CSCB09 Software Tools and Systems Programming

I/O & memory Model

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Today's lecture

File System

File IO

Arrays & Pointers

Memory Model

File System

File System, Inodes and Blocks

- Components of the OS in charge of managine *files*.
- Interact with lower-level IO subsystems
- All Unix filesystems use two basic components to organize and store data: **blocks** and **inodes**.

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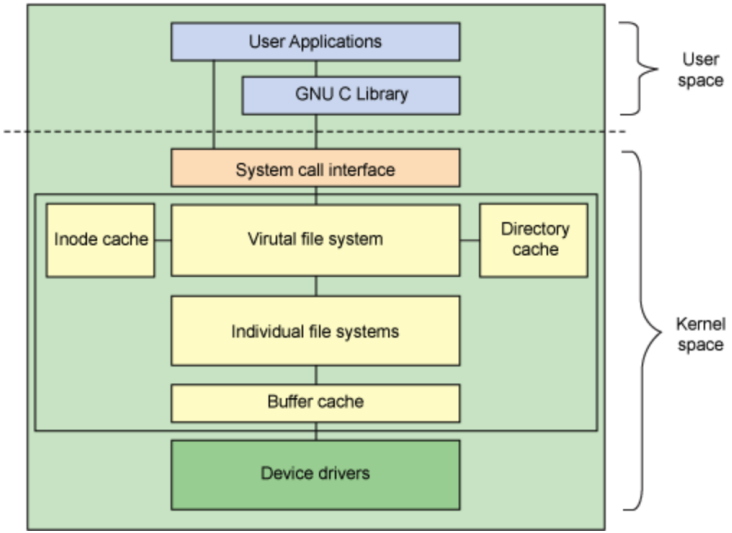
Blocks

- abstractions of data on the filesystem
- have a fixed size, determine at the time the filesystem is created
- the *block size* determines how many bytes are allocated to each block
- e.g. 32-bit: 1 KB, 2 KB, or 4 KB; 64-bit: 8 KB

Inodes

- data structure used to map blocks to physical disk locations
- every file, is assigned an inode
- analogous to pointers
- when a filesystem runs out of inodes, no new files can be created until existing files are deleted

Linux file system Architecture



SRC: https://developer.ibm.com/tutorials/l-linux-filesystem/

File IO

Basic Input/Output Operations – IOPS

What are I/O operations, or IOPS?

- Finding a file (ls)
  Check if that file exists, read metadata (file size, date stamp etc.)
- Opening a file:
  Check if that file exists, see if opening the file is allowed, possibly create it, find the block that has the (first part of) the file system.
- Reading a file:
  Position to the right spot, read a block, take out right part
- Writing to a file:
  Check where there is space, position to that spot, write the block. Repeated if the data read/written spans multiple blocks.
- Move the file pointer ("seek"):
  File system must check were on disk the data is.
- Close the file.

Basic File I/O functions (stdio.h)

```c
// Open
FILE *fopen(const char *path, const char *mode);

// Input:
int fscanf(FILE *stream, const char *format,...);
char *fgets(char *s, int size, FILE *stream);
char fgetc(FILE *stream);

// Output:
int fprintf(FILE *stream, const char *format,...);
int fputs(const char *str, FILE *stream);

// Position cursor:
int fseek(FILE *stream, long int offset, int whence);
void rewind(FILE *stream);

// Close
int fclose(FILE *stream);
```

Some reflections about basics of file I/O and command line arguments...

Questions...?

- Why do we need to open files before reading/writing on them?
- Why do we need to close files when done with them?
- Why did we not have to open STDOUT before we could use printf?

File interfaces in C/Unix

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- File *descriptors* (low-level, managed by OS):
  - Each open file is identified by a small integer
  - STDIN is 0, STDOUT is 1
  - Use for pipes, sockets (will see later what those are ...)
  - (Remember how I said in first lecture that everything is a file ..?)

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  - Each open file is identified by a small integer
  - STDIN is 0, STDOUT is 1
  - Use for pipes, sockets (will see later what those are ...)
  - (Remember how I said in first lecture that everything is a file ..?)
- File *pointers* (aka streams, file handles) for regular files:
  - A C language construct for easier working with file descriptors
  - You use a pointer to a file structure (FILE *) as handle to a file.
  - The file struct contains a file descriptor and a buffer.
  - Use for regular files

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- All C programs automatically have three files stream open:

```
FILE *stdin;
FILE *stdout;
FILE *stderr;
```

- Those are ready to use:

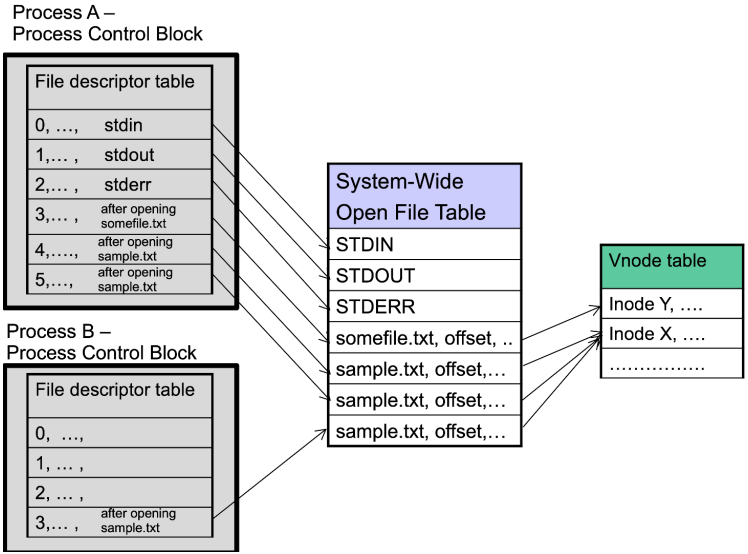
```
// using fprint and a file handler
fprintf(stdout, "Hello!\n");

// identical to use printf
printf("Hello!\n");
```

OS managing open files (in-memory data structures)

A new entry is added to the file descriptor table each time a file is opened

- Find *inode*
- Check permissions
- Initialize cursor to beginning of file



Arrays & Pointers

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int x[5];
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for (int i = 0; i < 5; i++){
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y	NULL	0x88681140
x[0]	1	0x88681144
x[1]	1	0x88681148
x[2]	1	0x8868114c
x[3]	1	0x88681150
x[4]	1	0x88681154
	?	0x88681158

If an array of ints contains 10 ints, then the array size is 40 bytes. There is nothing extra.

- In particular, size is not stored.
- No memory is reserved to hold the address where array starts.

For a pointer variable, space to hold size of an address (4 or 8 bytes) is reserved.

Arrays & Pointers

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int x[5];
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y = x;

for (int i = 0; i < 5; i++)
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}
```

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An array name in expression context decays into the array's starting address (address of zero'th element).

However this would **not** be ok: `x = y;` $\Rightarrow$ No space reserved for x to hold an address.

Any pointer can be used with the array access operator [ ]. $\Rightarrow$ y in the example above can be used like x.

Pointer Arithmetics

- The array access operator [ ] is really only a shorthand for **pointer arithmetic + dereference**
- These are equivalent in C: `x[i] == *(x + i)`

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- The compiler resolves the name of an array to the starting address of the array and adds to it.
- So the program will happily try to access contents at address `*(x+999999)`, even if array size is much smaller than `999999`.
- Behaviour of exceeding array bounds is "undefined"
  - program might appear to work
  - program might crash (segmentation fault)
  - program might do something apparently random

Pointers Types

- Why do pointers have a type, e.g. `int*` or `char*`?

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- Why do pointers have a type, e.g. `int*` or `char*`?
  - Pointer arithmetic needs to know the size of object that pointer points to so it knows by how much to increment to get to `a[i]`.

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Differences between pointers and arrays

```
////////////////////////////

int x[5];
int *y = NULL;
y = x;

// what is sizeof(x)
// what is sizeof(y)

func(x);
func(y);

////////////////////////////
```

```
////////////////////////////

void func(int x[]) {
  // what is sizeof(x)
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- Inside `main`:

$$\underbrace{\texttt{sizeof(y)}}_{\substack{\text{size of an address}\\ \text{(4 or 8 bytes)}}} \neq \underbrace{\texttt{sizeof(x)}}_{\substack{\text{5 * size of an int}\\ \text{(typically 20 bytes)}}}$$

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- Inside `void func(int x[])`:

  `sizeof(x) == size of an address`

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- The memory for a process (a running program) is called its **address space**.
- Memory is just a sequence of bytes.
- A memory location (a byte) is identified by an *address*.

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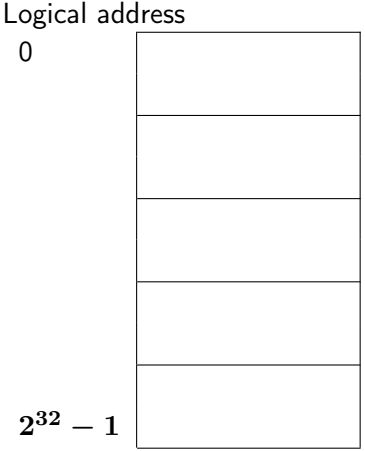
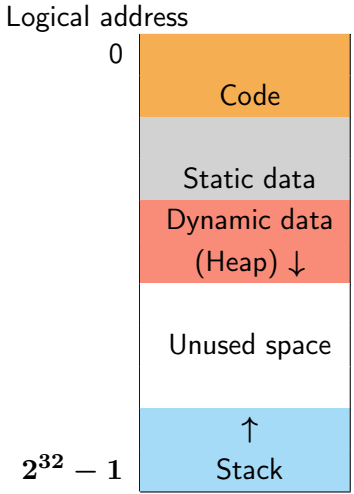
- In A48, you learned about the "memory model"... that was an "incomplete" picture...



The Address Space

- **Static data** Space for the *evil* **global** variables and variables declared as **static**
- **Dynamic data (Heap)** Space for dynamically allocated data structures (`malloc`, `calloc`).
- **Stack** Space for variables created in function calls: a function's parameters and a function's local variables



Examples

```
1  int x = 10;
2  int y;
3
4  int f(int p, int q) {
5      int j = 5;
6      return p * q + j;
7  }
8
9  int main() {
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11     int i = x;
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Logical address

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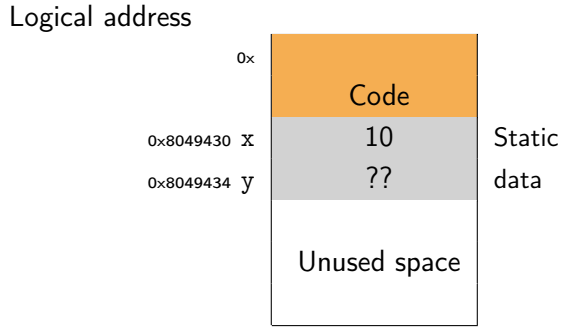

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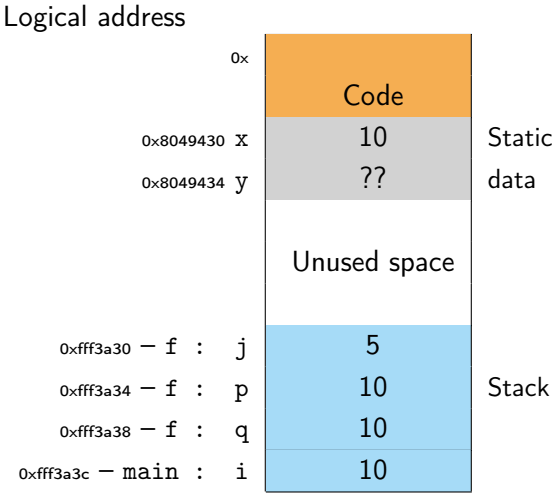

Examples – Global Variables

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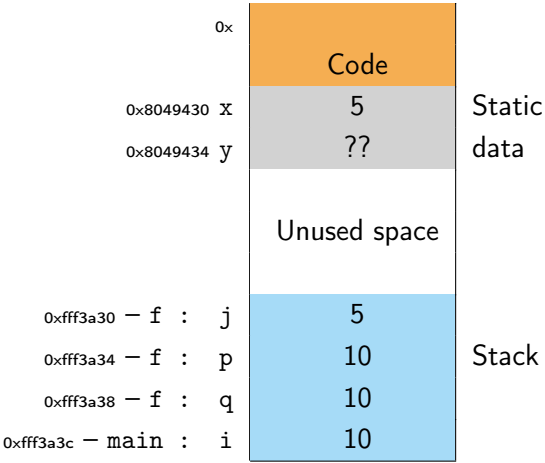

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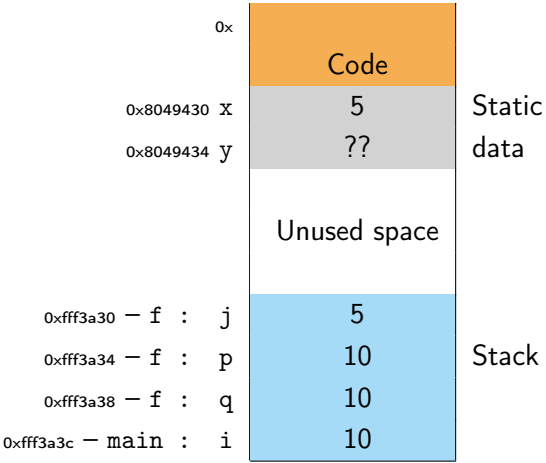
Evil global variables!



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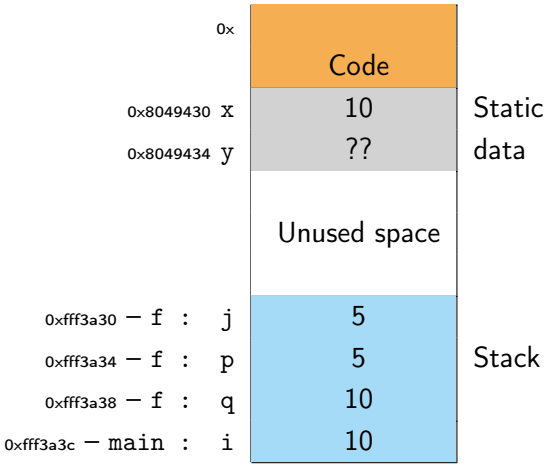

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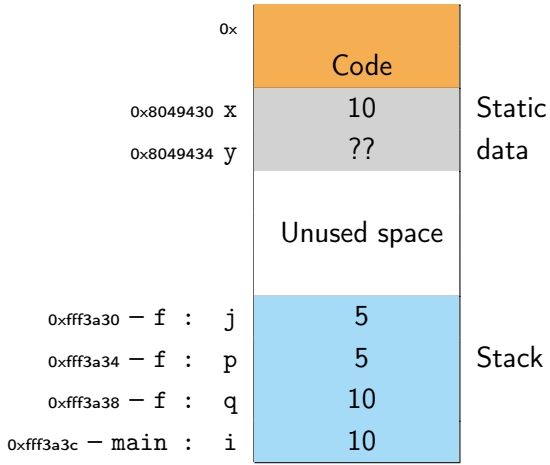
C passes basic data structures **by value**



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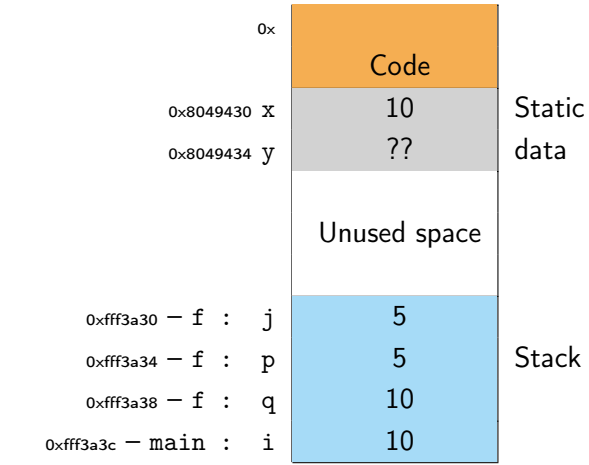

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C passes basic data structures **by value** ⇒ What change is needed for `f()` to change one of `main`'s variables?

Examples – Passing Function Arguments

```
1  int x = 10;
2  int y;
3
4  void f(int *p, int q) {
5      *p = 5;
6  }
7
8  int main() {
9
10     int i = x;
11     f(&i, i);
12     return 0;
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```

Changes

```
f(&i,i);
void f(int *p, q)
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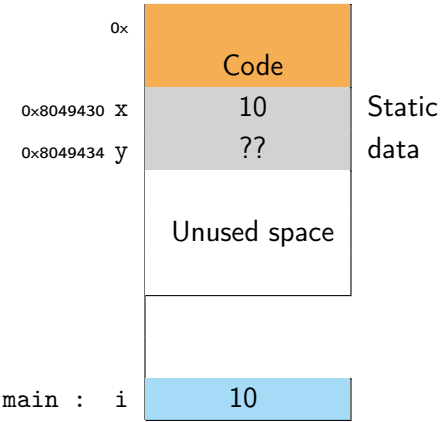
```



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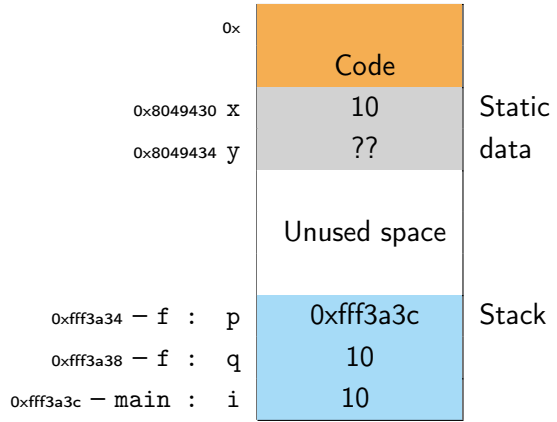
When calling `f()`



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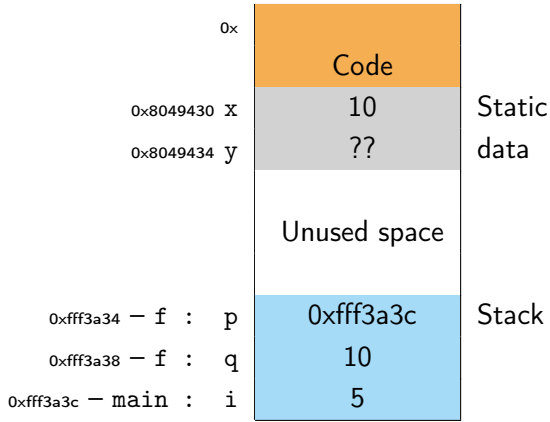
After `f()` returns



Changes

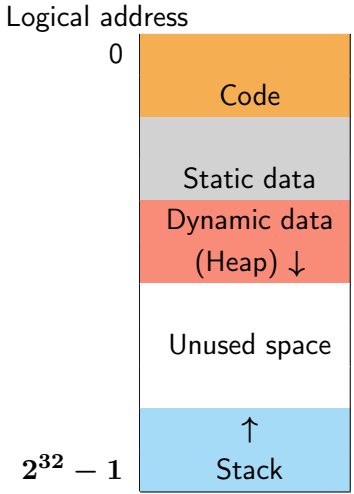
`f(&i,i);`

`void f(int *p, q)`

`*p = 5;`

The Address Space, continued...

- **Static data**
  .data = global or static variables with predefined values that can be modified
  BSS segment = global/static without predefined values
- **Dynamic data (Heap)**
- **Stack**
- **Code/Text**



Dynamic Memory Management

Let's write our own `concat` function:

```
1
2 char *concat(const char *s1,
      const char *s2) {
3     char result[70];
4
5     strcpy(result, s1);
6     strcat(result, s2);
7
8     return result;
9 }
```

Any problems with this implementation?

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Any problems with this implementation?

- `strncpy` & `strncat` would be safer..
- But what else?

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```
1  char *concat(const char *s1, const char *s2)
       {
2      // temp local variable to store result
3      char *result;
4
5      // allocating enough memory
6      result = malloc(strlen(s1) + strlen(s2)
           + 1);
7      if (result == NULL) {
8          printf ( Error: malloc failed\n
               );
9          exit(1);
10     }
11     //
12
13     strcpy (result, s1);
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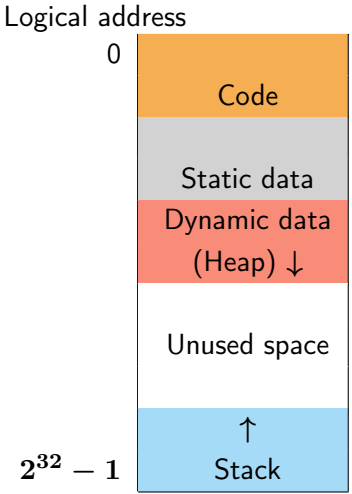
```

The Address Space, continued...

- **Static data**
- **Dynamic data (Heap)**
  Space for dynamically allocated data structures (`malloc`, `calloc`).
  - Memory allocated here will never be released/freed automatically by the system.
  - Completely under programmers control.
  - Memory here can be allocated at any time during the run of a program
- **Stack**
- **Code/Text**



Differences between `char` pointers and `char` arrays

```c
// char array
char a[] = "array";

// char pointer
// AKA "string literal"
char *p = "pointer";
```

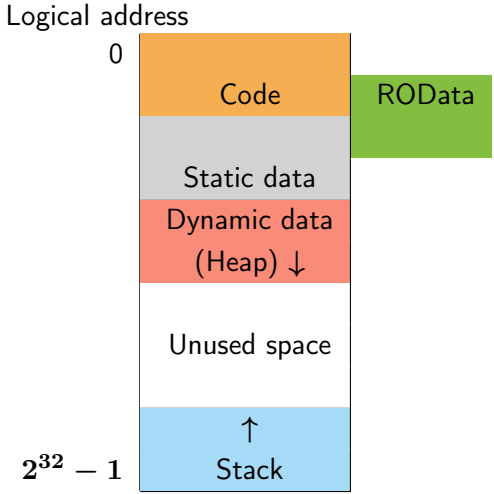
```c
p[0] = 'z';   // Illegal!
a[0] = 'z';   // OK!
```

`"pointer"` is stored in **read-only memory**.

No other space is reserved for `p`, except to store a memory address.

The *Complete* Memory Model

- **Static data**
  Space for the *evil* **global** variables and variables declared as **static**
- **Dynamic data (Heap)**
  Space for dynamically allocated data structures (`malloc`, `calloc`).
- **Stack**
  Space for variables created in function calls: a function's parameters and a function's local variables
- **Code/Text**
  string literals: RODdata (read-only data)
  code/text, or static data depending on platform



Passing Arrays as Parameters

Suppose we want to write a function to sum an array of ints.

```
int main()
{
  int i[3] = {10, 9, 8};

  printf("sum␣is␣%d\n", sum(i)); /*??*/

  return 0;
}

int sum( /* What goes here? */ ) {

}
```

What is being passed to the function is the name of the array which *decays* to a pointer to the first element – a pointer of type `int`.

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```c
int sum( int *a ) {
  int i, s = 0;

  for(i = 0; i < ??; i++)
    s += a[i];  /* this is
        legal */

  return s;
}
```

Passing Arrays as Parameters

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  for(i = 0; i < ??; i++)
    s += a[i];  /* this is
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  return s;
}
```

- How do we know how big the array is?
- Pass in the *size* of the array as another parameter.

Array Parameters

- `int sum(int *a, int size)`
- Also valid C code is:

```
int sum(int a[], int size)
```

Array Parameters

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- Also valid C code is:

  `int sum(int a[], int size)`
- However, many reasons against using this form:
  - We are really passing a pointer-to-int **not** an array.
  - We still don't know how big the array is.
  - Outside of a *formal parameter declaration* `int a[];` is **illegal**
- `int a;` and `int a[10];` are completely different things

Arrays/Pointers ... i

- Arrays are **not** pointers
- "Equivalence" of pointers and arrays
  Decay: An *lvalue* of type *array-of-T* which appears in an expression **decays** (with three exceptions) into a pointer to its first element; the type of the resultant pointer is pointer-to-T.
  (The exceptions are when the array is the operand of a `sizeof` or & operator, or is a *literal string* initializer for a character array.)
- Array and pointer declarations are interchangeable as function formal parameters
- Arrays automatically allocate space, but can't be relocated or resized.
  Pointers must be explicitly assigned to point to allocated space (perhaps using `malloc`), but can be reassigned (i.e. pointed at different objects) at will, and have many other uses besides serving as the base of blocks of memory.

Arrays/Pointers ... ii

- Due to the so-called equivalence of arrays and pointers, arrays and pointers often seem interchangeable, and in particular a pointer to a block of memory assigned by `malloc` is frequently treated (and can be referenced using [] exactly) as if it were a true array.