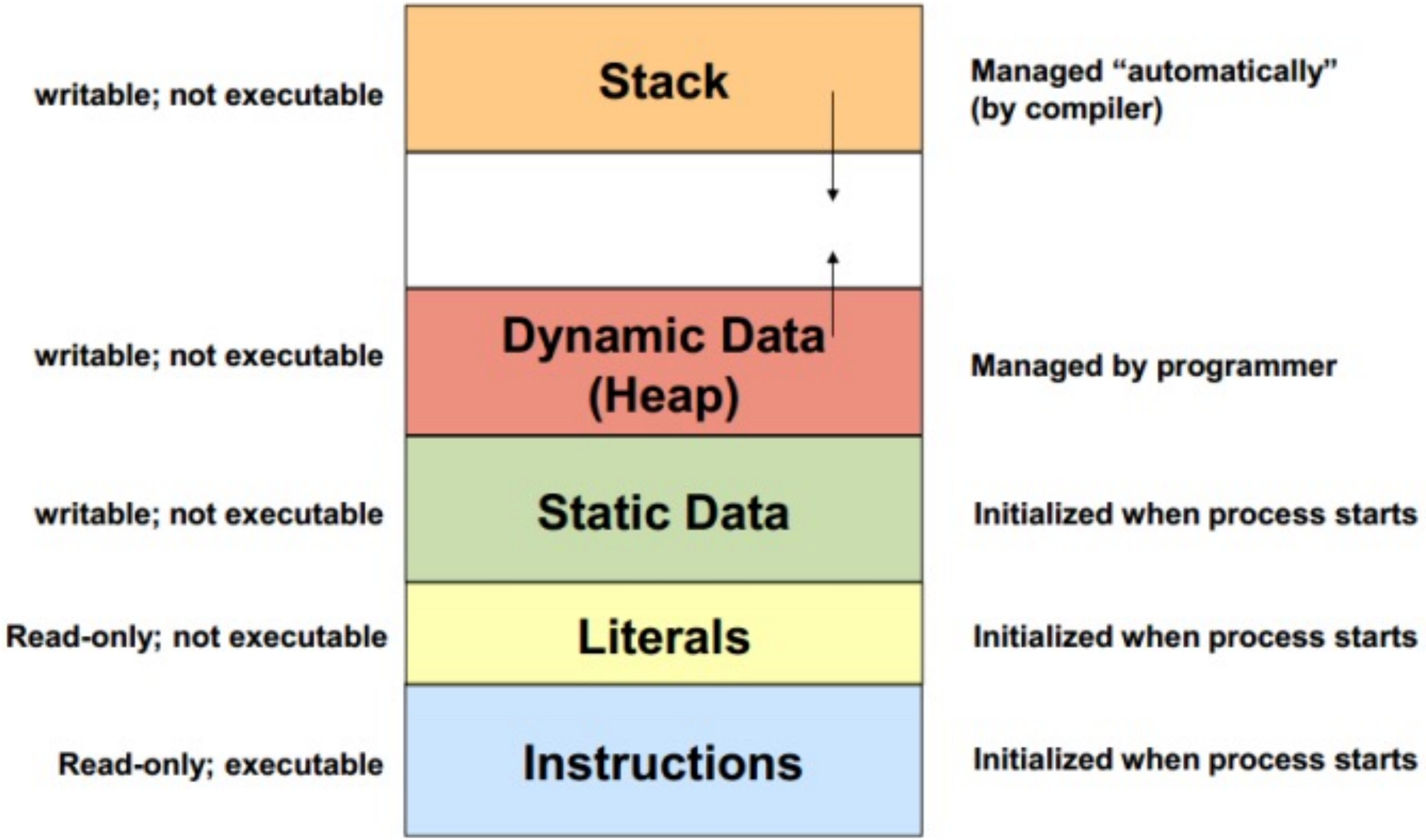
CS 288 Intensive Programming in Linux

Professor Ding, Xiaoning

Organization of memory space



Understand memory space with a C prog

```
#include <stdio.h>
#include <stdlib.h>
char global_data[]="This is in heap";
int depth=0;
void func() {
   char func_data[20];
   if (depth++>5) return;
   sprintf(func_data, "*#*#*#*#* %d *#*#*#*#", depth);
   printf("func_data (layer %d)@ %p\n",depth,(void *)func_data);
   func();
}
main(int argc, char **argv) {
   char main_data[20],*dynamic_alloc_data;
   strcpy(main_data, "#$#$#$#$#$#$#$#$");
   dynamic_alloc_data=(char *)malloc(50);
   strcpy(dynamic_alloc_data, "Text in allocated mem. space");
   printf("Code: main @ %p, func @ %p\n", (void *)main,(void *)func);
   printf("global_data @ %p\n", (void *)global_data);
   printf("dynamic_alloc_data @ %p\n", (void *)dynamic_alloc_data);
   func();
}
```

Execution results:

Instructions

```
Code: main @ 0x55a2c31d5788, func @ 0x55a2c31d56fa
global_data @ 0x55a2c33d6010
dynamic_alloc_data @ 0x55a2c3eb9260
func_data (layer 1)@ 0x7ffc08380bd0
func_data (layer 2)@ 0x7ffc08380ba0
func_data (layer 3)@ 0x7ffc08380b70
func_data (layer 4)@ 0x7ffc08380b40
func_data (layer 5)@ 0x7ffc08380b10
func_data (layer 6)@ 0x7ffc08380ae0
```

Heap growing from low mem address to high mem address

Stack growing from high mem address to low mem address

Examine code, heap data, and stack using gdb

- Check the code (e.g., `disassemble main`, `disassemble func`)
- Locate and examine the data in memory (e.g., `x/32cb func_data`)
- Monitor the growth of stack (e.g., `x/256cb $sp`)

Basic pointer concepts and pointer operations

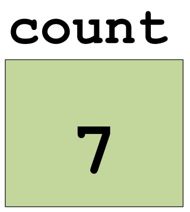
pointers and array, passing pointers to a function, pointers and strings, strtok

Pointers overview

- Pointers save addresses.
- With a pointer, you can locate and access the corresponding data.
- The type of the pointer (e.g., int *, float *) determines how many bytes are interpreted together and how to interpret the data.
- By changing the address in a pointer, you can locate and access other data.
- What you can do with pointers?
  - Controlling the way in which data is interpreted
  - Sharing data by passing pointers (addresses) instead of data
  - Dynamically organizing data into different structures

Normal variables and pointer variables

- Pointer variables
  - Contain memory addresses as their values
  - A normal variable contains a specific value
    - You can consider a variable name as an "alias" of a memory address
  - A pointer variable contains the *address* of another variable
    - The pointer variable is an "alias" of a memory address, in which another memory address is stored.



Pointer variable declarations

- **`*`** used with pointer variables

```
int *myPtr;
/* Declares a pointer to an int
 * Pointer type:  int *
 */
```

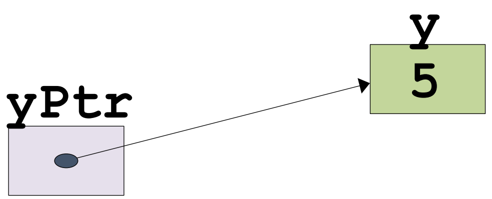
- Multiple pointers, multiple **`*`**

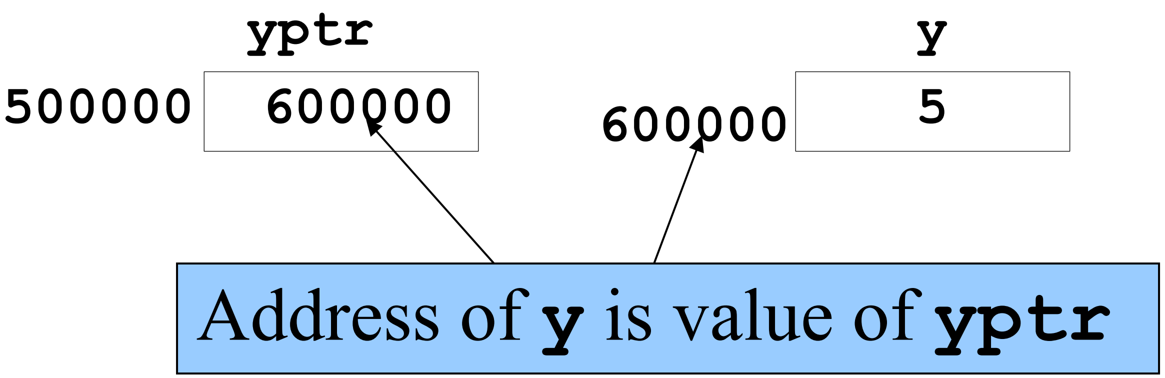
```
int *myPtr1, *myPtr2;
```

- Can declare pointers to any data type, even pointer to point
- Initialize pointers to **`0`**, **`NULL`**, or an address
  - **`0`** or **`NULL`** - points to nothing (**`NULL`** preferred)

& (address operator) returns address of operand

```
int y = 5;
int *yPtr, *yPtr2;
yPtr = &y;
/*yPtr gets address of y, i.e., yPtr "points to " y */
```






```
yPtr2 = yPtr; /*yPtr2 points to y too. */
```

***** (indirection/dereferencing operator)

Returns a synonym/alias of what a pointer *points* to

`yptr` returns the address of **`y`**

`*yptr` returns **`y`** (because **`yptr`** points to **`y`**)

- ***** can be used for assignment

```
*yptr = 7; // changes y to 7
```

- ***** can only be used to dereference pointer variables.

```
*(0x55a2c31d5788)   //invalid
```

`*` and `&` are inverses

`*` and `&` cancel each other out

```
*&yptr  ->  * (&yptr) -> * (address of yptr)->
 returns alias of what operand points to -> yptr

&*yptr -> &(*yptr) -> &(y) -> returns address of y,
 which is yptr -> yptr
```

```c
/* Using the & and * operators */
#include<stdio.h>

int main(){
int a;      /* a is an integer */
int *aPtr; /* aPtr is a pointer to an integer */

a = 7;
aPtr = &a; /* aPtr set to address of a */

printf("The address of a is %p\n"
  "The value of aPtr is %p", &a, aPtr);

printf("\nThe value of a is %d\n"
  "The value of *aPtr is %d", a, *aPtr);

printf("\n* and & are inverses\n"
  "&*aPtr = %p, *&aPtr = %p\n",
  &*aPtr, *&aPtr);

return 0;
}
```

The address of **a** is the value of **aPtr.**

The ***** operator returns an alias to what its operand points to. **aPtr** points to **a**, so ***aPtr** returns **a**.

Notice how ***** and **&** are inverses

```
The address of a is 0012FF88
The value of aPtr is 0012FF88
The value of a is 7
The value of *aPtr is 7
* and & are inverses
&*aPtr = 0012FF88, *&aPtr = 0012FF88
```

Typecasting using a pointer

Change the type of the pointer to change the way the data is interpreted

```
main(){
 float f=123.45;
 unsigned int *p = (unsigned int *) &f, i, j, value_of_bits4to7;
 i = *p; j=(int)f; value_of_bits4to7 = (*p & 0xF0)>>4;
 printf("%d %d %d\n", i, j, value_of_bits4to7);
}
```

j
123

f
123.45

i
1123477094

0100 0010 1111 0110 1110 0110 **0110** 0110

p
0x7fffffffe3f8

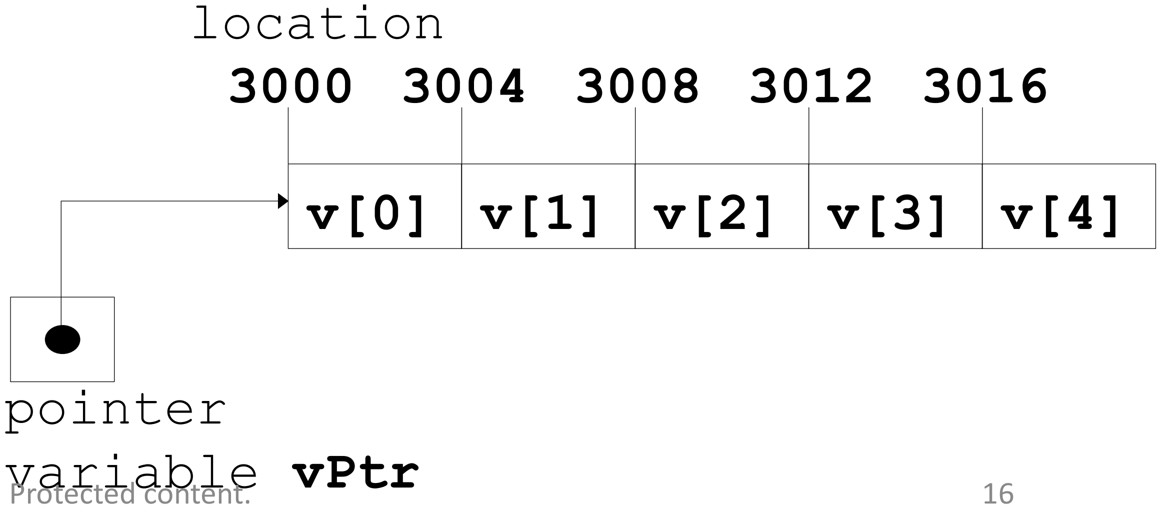
value of bits4to7
6

Two types of type casting

```
#include <stdio.h>
void main(){
  float f=123.45;
  unsigned int i, j, *p;

  /*1st*/
  i=(int)f;

  /*2nd*/
  p=(int *)&f;
  j=*p;

  /* output: 123 1123477094 */
  printf("%d %d\n", i, j);
}
```

Pointer expressions and pointer arithmetic

- Arithmetic operations can be performed on pointers
  - Increment/decrement pointer (**`++`** or **`--`**)
  - Add an integer to a pointer(**`+`** or **`+=`** , **`-`** or **`-=`**)
  - Pointers may be subtracted from each other
  - Operations meaningless unless performed on an array
- 5-element **`int`** array on machine with 4-byte **`int`**s
  - **`vPtr`** points to first element **`v[0]`** at location **`3000`**. (**`vPtr = v`**)
  - **`vPtr +=2;`** sets **`vPtr`** to **`3008`**
    - **`vPtr`** points to **`v[2]`** (incremented by 2), but machine has 4 byte **`int`**s.



Pointer expressions and pointer arithmetic

- Subtracting pointers
  - Returns number of elements from one to the other.

```
vPtr2 = &v[2];
vPtr = &v[0];
vPtr2 - vPtr == 2.
```

- Pointer comparison (**<**, **==** , **>**)
  - See which pointer points to the higher numbered array element
  - Also, see if a pointer points to **0**
- Pointers of the same type can be assigned to each other
  - If not the same type, a cast operator must be used

```
int *ptr1 = &b;
char *ptr2= (char *)ptr1;
char c=*ptr2;
```

Relationship between pointers and arrays

- Array variables and pointers can be used interchangeably in most cases.
  - Array variables save starting addresses of the arrays.
- Pointers can do array subscripting operations

  Declare an array **`b[5]`** and a pointer **`bPtr`**

  `bPtr = b; //`Array name is actually a address of first element

  OR

  `bPtr = &b[0]; //`Explicitly assign **`bPtr`** to address of first element

  Element **`b[n]`** can be accessed by **`*( bPtr + n )`**

  Array itself can use pointer arithmetic.

  `b[3]` same as **`*(b + 3)`**

  Pointers can be subscripted (pointer/subscript notation)

  `bPtr[3]` same as **`b[3]`**
- You can also malloc some memory pointed by a pointer and use it as an array (will introduce later).

Relationship between pointers and arrays

- Array variables are constant pointers and are attached with array size info
  - Array variables save starting addresses of the arrays, and cannot be changed.
  - Array variables cannot be changed
  - sizeof() returns different values.
- **`sizeof()`** returns size of operand in bytes
  - Can be used with variable names (e.g., sizeof(a)), type name (e.g., sizeof(int)), and constant values (e.g., sizeof("hello world!\n")).
  - Return value is in `unsigned long` type.
  - For arrays: size of 1 element * number of elements

```
int myArray[10], *p=myArray;
printf("%lu, %lu", sizeof(myArray), sizeof(p)); /* print 40,8 */
```

Memory allocation

- Header file: <stdlib.h>
- `void *` **`malloc`**`(size_t esize)` -- allocate a single block of memory of `esize` bytes
- `void *` **`calloc`**`(size_t num, size_t esize)` -- allocate a block of memory of `num*esize` bytes
- `void *` **`realloc`**`(void * ptr, size_t esize)` -- extend the amount of space (pointed by `ptr`) allocated previously to `esize`
- Returns `void *` if succeed (cast the result to an appropriate type before use).
- Returns NULL if not enough memory available.
- If realloc() cannot extend the current memory block (ptr), it allocates memory from a new location, copies over the data, and frees up the memory pointed by ptr.
- `void free(void *ptr)`

memory pointed by `ptr` is no longer needed. Memory allocated dynamically does not go away at the end of functions, you MUST explicitly free it up.

```
float *nums;
int N;
int I;

printf("Read how many numbers:");
scanf("%d",&N);
nums = (float *) calloc(N, sizeof(float));
/* nums is now an array of floats of size N */
for (I = 0; I < N; I++) {
  printf("Please enter number %d: ",I+1);
  scanf("%f",&(nums[I]));
}
/* Calculate average, etc. */

…
```

Allocated with calloc() and used like an array.

```c
float *nums;
int I;

nums = (float *) calloc(5, sizeof(float));
/* nums is an array of 5 floating point values */

for (I = 0; I < 5; I++)  nums[I] = 2.0 * I;
/* nums[0]=0.0, nums[1]=2.0, nums[2]=4.0, etc. */

nums = (float *) realloc(nums,10 * sizeof(float));
/* An array of 10 floating point values is allocated, the
 first 5 floats from the old nums are copied as the first 5
 floats of the new nums, then the old nums is released */
```

Releasing memory (free)

`void free(void *ptr)`

- memory at location pointed to by ptr is released (so we could use it again in the future)
- program keeps track of each piece of memory allocated by where that memory starts
- if we free a piece of memory allocated with calloc, the entire array is freed (released)
- results are problematic if we pass as address to free an address of something that was not allocated dynamically (or has already been freed)

Suggested practice: to free the memory in the function where it is allocated

```
void problem() {
  float *nums;  int N = 5;
  nums = (float *) calloc(N, sizeof(float));
  /* But no call to free with nums */
}
```

- When function problem called, space for array of size N allocated.
- When function ends, variable nums goes away, but the space nums points at (the array of size N) does not.
- There is no way to figure out where the space is.
- This problem is called *memory leak.*

Strings are arrays of characters ended with NULL

"abcd" is actually "abcd\0"

```
char str[]="abcd", *p=str;
sizeof("abcd");     /* returns 5 */
strlen("abcd");     /*  returns 4 */
p[0]=='a';          /* returns 1 (true) */
p[4]==0;            /*returns 1 (true)*/
scanf("%s",str);   /* not &str */
```

Is a NULL pointer an empty string?

Passing addresses between functions

- Many library functions use pointers.
- Most useful when you want to
  - **pass an array or a string:** passing an address is more efficient than copying all data; passing all data using one argument;..
  - **have some data updated in a function**, e.g., sorting an array
- Use **`*`** operators for pointer arguments when defining the function
- Use pointer arguments when calling the function
  - Pass address of argument using **`&`** operator (e.g., `cube(`**`&mynumber`**`)`)
    - Passing non-pointers (e.g., `cube(`**`2`**`)`) may cause segmentation faults.
  - Arrays are not passed with **`&`** because the array name is already a pointer

```c
#include <stdio.h>
void cube(int *);

int main(){
  int number = 5;
  printf("Original value of number: %d\n", number);
  cube(&number);
  printf("New value of number: %d\n", number);
  return 0;
}

void cube(int *nPtr ){
*nPtr = (*nPtr) * (*nPtr) * (*nPtr);
}
```

Address of **number** is given because **cube** expects a pointer.

Inside **cube**, ***nPtr** is used (***nPtr** is **number**).

Output:

```
Original value of number: 5
New value of number: 125
```

Bubble-sort using pointers

- bubbleSort() sorts elements in place
- Swap() swaps two array elements

```
#include <stdio.h>

#define SIZE 10
void swap(int *, int *);
void bubbleSort(int *, const int);

int main() {
  int a[SIZE]={2,6,4,8,10,12,89,68,45,37 };
  int i;
  printf("Data items in original order\n" );
  for ( i = 0; i < SIZE; i++)
    printf( "%4d", a[ i ] );
  bubbleSort(a, SIZE);
  printf("\nData items in ascending order\n" );
  for ( i = 0; i < SIZE; i++)
    printf( "%4d", a[ i ] );
  printf( "\n" );
  return 0;
}
```

- **`Bubblesort`** gets passed the address of array **`a`** (pointer).
- When passing an array of values, array size must also be passed.

```c
void bubbleSort(int *array, const int size) {
  int pass, j;
  for ( pass = 0; pass < size - 1; pass++ )
    for ( j = 0; j < size - 1; j++ )
      if ( array[ j ] > array[ j + 1 ])
        swap( &array[ j ], &array[ j + 1 ] );
}

void swap(int *element1Ptr, int *element2Ptr) {
  int hold = *element1Ptr;
  *element1Ptr = *element2Ptr;
  *element2Ptr =hold;
}
```

```
Data items in original order
   2   6   4   8  10  12  89  68  45  37
Data items in ascending order
   2   4   6   8  10  12  37  45  68  89
```

Strtok(): splitting a string into tokens

```
#include <string.h>
char * strtok (char *string, const char *delimiters)
```

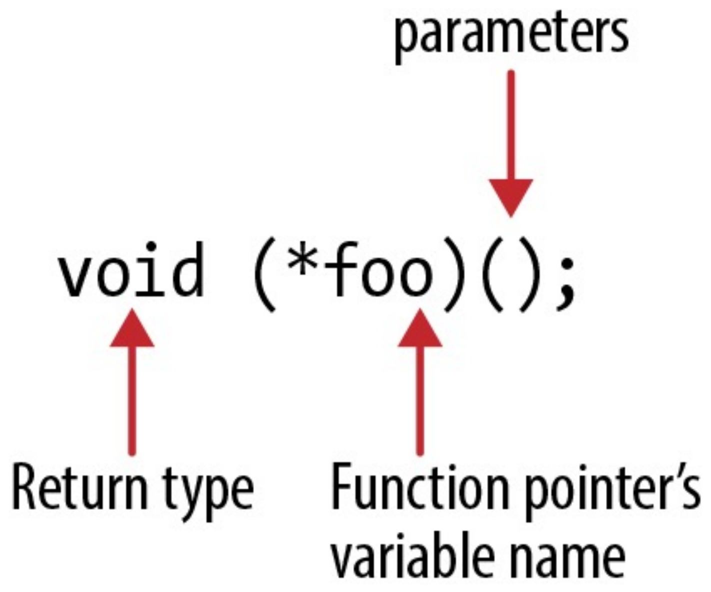
- A string can be split into tokens by making **a series of strtok calls.**
  - return a token on each call.
  - The searching begins at the next character after the token previously found.
  - Return NULL when no other tokens can be found (string end is reached or string contains only delimiters)
  - Contents in `string` may be changed (delimiters replaced with NULL, 1 string to multiple)
- On the first call, the ***string* argument** specifies the string to be split up.
- Subsequent calls, the ***string* argument** must be **null.**
  - If it is not NULL, the searching and splitting will restart from the beginning of the string.
- *delimiters* specifies a set of delimiters (no need to be same in a series of strtok calls)

```c
#include <string.h>
#include <stdio.h>
int main(){
   char address[] =
      "tom@www.auckland.ac.nz:/home/tom/fall2020/cs288/";
   char delimiter[] = ".@:/";
   char *token;
   /* get the first part */
   token = strtok(address, delimiter);
   /* get the rest */
   while( token != NULL ) {
      printf( "%s\n", token );
      token = strtok(NULL, delimiter);
   }
   return(0);
}
```

```
tom
www
auckland
ac
nz
home
tom
fall2020
cs288
```

Function pointers

- A function pointer is a pointer that holds the address of a function.
  - Function name is starting address of the function.
- A important and useful feature in C.
  - Your program can dynamically change which function is to be called.
- Function pointers can be
  - Passed to functions
  - Stored in arrays
  - Assigned to other function pointers
- Declare a function pointer
  - Similar to declaring a function
  - var name and * in ()




```
int (*f1)(double);       //Passed a double and
                         // returns an int
void (*f2)(char*);       // Passed a pointer to char
                         // and  returns void
double* (*f3)(int, int); // Passed two integers
                         //returns a pointer to a double
```

Some examples for function pointers.

```
int   *f4();     // a function returns int
int   (*f5)();   // a function pointer returns int
int*  (*f6)();   // a function pointer returns int *
```

```
#include <stdio.h>
int (*fptr1)(int);
int square(int num) {
    return num*num;
}
main(){
    int n = 5;
    fptr1 = square;
    printf("%d squared is %d\n",n, fptr1(n));
}
```

Passing function pointers (using bubblesort as an example)

- Function **`bubble`** takes a function pointer pointing to a helper function
  - **`bubble`** calls this helper function, which determines ascending or descending sorting
- The argument in **`bubble`** for the function pointer:

  `int ( *compare )( int, int )`

  tells **`bubblesort`** to expect a pointer to a function that takes two **`int`**s and returns an **`int`**.
- If the parentheses were left out: **`int *compare( int, int ),`** it is to declares a function that receives two integers and **returns a pointer** to a **`int`**

```c
#include <stdio.h>
#define SIZE 10
int ascending( int a, int b ){
  return b < a;
}
int descending( int a, int b ){
  return b > a;
}
void swap( int *element1Ptr, int *element2Ptr){
  int temp = *element1Ptr;
  *element1Ptr = *element2Ptr;
  *element2Ptr = temp;
}
void bubble(int work[], int size, int (*compare)(int, int ))
{
  int pass, count;
  for ( pass = 1; pass < size; pass++)
    for ( count = 0; count < size - 1; count++ )
      if ( (*compare)(work[count], work[count+1]) )
        swap( &work[count], &work[count+1] );
}
```

```
int main(){
  int order, counter,
  a[ SIZE ] = { 2, 6, 4, 8, 10, 12, 89, 68, 45, 37 };
  printf( "Enter 1 to sort in ascending order, \n"
          "Enter 2 to sort in descending order: ");
  scanf( "%d", &order );
  printf( "\nData items in original order \n" );
  for ( counter = 0; counter < SIZE; counter++)
    printf( "%5d", a[ counter ] );
  if ( order == 1 ){
    bubble( a, SIZE, ascending );
    printf( "\nData items in ascending order\n" );
  }
  else{
     bubble( a, SIZE, descending );
     printf( "\nData items in descending order\n" );
  }

  for ( counter = 0; counter < SIZE; counter++)
    printf( "%5d", a[ counter ] );
  printf( "\n" );
}
```

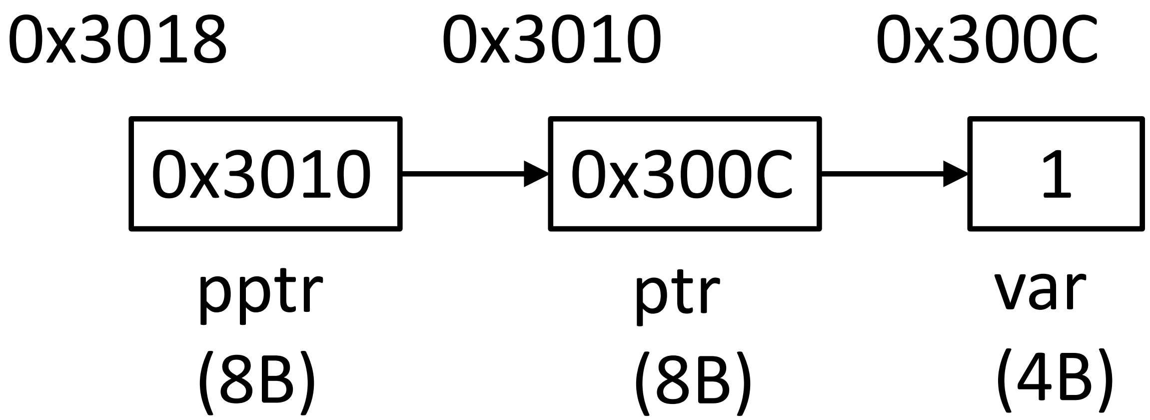
Pointer to pointer and (dynamic) multidimensional arrays

Pointer to pointer, array of pointers and dynamic multi-dimensional arrays, parsing command-line arguments and environment variables,

function pointers

Pointer to pointer: memory address of pointer variable

```
#include <stdio.h>
int main () {
    int  var = 1;
    int  *ptr = &var;
    int  **pptr = &ptr;

    printf("Value of var = %d\n", var );
    printf("Value available at *ptr = %d\n", *ptr );
    printf("Value available at **pptr = %d\n", **pptr);
    return 0;
}
```




```
Value of var = 1
Value available at *ptr = 1
Value available at **pptr = 1
```

- Defined using ** (2nd * denotes that it is a pointer; 1st * denotes that the data pointed by it is pointer).
- Saves the address of a pointer variable.
- Dereferenced using **

Pointer vs. pointer to pointer

- A pointer to pointer is also a pointer
  - A pointer to pointer (e.g., pptr) saves a memory address, as a normal pointer (e.g., ptr) does.
- Different types determine different ways to interpret the data (1s and 0s).
  - e.g., *pptr and *ptr are interpreted differently.
  - Type of *pptr is int *, it is an "alias" of ptr.
  - Type of *ptr is int, it is an "alias" of var.
  - Type of **pptr also int, it is an "alias" of var.

A "weird" program.

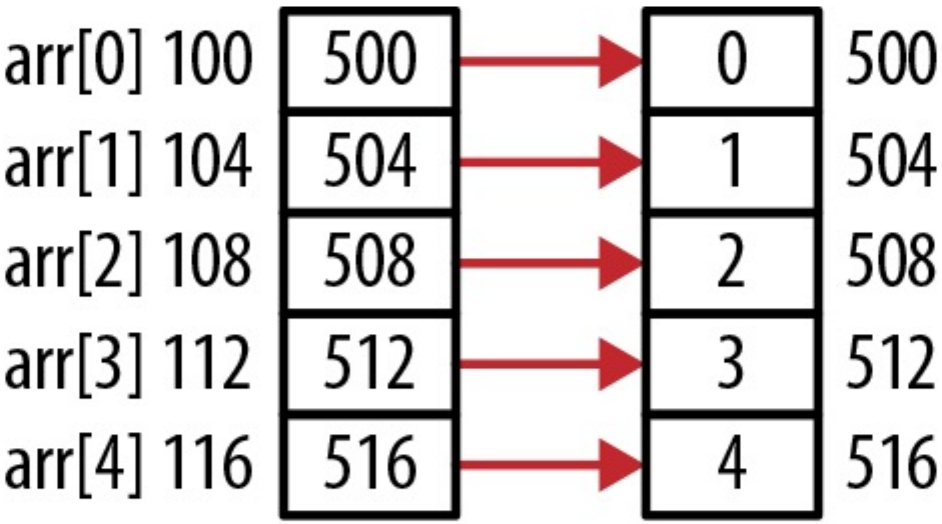
This program is only for help you understand pointer to pointer. It is not a good way to use pointers to pointer.

```
#include <stdio.h>
int main () {
    int  var = 1;
    int  *ptr = &var;
    int  **pptr = &var;

    printf("Value of var = %d\n", var );
    printf("Value available at *ptr = %d\n", *ptr);
    printf("Value available at *pptr = %lu\n", * ((int *)pptr));
    return 0;
}
```

```
Value of var = 1
Value available at *ptr = 1
Value available at *pptr = 1
```

Array of pointers

```c
#include <stdio.h>
int main () {
  int* arr[5];
  for(int i=0; i<5; i++) {
    arr[i] = (int*)malloc(sizeof(int));
    *arr[i] = i;
  }
  return 0;
}
```




```c
#include <stdio.h>
int main () {
  int* arr[5];
  for(int i=0; i<5; i++) {
    *(arr+i)=(int*)malloc(sizeof(int));
    **(arr+i)=i;
  }
  return 0;
}
```

What are these values?

*arr[0]

**arr

**(arr+1)

arr[0][0]

arr[3][0]

Multi-dimensional arrays

```c
#include <stdio.h>
int main () {
 int matrix[2][5] = {
          {1,2,3,4,5},
          {6,7,8,9,10}};

 for(int i=0; i<2; i++) {
   for(int j=0; j<5; j++) {
     printf("matrix[%d][%d] "
    "Address: %p Value: %d\n",
       i, j, &matrix[i][j],
           matrix[i][j]);
    }
  }
}
```

matrix[0][0]	100	1
matrix[0][1]	104	2
matrix[0][2]	108	3
matrix[0][3]	112	4
matrix[0][4]	116	5
matrix[1][0]	120	6
matrix[1][1]	124	7
matrix[1][2]	128	8
matrix[1][3]	132	9
matrix[1][4]	136	10

```
matrix[0][0] Address: 100 Value: 1
matrix[0][1] Address: 104 Value: 2
matrix[0][2] Address: 108 Value: 3
matrix[0][3] Address: 112 Value: 4
matrix[0][4] Address: 116 Value: 5
matrix[1][0] Address: 120 Value: 6
matrix[1][1] Address: 124 Value: 7
matrix[1][2] Address: 128 Value: 8
matrix[1][3] Address: 132 Value: 9
matrix[1][4] Address: 136 Value: 10
```

- Elements in a multi-dimensional array are saved contiguously in memory.
- Rows/columns must have the same number of elements
- Address of matrix[i][j]=starting address of matrix + i *size_of_row+j*size_of_element.

Let's explore how 2D and 3D arrays are saved in memory

```
$ cat ./array2d.c
#include <stdio.h>
#include <stdlib.h>

main(){
    int array[3][2], value=0, i, j;

    for( i = 0; i < 3; i++) {
        for ( j = 0; j < 2; j++){
            array[i][j] = value;
            value = value + 1;
        }
    }
    printf("Examine memory now.\n");
}
```

How are the elements in a 2D array saved in memory?

Let’s explore how 2D and 3D arrays are saved in memory

```
$ gcc -ggdb -o array2d ./array2d.c
$ gdb ./array2d
(gdb) list
(gdb) list
(gdb) break 14
(gdb) r
(gdb) x/8dw array
0x7fffffffe3f0: 0        1        2        3
0x7fffffffe400: 4        5        1713559808        143097460
```

Can you tell whether it is a 1D or 2D array?
1D: 0 1 2 3 4 5
2D: ((0 1 2) (3 4 5))

Questions:

- Since there is no difference in memory, can we use a 2D array as a 1D array in a program, or vise versa?
- Since there is no dimensional information (part of type info), how does a processor locate the proper elements based on indexes?

Data in 2D array used as that in a 1D array

```
$ cat ./array2d_to_1d.c
#include <stdio.h>
#include <stdlib.h>

main(){
    int array[3][2], value=0, i, j;
    int *p=(int *)array;

    for( i = 0; i < 3; i++) {
        for ( j = 0; j < 2; j++){
            array[i][j] = value;
            value = value + 1;
        }
    }

    for( i = 0; i < 6; i++)
        printf("%d ", p[i]);
    printf("\n");
}
```

This allows us to interpret the 2D data as 1D data. (int *) changes the type.

Prints out 0 1 2 3 4 5

Data in 2D array used as that in a 1D array

This allows us to interpret the 2D data as 1D data. (int *) changes the type.

Prints out 0 1 2 3 4 5

```
$ cat ./array2d_to_1d.c
#include <stdio.h>
#include <stdlib.h>

main(){
    int array[3][2], value=0, i, j;
    int *p=(int *)array;

    for( i = 0; i < 3; i++) {
        for ( j = 0; j < 2; j++){
            array[i][j] = value;
            value = value + 1;
        }
    }

    for( i = 0; i < 3; i++)
        for ( j = 0; j < 2; j++)
            printf("%d ", p[i*2+j]);
    printf("\n");
}
```

Your turn to explore how 3D arrays are saved in memory

```
#include <stdio.h>
#include <stdlib.h>

main(){
   int array[3][2][2], value=0, i, j,
k;

   for( i = 0; i < 3; i++) {
      for ( j = 0; j < 2; j++){
         for ( k = 0; k < 2; k++) {
            array[i][j][k] = value;
            value = value + 1;
         }
      }
   }
   printf("Examine memory now.\n");
}
```

Use gdb to show the location and contents of the 3D array in memory.

Modify the program and access the elements of the 3D array as accessing those in a 1D array.

Data in 3D array used as that in a 1D array

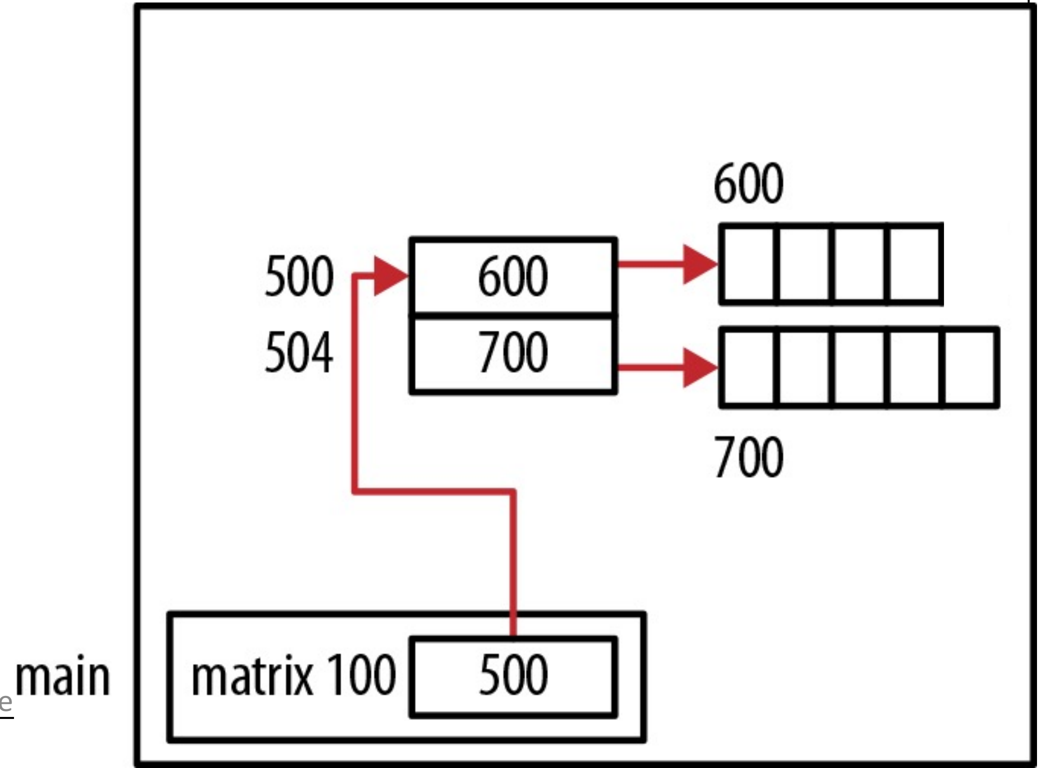
```
#include <stdio.h>
#include <stdlib.h>

main(){
   int array[3][2][2], value=0, i, j, k;
   int *p=(int *)array;

   for( i = 0; i < 3; i++) {
      for ( j = 0; j < 2; j++){
         for ( k = 0; k < 2; k++) {
            array[i][j][k] = value;
            value = value + 1;
         }
      }
   }
   for( i = 0; i < 12; i++)
      printf("%d ", p[i]);
   printf("\n");
   printf("Examine memory now.\n");
}
```

Dynamic multi-dimensional array

- Elements in a multi-dimensional array are saved contiguously in memory.
  - Rows and columns cannot be expanded dynamically.
- Rows/columns in a multi-dimensional array must have the same number of elements.
  - Array cannot be jagged
- What if we want to have more flexibility?
- Create dynamic multi-dimensional array using array of pointers.
  - Typical example is argv parameter of main().

Dynamic multi-dimensional array

```
#include <stdio.h>
int main () {
 int rows=2, min_columns=4, val=1;
 int **matrix = (int **) malloc(rows * sizeof(int *));
 for (int i = 0; i < rows; i++)
   matrix[i] = (int *) malloc((min_columns + i) * sizeof(int));

 for(int i=0; i<2; i++) {
   for(int j=0; j<4+i; j++) {
     matrix[i][j] = val++;
    }
 }
 free(matrix[0]);
 free(matrix[1]);
 free(matrix);
}
```

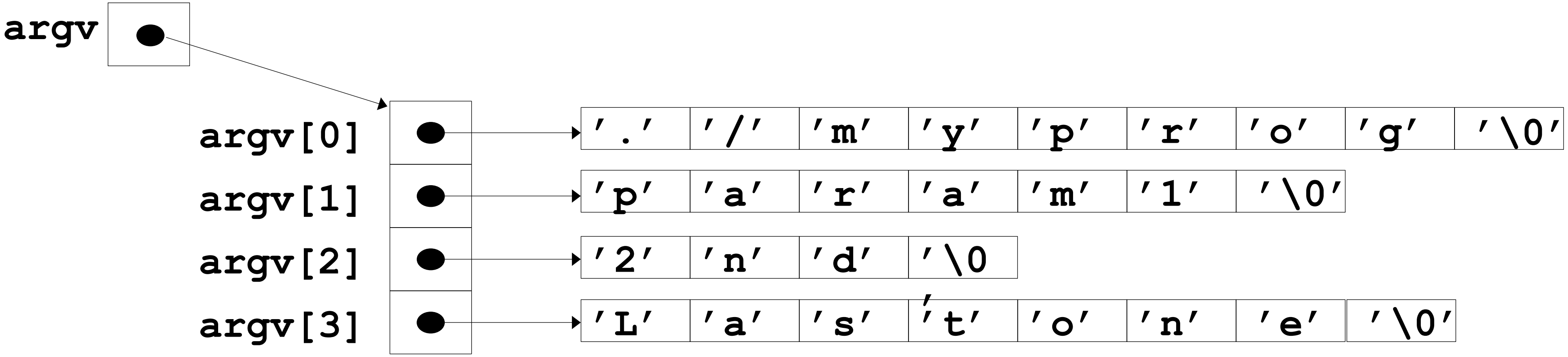


Processing arguments

```
int main(
  int argc,   // specifies # in argv[]
  char * argv[]);// list of parameters

int main(int argc, char **argv);
```

- for argv[], an ancillary data structure is provided: argc
- argc pointers pointing to argc strings, each of which is an argument

./myprog parameter1 2nd Lastone



An example: reverse-print command line args

```
// output all command line arguments in reverse order
#include <stdio.h>
#include <stdlib.h>

int main( int argc, char * argv[] ) {
    printf( "%d command line args passed.\n", argc );
    while( --argc > 0 ) { // pre-decrement skips argv[0]
      printf( "arg %d = \"%s\"\n", argc, argv[argc] );
    }
}
```

```
$ ./myprog 3 r 55 ""
5 command line args passed.
arg 4 = ""
arg 3 = "55"
arg 2 = "r"
arg 1 = "3"
```

Parsing command line arguments needs much more work (will introduce later).

What is argv[0]?

```c
#include <stdlib.h>
#include <stdio.h>

int main(int argc, char **argv){
  printf("mem. addr. of argc: %p\n", &argc);
  printf("mem. addr. of argv: %p\n", &argv);
  printf("mem. addr. of argv[0]: %p\n", argv);
  printf("mem. addr. in argv[0]: %p\n", argv[0]);
  printf("1st char %c in argv[0]:\n", argv[0][0]);
  return 0;
}
```

```
mem. addr. of argc: 0x7fff91892a0c
mem. addr. of argv: 0x7fff91892a00
mem. addr. of argv[0]: 0x7fff91892af8
mem. addr. in argv[0]: 0x7fff91893774
1st char . in argv[0]:
```

Check how arguments are saved in memory using gdb. Example gdb commands

```
break 10
run param1 param2 param3
x/8xg argv
x/64cb argv[0]
```

POSIX argument rules (IEEE Std 1003.1-2017 Chap 12)

- Followed by most Unix/Linux programs
  - http://pubs.opengroup.org/onlinepubs/9699919799/basedefs/V1_chap12.html
- General format:
  - utility_name [-a] [-b] [-c option_argument] [-d|-e] [-f [option_argument]] [operand...]
- Three types of arguments
  - Options; option arguments, operand
- Examples
  - ls -l -t -r
  - ls -ltr
  - head -n 5 /etc/passwd
  - rm -f ~/a.tmp
  - gcc -o myprog myprog.c

POSIX argument rules (IEEE Std 1003.1-2017 Chap 12)

- **options**: arguments that consist of '-' characters and single letters or digits
  - The character after '-' is an option character.
  - Every command/tool has a different set of options.
  - Options supported and their meanings are hard-coded in a program
  - The same option may have different meanings in different commands/tools.
    - e.g., -f may means “file", “force” in rm, or “fields” in cut
  - Several options can be combined and put in a single argument
    - e.g., `ls -l -t -r` is the same as `ls -ltr`
  - The order of different options relative to one another should not matter.
    - e.g., `ls -l -t -r` is the same as `ls -t -r -l`
- **Option arguments**: arguments shown separated from their options by <blank> characters
  - when an option-argument is enclosed in the '[' and ']' notation in command line description, it is optional
  - Some options have option arguments, and some do not have.
- **Operands**: arguments other than options and option arguments
  - The order of operands may matter and position-related interpretations should be determined by the program.

```c
/* Parsing command line */
#include <stdio.h>
int main(int argc, char *argv[])
{
    int arg;
    for(arg = 1; arg < argc; arg++) {
        if(argv[arg][0] == '-')
            printf("option: %s\n", argv[arg]+1);
        else
            printf("argument %d: %s\n", arg, argv[arg]);
    }
    exit(0);
}
```

```
%./args -i -lr  'hi there' -f fred.c
option: i
option: lr
argument 3: hi there
option: f
argument 5: fred.c
```

Not easy to extend when a program supports complex options.

Parsing command line arguments using `getopt()`

```
#include <unistd.h>
int getopt(int argc, char *const argv[], const char *optstring);
extern char *optarg;
extern int optind, opterr, optopt;
```

- The ***getopt*()** function parses the command line arguments.
  - Mainly used to process options and option arguments.
  - Need to be called repeated.
    - Return one option each time called. ***Optarg*** points to the corresponding option argument
- ***optstring*** is a string summarizing the legitimate option characters.
  - If an option character is followed by a colon, the option requires an option argument.
  - ":" being first character has special meaning (next page).
- External variable, ***optind*** is set to the index of the next argument to be process.
- ***operands***
  - arguments in *argv[]* are permuted with all operands are moved to the end, starting at ***argv[optind]***.

Parsing command line arguments using `getopt()`

Possible getopt() return values

- ***-1*** for the end of the option list
- A positive value: **the value is the ASCII code of a character**, which may be
  - ***An option character*** in optstring when the option is found successfully, and
    - the option does not need an option argument, or
    - the option needs an option argument, and the option argument is found
      - ***optarg*** saves the actual option argument
  - *'**?**'* for an unknown option character, ***optopt*** stores the actual option
  - *'**?**'* when option argument is missing for an option and first character in optstring is NOT *'**:**'*
  - *'**:**'* when option argument is missing for an option and first character in optstring is *'**:**'*
- getopt() stops scanning when it sees long options started with "--" (e.g., ls --all).
  - use getopt_long() to process long options.

```c
#include <stdio.h>
#include <unistd.h>

int main(int argc, char *argv[])
{
  int opt;
  while((opt=getopt(argc,argv,“:if:lr"))!=-1){
    switch(opt) {
      case 'i':
      case 'l':
      case 'r':
        printf("option: %c\n", opt); break;
      case 'f':
        printf("filename: %s\n", optarg); break;
      case ':':
        printf("option %c needs a value\n", optopt); break;
      case '?':
        printf("unknown option: %c\n", optopt); break;
    }
  }
  for(; optind < argc; optind++)
    printf("argument: %s\n", argv[optind]);
  exit(0);
}
```

```
%./arg -i -lr 'hi there' -f fred.c -q
option: i
option: l
option: r
filename: fred.c
unknown option: q
argument: hi there
```

```
%./arg -i -lr 'hi there' -f
option: i
option: l
option: r
option f needs a value
argument: hi there
```

```
%./arg -i 'hi there' -f -q
option: i
filename: -q
argument: hi there
```

Processing environmental variables

```
int main( int argc,  char * argv[],
  char * envp[])// all environment vars
{ // main
  . . .
} //end main
```

- envp: a set of pointers, each of which points to a string.
- NULL marks the end of the list

Printing out environment variables

```
#include <stdio.h>
#include <stdlib.h>

int main( int argc, char ** argv, char * envp[] )
{
  int index = 0;

  while(envp[index]){
    printf("envp[%d] = \"%s\"\n", index, envp[index]);
    index++;
  }
  printf("Number of environment vars = %d\n", index );
  exit( 0 );
}
```

Sample output

```
envp[0] = "LS_COLORS=rs=0 …"
envp[1] = "SSH_CONNECTION=…"
envp[2] = "LESSCLOSE=/usr/bin/lesspipe %s %s"
envp[3] = "LANG=en_US.UTF-8"
envp[4] = "XDG_SESSION_ID=4120"
envp[5] = "USER=ubuntu"
envp[6] = "PWD=/tmp"
envp[7] = "HOME=/home/ubuntu"
…
envp[20] = "OLDPWD=/bin"
Number of environment vars = 21
```

Library functions for handling env variables

- get an environment variable
  - char *getenv(const char *name);
- change or add an environment variable
  - int setenv(const char *name, const char *value, int overwrite);
- delete an environment variable
  - int unsetenv(const char *name);

```
#include <stdio.h>
#include <stdlib.h>

int main() {
    printf("HOME = %s\n", getenv("HOME"));
}
```