The Standard C Library

The C Standard 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 gcc -static)
- At run time (if dynamically linked)
  - Use "ldd" command to list dependencies
- Use "file" command to determine binary type

The C Standard Library

Examples (for this class)

- I/O stdio.h
  - `printf, scanf, puts, gets, open, close, read, write`
  - `fprintf, fscanf, … , fseek`
- Memory and string operations string.h
  - `memcpy, memcmp, memset`
  - `strlen, strncpy, strncat, strncmp`
  - `strtod, strtol, strtoul`
- Character Testing ctype.h
  - `isalpha, isdigit, isupper, …`
  - `tolower, toupper`
- Argument Processing stdarg.h
  - `va_list, va_start, va_arg, va_end`

The C Standard Library

Examples

- Utility functions stdlib.h
  - `rand, srand, exit, system, getenv, malloc, free, atoi…`
- Time time.h
  - `clock, time, gettimeofday`
- Jumps setjmp.h
  - `setjmp, longjmp`
- Processes
  - `fork, execve`
- Signals signals.h
  - `signal, raise, wait, waitpid`
- Implementation-defined constants limits.h, float.h
  - `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

Format string composed of ordinary characters (except '%')

- **Copied unchanged into the output**

Format directives specifications (start with %)

- **Character (%c), String (%s), Integer (%d), Float (%f)**
- **Formatting commands for padding or truncating output and for left/right justification**
  - **%10s => Pad short string to 10 characters, right justified**
  - **%-10s => Pad short string to 10 characters, left justified**
  - **%.10s => Truncate long strings after 10 characters**
  - **%10.15 => Pad to 10, but truncate after 15, right justified**
- **Fetches one or more arguments**

For more details: `man 3 printf`

I/O

```
#include <stdio.h>

int main() {
  char *p;
  char *q;
  float f;

  p = "This is a test";
  q = "This is a test";
  f = 909.2153258;

  printf(":%10.15s:\n", p); /* right justified, truncate to 15, pad to 10 */
  printf(":%15.10s:\n", q); /* right justified, truncate to 10, pad to 15 */
  printf(":%0.2f:\n", f);   /* Cut off anything after 2nd decimal, No pad */
  printf(":%15.5f:\n", f);  /* Cut off anything after 5th decimal, Pad to 15 */

  return 0;
}
```

OUTPUT:

```
% test_printf_example
:This is a test:
:     This is a :
:909.22:
:      909.21533:
%
```

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

Example: scanf

```
#include <stdio.h>

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

Q: Why are pointers given to scanf?

A: We need to assign the value to x.

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:

```
% test_scanf_example
Enter the first value: 20
Enter the second value: 30
20 + 30 = 50
%
```

I/O

Line-based input

- `char *gets(char *s);`
  - Reads the next input line from `stdin` into buffer pointed to by `s`
  - Null terminates

Line-based output

- `int puts(char *line);`
  - Outputs string pointed to by `line` followed by newline character to `stdout`

I/O

Direct system call interface

- `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`

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;
}
```

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

I/O

Using standard file descriptors in shell

- **Redirecting to/from files**
  - **`ls -l > outfile`**
    - » redirects output to "`outfile`"
  - **`./a.out < infile`**
    - » standard input taken from "`infile`"
  - **`ls -l > outfile 2> errorfile`**
    - » `sends standard error and standard out to separate files`
- **Connecting them to each other 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:

```
% test_file_ops HELLO
% cat tmpfile.txt
HELLO
%
```

Memory allocation and management

malloc

- Dynamically allocates memory from the heap
  - 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));
```

Be careful to allocate enough memory

- 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

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);
```

Freeing the same memory block twice corrupts memory and leads to exploits

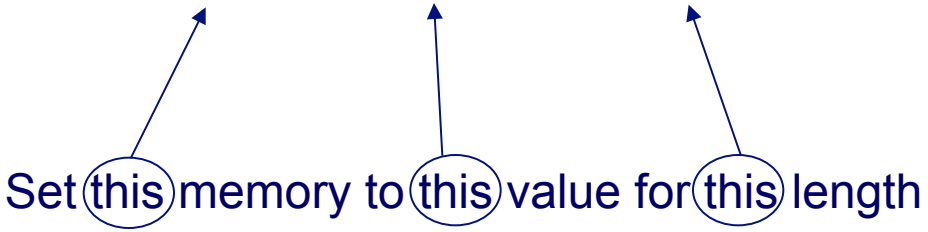
Memory allocation and management

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);`



Memory allocation and management

Because not all data consists of text strings…

```
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>
```

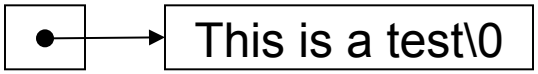
- **Includes functions such as:**
  - **Computing length of string**
  - **Copying strings**
  - **Concatenating strings**

Strings

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

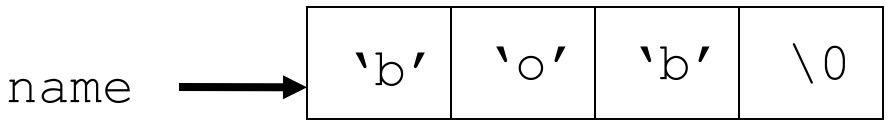
- **Character pointer p**
  - **Sets p to address of a character array**
  - **p can be reassigned to another address**

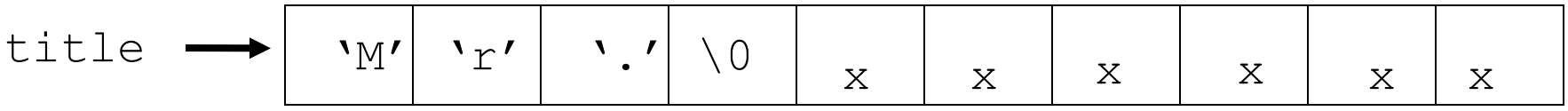
char *p = "This is a test";



- **Examples**

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

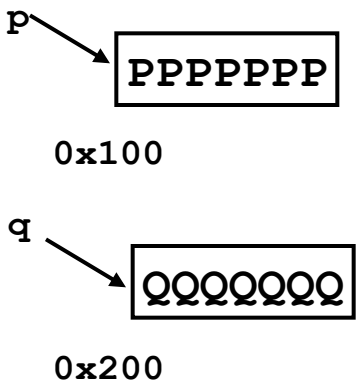




Copying strings

Consider

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



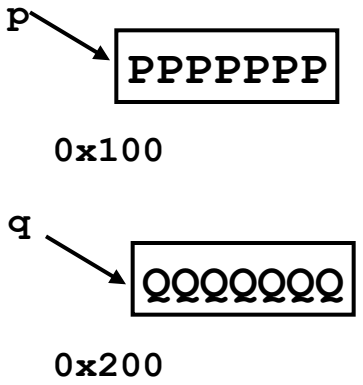
What does this do?

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

Copying strings

Consider

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

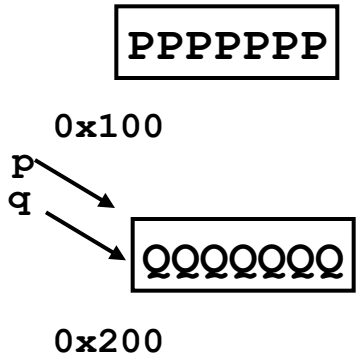


What does this do?

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

Copying strings

1. Must manually copy characters
2. 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

String code example

```
#include <stdio.h>
#include <string.h>
int main() {
     char first[10] = "bobby ";
     char last[15] = "smith";
     char name[30];
     char you[5] = "bobo";

     strncpy ( name, first, strlen(first)+1 );
     strncat ( name, last, strlen(last)+1);
     printf ("%d, %s\n", strlen(name), name );
     printf ("%d \n", strncmp(you, first, 3));

}
```

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>
main()  {
     char a[20]="The quick brown fox";
     char b[9]="01234567";
     strncpy (a, b, 8);
     printf ("%s\n", a);
}
```

```
% ./a.out
01234567k brown fox
```

Other string functions

Converting strings to numbers

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

Takes a character string and converts it to a (long) 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 due to error)

Some examples:

String	Value returned
"157"	157
"-1.6"	-1
"+50x"	50
"twelve"	0
"x506"	0

Other string functions

```
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>

int main(int argc, char** argv) {
  int i,seed;

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

OUTPUT:

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

Makefiles

Recipe for compiling and running your code

Call it makefile or Makefile (big or little M)

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

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
```

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
```

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
```

How to make a tar file

```
mkdir john

cp *.c *.h Makefile john

tar cvf john.tar john
```

How to extract the tar file:

```
tar xvf john.tar
```

GDB debugger

gdb is Our Friend

Some might say “our best friend”

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

Better graphical interfaces

- Most debuggers provide the same functionality
- gdb -tui
  - layout split, layout regs
- Insight: http://sourceware.org/insight/
- DDD: http://www.gnu.org/software/ddd/
- TDB: http://pdqi.com/browsex/TDB.html
- KDbg: http://www.kdbg.org/

Controlling program execution

run

- Starts the program

step

- Step program until it reaches a different source line.

next

- Step program, proceeding through subroutine calls.
- Single step to the next source line, not into the call.

continue

- Continue program execution after 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)

Printing out code and data

print

- Print expression
- Basic
  - print argc
  - print argv[0]
- print {type} addr
  - (gdb) p {char *} 0xbfffdce4
- 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]

list

- Display source code (useful for setting breakpoints)

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

Example Program

```
1     #include <stdio.h>
2
3     void sub(int i) {
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
13    int main(int argc, char** argv)
14    {
15          int x;
16          x = 30;
17          sub2 (x);
18          x = 90;
19          sub2 (x);
20          sub (3);
21          printf ("%s %d\n", argv[0], argc);
22          return (0);
23    }
```

http://cs.pdx.edu/~harry/cs201/gdb_example.c

Walkthrough example

% **gcc –g –o gdb_example gdb_example.c**
% **gdb gdb_example**

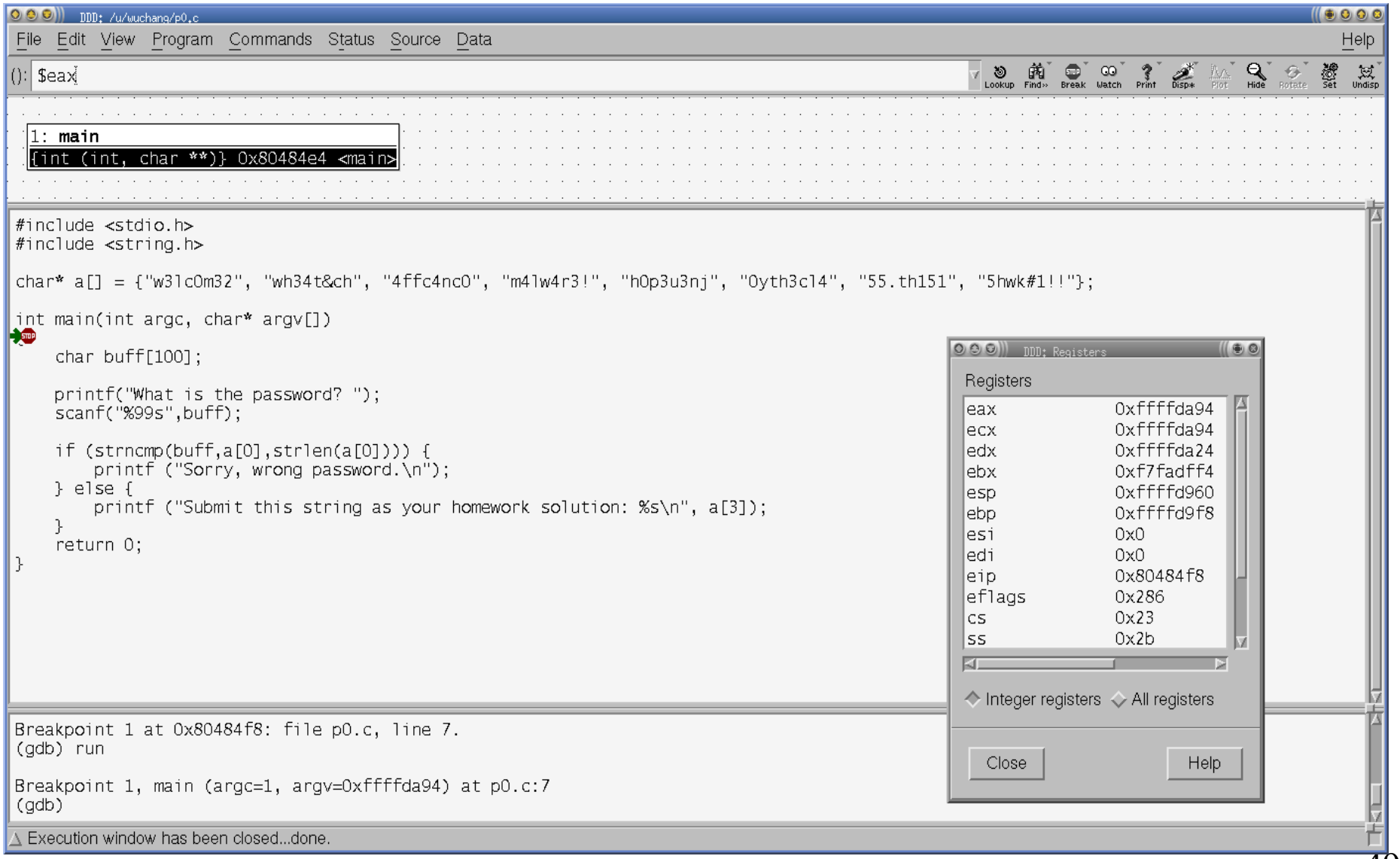
(gdb) **set args a b c d**	set program arguments
(gdb) **list 1,99**	list source file through line 99
(gdb) **break main**	set breakpoint at beginning of “main” function
(gdb) **break sub**	set another breakpoint
(gdb) **break 6**	set break at source line
(gdb) **run**	start program (breaks at line 16)
(gdb) **disass main**	show assembly code for “main” function
(gdb) **info r**	display register contents
(gdb) **p argv**	hex address of argv (char**)
(gdb) **p argv[0]**	prints “gdb_example”
(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, prints some #
(gdb) **n**	execute to the next line
(gdb) **p x**	x is 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 (breaks at line 6 in sub)
(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
(gdb) **quit**	quit

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.