CS4414 Recitation 2

C++ functions and memory management

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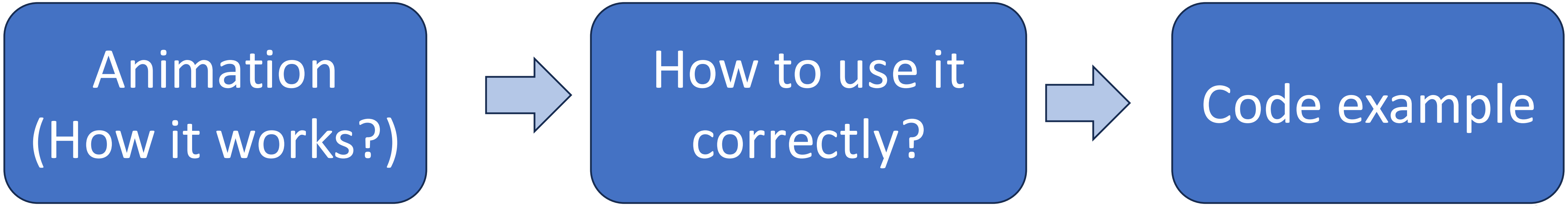
Alicia Yang

Overview

- C++ functions
    - Function parameters
    - Function return
- C++ memory management
- C++ smart pointer



Functions

- Function parameters
- Function returns

C++ Function

A sequence of statements with a name and a list of parameters

Return type
(function derived type)

Function parameters

```
int add(int a, int b){
    return a+b;
}
```

Function body

Ways to pass in function parameters

- Pass by value : passing a copy of the value
- Pass by pointer : passing the copy of the value’s pointer
- Pass by reference : passing a reference

Function Parameter

--- Passing value

When a value is passed to a function, a copy of the value is created.

```
void increment(int value){
    value ++;
}
int main(){
        int a = 0;
        increment(a);
        …
}
```

a = ?

Function Parameter

--- Passing value

When a value is passed to a function, a copy of the value is created.

```
void increment(int value){
   value ++;
}
int main(){
       int a = 0;
       increment(a);
       std::cout << a << std::endl;
}                    // print 0
```

1. changes inside the function are **NOT** reflected after the function call.

Function Parameter

--- Passing value

When a value is passed to a function, a copy of the value is created.

```
void print_str(std::string value){
    std::cout << value << std::endl;
}
int main(){
    std::string paragraph;
    … …
    print_str(a);
}
```

2. Copying is time-consuming for large objects

Function Parameter

What if I want to change an external variable?
Can I avoid copying of parameters?

- Pass by value : p

- Pass by pointer : passing the copy of the value's pointer

- Pass by reference : passing a reference

* Function Parameters --- Passing pointer

Semantics:

providing the function with the **address** of the variable rather than its **value**.

- Function can **modify** the original value through dereferencing
- **Direct access** to original variable
- **Memory efficiency**

Function Parameter

--- Passing pointer

```
void increment(int* a){
    (*a)++;
}

int main(){
        int a = 0;
        increment(&a);
        …
}
```

a = ?

& Function Parameter --- Passing reference

Semantics: allowing the function to operate directly on the original variable, rather than on a copy

- Function can modify the argument
- Direct access to original variable
- No copy is made

& Function Parameter

--- Passing reference

```
void increment(int& a){
    a++;
}

int main(){
        int a = 0;
        increment(a);
        …
}
```

a = ?

Poll

PollEv.com/cs4414c552

What does it print?

```
#include <iostream>

void func(int* x, int y) {
    *x = 5;
    y = y + *x;
    x = &y;
    *x = *x + 10;
}
```

```
int main() {
    int x = 0;
    int y = 10;
    func(&x, y);
    std::cout << x << std::endl;
    return 0;
}
```

Demo

Poll

Pointer variable itself is passed by copy

```
#include <iostream>

void func(int* x, int y) {
    *x = 5;
    y = y + *x;
    x = &y;
    *x = *x + 10;
}
```

```
int main() {
    int x = 0;
    int y = 10;
    func(&x, y);
    std::cout << x << std::endl;
    return 0;
}
```

Functions

- Function parameters
- Function returns

Function Returns --- value

- Return by value : returning a copy of the value

```
int value( int a ) {
        int b = a * a;
        return b;       // return a copy of b
}
```

Note: Return by value could avoid copying under compiler's C++ Return Value Optimization (RVO)

* Function Returns --- pointer

Why return pointers?

- Allow direct access to memory

Demo

Function Returns --- pointer

Incorrect way of returning a pointer

- return a pointer to a **local variable**

Function Returns --- pointer

What can go wrong?

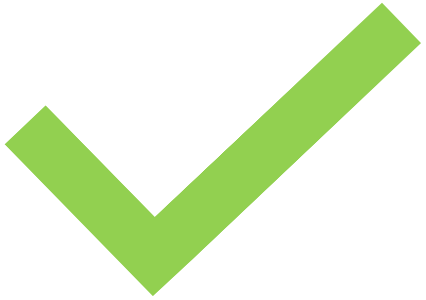
Dangling pointers

```
int* dangerousFunc() {
        int localVar = 100;
        return &localVar;
}

int main() {
        int* res = dangerousFunc();
        std::cout << *res << std::endl;
}
```

Undefined behavior!

Function Returns --- pointer

```cpp
int* safeFunc() {
        static int localVar = 100;
        return &localVar;
}
int main() {
        int* res = safeFunc();
        std::cout << *res << std::endl;
}
```



Function Returns --- pointer

Correct ways of returning a pointer

- Returning a pointer to a global or static variable
- Returning a pointer to a non-local array element
- Returning a pointer from a class member function
- Returning a pointer to memory on heap

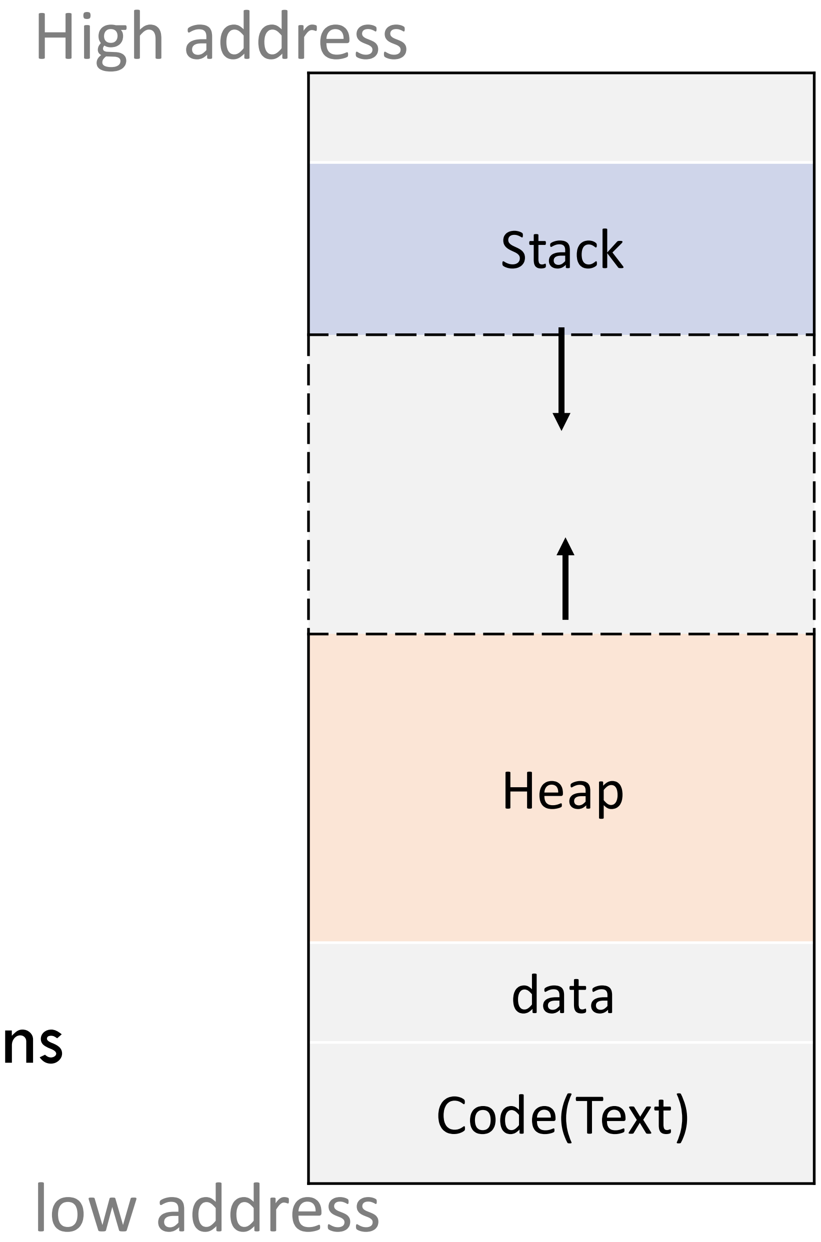
C++ Memory Management

- How does stack and heap memory work?
- How to use stack and heap memory in my program?

Stack memory

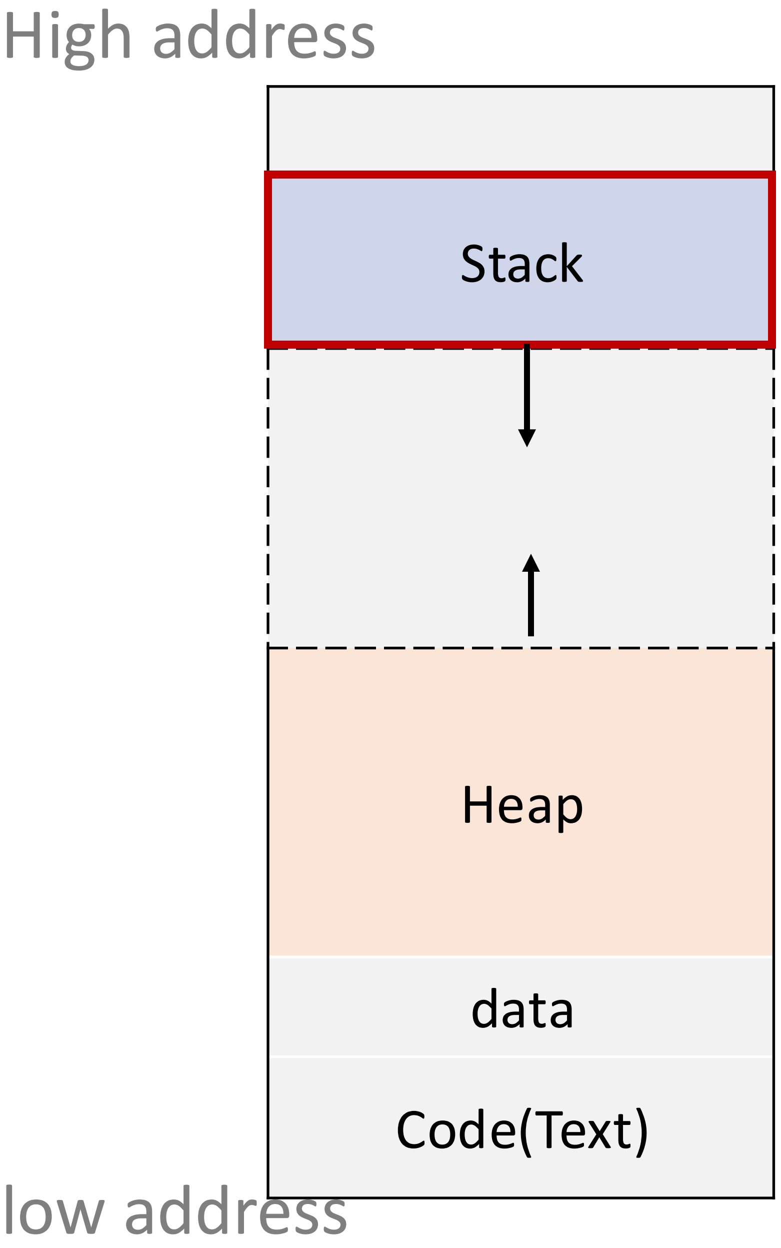
Memory

- **Stack:** used for memory needed to call methods(such as local variables), or for inline variables
- **Heap:** Dynamically memory used for programmers to allocate. The memory will often be used for longer period than stack
- **Data:** use for constants and initialized global objects
- **Code:** segments that holds compiled instructions



Stack Memory

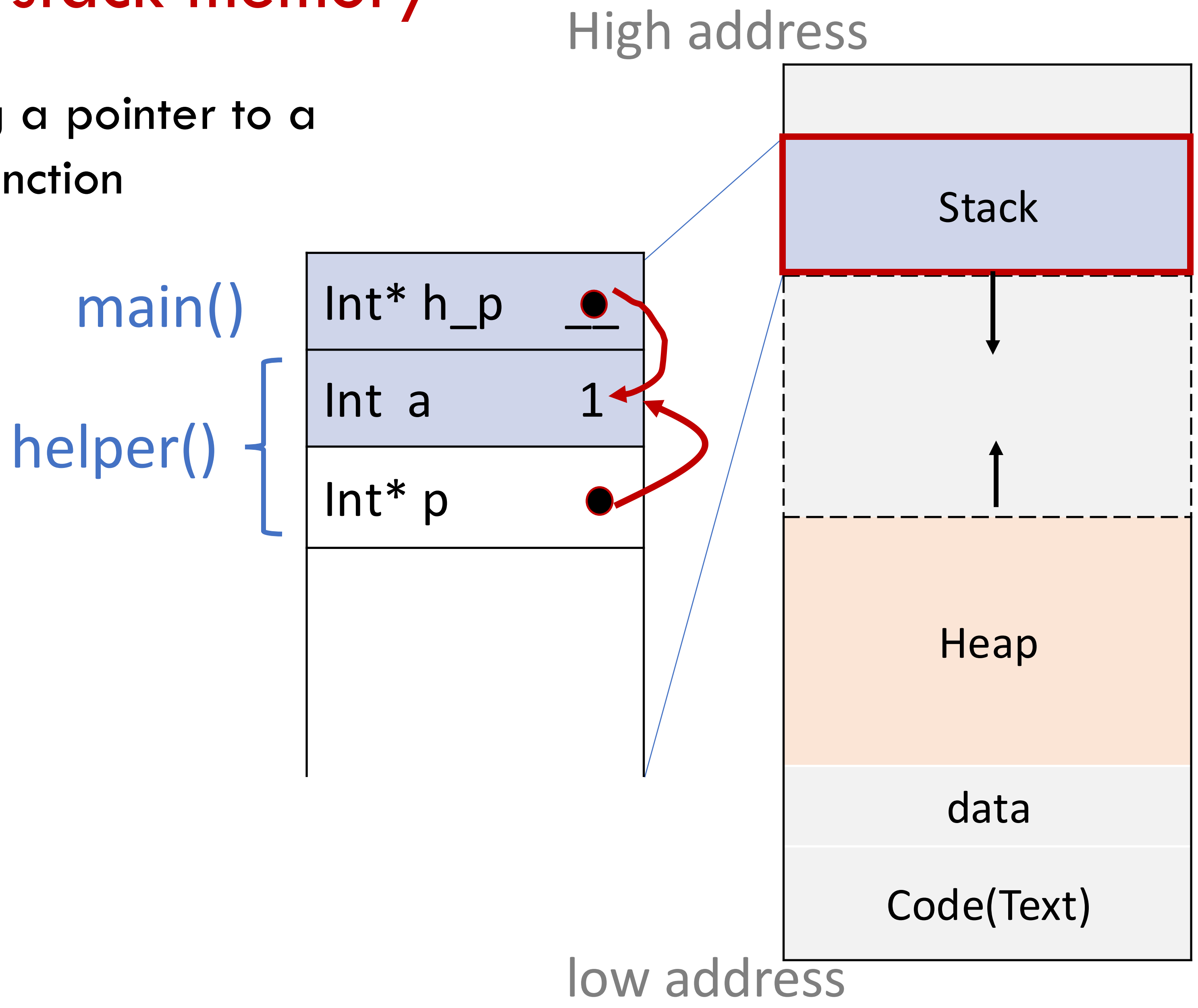
- Stack Allocation (Temporary memory allocation):
  - Allocate on contiguous blocks of memory, in a fixed size
  - Allocation happens in function call stack
  - When a function called, its variables got allocated on stack; when the function call is over, the memory for the variables is deallocated. (scope)
  - The allocation and deallocation for stack memory is **automatically done**.
  - Fast to allocate memory on stack(1CPU operation), faster than heap



Common mistake with stack memory

- A common mistake: returning a pointer to a stack variable in a helper function

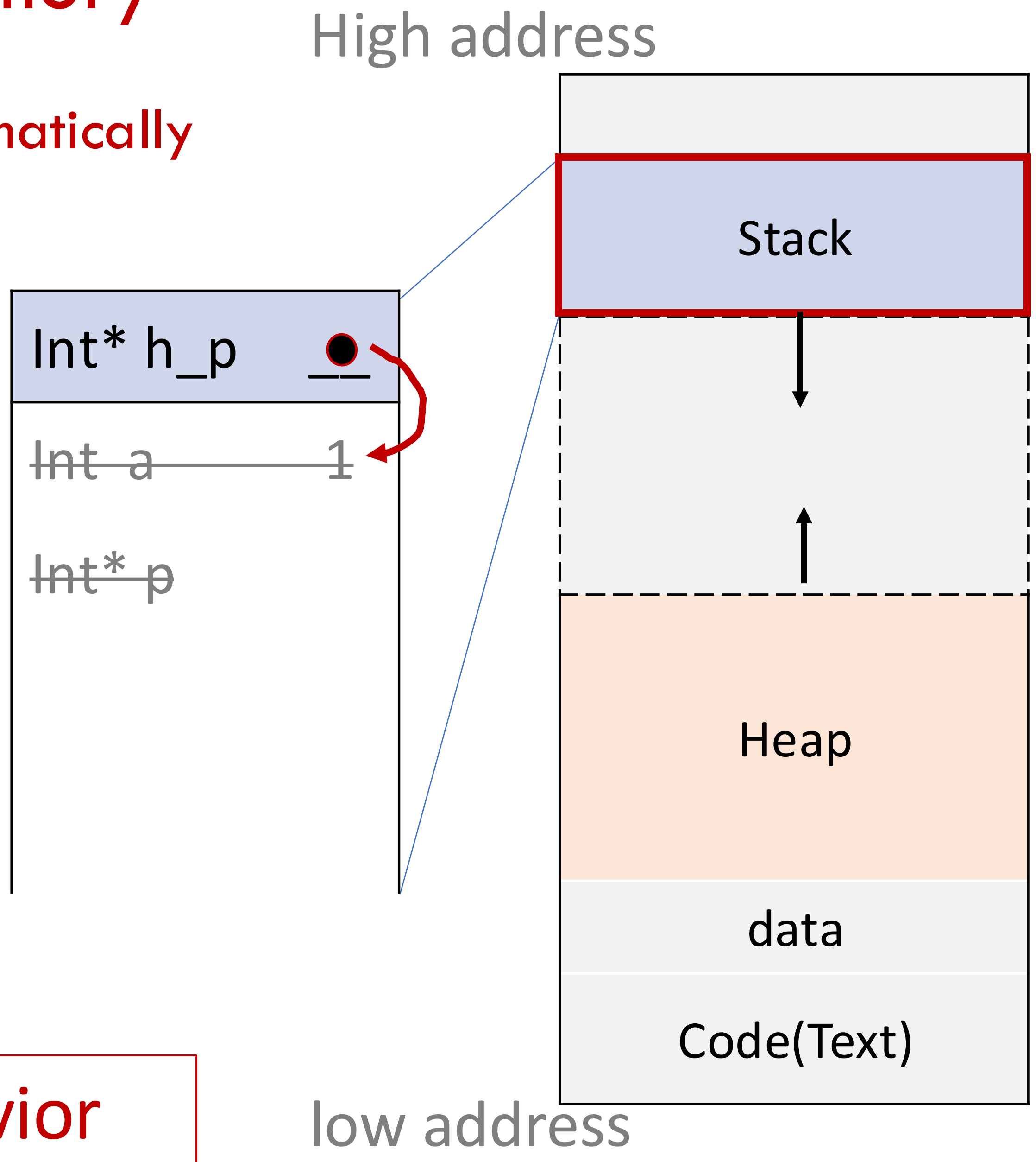
```
int* helper()
{
    int a = 3;
    int * p = &a;
    return p;
}
int main(){
     int* h_p = helper();
     …
}
```



Common mistake with stack memory

- The stack memory of a function gets automatically deallocated after the function returns

```
int* helper()
{
    int a = 3;
    int * p = &a;
    return p;
}
int main(){
    int* h_p = helper();
    …
}
```



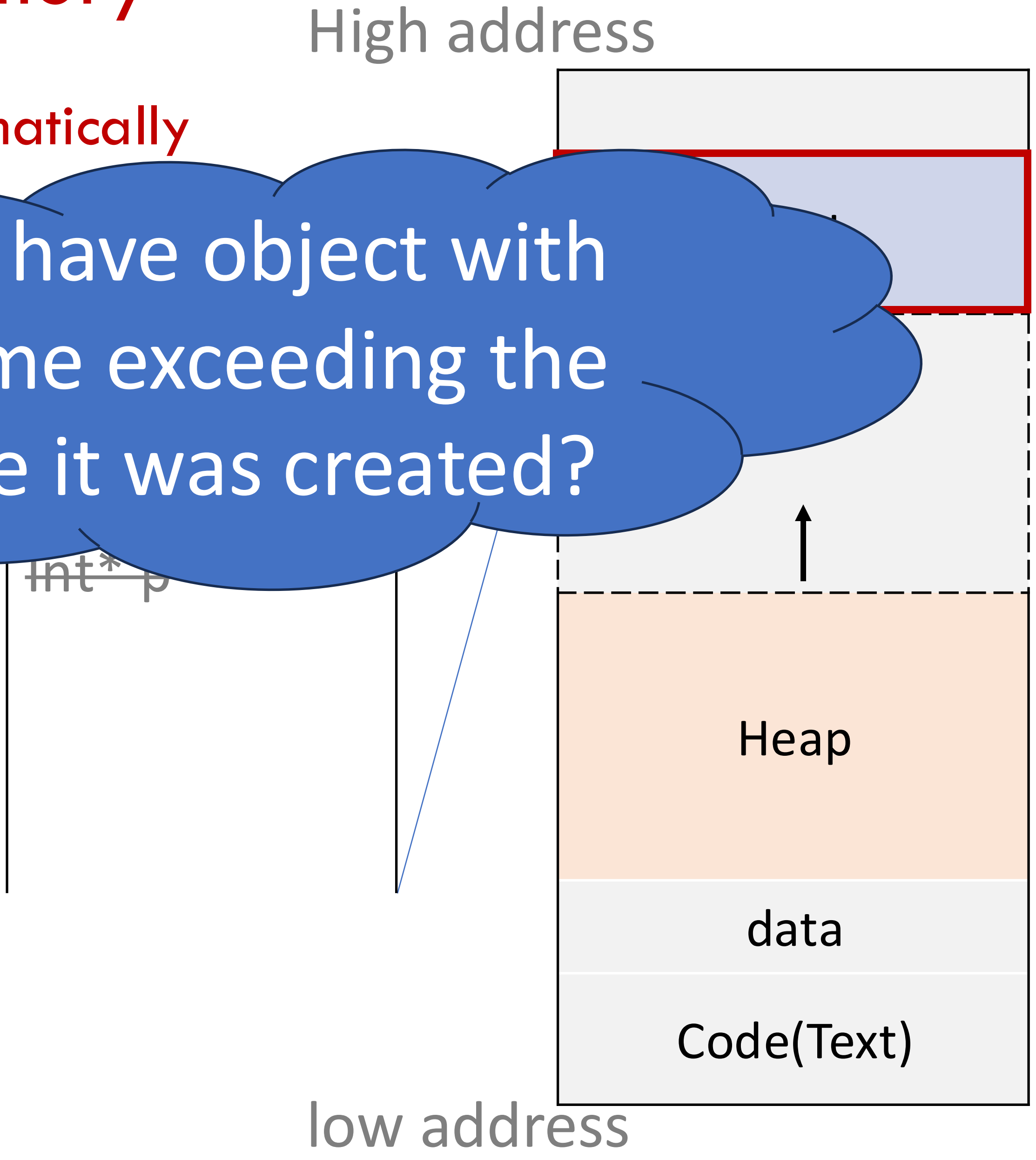
Undefined behavior

Common mistake with stack memory

- The stack memory of a function gets automatically deallocated after the function retu

Can I have object with lifetime exceeding the scope it was created?

```
int* helper()
{
    int a = 3;
    int * p = &a;
    return p
}
int main(){
    int* h_
                  );
    …
}
```

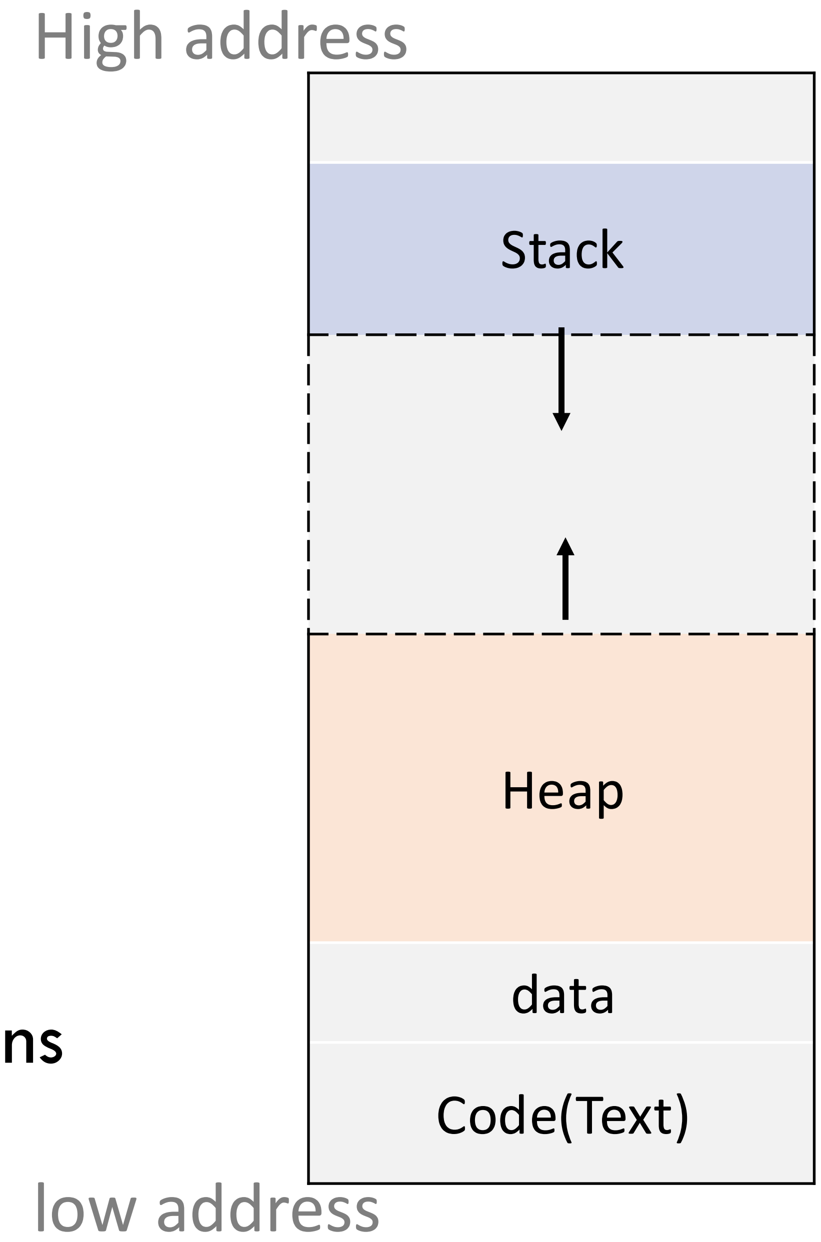


Heap memory

new
delete

Memory

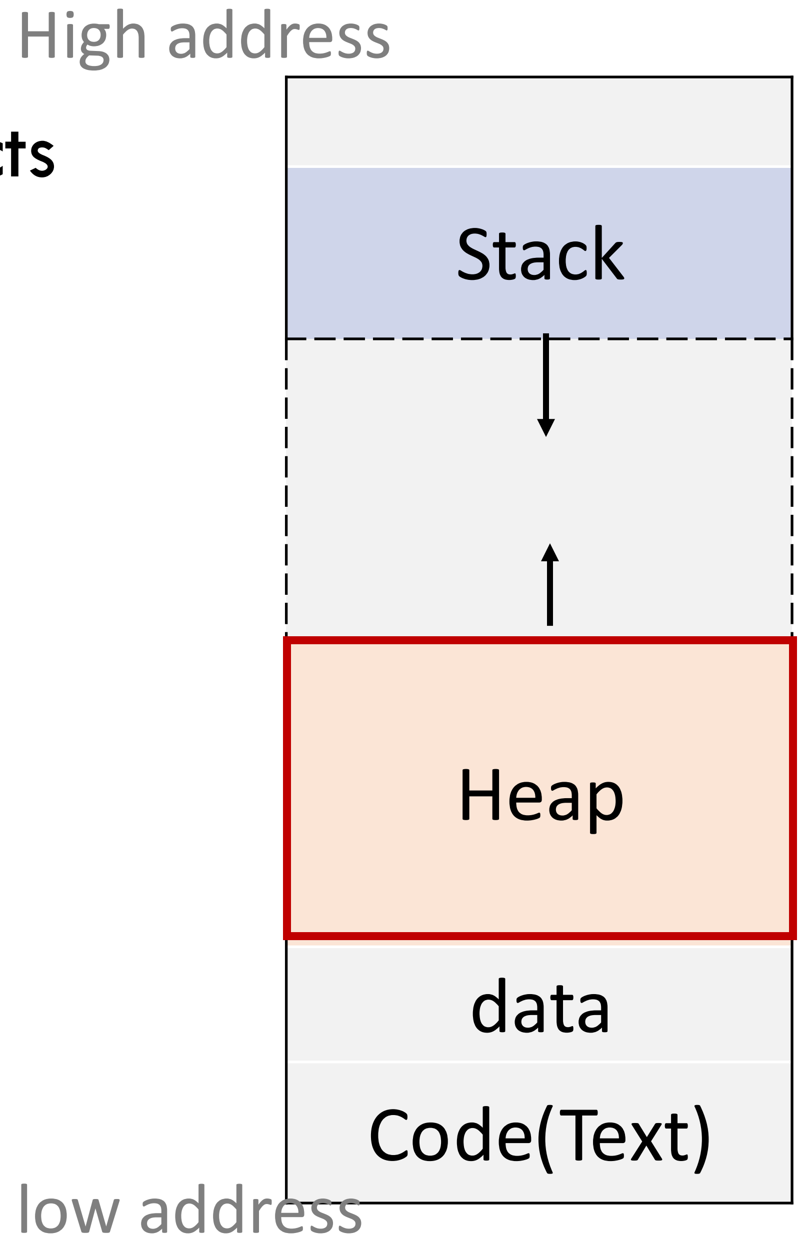
- **Stack:** used for memory needed to call methods(such as local variables), or for inline variables
- **Heap:** Dynamically memory used for programmers to allocate. The memory will often be used for longer period than stack
- **Data:** use for constants and initialized global objects
- **Code:** segments that holds compiled instructions



Heap Memory   new expression

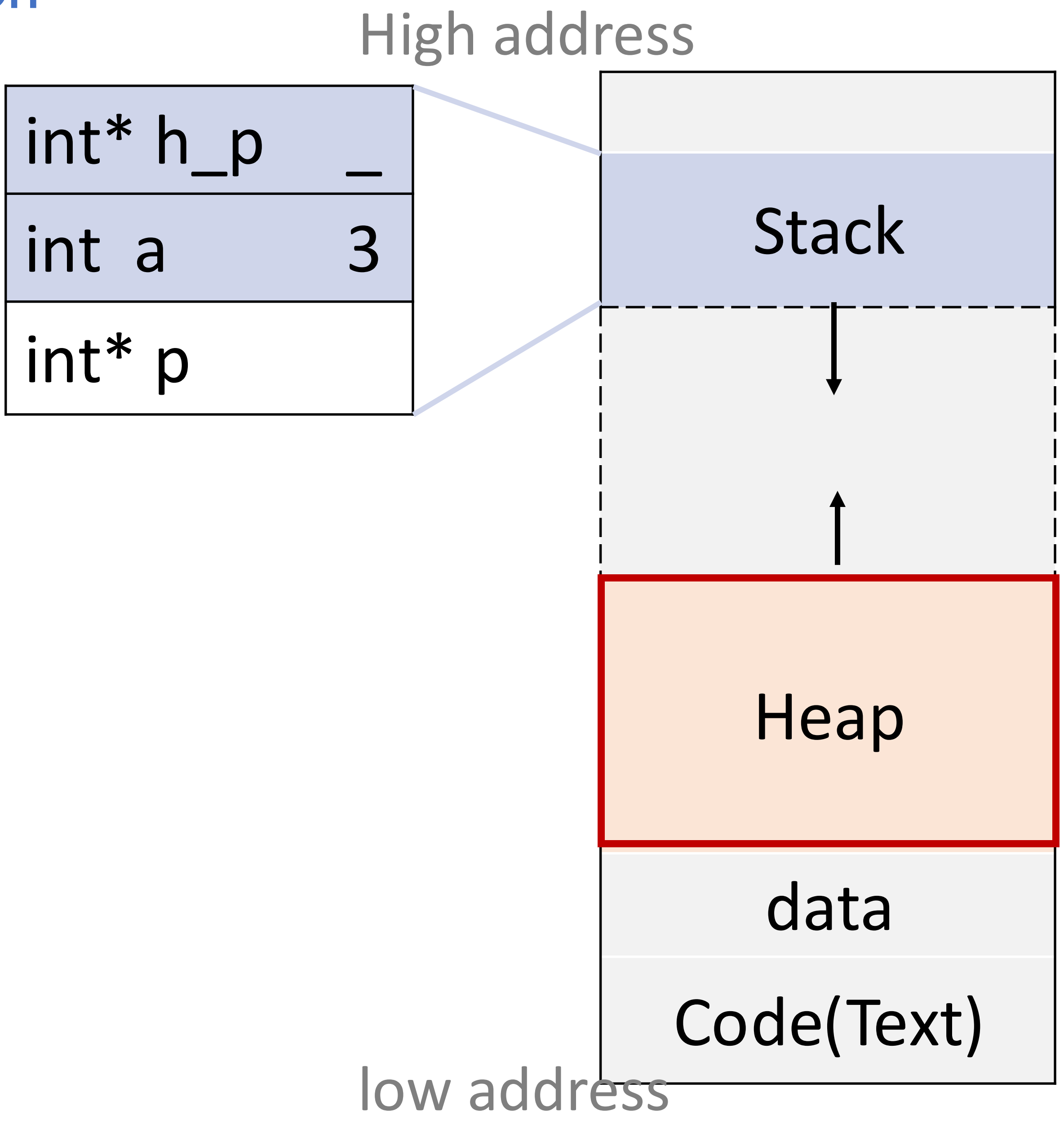
- new expression: create and initialize objects on heap (dynamic storage duration)

```
int* p = new int(7);

double* arr_p = new double[]{1, 2, 3};

T* obj_p = new T(arg0, arg1, arg2,…);
```



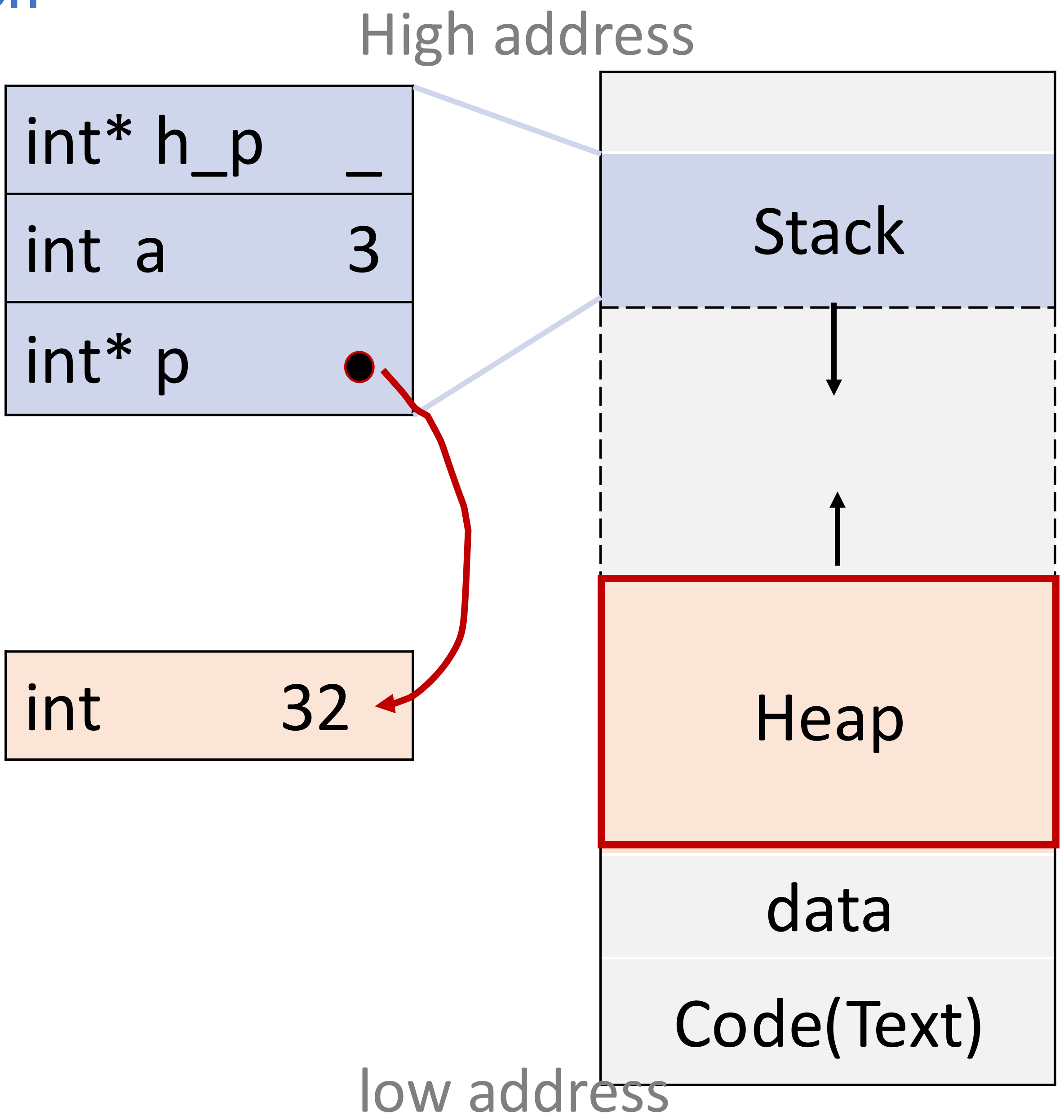
Heap Memory   new expression

```
int* helper()
{
    int a = 3;
    int * p = new int(32);
    return p;
}

int main(){
     int* h_p = helper();
      ...
}
```



Heap Memory   new expression

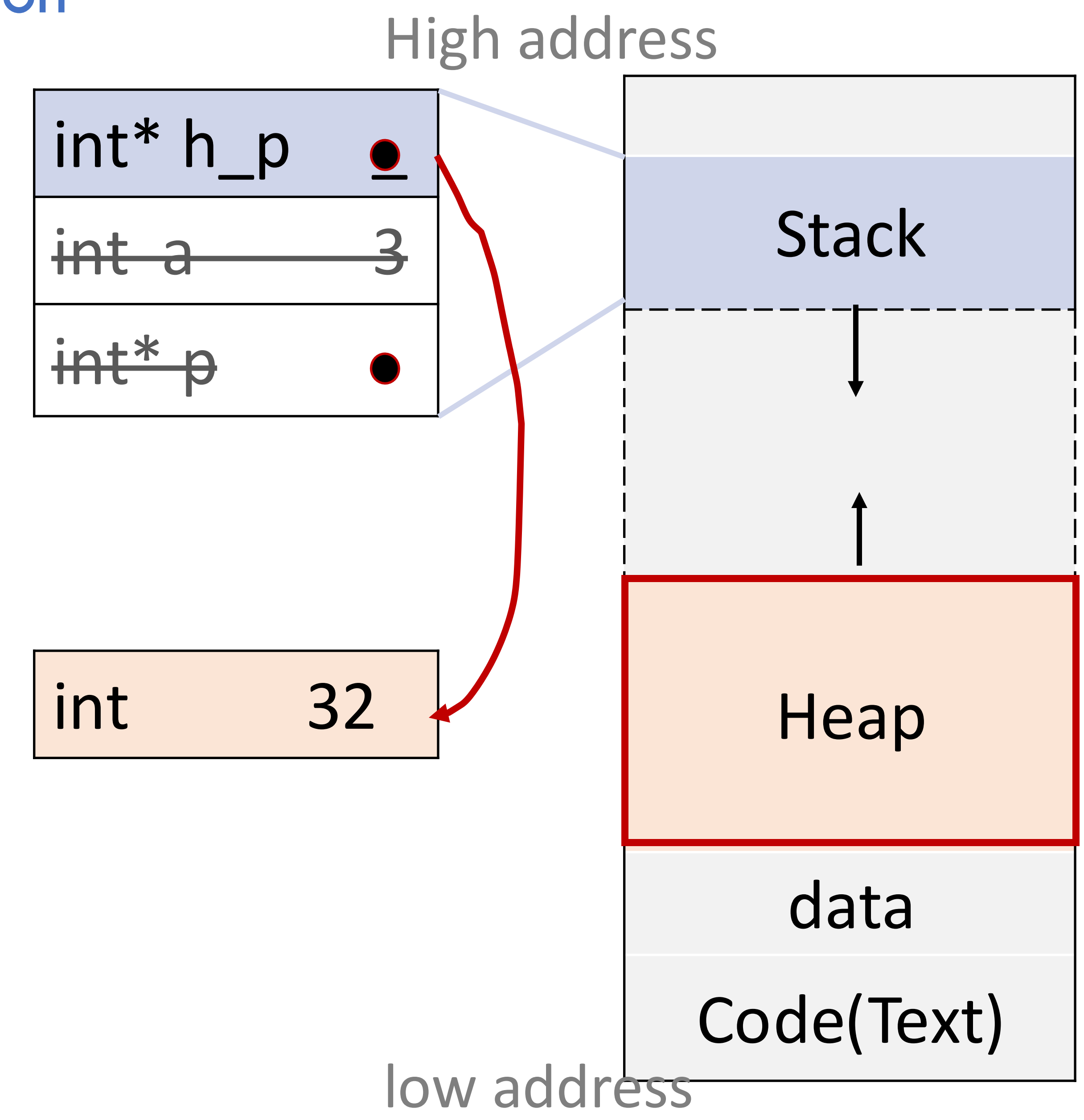
```
int* helper()
{
    int a = 3;
    int * p = new int(32);
    return p;
}

int main(){
    int* h_p = helper();
     ...
}
```



Heap Memory

new expression

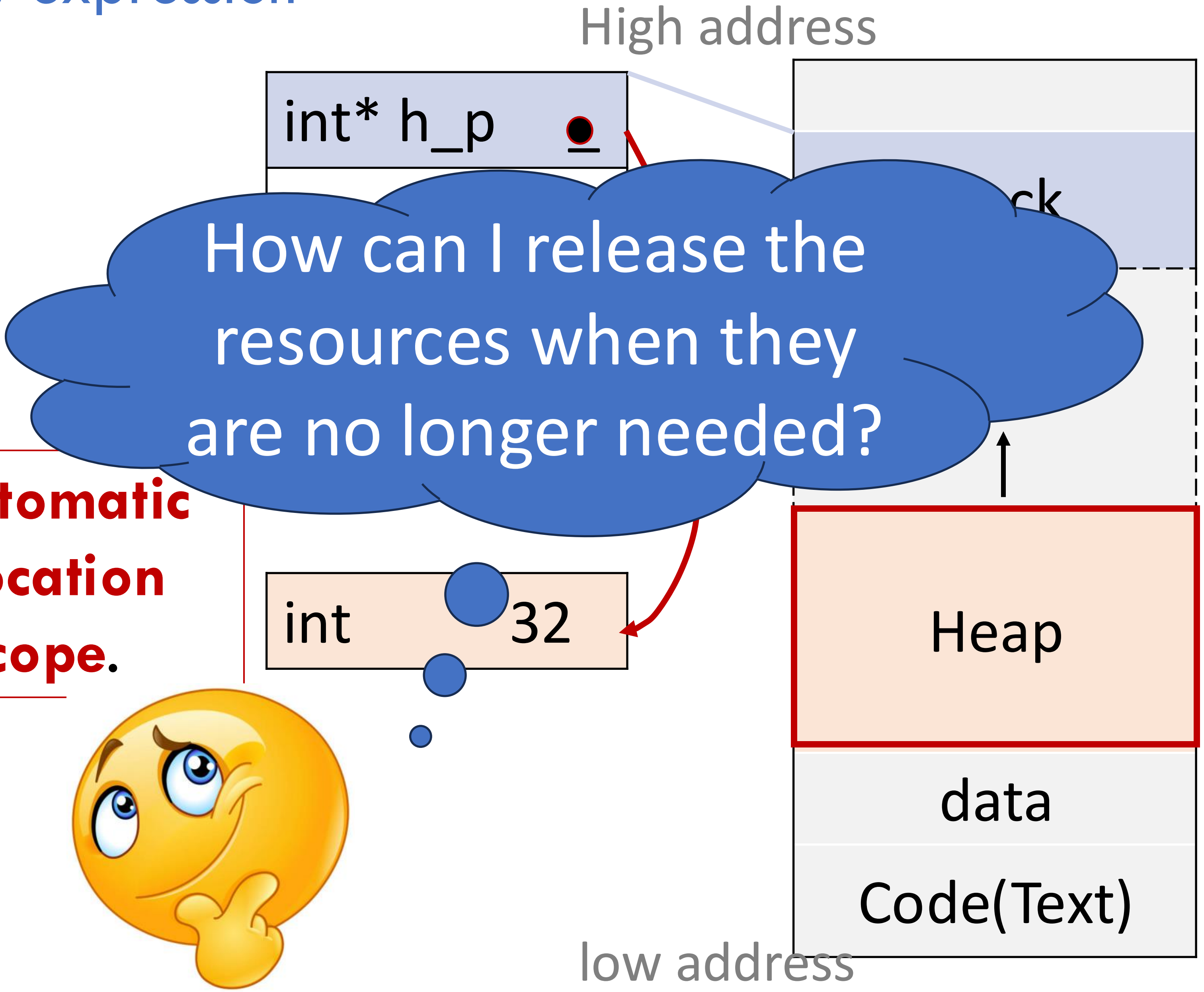
```
int* helper()
{
    int a = 3;
    int * p = new int(32);
    return p;
}

int main(){
     int* h_p = helper();
      ...
}
```



Heap Memory   new expression

```
int* helper()
{
    int a = 3;
    int * p = new int(32);
    return p;
}

int main(){
    int* h_p = helper();
    ...
}
```

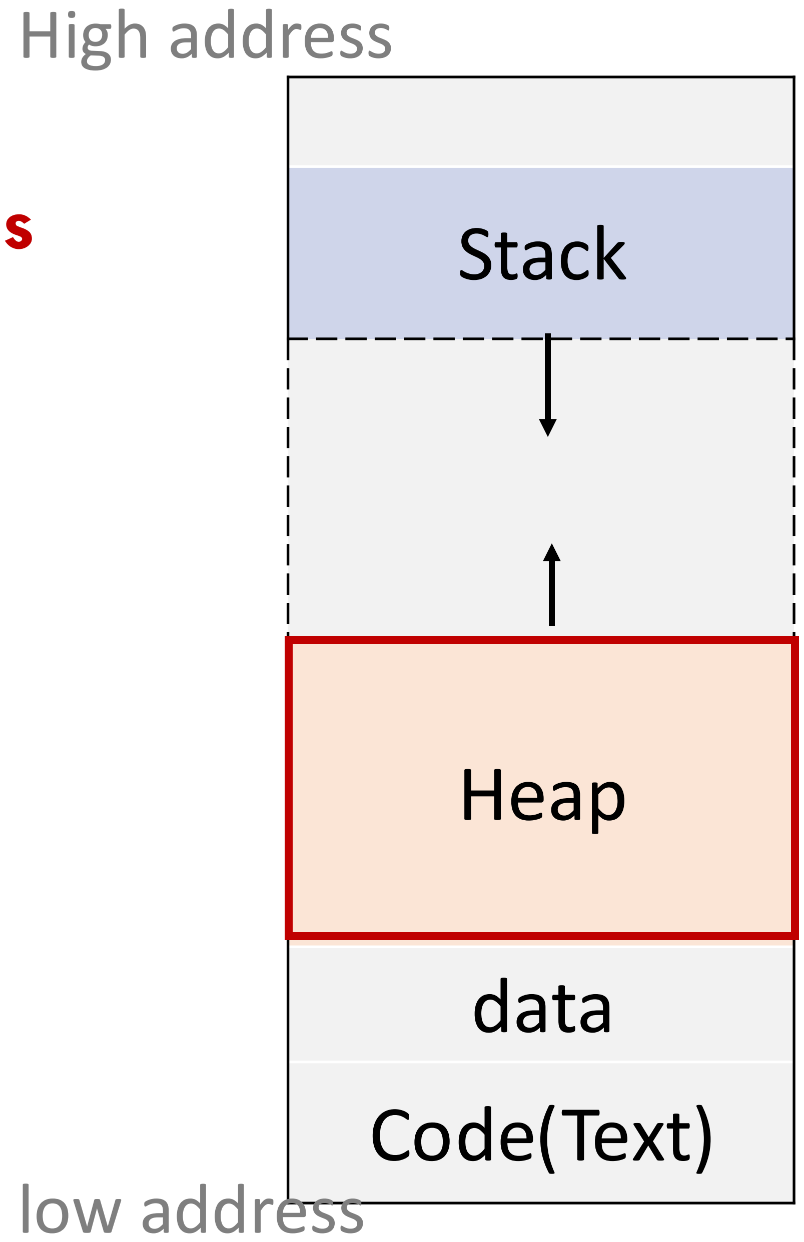
NO automatic de-allocation with scope.



Heap Memory   delete expression

- delete expression: **destroys** object previously allocated by the new-expression and **releases** obtained memory area back to OS.

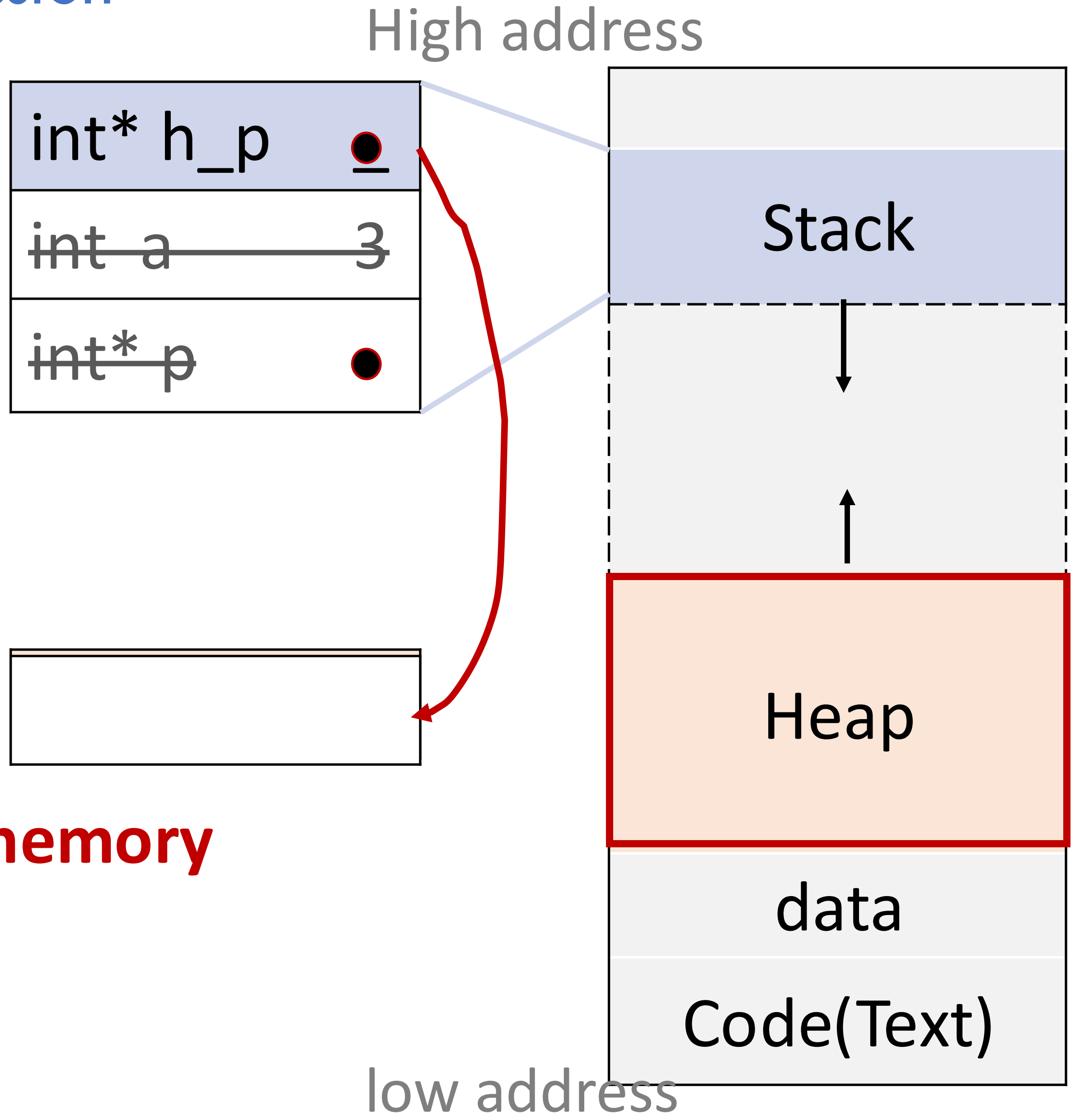
```
int* p = new int(7);
delete p;

double* arr_p = new double[]{1, 2, 3};
delete[] arr_p;

T* p = new T(arg0, arg1, arg2,…);
delete obj_p;
```



Heap Memory

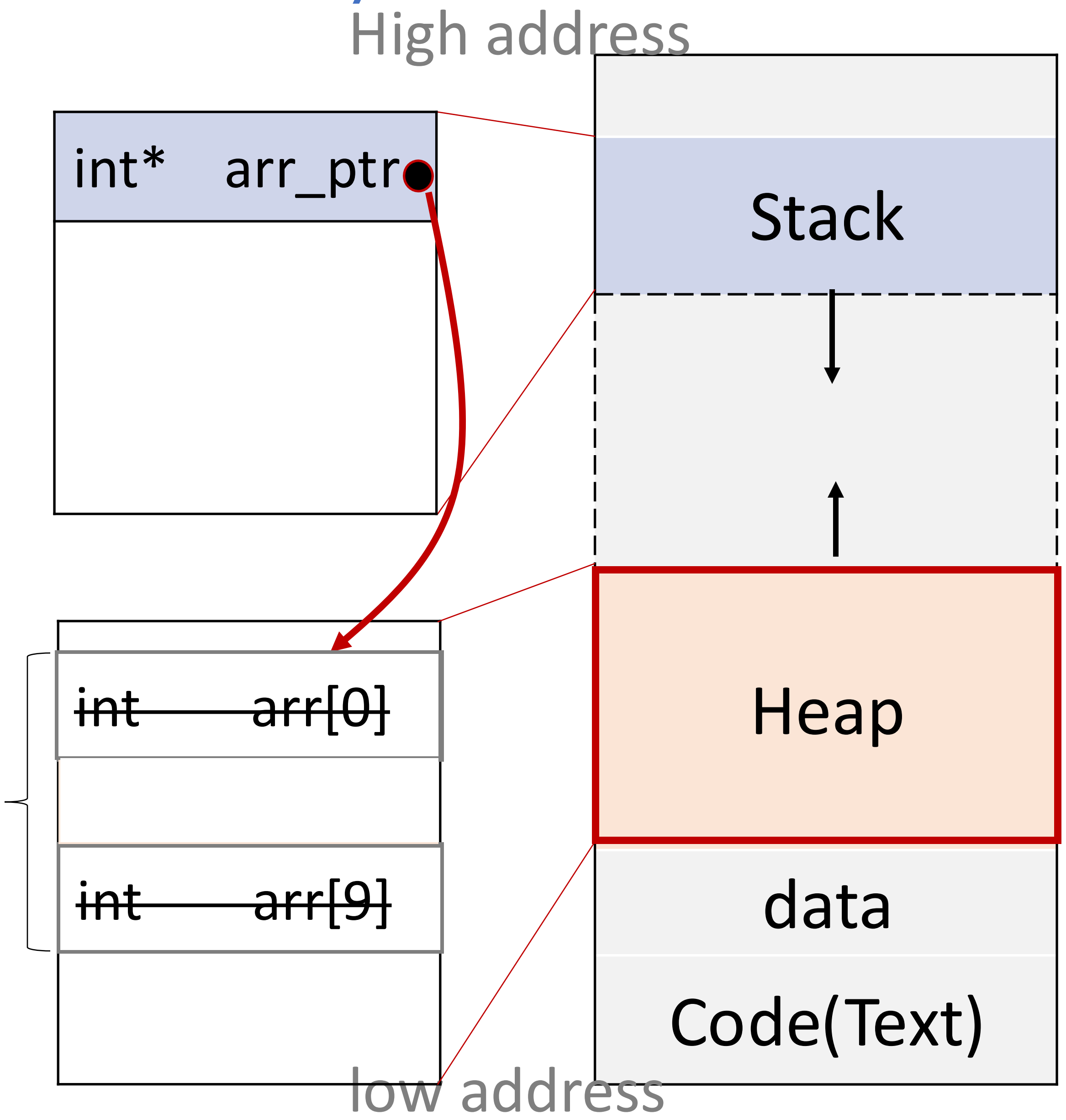
delete expression

```
int* helper()
{
    int a = 3;
    int * p = new int(32);
    return p;
}
int main(){
    int* h_p = helper();
    delete h_p;     // release the memory
    .....
}
```



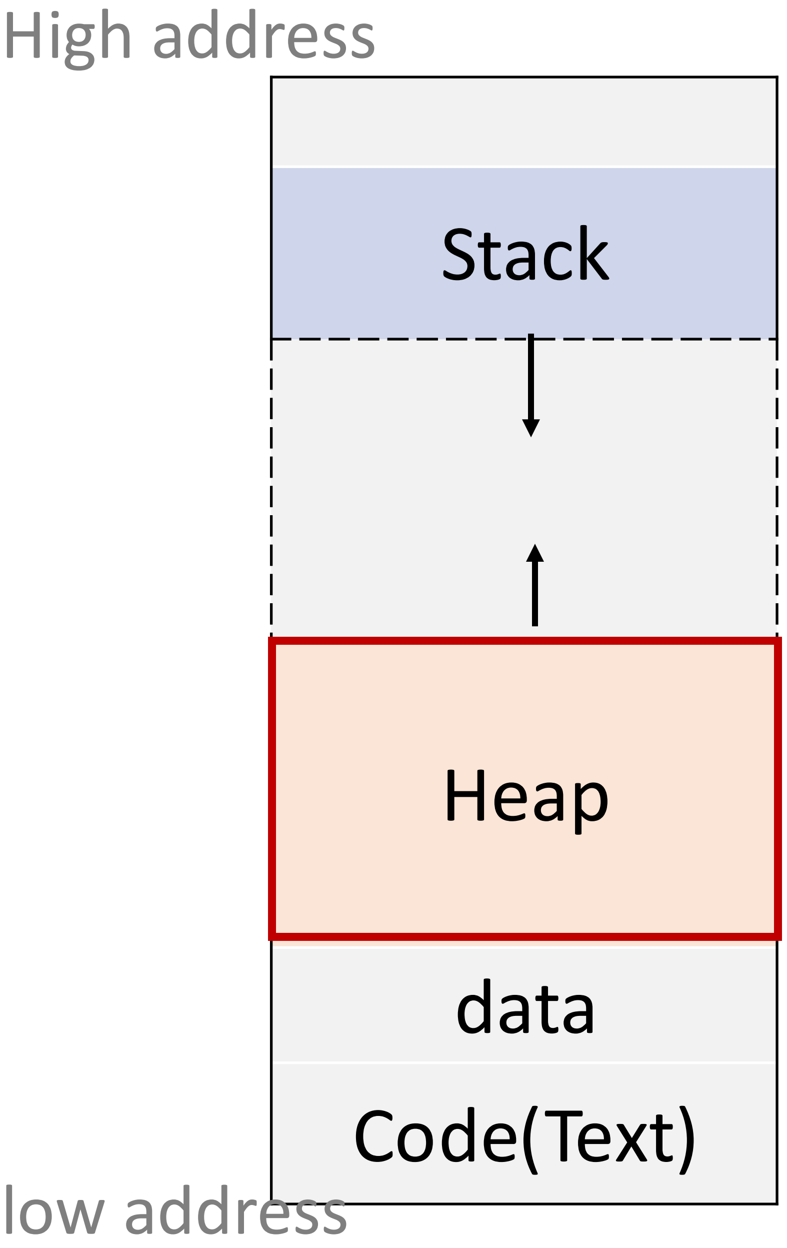
Heap Memory   delete expression for array

```
int * arr_ptr  = new int[10];

delete arr_ptr;      ✗

delete[] arr_ptr;    ✓
```



Heap Memory

- Heap memory is allocated explicitly by **new** expression.
- To release heap memory, program needs explicitly call **delete** expression.
- Unlike stack, memory allocated on heap is **not** necessarily **contiguous**

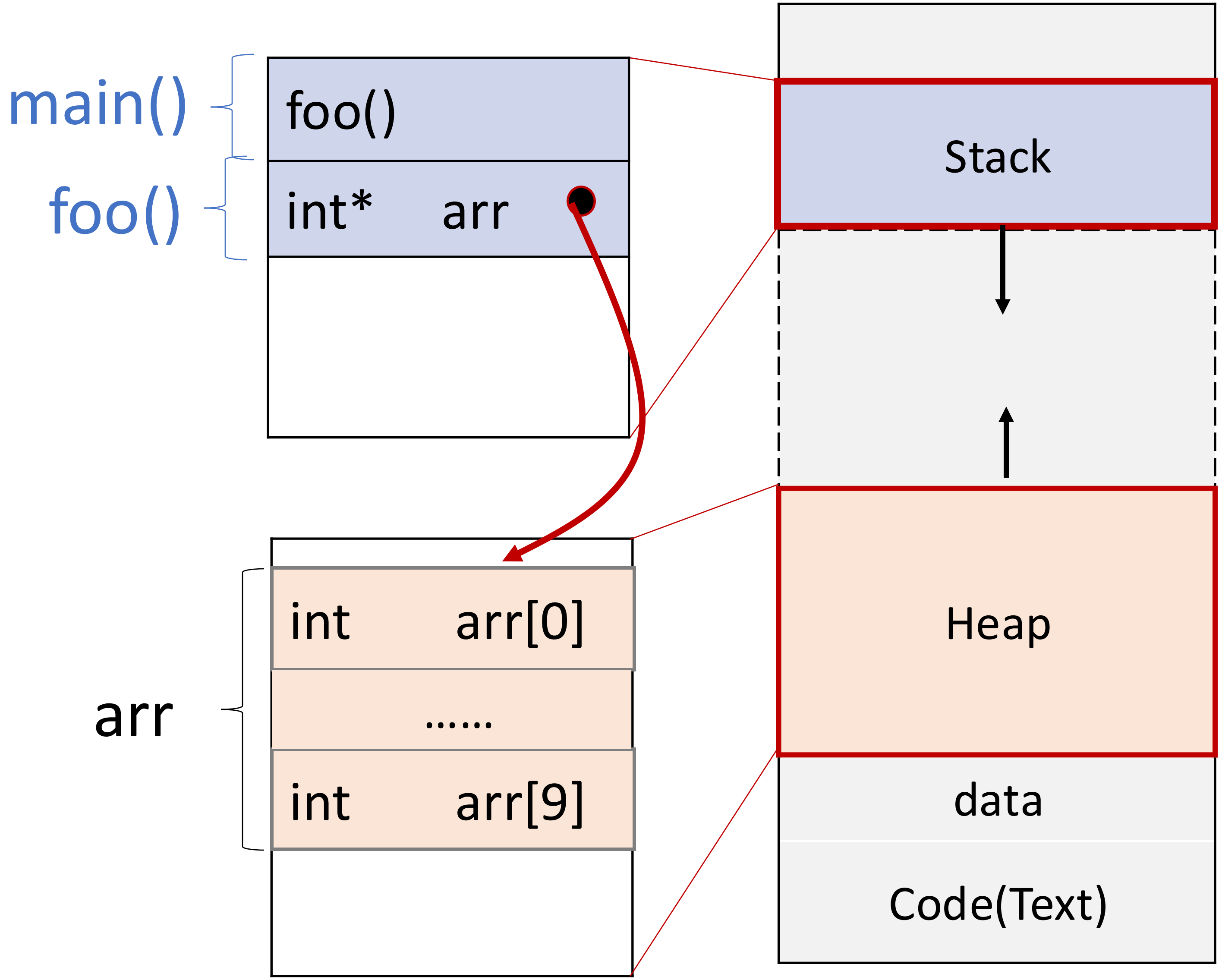


C++ Memory

- How does stack and heap memory work?
- How to use stack and heap memory in my program?

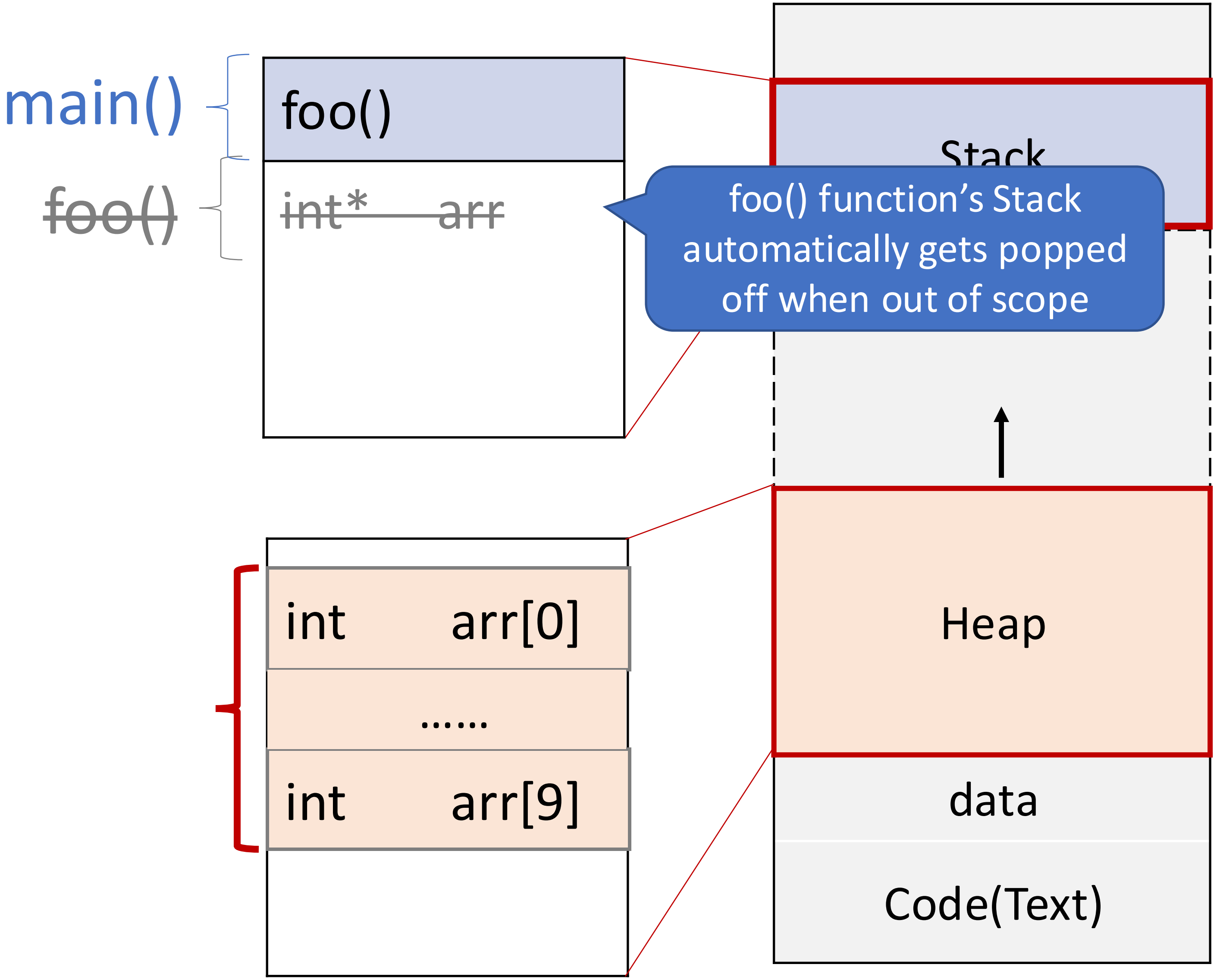
heap-based memory allocation

```
void foo(){
    int* arr = new int[10];
    arr[0] = 0;
}

int main(){
    foo();
    .......
}
```



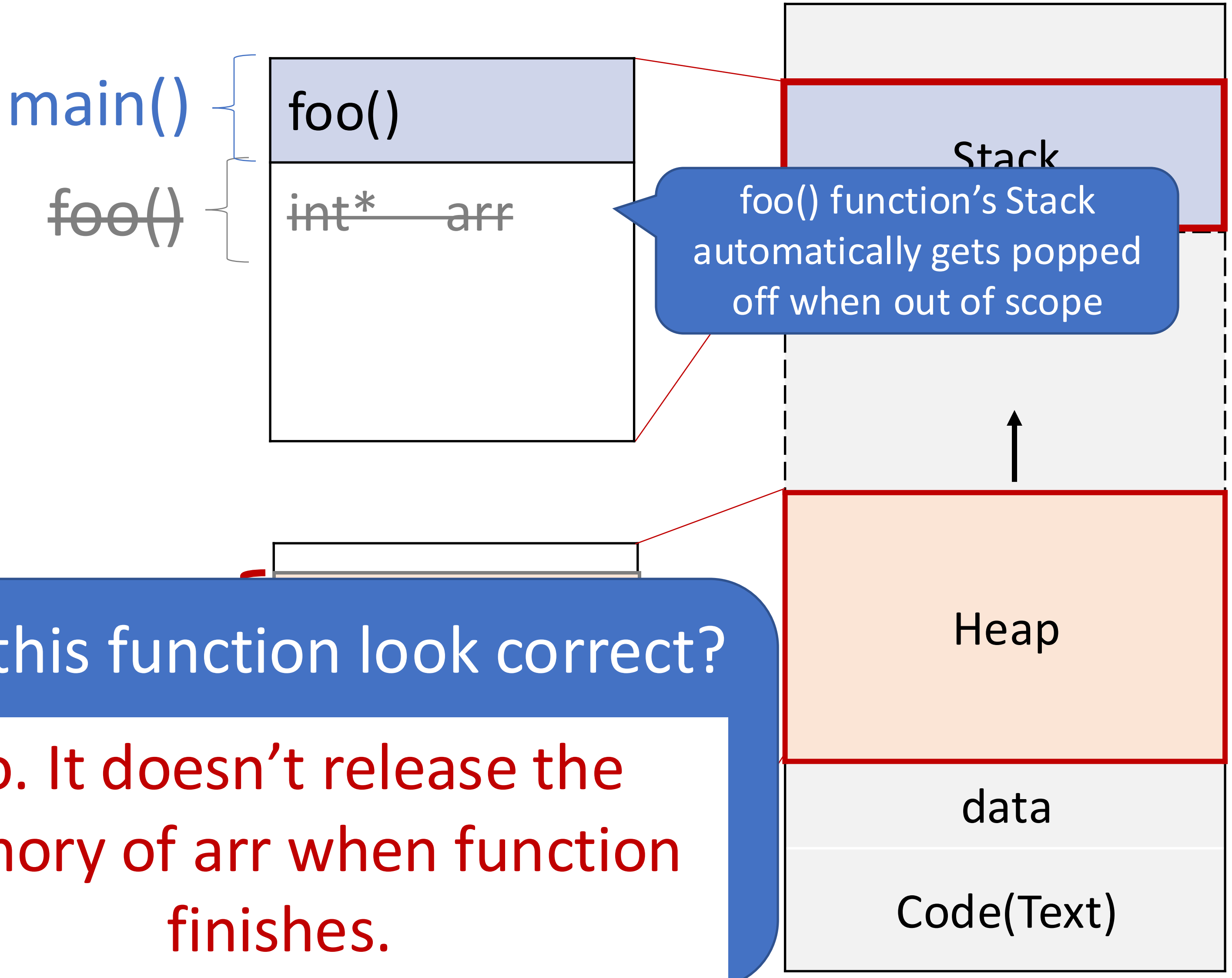
heap-based memory allocation

```
void foo(){
    int* arr = new int[10];
    arr[0] = 0;
}

int main(){
    foo();
    .......
}
```



heap-based memory allocation

```
void foo(){
    int* arr = new int[10];
    arr[0] = 0;
}

int main(){
    foo();
    .......
}
```

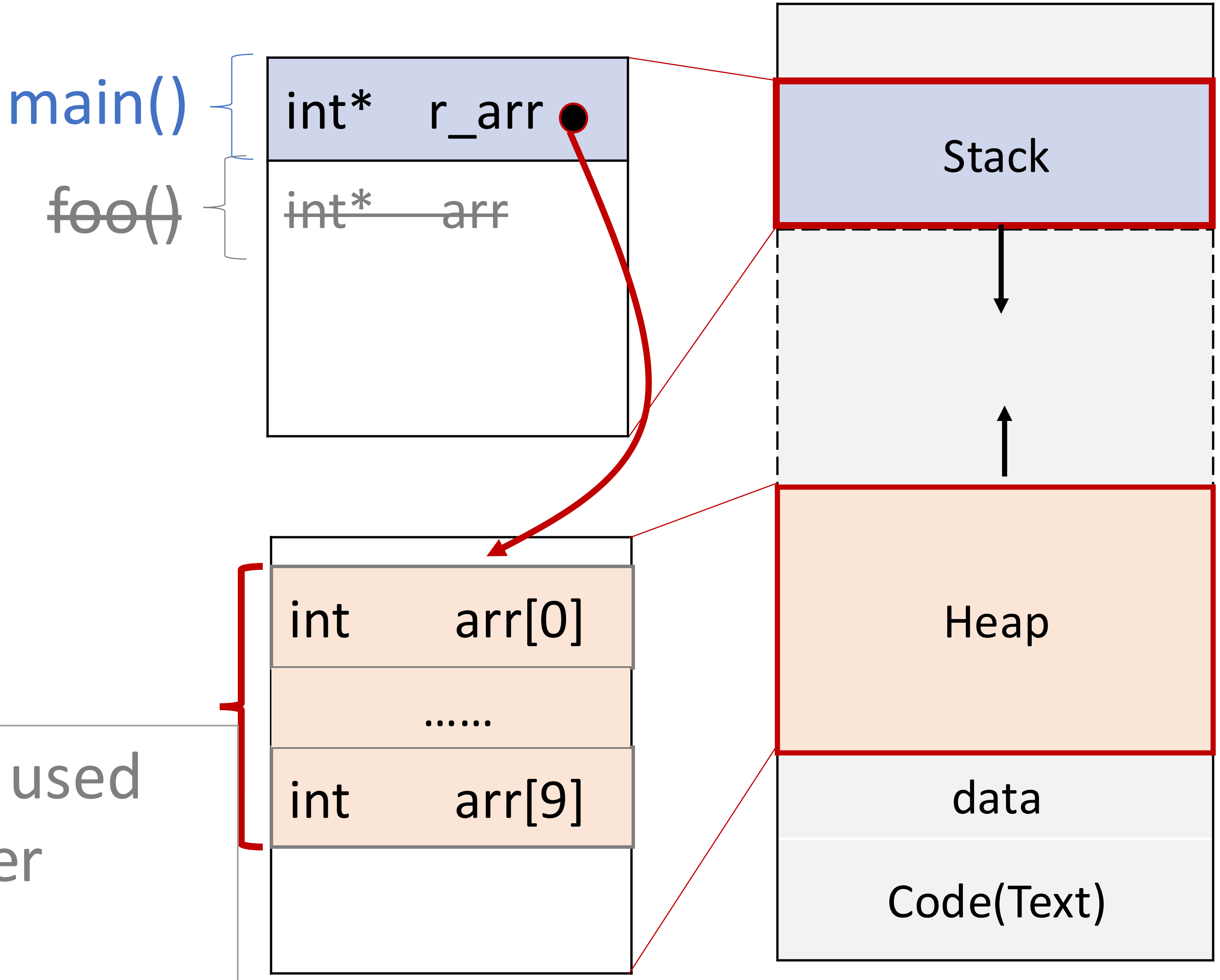


Does this function look correct?

No. It doesn't release the memory of arr when function finishes.

heap-based memory allocation

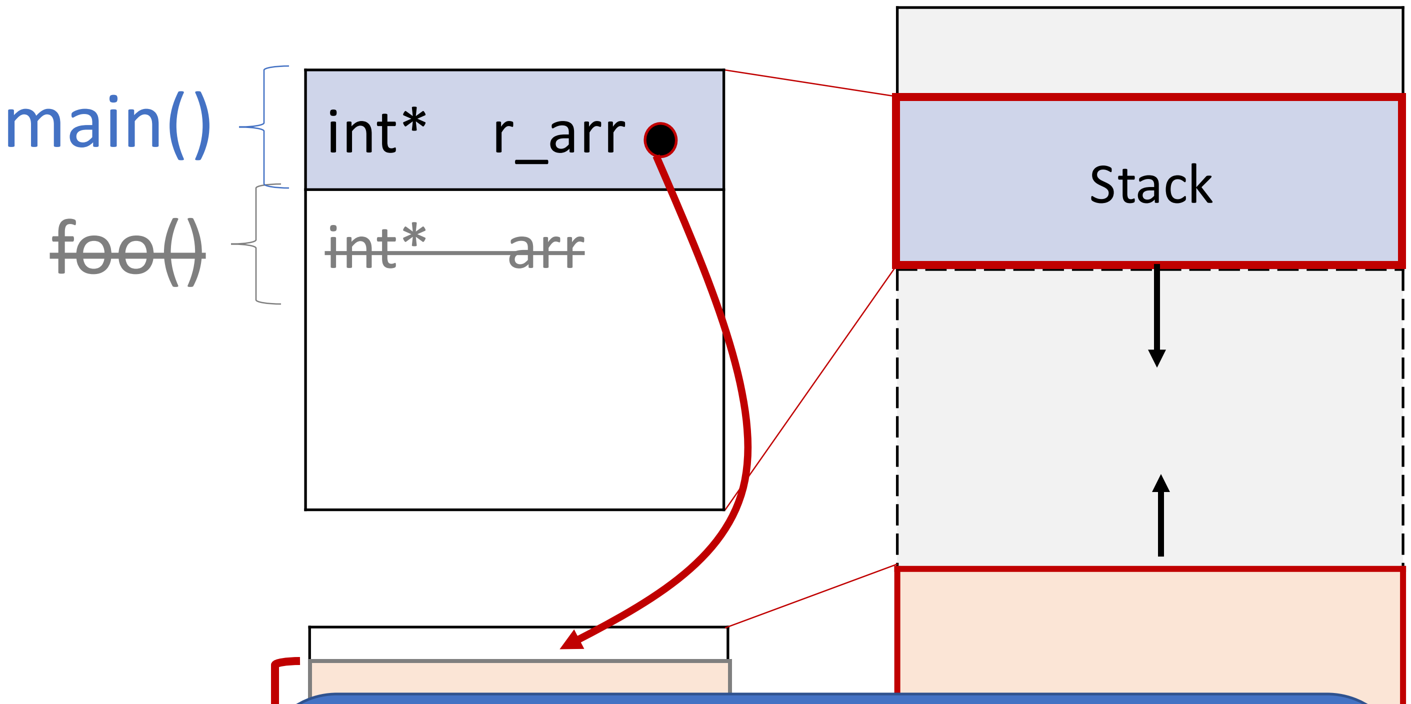
```
int* foo(){
    int* arr = new int[10];
    arr[0] = 0;
    return arr;
}

int main(){
    int* r_arr = foo();
    .......  // r_arr is neither used nor deleted in later program
}
```



demo

heap-based memory allocation

```
int* foo(){
    int* arr = new int[10];
    arr[0] = 0;
    return arr;
}

int main(){
    int* r_arr = foo();
    ……. // r_arr is neither used nor deleted in later program
}
```



Is the program correct?

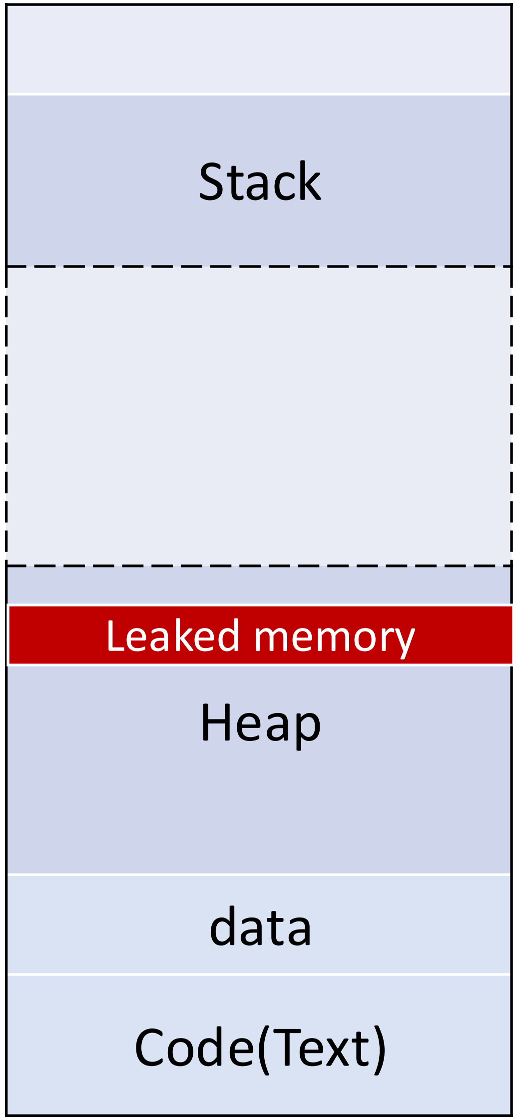
No. It never releases the memory of arr, which causes **memory leak**.

What is memory leak in C++?

- Memory leakage in C++ is when programmers allocates heap-based memory by using new keyword and forgets to deallocate the memory

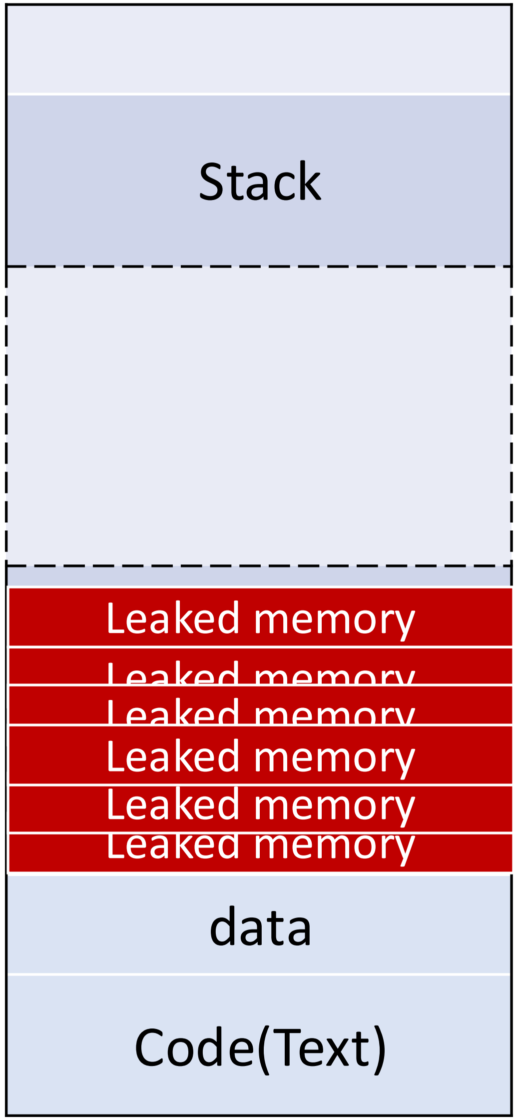
Memory Leak

```
int* foo(){
    int* arr = new int[10];
    arr[0] = 0;
    return arr;
}

int main(){
    int* r_arr = foo();
    .......
}
```



Memory Leak

```
int* foo(){
    int* arr = new int[10];
    arr[0] = 0;
    return arr;
}
int main(){
    for( int i = 0; i < 100; i++){
        int* r_arr = foo();
    }.......
}
```



Consequences of memory leak ?

- Reduces the amount of available memory, negatively impacts the runtime performance
- If memory leaks accumulate over time and left unchecked, may thrash or even crash a program

Memory Leak

demo

- What is memory leak in C++?
- Consequences of memory leak?
- How to check if my program has memory leak?
  - **Valgrind:** https://valgrind.org

```
$ valgrind --leak-check=full ./exec
```

Memory Leak

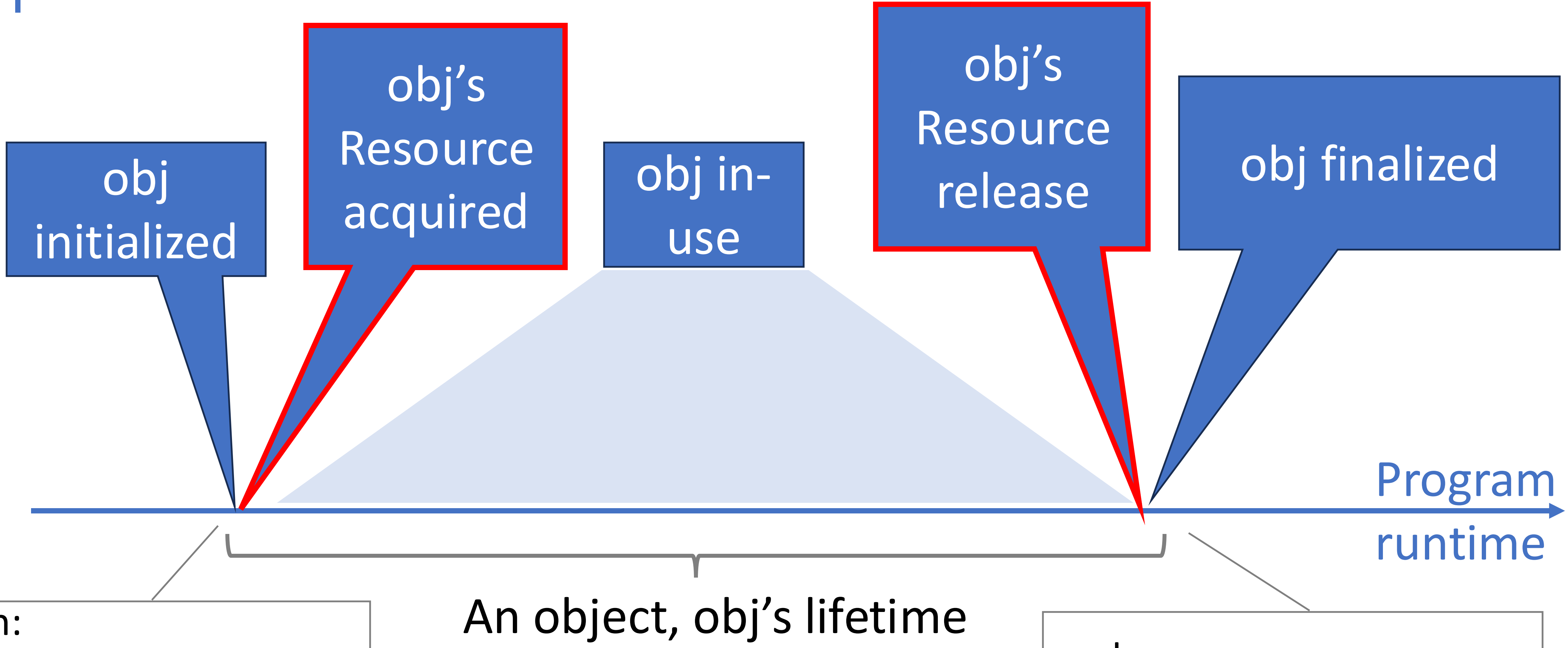
- What is memory leak in C++?
- How to check if my program has memory leak?
- How to avoid memory leak in my program?
  - Follow **RAII principles** (Resource acquisition is initialization)
  - Use **smart pointers and standard containers** whenever possible instead of using raw pointers and new/delete

RAII Principle

- **RAII principle**(Resource acquisition is initialization):
  - Resource acquisition must succeed for initialization to succeed.
  - The resource is guaranteed to be held during its lifetime(between when initialization finishes and finalization starts)
  - The resources need to be released when not used.

https://en.cppreference.com/w/cpp/language/lifetime

Example.



Begin:
- storage for its type is obtained
- initialization is complete

end:
- the object is destroyed
- Obj's storage is released

C++ pointers

Types of Pointers

- C-style raw pointers
- Smart pointers
  - unique_ptr
  - shared_ptr

Ownership

- For C++ ownership is the responsibility for cleanup.
  - C-style raw pointer : does not represents ownership — can do anything you want with it, and you can happily use it in ways which lead to memory leaks or double-frees.

C-style raw pointers

```
int* p = new int(7);

double* arr_p = new double[]{1, 2, 3};

T* obj_p = new T(arg0, arg1, arg2,...);
  // a pointer to an object of class T on heap
```

Types of Pointers

- C-style raw pointers
- Smart pointers: wrapper of a raw pointer and make sure the object is deleted if it is no longer used
  - unique_ptr
  - shared_ptr

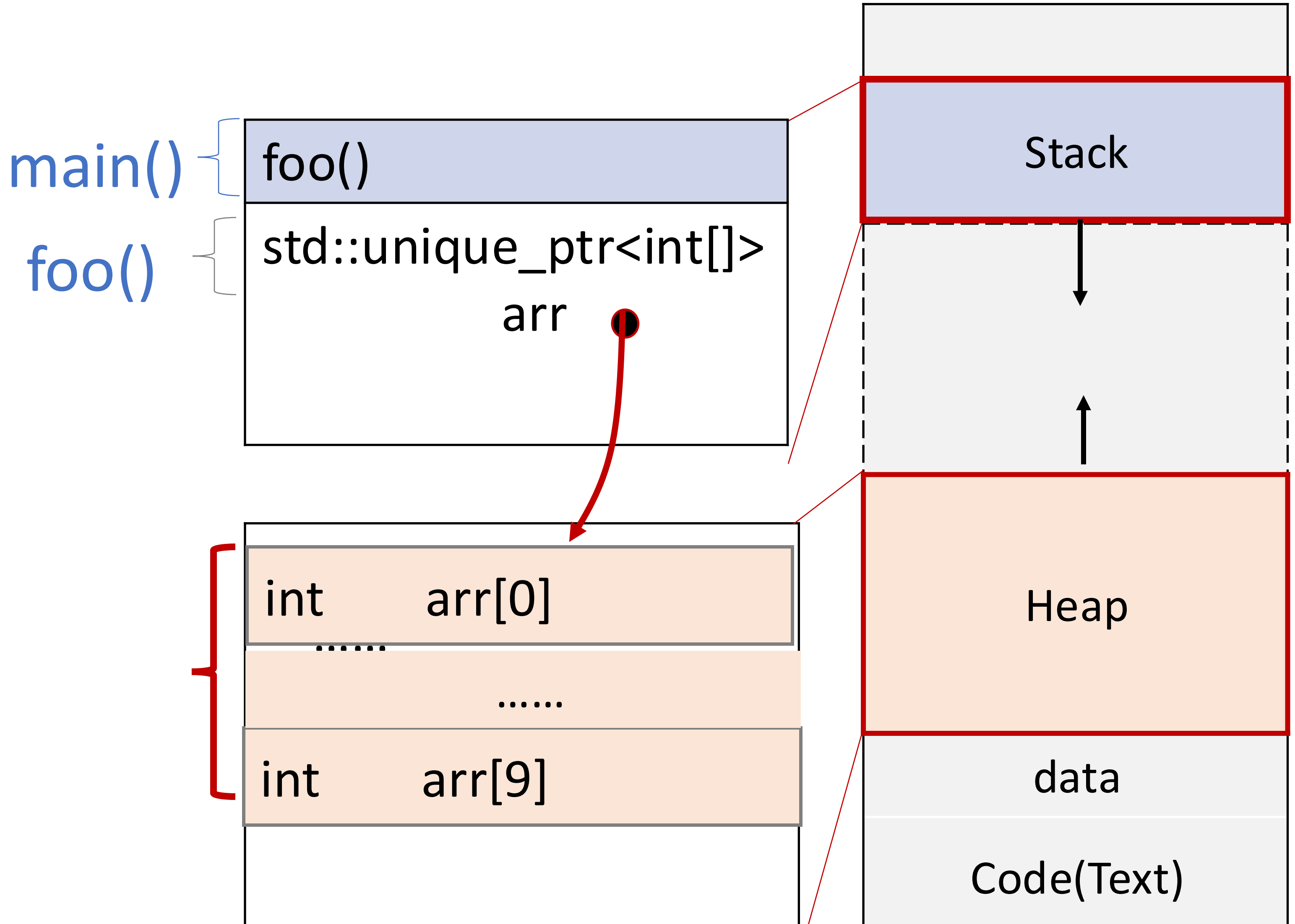
smart pointer: unique_ptr

- Owns and manages another object through a pointer and disposes of that object when the unique_ptr goes out of scope
- Represents the sole owner of resource and will get destroyed and cleaned up correctly
- Provides safety to classes and functions that handle objects with dynamic lifetime, by guaranteeing deletion on both normal exit and exit through exception

```
template <
    class T,
    class Deleter
> class unique_ptr<T[], Deleter>;
```

https://en.cppreference.com/w/cpp/memory/unique_ptr

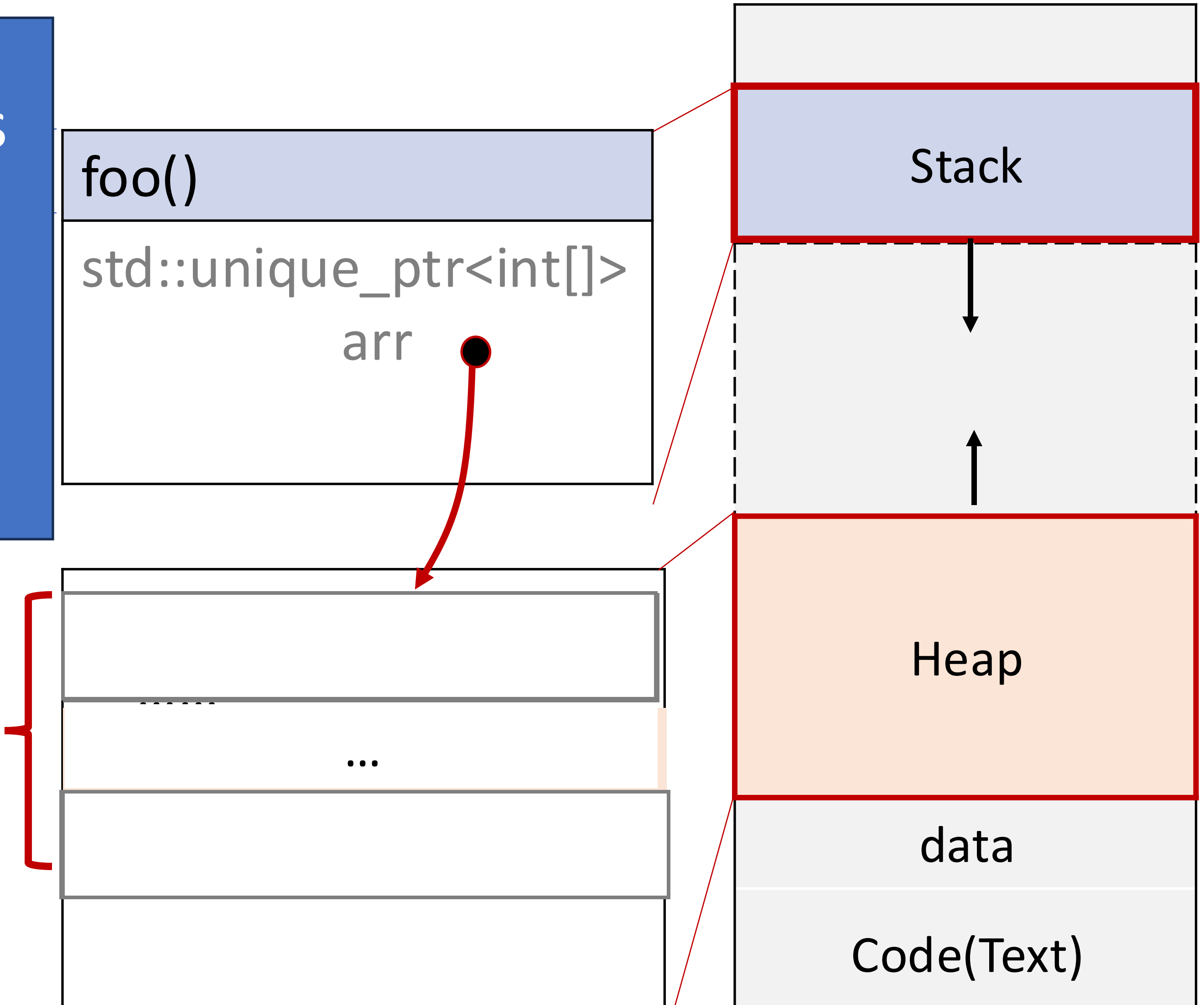
```
void foo(){
    std::unique_ptr<int[]> arr = std::make_unique<int[]>(10);
    arr[0] = 0;
}

int main(){
    foo();
    .......
}
```



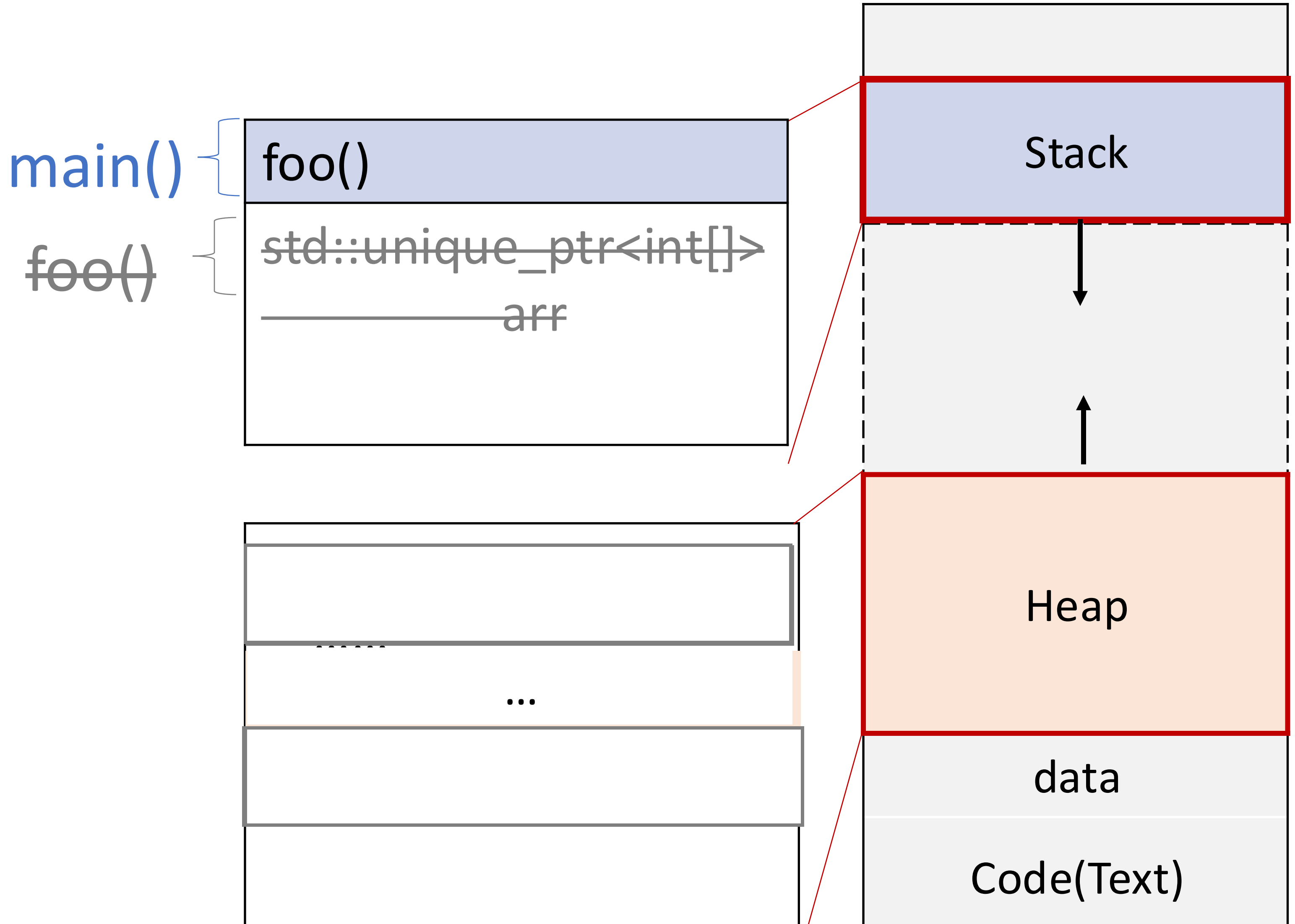
```
void foo(){
    std::unique_ptr<int[]> arr = std::make_unique<int[]>(10);
     arr[0] = 0;
}

int main(){
     foo();
     .......
}
```

std::unique_ptr is disposed:

delete[] arr;
is called



```
void foo(){
    std::unique_ptr<int[]> arr = std::make_unique<int[]>(10);
     arr[0] = 0;
}

int main(){
     foo();
     .......
}
```



smart pointer: unique_ptr

```
std::unique_ptr<int> a = new int(42);
```

Unique_ptr needs to call the constructor explicitly

```
std::unique_ptr<int> b(new int(42));
```

```
std::unique_ptr< int > explicit_ptr = std::make_unique< int>(42);
```

```
std::unique_ptr< int > ptr2 = explicit_ptr ;
```

unique_ptr class doesn’t allow copy of unique_ptr

```
std::unique_ptr< int > ptr3 = std::move(explicit_ptr );
```

std::move() : transferring of ownership(resources) from one object to another

smart pointer: shared_ptr

- a group of owners who are collectively responsible for the resource. The last of them to get destroyed will clean it up.

demo

smart pointer: shared_ptr

- std::shared_ptr: a smart pointer that retains shared ownership of an object through a pointer. Several shared_ptr objects may own the same object.
- The object is destroyed and its memory deallocated, when the last shared_ptr owning the object is destroyed or is assigned to another pointer. (when Reference counting==0)

```
std::shared_ptr<int> s_ptr = std::make_shared<int>(30);

std::shared_ptr< int> s_ptr2(new int(42));

std::shared_ptr< int> s_ptr3 = s_ptr2;
```

Where to find the resources?

- Memory Heap and Stack: https://courses.engr.illinois.edu/cs225/fa2022/resources/stack-heap/
- RAII: https://learn.microsoft.com/en-us/cpp/cpp/object-lifetime-and-resource-management-modern-cpp?view=msvc-170
- Move semantics: https://www.cprogramming.com/c++11/rvalue-references-and-move-semantics-in-c++11.html
- Passing arguments by reference: https://www.learncpp.com/cpp-tutorial/passing-arguments-by-reference/
- Effective C++: 55 specific ways to improve your programs and designs, Scott Meyers, 3rd edition
- A Tour of C++, Bjarne Stroustrup