The Standard C Library

Slides by Wu Chang Feng

The Standard C Library

Common functions we don't need to write ourselves

- Provides a portable interface to many system calls

Analogous to class libraries in Java or C++

Function prototypes declared in standard header files

```
#include <stdio.h>    #include <stddef.h>
#include <time.h>     #include <math.h>
#include <string.h>   #include <stdarg.h>
#include <stdlib.h>
```

- Must include the appropriate ".h" in source code
  - "man 3 printf" on linuxlab shows which header file to include
- K&R Appendix B lists all functions

Code linked in automatically

- At compile time (if statically linked)
- At run time (if dynamically linked)

The Standard C Library

Examples (for this class)

- I/O
  - `printf, scanf, puts, gets, open, close, read, write`
  - `fprintf, fscanf, … , fseek`
- Memory operations
  - `memcpy, memcmp, memset, malloc, free`
- String operations
  - `strlen, strncpy, strncat, strncmp`

The Standard C Library

Examples for you to "man"

- **Utility functions**
  - `rand, srand, exit, system, getenv`
- **Time**
  - `clock, time, gettimeofday`
- **Processes**
  - `fork, execve`
- **Signals**
  - `signal, raise, wait, waitpid`
- **Implementation-defined constants**
  - `INT_MAX, INT_MIN, DBL_MAX, DBL_MIN`

I/O

Formatted output

- `int printf(char *format, …)`
  - Sends output to standard output
- `int fprintf(FILE *stream, const char *format, ...);`
  - Sends output to a file
- `int sprintf(char *str, char *format, …)`
  - Sends output to a string variable
- Return value
  - Number of characters printed (not including trailing \0)
  - On error, a negative value is returned

I/O

Formatted input

- `int scanf(char *format, …)`
  - Read formatted input from standard input
- `int fscanf(FILE *stream, const char *format, ...);`
  - Read formatted input from a file
- `int sscanf(char *str, char *format, …)`
  - Read formatted input from a string
- Return value
  - Number of input items assigned
- Note
  - Requires pointer arguments

I/O

Format string composed of characters (except '%')

- Copied unchanged into the output

Format directives specifications (start with %)

- Character (%c)
- String (%s)
- Integer (%d)
- Long (%ld)
- Float/Double (%f)
- Fetches one or more arguments

For more details: `man 3 printf`

Example

```
#include <stdio.h>

int main()
{
  int x;
  scanf("%d\n", &x);
  printf("%d\n", x);
}
```

Note: Pointer given to scanf to assign value to x in program

I/O

```
#include <stdio.h>
#include <stdlib.h>
int main()
{
        int a, b, c;
        printf("Enter the first value: ");
        if (scanf("%d",&a) == 0) {
            perror("Input error\n");
            exit(255);
        }
        printf("Enter the second value: ");
        if (scanf("%d",&b) == 0) {
            perror("Input error\n");
            exit(255);
        }
        c = a + b;
        printf("%d + %d = %d\n", a, b, c);
     return 0;
    }

    OUTPUT
    mashimaro 2:25PM % ./scanf
    Enter the first value: 20
    Enter the second value: 30
    20 + 30 = 50
```

Format specifiers

Formatting commands for padding/truncating, precision, justification

Useful `printf`

- "%10s" Pad string or truncate string to 10 characters
- "%5.2f" Use at least 5 characters, but only 2 past decimal

Useful `scanf`

- "%10s" Accept no more than 10 characters

For more details:

```
man 3 printf
man 3 scanf
```

Why do format specifiers matter?

```
#include <stdio.h>

int main()
{
  long is_administrator = 0;
  char password[9];
  scanf("%s", password);
}
```

```
#include <stdio.h>

int main()
{
  long is_administrator = 0;
  char password[9];
  scanf("%8s", password);
}
```

Allocating memory for I/O

What happens here?

```
#include <stdio.h>

int main()
{
  char *cp;
  scanf("%s\n", cp);
}
```

Must ensure memory has been allocated

```
#include <stdio.h>

int main()
{
  char cp[50];
  scanf("%49s\n", cp);
}
```

I/O

Direct system call interface for non-formatted data (eg. raw binary data)

- `open()` = returns an integer file descriptor
- `read()`, `write()` = takes file descriptor as parameter
- `close()` = closes file and file descriptor

Standard file descriptors for each process

- Standard input (keyboard)
  - `stdin or 0`
- Standard output (display)
  - `stdout or 1`
- Standard error (display)
  - `stderr or 2`

I/O

Using standard file descriptors in shell

- Redirecting to/from files
  - Redirect stdout to a file: `ls -l > outfile`
  - Take stdin from a file: `./a.out < infile`
  - Redirect stdout and stderr to different files

```
% ls
x   y
% ls -l x does_not_exist > outfile 2> errorfile
% cat outfile
-rw------- 1 wuchang wuchang 53 Oct  1 14:51 x
% cat errorfile
ls: cannot access does_not_exist: No such file or directory
```

- Connecting stdout from one command into stdin of another via Unix pipes
  - `ls -l | egrep tar`
    - » standard output of "`ls`" sent to standard input of "`egrep`"

I/O via file interface

Supports formatted, line-based and direct I/O

- Calls similar to analogous calls previously covered

Opening a file

- `FILE *fopen(char *name, char *mode);`
  - Opens a file if we have access permission
  - Returns a pointer to a file
  - `FILE *fp;`

```
fp = fopen("/tmp/x", "r");
```

Once the file is opened, we can read/write to it

- `fscanf, fread, fgets, fprintf, fwrite, fputs`
- Must supply `FILE*` argument for each call

Closing a file after use

- `int fclose(fp);`
  - Closes the file pointer and flushes any output associated with it

I/O via file interface

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

main(int argc, char** argv)
{
  int i;
  char *p;
  FILE *fp;

  fp = fopen("tmpfile.txt","w+");
  p = argv[1];
  fwrite(p, strlen(p), 1, fp);
  fclose(fp);
  return 0;
}
```

```
OUTPUT:
mashimaro <class/03>  2:31PM % ./fops HELLO
mashimaro <class/03>  2:31PM % cat tmpfile.txt
HELLO
mashimaro <class/03>  2:32PM %
```

Memory allocation and management

malloc

- Dynamically allocates memory from the heap at run-time
  - Memory persists between function invocations (unlike local variables)
- Returns a pointer to a block of at least `size` bytes – not zero filled!
  - Allocate an integer

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

  - Allocate a structure
  -

```
struct name* nameptr = (struct name*)
malloc(sizeof(struct name));
```

  - Allocate an integer array with “value” elements

```
int *ptr = (int *) malloc(value * sizeof(int));
```

Memory allocation and management

Be careful to allocate enough memory in malloc

- Overrun on the space is undefined
- Common error

```
char *cp = (char *) malloc(strlen(buf)*sizeof(char))
```

  - `strlen` doesn't account for the NULL terminator

- Fix:

```
char *cp = (char *) malloc((strlen(buf)+1)*sizeof(char))
```

Memory allocation and management

Memory no longer needed must be explicitly deallocated

- Failure to do so leads to memory leaks

free

- Deallocates memory in heap.
- Pass in a pointer that was returned by `malloc`.
- Integer example

```
int* iptr = (int*) malloc(sizeof(int));
free(iptr);
```

- Structure example

```
struct table* tp = (struct table*)malloc(sizeof(struct table));
free(tp);
```

Common security exploits involving the heap

- Freeing the same memory block twice corrupts memory
- Overflowing malloc'd data to corrupting heap data structures

Memory allocation and management

Sometimes, before you use memory returned by malloc, you want to zero it

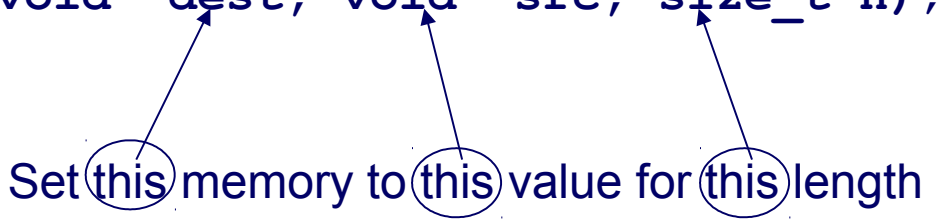
- **Or maybe set it to a specific value**

`memset()` sets a chunk of memory to a specific value

```
void *memset(void *s, int c, size_t n);
```

Copying and moving memory

```
void *memcpy(void *dest, void *src, size_t n);
void *memmove(void *dest, void *src, size_t n);
```



Strings

String functions are provided in an ANSI standard string library.

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

- **Includes functions such as:**
  - **Computing length of string**
  - **Copying strings**
  - **Concatenating strings**

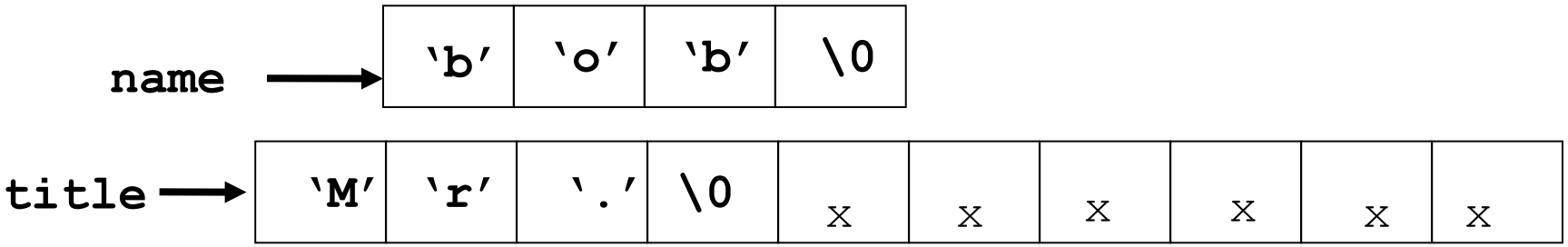
Strings

In C, a string is an array of characters terminated with the "null" character ('\0', value = 0)

Can declare as an array whose values can be modified.

- **Examples**

```
char name[4] = "bob";
char title[10] = "Mr.";
```

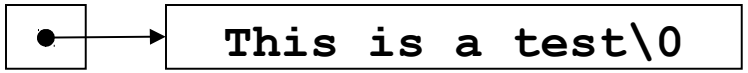


- **Symbols "name" and "title" can not be reassigned like pointers**

Strings

Can declare a pointer and have it point to a string constant

```
char *p = "This is a test";
```



- Sets p to address of a character array stored in memory elsewhere
- Value of pointer p can be reassigned to another address, but characters in string constant can not be changed

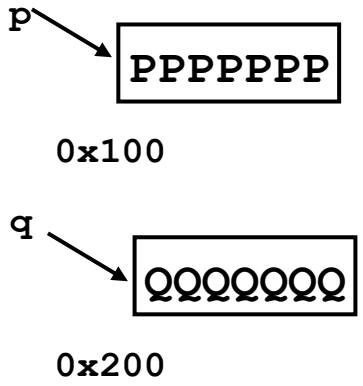
Copying strings

Consider

```
char* p="PPPPPPP";
char* q="QQQQQQQ";
p = q;
```

What does this do?

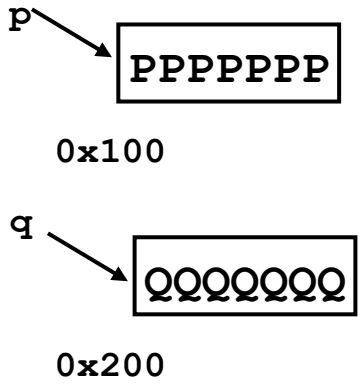
1. Copy QQQQQQ into 0x100? NO
2. Set p to 0x200



Copying strings

Consider

```
char* p="PPPPPPP";
char* q="QQQQQQ";
p = q;
```

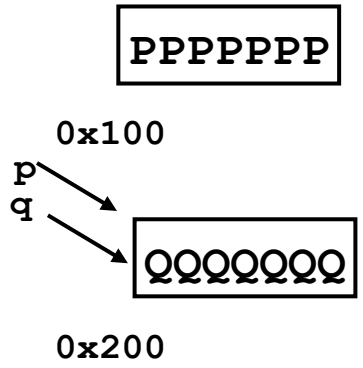


What does this do?

1. Copy QQQQQQ into 0x100?
2. Set p to 0x200

Copying strings

3. Must manually copy characters
4. Or use `strncpy` to copy characters



Strings

Assignment(=) and equality (==) operators

```
char *p;
char *q;
if (p == q) {
   printf("This is only true if p and q point to the
   same address");
}
p = q; /* The address contained in q is placed */
          /*    in p.  Does not change the memory */
          /*    locations p previously pointed to.*/
```

C String Library

Some of C's string functions

`strlen(char *s1)`

- Returns the number of characters in the string, not including the “null” character

`strncpy(char *s1, char *s2, int n)`

- Copies at most n characters of s2 on top of s1. The order of the parameters mimics the assignment operator

`strncmp (char *s1, char *s2, int n)`

- Compares up to n characters of s1 with s2
- Returns < 0, 0, > 0 if s1 < s2, s1 == s2 or s1 > s2 lexigraphically

`strncat(char *s1, char *s2, int n)`

- Appends at most n characters of s2 to s1

Insecure deprecated versions: strcpy, strcmp, strcat

strncpy and null termination

strncpy does not guarantee null termination

- Intended to allow copying of characters into the middle of other strings
- Use `snprintf` to guarantee null termination
- Example
-

```
#include <string.h>
#include <stdio.h>
  main()  {
     char a[20]="The quick brown fox";
     char b[9]="01234567";
     strncpy(a,b,strlen(b));
     printf("%s\n",a);
   }
```

```
mashimaro <~> 10:33AM % ./a.out
01234567k brown fox
```

Other string functions

Converting strings to long integer

```
#include <stdlib.h>
long strtol (char *ptr, char **endptr, int base);
```

Takes a character string and converts it to an integer.

- White space and + or - are OK.
- Starts at beginning of ptr and continues until something non-convertible is encountered.
- endptr (if not null, gives location of where parsing stopped)

Some examples:

String	Value returned
"157"	157
"-1.6"	-1
"+50x"	50
"twelve"	0

Other string functions

```
#include <stdlib.h>
double strtod (char * str, char **endptr)
```

- String to floating point
- Handles digits 0-9.
- A decimal point.
- An exponent indicator (e or E).
- If no characters are convertible a 0 is returned.

Examples:

String	*Value returned*
"12"	12.000000
"-0.123"	-0.123000
"123E+3"	123000.000000
"123.1e-5"	0.001231

Examples

```
/* strtol Converts an ASCII string to its integer
equivalent; for example, converts “-23.5” to the value
-23. */

   int my_value;
   char my_string[] = "-23.5“;
   my_value = strtol(my_string, NULL, 10);
   printf("%d\n", my_value);

/* strtod Converts an ASCII string to its floating-point
   equivalent; for example, converts “+1776.23” to the
   value 1776.23. */

   double my_value;
   char my_string[] = "+1776.23“;
   my_value = strtod(my_string, NULL);
   printf("%f\n", my_value);
```

Random number generation

Generate pseudo-random numbers

- `int rand(void);`
  - Gets next random number
- `void srand(unsigned int seed);`
  - Sets seed for PRNG
- man 3 rand

Random number generation

```
#include <stdio.h>
#include <stdlib.h>
int main(int argc, char** argv) {
  int i,seed;

  sscanf(argv[1],”%d”,&seed);
  srand(seed);
  for (i=0; i < 10; i++)
        printf("%d : %d\n", i , rand());
}
```

```
OUTPUT:
mashimaro 2:41PM % ./myrand 30
0 : 493850533
1 : 1867792571
2 : 1191308030
3 : 1240413721
4 : 2134708252
5 : 1278462954
6 : 1717909034
7 : 1758326472
8 : 1352639282
9 : 1081373099
mashimaro 2:41PM %
```

Make

Makefiles

Recipe for compiling and running your code

Call it Makefile (big M) so that it sorts to the top

- The “make” utility will use that by default
- You only have to specify the name if it’s called something other than Makefile or makefile

The first rule in the Makefile is used by default if you just say “make” with no arguments

The second line of each rule (the command) must start with a tab, not spaces!

A simple Makefile

```
sd:  sd.c
   cc –Wall -g -o sd sd.c
```

What target depends on

Target to build

Command to run to build target when file target depends upon changes

A little more complex

```
  all: sd test1 t1check test2

sd:  sd.c
   cc -g -o sd sd.c

test1:  test1.c
   cc -o test1 test1.c

test2:  test2.c
   cc -o test2 test2.c

t1check:  t1check.c
   cc -o t1check t1check.c

clean:
   rm sd test1 t1check test2
```

Sub-targets to build

Command always runs when target is clean

A slightly more complex makefile

```
   CC = gcc
CFLAGS = -Wall -O2
LIBS = -lm
OBJS = driver.o kernels.o fcyc.o clock.o

all: driver

driver: $(OBJS) config.h defs.h fcyc.h
    $(CC) $(CFLAGS) $(OBJS) $(LIBS) -o driver

driver.o: driver.c defs.h

kernels.o: kernels.c  defs.h

fcyc.o: fcyc.c fcyc.h

clock.o: clock.c
```

Simple definitions

Use default rule to build

GDB debugger

gdb

Some might say “our best friend”

To compile a program for use with gdb, use the ‘-g’ compiler switch

- Most debuggers provide the same functionality

Other graphical options on MCECS Linux systems

- gdb -tui
  - http://beej.us/guide/bggdb/
- DDD: http://www.gnu.org/software/ddd/
- Eclipse

Controlling program execution

run

- Starts the program

step

- Execute until a different source line reached (step into calls)

next

- Execute until next source line reached, proceeding through subroutine calls.

continue

- Resume program execution until signal or breakpoint.

Controlling program execution

break, del

- Set and delete breakpoints at particular lines of code

watch, rwatch, awatch

- Data breakpoints
- Stop when the value of an expression changes (watch), when expression is read (rwatch), or either (awatch)

Displaying data

print

- Print expression
- Basic
  - print argc
  - print argv[0]
  - print $rsp
- print /x addr
  - '/x' says to print in hex. See "help x" for more formats
  - Same as examine memory address command (x)
- printf "format string" arg-list
  - (gdb) printf "%s\n", argv[0]

x (examine)

- Examine memory
  - x /s $rax => print the string at address contained in %rax
  - x /32xw 0x4006b7 => print 32 words at 0x4006b7 in hexadecimal

Displaying code

list

- **Display source code (useful for setting breakpoints)**
- **Requires -g**

disassemble <fn>

- **Disassemble C function fn**

Other Useful Commands

where, backtrace

- Produces a backtrace - the chain of function calls that brought the program to its current place.

up, down

- Change scope in stack

info

- Get information
- ‘info’ alone prints a list of info commands
- ‘info br’ : a table of all breakpoints and watchpoints
- ‘info reg’ : the machine registers

quit

- Exit the debugger

gdb tui

layout <cmd>

- split (creates a split screen with multiple panes)
- asm (loads assembly up in a pane)
- regs (loads registers up in a pane)

focus <pane>

- Puts focus onto a particular pane (cmd, asm, regs)

Example Program

```
1     #include <stdio.h>
2     void sub(int i)
3     {
4           char here[900];
5           sprintf((char *)here,"Function %s in %s", __FUNCTION__ ,__FILE__);
6           printf("%s @ line %d\n", here, __LINE__);
7     }
8
9     void sub2(int j)
10     { printf("%d\n",j); }
11
12     int main(int argc, char** argv)
13     {
14          int x;
15          x = 30;
16          sub2(x);
17          x = 90;
18          sub2(x);
19          sub(3);
20          printf("%s %d\n",argv[0],argc);
21          return(0);
22     }
```

Walkthrough example

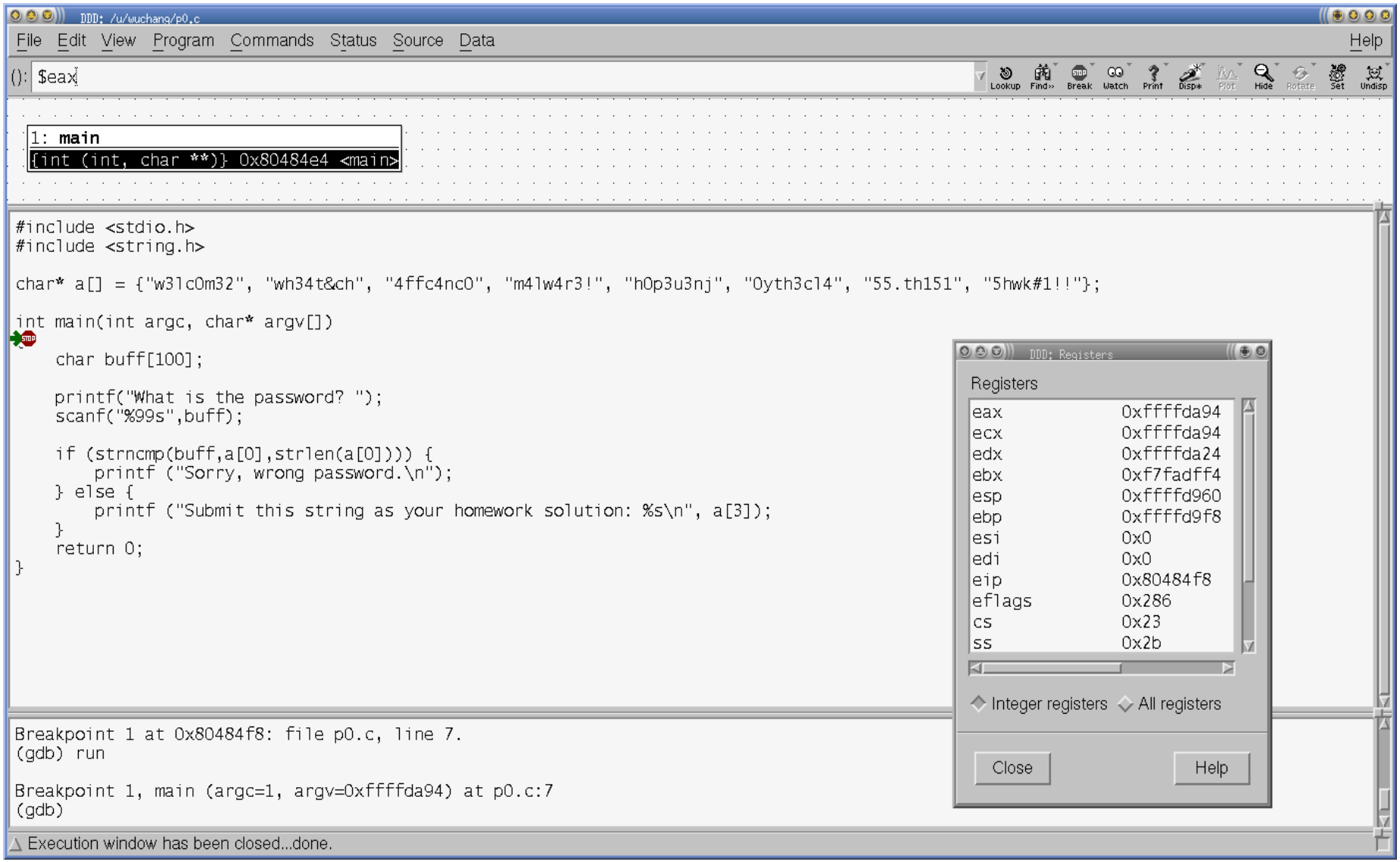
% gcc –g –o gdb_ex gdb_ex.c
% gdb –tui gdb_ex
(gdb) **set args a b c d** set program arguments
(gdb) **list 1,22** list source file
(gdb) **break 14** break at source line at program start
(gdb) **break sub** subroutine break
(gdb) **break 6**
(gdb) **run** start program (breaks at line 14)
(gdb) **p argv** hex address of argv (char**)
(gdb) **p argv[0]** prints “gdb_ex”
(gdb) **p argv[1]** prints “a”
(gdb) **p strlen(argv[1])** prints 1
(gdb) **p argc** prints 5
(gdb) **p /x argc** prints 0x5
(gdb) **p x** uninitialized variable
(gdb) **n** go to next line
(gdb) **p x** x now 30
(gdb) **p /x &x** print address of x
(gdb) **x/w &x** print contents at address of x

Walkthrough example

(gdb) **n**	go to next line (execute entire call)
(gdb) **s**	go to next source instr
(gdb) **s**	go to next source instr (follow call)
(gdb) **continue**	go until next breakpoint
(gdb) **where**	list stack trace
(gdb) **p x**	x no longer scoped
(gdb) **up**	change scope
(gdb) **p x**	x in scope, prints 90
(gdb) **del 3**	delete breakpoint
(gdb) **continue**	finish

(gdb) **info br**	get breakpoints
(gdb) **del 1**	delete breakpoint
(gdb) **break main**	breakpoint main
(gdb) **run**	start program
(gdb) **watch x**	set a data write watchpoint
(gdb) **c**	watchpoint triggered

DDD


DDD: /u/wuchang/p0.c
File Edit View Program Commands Status Source Data Help
(): $eax
Lookup Find» Break Watch Print Disp* Plot Hide Rotate Set Undisp
1: main
{int (int, char **)} 0x80484e4 <main>
#include <stdio.h>
#include <string.h>
char* a[] = {"w3lcOm32", "wh34t&ch", "4ffc4ncO", "m4lw4r3!", "hOp3u3nj", "Oyth3cl4", "55.th151", "5hwk#1!!"};
int main(int argc, char* argv[])
{
char buff[100];
printf("What is the password? ");
scanf("%99s",buff);
if (strncmp(buff,a[0],strlen(a[0]))) {
printf ("Sorry, wrong password.\n");
} else {
printf ("Submit this string as your homework solution: %s\n", a[3]);
}
return 0;
}
DDD: Registers
Registers
eax 0xffffda94
ecx 0xffffda94
edx 0xffffda24
ebx 0xf7fadff4
esp 0xffffd960
ebp 0xffffd9f8
esi 0x0
edi 0x0
eip 0x80484f8
eflags 0x286
cs 0x23
ss 0x2b
Integer registers All registers
Close Help
Breakpoint 1 at 0x80484f8: file p0.c, line 7.
(gdb) run
Breakpoint 1, main (argc=1, argv=0xffffda94) at p0.c:7
(gdb)
Execution window has been closed...done.

Extra

Error handling

Standard error (`stderr`)

- Used by programs to signal error conditions
- By default, `stderr` is sent to display
- Must redirect explicitly even if `stdout` sent to file

```
fprintf(stderr, "getline: error on input\n");
perror("getline: error on input");
```

- Typically used in conjunction with `errno` return error code
  - `errno` = single global variable in all C programs
  - Integer that specifies the type of error
  - Each call has its own mappings of `errno` to cause
  - Used with `perror` to signal which error occurred

Example

```
#include <stdio.h>
#include <fcntl.h>
#define BUFSIZE 16
int main(int argc, char* argv[]) {
        int f1,n;
        char buf[BUFSIZE];
        long int f2;

        if ((f1 = open(argv[1], O_RDONLY, 0)) == -1)
            perror("cp: can't open file");
        do {
          if ((n=read(f1,buf,BUFSIZE)) > 0)
            if (write(1, buf, n) != n)
                perror("cp: write error to stdout");
        } while(n==BUFSIZE);
        return 0;
}
```

```
mashimaro <~>  2:01PM % cat opentest.txt
This is a test of CS 201
and the open(), read(),
and write() calls.
mashimaro <~>  2:01PM % ./opentest opentest.txt
This is a test of CS 201
and the open(), read(),
and write() calls.
mashimaro <~>  2:01PM % ./opentest asdfasdf
cp: can't open file: No such file or directory
mashimaro <~>  2:01PM %
```

Strings

Static arrays

- **Similar to character arrays**

char amsg[ ] = “This is a test”; → This is a test\0

- **Symbol amsg points to a fixed location in memory**
- **Can change characters in string (amsg[3] = 'x';)**
- **Can not reassign amsg to point elsewhere (i.e. amsg = p)**