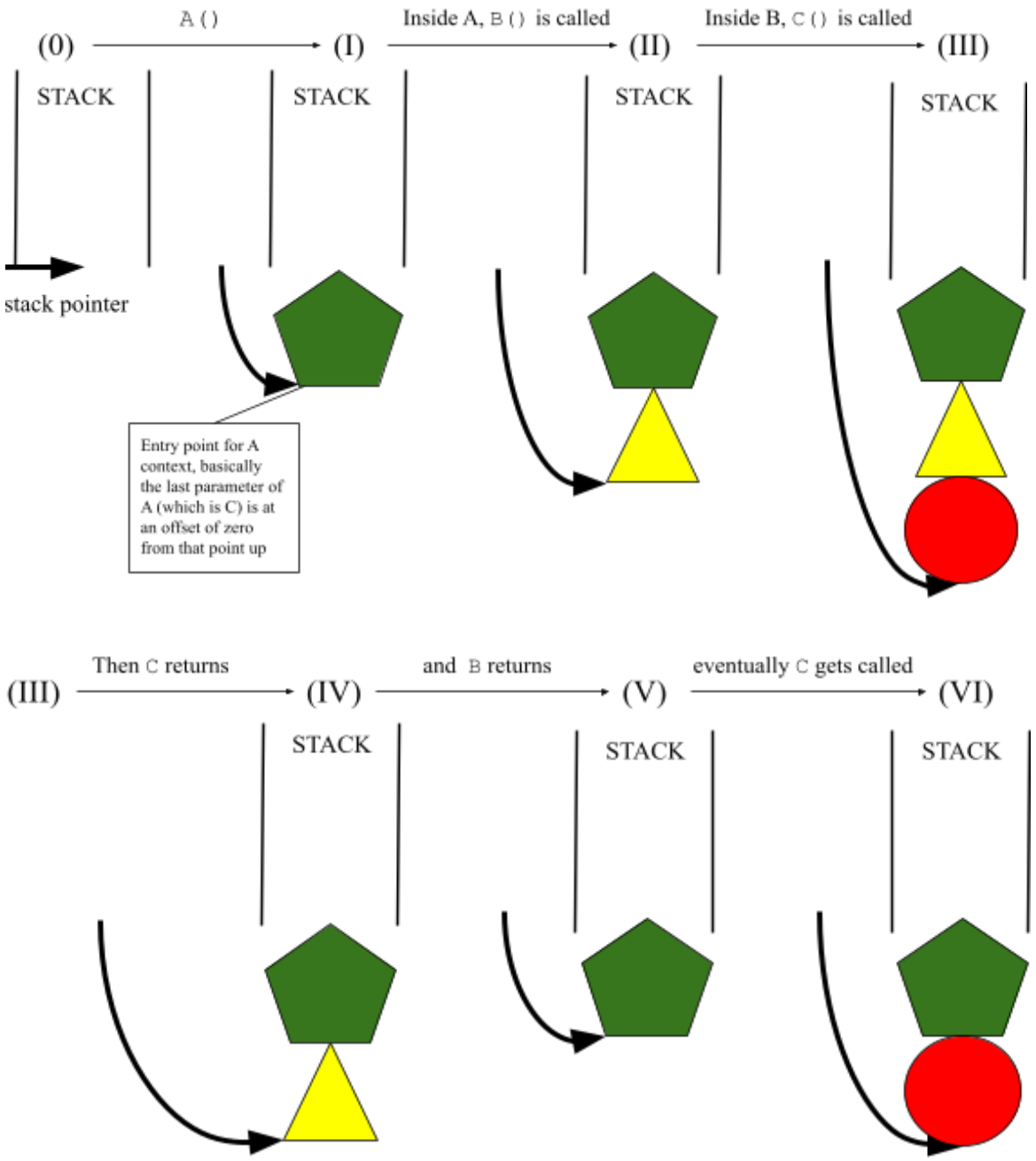
Suppose we have:



When:

```
int main() {
    A();
    return 0;
}
```

is executed, the stack pointer descends (higher memory address → lower memory address) by the amount given by A's activation record memory footprint, then B's and C's, without losing track of the higher frames.

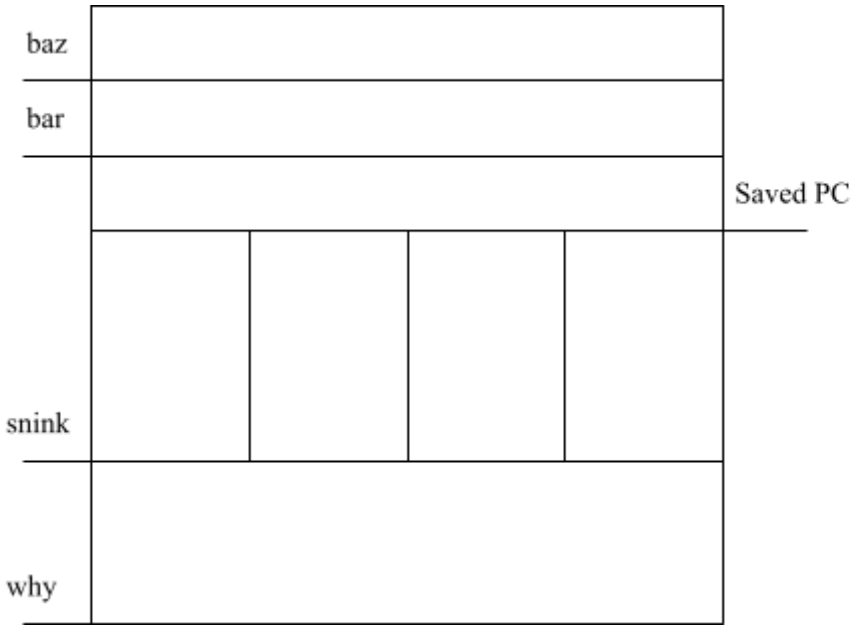


Zeroing on the activation record

Now suppose we have:

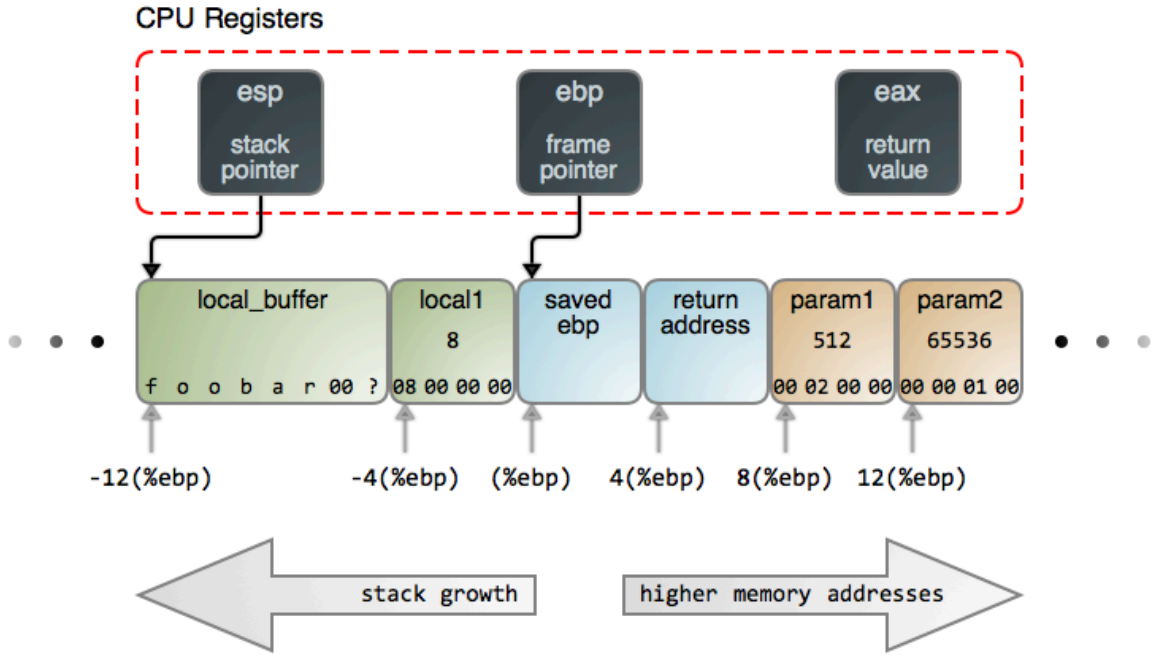
```
void foo(int bar, int *baz) {
    char snink[4];
    short *why;
}
```

Foo's activation record of would be filled top-down starting right-to-left on the function signature:



Where ***Saved PC*** is also known as ***Program Counter*** or ***Return Address*** and it stores the address of the instruction to be executed upon the function's exit.

It's worth mentioning that some architectures like Intel's x86 also contain something called the ***Frame Pointer***, ***Base Pointer*** or ***EBP***, which sits on top of the *Saved PC* pointing to a fixed location within the stack frame of the function currently running providing a stable reference point (base) for access to arguments and local variables, traditionally for such architectures both the base pointer (*EBP*) and the return address (*Saved PC*) are saved on the stack during a function call.



Intel x86 stack example, source: https://manybutfinite.com/post/journey-to-the-stack/

In modern compilers and architectures, there's a technique called ***frame pointer omission*** (***FPO***). This technique eliminates the use of the *base pointer (EBP)* to save registers, making the function more efficient by freeing up ***EBP*** for general-purpose use. In these cases:

- Only the *Saved PC* (return address) is pushed onto the stack.
- The stack is managed solely by the *stack pointer (ESP*), and offsets from *ESP* are used to access local variables and parameters.

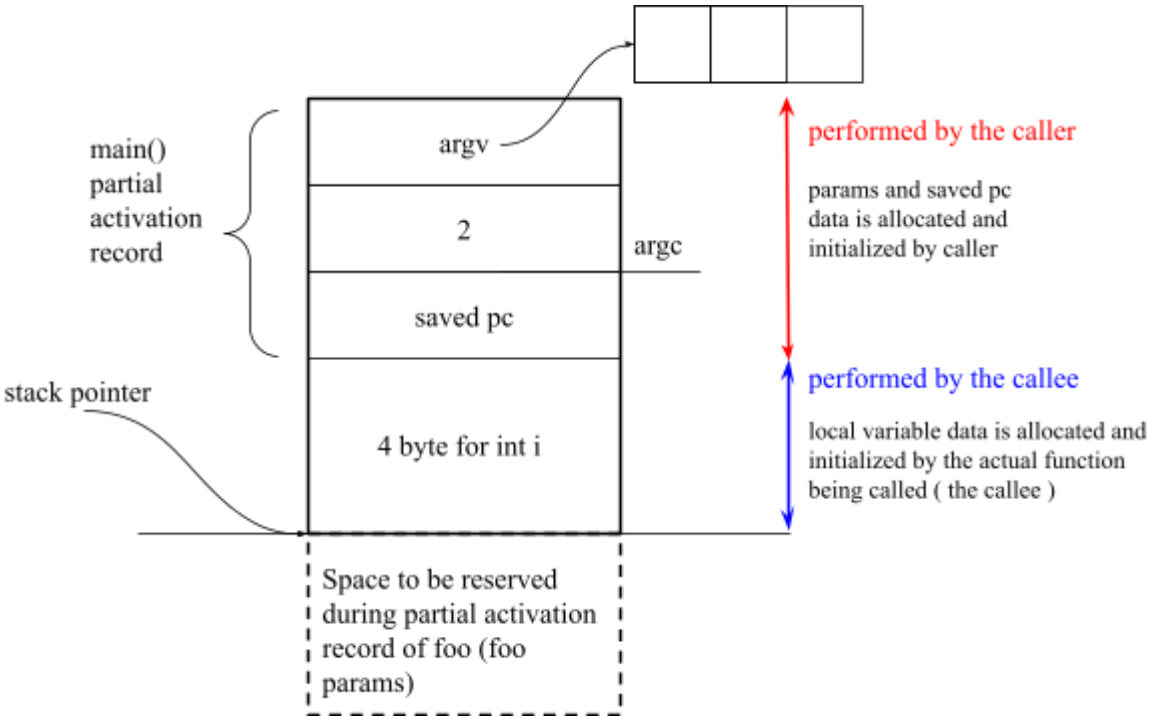
This results in slightly faster and smaller code because there's no need to preserve or restore the base pointer, and fewer instructions are used during function calls and returns.

Note that when I say "pushed", I mean added to the top of the stack. Since the stack grows downward in memory addresses, pushing an item essentially means placing it at a lower memory address than the previous "top" item.

Continuing, suppose we now have:

```
int main(int argc, char** argv) {

    int i = 4;
    foo(i, &i);
    return 0;

}
```

In such case, the activation record diagram for it would look like:



More information about *argc* and *argv* can be found here:
https://stackoverflow.com/questions/3024197/what-does-int-argc-char-argv-mean

Partial activation record of main():

During the partial activation record for main (performed by main's caller), we have parameters and program counter initialization followed by control delegation, namely:

1. caller makes room for main stack data
2. `argc` and `argv` are initialized (pushed into main stack) by the caller;
3. call <main> instruction is executed by the runtime environment, pushing the saved PC (return address) onto the stack and then transfers control to main()

Once main's partial activation is complete, main's function prologue allocates space for its local variables and initializes them.

Partial activation record of foo():

During the partial activation record for foo (performed by main), the cycle repeats itself and we also have parameters and program counter initialization followed control delegation, namely:

1. main makes room for foo stack data
2. The parameters passed to `foo()` within `main` (i and &i) are pushed by the caller (main) onto foo's stack;
3. Main executes call <foo> instruction, which pushes the saved PC (return address) onto the stack and then transfers control to foo()

Once foo's partial activation is complete, foo's function prologue allocates space for its local variables and initializes them.

Taking M as a notation for "all RAM", we could rewrite the partial activation record of foo() with a mock assembly language to help grasp the flow:

```
```
...

SP = SP - 4;   # Allocate space for main's local variable
'i'
M[SP] = 4;   # Initialize 'i' with the value 4

Partial Activation of foo

R1 = SP + 8;   # Load the address (&i) of `i` into register
R1
R2 = M[SP+8];   # Load the value of `i` into register R2
SP = SP - 8;   # Allocate space for foo's arguments
```
```

```
# -------------------------
# Marks the bottom of the full activation record for main() stack
# -------------------------

M[SP] = R2;          # foo's first argument (in the "top" of the
                     # pile, since the stack grows downwards)

M[SP+4] = R1;        # foo's second argument

# Control transfer to foo()
# automatically pushes the return address (Saved PC) onto the
stack

call <foo>

```

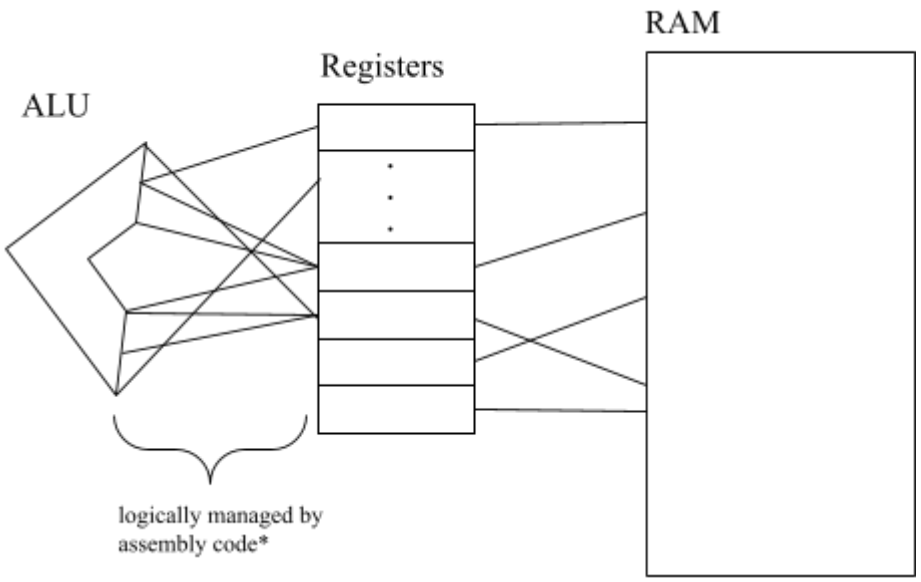
Assembly

Assembly code (or assembly language) is a low-level programming language that is closely related to machine code, the instructions directly executed by a computer's CPU. However, instead of writing in binary or hexadecimal (which machine code uses), assembly code allows programmers to use symbolic names and mnemonics that are easier to understand. Each assembly instruction corresponds to a single machine instruction, providing control over hardware at a detailed level.

Registers

Registers are small and fast storage locations within the CPU that hold data temporarily during instruction execution. The relationship between assembly code and registers is tight because assembly instructions often involve manipulating data stored directly in these registers.

The CPU constantly moves data between RAM (which is slow compared to registers) and registers**.** Data and instructions are loaded from RAM into registers, processed by the CPU, and then results may be written back to RAM.



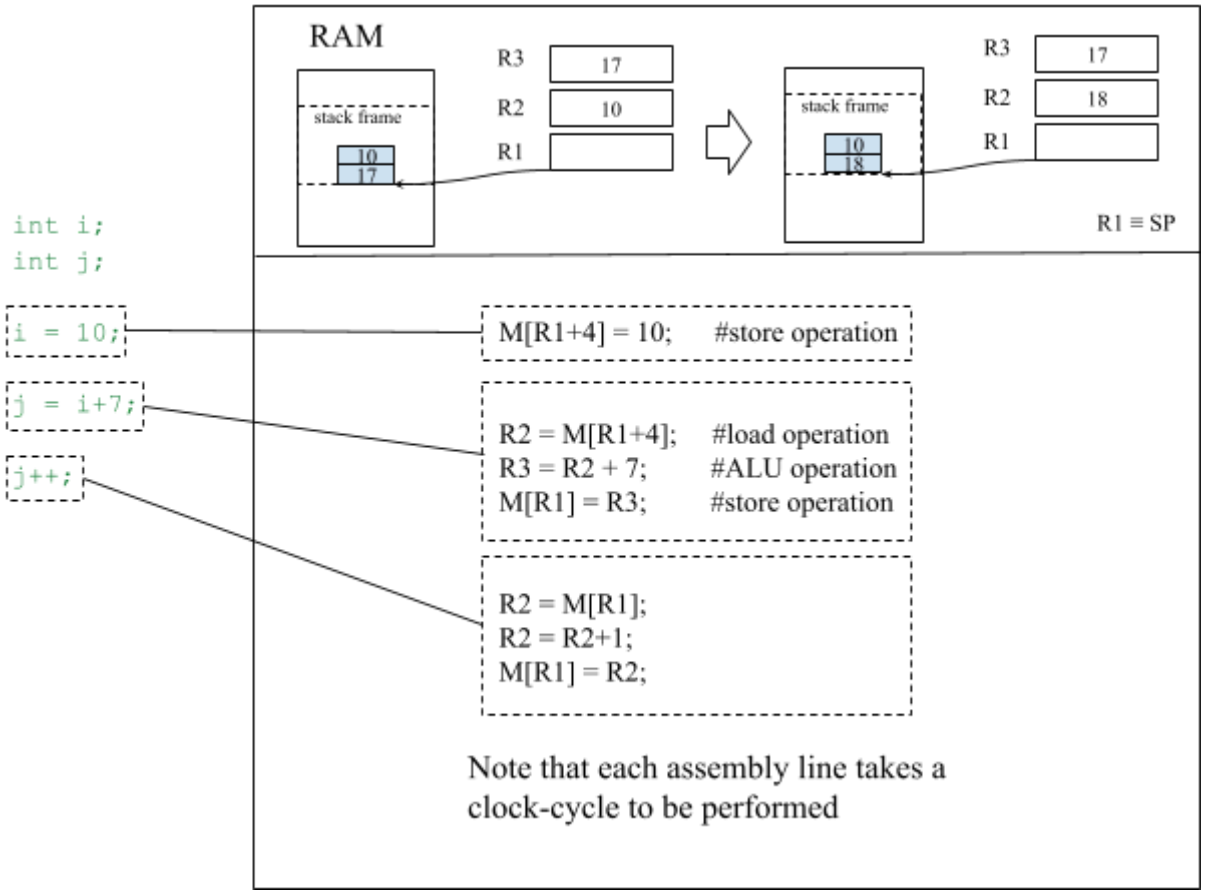
*ALU is electrically in touch with registers, but not with RAM

C to assembly

Continuing with our mock assembly language where M is a notation for "all RAM", suppose we have the following C code:

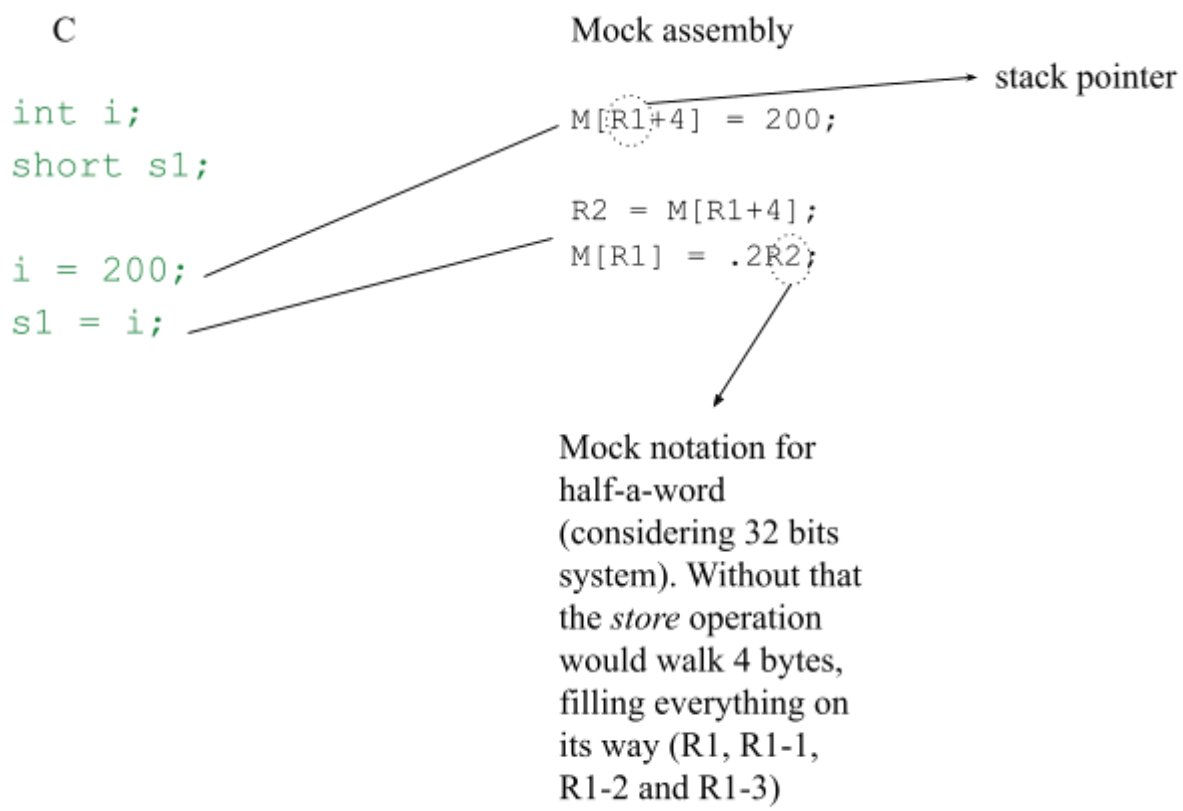
```
int i;
int j;

i = 10;
j = i+7;
j++;
```

How would it translate to our mock assembly?



Half word notation

Registers are typically designed to hold a single *word* and its operations are made in word-wide steps.



To properly store s1 in RAM at `s1 = i` we have to cast/truncate the 200 int (4 bytes) to short (2 bytes) by using a different mnemonic that operates only half-a-word.