CS631 - Advanced Programming in the UNIX Environment
–
Process Environment, Process Control

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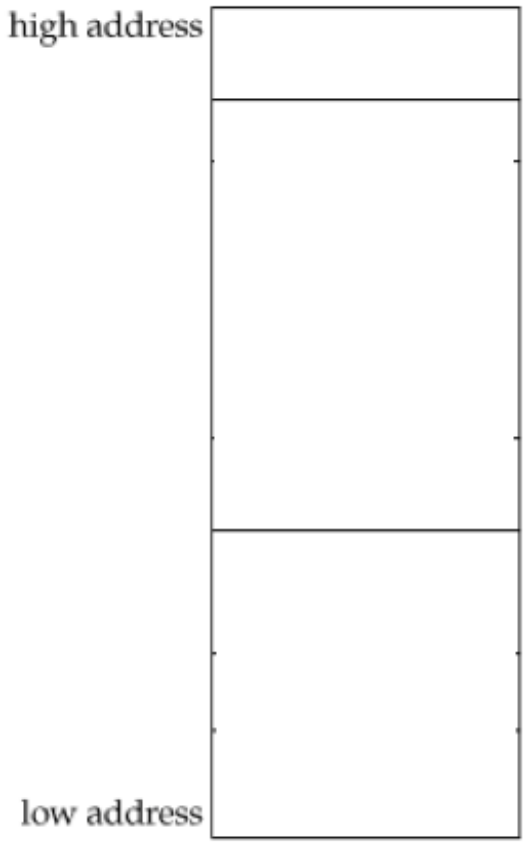
Shell Command-Line Processing

```
$ cc -Wall argv.c
$ ./a.out
$ ./a.out *.c
$ ./a.out *.none
$ ./a.out *.[1c]
$ ./a.out "*.c"
$ ./a.out $USER
$ ./a.out "$(echo *.1)"
$ ./a.out {foo,bar,baz}.whatever
$ ./a.out {1..5}
$ ./a.out {1..5}{a..f}
```

See also: `https://is.gd/kJXbpa` and `http://is.gd/iZa9rC`

Memory Layout of a C Program

`memory-layout.c`



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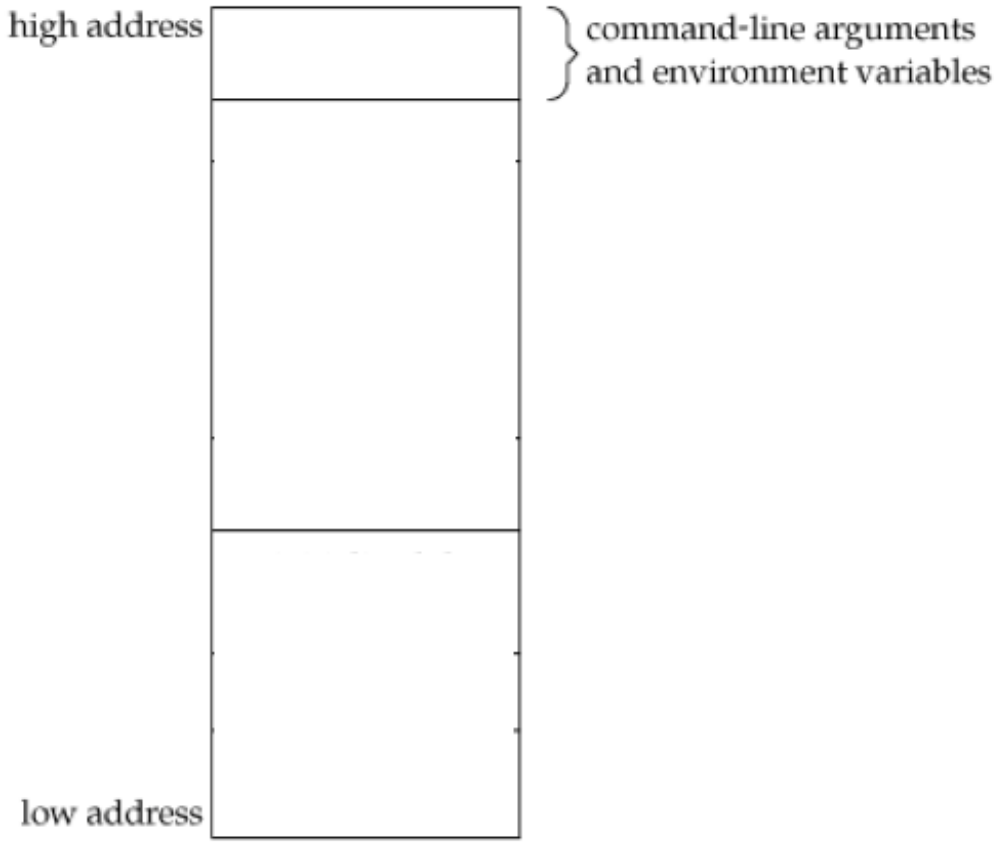

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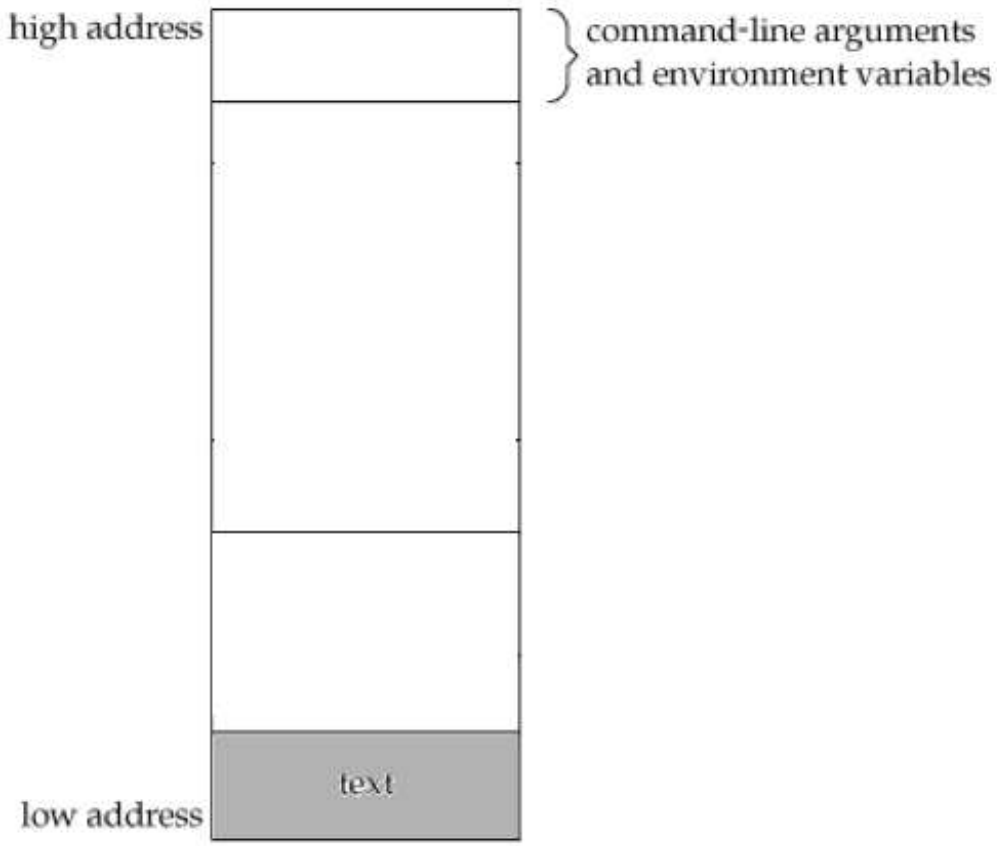

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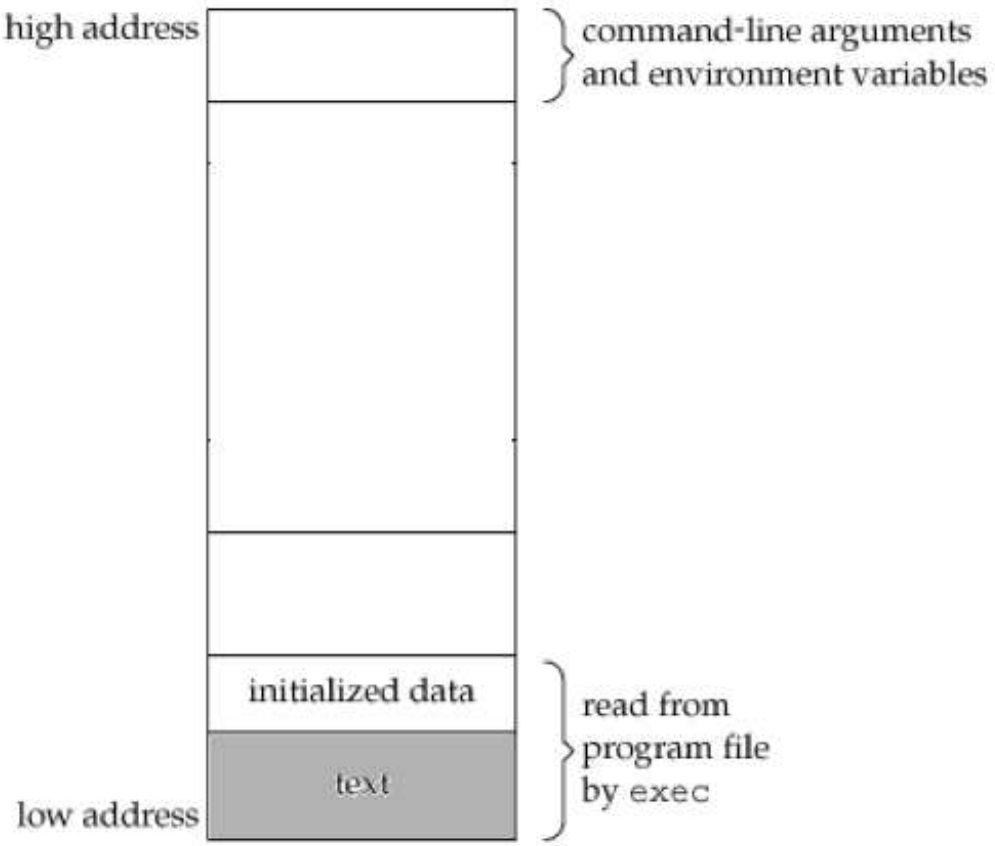

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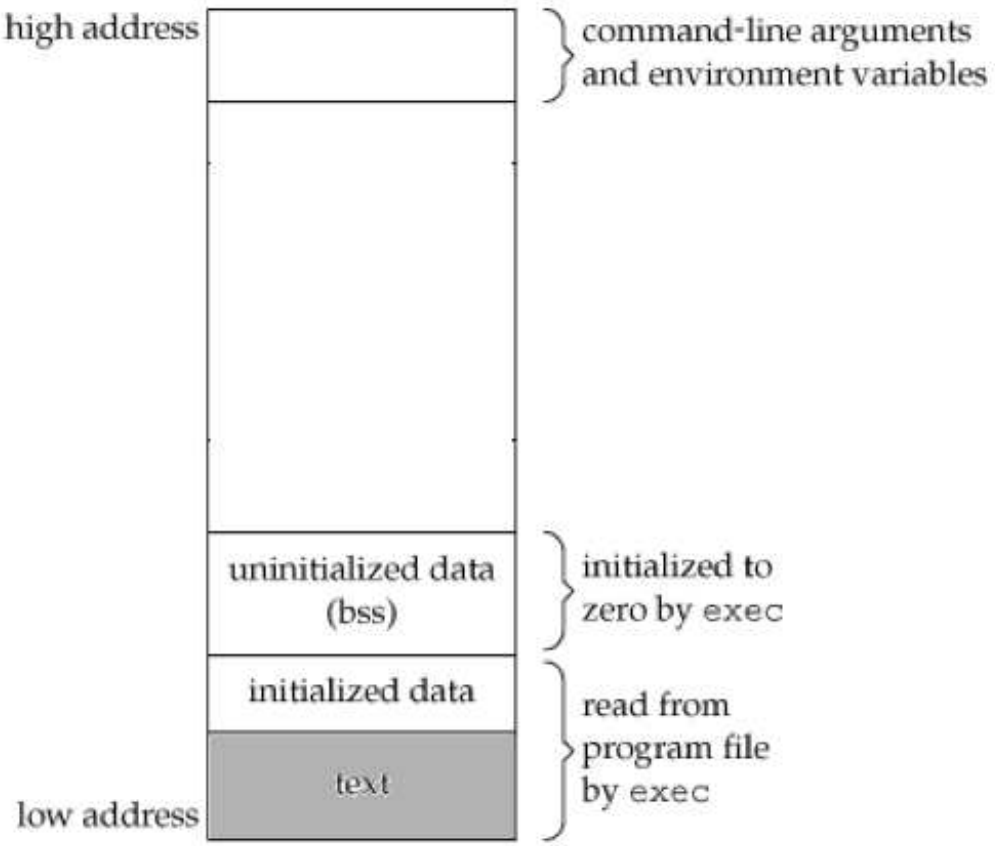

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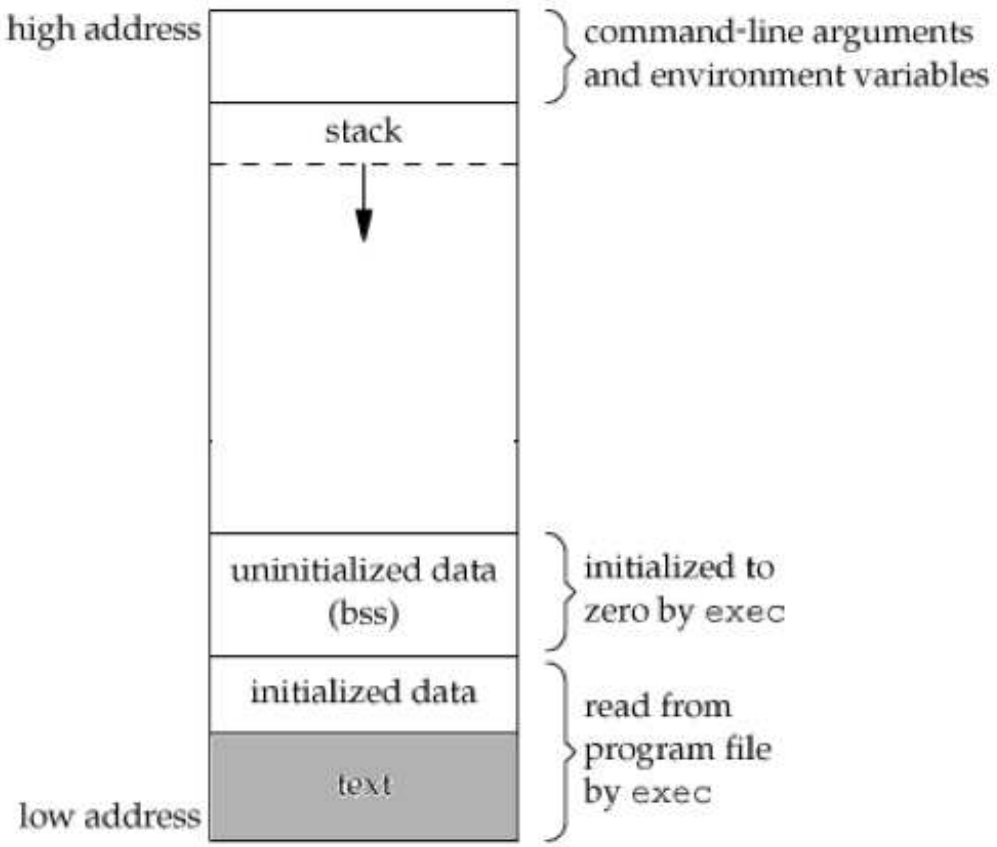

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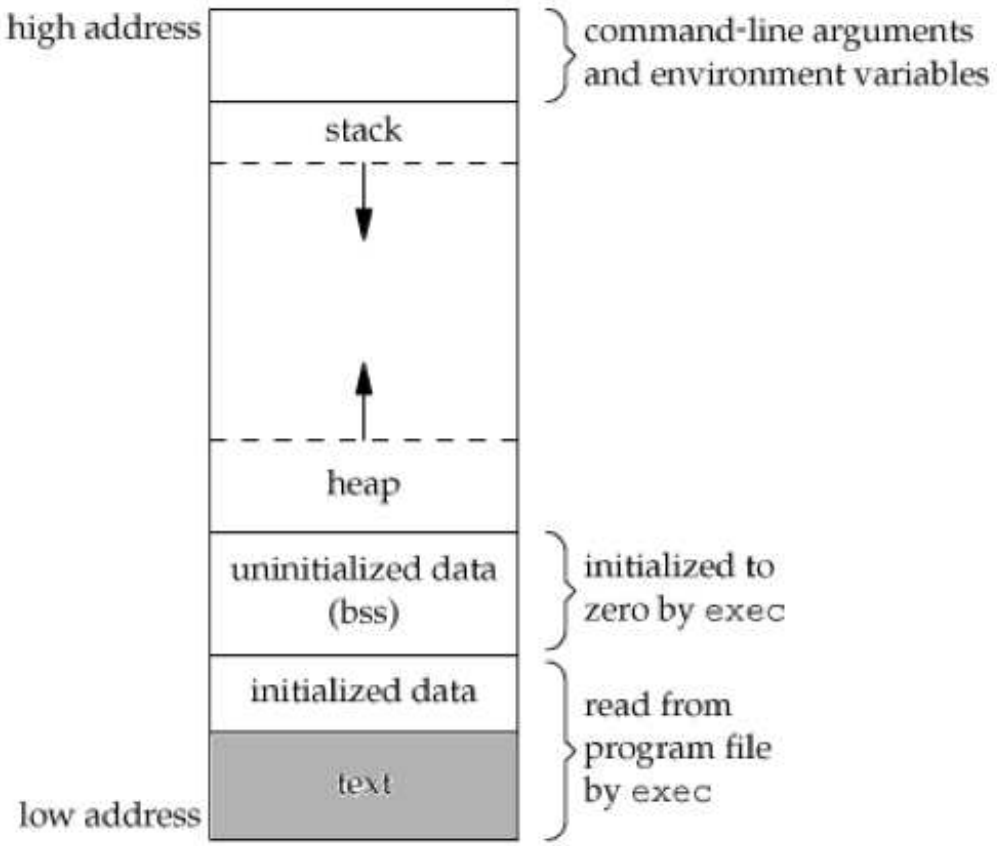

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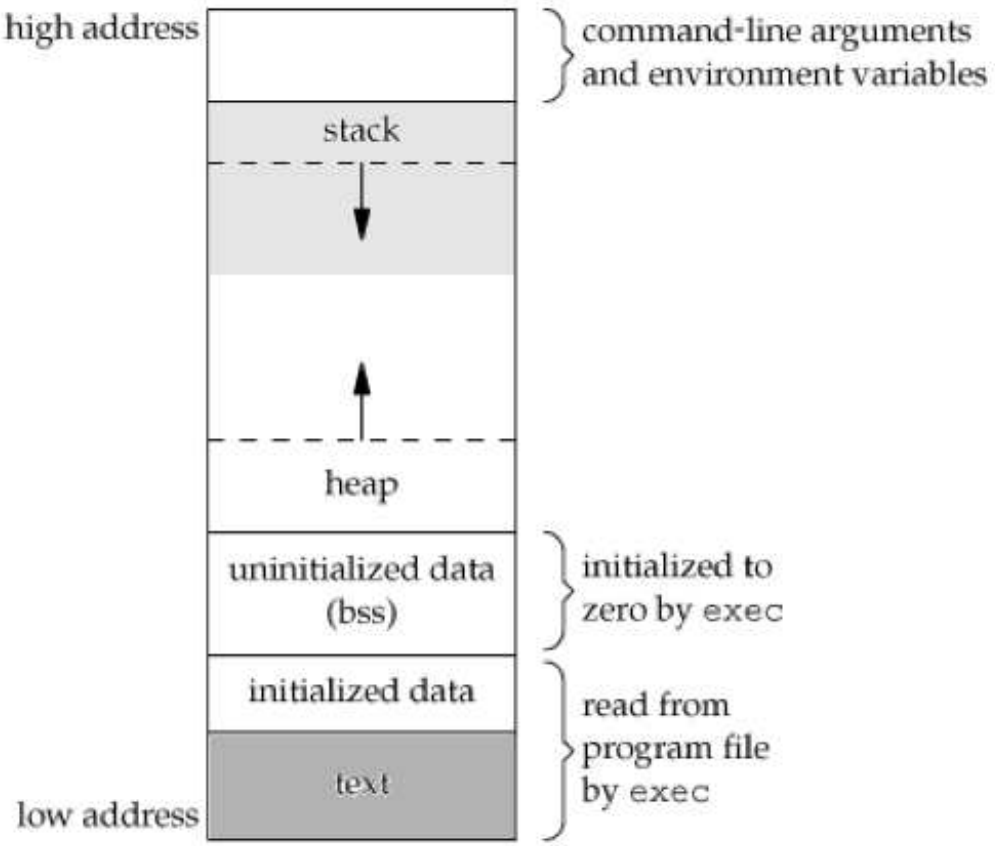

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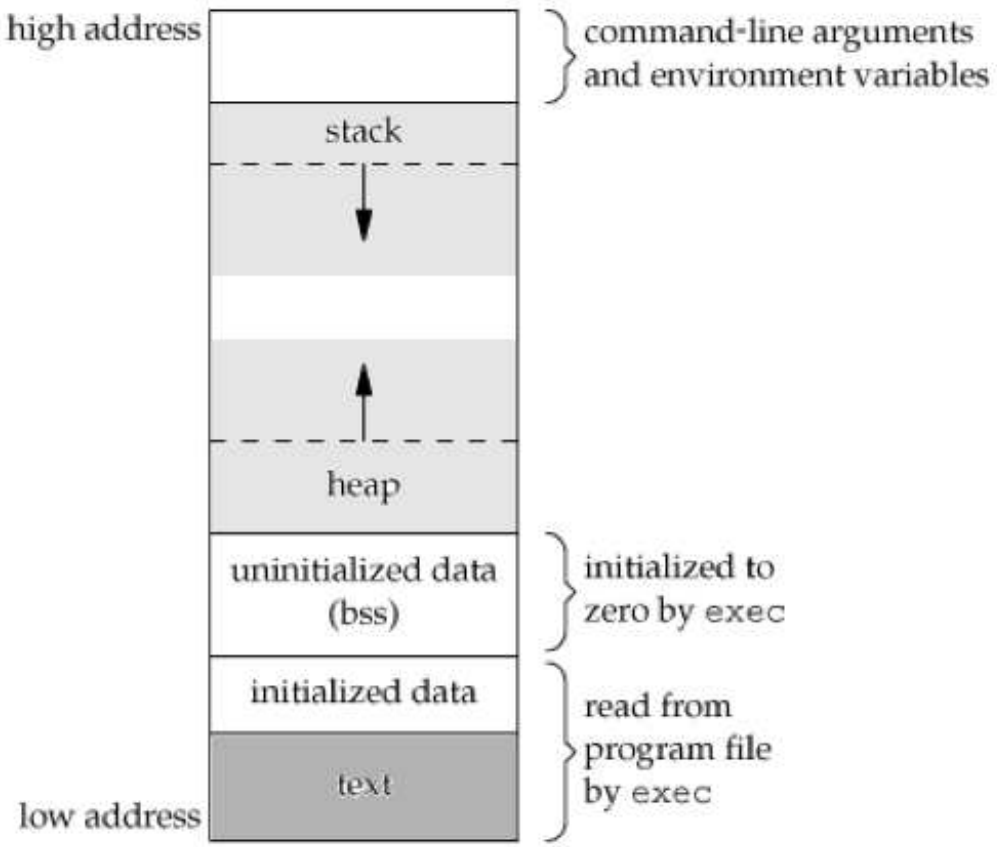

Memory Layout of a C Program

Obligatory ”Smashing The Stack For Fun And Profit” links:

`http://insecure.org/stf/smashstack.html`

The `main` function

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

The `main` function

```
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```

- C program started by kernel (by one of the `exec` functions)
- special startup routine called by kernel which sets up things for `main` (or whatever entrypoint is defined)
- `argc` is a count of the number of command line arguments (including the command itself)
- `argv` is an array of pointers to the arguments
- it is guaranteed by both ANSI C and POSIX.1 that `argv[argc] == NULL`

Process Creation

On Linux:

```
$ cc -Wall entry.c
$ readelf -h a.out | more
ELF Header:
[...]
  Entry point address:                0x400460
  Start of program headers:           64 (bytes into file)
  Start of section headers:           4432 (bytes into file)
$ objdump -d a.out
[...]
0000000000400460 <_start>:
  400460:       31 ed                   xor    %ebp,%ebp
  400462:       49 89 d1                mov    %rdx,%r9
[...]
$
```

Process Creation

glibc/sysdeps/x86_64/start.S

```
0000000000401058 <_start>:
  401058:       31 ed                   xor    %ebp,%ebp
  40105a:       49 89 d1                mov    %rdx,%r9
  40105d:       5e                      pop    %rsi
  40105e:       48 89 e2                mov    %rsp,%rdx
  401061:       48 83 e4 f0             and    $0xfffffffffffffff0,%rsp
  401065:       50                      push   %rax
  401066:       54                      push   %rsp
  401067:       49 c7 c0 e0 1a 40 00    mov    $0x401ae0,%r8
  40106e:       48 c7 c1 50 1a 40 00    mov    $0x401a50,%rcx
  401075:       48 c7 c7 91 11 40 00    mov    $0x401191,%rdi
  40107c:       e8 2f 01 00 00          callq  4011b0 <__libc_start_main>
  401081:       f4                      hlt
  401082:       90                      nop
  401083:       90                      nop
```

Process Creation

glibc/csu/libc-start.c

```
STATIC int
LIBC_START_MAIN (int (*main) (int, char **, char ** MAIN_AUXVEC_DECL),
                 int argc, char **argv,
                 __typeof (main) init,
                 void (*fini) (void),
                 void (*rtld_fini) (void), void *stack_end)
{
[...]
  result = main (argc, argv, __environ MAIN_AUXVEC_PARAM);

  exit (result);
}
```

Process Creation

On Linux:

```
$ cc -Wall entry.c
$ readelf -h a.out | more
ELF Header:
[...]
  Entry point address:                0x400460
  Start of program headers:           64 (bytes into file)
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$ objdump -d a.out
[...]
0000000000400460 <_start>:
  400460:       31 ed                   xor    %ebp,%ebp
  400462:       49 89 d1                mov    %rdx,%r9
[...]
$
```

http://dbp-consulting.com/tutorials/debugging/linuxProgramStartup.html

Process Creation

On Linux:

```
$ cc -e foo entry.c
$ ./a.out
Foo for the win!
Memory fault
$ cc -e bar entry.c
$ ./a.out
bar rules!
$ echo $?
1
$ cc entry.c
$ ./a.out
Hooray main!
$ echo $?
13
$
```

Process Termination

There are 8 ways for a process to terminate.

Normal termination:

- return from `main`
- calling `exit`
- calling `_exit` (or `_Exit`)
- return of last thread from its start routine
- calling `pthread_exit` from last thread

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- return of last thread from its start routine
- calling `pthread_exit` from last thread

Abnormal termination:

- calling `abort`
- terminated by a signal
- response of the last thread to a cancellation request

`exit(3)` and `_exit(2)`

```
#include <stdlib.h>
void exit(int status);
void _Exit(int status);

#include <unistd.h>
void _exit(int status);
```

- `_exit` and `_Exit`
  - return to the kernel immediately
  - `_exit` required by POSIX.1
  - `_Exit` required by ISO C99
  - synonymous on Unix
- `exit` does some cleanup and then returns
- both take integer argument, aka *exit status*

atexit(3)

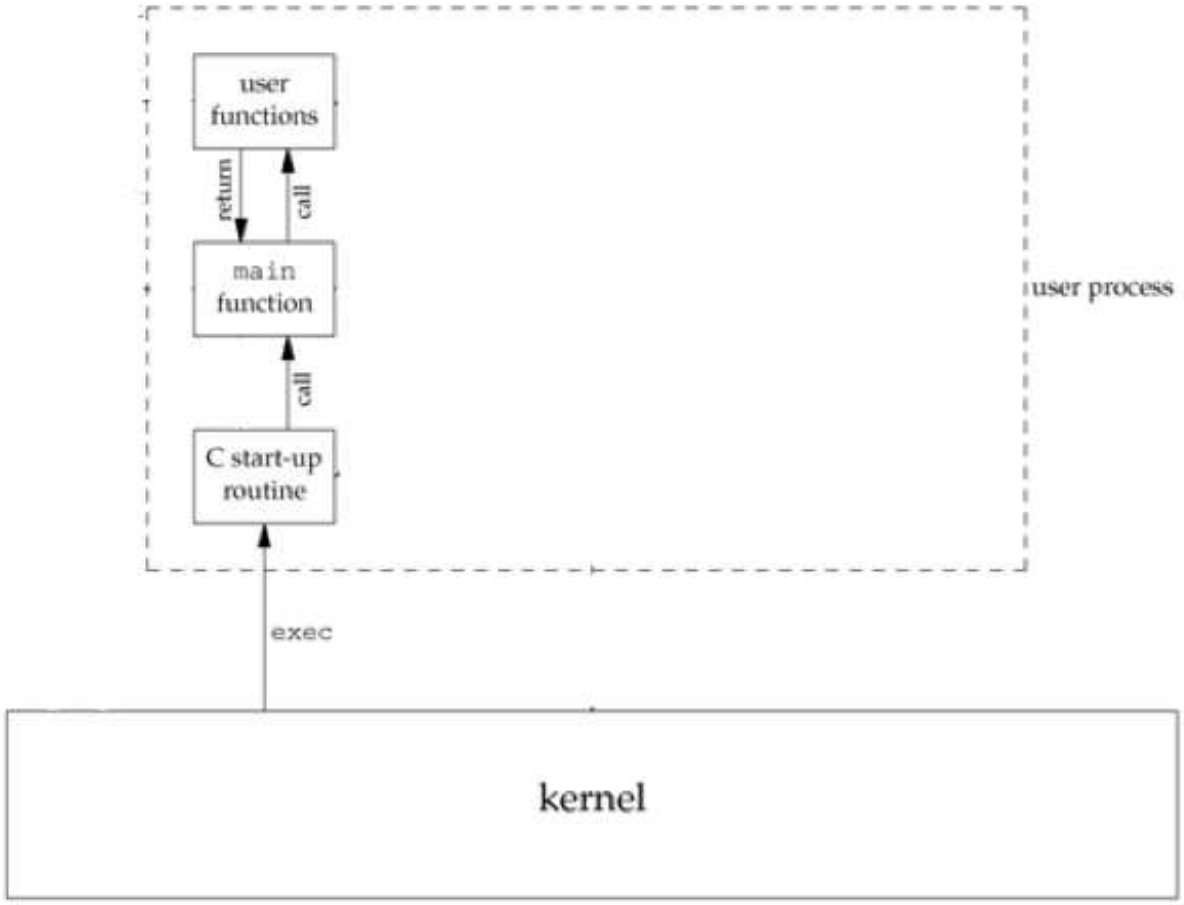
```
#include <stdlib.h>

int atexit(void (*func)(void));
```

- Registers a function with a signature of `void funcname(void)` to be called at exit
- Functions invoked in reverse order of registration
- Same function can be registered more than once
- Extremely useful for cleaning up open files, freeing certain resources, etc.

`exit-handlers.c`

Lifetime of a UNIX Process



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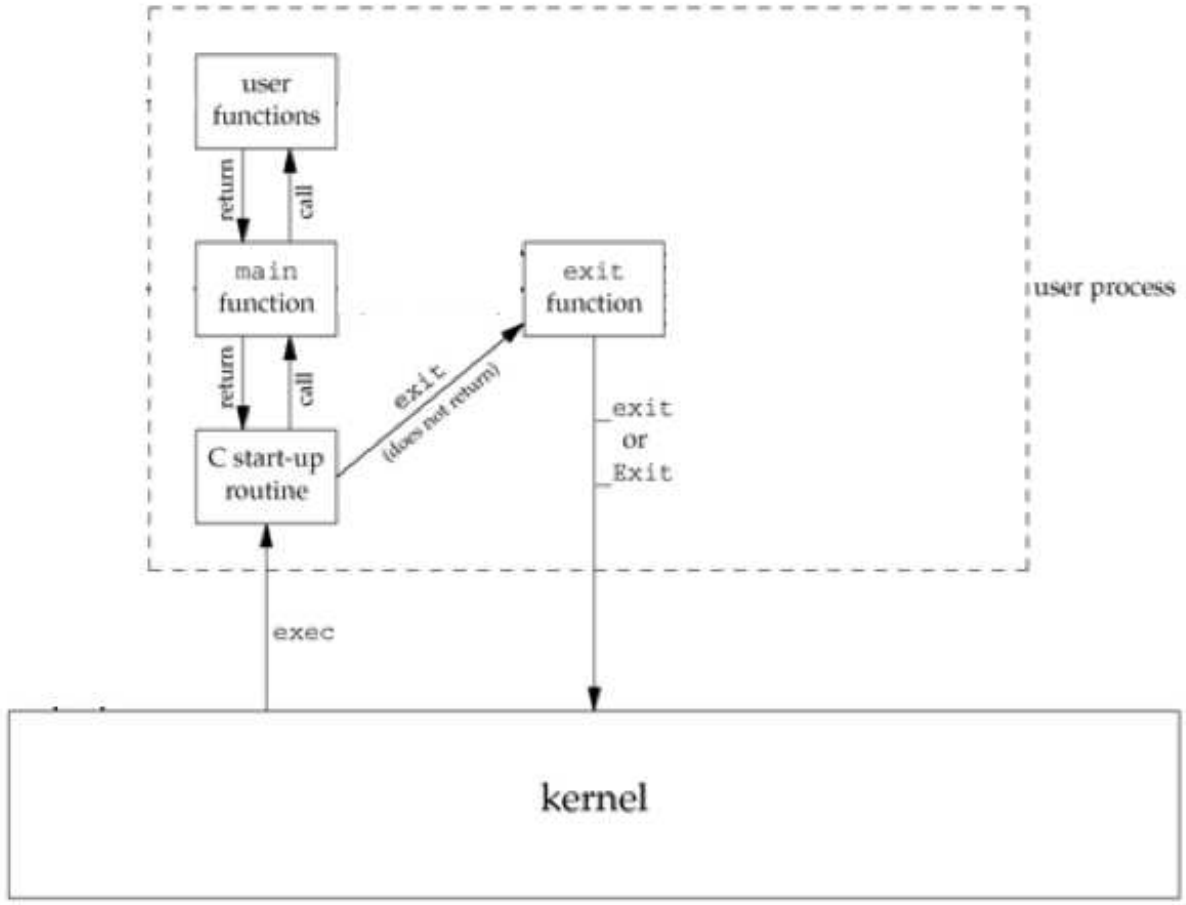

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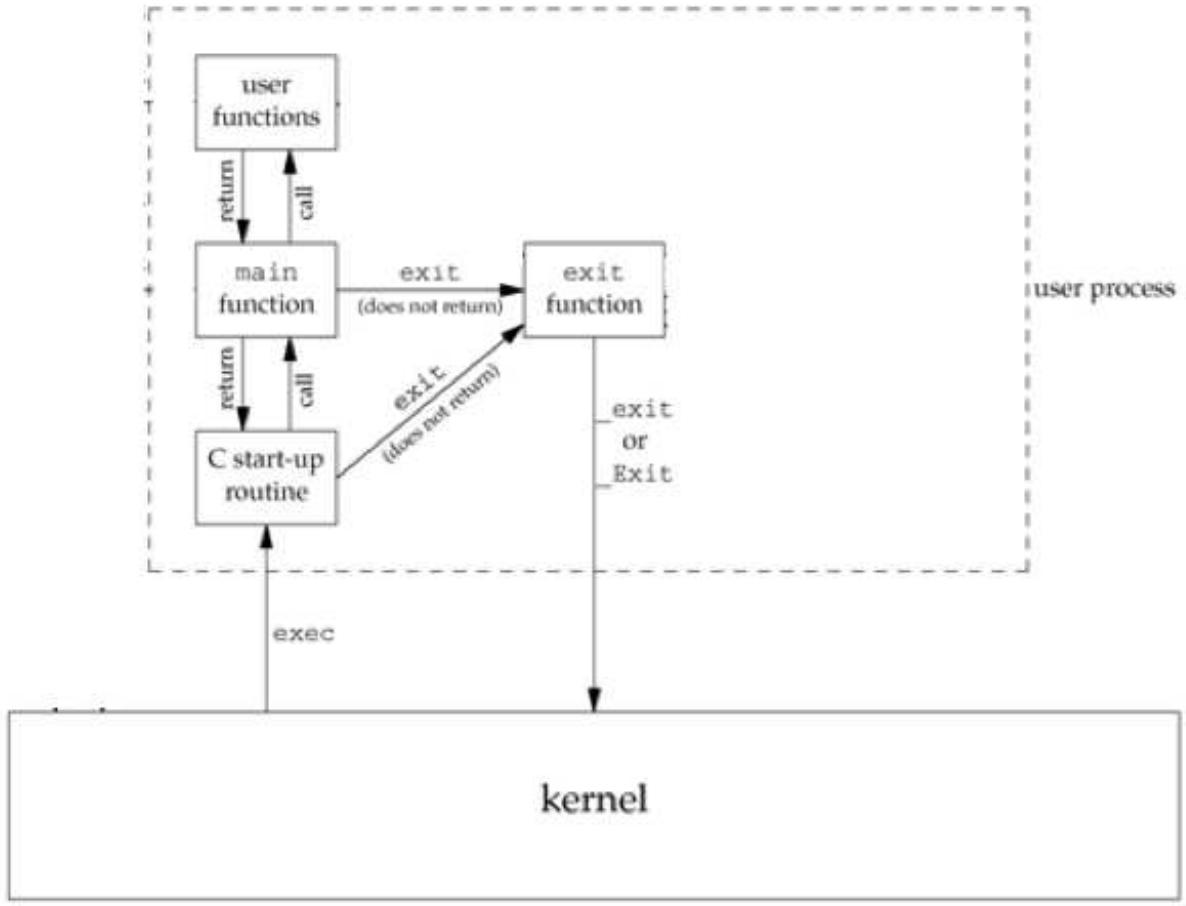
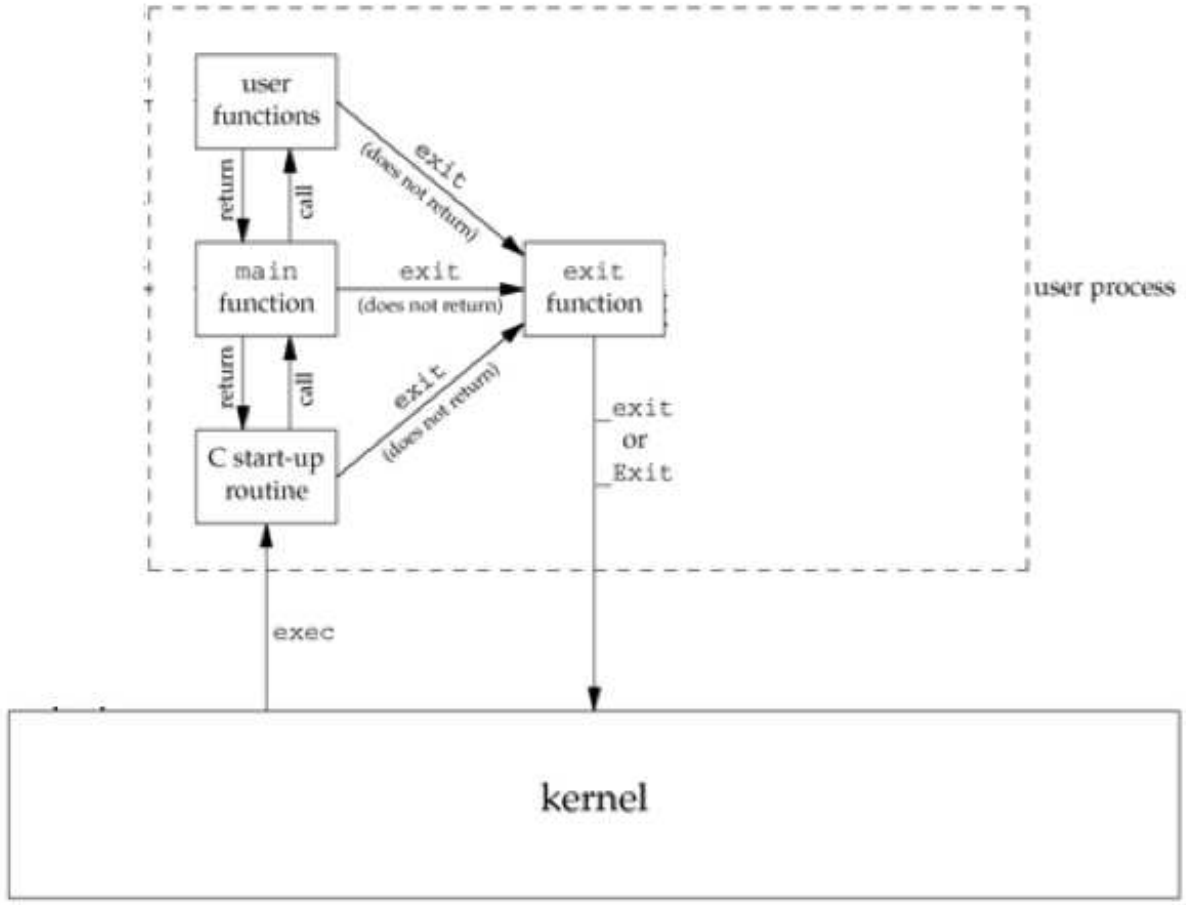


Lifetime of a UNIX Process



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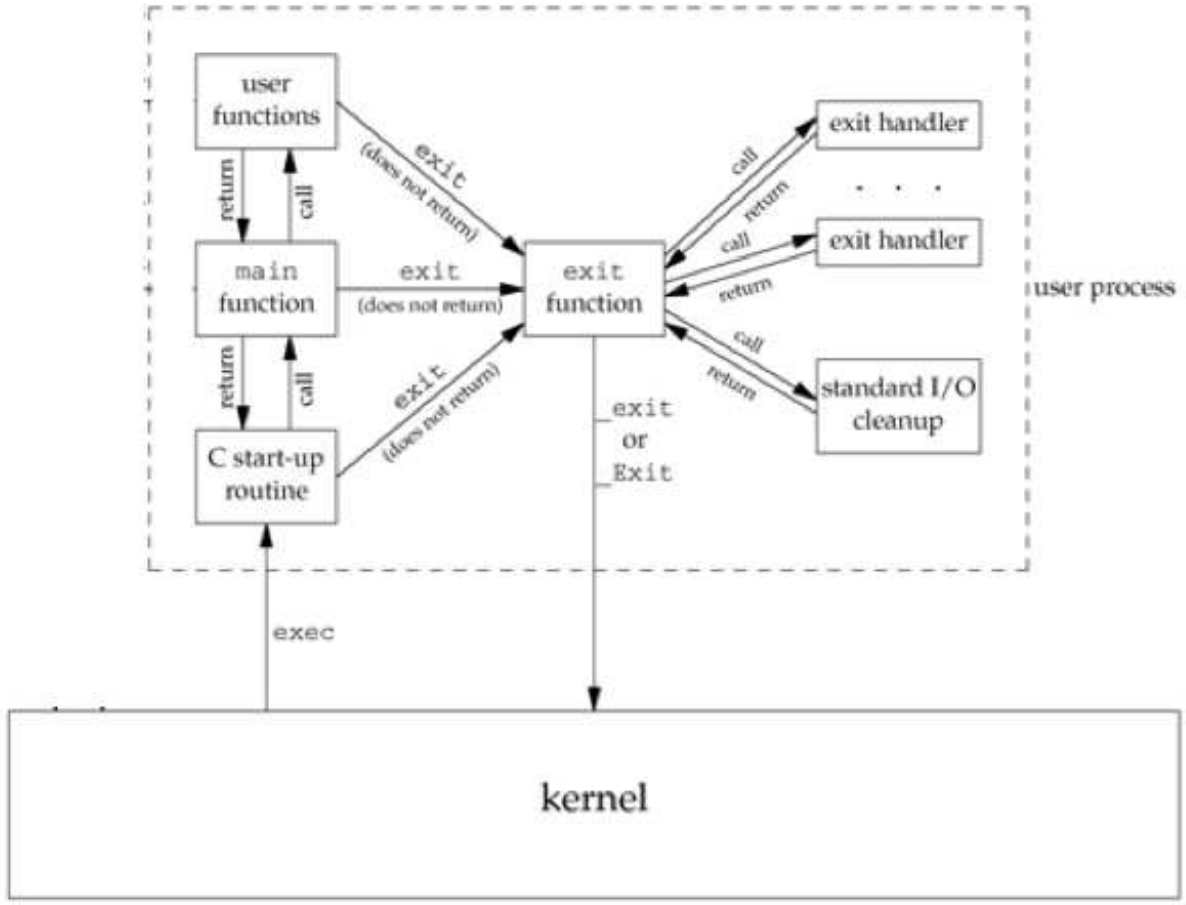

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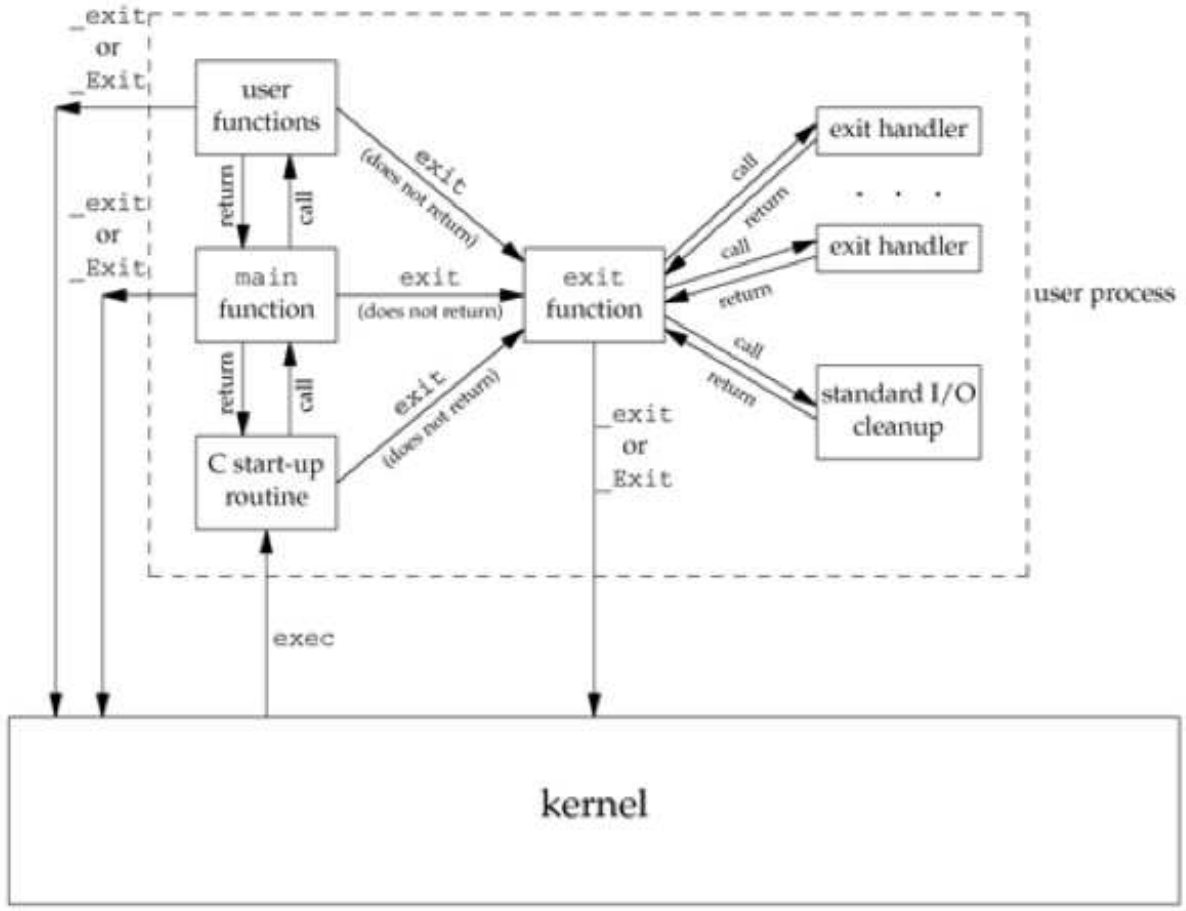

Exit codes

```
$ cc -Wall hw.c
hw.c: In function 'main':
hw.c:7: warning: control reaches end of non-void function
$ ./a.out
Hello World!
$ echo $?
13
$
```

Exit codes

```
$ cc -Wall hw.c
hw.c: In function 'main':
hw.c:7: warning: control reaches end of non-void function
$ ./a.out
Hello World!
$ echo $?
13
$ cc -Wall --std=c99 hw.c
$ ./a.out
Hello World!
$ echo $?
0
$
```

Environment List

Environment variables are stored in a global array of pointers:

```
extern char **environ;
```

The list is `null` terminated.

These can also be accessed by:

```
#include <stdlib.h>


char *getenv(const char *name);
int putenv(const char *string);
int setenv(const char *name, const char *value, int rewrite);
void unsetenv(cont char *name);
```

Environment List

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extern char **environ;
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char *getenv(const char *name);
int putenv(const char *string);
int setenv(const char *name, const char *value, int rewrite);
void unsetenv(cont char *name);
```

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

Memory Allocation

```
#include <stdlib.h>

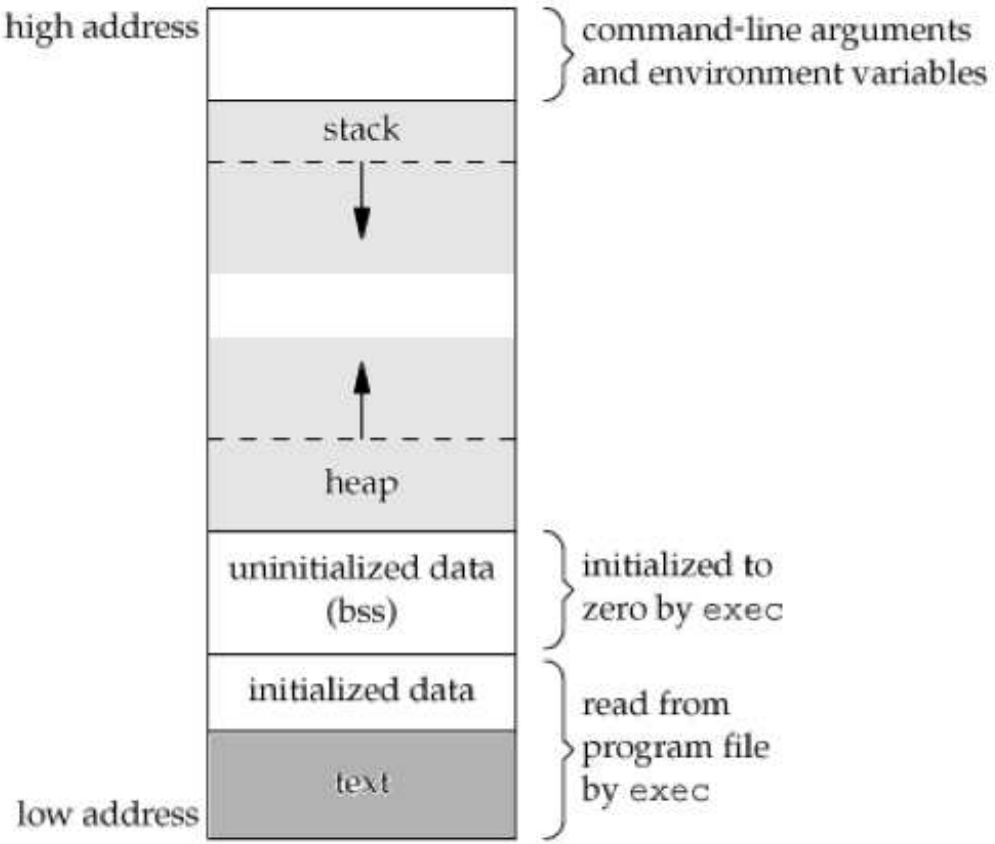
void *malloc(size_t size);
void *calloc(size_t nobj, size_t size);
void *realloc(void *ptr, size_t newsize);
void *alloca(size_t size);

void free(void *ptr);
```

- *malloc* – initial value is indeterminate.
- *calloc* – initial value set to all zeros.
- *realloc* – changes size of previously allocated area. Initial value of any additional space is indeterminate.
- *alloca* – allocates memory on stack

Now consider manipulation of the environment by your program...

Memory Layout of a C Program



Memory Layout of a C Program

On NetBSD:

```
$ cc hw.c
$ file a.out
a.out: ELF 64-bit LSB executable, x86-64, version 1 (SYSV), dynamically
linked (uses shared libs), for NetBSD 5.0, not stripped
$ ldd a.out
a.out:
        -lc.12 => /usr/lib/libc.so.12
$ size a.out
   text    data     bss     dec     hex filename
   2301     552     120    2973     b9d a.out
$ objdump -d a.out > obj
$ wc -l obj
     271 obj
$
```

Memory Layout of a C Program

On Mac OS X:

```
$ cc hw.c
$ file a.out
a.out: Mach-O 64-bit executable x86_64
$ otool -L a.out
a.out:
/usr/lib/libSystem.B.dylib (compatibility version 1.0.0,
current version 125.2.11)
$ size a.out
__TEXT __DATA __OBJC others dec hex
4096 4096 0 4294971392 4294979584 100003000
$ otool -t -v a.out > obj
$ wc -l obj
      32 obj
$
```

Memory Layout of a C Program

On Linux:

```
$ cc hw.c
$ file a.out
a.out: ELF 32-bit LSB executable, Intel 80386, version 1 (SYSV),
dynamically linked (uses shared libs), for GNU/Linux 2.6.15, not stripped
$ ldd a.out
linux-gate.so.1 =>  (0x00c66000)
libc.so.6 => /lib/tls/i686/cmov/libc.so.6 (0x006b4000)
/lib/ld-linux.so.2 (0x005fe000)
$ size a.out
   text    data     bss     dec     hex filename
    918     264       8    1190     4a6 a.out
$ objdump -d a.out >obj
$ wc -l obj
225 obj
$
```

Memory Layout of a C Program

On NetBSD:

```
$ cc -static hw.c
$ file a.out
a.out: ELF 64-bit LSB executable, x86-64, version 1 (SYSV), statically
linked, for NetBSD 5.0, not stripped
$ ldd a.out
ldd: a.out: unrecognized file format2 [2 != 1]
$ size a.out
   text    data     bss     dec     hex filename
 151877    4416   16384  172677   2a285 a.out
$ size a.out.dyn
   text    data     bss     dec     hex filename
   2301     552     120    2973     b9d a.out
$ objdump -d a.out > obj
$ wc -l obj
   35029 obj
$
```

Memory Layout of a C Program

On Mac OS X:

```
$ cc -static hw.c
ld: library not found for -lcrt0.o
collect2: ld returned 1 exit status
$
```

Memory Layout of a C Program

On Linux:

```
$ cc -static hw.c
$ file a.out
a.out: ELF 32-bit LSB executable, Intel 80386, version 1 (SYSV),
statically linked, for GNU/Linux 2.6.15, not stripped
$ ldd a.out
/usr/bin/ldd: line 161: /lib64/ld-linux-x86-64.so.2: cannot execute binary file
not a dynamic executable
$ size a.out
   text    data     bss     dec     hex filename
 510786    1928    7052  519766    7ee56 a.out
$ objdump -d a.out >obj
$ wc -l obj
114420 obj
$
```

Process limits

```
$ ulimit -a
time(cpu-seconds)    unlimited
file(blocks)         unlimited
coredump(blocks)     unlimited
data(kbytes)         262144
stack(kbytes)        2048
lockedmem(kbytes)    249913
memory(kbytes)       749740
nofiles(descriptors) 128
processes            160
vmemory(kbytes)      unlimited
sbsize(bytes)        unlimited
$
```

`getrlimit(2)` and `setrlimit(2)`

```
#include <sys/resource.h>

int getrlimit(int resouce, struct rlimit *rlp);
int setrlimit(int resouce, const struct rlimit *rlp);
```

Changing resource limits follows these rules:

- a *soft limit* can be changed by any process to a value less than or equal to its hard limit
- any process can lower its *hard limit* greater than or equal to its soft limit
- only superuser can raise *hard limits*
- changes are per process only

`getrlimit(2)` and `setrlimit(2)`

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- any process can lower its *hard limit* greater than or equal to its soft limit
- only superuser can raise *hard limits*
- changes are per process only (which is why `ulimit` is a shell built-in)

Process Control

Review from our first class, the world's simplest shell:

```
int
main(int argc, char **argv)
{
    char buf[1024];
    pid_t pid;
    int status;

    while (getinput(buf, sizeof(buf))) {
        buf[strlen(buf) - 1] = '\0';

        if((pid=fork()) == -1) {
            fprintf(stderr, "shell: can't fork: %s\n",
                        strerror(errno));
            continue;
        } else if (pid == 0) {
            /* child */
            execlp(buf, buf, (char *)0);
            fprintf(stderr, "shell: couldn't exec %s: %s\n", buf,
                        strerror(errno));
            exit(EX_DATAERR);
        }

        if ((pid=waitpid(pid, &status, 0)) < 0)
            fprintf(stderr, "shell: waitpid error: %s\n",
                strerror(errno));
    }

    exit(EX_OK);
}
```

Process Identifiers

```
#include <unistd.h>

pid_t getpid(void);
pid_t getppid(void);
```

Process ID's are guaranteed to be unique and identify a particular executing process with a non-negative integer.

Certain processes have fixed, special identifiers. They are:

- *swapper*, process ID 0 – responsible for scheduling
- *init*, process ID 1 – bootstraps a Unix system, owns orphaned processes
- *pagedaemon*, process ID 2 – responsible for the VM system (some Unix systems)

fork(2)

```
#include <unistd.h>

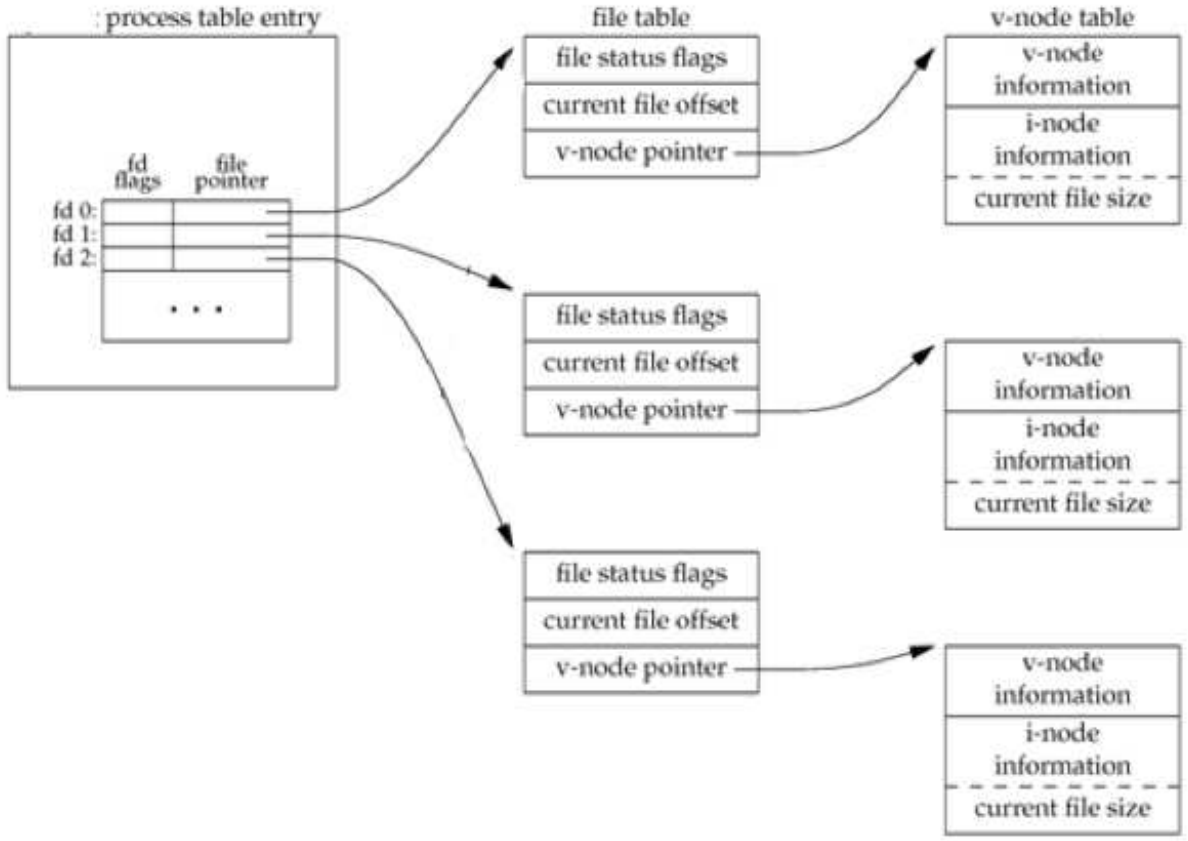
pid_t fork(void);
```

`fork(2)` causes creation of a new process. The new process (child process) is an exact copy of the calling process (parent process) except for the following:

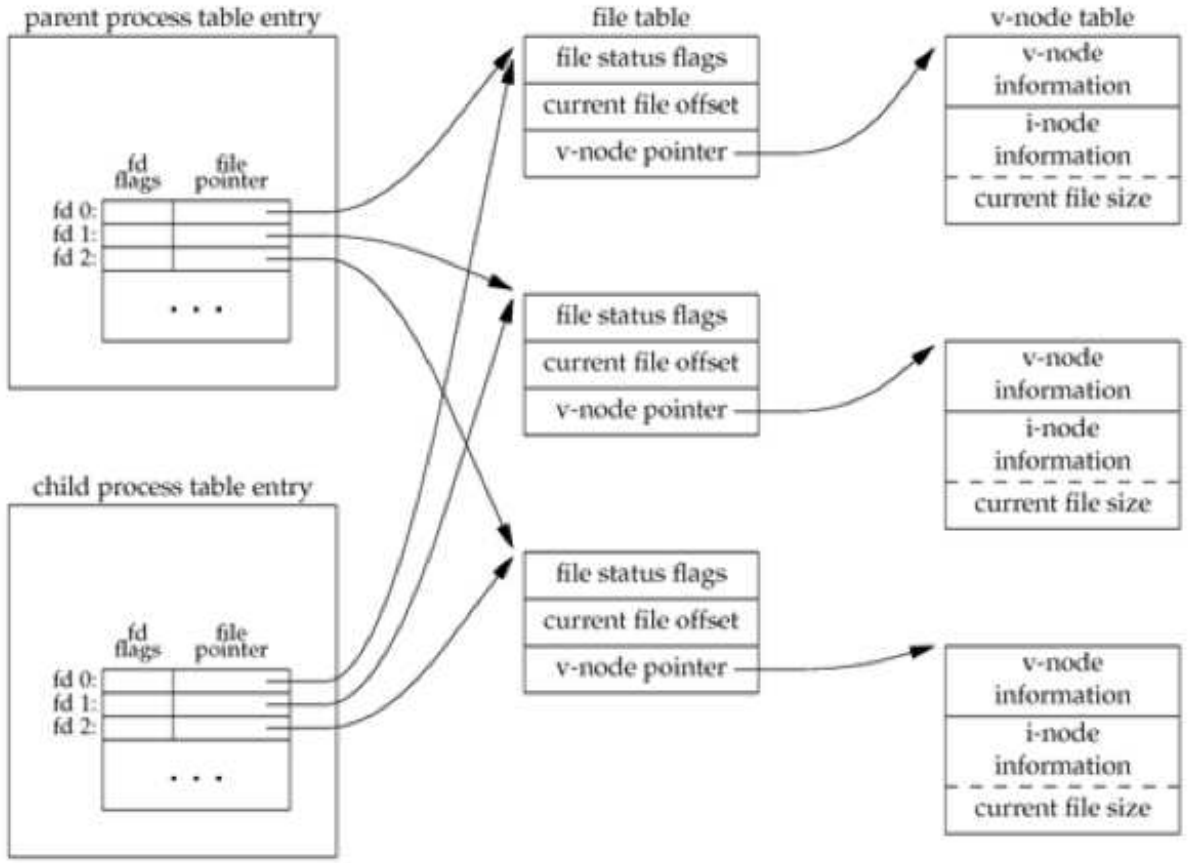
- The child process has a unique process ID.
- The child process has a different parent process ID (i.e., the process ID of the parent process).
- The child process has its own copy of the parent's descriptors.
- The child process' resource utilizations are set to 0.

Note: no order of execution between child and parent is guaranteed!

fork(2)


process table entry
fd flags
file pointer
fd 0:
fd 1:
fd 2:
file table
file status flags
current file offset
v-node pointer
file status flags
current file offset
v-node pointer
file status flags
current file offset
v-node pointer
v-node table
v-node information
i-node information
current file size
v-node information
i-node information
current file size
v-node information
i-node information
current file size

fork(2)


parent process table entry
fd flags
file pointer
fd 0:
fd 1:
fd 2:
child process table entry
fd flags
file pointer
fd 0:
fd 1:
fd 2:
file table
file status flags
current file offset
v-node pointer
file status flags
current file offset
v-node pointer
file status flags
current file offset
v-node pointer
v-node table
v-node information
i-node information
current file size
v-node information
i-node information
current file size
v-node information
i-node information
current file size

fork(2)

```
$ cc -Wall forkflush.c
$ ./a.out
a write to stdout
before fork
pid = 12149, glob = 7, var = 89
pid = 12148, glob = 6, var = 88
$ ./a.out | cat
a write to stdout
before fork
pid = 12153, glob = 7, var = 89
before fork
pid = 12151, glob = 6, var = 88
$
```

The exec(3) functions

```
#include <unistd.h>

int execl(const char *pathname, const char *arg0, ...  /* (char *) 0 */);

int execv(const char *pathname, char * const argvp[]);

int execle(const char *pathname, const char *arg0, ...  /* (char *) 0, char *const envp[] */ );

int execve(const char *pathname, char * const argvp[], char * const envp[]);

int execlp(const char *filename, const char *arg0, ...  /* (char *) 0 */);

int execvp(const char *filename, char *const argv[]);
```

The `exec()` family of functions are used to completely replace a running process with a a new executable.

- if it has a v in its name, argv's are a vector: `const * char argv[]`
- if it has an l in its name, argv's are a list: `const char *arg0, ... /* (char *) 0 */`
- if it has an e in its name, it takes a `char * const envp[]` array of environment variables
- if it has a p in its name, it uses the `PATH` environment variable to search for the file

wait(2) and waitpid(2)

```
#include <sys/types.h>
#include <sys/wait.h>

pid_t wait(int *status);
pid_t waitpid(pid_t wpid, int *status, int options);
pid_t wait3(int *status, int options, struct rusage *rusage);
pid_t wait4(pid_t wpid, int *status, int options, struct rusage *rusage);
```

A parent that calls wait(2) or waitpid(2) can:

- block (if all of its children are still running)
- return immediately with the termination status of a child
- return immediately with an error

`wait(2)` and `waitpid(2)`

Differences between `wait(2)`, `wait3(2)`, `wait4(2)` and `waitpid(2)`:

- `wait(2)` will block until the process terminates, `waitpid(2)` has an option to prevent it from blocking
- `waitpid(2)` can wait for a specific process to finish
- `wait3(2)` and `wait4(2)` allow you to get detailed resource utilization statistics
- `wait3(2)` is the same as `wait4(2)` with a *wpid* value of `-1`

`wait(2)` and `waitpid(2)`

Once we get a termination status back in `status`, we'd like to be able to determined how a child died. We do this with the following macros:

- `WIFEXITED(status)` – true if the child terminated normally. Then execute `WEXITSTATUS(status)` to get the exit status.
- `WIFSIGNALED(status)` – true if child terminated abnormally (by receiving a signal it didn't catch). The we call:
  - `WTERMSIG(status)` to retrieve the signal number
  - `WCOREDUMP(status)` to see if the child left a core image
- `WIFSTOPPED(status)` – true if the child is currently stopped. Call `WSTOPSIG(status)` to determine the signal that caused this.

Additionally, `waitpid`'s behavior can be modified by supplying `WNOHANG` as an option, which says that if the requested pid has not terminated, return immediately instead of blocking.

What if we don't `wait(2)`?

What if we don't `wait(2)`?

What if we don't `wait(2)`?

```
$ cc -Wall zombies.c
$ ./a.out
Let's create some zombies!
====
15603 s003  S+     0:00.00 ./a.out
15604 s003  Z+     0:00.00 (a.out)
====
15603 s003  S+     0:00.00 ./a.out
15604 s003  Z+     0:00.00 (a.out)
15608 s003  Z+     0:00.00 (a.out)
====
15603 s003  S+     0:00.00 ./a.out
15604 s003  Z+     0:00.00 (a.out)
15612 s003  Z+     0:00.00 (a.out)
====
15603 s003  S+     0:00.00 ./a.out
15604 s003  Z+     0:00.00 (a.out)
15612 s003  Z+     0:00.00 (a.out)
15616 s003  Z+     0:00.00 (a.out)
```

Notes and Homework

Reading:

- Stevens, Chapter 7 and 8

Other:

- work on your midterm project!