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# **Creative Software Design**

## **4 – Dynamic Memory Allocation, References**

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Fall 2022

# Today's Topics

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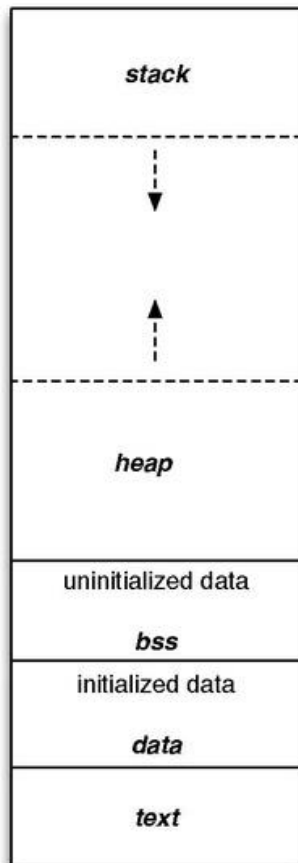
- Dynamic Memory Allocation
  - Typical Memory Layout of a Process
  - malloc() / free() and new / delete
  - Memory leak
- References
  - What is the Reference?
  - Differences btwn. Pointer & Reference
  - When to use Pointer / Reference?

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# **Dynamic Memory Allocation**

# Typical Memory Layout of a Process

- When you run a program, OS allocates memory space for the process as follows:

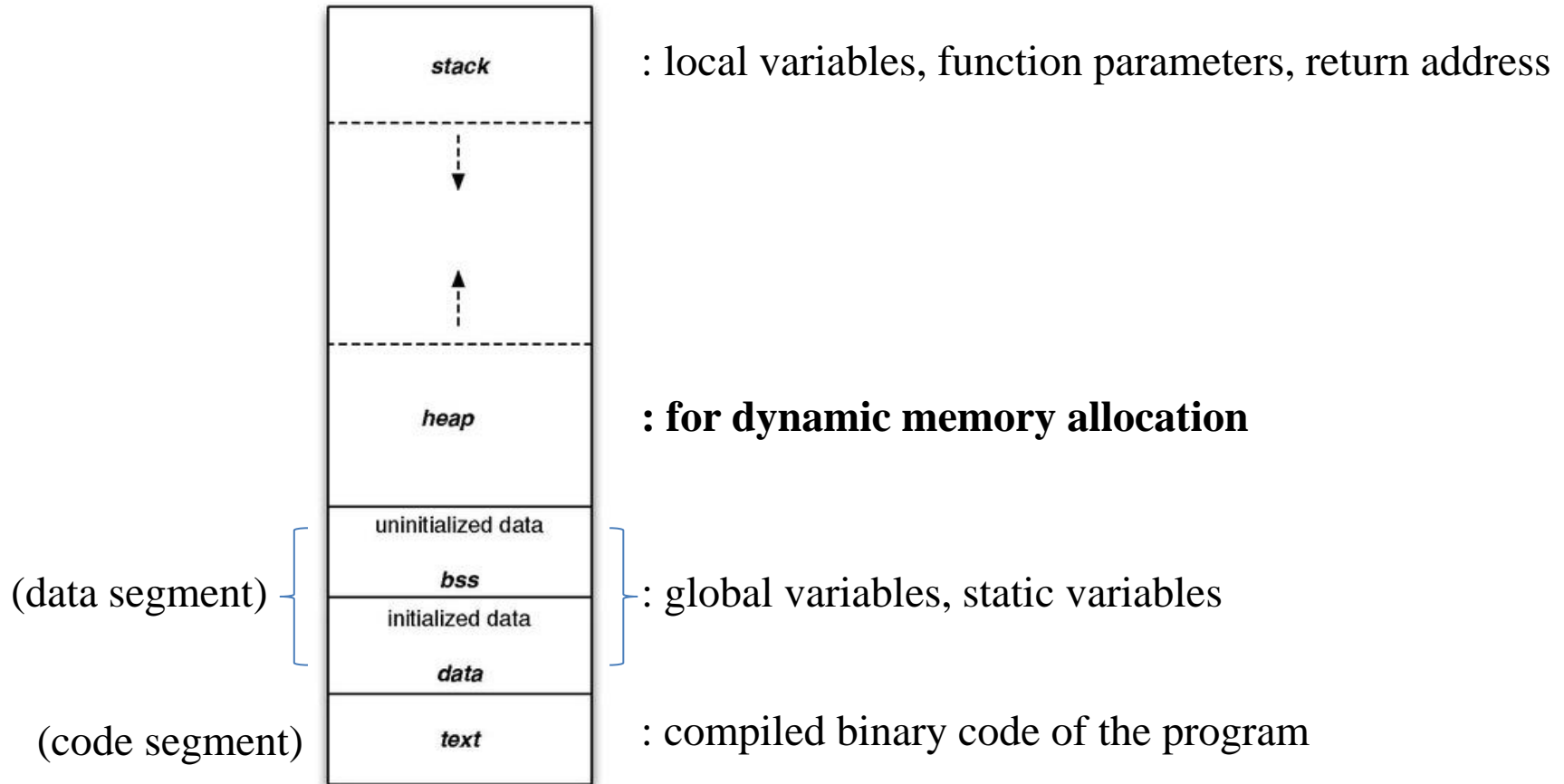


(an executing instance of a program)

Organized in several segments:

- Stack segment
- Heap segments
- BSS segments
- Data segments
- Text segments

# Typical Memory Layout of a Process



- The reason of "typical" is, the actual memory layout might differ slightly depending on OS.
- FYI, modern OSs usually separate the memory space of a process into "kernel space" and "user space". This figure only shows "user space".

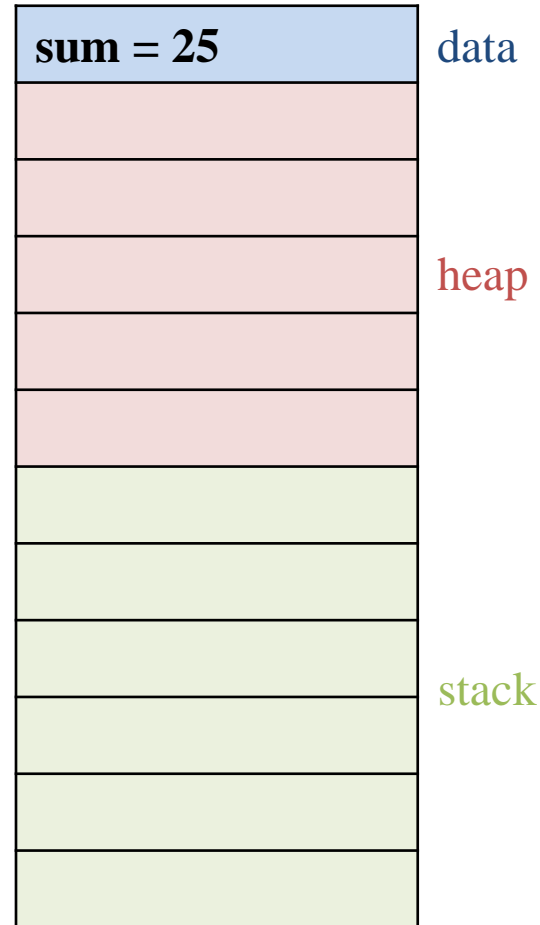
# Example - Memory Layout 1

(Program starts)

```
int sum=25;

int main()
{
    int num1=10;
    func(num1);
    num1++;
    func(num1);
    return 0;
}

void func(int n)
{
    int num2=20;
}
```



# Example - Memory Layout 2

```
int sum=25;
```

```
int main()
```

```
{
```

```
    int num1=10; ←
```

```
    func(num1);
```

```
    num1++;
```

```
    func(num1);
```

```
    return 0;
```

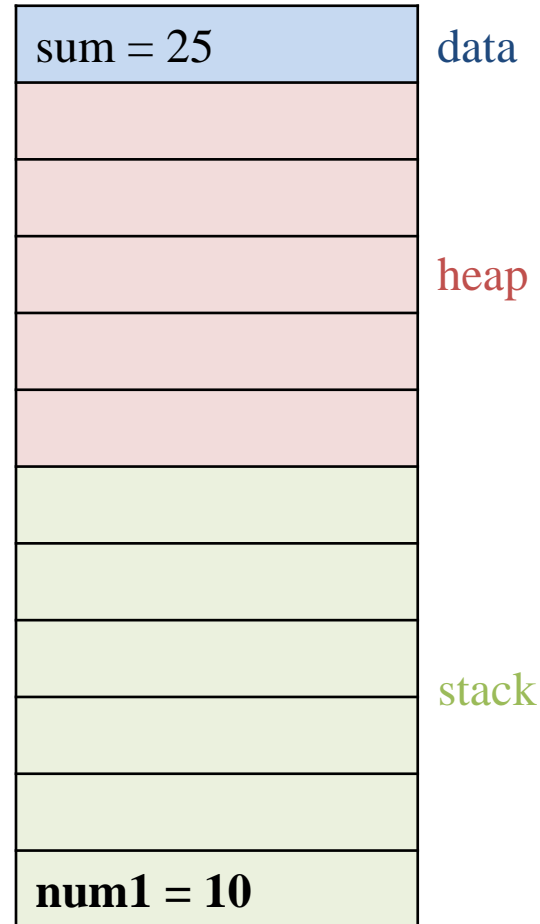
```
}
```

```
void func(int n)
```

```
{
```

```
    int num2=20;
```

```
}
```



# Example - Memory Layout 3

```
int sum=25;
```

```
int main()
```

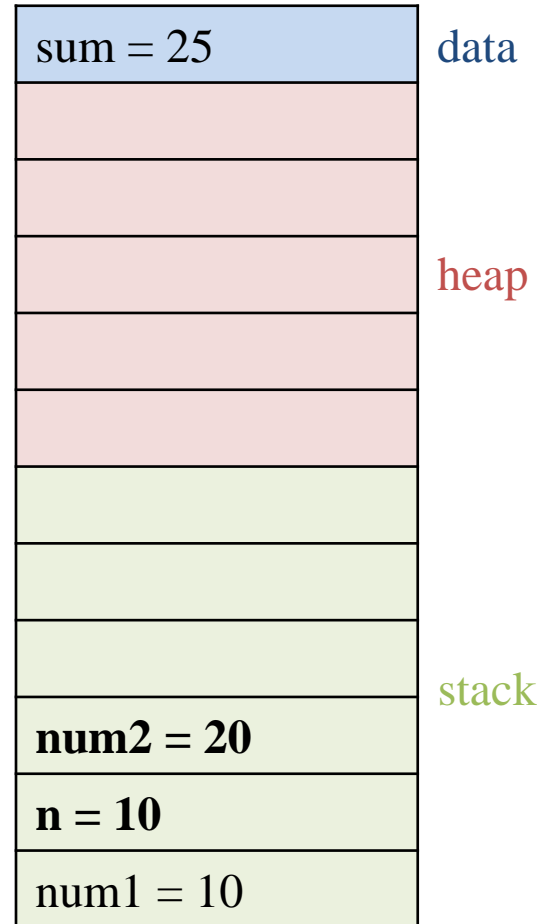
```
{  
    int num1=10;  
    func(num1);  
    num1++;  
    func(num1);  
    return 0;  
}
```

```
void func(int n)
```

```
{  
    int num2=20;  
}
```

← call

←



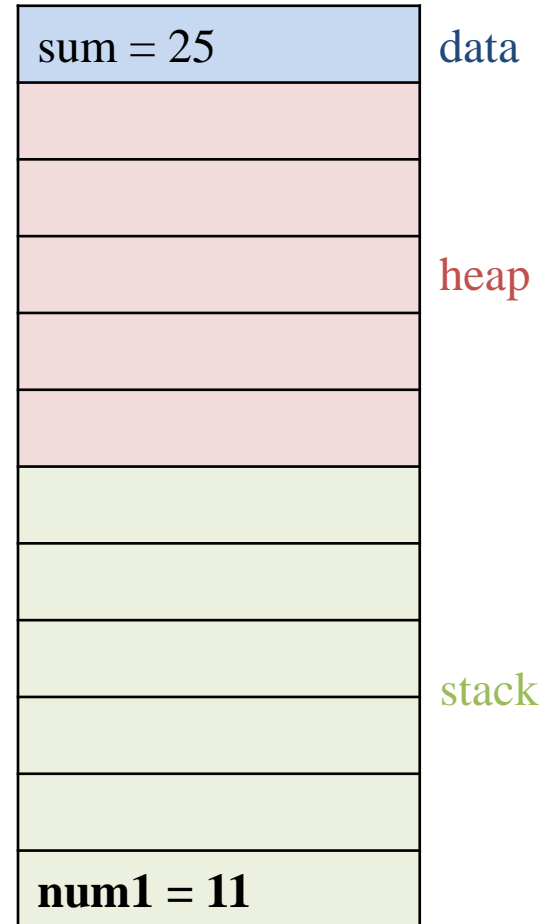


# Example - Memory Layout 4

```
int sum=25;

int main()
{
    int num1=10;
    func(num1);
    num1++;
    func(num1);
    return 0;
}

void func(int n)
{
    int num2=20;
}
```



# Example - Memory Layout 5

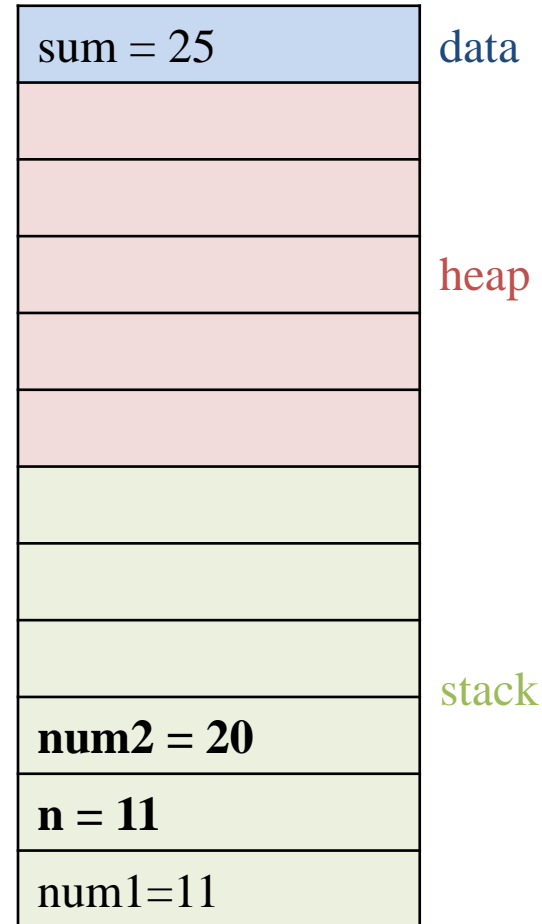
```
int sum=25;

int main()
{
    int num1=10;
    func(num1);
    num1++;
    func(num1);
    return 0;
}

void func(int n)
{
    int num2=20;
}
```

← call

←



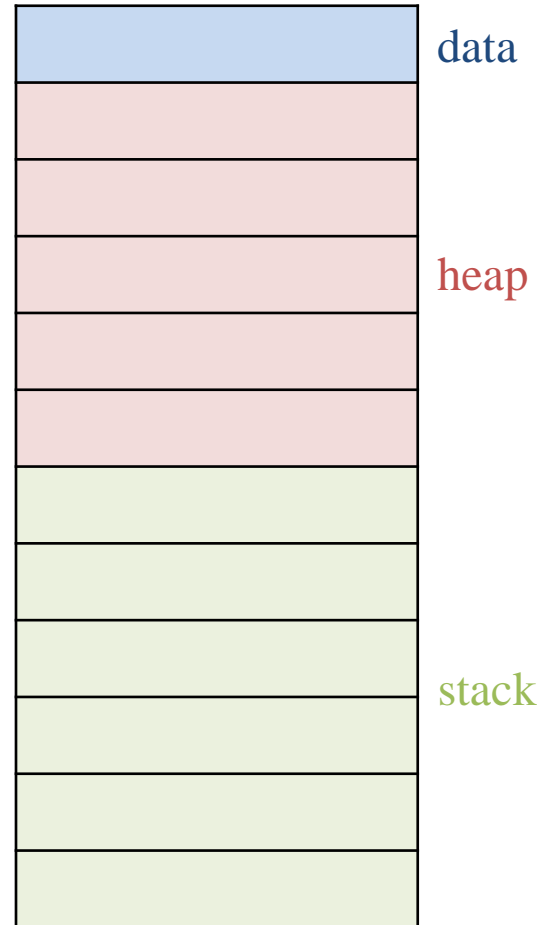
# Example - Memory Layout 6

(Program ends)

```
int sum=25;

int main()
{
    int num1=10;
    func(num1);
    num1++;
    func(num1);
    return 0;
}

void func(int n)
{
    int num2=20;
}
```



# Dynamic Memory Allocation

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- How to create an array whose length changes while the program is running?
- What if you could not determine the type and number of data to use when writing code?
- → Your program should **dynamically** allocate the required memory space during execution.
- Dynamically allocated data is store in the **heap**.

# An Example

- Allocate and deallocate memory block.
  - Example: C arrays are with fixed sizes.
  - How can we use variable size array?

```
void TestFunction(int n) {
    int fixed_size_array[20];
    int variable_size_array[n]; // Compile error.

    for (int i = 0; i < n; ++i) {
        cout << fixed_size_array[i] << ", " // SEGFAULT if n > 20.
             << variable_size_array[i];
    }
}
```

- (FYI) C99 standard supports variable-length array, but it's not encouraged to use. ([https://en.wikipedia.org/wiki/Variable-length\\_array](https://en.wikipedia.org/wiki/Variable-length_array))

# C malloc / free

- Allocate and deallocate memory block.
  - Use malloc/free to manage memory allocation.

```
#include <iostream>
#include <stdlib.h>
using namespace std;

void TestFunction(int n) {
    int* variable_size_array = (int*) malloc(sizeof(int) * n);
    for (int i = 0; i < n; ++i) {
        cout << variable_size_array[i] << endl;
    }
    free(variable_size_array);
}

int main() {
    TestFunction(3);
    return 0;
}
```

- malloc (n) : allocates n bytes of memory block and return the pointer to the block.
- free (ptr) : deallocates the allocated memory block.

# Dynamic Memory Allocation

---

- **C: malloc(), free() functions**
  - `#include <stdlib.h>`
  - `int* pNum = (int*)malloc(sizeof(int));`
  - `free(pNum);`
- **C++: new, delete operators**
  - `int* pNum = new int;`
  - `delete pNum;`
  - Use this way in C++ (especially for class objects)

# C++ new / delete

- C++ has `new` and `delete` operators built-in.
  - `new` : creates a variable(instance) of the type(class).
  - `delete` : destructs a variable(instance) created by `new`.
  - `new []` : creates an **array** of variables(instances) of the type(class).
  - `delete []` : destructs an **array** created by `new []`.

	One instance	Array
Allocate	<code>new</code>	<code>new []</code>
Deallocate	<code>delete</code>	<code>delete[]</code>



# Examples - Dynamic Memory Allocation 1

## C version

```
#include <iostream>
#include <stdlib.h>
using namespace std;

int main()
{
    int n;
    cin >> n;

    // allocate one instance
    int* num = (int*)malloc(sizeof(int));
    // allocate an array
    int* numArr = (int*)malloc(sizeof(int)*n);

    *num = n;
    for(int i=0; i<n; i++)
        numArr[i] = i;

    cout << *num << endl;
    for(int i=0; i<n; i++)
        cout << numArr[i] << " ";
    cout << endl;

    free(num); // deallocate the instance
    free(numArr); // deallocate the array

    return 0;
}
```

## C++ version

```
#include <iostream>
using namespace std;

int main()
{
    int n;
    cin >> n;

    // allocate one instance
    int* num = new int;
    // allocate an array
    int* numArr = new int[n];

    *num = n;
    for(int i=0; i<n; i++)
        numArr[i] = i;

    cout << *num << endl;
    for(int i=0; i<n; i++)
        cout << numArr[i] << " ";
    cout << endl;

    delete num; // deallocate the instance
    delete[] numArr; // deallocate the array

    return 0;
}
```

# Examples - Dynamic Memory Allocation 2

## C version

```
#include <iostream>
#include <stdlib.h>
using namespace std;

void TestFunction(int n) {
    int* int_instance = (int*)
    malloc(sizeof(int));
    int* variable_size_array = (int*)
    malloc(sizeof(int) * n);

    *int_instance = 10;
    for (int i = 0; i < n; ++i)
        cin >> variable_size_array[i];

    free(int_instance);
    free(variable_size_array);
}

int main() {
    TestFunction(3);
    return 0;
}
```

## C++ version

```
#include <iostream>
#include <stdlib.h>
using namespace std;

void TestFunction(int n) {
    int* int_instance = new int;
    int* variable_size_array = new int[n];

    *int_instance = 10;
    for (int i = 0; i < n; ++i)
        cin >> variable_size_array[i];

    delete int_instance;
    delete[] variable_size_array;
}

int main() {
    TestFunction(3);
    return 0;
}
```

# Quiz #1

---

- Go to <https://www.slido.com/>
- Join #csd-ys
- Click "Polls"
  
- Submit your answer in the following format:
  - **Student ID: Your answer**
  - e.g. **2022123456: 4)**
  
- Note that you must submit all quiz answers **in this format** to be counted as attendance.

# Memory Leak

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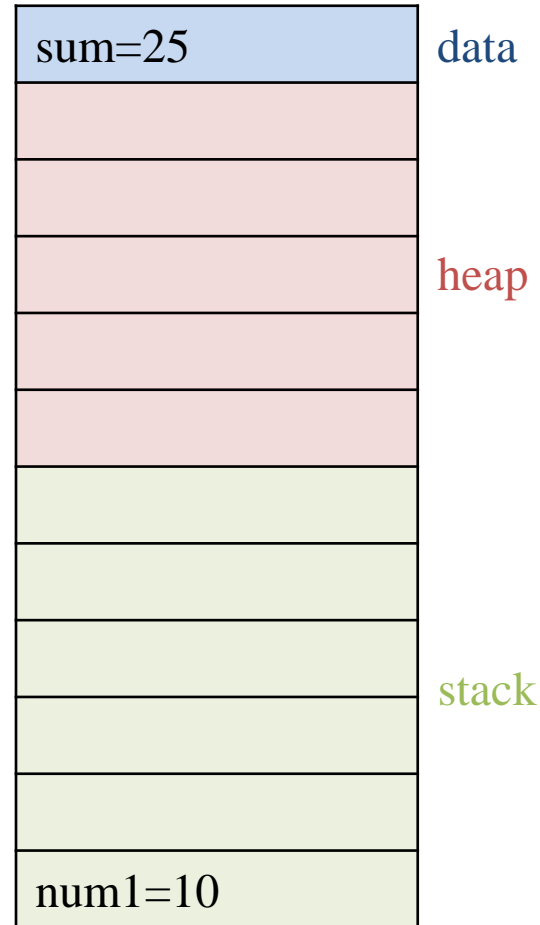
- What happens if allocated blocks are not freed?
- Memory leak : An allocated but unused memory block is not returned to OS.
  - Usually happens when the pointer to the allocated memory block gets lost.
- Just like C malloc() / free(), C++ new / delete can cause memory leak.
- Be sure to call delete every time you call new.
  - Always use new and delete in pairs.
  - Do not call new and delete in different functions (More likely to make a mistake not to call delete).

# Example - Memory Layout (Dynamic Alloc.) 1

```
int sum=25;

int main(void)
{
    int num1=10; ←
    fct(num1);
    num1++;
    fct(num1);
    return 0;
}

void fct(int n)
{
    int* pNum = new int;
    *pNum = n;
    delete pNum;
}
```



# Example - Memory Layout (Dynamic Alloc.) 2

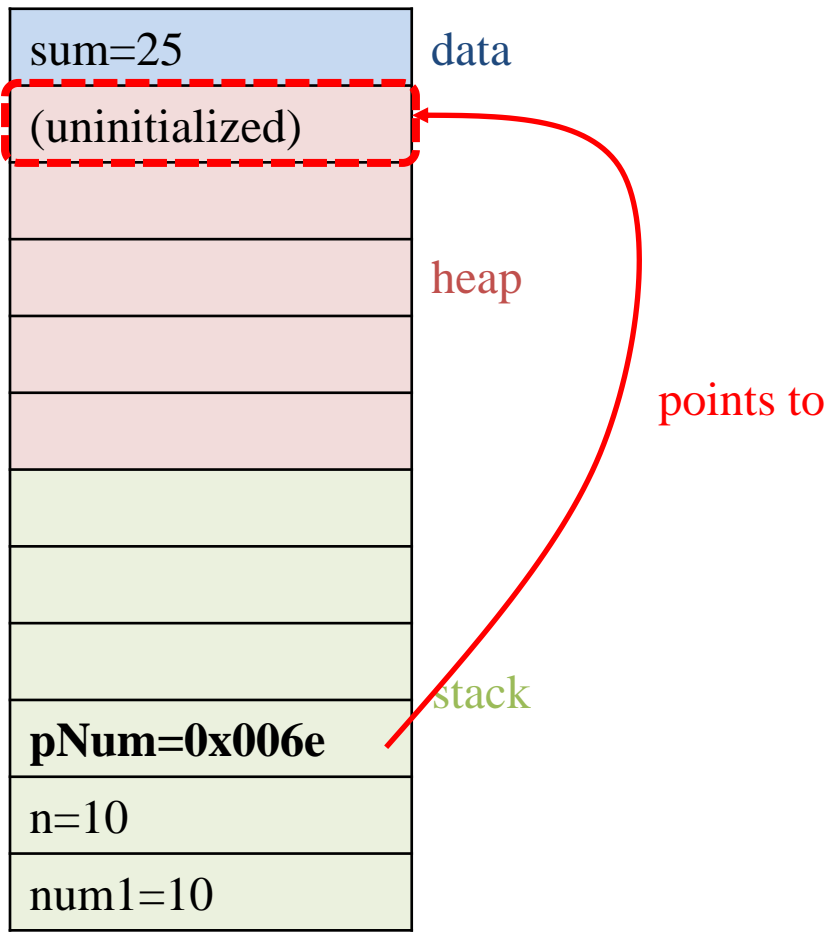
```
int sum=25;

int main(void)
{
    int num1=10;
    fct(num1);
    num1++;
    fct(num1);
    return 0;
}

void fct(int n)
{
    int* pNum = new int;
    *pNum = n;
    delete pNum;
}
```

← call

←

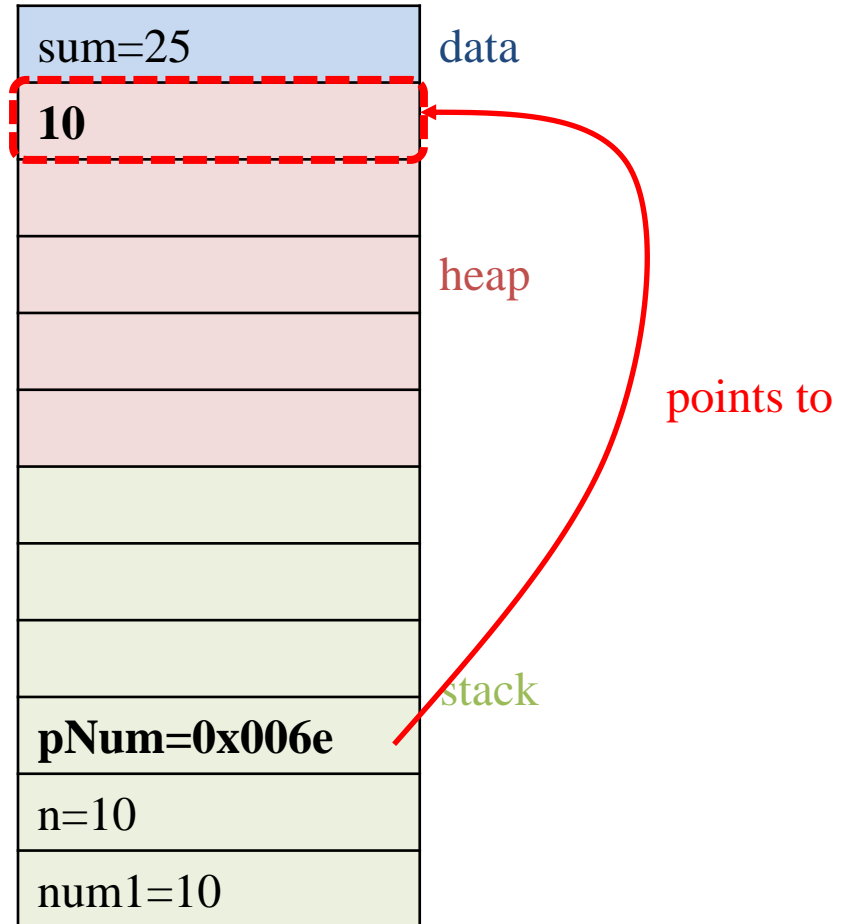


# Example - Memory Layout (Dynamic Alloc.) 3

```
int sum=25;

int main(void)
{
    int num1=10;
    fct(num1); ← call
    num1++;
    fct(num1);
    return 0;
}

void fct(int n)
{
    int* pNum = new int;
    *pNum = n; ←
    delete pNum;
}
```

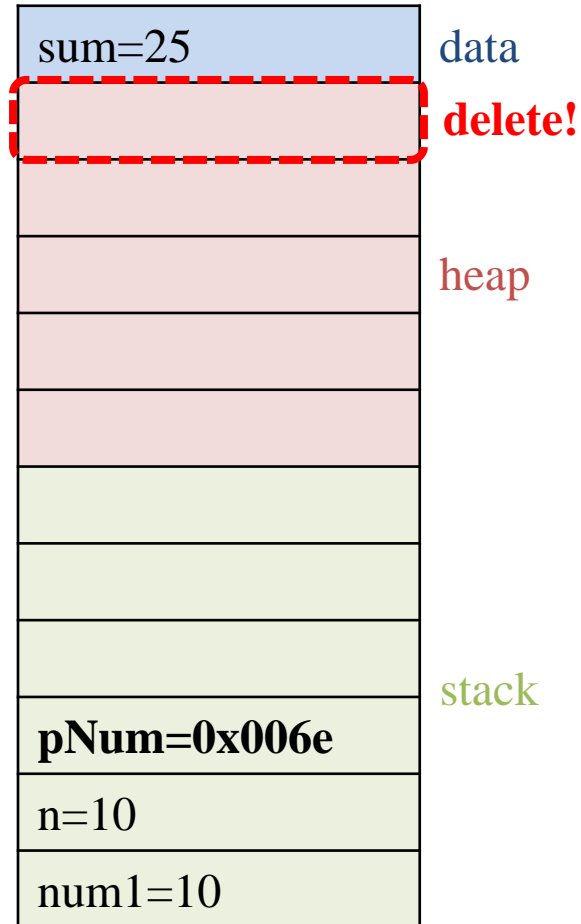


# Example - Memory Layout (Dynamic Alloc.) 4

```
int sum=25;

int main(void)
{
    int num1=10;
    fct(num1); ← call
    num1++;
    fct(num1);
    return 0;
}

void fct(int n)
{
    int* pNum = new int;
    *pNum = n;
    delete pNum; ←
}
```



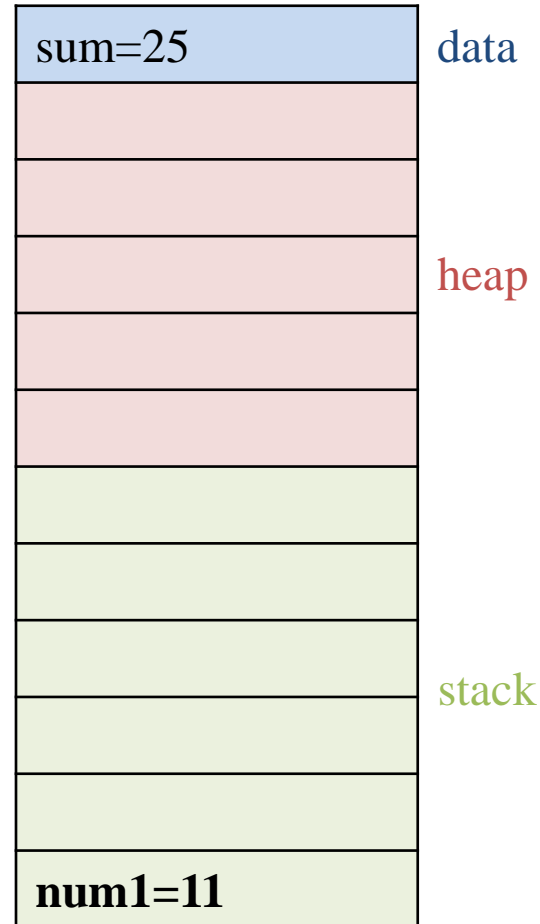


# Example - Memory Layout (Dynamic Alloc.) 5

```
int sum=25;

int main(void)
{
    int num1=10;
    fct(num1);
    num1++;
    fct(num1);
    return 0;
}

void fct(int n)
{
    int* pNum = new int;
    *pNum = n;
    delete pNum;
}
```

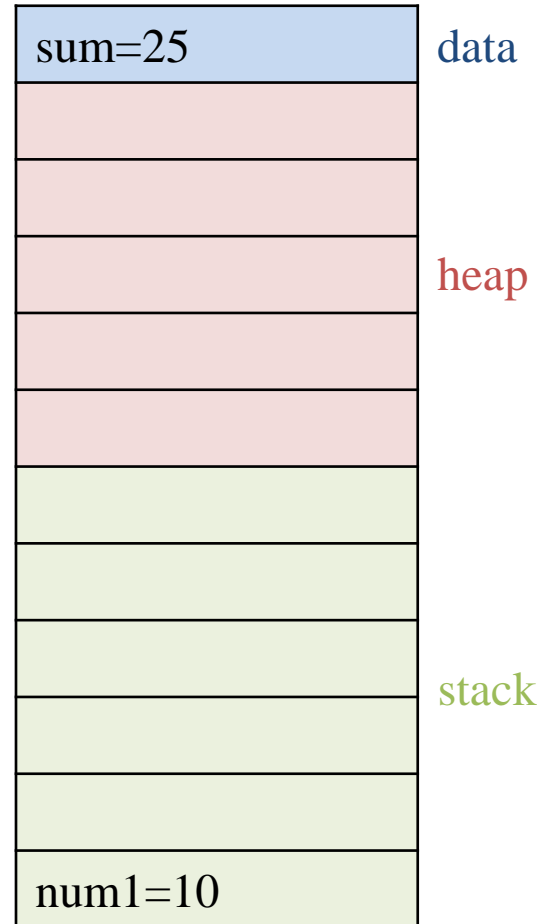


# Example - Memory Layout (Memory Leak) 1

```
int sum=25;

int main(void)
{
    int num1=10; ←
    fct(num1);
    num1++;
    fct(num1);
    return 0;
}

void fct(int n)
{
    int* pNum = new int;
    *pNum = n;
    //delete pNum;
}
```

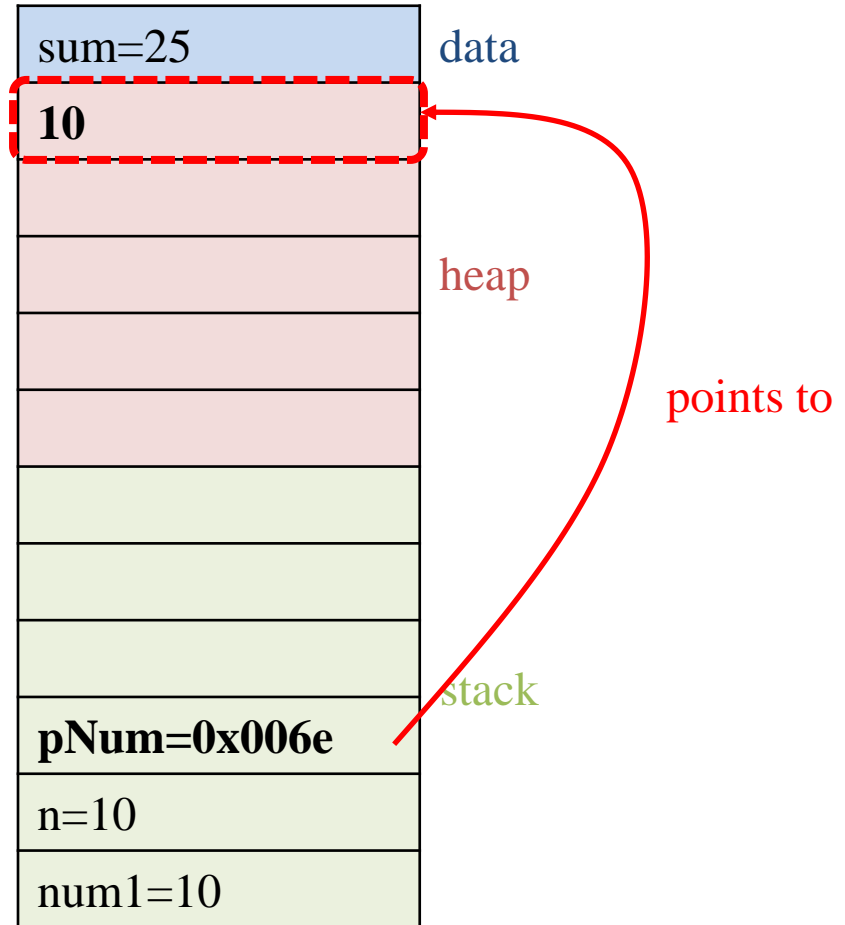


# Example - Memory Layout (Memory Leak) 2

```
int sum=25;

int main(void)
{
    int num1=10;
    fct(num1); ← call
    num1++;
    fct(num1);
    return 0;
}

void fct(int n)
{
    int* pNum = new int;
    *pNum = n; ←
    //delete pNum;
}
```

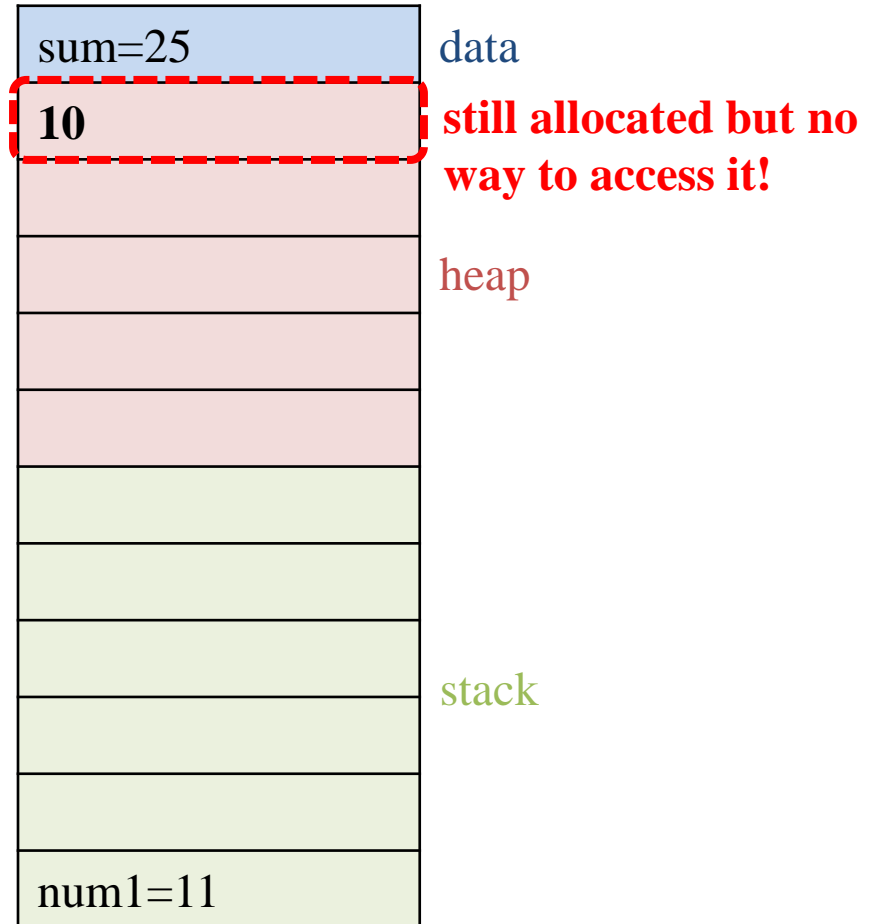


# Example - Memory Layout (Memory Leak) 3

```
int sum=25;

int main(void)
{
    int num1=10;
    fct(num1);
    num1++;
    fct(num1);
    return 0;
}

void fct(int n)
{
    int* pNum = new int;
    *pNum = n;
    //delete pNum;
}
```



# Quiz #2

---

- Go to <https://www.slido.com/>
- Join #csd-ys
- Click "Polls"
  
- Submit your answer in the following format:
  - **Student ID: Your answer**
  - e.g. 2022123456: 4)
  
- Note that you must submit all quiz answers **in this format** to be counted as attendance.

---

# References

# C++ Reference (&)

- References can be used similar to pointers (Think of it as a “referenced pointer”)
  - Less powerful but safer than the pointer type.

```
#include <iostream>
using namespace std;

int main()
{
    int a = 10;
    int* pa = &a; // pa can be regarded as an "alias" of a
    *pa = 20;
    cout << a << " " << *pa << endl;    // 20 20

    int b = 10;
    int& rb = b; // rb can be regarded as an "alias" of b
    rb = 20;
    cout << b << " " << rb << endl;    // 20 20

    return 0;
}
```

# Differences btwn. Pointer & Reference

- A pointer is assigned by an address.

```
void func(int* pn) {...}

void main(){
    int a = 10;
    int* pa = &a;

    func(&a);
}
```

- A reference is initialized to an object (variable).

```
void func(int& rn) {...}

void main(){
    int b = 10;
    int& rb = b;

    func(b);
}
```



# Differences btwn. Pointer & Reference

---

- A pointer can be uninitialized.

```
int* pa; // ok
```

- A reference MUST be initialized.

```
int& rb; // error
```

```
int b = 10;
```

```
int& rb = b; // ok
```

# Differences btwn. Pointer & Reference

- A pointer can be reassigned.

```
int a=1, b=2;
int* p;
p = &a;
p = &b;
```

- A reference CANNOT be reassigned (only initialized once).

```
int a=1, b=2;
int& r = a;
r = b; // Not refer to b, just copy value of b to a
cout << a << " " << b << " " << r << endl; // 2 2 2

r = 100;
cout << a << " " << b << " " << r << endl; // 100 2 100
```

# Differences btwn. Pointer & Reference

---

- A pointer can point to a null object (NULL or nullptr in c++11).

```
int* p = NULL; // ok
```

- A reference CANNOT refer to a null object.

```
int& r = NULL; // error
```

# Recall: When to use Pointers in C?

---

- Passing read-only arguments to a function
  - Recall: `void printPoint(const Point* p)`
  - C/C++ uses "call-by-value" (or "pass-by-value")
    - Arguments are passed to functions by **copying values**
  - If a function does not need to modify the value of passed variables, use **“pointer to constant”** to **avoid copying**
- You can use **references** for this purpose as well!
  - `void printPoint(const Point& p)`

# Reference to Constant

```
const int b1 = 10;
const int& r1 = b1; // ok

int b2 = 20;
const int& r2 = b2; // also ok

r1 = 100; // error
r2 = 100; // error
```

- A *reference to a const* is often called a *const reference* for short, though this creates some inconsistent nomenclature with pointers.

```
int num = 20;
const int* ptr1 = &num; // pointer to constant
int* const ptr2 = &num; // constant pointer
```

# Passing by Reference to Constant

- Passing arguments using const reference type (const &)
  - The instances **remains unchanged after the function call.**
  - Avoids copying the arguments.
  - Guarantees a reference to a valid instance (whereas a pointer can be null).

```
struct Triplet { int a, b, c; };

void TestConstReference(const Triplet ct, const Triplet* cpt,
                       const Triplet& crt) {
    ct.a = 10, cpt->b = 20, crt.c = 30; // All are errors.
    printf("%d, %d, %d\n", ct.a, cpt->b, crt.c);
}

int main() {
    Triplet triplet;
    triplet.a = 10, triplet.b = 20, triplet.c = 30;

    TestConstReference(triplet, &triplet, triplet);
    return 0;
}
```

# Recall: When to use Pointers in C?

---

- “Simulation” of call-by-reference in C
  - Recall: `void swap(int* p1, int* p2)`
  - swap function can **modify** the value of passed variables
  - These parameters are often called *out parameters*
- You can use **references** for this purpose as well!
  - `void swap(int& i1, int& i2)`

# Passing by Reference

- Passing arguments using reference type (&)
  - The instances **probably are modified by the function.**
  - Avoids copying the arguments.
  - Guarantees a reference to a valid instance (whereas a pointer can be null).

```
struct Triplet { int a, b, c; };
```

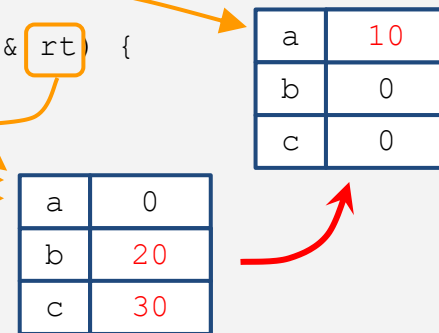
```
void TestReference(Triplet t, Triplet* pt, Triplet& rt) {  
    t.a = 10, pt->b = 20, rt.c = 30;  
}
```

```
int main() {  
    Triplet triplet;  
    triplet.a = 0, triplet.b = 0, triplet.c = 0;
```

```
    TestReference(triplet, &triplet, triplet);  
    // triplet.a == 0, triplet.b == 20, triplet.c == 30
```

```
    TestReference(triplet, NULL, triplet); // Causes SEGFAULT.  
    return 0;
```

```
}
```





# Recall: When to use Pointers in C?

---

- Dynamic memory allocation
  - One has to use pointers to access memory on the **heap**
  - `int* pNum = (int*)malloc(sizeof(int));`
  - `int* pNum = new int;`
- References cannot be used for this purpose.

# Quiz #3

---

- Go to <https://www.slido.com/>
- Join #csd-ys
- Click "Polls"
  
- Submit your answer in the following format:
  - **Student ID: Your answer**
  - e.g. **2017123456: 4)**
  
- Note that you must submit all quiz answers **in this format** to be counted as attendance.

# DO NOT Confuse Address-of Operator(&) and Reference(&)!

---

- Address-of operator

```
int a = 0;  
int* pa = &a; // '&'+[variable name]
```

- Reference

```
int a = 0;  
int& a_ref = a; // [type name]+'&'
```

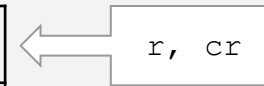
# Local Variable, Pointer, Reference

```
int a = 10;
int b = a;

int* p = &a;
const int* cp = &a;

int& r = a;
const int& cr = a;
```

a	10
b	10
p	&a
cp	&a



```
a = 20; // a: 20, b: 10, p: &a, *p: 20, cp: &a, *cp: 20, r: 20 ,cr: 20.
b = 30; // a: 20, b: 30, p: &a, *p: 20, cp: &a, *cp: 20, r: 20 ,cr: 20.

*p = 10; // a: 10, b: 30, p: &a, *p: 10, cp: &a, *cp: 10, r: 10 ,cr: 10.
*cp = 0; // Error!
r = 40; // a: 40, b: 30, p: &a, *p: 40, cp: &a, *cp: 40, r: 40 ,cr: 40.
cr = 0; // Error!

p = &b; // a: 40, b: 30, p: &b, *p: 30, cp: &a, *cp: 40, r: 40 ,cr: 40.
*p = 50; // a: 40, b: 50, p: &b, *p: 50, cp: &a, *cp: 40, r: 40 ,cr: 40.

int** pp = &p;
*pp = &a; // pp: &p, p: &a, *p: 40
*pp = &b; // pp: &p, p: &b, *p: 50
```

# Next Time

---

- Labs in this week:
  - Lab1 (next Mon): Assignment 4-1
  - Lab2 (next Thur): Assignment 4-2
- Next lecture (next Fri):
  - 5 - Compilation and Linkage, CMD Args