Reminder of midterm 1

- Next Thursday, Feb. 14, in class
- Look at Piazza announcement for rules and preparations

A New Example to see effect of E++ (better than the one in previous lecture)

- Purpose of showing *increment.c*
  - *Compiler error if misuse non-lvalue*
  - *Difference between *p++ and (*p)++*

```
#include <stdio.h>
main() {
      int i=0, j[2], *p, *q;
      p = &i;
      q = j;
      printf("i++ = \t %d\n", i++);
      printf("i is now  \t %d\n", i);
      printf("*p is now  \t %d\n", *p);

/*     (i++)++;  */
      j[0]=2;
      j[1]=3;
      *q++ = 0;
      printf("j is now  \t %p\n", j);
      printf("j[0] is now  \t %d\n", j[0]);
      printf("j[1] is now  \t %d\n", j[1]);
      printf("q is now  \t %p\n", q);

      q = j;
      printf("q is now  \t %p\n", q);
      printf("(*q)++ is now  \t %d\n", (*q)++);
      printf("q is now  \t %p\n", q);
      printf("(*q)++ is now  \t %d\n", (*q)++);
      printf("q is now  \t %p\n", q);
      printf("j[0] is now  \t %d\n", j[0]);
      printf("j[1] is now  \t %d\n", j[1]);
}
```

- We’ll leave other expressions to next Tuesday’s review lecture
- Next we discuss more complex way to organize and address data
  - Arrays of arrays
- In future lectures, we discuss
  - Nested structures
  - Recurrent (i.e. self-referential) structures
  - Arrays of structures (AOS)
  - Structure of arrays (SOA)

Arrays of arrays

- int ndigit[4][4]
  - Declares a 4-element array ndigit[4], in which each element is another 4-element array of integers
- It is the programmer's responsibility to not go beyond the array bound
  - The compiler by default does not issue warnings
  - Neither does it insert run-time check of array bound, by default

Arrays of arrays

```
#include <stdio.h>    /* main1.c, local array, going out of bound
*/

main() {

    int i, j, ndigit[4][4];
    for (i = 0; i < 4; ++i)
        for (j = 0; j < 4; ++j)
        ndigit[i][j] = i+j;
    for (i = 0; i < 10; ++i)
        for (j = 0; j < 4; ++j)
        printf("ndigit[%d][%d] = \t %d\n", i, j, ndigit[i][j]);
}
```

Declaring global multiple dimension arrays

```
#include <stdio.h>    /* f.c */
extern int ndigit[][];

void f() {
    int i;

    for (i = 0; i < 4; ++i)
        for (j = 0; j < 4; ++j)
        printf("ndigit[%d][%d] = \t
%d\n", i, j, ndigit[i][j]);

}
```

```
/* Purpose: show how different files pass
data through global arrays, main2.c */
int ndigit[4][4];
extern void f();
main() {
    int i, j;
    for (i = 0; i < 4; ++i) {
        for (j = 0; j < 4; ++j) {
        ndigit[i][j] = i+j;
    }
    f();
}
```

Let us run the following program and examine the addresses of the array elements

```
#include <stdio.h>  /* main3.c  */

main() {
	int i, j, ndigit[4][4];
	for (i = 0; i < 4; ++i)
		for (j = 0; j < 4; ++j)
		ndigit[i][j] = i+j;
	for (i = 0; i < 4; ++i)
		for (j = 0; j < 4; ++j)
		printf("ndigit[%d][%d] is at \t %p\n", i, j, &ndigit[i][j]);
}
```

Memory Layout of a 2-dim Integer Array

- In C, the array int i[][] is allocated *row-wise*
  - We call the first index the *row* index and the second the *column* index
  - This allocation scheme is known as row-major allocation
    - All elements of an entire row are allocated consecutively
    - For good performance, it is important that the program accesses the array elements in a consecutive way
    - We will discuss more on data locality and performance issues in later lectures

Array of pointers

- Let’s compile and run the following program

```
#include <stdio.h>  /* main4.c *

main() {

        int i, j, *ndigit[4][4];
        for (i = 0; i < 4; ++i)
                for (j = 0; j < 4; ++j)
                *ndigit[i][j] = i+j;
}
```

What happened?

ndigit[i][j] does not have any values yet!

```
/* examine the contents of arrays of pointers */
#include <stdio.h>  /* main5.c */

main() {

    int i, j, *ndigit[4][4];
    for (i = 0; i < 4; ++i)
        for (j = 0; j < 4; ++j)
        printf("ndigit[%d][%d] = \t %p\n", i, j, ndigit[i][j]);
}
```

Bad Memory Addresses

ndigit[0][0] = 0x7f5a52a53000
ndigit[0][1] = 0x400379
ndigit[0][2] = 0xa
ndigit[0][3] = 0x8000
ndigit[1][0] = 0x1
ndigit[1][1] = 0x7fffef9dfc58
ndigit[1][2] = 0x1
ndigit[1][3] = 0x4005b0
ndigit[2][0] = (nil)
ndigit[2][1] = 0x40041b
ndigit[2][2] = 0x7fffef9dfc58
ndigit[2][3] = 0x4005f5
ndigit[3][0] = 0x7f5a524f56e0
ndigit[3][1] = 0x4005b0
ndigit[3][2] = (nil)
ndigit[3][3] = 0x400450

A different example

```
#include <stdio.h>   /* main7.c */
main() {
      int i, j, ndigit[4][4], *address[4][4];
      for (i = 0; i < 4; ++i)
            for (j = 0; j < 4; ++j) {
            ndigit[i][j] = i+j;
            address[i][j]=&ndigit[i][j];
      }

      for (i = 0; i < 4; ++i)
            for (j = 0; j < 4; ++j)
            printf("ndigit[%d][%d] = \t %d\n", i, j, *address[i][j]);
}
```

2-dim array viewed as rows of pointers

```
#include <stdio.h>        /* main8.c */
main() {
      int i, j, ndigit[4][4], *address[4];
      for (i = 0; i < 4; ++i)
            for (j = 0; j < 4; ++j) {
            ndigit[i][j] = i+j;
         /*    address[i]=&ndigit[i][0]; */
           address[i]=ndigit[i];
      }
      for (i = 0; i < 4; ++i)
            for (j = 0; j < 4; ++j)
            printf("ndigit[%d][%d] = \t %d\n", i, j,*address[i]++);
}
```

2-dim Array Initialization

- Bracketed initialization: row by row

```
#include <stdio.h>     /* arrayinit.c */
main() {
float y[3][3] = {
    { 1, 3, 5 },
    { 2, 4, 6 },
    { 3, 5, 7 } };

     int i, j;
     for (i = 0; i < 3; ++i)
          for (j = 0; j < 3; ++j)
          printf("y[%d][%d] = \t %f\n", i, j, y[i][j]);
}
```

Alternatively

```
#include <stdio.h>

main() {
float y[3][3] = {1, 3, 5 , 2, 4, 6 , 3, 5, 7};

	int i, j;
	for (i = 0; i < 3; ++i)
		for (j = 0; j < 3; ++j)
		printf("y[%d][%d] = \t %f\n", i, j,
y[i][j]);
}
```

Avoid Modifying Constant Array by Mistake

```
#include <stdio.h>    /* try to compile
constarray.c */

main() {
const float y[3][3] = {1, 3, 5 , 2, 4, 6 , 3, 5, 7};

        int i, j;
        for (i = 0; i < 3; ++i)
                for (j = 0; j < 3; ++j)
                 y[i][j]=0.0;
}   /* Compiler will report the error  */
```

An array of strings

- `char my[2][3] = { "me", "my" };`
  - Remember each string literal has the terminating ‘\0’
  - For fixed sized strings, arrays of arrays of characters work well
- For variable sized strings, char pointers must be used

  `char* you[2] = { "you", "yours" };`
- `my[2][3] has 6 bytes allocated in memory`
- `you[2] has memory allocated for two pointers`
  - `16 bytes if each pointer takes 8 bytes`

```
/* size of pointer */
#include <stdio.h>

main() {

	int i, *j=&i;

	printf("size of pointer j is \t %lu\n", 
sizeof(j));
}
```

For array my[2][3]

- The pointer value of my[i] can be computed by the compiler
  - Because the rows are stored consecutively in memory
- No need to store a pointer in the memory

Compile and run this program

```
#include <stdio.h>    /* arraystring.c */
main() {
char my[2][3] = { "me", "my" };
char* you[2] = { "you", "yours" };
	int i, j;
	for (i = 0; i < 2; ++i)
		for (j = 0; j < 3; ++j) {
		printf("my[%d][%d] code \t %d\n", i, j, my[i][j]);
		printf("my[%d][%d] = \t %c\n", i, j, my[i][j]);
	}
	for (i = 0; i < 2; ++i)
		for (j = 0; j < 3; ++j) {
		printf("you[%d][%d] code \t %d\n", i, j, *you[i]);
		printf("you[%d] string \t %s\n", i, you[i]++);
	}
}
```

- More commonly, a 2-dimensional array may be formed dynamically by calling memory management routine such as malloc()
- Consecutive rows may not be neighbors in the memory
- We discuss malloc() later

The void type

- The type `void` is not actually a type. It is rather saying “to be determined” or “undefined”
  - `sizeof(void)` is undefined
- A pointer of type `void*` is a generic pointer, that can not be used without first *casting* it to an actual type

  - The `void*` type is used by functions that return a pointer to a memory area

```
void* malloc(size_t size);
```

- A typical use of malloc is

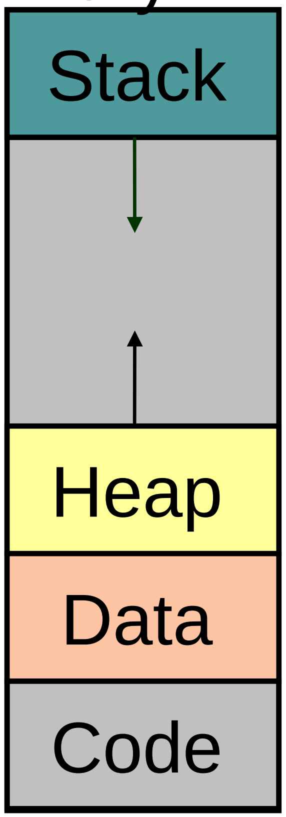
```
int* p = (int*) malloc(sizeof(int));
```

- Notice the type cast in the above statement

The Heap memory

- Heap:
  - *dynamic memory for variables that are created with calls to standard C utility functions malloc, calloc, realloc and are disposed of with calls to free*

Virtual Memory



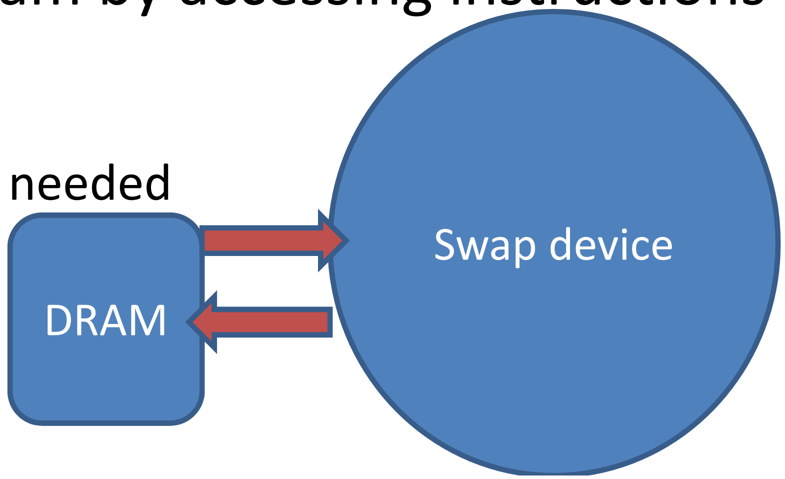
Address space versus physical memory

- A 64-bit machine provides a range of addresses from 0x0000000000000000 to 0xffffffffffffffff
  - 2^32 is covers 4 GB memory, 2^52 covers 4 peta bytes … …
- At any given time, not all address ranges are mapped to physical memory
  - Otherwise, with so many processes (i.e., instances of programs) running or loaded to run, we run out of physical memory very fast

What is physical memory

- In a simplified view, the physical memory is
  - The semiconductor DRAM (dynamic random access memory), with the backup of
  - The (magnetic or semiconductor) secondary storage (often also known as the disk device)
  - The secondary storage is usually several orders of magnitude larger than the DRAM, but several orders of magnitude slower
    - The secondary storage is divided between the file system and the swap device (to support the program address space)
- The processor executes a program by accessing instructions and variables in the DRAM
  - The OS swaps instructions/data

between DRAM/secondary storage as needed



- OS uses sophisticated algorithms to allocate DRAM and the swap device to each running program
- The allocated swap size is increased as requested
- The UNIX OS allows a C program to directly request a block of “memory” (i.e. a chunk of swap storage) through calls to routine such as sbrk(size)
  - The OS automatically round up the requested size to the size that is suitable for allocation

- How to fit a dynamic data structure, e.g. a graph, a linked list, to the allocated chunk of memory
- How to keep track of and reuse the freed parts of the memory
- These will soon become a nightmare to the programmer
- Hence, we are provided with heap management utility routines in C standard library via the header file <stdlib.h>

Dynamic memory management interface

- `#include <stdlib.h>`

- `void* calloc(size_t n, size_t s)`
- `void* malloc(size_t s)`
- `void  free(void* p)`
- `void* realloc(void* p, size_t s)`

- Allocate and free dynamic memory

- Using such C routines, the programmer does not need to directly interact with the OS
- Instead, these routines implement a "*memory manager*" to
  - keep track of the "free" areas of the memory (i.e. the data segment obtained from the swap device)
  - find a suitable piece of the "free" areas when requested
  - put back a "freed" piece of memory back to the free areas
  - Various allocation algorithms have been discussed in literature
  - We can see the exact algorithm used in our utility routines

Warm up your iclickers

- Quizzes 3

Q3.#1

- What number is printed by the following program?

```
#include <stdio.h>
main() {
 int j[2], *q;
 q=j;
 j[0]=2;
 j[1]=3;
 *q++ = 0;
printf("%d\n", j[0]); }
```

- (a) 2
- (b) 3
- (c) 0
- (d) none of the above

- Answer is 0

Q3.#2

- What number is printed by the following program?

```
#include <stdio.h>
main() {
 int j[2], *q;
 q=j;
 j[0]=2;
 j[1]=3;
 *++q = 0;
printf("%d\n", j[0]); }
```

- (a) 2
- (b) 3
- (c) 0
- (d) none of the above

- Answer is 2

Q3.#3

- What number is printed by the following program?

```
#include <stdio.h>
main() {
int j[2], *q;
q=j;
j[0]=2;
j[1]=3;
printf("%d\n", *q++); }
```

- (a) 2
- (b) 3
- (c) 0
- (d) none of the above

- Answer is 2