CS601: Software Development for Scientific Computing

Autumn 2021

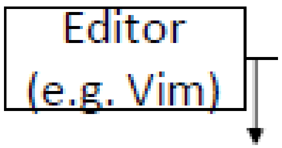
Week2: Program Development Environment, Minimal C++, Version Control Systems, Structured Grid

Program Development Environment

- Demo

Creating a Program

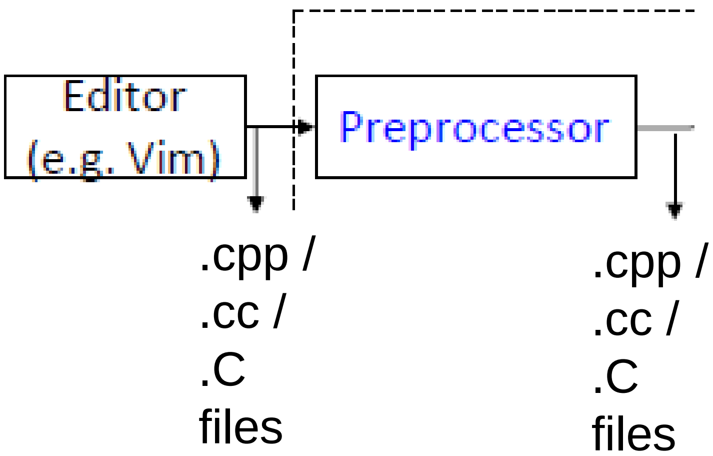
- Create your c++ program file



.cpp /
.cc /
.C
files

Creating a Program

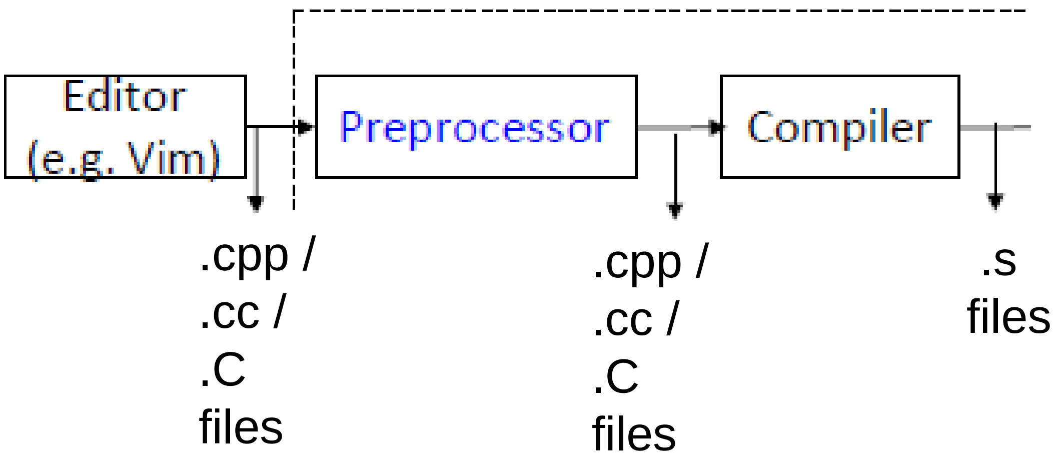
- Preprocess your c++ program file



- removes comments from your program,
- expands #include statements

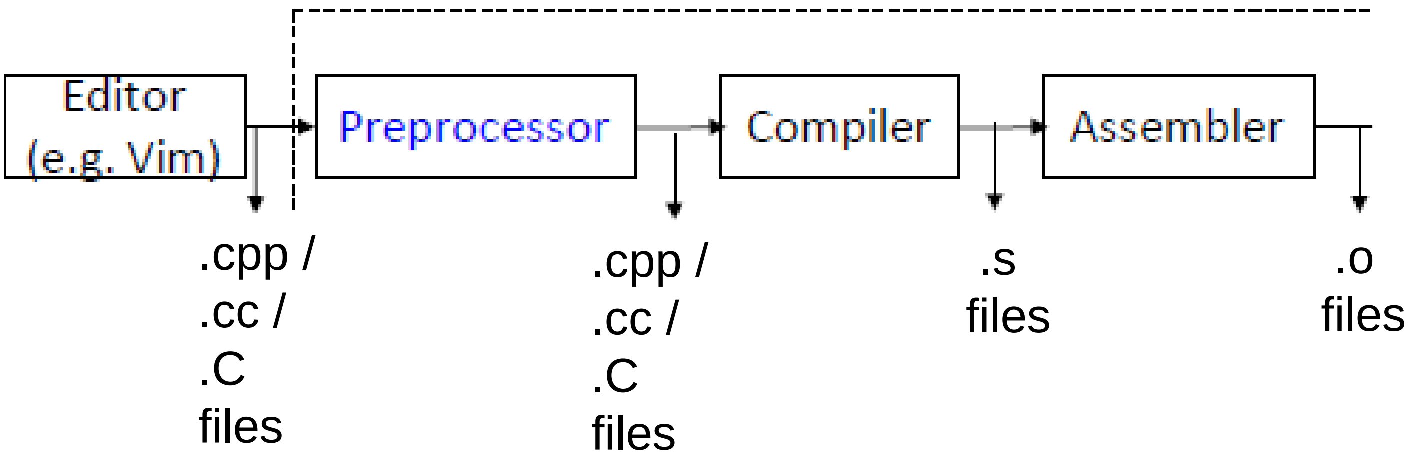
Creating a Program

- Translate your source code to assembly language



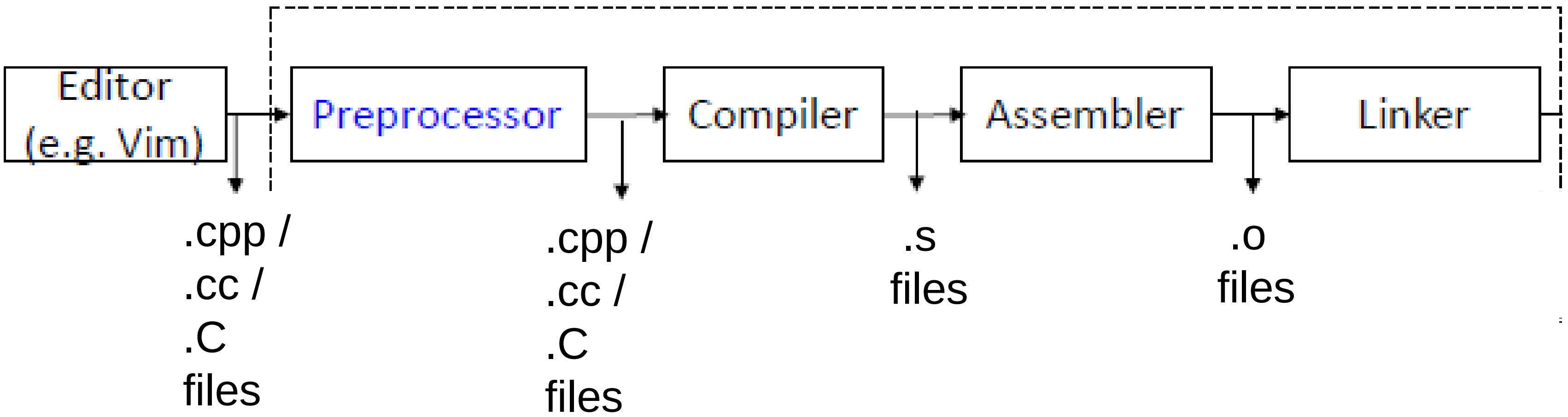
Creating a Program

- Translate your assembly code to machine code



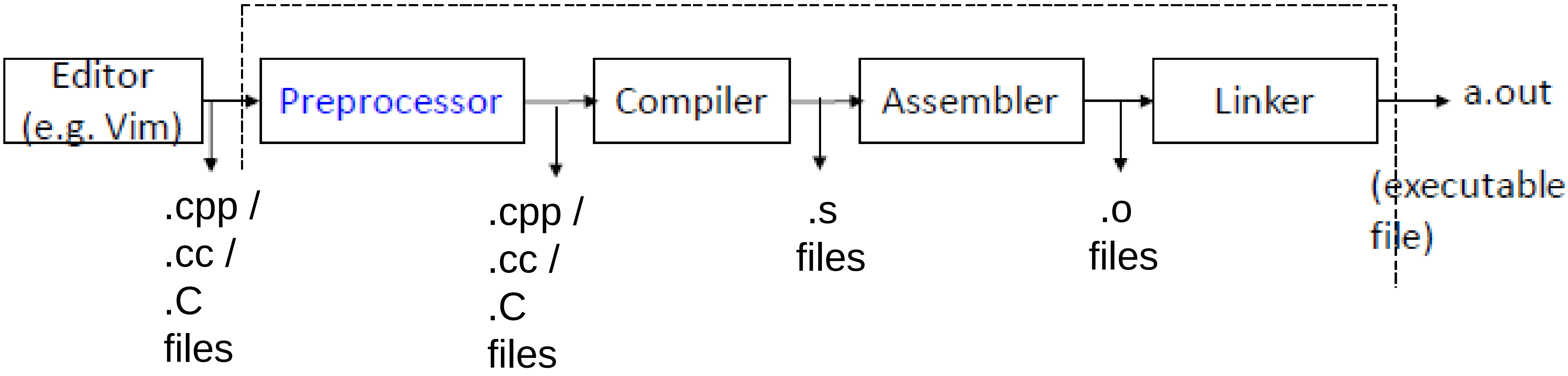
Creating a Program

- Get machine code that is part of libraries



Creating a Program

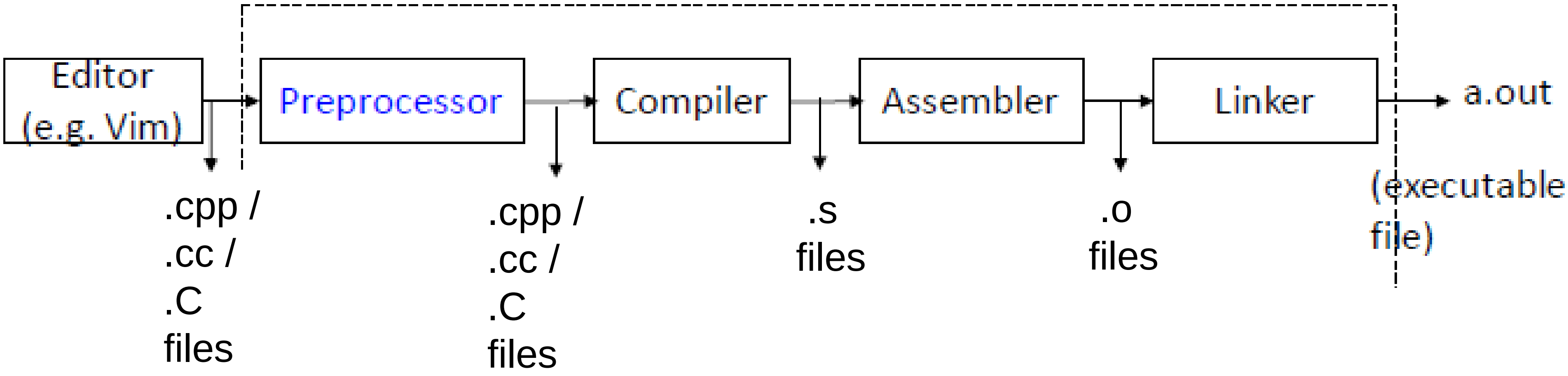
- Create executable



1. Either copy the corresponding machine code OR
2. Insert a 'stub' code to execute the machine code directly from within the library module

Creating a Program

- `g++ 4_8_1.cpp -lm`



- `g++` is a command to translate your source code (by invoking a collection of tools)
  - Above command produces `a.out` from `.cpp` file
- `-l` option tells the linker to 'link' the math library

Creating a Program

- `g++:` other options

  `-Wall` - Show all warnings

  `-omyexe` - create the output machine code in a file called `myexe`

  `-g` - Add debug symbols to enable debugging

  `-c` - Just compile the file (don't link) i.e. produce a `.o` file

  `-I/home/mydir` -Include directory called `/home/mydir`

  -O1, -O2, -O3 – request to optimize code according to various levels

  Always check for program correctness when using optimizations

Creating a Program

- The steps just discussed are ‘compiled’ way of creating a program. E.g. C++
- Interpreted way: alternative scheme where source code is ‘interpreted’ / translated to machine code piece by piece e.g. MATLAB
- Pros and Cons.
  - Compiled code runs faster, takes longer to develop
  - Interpreted code runs normally slower, often faster to develop

Creating a Program

- For different parts of the program different strategies may be applicable.
  - Mix of compilation and interpreted – interoperability
- In the context of scientific software, the following are of concern:
  - Computational efficiency
  - Cost of development cycle and maintainability
  - Availability of high-performant tools / utilities
  - Support for user-defined data types

Creating a Program

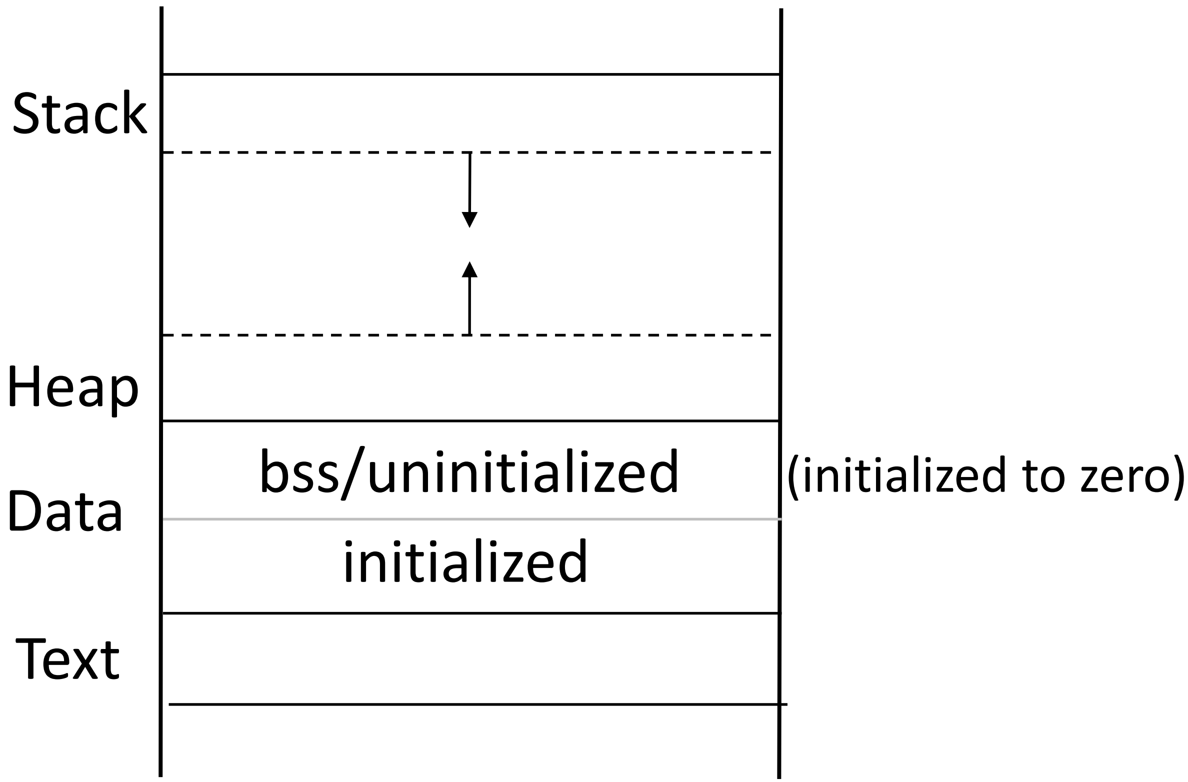
- `a.out` is a pattern of 0s and 1s laid out in memory – sequence of machine instructions
- How is a program laid out in memory?
  - Helpful to debug
  - Helpful to create robust software
  - Helpful to customize program for embedded systems

Program Layout in Memory

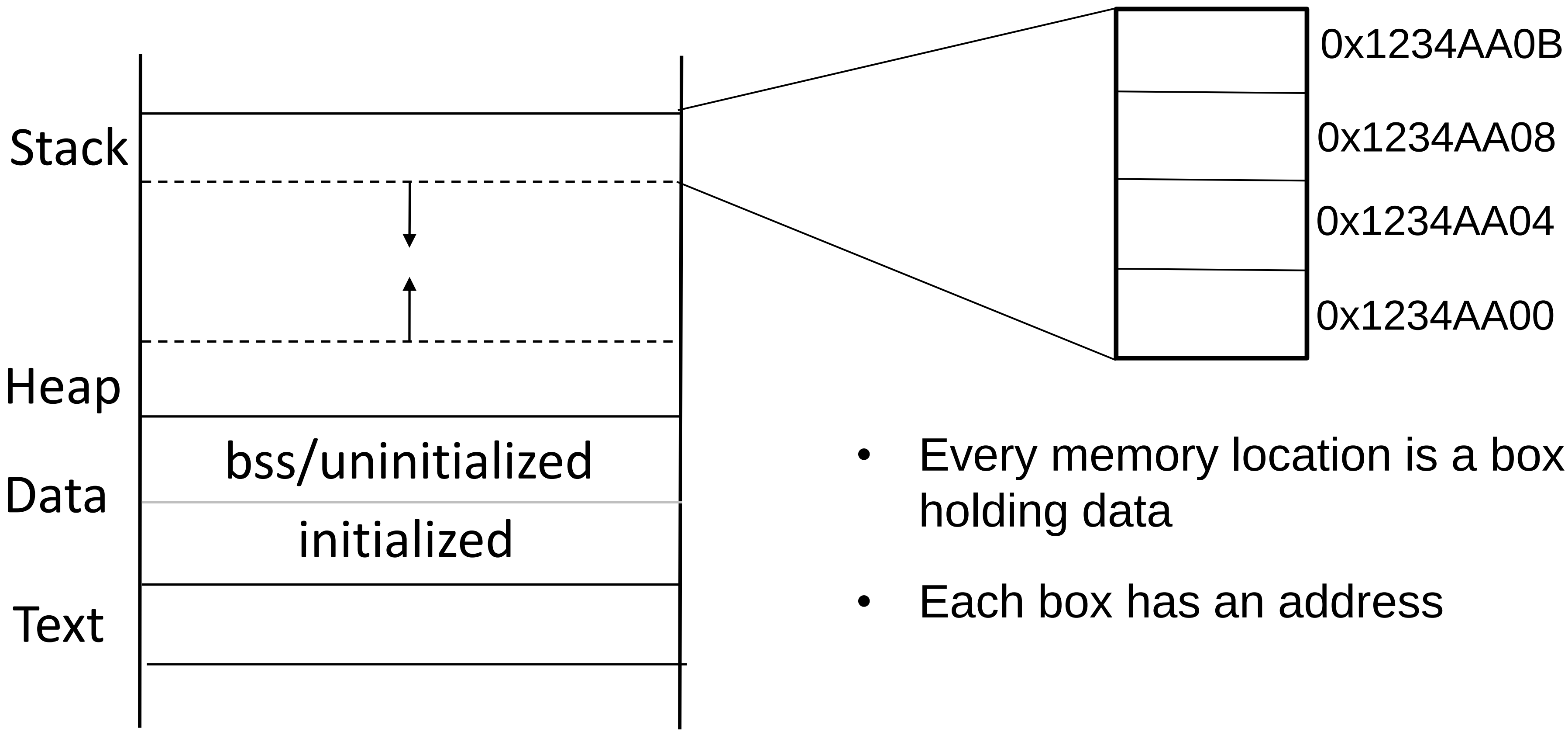
- A program's memory space is divided into four segments:

    1. Text
        - source code of the program
    2. Data
        - Broken into uninitialized and initialized segments; contains space for global and static variables. E.g. `int x = 7; int y;`
    3. Heap
        - Memory allocated using malloc/calloc/realloc/new
    4. Stack
        - Function arguments, return values, local variables, special registers.

Program Layout in Memory



Program Layout in Memory

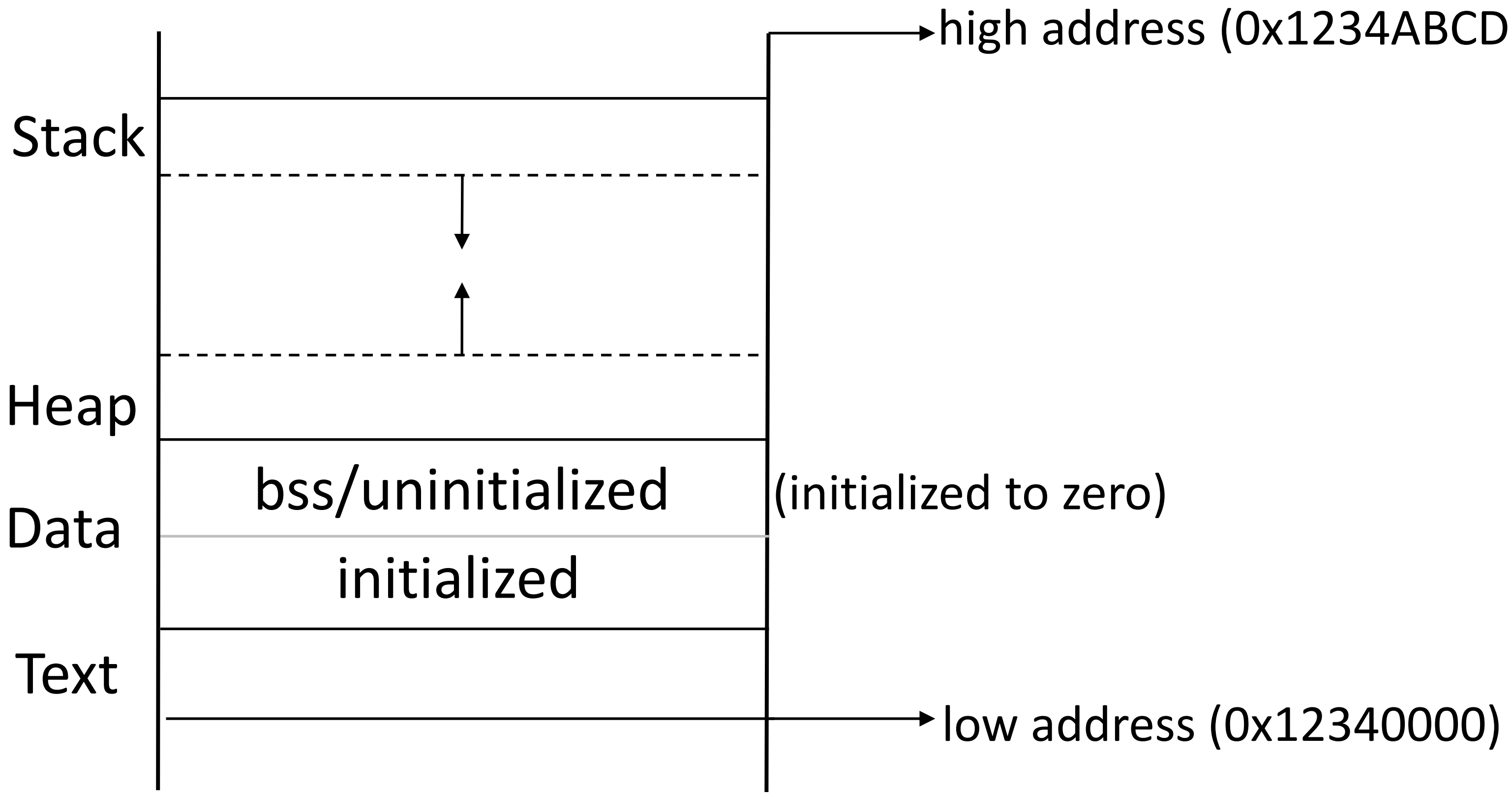


- Every memory location is a box holding data
- Each box has an address

Addresses

- Computer programs think and live in terms of memory locations
- Addresses in computer programs are just numbers identifying memory locations
- A program navigates by visiting one address after another

Program Layout in Memory



Addresses

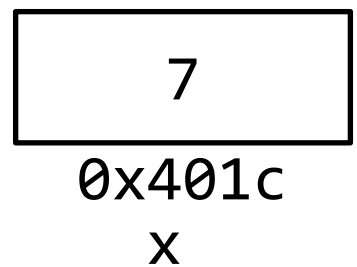
- Humans are not good at remembering numerical addresses.

what are the GPS coordinates (latitude and longitude) of your residence?

- We (humans) choose convenient ways to identify addresses so that we can give directions to a program. E.g. Variables

Handles to Addresses

- Variables
  - Its just a handle to an address / program memory location
- `int x = 7;`



- Read `x` => Read the content at address `0x401C`
- Write `x`=> Write at address `0x401C`

```
int x;
```

1. *What is the set of values this variable can take on in C?*

   -2^{31} to $(2^{31} - 1)$

2. *How much space does this variable take up?*

   32 bits

3. *How should operations on this variable be handled?*

   integer division is different from floating point divisions

   ```
   3 / 2 = 1  //integer division
   
   3.0 / 2.0 = 1.5  //floating-point division
   ```

C++ standard types

- Integer types: `char`, `short int`, `int`, `long int`, `long long int`, `bool`
- Float: `float`, `double`, `long double`
- `Pointers`: handle to addresses
- `References`: safer than pointers but less powerful
- `void`: nothing

C++ standard types

- Modifiers
  - `short, long, signed, unsigned.`
- Compound types
  - pointers, structs, enums, arrays, etc.

C++ standard types – storage space

Data type	Number of bytes
`char`	1
`short int`	2
`int / long int`	4
`long long int`	8
`float`	4
`double`	8
`long double`	12

- All built-in types are represented in memory as a contiguous set of bytes
- Use sizeof() operator to check the size of a type
  - e.g. `sizeof(int)`

Data types - quirks

- if no type is given compiler automatically converts it to `int` data type.
  - `signed x;`
- `long` is the only modifier allowed with `double`
  - `long double y;`
- `signed` is the default modifier for `char` and `int`
- Can’t use any modifiers with `float`

Visualizing Addresses

- The *address of* (&) operator fetches a variable's address in C
- &x would return the address of x

```
#include<iostream>
int main(int argc, char* argv[]) {
        int x = 7;
        std::cout<<"Address of x is:"<<&x<<std::endl;
        return 0;
}
```

  - prints the Hexadecimal address of x

```
Address of x is:0x7ffd1d5e2844
```

Pointers

- Pointer is a data type that *holds an address*.

```
<type>* <pointer_name>;
```

- Example:
  - `int* p;` //is a variable named `p` whose type is //pointer to `int` OR `p` is an integer //pointer

Note that the variable declared is `p`, *not* `*p`

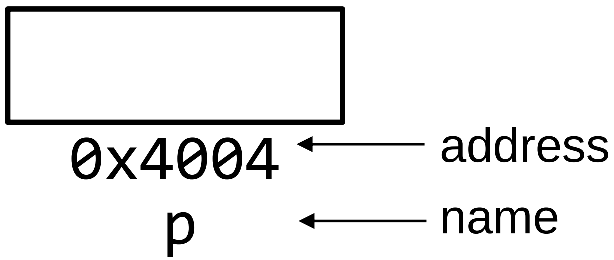
- A pointer always stores an address
- `<type>` of the pointer tells us what kind of data is stored at that address
- Example:
  - `int* p;`

    declares a pointer variable p holding an address, which identifies a memory location capable of storing an integer.

Initializing Pointers

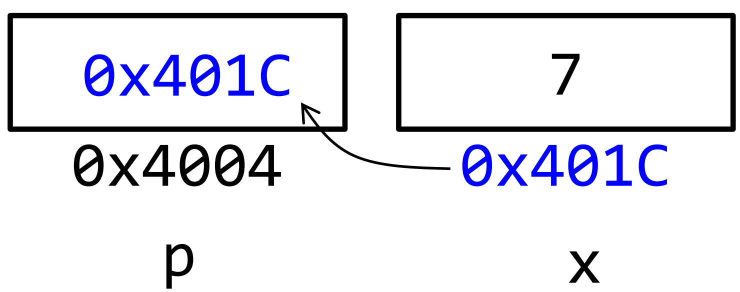
- `int* p;`

Remember p is a variable and all variables are just names identifying addresses.



In addition, p holds the address of a memory location that stores an integer

- `p=&x;`



- Cannot assign arbitrary addresses to pointers.
- Example:

```
int* p=5;
```

- Operating system determines addresses available to each program.

The NULL address

- NULL is a special address
- Example

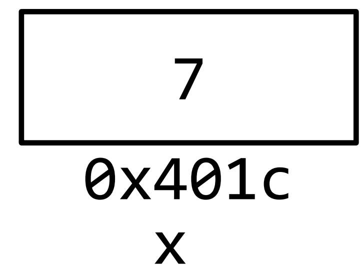
```
int* p=NULL; //p points to nowhere
```

- Useful when it is not yet known where p points to.
- Uninitialized pointers store garbage addresses

Using Pointers

- The *dereference* operator `(*)`
  - Lets us access the memory location at the address stored in the pointer

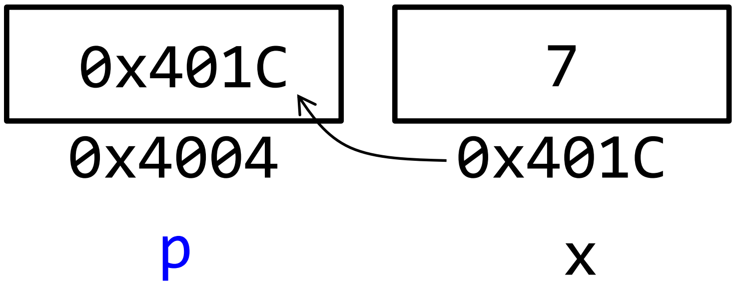
```
int x=7;
```



Using Pointers

- The *dereference* operator `(*)`
  - Lets us access the memory location at the address stored in the pointer

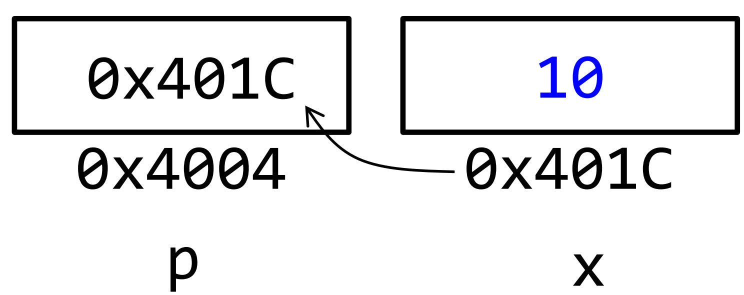
```
int x=7;
int* p = &x; //p now points to x
```



Using Pointers

- The *dereference* operator `(*)`
  - Lets us access the memory location at the address stored in the pointer

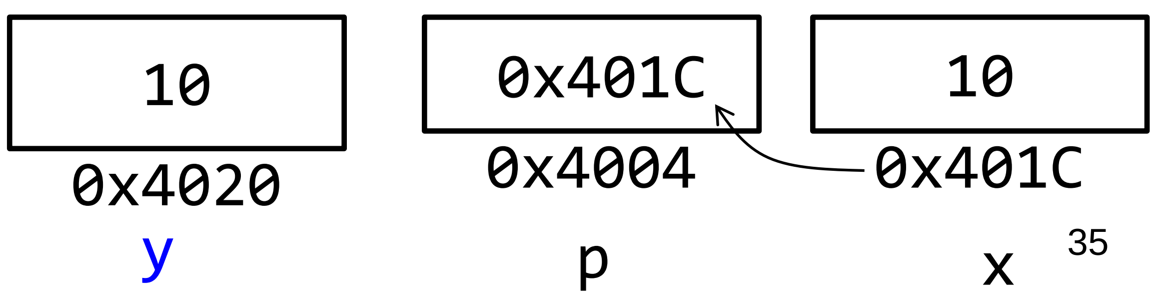
```
int x=7;
int* p = &x; //p now points to x
*p = 10; //this is the same as x=10
```



Using Pointers

- The *dereference* operator `(*)`
  - Lets us access the memory location at the address stored in the pointer

```
int x=7;
int* p = &x; //p now points to x
*p = 10; //this is the same as x=10
int  y=*p; //this is the same as y=x
```



- Pointers as alternate names to memory locations

```
int x=7;
int *p = &x;
```

`x` is the name for an address

`*p` is the name for an address

10

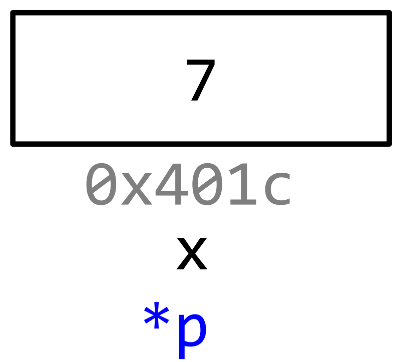
0x401c

x

*p

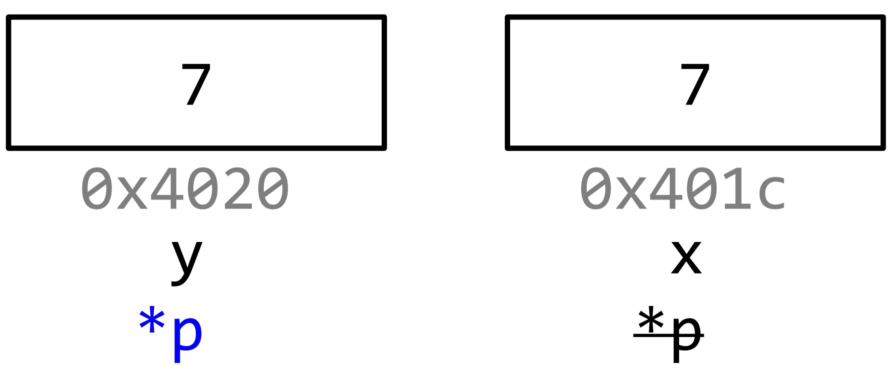
- Pointers as “dynamic” names to memory locations

```
int x=7; //x always names the location 0x401C
int *p = &x; //*p is now another name for x
```



- Pointers as “dynamic” names to memory locations

```
int x=7; //x always names the location 0x401C
int *p = &x; //*p is now another name for x
int y = *p //like saying y=x
p = &y; //*p is now another name for y
```



Pointers to Different Types

- What can pointers point to? any data type!
  - Basic data types – we have seen these.
  - Structures – Next set of slides.
  - Pointers! and
  - Functions

Typedef

– Lets you give alternative names to C data types

– Example:

```
typedef unsigned char BYTE;
```

This gives the name `BYTE` to an `unsigned char` type. Now,

```
BYTE a;
BYTE b;
```

Are valid statements.

Typedef Syntax

```
typedef <existing_type> <new_type>;
```

– Resembles a declaration without initializer;

  E.g. `int x;`

– Mostly used with user-defined types

User-defined Types

- *Structures* in C are one way of defining your own type.
- Arrays are compound types but have the *same* type within.
  - E.g. A string is an array of `char`
  - `int arr[]={1,2,3}; arr` is an array of integer types
- Structures let you compose types with *different* basic types within.

Structures - Declaration

Type name → `struct Point{`

Declarations of fields → `float xCoordinate; float yCoordinate;`

```
struct Point{
float xCoordinate;
float yCoordinate;
};
```

– Variable definition:

- `struct Point p1;`
- ```
  struct Point{
   float xCoordinate;
   float yCoordinate;
   }p1;
  ```

p1 is a variable (an object) of type `struct Point`
  ```

Structures - Definition

```c
typedef struct _Point{
float xCoordinate;
float yCoordinate;
}Point;
```

Declarations of fields

New Type name

Canonical type name (long form)

- Variable definition:
  - `Point p1;`

Structures - Usage

– Structure fields are accessed using dot (.) operator

– Example:

```
Point p;

p.xCoordinate = 10.1;

p.yCoordinate = 22.8;

printf(“(x,y)=(%f,%f)\n”,p.xCoordinate,
p.yCoordinate);
```

Structures - Initialization

– Error to initialize fields in declaration;

```
typedef struct{
float xCoordinate = 10.1;
float yCoordinate = 22.8;
}Point;
```

Structures - Initialization

- `Point p1={10.1,22.8};`

- `Point p2={.x=10.1,.y=22.8};`

  ```
  //Introduced in C99.
  //Designated initializers
  //Best-way
  ```

Pointers to Structures

```
typedef struct {
   int year;
   char model;
   float acceleration; //0-60mph in seconds
}Car;

Car t1 = {.year = 2017, .model = ‘S’,
.acceleration = 2.8 };

Car * pt1 = &t1; //now you can use *pt1
anywhere you use t1
```

```
(*pt1).acceleration = 2.3;
(*pt1).year = 2019;
(*pt1).model = ‘X’;
float avg_acceleration = ((*pt1).acceleration
+ (*pt2).acceleration) / 2.0;
```

We can also use the -> operator to access structure members.

```
pt1->acceleration = 2.3;
pt1->year = 2019;
pt1->model = ‘X’
float avg_acceleration = (pt1->acceleration +
pt2->acceleration) / 2.0;
```

Pointer Chains

```
int x = 7;
int *p = &x; //p points to x; *p is same as x.

int ** q=&p; //q is a pointer to pointer to int
```

`*q` is same as `p`.
`*(*q)` is the same as `*p`, which is same as `x`

Address of (&) operator and Type

- Adding & to a variable adds * to its type
- Example:
  - if a is an int, then &a is an int*
  - if b is an int*, then &b is an int**
  - if c is an int**, then &c is an int***
  - …

Dereference (*) operator and Type

- Adding * to a variable subtracts * from its type
- Example:
  - if a is an int*, then *a is an int
  - if b is an int**, then *b is an int*
  - if c is an int***, then *c is an int**
  - …

Pointer Arithmetic

```
int y = 1040;
int* p= &y;
```

- What does *(p+1) mean?
  - Data at “one element past” `p`
- What does “one element past” mean?
  - p is a pointer, so holds the address of a memory location
  - p is an `int` pointer, so that memory location holds an integer
  - p+1 is interpreted as address of the next integer

Pointer Arithmetic

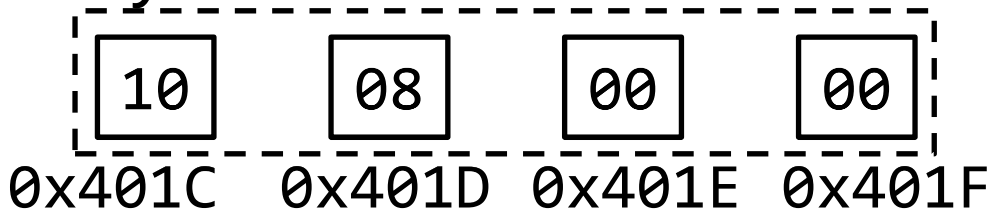
- Our representation of

```
int y=2064;
int* p = &y;
```

0x401C	2064
0x1000	**0x401C**
p	y

Pointer Arithmetic

- `ints` occupy 4 bytes. `0x401C` is the address of the first byte*:



*2064 = 0x810 (=0x00,00,08,10 when written using 8 digits and x86 is little-endian)

- (*p) = data at 0x401C
  - *returns the correct value of 2064 and not 0x10. Why?*

Pointer Arithmetic

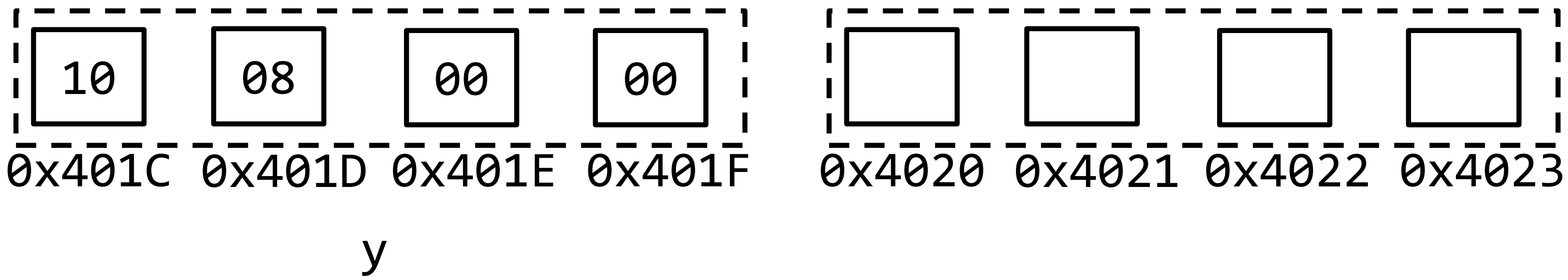
- (p+1) gets the "address of the next integer"

0x401C	2064
0x1000	0x401C
p	y

What is the address of the next integer?

Pointer Arithmetic

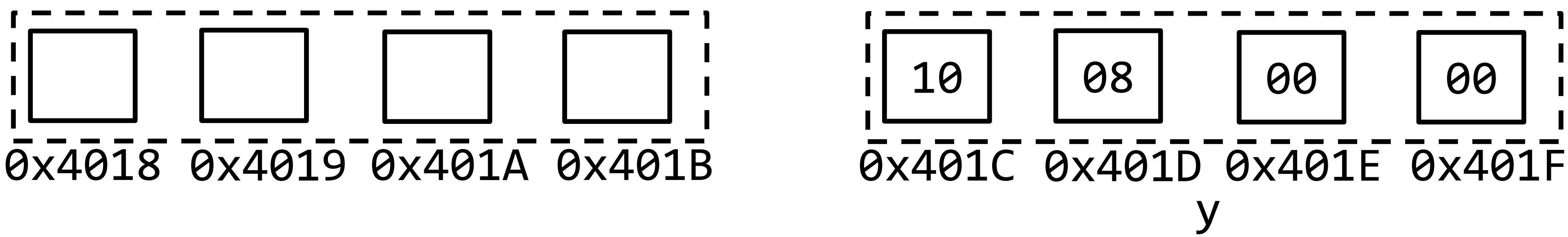
- What is the address of the next integer?
  - Add 4 to current value of p (0x401C) = `0x4020`



Pointer Arithmetic

- (p-1) computes the address before y

```
int y=2064;
int* p = &y;
```



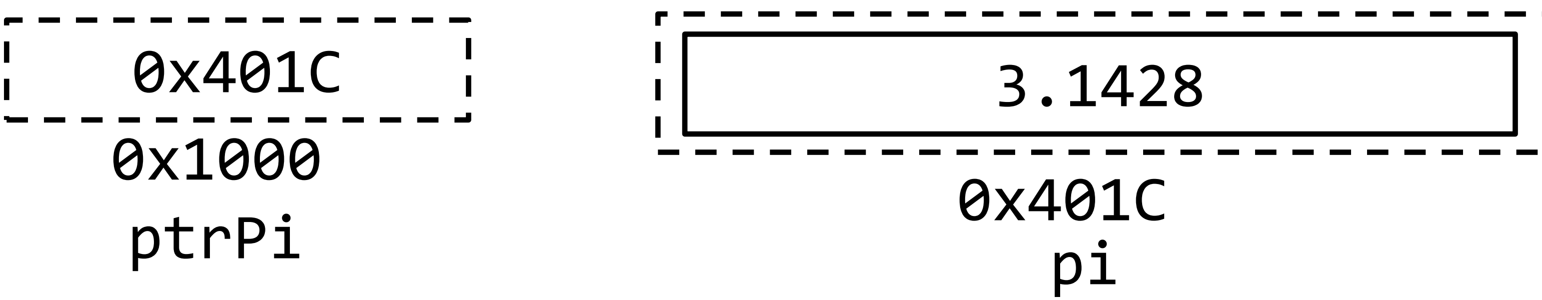
subtract 4 from the current value of `p (0x401C)` = `0x4018`

- Similarly we can add/subtract any number to/from a pointer variable.
- Compare to a specific address (E.g. `if(p == NULL)`)

Pointer Arithmetic

- Pointer to `double` (`double` occupies 8 bytes)

```
double pi=3.1428;
double* ptrPi = &pi;
```



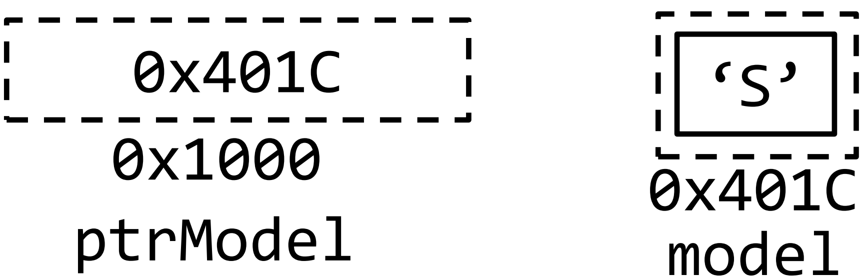
What is the address computed for `(ptrPi+1)`*?* `0x4024`

What is the address computed for `(ptrPi-1)`*?* `0x4014`

Pointer Arithmetic

- Pointer to `char`

```
char model='S';
char* ptrModel = &model;
```

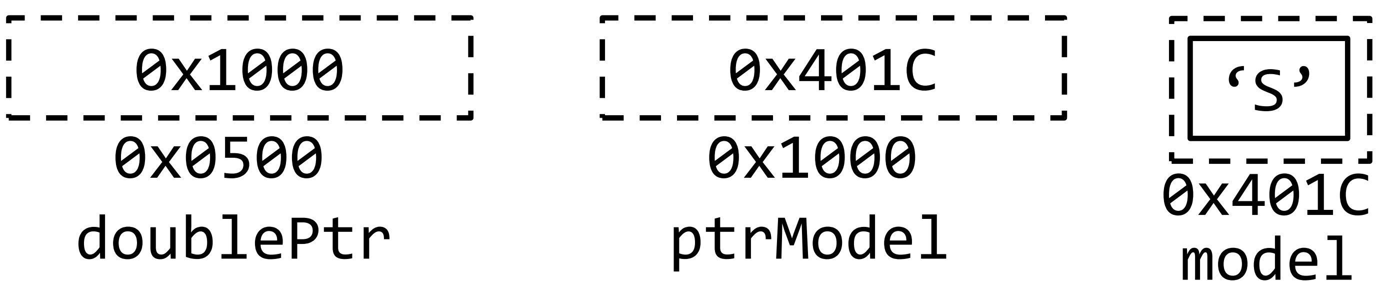


What is the address computed when we do `(ptrModel+1)`*?*

Pointer Arithmetic

- Pointer to pointer

```
char model='S';
char* ptrModel = &model;
char** doublePtr = &ptrModel;
```



Bonus: what is the address computed when we do `(doublePtr+1)`*?* (assuming we are using 32-bit machines)

C-style Arrays

Declaring arrays:

```
type <array_name>[<array_size>];
int num[5];
```

Initializing arrays:

```
int num[3]={2,6,4};
int num[]={2,6,4};//array_size is not
required.
```

Accessing arrays:

num[0] accesses the first integer

num[1] accesses the second integer and so on..

Arrays

- Another data type!
  - Array of `ints`, `structs` etc.
  - Array of `chars` (strings in C)
- Work a little bit like pointers

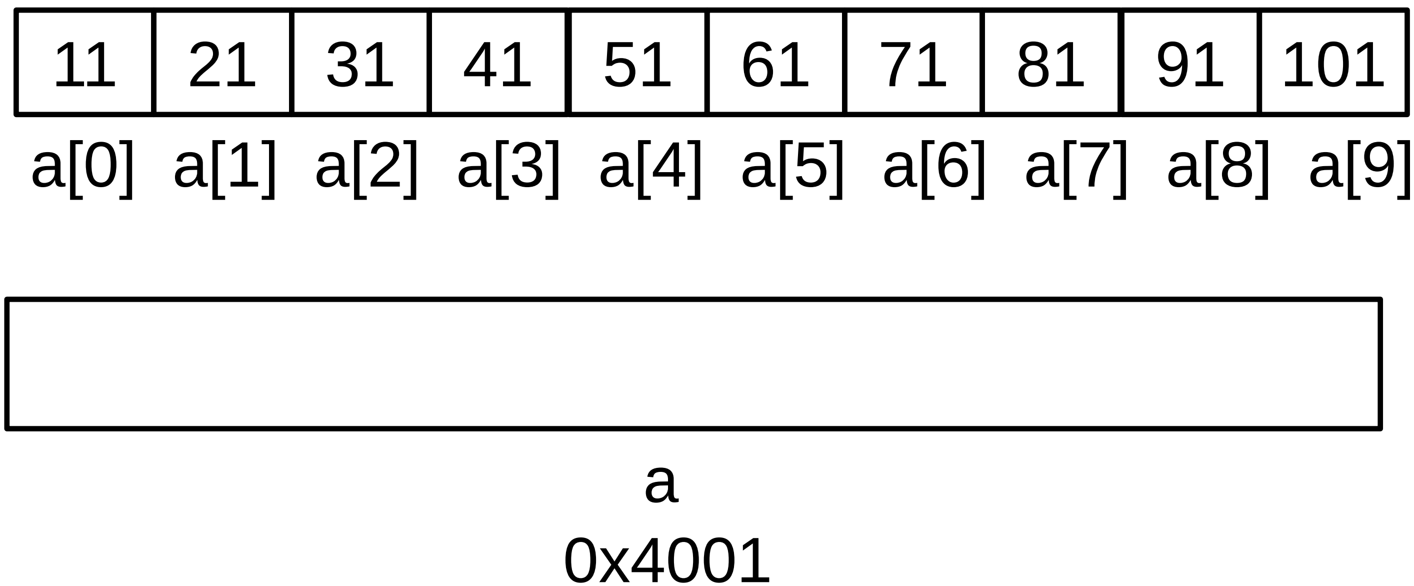
```
int a[10]={11,21,31,41,51,61,71,81,91,101};
//array of 10 integers
```

11	21	31	41	51	61	71	81	91	101
a[0]	a[1]	a[2]	a[3]	a[4]	a[5]	a[6]	a[7]	a[8]	a[9]

10 elements guaranteed to be next to each other in memory

Arrays

```
int a[10]={11,21,31,41,51,61,71,81,91,101};
```



- 0x4001 is starting address of the array = address of `a[0]` = **`&a[0]`**
- Fetch the address of `a = &a = 0x4001`

Arrays

- Array name in C is the address of the first element of the array

```
int a[10]={1,2,3,4,5,6,7,8,9,10};
```

Therefore, **`a == &a[0]`**

`a, &a, &a[0]` are the same and have values `0x4001`.

Arrays

- Array name in C is the address of the first element of the array

  Array names are converted to pointers (in most cases) but a's type is not a pointer.

```
int* ptr=a; //ptr holds the address of the
first element of the array (also &a[0]).

ptr[1] gets a[1]
ptr[2] gets a[2]
...
```

How is this possible?

Arrays

- Array dereferencing operator [ ] is implemented in terms of pointers.
  - `a[3]` means: start at the address a, go forward 3 elements, fetch the *data at* that address.
  - In pointer arithmetic syntax, this is equivalent to:

    *(a+3)

  So,

  a[0] really means: *(a+0)
  a[1] really means: *(a+1)

Arrays

- So, when

```
int* ptr = a;
```

  - `ptr[0]` really means `*(ptr+0)`, which is the same as `*(a+0)`, which is `a[0]`
  - `ptr[1]` really means `*(ptr+1)`, which is the same as `*(a+1)`, which is `a[1]`

...

Exercise

```
char s[3] = “Hi”;
char *t = “Si”;
int u[3] = {5, 6, 7};
int n=8;
```

Expression	Type	Comments
`s`	`char[3]`	`array of 3 chars`
`t`	`char*`	`address of a char`
`u`	`int[3]`	`array of 3 ints`
`&u[0]`	`int*`	`address of an int`

Exercise

```
char s[3] = “Hi”;
char *t = “Si”;
int u[3] = {5, 6, 7};
int n=8;
```

Expression	Type	Comments
`*&n`	`int`	`value at n`
`*t`	`char`	`data at address Held by t`

Exercise

- Array initializers:

```
1. int u[3] = {5, 6};
```

Is this valid?
If yes, what is the value held in the third element u[2]?

```
2. int u[3] = {5, 6, 7, 8};
```

Is this valid?

```
3. char s1[]="Hi";
```

What is the size of s1? (how many bytes are reserved for s1)

```
4. char s2[3]="Si";
```

Is this valid?

Exercise

```
int u[3] = {5, 6, 7};
int* p=u;
p[0]=7;
p[1]=6;
p[2]=5;
```
//At this line, u *would contain the numbers in reverse order. u[0] = 7, u[1]=6, u[2]=5.*

```
char *str = “Hello”;
char* p=str;
p[0]=‘Y’;
```
//At this line, what would `str` contain?

Dynamic Memory Allocation

- Statically allocated arrays:

```
int arr[3]={1, 2, 3};
```

Must be known
at compile time

- Can't expand `arr` once defined

Dynamic Memory Allocation

- What if we don't know the array length?
  - Option 1: Variable length arrays.

  Not an option with `-Wvla, -Wall,` and `-Werror` flags

  - Option 2: use heap.

  Preferred option

Dynamic Memory Allocation

- We interact with heap using
  - `new`

    "Give us X bytes of storage space (memory) from the heap so that we can use it to store data"
  - `delete`

    "take back this memory so that it can be used for something else"

Functions

- Definition

```
return_type function_name(parameters) {
    //statements
    return <optional_value>
}
```

- Function name and parameters form the *signature* of the function
- In a program, you can have multiple functions with same name but with differing signatures - *function overloading*
- Example:

```
double product(double a, double b) {
    double result = a*b;
    return result;
}
```

Functions

- Declaration: `return_type **function_name**(parameters);`
- Function definition provided the complete details of the internals of the function. Declaration just indicates the signature.
  - Declaration exposes the interface to the function

```
double product(double a, double b); //OK
double product(double, double); //OK
```

The `main` Function

- Signatures

```
int main()
int main(int argc, char* argv[])
```

- Every program must have exactly one `main` function. Program execution begins with this function.
- Return 0 usually means success and failure otherwise
  - EXIT_SUCCESS and EXIT_FAILURE are useful definitions provided in the library `cstdlib`

Functions

- Calling: `function_name(parameters);`
- Example:

```
double product(double a, double b) {
    double result = a*b;
    return result;
}

int main() {
    double retVal, pi=3.14, ran=1.2;
    retVal = product(pi,ran);
    cout<<retVal;
}
```

Functions

- Calling: **function_name**(parameters);
- Example:

```
double product(double a, double b) {
    double result = a*b;
    return result;
}

int main() {
    double retVal, pi=3.14, ran=1.2;
    retVal = product(pi,ran);
    cout<<retVal;
}
```

At least the signature of function must be visible at this line → (points to `retVal = product(pi,ran);`)

Functions

- Calling: **function_name**(parameters);
- Example:

```
double product(double a, double b) {
    double result = a*b;
    return result;
}

int main() {
    double retVal, pi=3.14, ran=1.2;
    retVal = product(pi,ran);
    cout<<retVal;
}
```

pi and ran are copied to a and b

Functions

- Calling: `function_name(parameters);`
- Example:

```
double product(double a, double b) {
    double result = a*b;
    return result;
}

int main() {
    double retVal, pi=3.14, ran=1.2;
    retVal = product(pi,ran);
    cout<<retVal;
}
```

pi and ran are copied to a and b
Pass-by-value

Functions

- Calling: **function_name**(parameters);
- Example:

```
double product(double& a, double& b) {
    double result = a*b;
    return result;
}

int main() {
    double retVal, pi=3.14, ran=1.2;
    retVal = product(pi,ran);
    cout<<retVal;
}
```

pi and ran are NOT copied to a and b
Pass-by-reference

Reference Variables

- Example:

```
int n=10;
int &re=n;
```

- Like pointer variables. re is constant pointer to n (re cannot change its value). Another name for n.
  – Can change the value of n through re though

Command Line Arguments

```
bash-4.1$./a.out
```

//this is how we ran 4_8_1.cpp (refer: week1_codesample)

- Suppose the initial guess was provided to the program as a command-line argument (instead of accepting user-input from the keyboard):

```
bash-4.1$./a.out 999
```

Command Line Arguments

```
bash-4.1$./a.out 999
```

```
int main(int argc, char* argv[]) {
      //some code here.
}
```

Identifier	Comments	Value
`argc`	Number of command-line arguments (including the executable)	2
`argv`	each command-line argument stored as a string	`argv[0]=“./a.out”` `argv[1]=“999”`

Exercise

- Write a C++ program with the following requirements:
  - User should be able to provide the dimension of two vectors (do not use C++ vectors from STL)
  - The program should allocate two vectors of the required size and initialize them with meaningful data
  - The program should compute the scalar product of the two vectors and print the result

Discretization

- Cannot store/represent infinitely many continuous values
  - To model turbulent features of flow through a pipe, say, I am interested in `velocity` and `pressure` at all `points` in a region of interest
    1. Represent region of interest as a mesh of small discrete cells - ***discretization spacing***
    2. Solve equations for each cell

Example:

```
diameter of the pipe = 5cm
length=2.5cm
discretization spacing = 0.1mm
```

(volume of cylinder = $\pi r^2 h$)

Exercise: *how many variables do you need to declare?*

Discretization

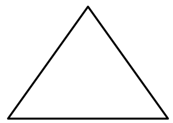
- All problems with ‘continuous’ quantities don’t require discretization
  - Most often they do.
- When discretization is done:
  - How refined is your discretization depends on certain parameters: step-size, cell shape and size. E.g.
    - Size of the largest cell (PDEs in FEM),
    - Step size in ODEs
  - Accuracy of the solution is of prime concern
    - Discretization always gives an approximate solution. Why?
    - Errors may creep in. Must provide an estimate of error.

Accuracy

- Discretization error
  - Is because of the way discretization is done
  - E.g. use more number of rays to minimize discretization error in ray tracing
- Solution error
  - The equation to be solved influences solution error
  - E.g. use more number of iterations in PDEs to minimize solution error
- Accuracy of the solution depends on both solution and discretization errors
- Accuracy also depends on cell shape

Cell Shape

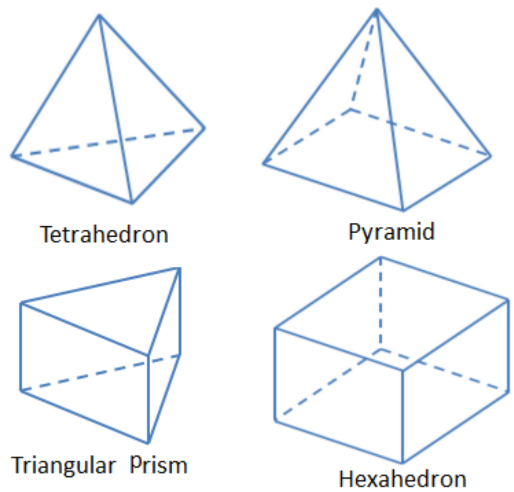
- 2D:



triangle

quadrilateral

- 3D: triangular or quadrilateral faced. E.g.



source: wikipedia

Tetrahedron: 4 vertices, 4 edges, 4△ faces
Pyramid: 5 vertices, 8 edges, 4 △ and 1 ▭ face
Triangular prism: 6 vertices, 9 edges, 2△ and 3 ▭ faces
Hexahedron: 8 vertices, 12 edges, 6 ▭ faces

Error Estimate

- You will have to deal with errors in the presence of discretization
  - Providing error estimate is necessary
- *Apriori* error estimate
  - Gives insight on whether a discretization strategy is suitable or not
  - Depends on discretization parameter
  - Properties of the (unknown) exact solution
  - Error is bound by: Ch^p where, C depends on exact solution, h is discretization parameter, and p is a fixed exponent. *Assumption: exact solution is differentiable, typically, p+1 times.*

Error Estimate

- *Aposteriori* error estimate
  - Is estimation of the error in computed (Approximate) solution and does not depend on information about exact solution
  - E.g. Sleipner-A oil rig disaster

Exercise

- *does increasing mesh size always yield better accuracy?*

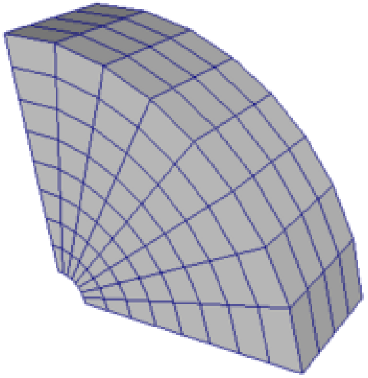
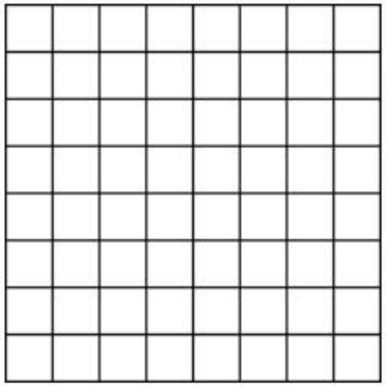
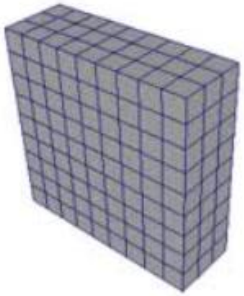
- *does decreasing cell size always yield better accuracy?*

- *How does changing mesh size affect computational cost?*

- *How does changing cell size affect computational cost?*

Structured Grids

- Have regular connectivity between cells
  - i.e. every cell is connected to a predictable number of neighbor cells
- Quadrilateral (in 2D) and Hexahedra (in 3D) are most common type of cells
- Simplest grid is a rectangular region with uniformly divided rectangular cells (in 2D).

credits: nanohub.org

Structured Grids – Problem Statement

- Given:
  - A geometry
  - A partial differential equation
  - Initial and boundary conditions
- Goal:
  - Discretize into a grid of cells
  - Approximate the PDE on the grid
  - Solve the PDE on the grid

Structured Grids - Representation

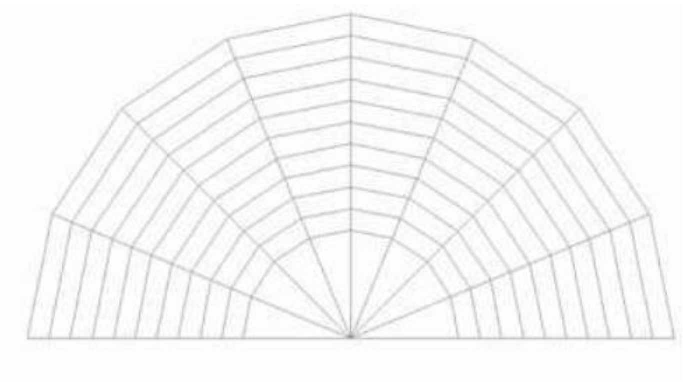
- Because of regular connectivity between cells
  - Cells can be identified with indices (x,y) or (x,y,z) and neighboring cell info can be obtained.
  - How about identifying a cell here?

    Given:

    ξ = ("Xi") radius

    η = ("Eta") angle

    Compute:



$$x = \left(\frac{1}{2} + \xi\right)\cos(\pi\eta)$$

$$y = \left(\frac{1}{2} + \xi\right)\sin(\pi\eta)$$

Structured Grids - Representation

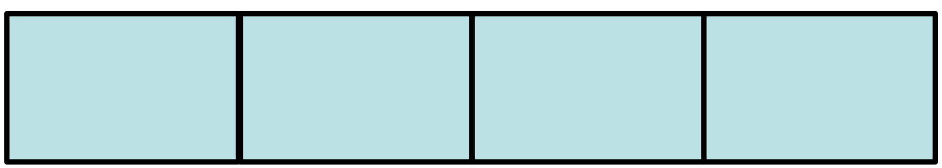
- In next class….
  - Grid generation and grid types
  - Partial Differential Equations (PDEs)
  - Solving PDEs (turning PDEs into large set of algebraic equations)
- Now.

2D Arrays

- 1D array gives us access to *a row* of data
- 2D array gives us access to *multiple rows* of data
  - A 2D array is basically an *array of arrays*
- Consider a fixed-length 1D array:

```
int arr1[4];//defines array of 4 elements; every
element is an integer. Reserves contiguous memory to
store 4 integers.
```

arr1[0] arr1[1] arr1[2] arr1[3]



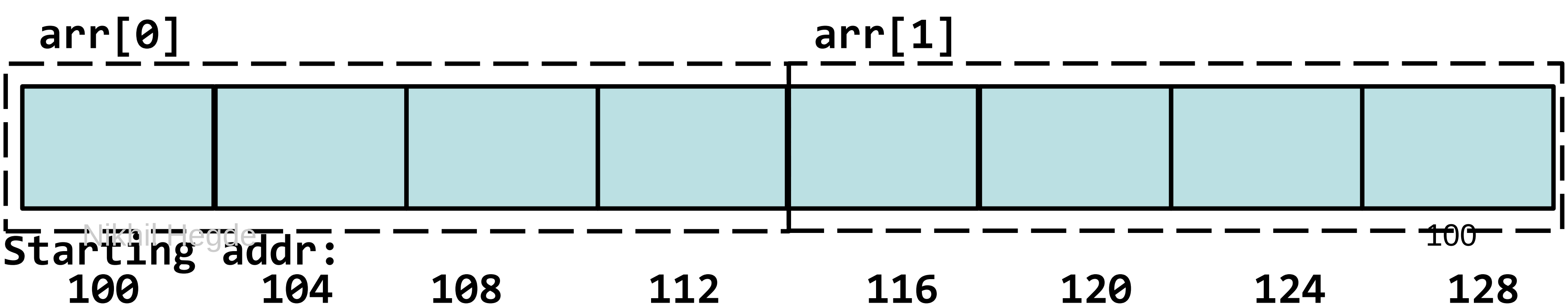
Starting addr:

100 104 108 112

We have seen this

2D Arrays (fixed-length)

- Consider a fixed-length 2D array (*array of arrays*). Think:
  array of integers => every element is an `int`
  array of characters => every element is a `char`
  array of array => every element is an *array*
- Example:
  `int arr[2][4];//defines array of 2 elements; every element is an array of 4 integers. Therefore, reserves contiguous memory to store 8 integers`



2D Arrays (on heap)

- What if we don’t know the length of the array upfront?

E.g. A line in a file contains number of people riding a bus every trip. Multiple trips happen per day and the number can vary depending on the traffic.

Day1 numbers: 10 23 45 44
Day2 numbers: 5 33 38 34 10 4
Day3 numbers: 9 17 10
……………………………………………
DayN numbers: 13 15 28 22 26 23 22 21

```
//we need array arr of N elements; every element is an
array of M integers. Both N and M vary with every file
input.
```

2D Arrays (on heap)

1. First, we need to create an array `arr2D` of N elements. So, get the number of lines in the input file.
   - But what is the *type* of every element? - array of M elements, where every element is an integer (i.e. every element is an integer array). `int *`
   - What is the type of `arr2D?` (array of array of integers)
     Think:
     type of an integer => `int`
     type of array of integers => `int *`
     (append a `*` to the type for every occurrence of the term array)
     type of array of array of integers => `int **`

2D Arrays (on heap)

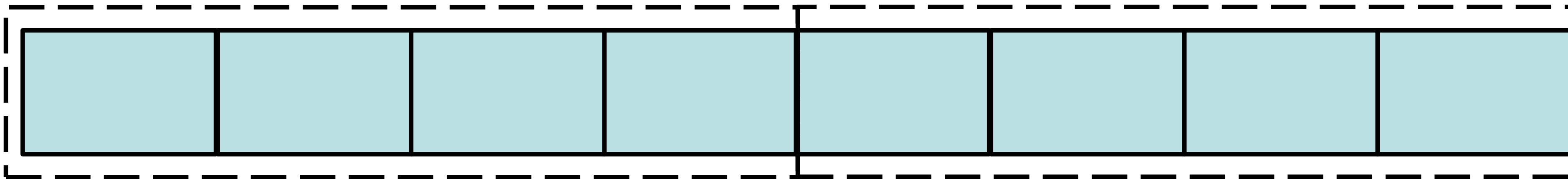
1. First, we need to create an array `arr2D` of N elements. So, get the number of lines in the input file.
   - What is the type of `arr2D`? (`int **`)

```
int N = GetNumberOfLinesFromFile(fileName);

int** arr2D = new int*[N];
```

Recall boxes with dashed lines in `int arr[2][4];`

arr[0] **arr[1]**

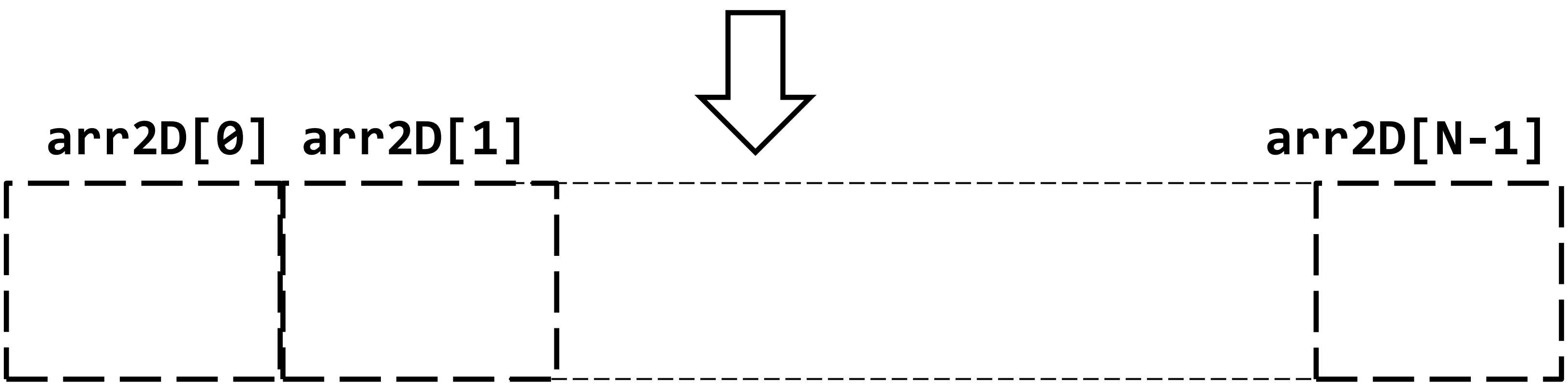


Starting addr:

100 104 108 112 116 120 124 128

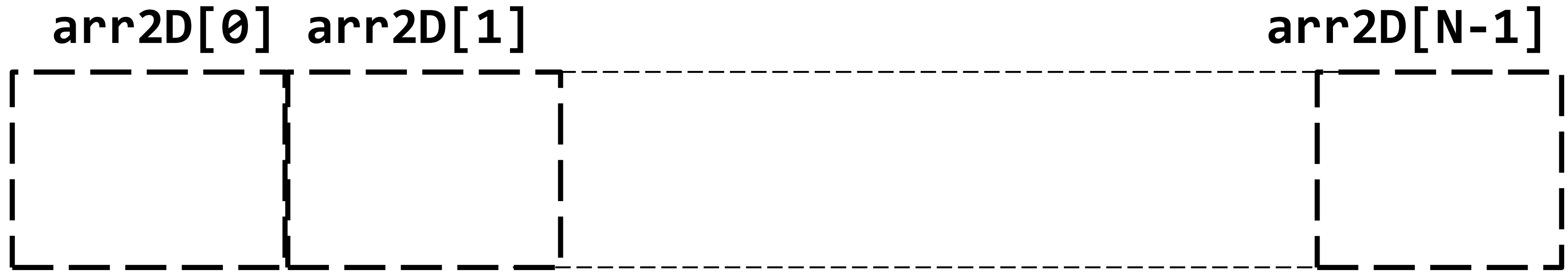
```
int N = GetNumberOfLinesFromFile(filename);
int** arr2D = new int*[N];
```

arr2D[0] arr2D[1] arr2D[N-1]



Starting addr(assuming 64-bit machine/pointer stored in 8 bytes):

100 108 100+(N-1)*8

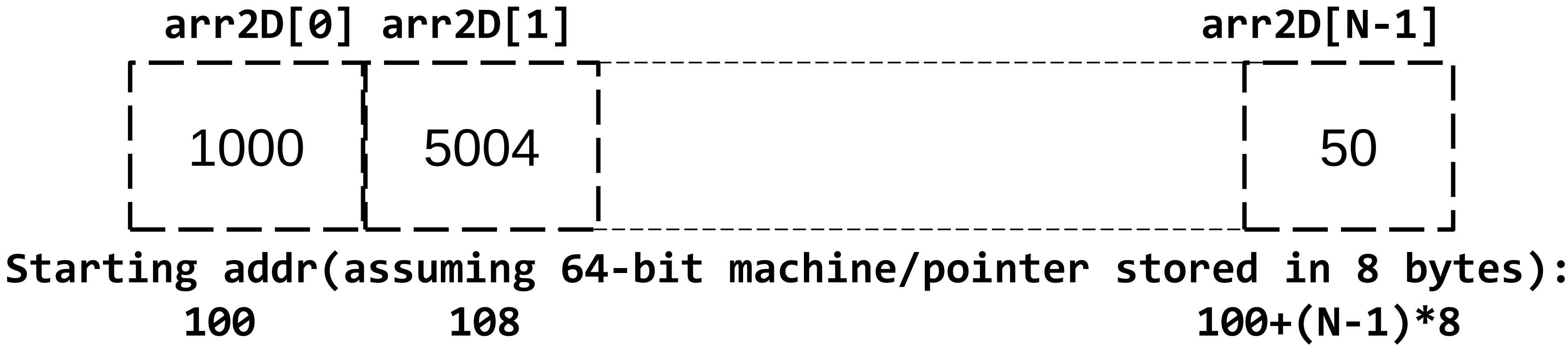


Starting addr(assuming 64-bit machine/pointer stored in 8 bytes):

100 **108** **100+(N-1)*8**

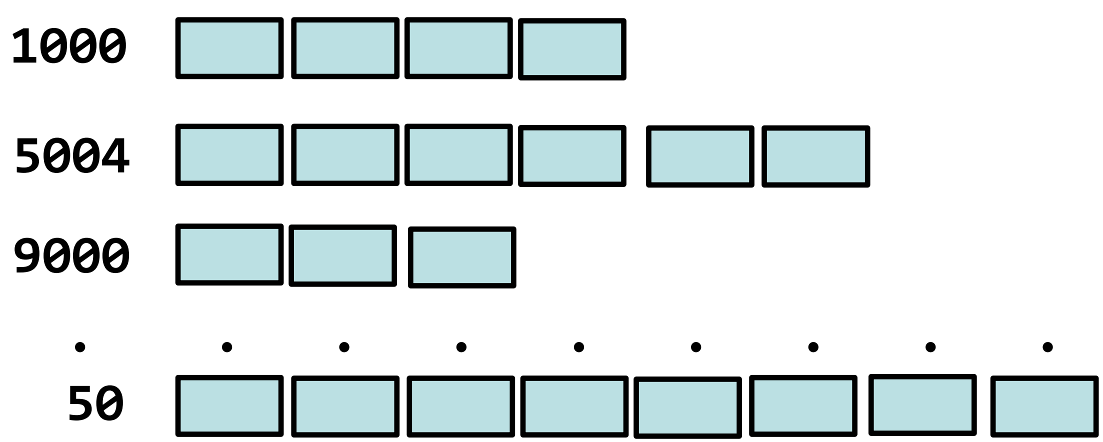
2. `arr2D[0]`, `arr2D[1]`, etc. are not initialized. They hold garbage values. How do we initialize them?

```
for(int i=0;i<N;i++) {
    char* line = ReadLineFromFile(filename);
    int M = GetNumberOfIntegersPerLine(line);
    arr2D[i] = new int[M]
}
```




```
for(int i=0;i<N;i++) {
   char* line = ReadLineFromFile(filename);
   int M = GetNumberOfIntegersPerLine(line);
   arr2D[i] = new int[M]
}
```

Starting addr:



2D Arrays (on heap)

Summary:

Creation: 2-steps

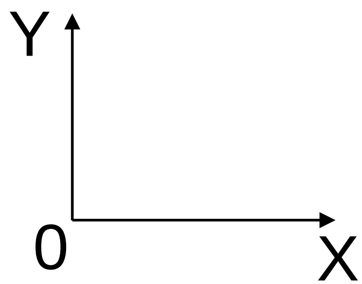
Initializing: 2-steps

Releasing: 2-steps

```
 for(int i=0;i<N;i++)
    delete [] arr2D[i]; //frees memory at 1000, 5004, etc.
 delete [] arr2D;//frees memory at 100
```

2D Arrays (trivia)

- Notation used to refer to elements different from cartesian coordinates
- Cartesian:



(M,N) = move `M` along `X` axis, `N` along Y axis

- 2D Arrays:

arr2D[M][N] = move to $(M+1)^{th}$ row (along Y axis), to $(N+1)^{th}$ column (along X axis)!

arr2D[0][0] accesses 1^{st} row, 1^{st} element
arr2D[0][1] accesses 1^{st} row, 2^{nd} element
arr2D[1][1] accesses 2^{nd} row, 2^{nd} element
arr2D[N][M] accesses $N+1^{th}$ row, $M+1^{th}$ element

- From the previous bus trip data, what if we wanted to:

Day1 numbers: 10 23 45 44
Day2 numbers: 5 33 38 34 10 4
Day3 numbers: 9 17 10
…………………………………………
DayN numbers: 13 15 28 22 26 23 22 21

- Drop certain days as we analyzed arr2D?
- Add more days to (read from another file) to arr2D ?

i.e.

modify arr2D as program executes?