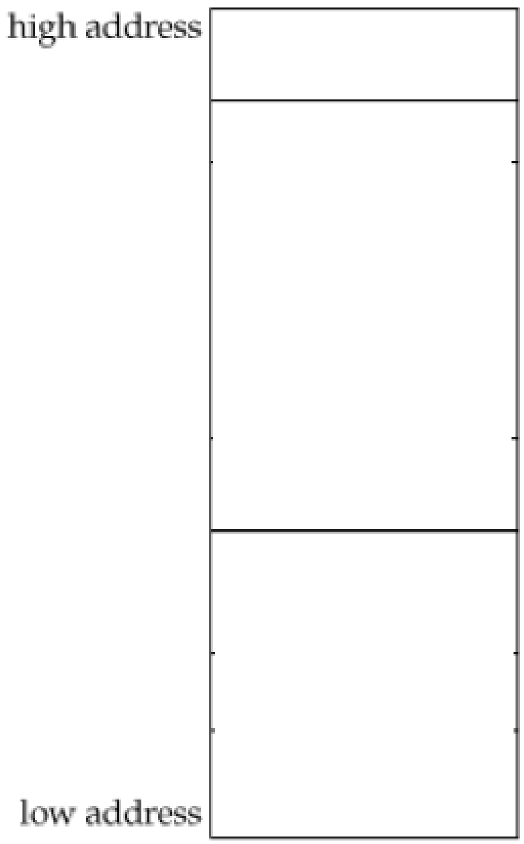
CS631 - Advanced Programming in the UNIX Environment
–
Process Environment, Process Control

Department of Computer Science
Stevens Institute of Technology
Jan Schaumann
jschauma@stevens.edu
https://stevens.netmeister.org/631/

Memory Layout of a C Program

`memory-layout.c`



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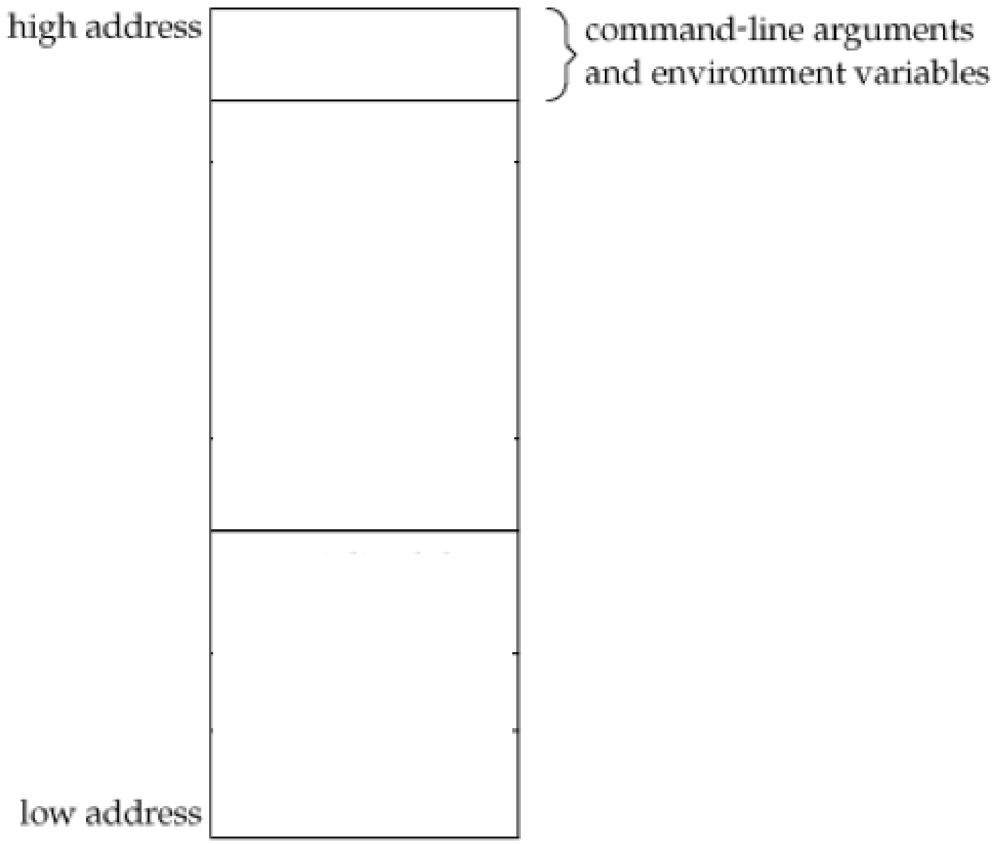

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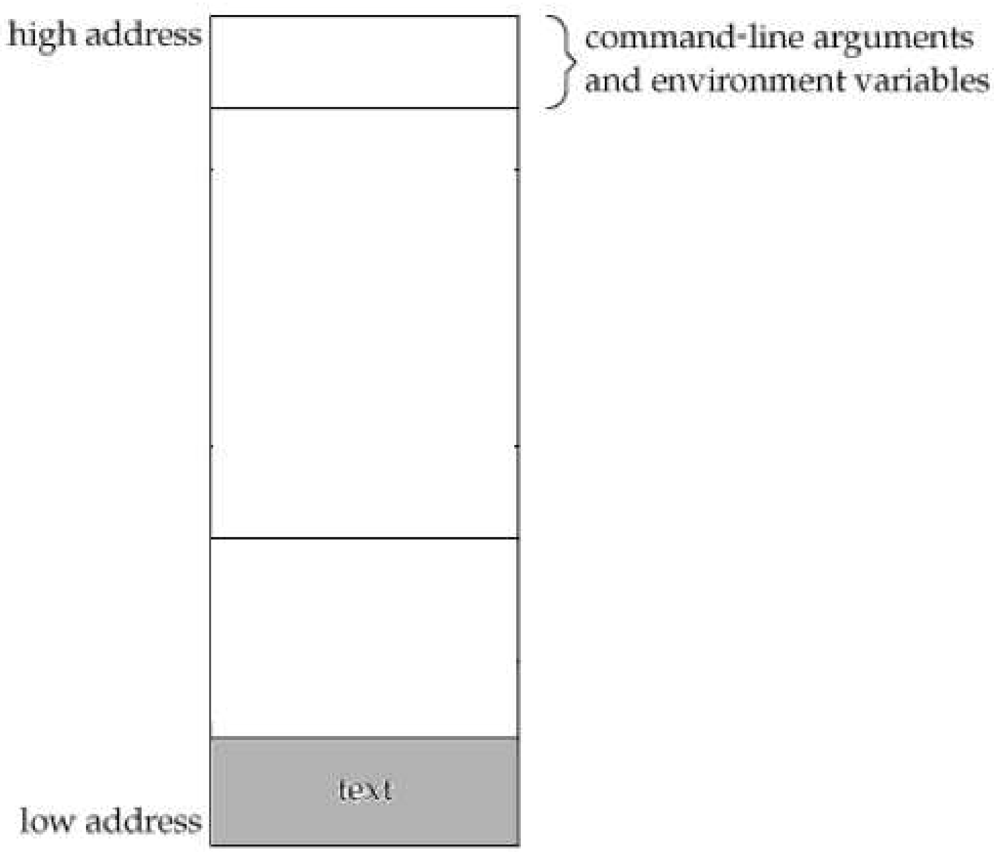

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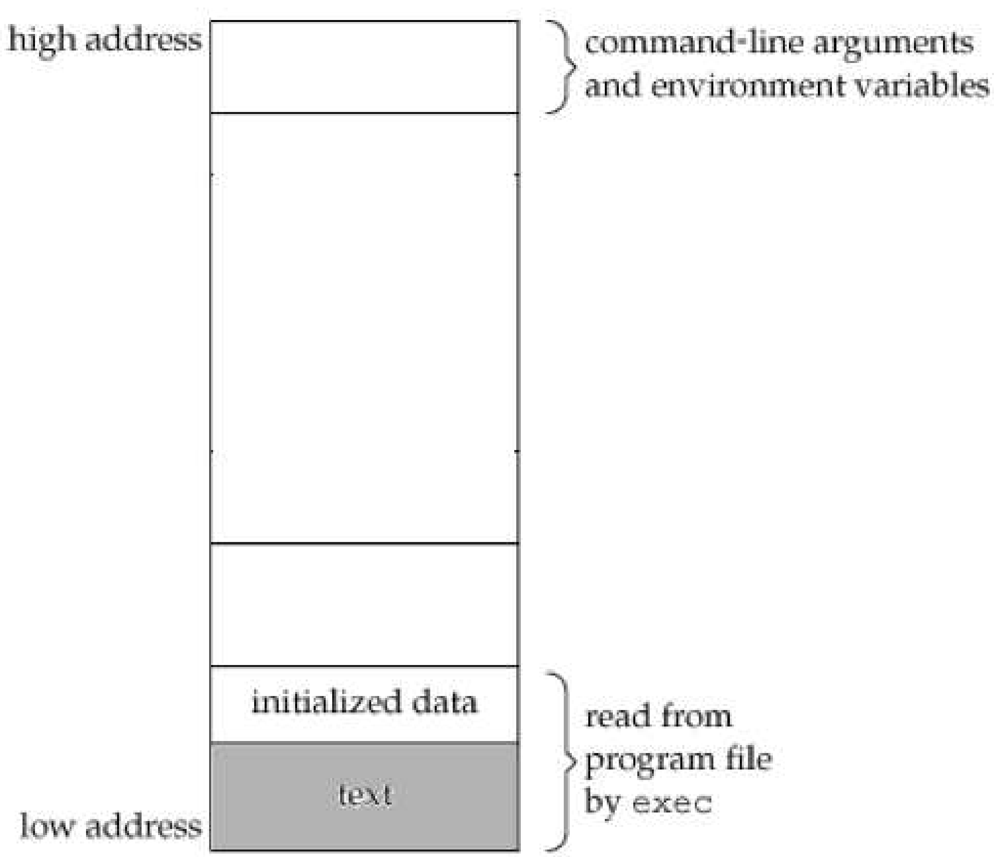

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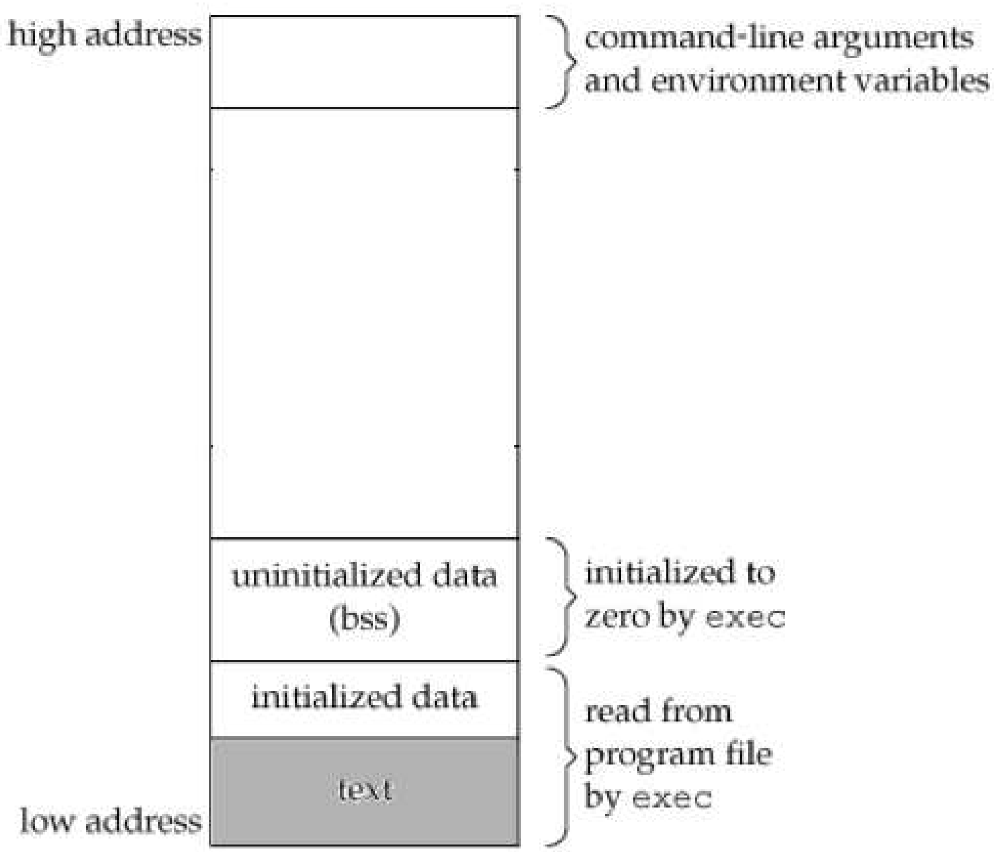

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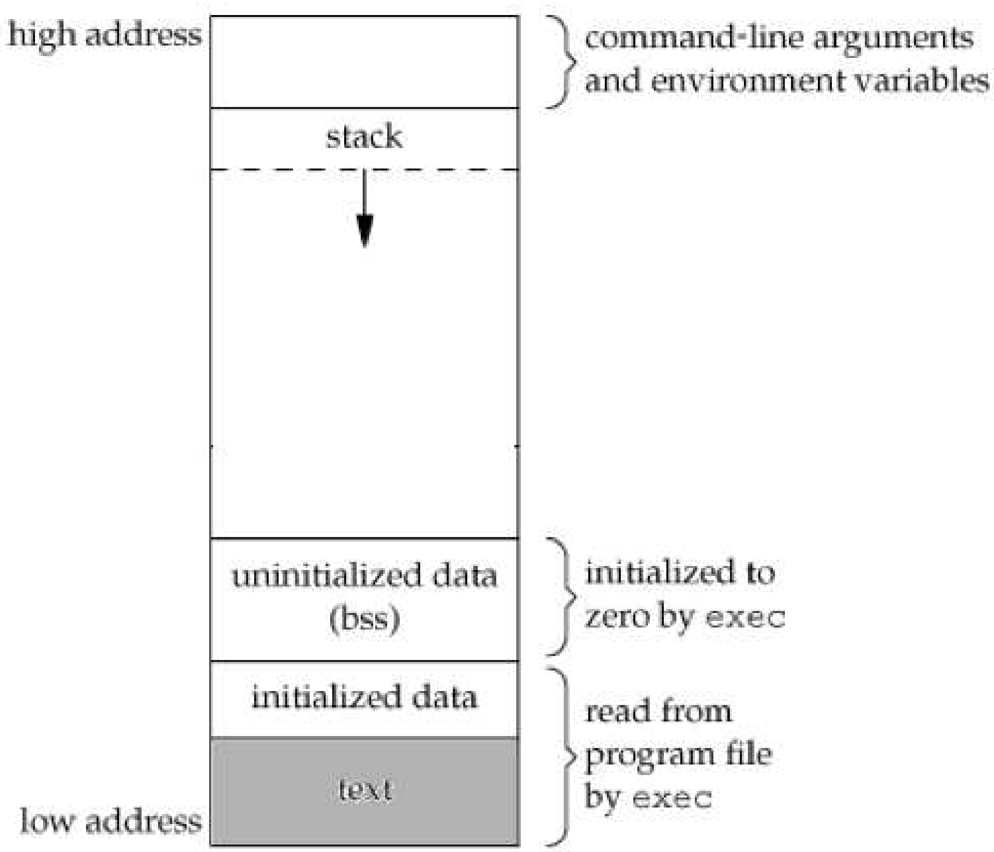

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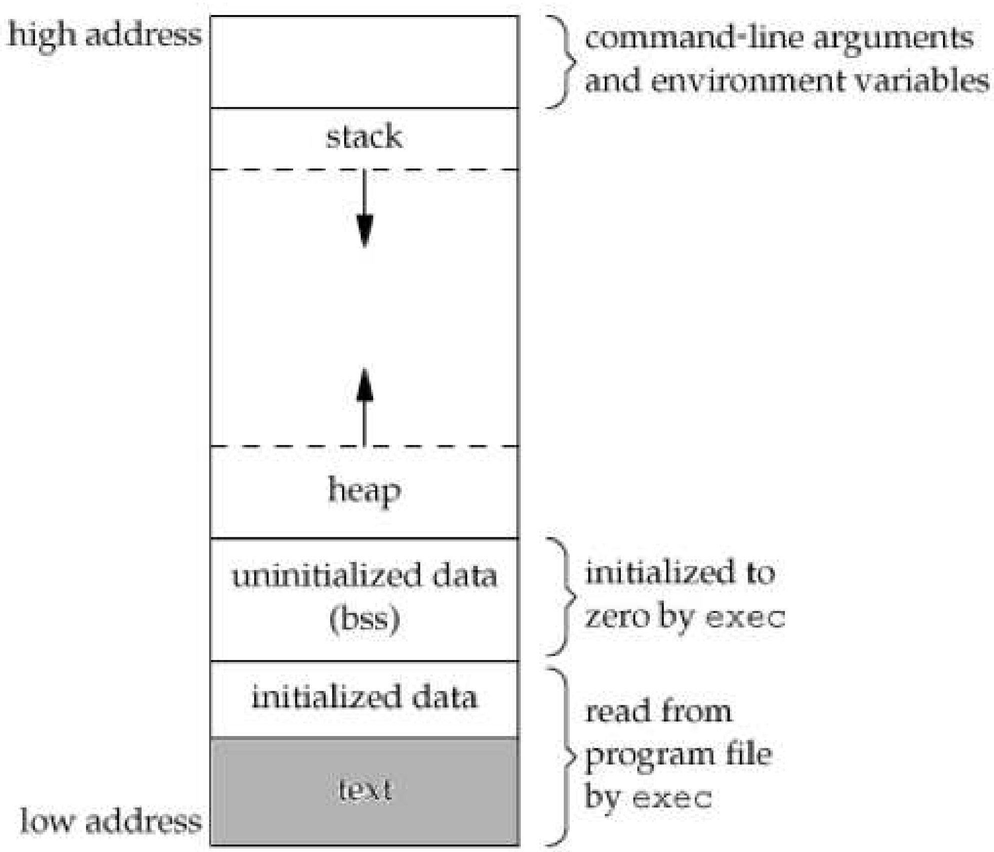

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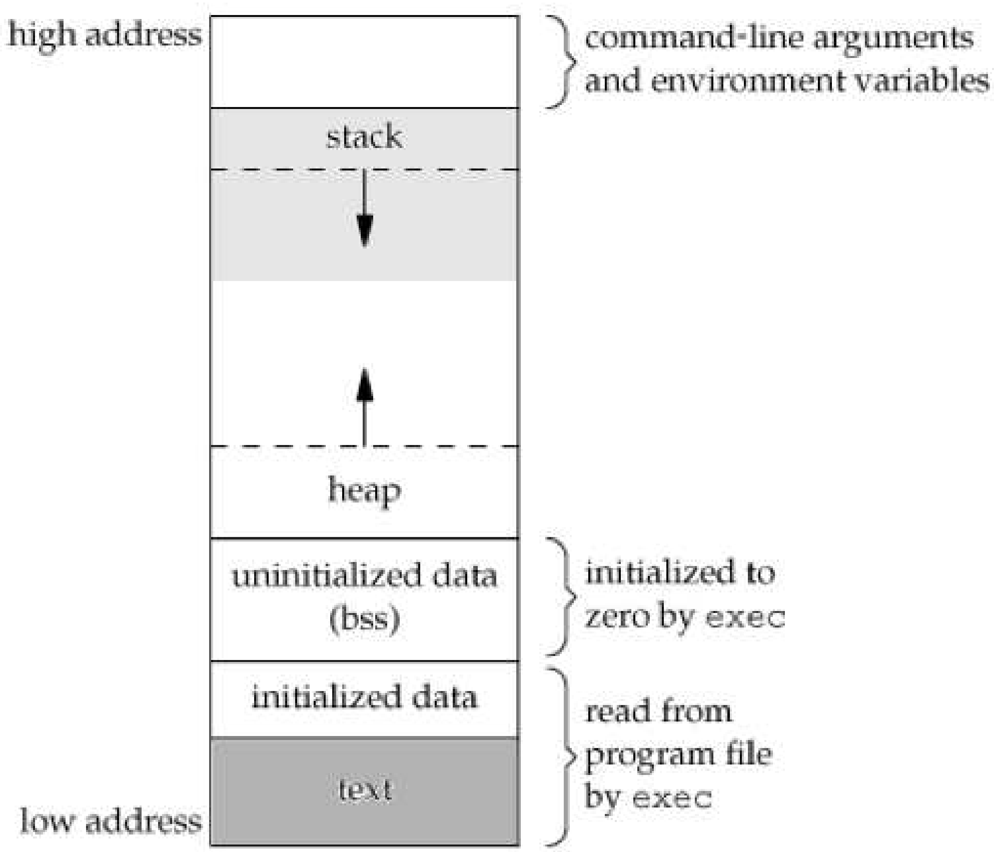

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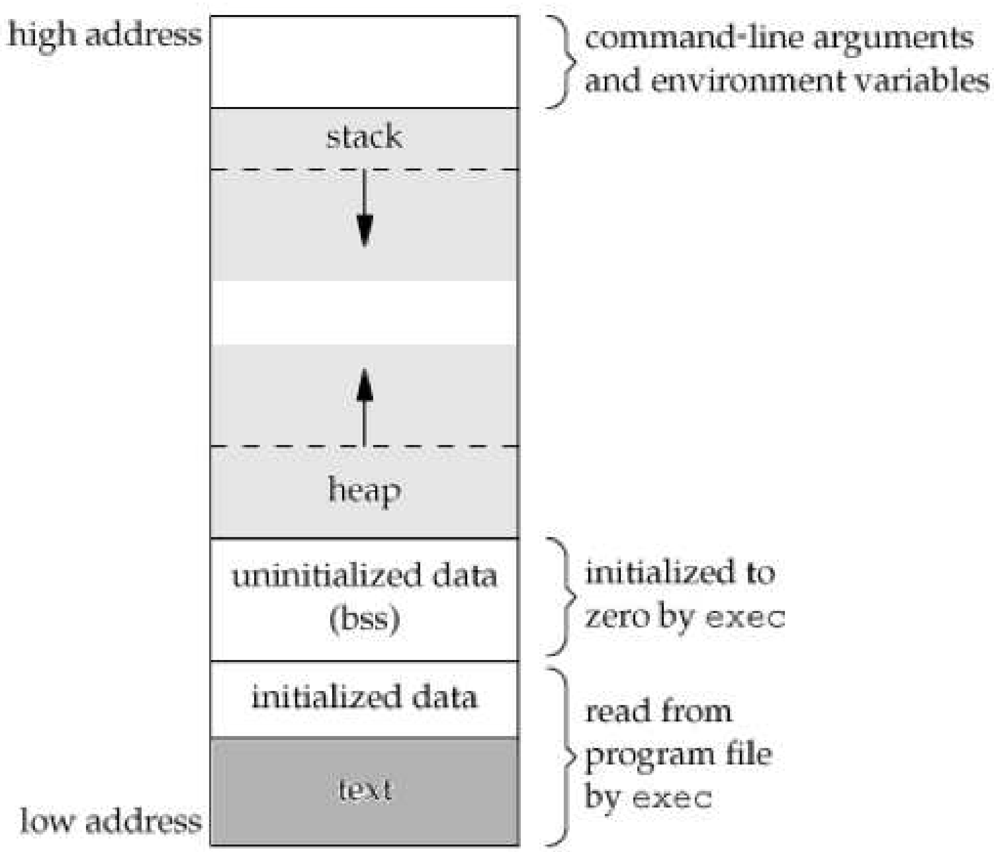

Memory Layout of a C Program

See also:

- `/proc/self/map`
- `pmap(1)` and `pmap(9)`

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

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

The `main` function

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

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

- 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

Linux: `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

NetBSD: `/usr/src/lib/csu/common/crt0-common.c`

Linux: `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

```
$ 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
[...]
$
```

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

Process Creation

```
$ 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 --std=c89 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)

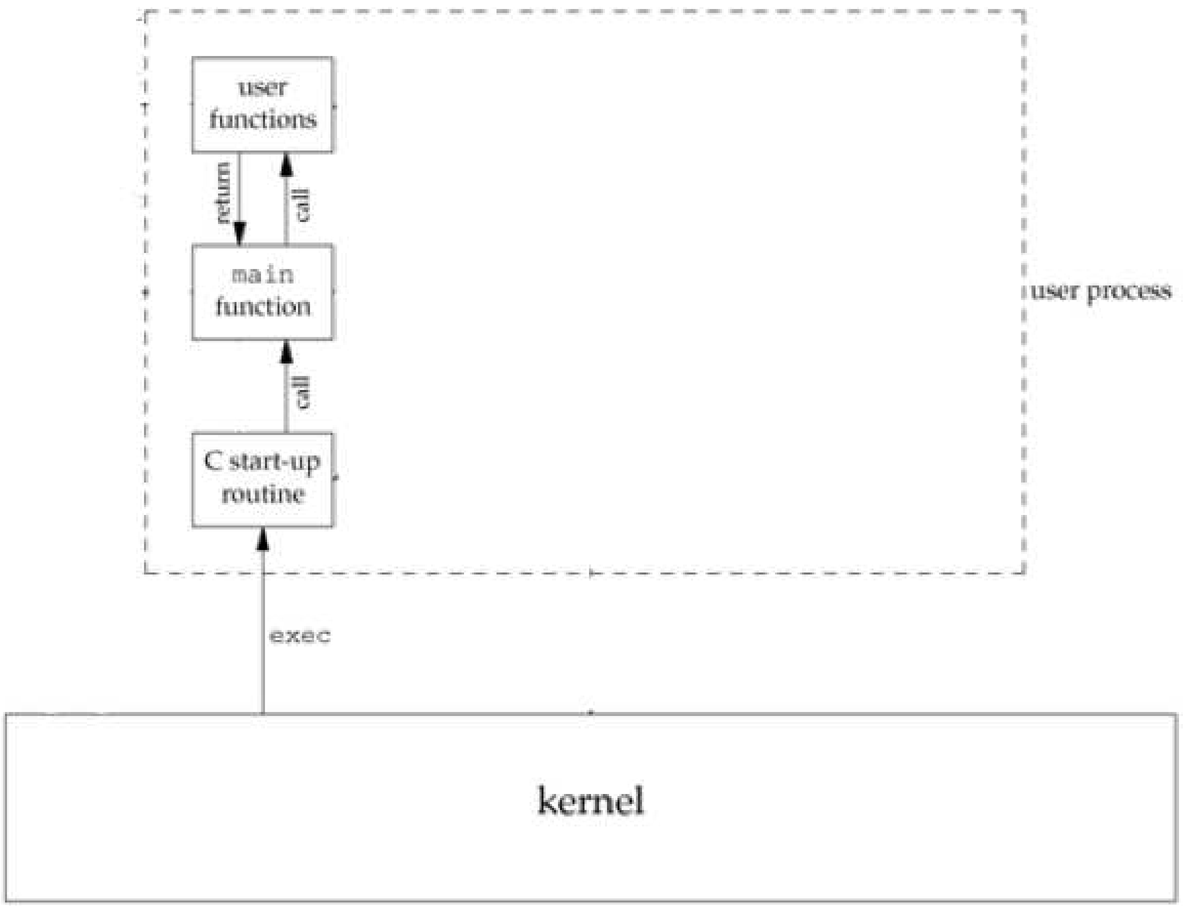
```
#include <stdlib.h>

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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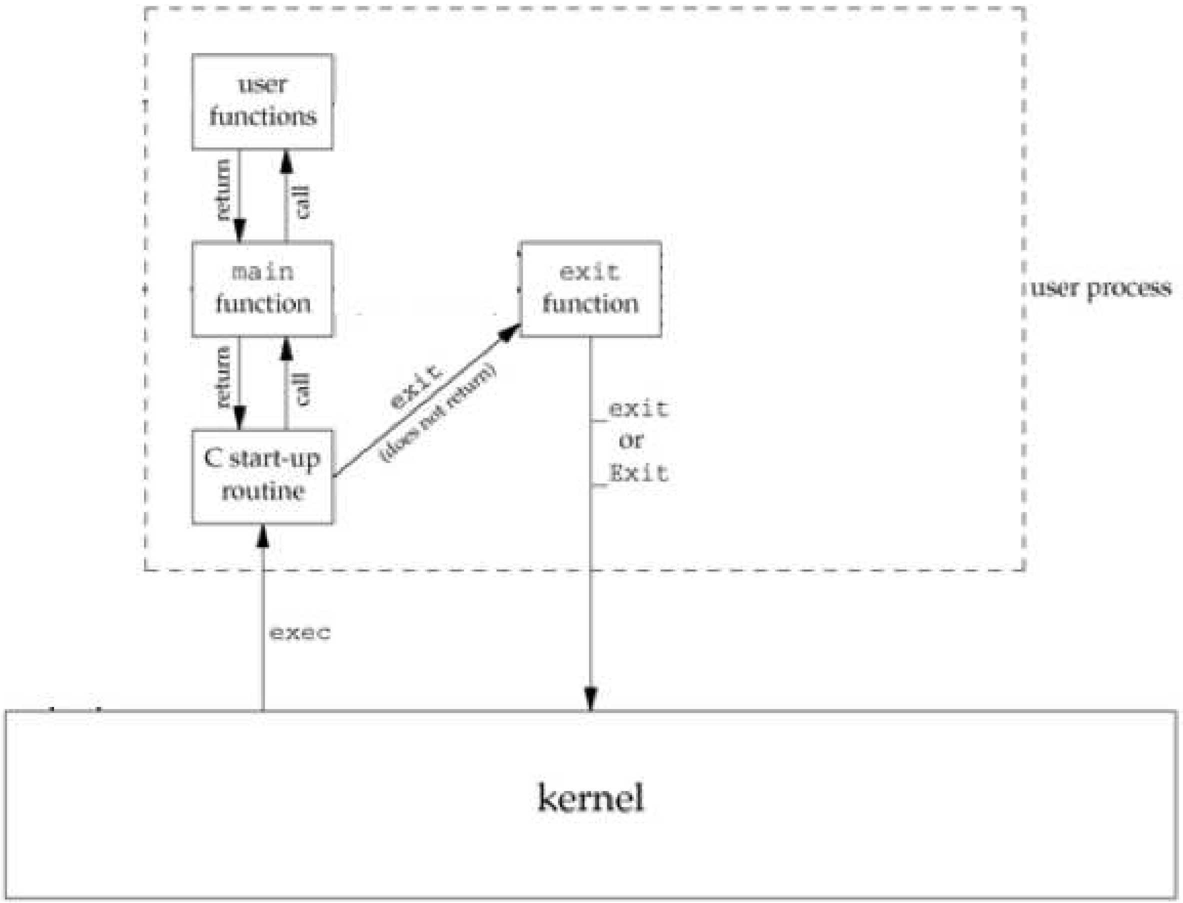

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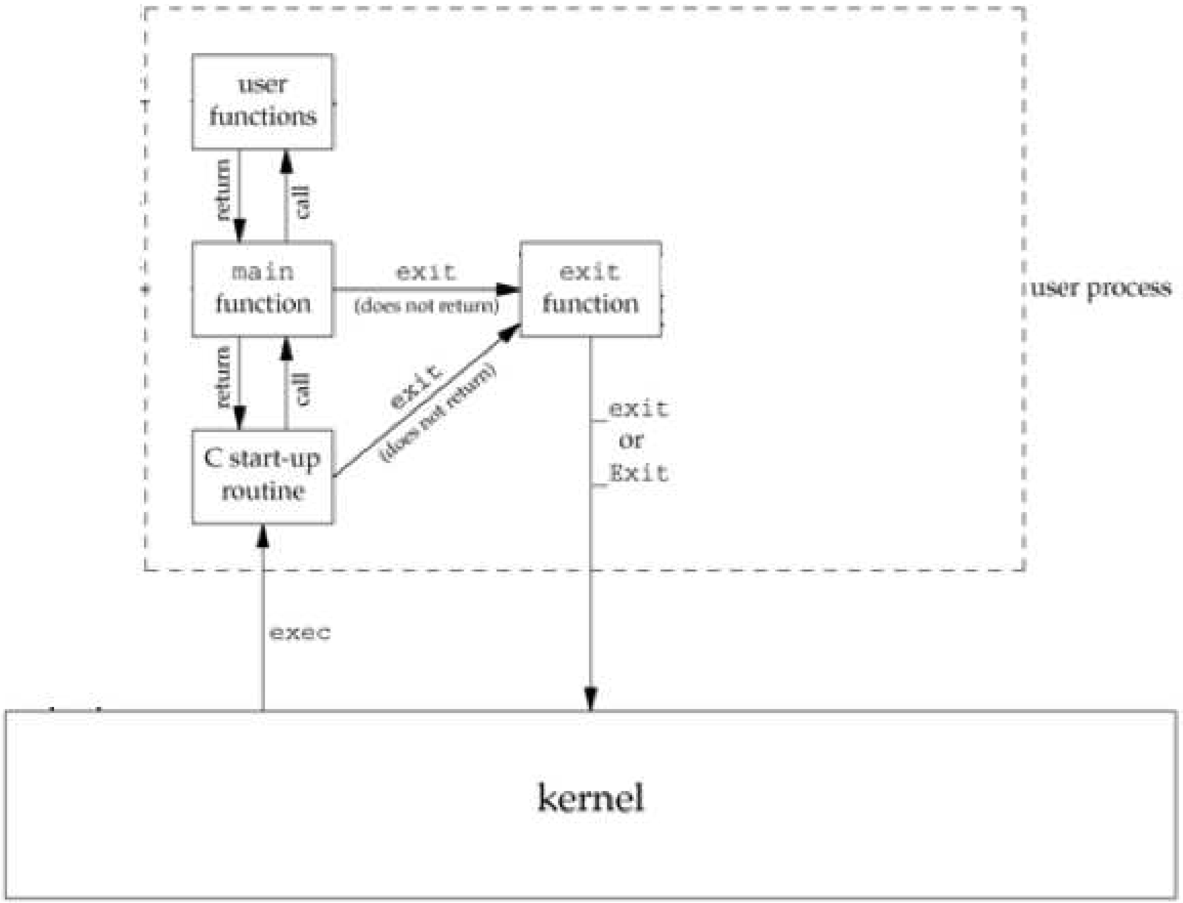

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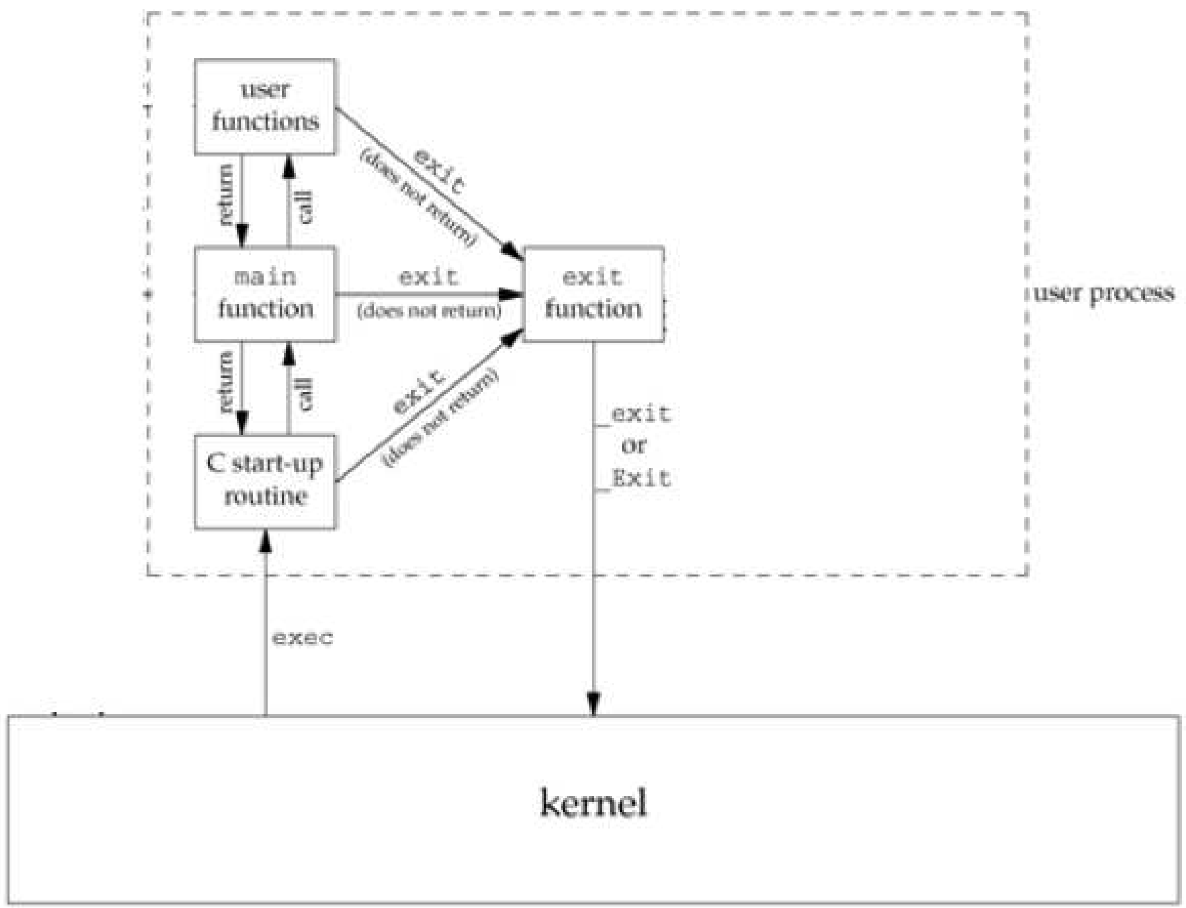

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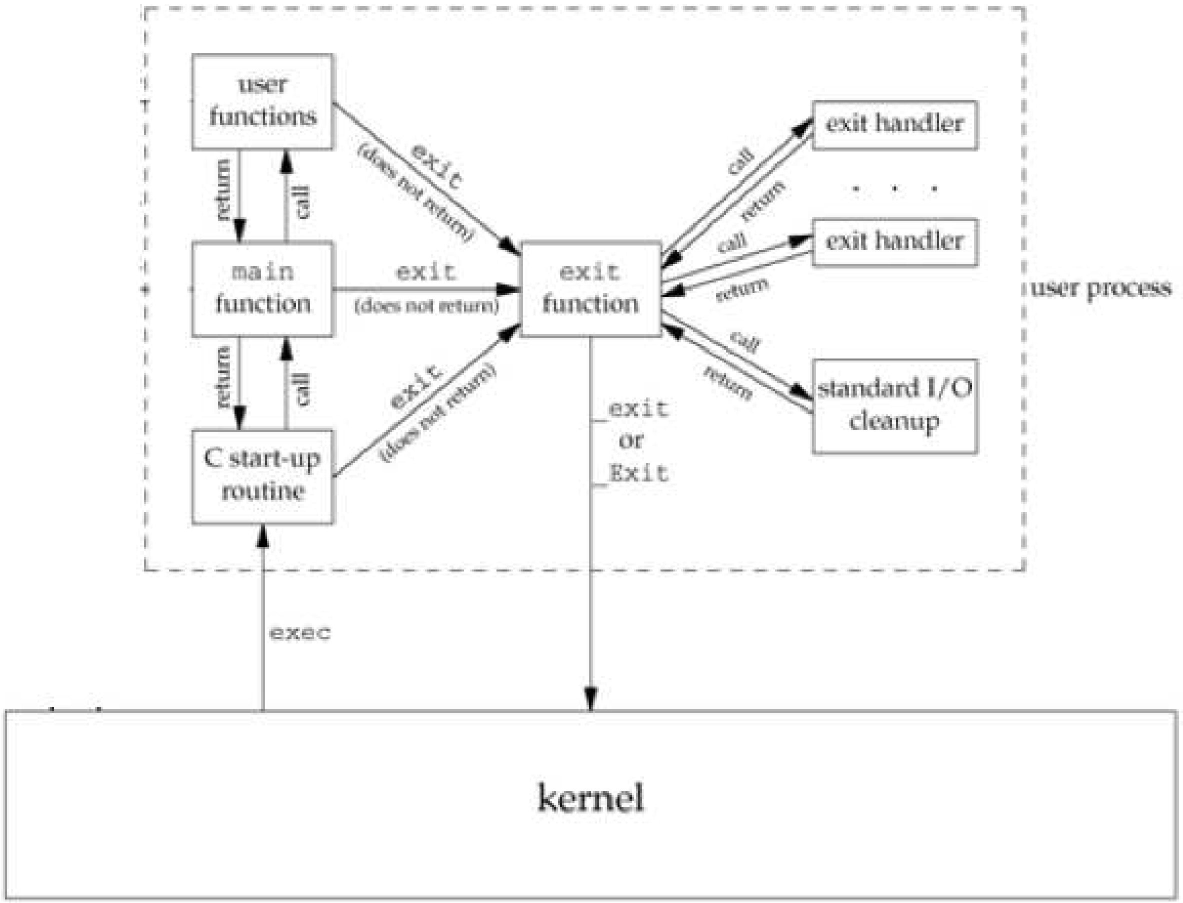

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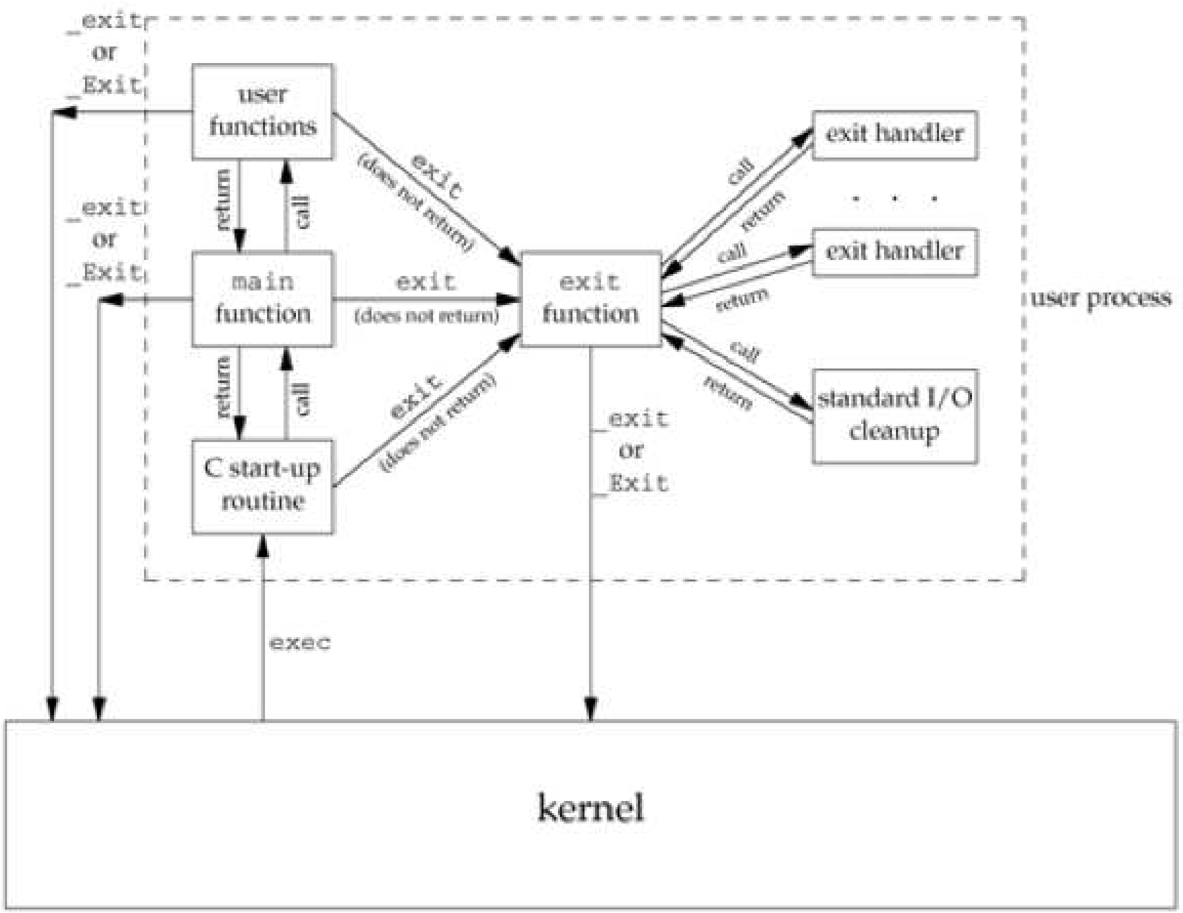

Exit codes

```
$ cc -Wall --std=c89 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 --std=c89 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;
```

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);
```

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

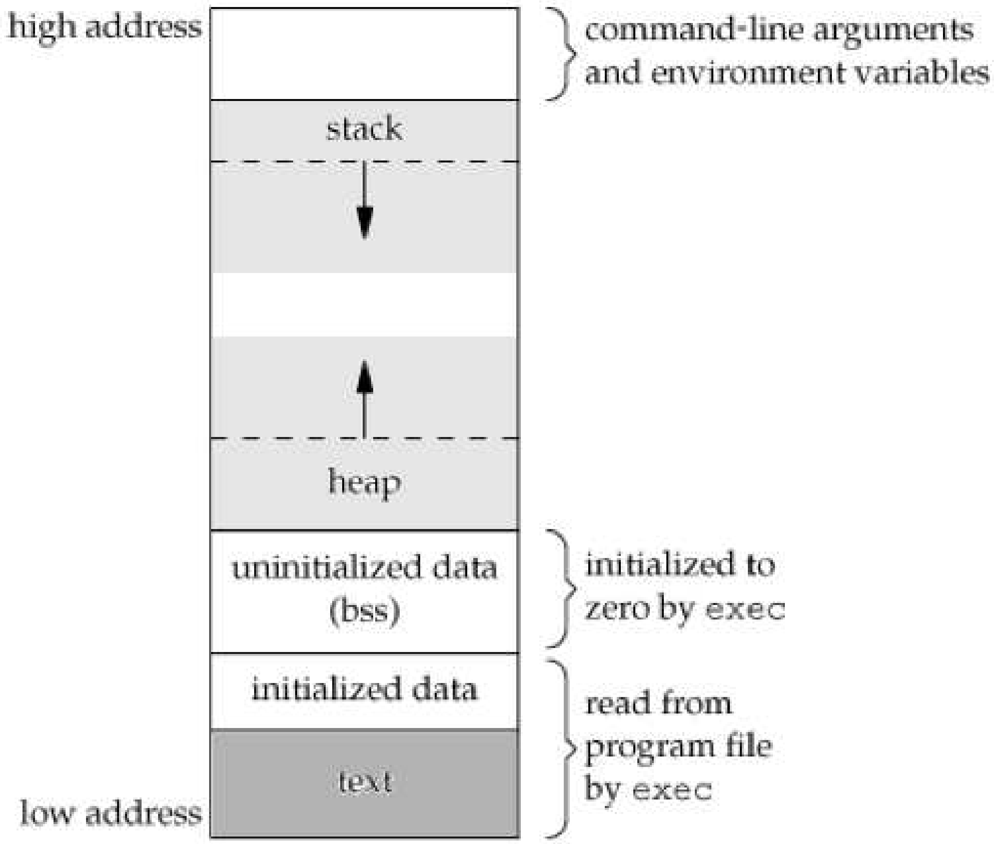
Memory Allocation

```
#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

```
argc at                                                      7F7FFFA3624C
argv at                                                      7F7FFFA36240
extern char **environ at                                           601C38
envp at                                                      7F7FFFA36238
_=./a.out from environ at                                    7F7FFFA40478
main (function) at                                                 400B6B
func (function) at                                                 400B40
func2 (function) at                                                400F07

num (initialized global int) at                                    601A58
num2 (uninitialized global int) at                                 601C48
string (initialized global char *) at                              601A50
string2 (uninitialized global char *) at                           601C40

array[] (uninitialized, fixed-size char[] on BSS) from:            601C60
array[] ends at                                                    60B8A0
stack (first variable inside main) begins around             7F7FFFA3FE94
func_array[] (like 'array[]', but on stack) from:            7F7FFFA36250
func_array[] ends at                                         7F7FFFA3FE90
malloced area begins at                                      740460F02000
malloced area ends at                                        740460F1A6A0

*environ[0] itself at                                        7F7FFFA3FEF8
environ[0] (_=./a.out) at                                    7F7FFFA40478
getenv("_") at                                               7F7FFFA4047A
getenv("USER") = jschauma at                                 7F7FFFA40598
getenv("USER") = root, after setenv                          740460F020A6

func: stack frame around                                     7F7FFFA3621C
func2 (from func): stack frame around                        7F7FFFA361FC
func popped off
func2 (from main): stack frame around                        7F7FFFA3621C
```

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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#include <sys/resource.h>

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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)

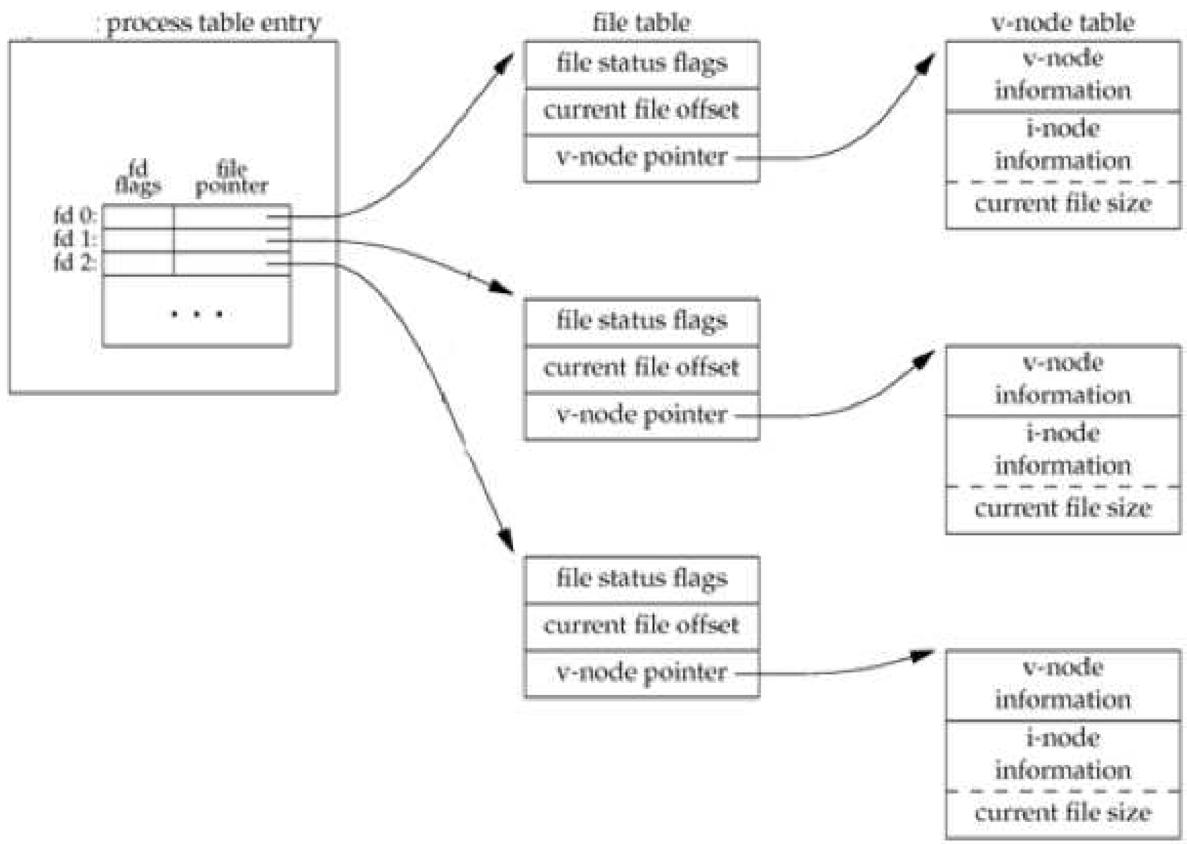
```
#include <unistd.h>

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:

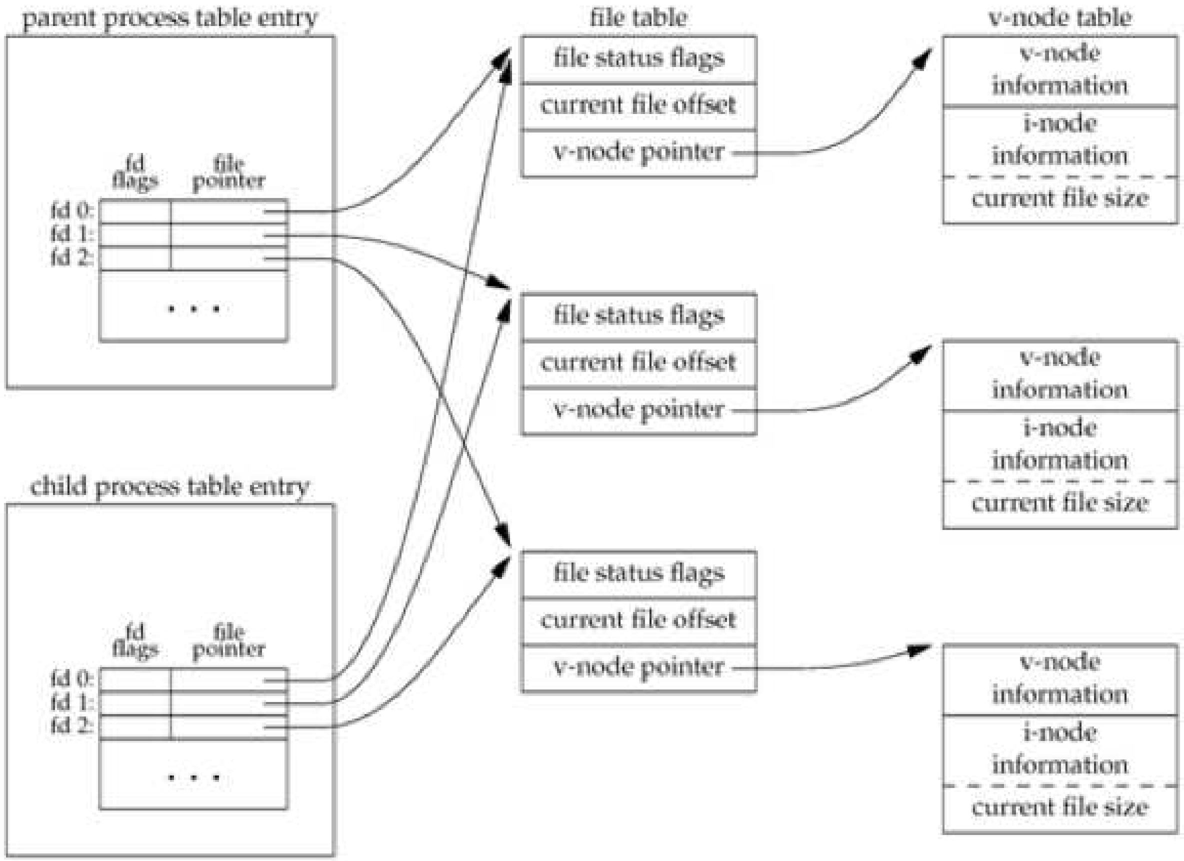
- The child process has a unique process ID.
- The child process has a different parent process ID (i.e., the process ID of the parent process).
- The child process has its own copy of the parent's descriptors.
- The child process' resource utilizations are set to 0.

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)`?

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```
$ 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

Thinking:

- trace process start through the source in NetBSD
- compare return codes on NetBSD of `printf(3)` vs `write(2)`; explain the difference
- Can you overflow the stack by setting many environment variables?
- What is the maximum size an environment variable can be? What happens when you set one larger than that (by e.g. manipulating `envp` directly)?

Other:

- update `memory-layout.c` to match the output on slide 35; play with `envp`, `environ`, `setenv(3)` etc. and see where things end up
- work on your midterm project!