211: Computer Architecture
Fall 2019

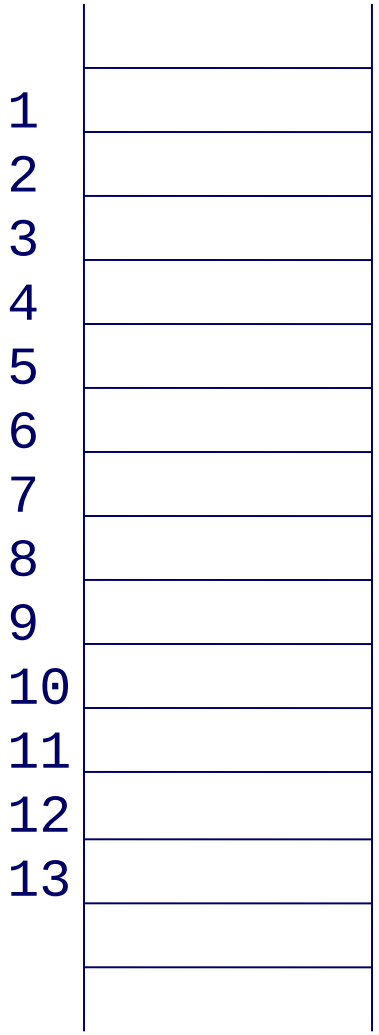
Topic:

- C Programming

Memory

C's memory model matches the underlying (virtual) memory system

- Array of addressable bytes



Memory

C's memory model matches the underlying (virtual) memory system

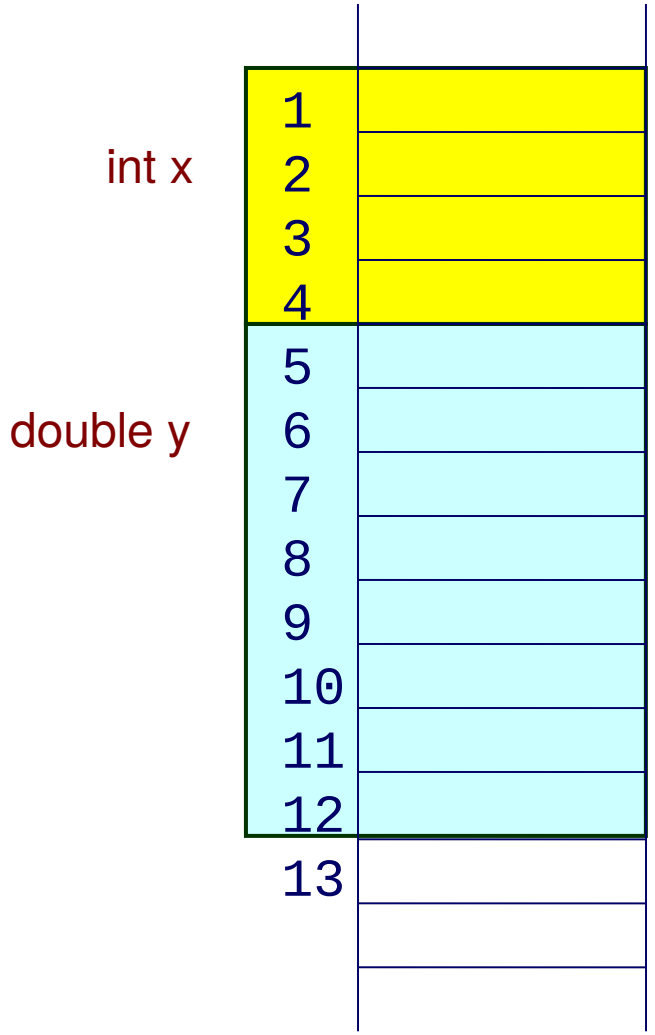
- Array of addressable bytes

Variables are simply names for contiguous sequences of bytes

- Number of bytes given by type of variable

Compiler translates names to addresses

- Typically maps to smallest address
- Will discuss in more detail later



Pointers

A pointer is just an address

Can have variables of type pointer

- Hold addresses as values
- Used for indirection

When declaring a pointer variable, need to declare the type of the data item the pointer will point to

- int *p; /* p will point to a int data item */

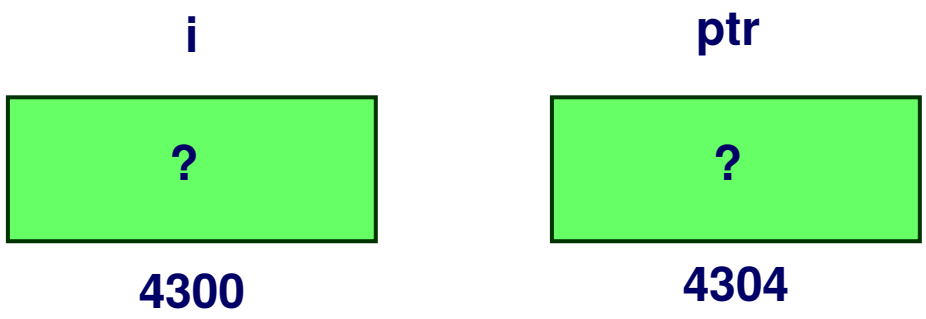
Pointer operators

- De-reference: *
  - *p gives the value stored at the address pointed to by p
- Address: &
  - &v gives the address of the variable v

Pointer Example

```
int i;
int *ptr;

i = 4;
ptr = &i;
*ptr = *ptr + 1;
```

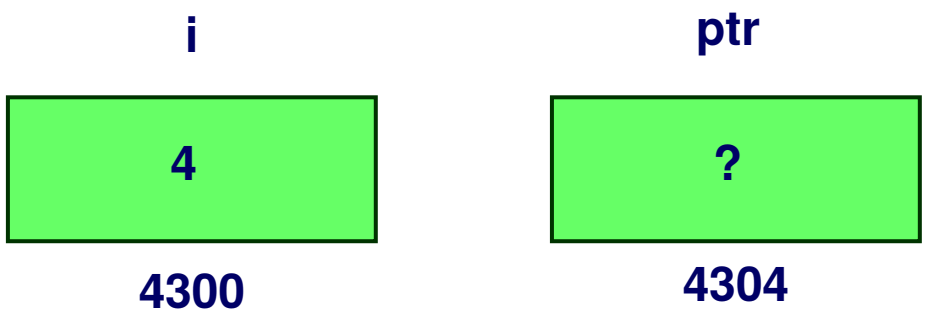


Pointer Example

```
int i;
int *ptr;

i = 4;
ptr = &i;
*ptr = *ptr + 1;
```

store the value 4 into the memory location associated with i

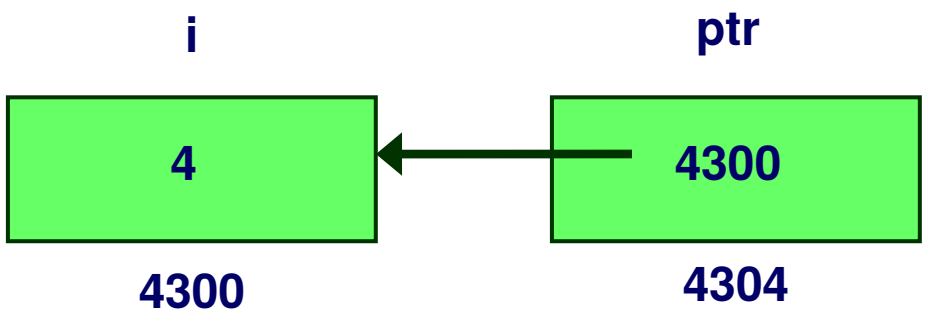


Pointer Example

```
int i;
int *ptr;

i = 4;
ptr = &i;
*ptr = *ptr + 1;
```

store the address of i into the memory location associated with ptr



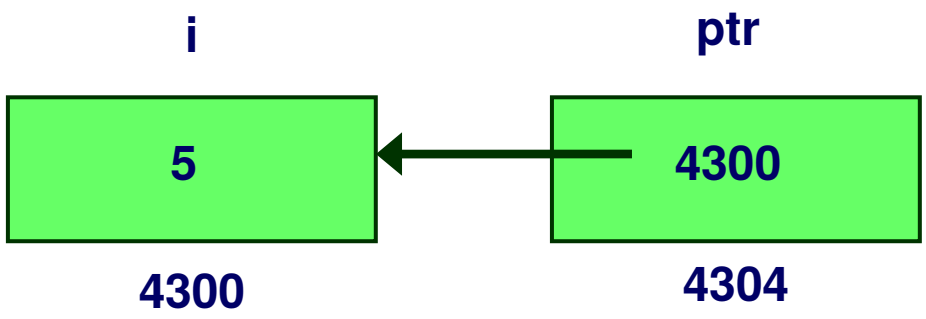
Pointer Example

```
int i;
int *ptr;

i = 4;
ptr = &i;
*ptr = *ptr + 1;
```

store the result into memory at the address stored in ptr

read the contents of memory at the address stored in ptr



Null Pointer

Sometimes we want a pointer that points to nothing

In other words, we declare a pointer, but we're not ready to actually point to something yet

```
int *p;
p = NULL;  /* p is a null pointer */
```

NULL is a predefined constant that contains a value that a non-null pointer should never hold

- Often, NULL = 0, because address 0 is not a legal address for most programs on most platforms

Example Use of Pointers

What does the following code produce? Why?

```
void Swap(int firstVal, int secondVal)
{
    int tempVal = firstVal;
    firstVal = secondVal;
    secondVal = tempVal;
}

…
int fv = 6, sv = 10;
Swap(fv, sv);
printf("Values: (%d, %d)\n", fv, sv);
```

Parameter Pass-by-Reference

Now what does the code produce? Why?

```
void Swap(int *firstVal, int *secondVal)
{
    int tempVal = *firstVal;
    *firstVal = *secondVal;
    *secondVal = tempVal;
}

…
int fv = 6, sv = 10;
Swap(&fv, &sv);
printf("Values: (%d, %d)\n", fv, sv);
```

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Type Casting

C is NOT strongly typed

Type casting allows programmers to dynamically change the type of a data item

Arrays

Arrays are contiguous sequences of data items

- All data items are of the same type
- Declaration of an array of integers: “int a[20];”
- Access of an array item: “a[15]”

Array index always start at 0

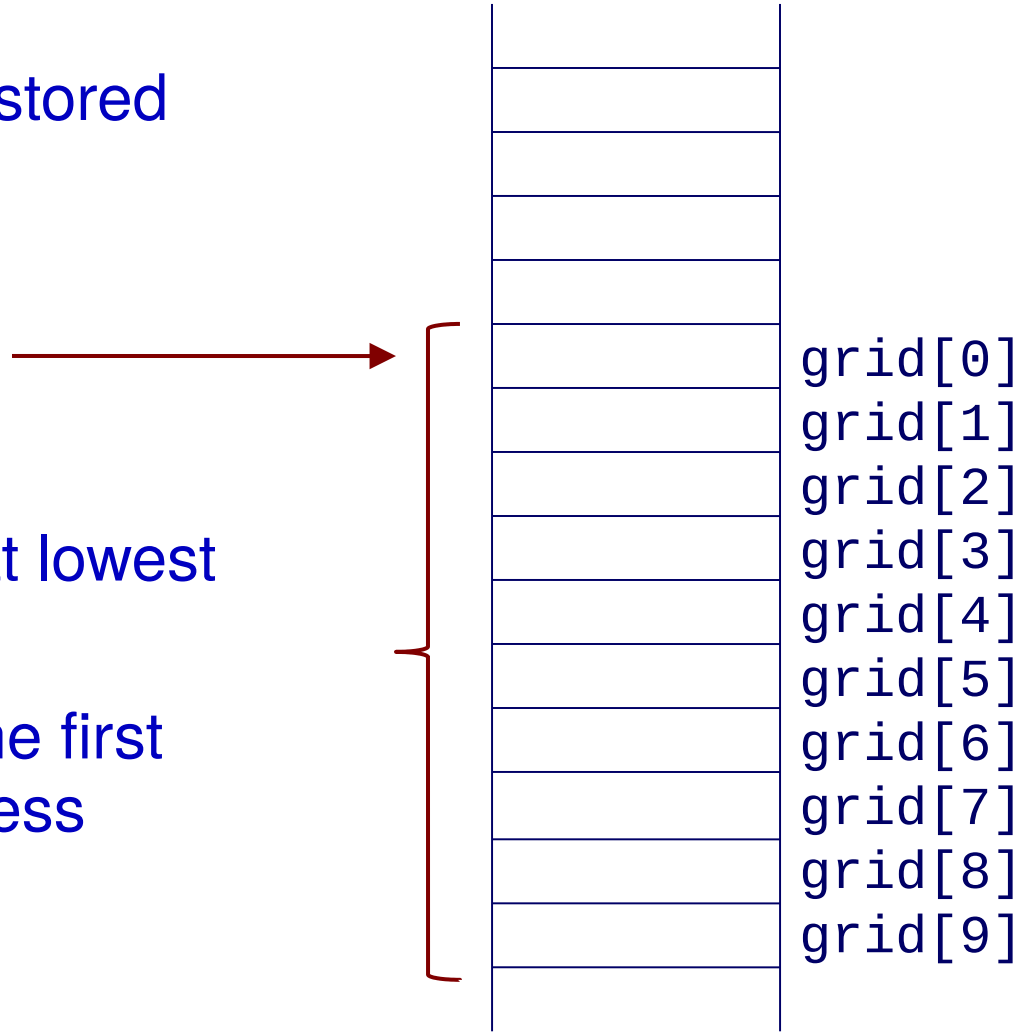
The C compiler and runtime system do not check array boundaries

- The compiler will happily let you do the following:
  - int a[10]; a[11] = 5;

Array Storage

Elements of an array are stored sequentially in memory

char grid[10];



First element (grid[0]) is at lowest address of sequence

Knowing the location of the first element is enough to access any element

Arrays & Pointers

An array name is essentially a pointer to the first element in the array

```
1. char word[10];
2. char *cptr;
3. cptr = word;  /* points to word[0] */
```

Difference:

- Line 1 allocates space for 10 char items
- Line 2 allocates space for 1 pointer
- Can change value of cptr whereas cannot change value of word
  - Can only change value of word[i]

Arrays & Pointers (Continued)

Given

```
char word[10];
char *cptr;
cptr = word;
```

Each row in following table gives equivalent forms

`cptr`	`word`	`&word[0]`
`cptr + n`	`word + n`	`&word[n]`
`*cptr`	`*word`	`word[0]`
`*(cptr + n)`	`*(word + n)`	`word[n]`

Pointer Arithmetic

Be careful when you are computing addresses

Address calculations with pointers are dependent on the size of the data the pointers are pointing to

Examples:

- `int *i; …; i++;  /* i = i  + 4 */`
- `char *c; …; c++;    /* c = c + 1 */`
- `double *d; …; d++;  /* d = d + 8 */`

Another example:

```
double x[10];
double *y = x;
*(y + 3) = 13;   /* x[3] = 13 */
```

Passing Arrays as Arguments

Arrays are passed by reference (Makes sense because array name ~ pointer)

Array items are passed by value (No need to declare size of array for function parameters)

```
#include <stdio.h>

int *bogus;

void foo(int seqItems[], int item)
{
    seqItems[1] = 5;
    item = 5;
    bogus = &item;
}

int main(int argc, char **argv)
{
    int bunchOfInts[10];

    bunchOfInts[0] = 0;
    bunchOfInts[1] = 0;

    foo(bunchOfInts, bunchOfInts[0]);

    printf("%d, %d\n", bunchOfInts[0], bunchOfInts[1]);
    printf("%d\n", *bogus);
}
```

Common Pitfalls with Arrays in C

Overrun array limits

- There is no checking at run-time or compile-time to see whether reference is within array bounds.

```
int array[10];
int i;
for (i = 0; i <= 10; i++) array[i] = 0;
```

Declaration with variable size

- Size of array must be known at compile time.

```
void SomeFunction(int num_elements) {
     int temp[num_elements];
     …
}
```

Strings: Arrays of Characters

Allocate space for a string just like any other array:

```
char outputString[16];
```

Each string should end with a '\0' character

Special syntax for initializing a string:

```
char outputString[16] = "Result";
```

…which is the same as:

```
outputString[0] = 'R';
outputString[1] = 'e';
...
outputString[6] = '\0';
```

The '\0' allows functions like strlen() to work on arbitrary strings

Useful functions for Strings

Useful string related functions in standard C libraries

```
#include <string.h>
```

`char *strcpy(char *d, char *s)` Copy string s to d

`int strcmp(s1, s2)` Compare string s1 to s2

`size_t strlen(s)` Returns length of cs

Use “man” to learn more about these functions

- man strcpy

Special Character Literals

Certain characters cannot be easily represented by a single keystroke, because they

- correspond to whitespace (newline, tab, backspace, ...)
- are used as delimiters for other literals (quote, double quote, ...)

These are represented by the following sequences:

`\n` newline
`\t` tab
`\b` backspace
`\\` backslash
`\'` single quote
`\"` double quote
`\0`*nnn* ASCII code *nnn* (in octal)
`\x`*nnn* ASCII code *nnn* (in hex)

Structures

A struct is a mechanism for grouping together related data items of different types.

Example: we want to represent an airborne aircraft

```
char flightNum[7];
int altitude;
int longitude;
int latitude;
int heading;
double airSpeed;
```

We can use a struct to group these data items together

Defining a Struct

We first need to define a new type for the compiler and tell it what our struct looks like.

```
struct flightType {
        char flightNum[7];    /* max 6 characters */
        int altitude;         /* in meters */
        int longitude;        /* in tenths of degrees */
        int latitude;         /* in tenths of degrees */
        int heading;          /* in tenths of degrees */
    double airSpeed;          /* in km/hr */
};
```

This tells the compiler how big our struct is and how the different data items are laid out in memory

- But it does not allocate any memory
- Memory is only allocated when a variable is declared

Declaring and Using a Struct

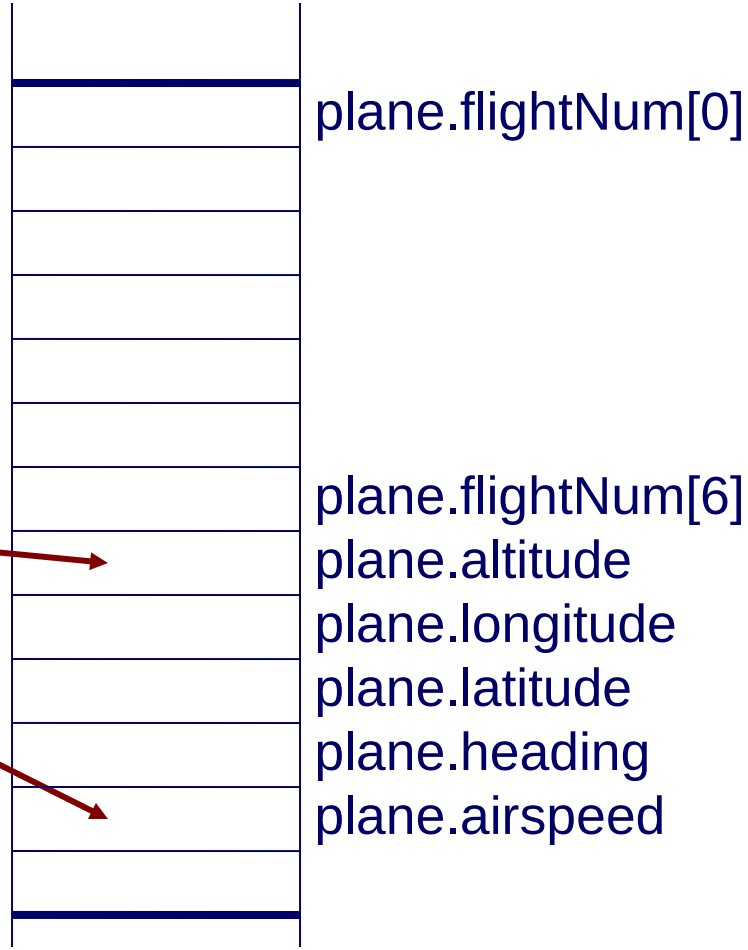
To allocate memory for a struct, we declare a variable using our new data type.

```
struct flightType plane;
```

Memory is allocated, and we can access individual members of this variable:

```
plane.altitude = 10000;
plane.airSpeed = 800.0;

foo(&(plane.airSpeed);
/* pass the address of
   plane.airSpeed */
```



Array of Structs

Can declare an array of struct items:

- struct flightType planes[100];

Each array element is a struct item of type “struct flightType”

To access member of a particular element:

- planes[34].altitude = 10000;

Because the [] and . operators are at the same precedence, and both associate left-to-right, this is the same as:

- (planes[34]).altitude = 10000;

Pointer to Struct

We can declare and create a pointer to a struct:

```
struct flightType *planePtr;
planePtr = &planes[34];
```

To access a member of the struct addressed by dayPtr:

```
(*planePtr).altitude = 10000;
```

Because the . operator has higher precedence than *, this is NOT the same as:

```
*planePtr.altitude = 10000;
```

C provides special syntax for accessing a struct member through a pointer:

```
planePtr->altitude = 10000;
```

Passing Structs as Arguments

Unlike an array, a struct item is passed by value

Most of the time, you'll want to pass a pointer to a struct.

```
int Collide(struct flightType *planeA, struct flightType *planeB)
{
  if (planeA->altitude == planeB->altitude) {
     ...
  }
  else
    return 0;
}
```

Dynamic Allocation

What if we want to write a program to handle a variable amount of data?

- E.g., sort an arbitrary set of numbers
- Can't allocate an array because don't know how many numbers we will get
  - Could allocate a very large array
  - Inflexible and inefficient

Answer: dynamic memory allocation

- Similar to "new" in Java

Memory Management 101

When a function call is performed in a program, the run-time system must allocate resources to execute it

- Memory for any local variables, arguments, and result

The same function can be called many times (Example: recursion)

- Each instance will require some resources

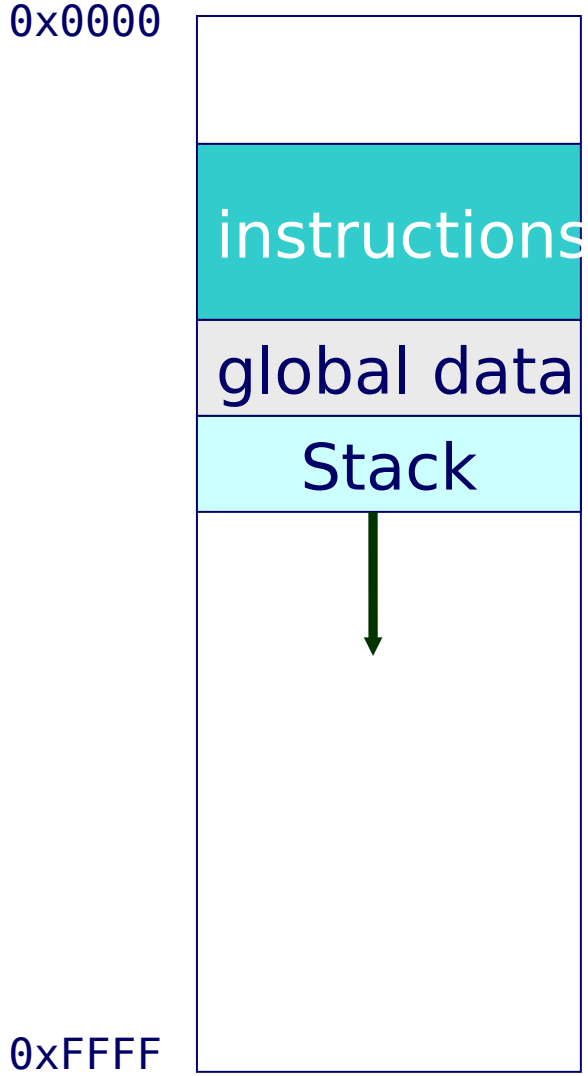
The state associated with a function is called an activation record

Allocating Space for Variables

Activation records are allocated on a call stack

- Function calls leads to a new activation record pushed on top of the stack
- Activation record is popped off the stack when the function returns

Let's see an example



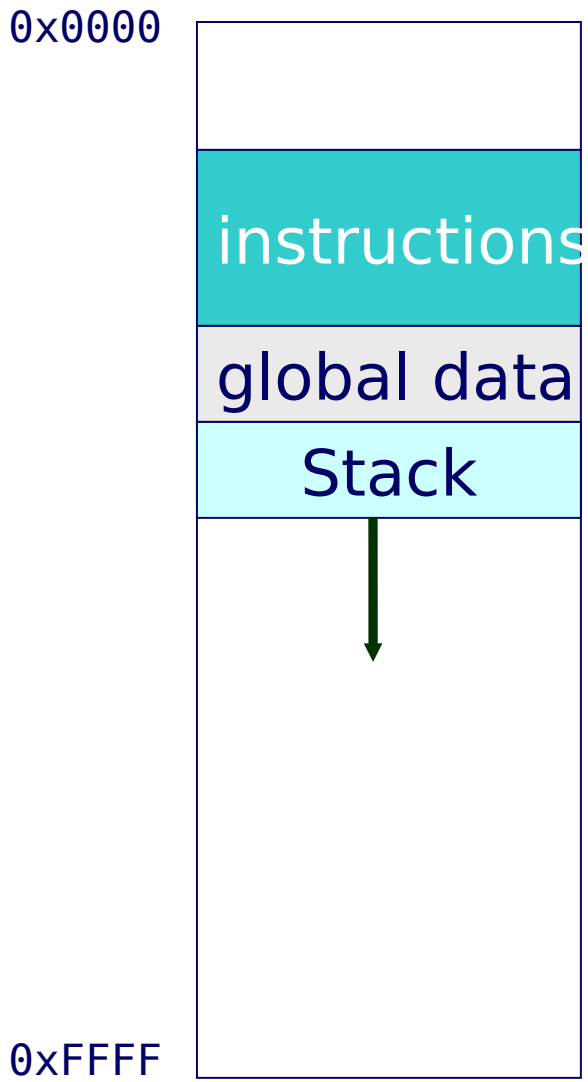
Allocating Space for Variables

Compute the sum of number from 1 to N

```
int summation(int n){
  if(n == 0) return 0
  else return n + summation(n-1);
}
…
summation(5);
```

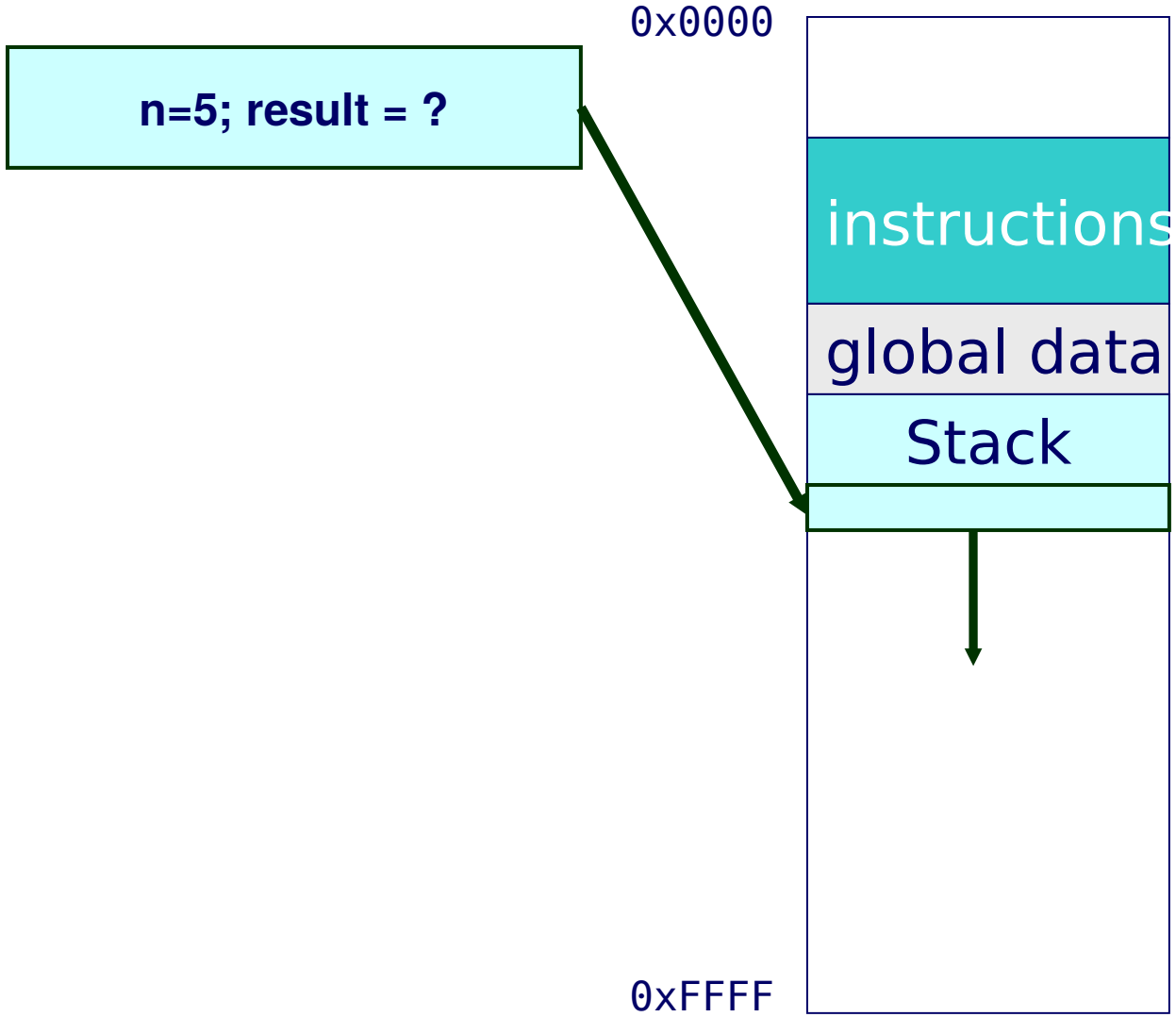
Recall that the activation record for a function contains state for all arguments, local variables, and result

int n; int result;

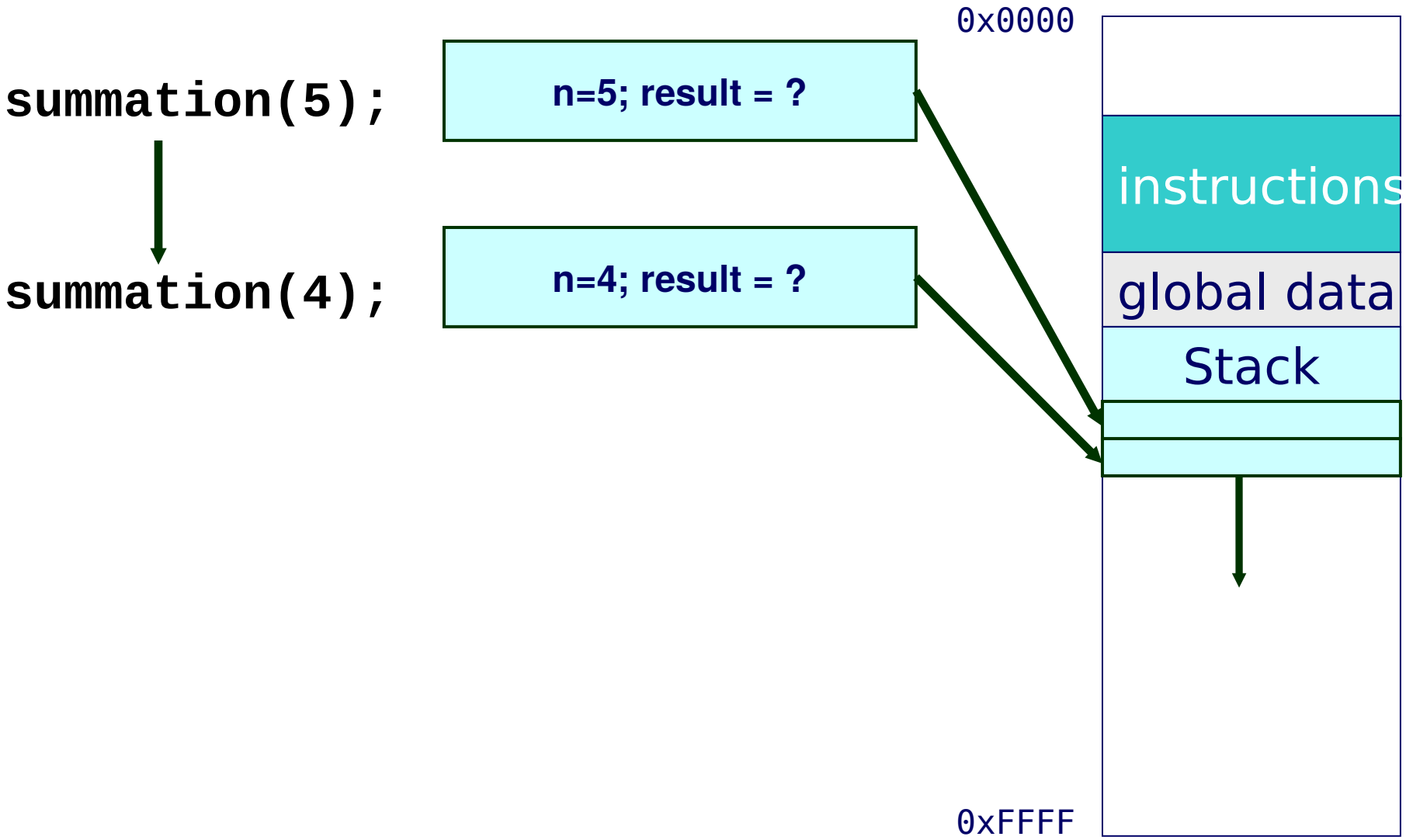


Allocating Space for Variables

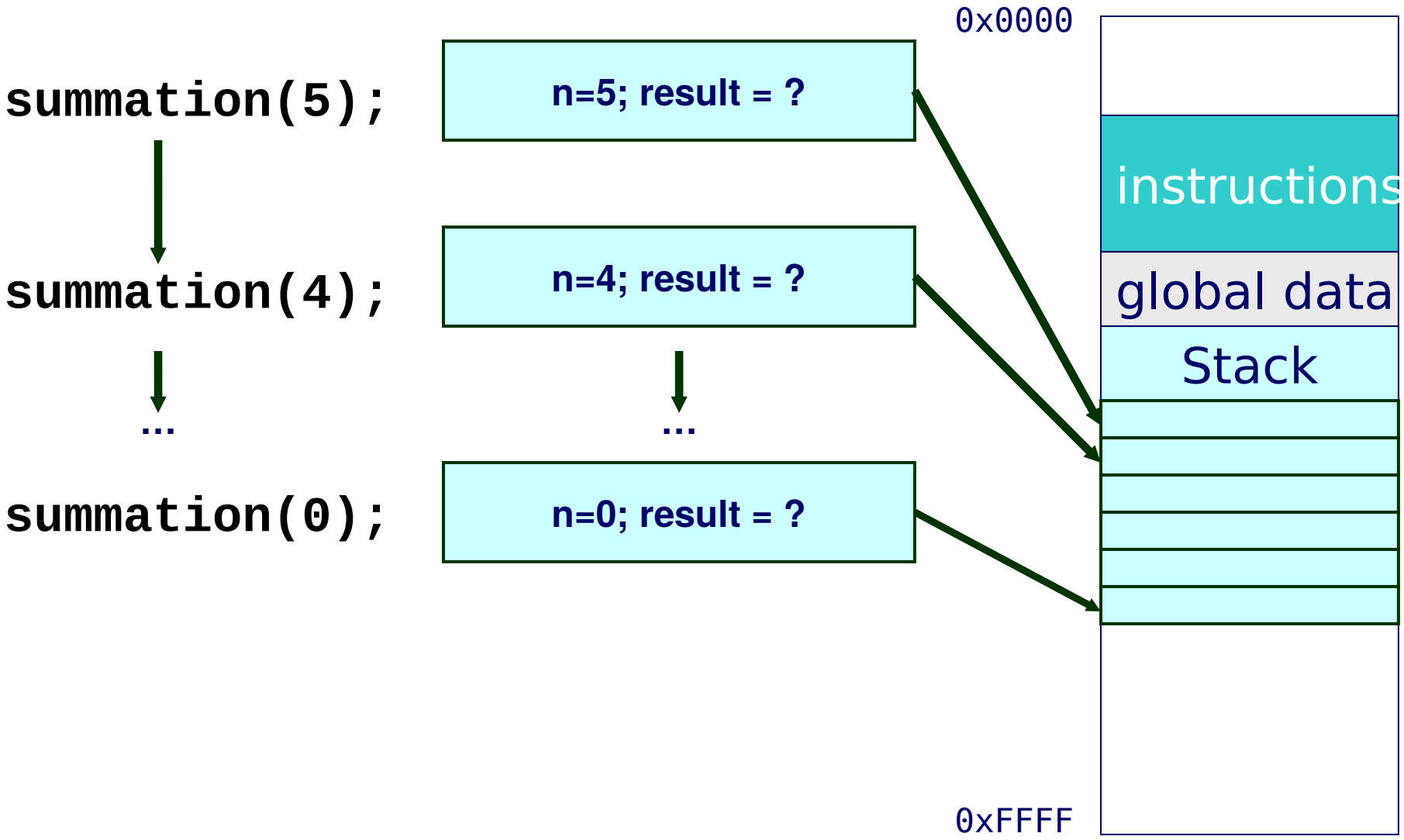
```
summation(5);
```



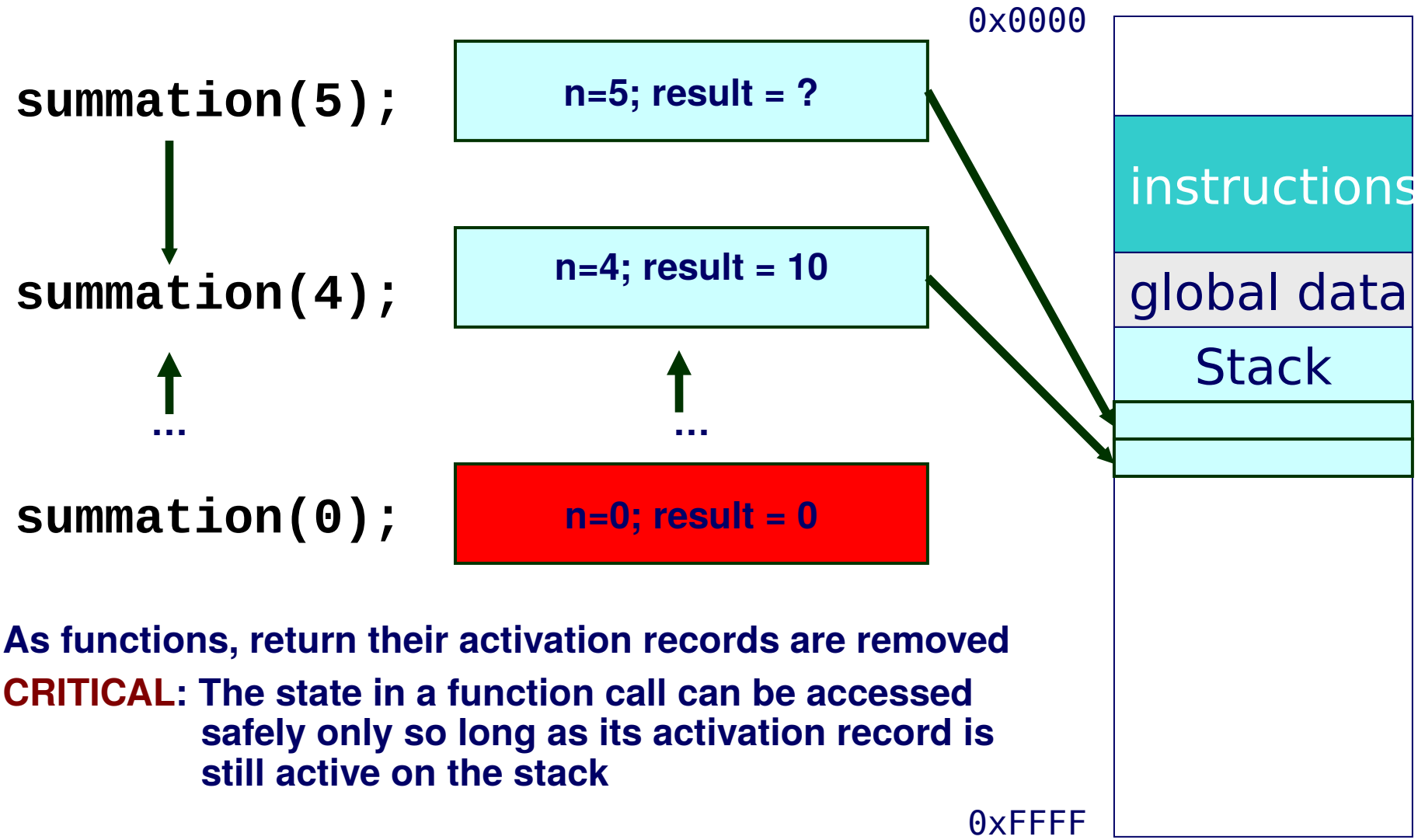
Allocating Space for Variables



Allocating Space for Variables



Allocating Space for Variables



As functions, return their activation records are removed

CRITICAL: The state in a function call can be accessed safely only so long as its activation record is still active on the stack

Dynamic Allocation

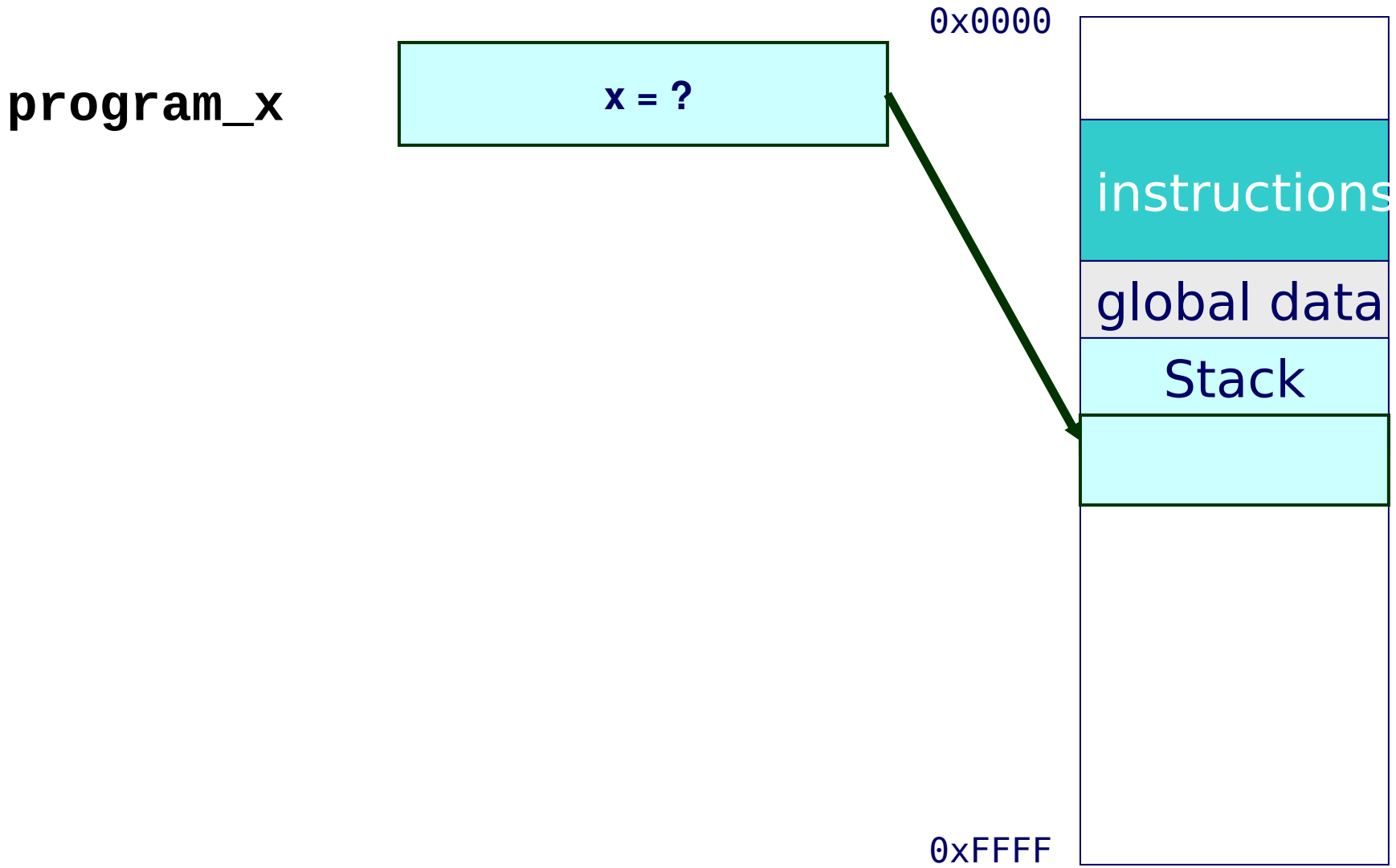
What if we want

- Memory area whose lifetime does not match any particular function?
- Memory area whose size is not known at compile time?

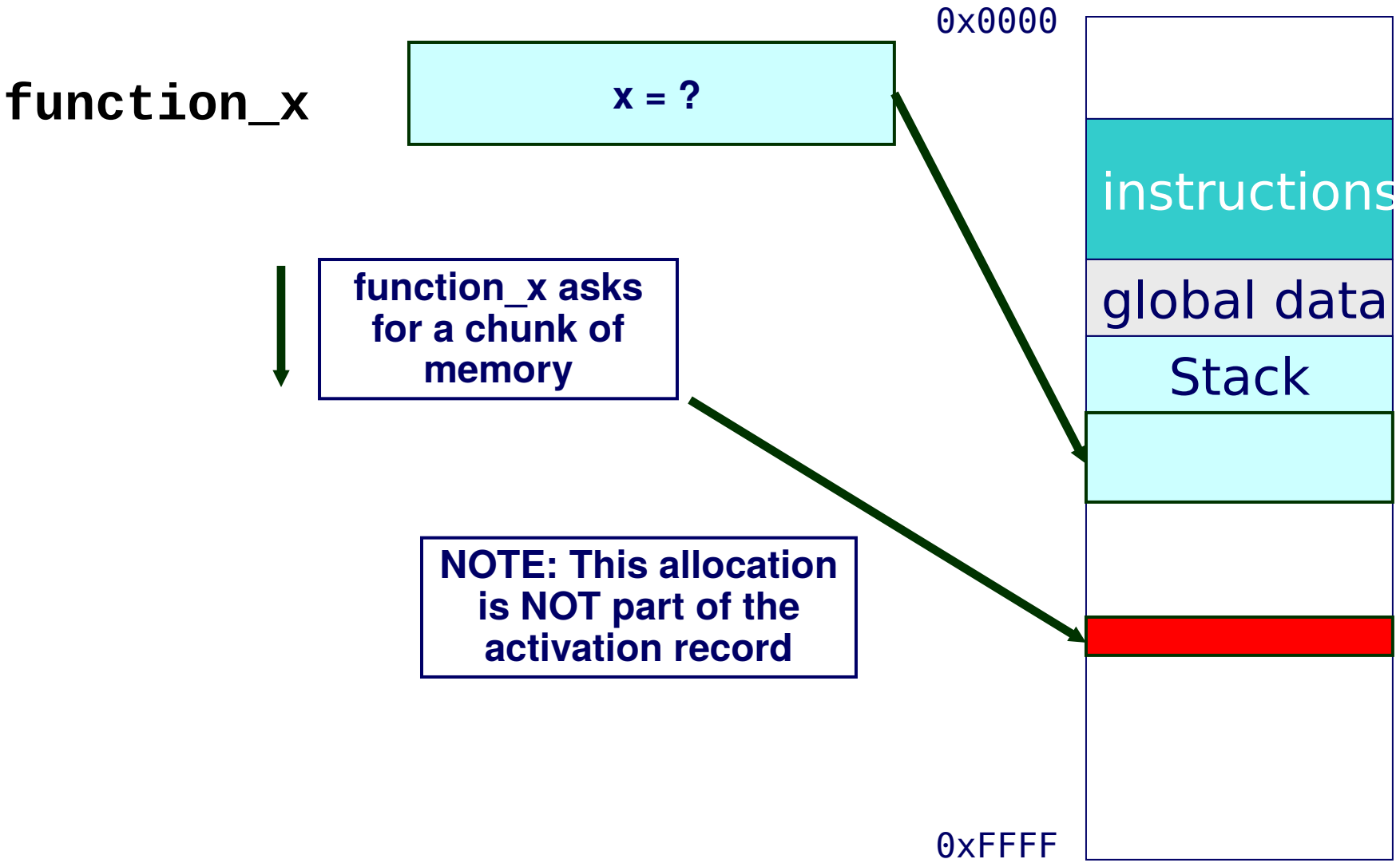
Two ways to “get memory”

- Declare a variable
  - Placed in global area or stack
  - Either “lives” forever or “live-and-die” with containing function
  - Size must be known at compile time
- Ask the run-time system for a “chunk” of memory dynamically

Allocating Space for Variables



Allocating Space for Variables

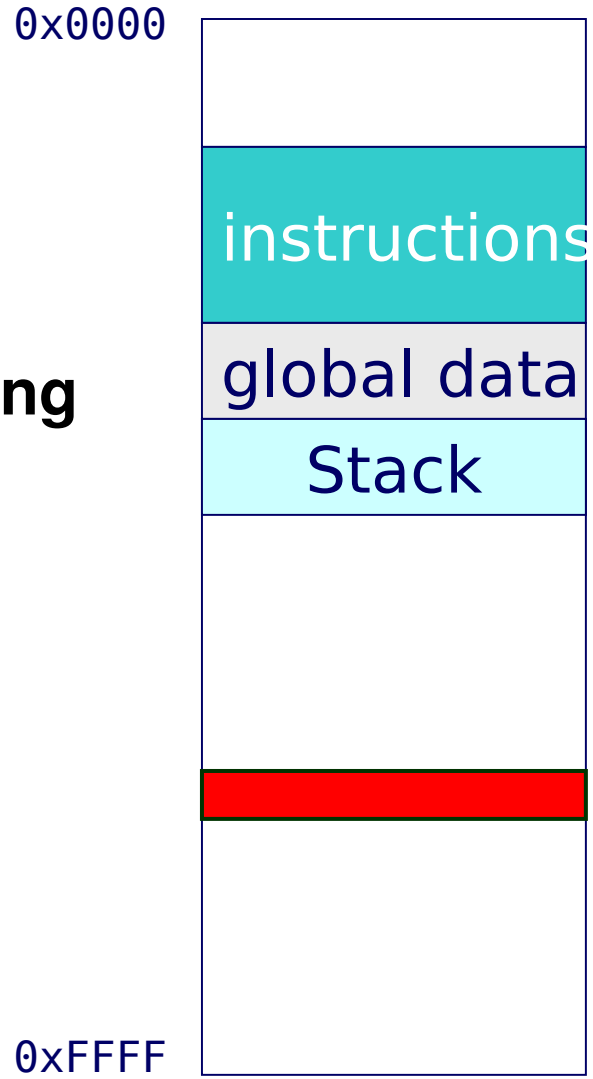


Allocating Space for Variables

After function returns, memory is still allocated

Request for dynamic chunks of memory performed using a call to the underlying runtime system (a system call).

- **Commands: malloc and free**



Dynamic Memory

Another area region of memory exists, it is called the heap

Dynamic request for memory are allocated from this region

Managed by the run-time system (actually, just a fancy name for a library that's linked with all C code)