Creative Software Design

4 – Dynamic Memory Allocation, References

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Outline

- Dynamic Memory Allocation
  - Typical Memory Layout of a Process
  - malloc() / free() and new / delete
  - Memory Leak
  - Smart Pointer (in Modern C++)

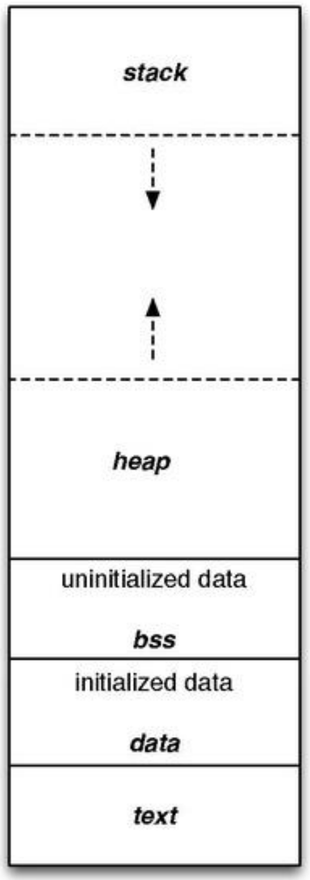
- References
  - What is the Reference?
  - Differences btwn. Pointer & Reference
  - When to use Pointer / Reference?

Dynamic Memory Allocation

Typical Memory Layout of a Process

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

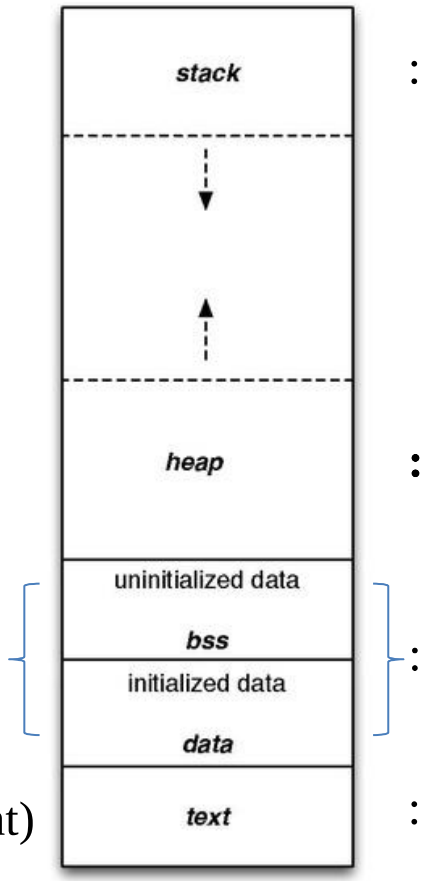
(an executing instance of a program)



Organized in several segments:

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

Typical Memory Layout of a Process



: local variables, function parameters, return address

: for dynamic memory allocation

: global variables, static variables

: compiled binary code of the program

- 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".

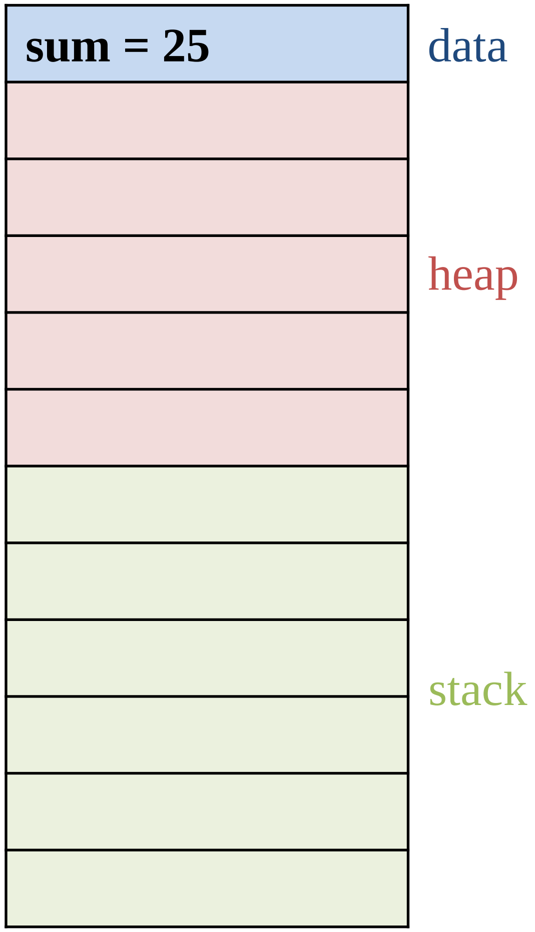
Example - Memory Layout 1

(Program starts)

```
int sum=25;

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

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

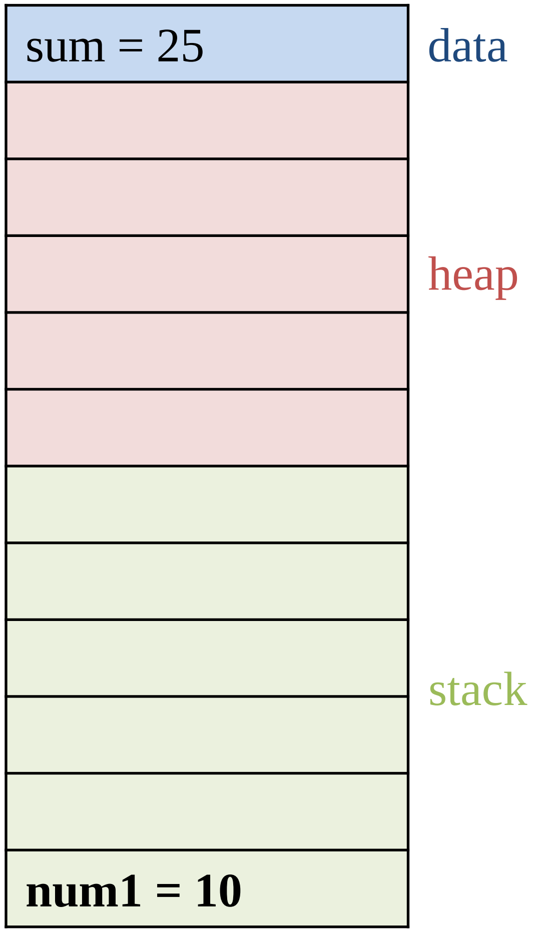


Example - Memory Layout 2

```
int sum=25;

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

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

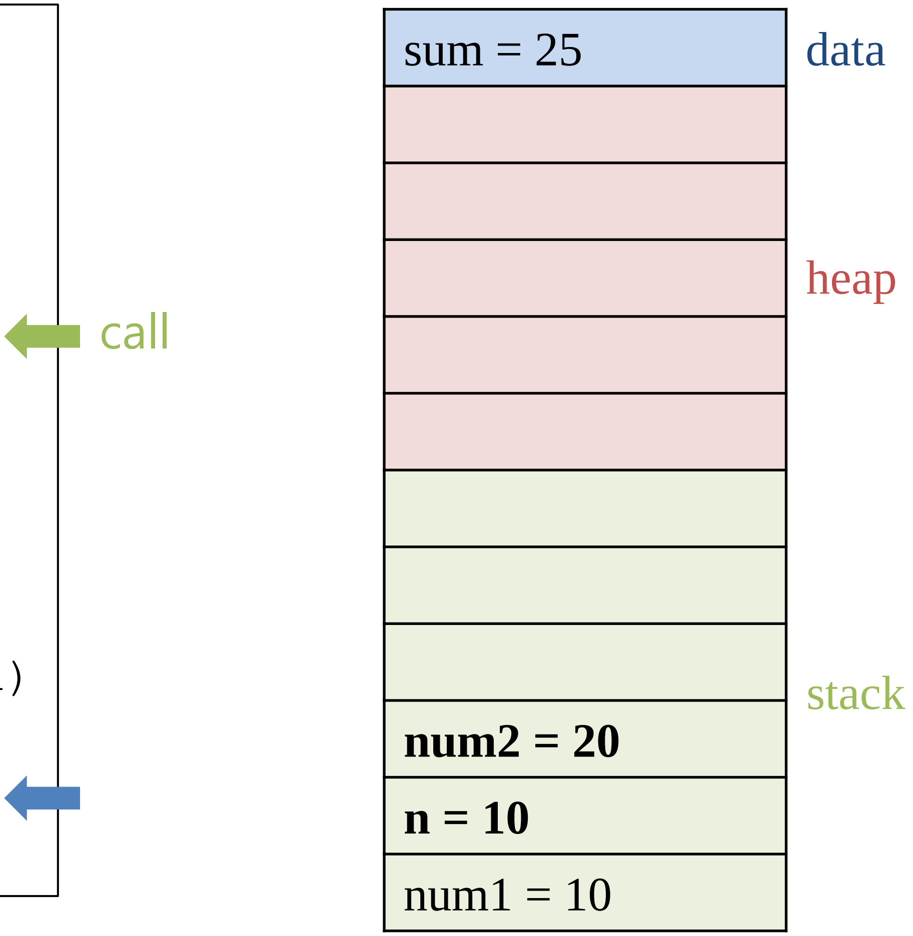


Example - Memory Layout 3

```
int sum=25;

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

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

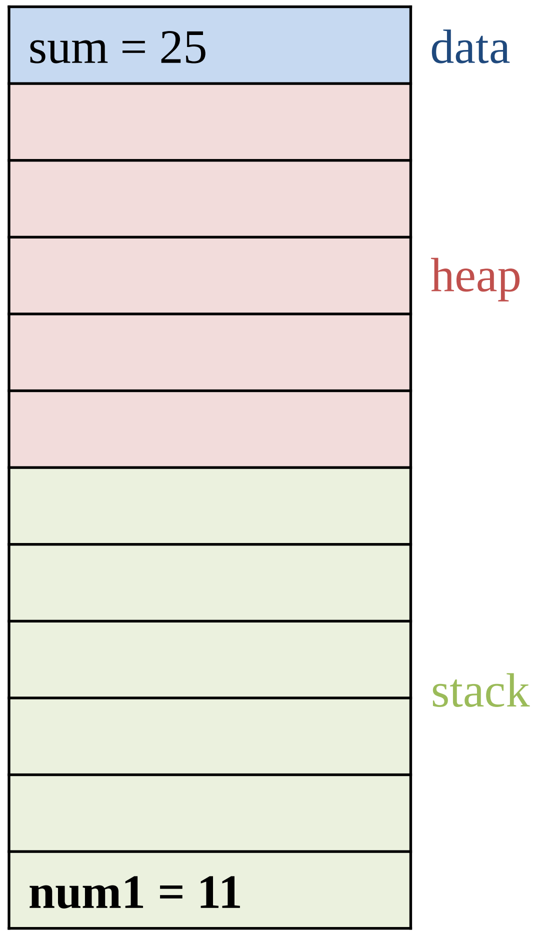


Example - Memory Layout 4

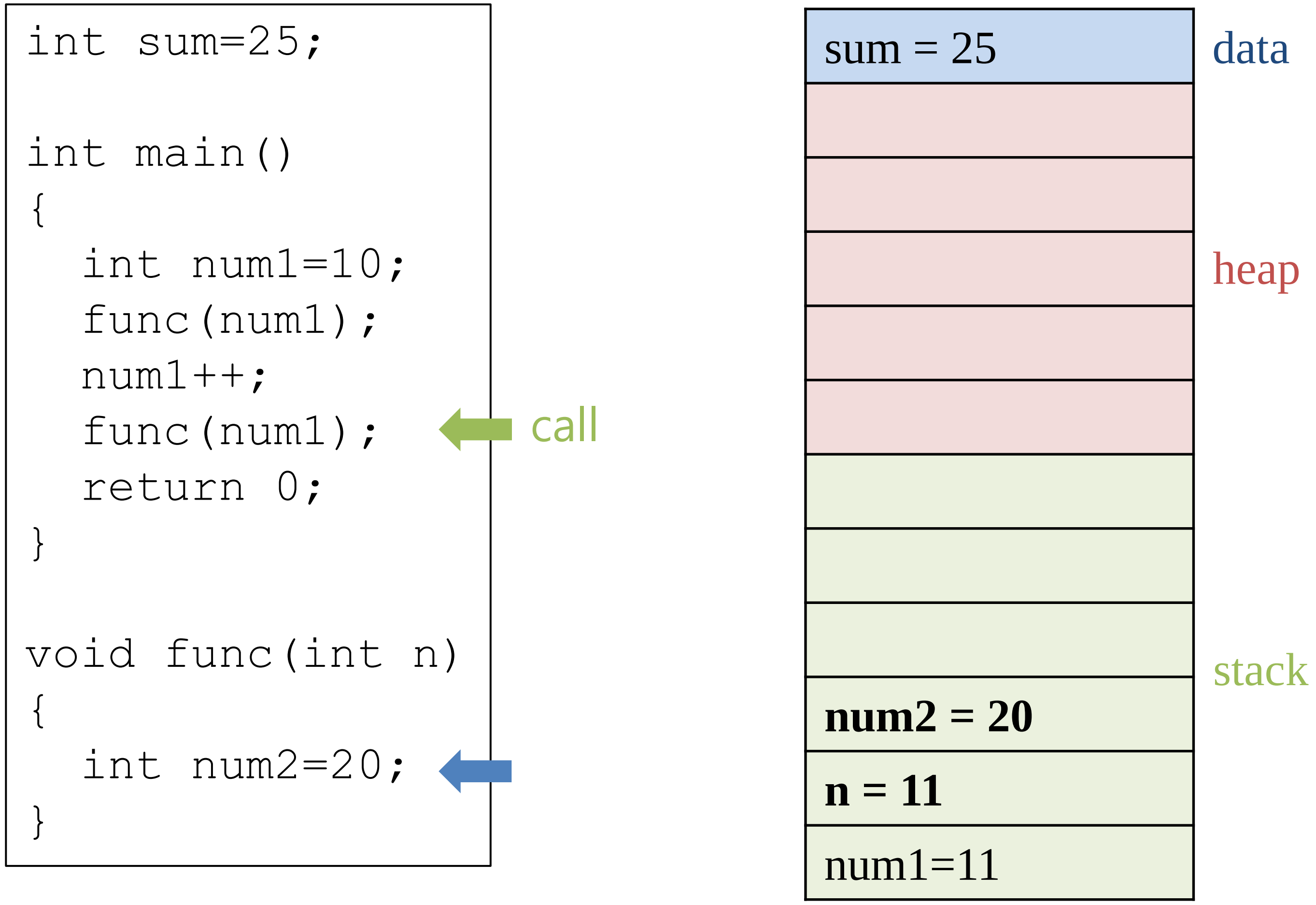
```
int sum=25;

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;
}
```

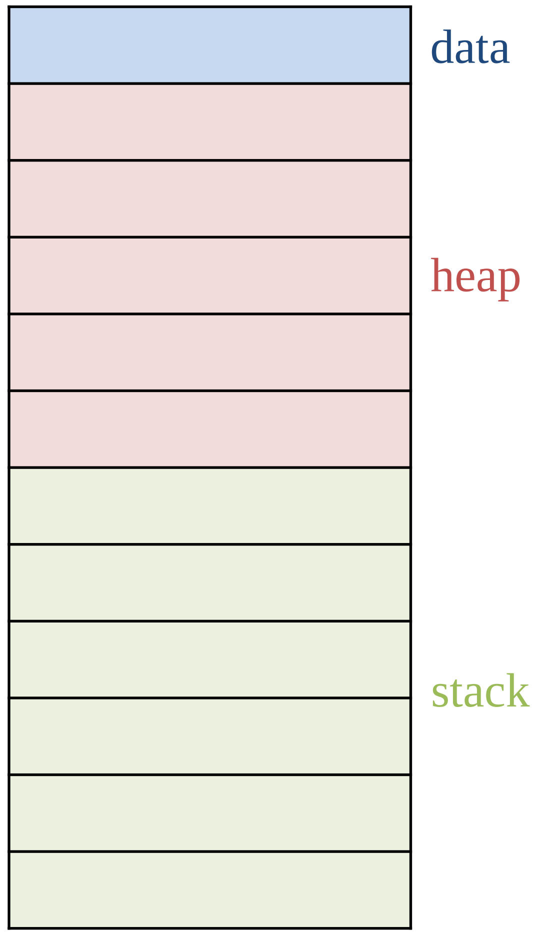
Example - Memory Layout 6

(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

- 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 enc ouraged to use. (https://en.wikipedia.org/wiki/Variable-length_arra y)

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 p ointer 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	`new`	`new []`
Deallocate	`delete`	`delete[]`

Examples - Dynamic Memory Allocation 1

C version

```c
#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

```cpp
#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/
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- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2022123456: 4)**

- Note that your quiz answer must be submitted **in the above format** to receive a quiz score!

Memory Leak

- 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.

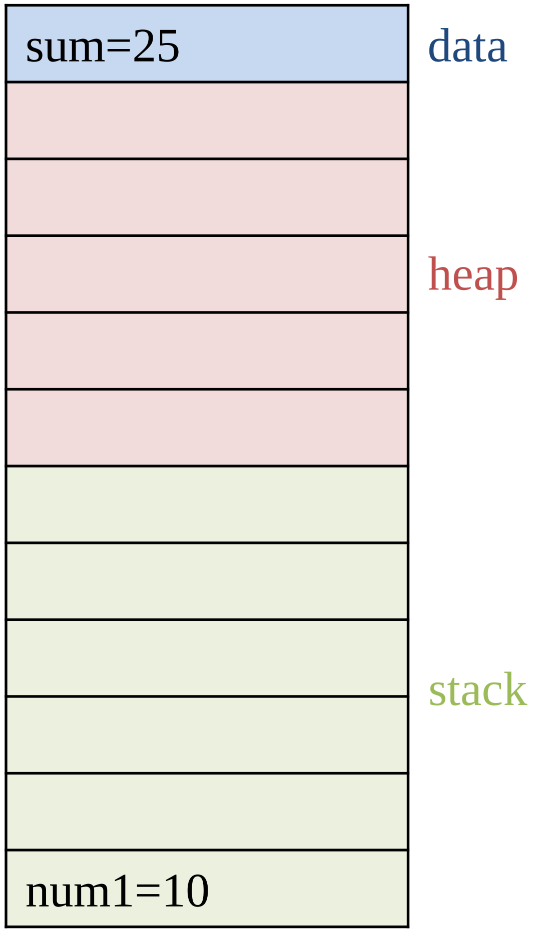
- Be sure to call delete every time you call new.
  - Always use new and delete in pairs.
  - Do not call new and delete in different functions (More likely to make a mistake not to call delete).

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;
}
```

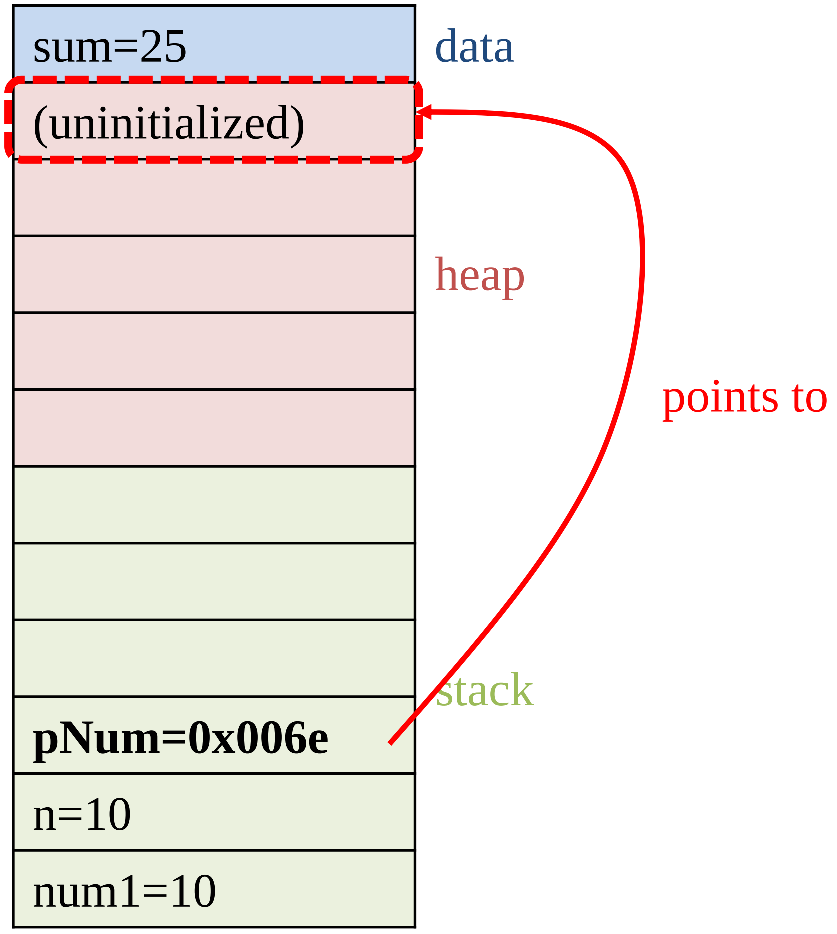


Example - Memory Layout (Dynamic Alloc.) 2

```
int sum=25;

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

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

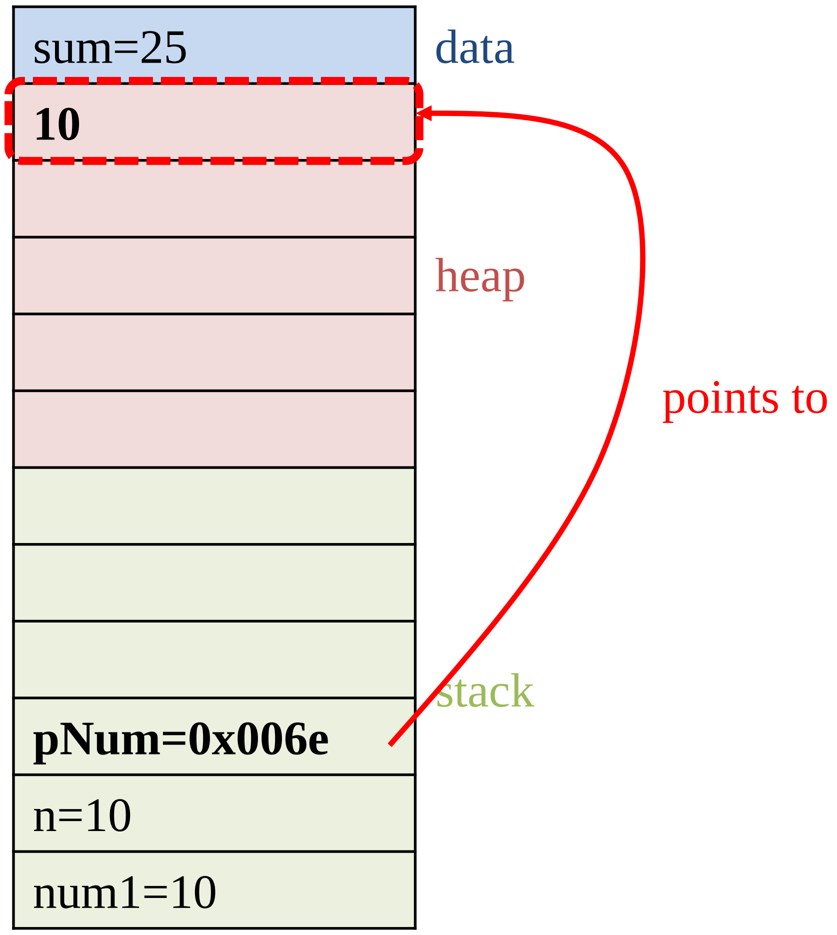


Example - Memory Layout (Dynamic Alloc.) 3

```
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;
}
```

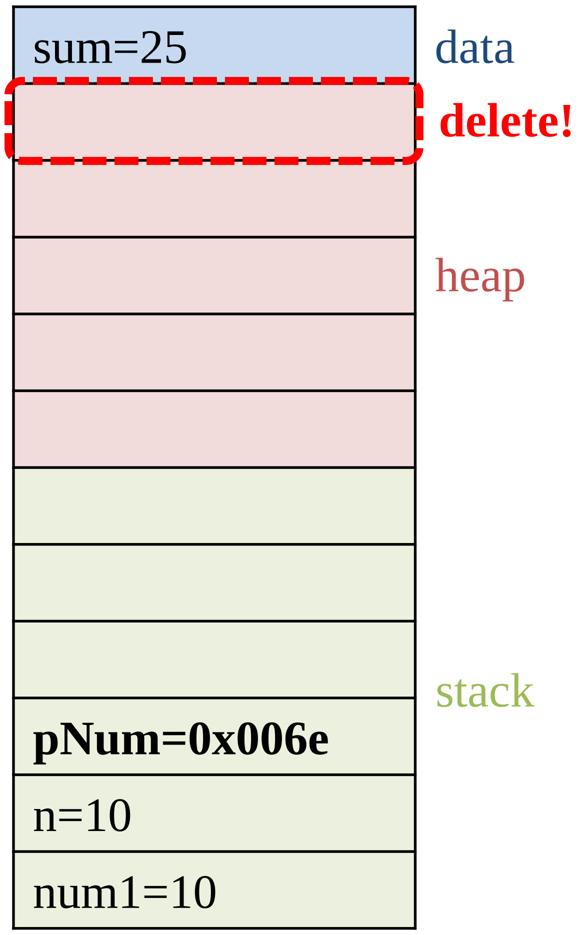


Example - Memory Layout (Dynamic Alloc.) 4

```
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;        ⇐
}
```

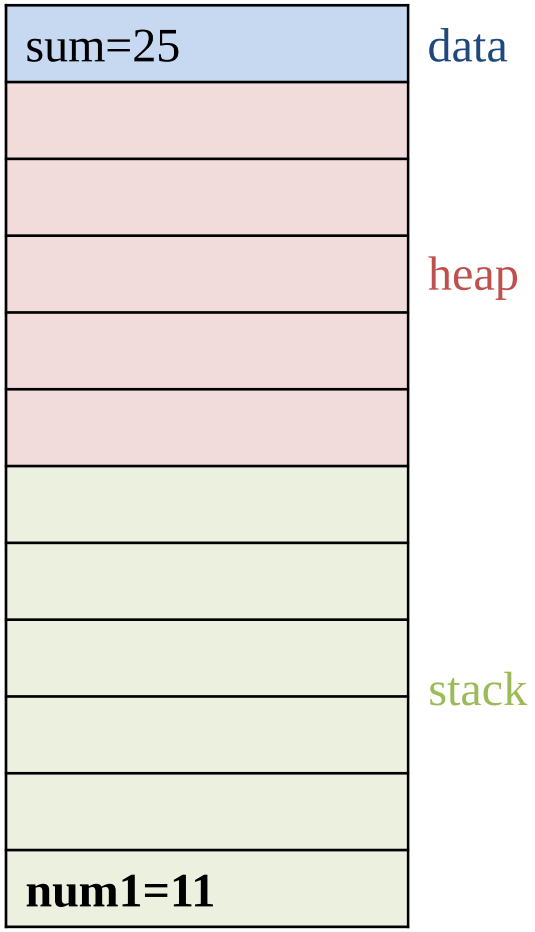


Example - Memory Layout (Dynamic Alloc.) 5

```
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;
}
```

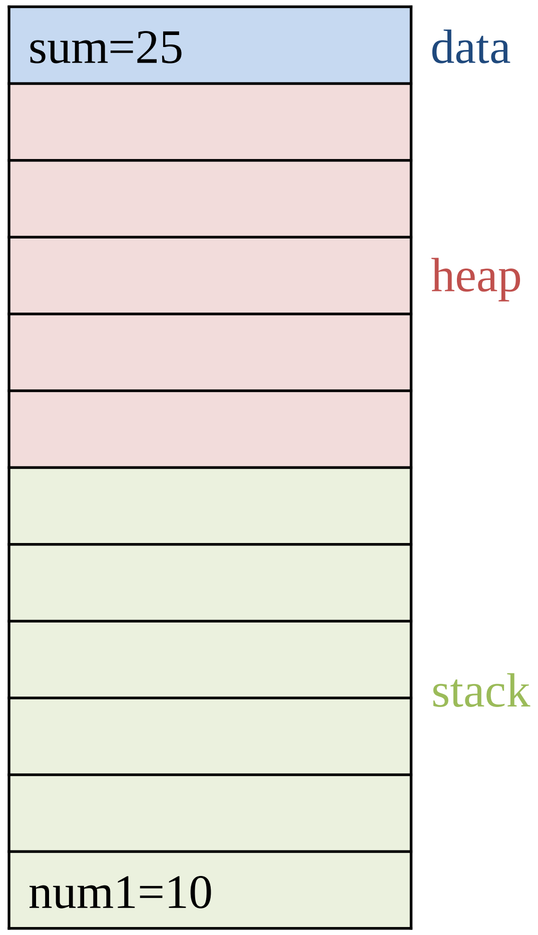


Example - Memory Layout (Memory Leak) 1

```
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;
}
```

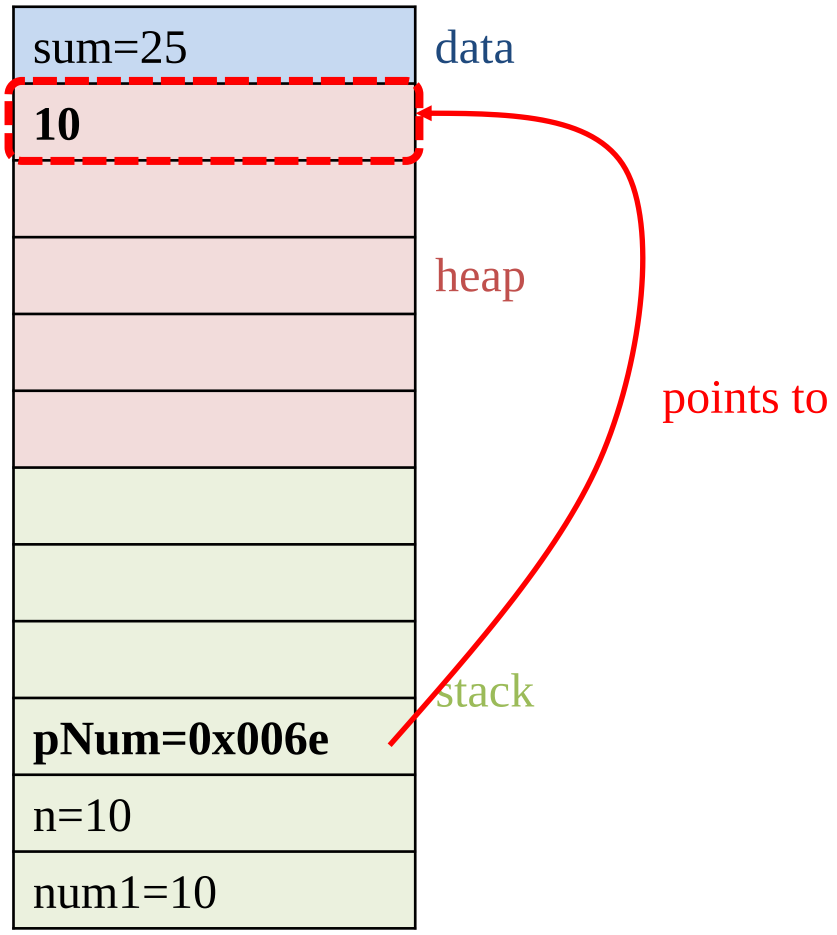


Example - Memory Layout (Memory Leak) 2

```
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;
}
```

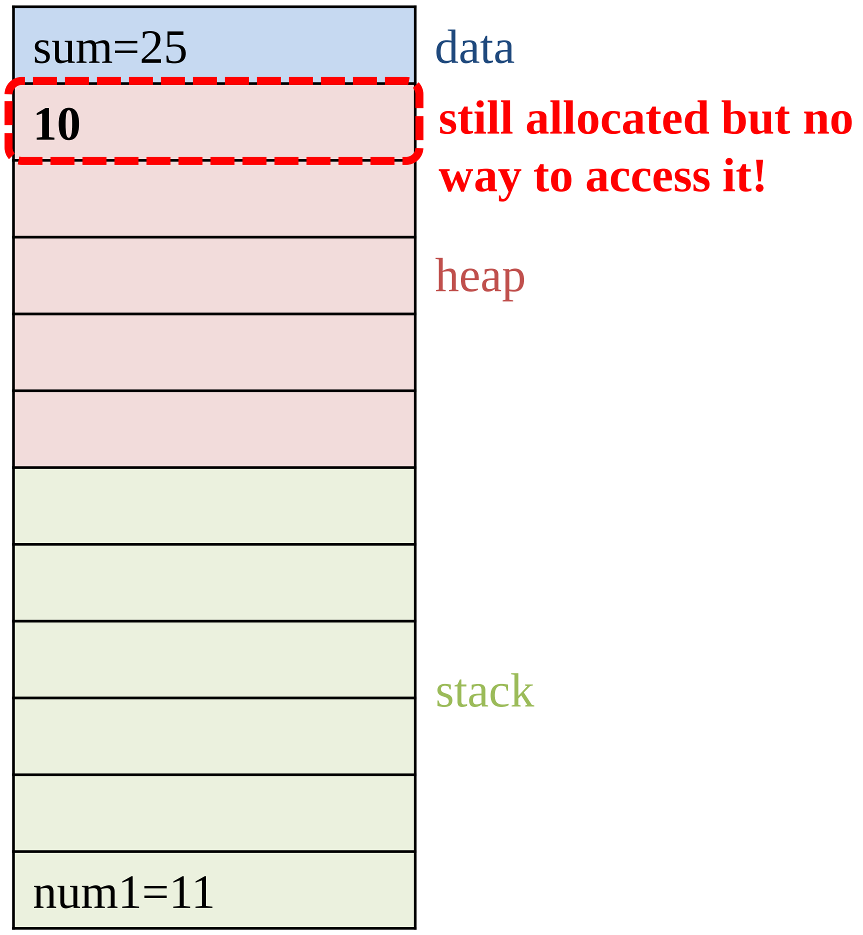


Example - Memory Layout (Memory Leak) 3

```
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/
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- Note that your quiz answer must be submitted **in the above format** to receive a quiz score!

Smart Pointer (Modern C++)

- Using `new` and `delete` can lead to several potential problems:
  - Memory leaks
  - Dangling pointers (pointers that point to memory that has been deallocated)
  - ...

- Actually, the use of `new` and `delete` is discouraged in Modern C++.

Smart Pointer (Modern C++)

- *Smart pointer* provides automatic memory management.
  - A smart pointer object is on the stack and has a raw pointer that points to a heap-allocated object.
  - Its *destructor* contains the call to `delete`, and because the smart pointer is declared on the stack, its *destructor* is invoked when the smart pointer goes out of scope.
  - Provides overloaded operators like * and ->.

```
void UseRawPointer()
{
    // Using a raw pointer -- not recommended.
    Song* pSong = new Song("Anti-Hero");

    // Use pSong...

    // Don't forget to delete!
    delete pSong;
}


void UseSmartPointer()
{
    // Declare a smart pointer on stack and
pass it the raw pointer.
    unique_ptr<Song> song2(new Song("Anti-
Hero"));

    // Use song2...
    wstring s = song2->duration_;
    //...

} // song2 is deleted automatically here.
```

Smart Pointer (Modern C++)

- Modern C++ provides thee types of smart pointers:
  - `std::unique_ptr`
  - `std::shared_ptr`
  - `std::weak_ptr`

- The differences between them and the specific usage details go beyond the scope of this lecture.

- If you're interested, please refer to the following resources:
  - https://www.geeksforgeeks.org/smart-pointers-cpp/
  - https://learn.microsoft.com/en-us/cpp/cpp/smart-pointers-modern-cpp

References

C++ Reference (&)

- References can be used similar to pointers.
  - 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 constant* 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 b e null).

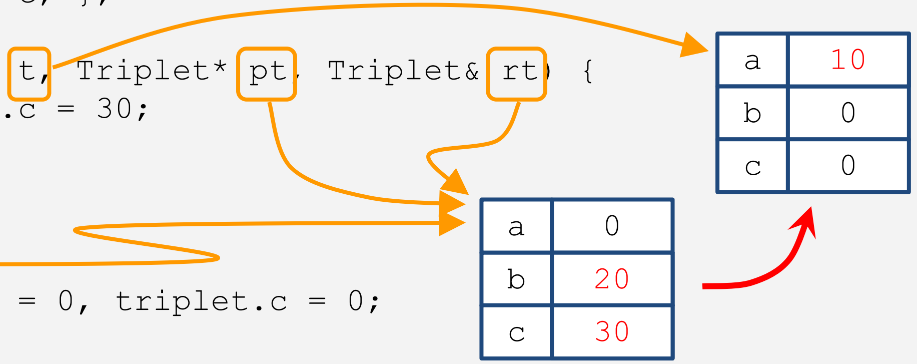
```
struct Triplet { int a, b, c; };

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

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

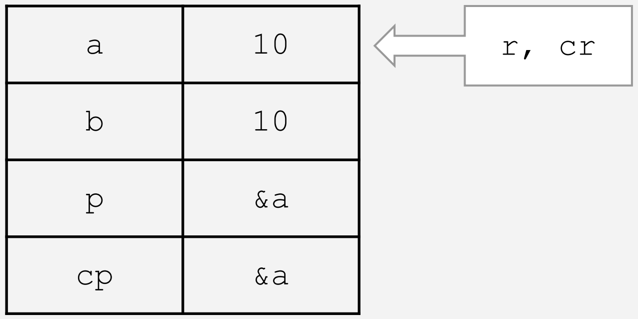
- Address-of operator

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

- Reference

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

Local Variable, Pointer, Reference



a	10
b	10
p	&a
cp	&a

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

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

int& r = a;
const int& cr = 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 for this lecture:
  - Lab1: Assignment 4-1, 4-2
  - Lab2: No lab. (추석연휴)

- Next lecture (**next Wed**):
  - 5 - Compilation and Linkage, CMD Args