Memory management

Bachelor of Science - École polytechnique

gael.thomas@inria.fr

Key concepts

- An array behaves like a pointer
- A local array or structure is allocated within the frame
- A caller receives
  - A pointer to an array for an array
  - A copy of a structure for a structure
- To copy an array or string: `memcpy`, `strncpy`, `sizeof`
- Dynamic memory management: `malloc` and `free`

Array, structure and call frame

Array, structure and call frame

- A local array or structure is allocated within a call frame
  - (i.e., not allocated if the function is not called)

```
void f() {
  struct strange s = {
    .c: 'a',
    .i: 3,
    .f: 3.14 };
  int t[3] = { 7, 8, 9 };
}

int main(int argc, char* argv[]) {
  f();
  return 0;
}
```

```
struct strange {
  char c;
  int i;
  float f;
};
```

Array, structure and call frame

- A local array or structure is allocated within a call frame
  - (i.e., not allocated if the function is not called)

```
void f() {
  struct strange s = {
    .c: 'a',
    .i: 3,
    .f: 3.14 };
  int t[3] = { 7, 8, 9 };
}

int main(int argc, char* argv[]) {
  f();
  return 0;
}
```

argc	1
argv	a value
	frame of main

Array, structure and call frame

- A local array or structure is allocated within a call frame
  - The memory is allocated when the function is called

```
void f() {
  struct strange s = {
    .c: 'a',
    .i: 3,
    .f: 3.14 };
  int t[3] = { 7, 8, 9 };
}

int main(int argc, char* argv[]) {
  f();
  return 0;
}
```

argc	1		
argv	a value		
	frame of main		
s	'a'	3	3.14
t	7	8	9
	frame of f		

Array, structure and call frame

- A local array or structure is allocated within a call frame
  - The memory is allocated when the function is called
  - And released at the end of the function

```
void f() {
  struct strange s = {
    .c: 'a',
    .i: 3,
    .f: 3.14 };
  int t[3] = { 7, 8, 9 };
}

int main(int argc, char* argv[]) {
  f();
  return 0;
}
```

argc	1
argv	a value
	frame of main

Structure and function parameters

Structure and function parameters

- When a parameter is a structure, the argument is fully copied
  - Can take time if the structure is large

```
void fct(struct strange y) {
}

void main(int argc, char* argv[]) {
  struct strange x = {
    .c: 'a',
    .i: 3,
    .f: 3.14
  };
  fct(x);
  return 0;
}
```

argc	1		
argv	a value		
x	'a'	3	3.14
	frame of main		
y	'a'	3	3.14
	frame of fct		

Structure and function parameters

- When a parameter is a structure, the argument is fully copied
  - Can take time if the structure is large
  - A modification in the caller modifies the copy, not the original

```
void fct(struct strange y) {
  y.i = 666;
}

void main(int argc, char* argv[]) {
  struct strange x = {
    .c: 'a',
    .i: 3,
    .f: 3.14
  };
  fct(x);
  return 0;
}
```

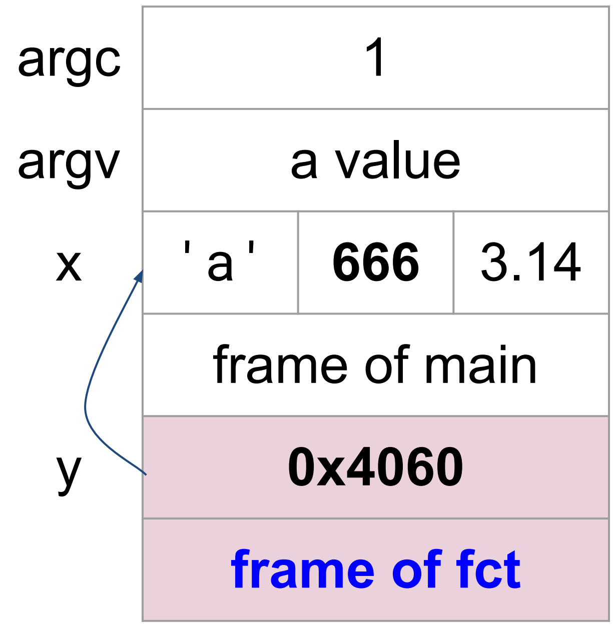
argc	1		
argv	a value		
x	'a'	**3**	3.14
	frame of main		
y	'a'	**666**	3.14
	frame of fct		

Structure and function parameters

- To avoid the copy or to modify the structure in the caller
  - Use a pointer!

```
void fct(struct strange* y) {
  (*y).i = 666;
}

void main(int argc, char* argv[]) {
  struct strange x = {
    .c: 'a',
    .i: 3,
    .f: 3.14
  };
  fct(&x);
  return 0;
}
```



The arrow operator: `->`

- To avoid the copy or to modify the structure in the caller
  - Use a pointer!

```
void fct(struct strange* y) {
  y->i = 666;
}
```

argc	1
argv	a value

Accessing a field of a structure through a pointer is so common that the C language has a specific operator for that:

the `->` operator

`y->i` ⇔ `(*y).i`

Array and pointers

Array and pointer

- We can access an array through a pointer
  - `p = tab` => p points to the first element of the array
  - Here, we suppose that `tab` is allocated at 0x4060
  - Note that we don't need the & operator in this case!

```
void fct(int x) {
  int tab[3];
  int* p = tab;
  for(int i=0; i<3; i++) {
    *(p + i) = x + i;
  }
}

int main(int argc, char* argv[]) {
  fct(7);
  return 0;
}
```

	...		
	frame of main		
x	7		
p	0x4060		
tab			
i			
	frame of fct		

Array and pointer

- We can access an array through a pointer
  - `p + i` computes a pointers to the `i`th element of the array
  - In details, `0x4060 + i*4` since `p` points to an `int` (4 bytes)

```
void fct(int x) {
  int tab[3];
  int* p = tab;
  for(int i=0; i<3; i++) {
    *(p + i) = x + i;
  }
}

int main(int argc, char* argv[]) {
  fct(7);
  return 0;
}
```

	...		
	frame of main		
x	7		
p	0x4060		
tab	7	8	
i	1		
	frame of fct		

Array and pointer

- In fact, **a variable with the type array behaves like a pointer!**
  - That’s why we don’t need the & operator
  - The difference between a pointer and an array is that the C language allocates the space for the array for an array, but allocates the space for a pointer for a pointer

```
void fct(int x) {
  int tab[3];
  for(int i=0; i<3; i++) {
    *(tab + i) = x + i;
  }
}

int main(int argc, char* argv[]) {
  fct(7);
  return 0;
}
```

	...		
	frame of main		
x	7		
tab	7	8	
i	1		
	frame of fct		

Array and pointer

- In fact, a variable with the type array **behaves like** a pointer!
  - And we can use a pointer as an array!
  - *(p + i) and p[i] are totally equivalent

```
void fct(int x) {
  int tab[3];
  int* p = tab;
  for(int i=0; i<3; i++) {
    p[i] = x + i;
  }
}

int main(int argc, char* argv[]) {
  fct(7);
  return 0;
}
```

	…		
	frame of main		
x	7		
p	0x4060		
tab	7	8	
i	1		
	frame of fct		

Array and function parameters

- If a parameter has the type array, the array is not copied
  - A pointer to the array is passed
  - We say that arrays are passed by pointer

```
void fct(int tab[]) {
  for(int i=0; i<3; i++) {
    tab[i] = -1;
  }
}

int main(int argc, char* argv[]) {
  int x[3] = { 4, 5, 6 };
  fct(x);
  return 0;
}
```

argc	7		
argv	a value		
x	4	5	6
	frame of main		

Array and function parameters

- If a parameter has the type array, the array is not copied
  - `tab` receives a pointer to the array `x` (`0x4060` for the example)

```
void fct(int tab[]) {
  for(int i=0; i<3; i++) {
    tab[i] = -1;
  }
}

int main(int argc, char* argv[]) {
  int x[3] = { 4, 5, 6 };
  fct(x);
  return 0;
}
```

argc	7		
argv	a value		
x	4	5	6
	frame of main		
tab	0x4060		
i			
	frame of fct		

Array and function parameters

- If a parameter has the type array, the array is not copied
  - `tab[i] = -1` modifies the array `x`

```cpp
void fct(int tab[]) {
  for(int i=0; i<3; i++) {
    tab[i] = -1;
  }
}

int main(int argc, char* argv[]) {
  int x[3] = { 4, 5, 6 };
  fct(x);
  return 0;
}
```

argc	7		
argv	a value		
x	-1	-1	6
	frame of main		
tab	0x4060		
i	1		
	frame of fct		

Array and function parameters

- There is no fundamental difference between
  - Declaring a parameter with an array type
  - Or with a pointer type

```
void fct(int tab[]) {
  for(int i=0; i<3; i++) {
    tab[i] = -1;
  }
}
```

⇔

```
void fct(int* tab) {
  for(int i=0; i<3; i++) {
    tab[i] = -1;
  }
}
```

Array and string

- A string is not a string
  - It's an array of characters (`char[]`)
  - That ends with the integer `0`, which indicates the end
  - And `char*` is a pointer to the first character of the string

```
int main(int argc, char* argv[]) {
  char* str = "hello";

  for(int i=0; str[i] != 0; i++) {
    printf("%c\n", str[i]);
  }
  // => h, e, l, l, o on each line
  return 0;
}
```

Array and string

- A string literal is a shortcut that
  - Creates a hidden global variable with the type `char[]`
  - Initialized with the characters of the string followed by `0`
  - Replaces the literal by the hidden variable

```
int main(int argc, char* argv[]) {
  char* str = "hello";
  ...
```

⇓

```
char hidden[] = { 'h', 'e', 'l', 'l', 'o', 0 };

int main(int argc, char* argv[]) {
  char* str = hidden;
  ...
```

Array and copy

- `t1 = t0` does not copy the array `t0` into the array `t1`
  - The expression either fails or copies the pointers

- To copy an array
  - `memcpy(dst, src, n)`: copy `n` bytes from `src` to `dst`
  - `strncpy(dst, src, n)`: copy the string `src` into `dst`
    - Stop the copy when the end of `src` is found (value `0`)
    - Or when `n` bytes are copied (avoid bugs if `dst` is too small)

- To use `memcpy`, we have to know the size of the elements
  - `sizeof(type)`: give the size of `type`
  - `sizeof(*var)` => give the size of the type of the value pointed by `var` (provided that `var` is a pointer)

Array and copy

- To use `memcpy` and `strncpy`, you have to include `<string.h>`

```
#include <string.h>

void test() {
  int t0[3] = { 1, 2, 3 };
  int t1[3];
  memcpy(t1, t0, sizeof(*t0) * 3);
}
```

```
#include <string.h>

void test() {
  char* s0 = "hello";
  char s1[128];
  strncpy(s1, s0, 128);
  // copy 6 bytes
  //   5 for hello
  // + 1 for the final 0
}
```

Heap and dynamic memory management

Why dynamic allocation

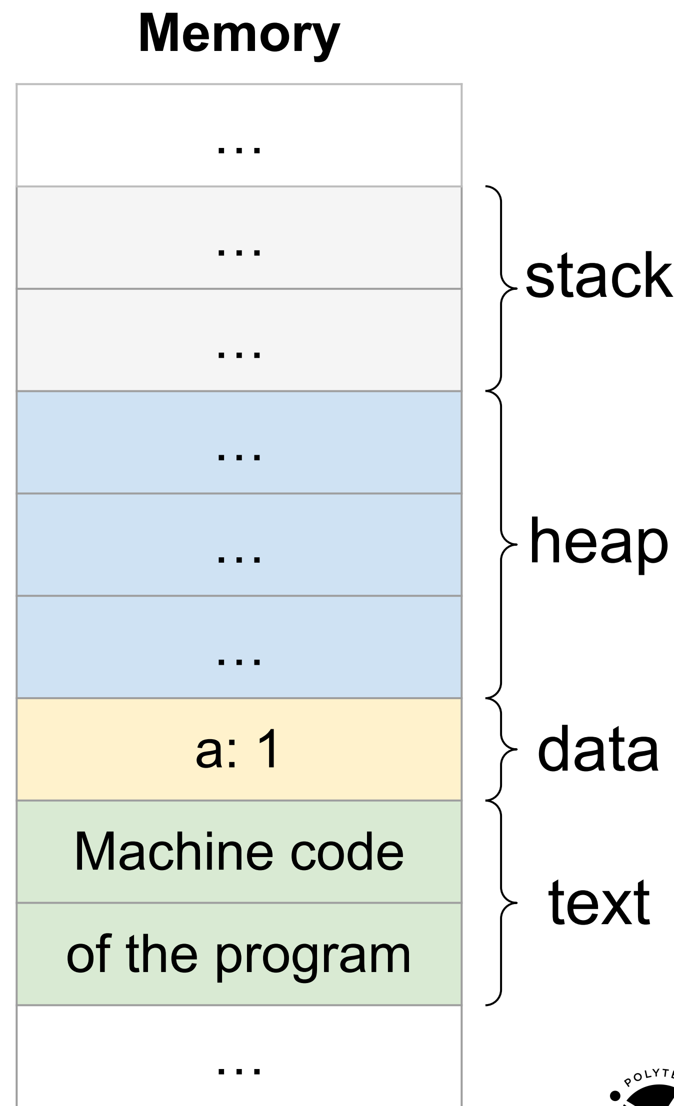
- Sometimes, the lifetime of a data structure does not match the lifetime of a function, for example:
  - The objects owned by a character in a video game
  - The user accounts of a web server
  - …

- Why the lifetime cannot match in these cases
  - The order of frame allocations gives the order of release
    - f call g => allocate frame f, allocate frame g, free frame g, free frame f
  - But for many objects, allocating and freeing them can have any order
    - find a potion, find a sword, drink the potion but keep the sword

The heap

- The heap is a fourth segment used to explicitly and dynamically allocate and free memory

	Used for	Read/Write	Data lifetime
Stack	Frames	R/W	Dynamic
Heap	Dynamic data	R/W	Dynamic
Data	Global variables	R/W	Whole execution
Text	Code	R	Whole execution



Dynamic memory allocation

- `void* malloc(size_t n)`
  - `size_t`: a type used to represent a size (`unsigned long int`)
  - n: the number of bytes to allocate
  - `void*`: returns a pointer to an unknown type

```
struct pokemon {
  char name[256];
  int health;
};

int main(int argc, char** argv) {
  struct pokemon* p = malloc(sizeof(*p));
  strncpy(p->name, "Pikachu", 256);
  p->health = 78;
  return 0;
}
```

Memory allocation and array

- To allocate an array, simply allocates N times a data structure

```
struct pokemon {
  char name[256];
  int health;
};

int main(int argc, char** argv) {
  // allocate 42 pokemons
  struct pokemon* p = malloc(42 * sizeof(*p));
  // allocate 666 int
  int* q = malloc(666 * sizeof(*q));
  q[33] = -1;
  return 0;
}
```

Free the memory of a data structure

- `void free(void* ptr)`
  - `ptr` has to have been allocated by malloc (otherwise the application crashes at runtime)

```
struct pokemon {
  char name[256];
  int health;
};

int main(int argc, char** argv) {
  struct pokemon* p = malloc(42 * sizeof(*p));
  int* q = malloc(666 * sizeof(*q));

  free(p);
  free(q);

  return 0;
}
```

Key concepts

- An array behaves like a pointer
- A local array or structure is allocated within the frame
- A caller receives
  - A pointer to an array for an array
  - A copy of a structure for a structure
- To copy an array or string: `memcpy`, `strncpy`, `sizeof`
- Dynamic memory management: `malloc` and `free`