
Processes, I/O Multiplexing

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20 November 2019



Web server



1

Main web server loop:

```
while (1) {  
    int clientfd = Accept(serverfd, NULL, NULL);  
    if (clientfd < 0) { fatal("Error accepting client connection"); }  
    server_chat_with_client(clientfd, webroot);  
    close(clientfd);  
}
```

Do you see any limitations of this design? ■

The server can only communicate with one client at a time

Concurrency



2

In general, servers (including web servers) can receive requests from many clients, *simultaneously*

Concurrency: Processing involving multiple tasks that can execute *asynchronously* with respect to each other

- E.g., multiple server/client conversations could be ongoing at the same time

It would be good if our web server could serve multiple clients concurrently

Concurrency vs. parallelism



3

Concurrency is distinct from *parallelism*

Consider two tasks, A and B, consisting of a sequence of instructions

A and B execute *concurrently* if relative ordering of instructions in A and B is not guaranteed

- I.e., an instruction in A could happen either ‘‘before’’ or ‘‘after’’ an instruction in B

A and B execute in *parallel* if instructions in A and B can execute *at the same time*

- Parallel execution requires multiple processors or cores

Parallelism implies concurrency, but concurrency does not imply parallelism

Concurrency with processes

Multi-process web server



5

Code on web page: `mp_webserver.zip`

- Only the main function is different than original `webserver.zip`

We'll discuss some of the interesting implementation issues

Processes



6

We've seen that the fork system call makes a new child process that is a duplicate of the parent process

- Including inheriting open files

Idea: each time the server accepts a connection, fork a child process to handle communication with that client

Multiple child processes can be executing concurrently

- OS kernel is responsible for allocating CPU time and handling I/O

Design



7

Issue: we may want to limit the number of simultaneous child processes

- Processes are somewhat heavyweight in terms of system resources

Before starting a child process, the server loop will wait to make sure fewer than the maximum number of child processes are running

wait, SIGCHLD



8

Several system calls exist to allow a parent process to receive a child process's exit status (wait, waitpid)

If a child terminates but the parent doesn't wait for it, it can become a zombie

A parent process can handle the SIGCHLD signal in order to be notified when a child process exits

Idea: parent will keep a count of how many child processes are running: use wait system call and SIGCHLD signal handler to detect when child processes complete

Signal handlers



9

The `signal` and `sigaction` system calls can be used to register a *signal handler* function for a particular signal

Signal handler for the `SIGCHLD` signal, so server is notified when a child process terminates:

```
/* current number of child processes running */
int g_num_procs;

void sigchld_handler(int signo) {
    int wstatus;
    wait(&wstatus);
    if (WIFEXITED(wstatus) || WIFSIGNALED(wstatus)) {
        g_num_procs--;
    }
}
```

Registering a signal handler

Register the `sigchld_handler` function as a handler for the `SIGCHLD` signal:

```
struct sigaction sa;  
sigemptyset(&sa.sa_mask);  
sa.sa_flags = 0;  
sa.sa_handler = sigchld_handler;  
sigaction(SIGCHLD, &sa, NULL);
```

When a child process terminates, the OS kernel will deliver a `SIGCHLD` signal, and the `sigchld_handler` function will be called

Preparing to fork

Before forking a child process, the server will wait until the number of processes is at least one less than the maximum:

```
while (g_num_procs >= MAX_PROCESSES) {  
    int wstatus;  
    wait(&wstatus);  
    if (WIFEXITED(wstatus) || WIFSIGNALED(wstatus))  
        g_num_procs--;  
}
```

```
int clientfd = Accept(serverfd, NULL, NULL);
```

```
g_num_procs++;  
pid_t pid = fork();
```

(Does this work?)

A data race

Consider the loop to wait until `g_num_procs` is less than the maximum:

```
while (g_num_procs >= MAX_PROCESSES) {  
    int wstatus;  
    wait(&wstatus);  
}
```

The thing to understand about signals is that, in general, they can be delivered at *any* time

Imagine that `SIGCHLD` is received *after* checking `g_num_procs` but *before* calling `wait`

Assuming that `sigchld_handler` detects that a child process has exited, the call to `wait` is unnecessary

- If `MAX_PROCESSES` is 1, server is deadlocked!

Another data race

Consider the following seemingly innocuous statement:

```
g_num_procs--;
```

The code generated by the compiler is likely to be something similar to:

```
int tmp = g_num_procs;  
tmp = tmp - 1;  
g_num_procs = tmp;
```

Note that tmp would really be a register

Consider what happens if a SIGCHLD signal is received *after* the initial value of g_num_procs is read, but *before* the updated value of tmp is stored back to g_num_procs ■

- A decrement of g_num_procs (in sigchld_handler) is lost, and the server no longer knows how many child processes are running!

Data race explained

Consider code implementing `g_num_procs--`:

```
// Assume tmp is a register  
int tmp = g_num_procs;  
  
tmp = tmp - 1;  
g_num_procs = tmp;
```

Data race explained

Consider code implementing `g_num_procs--`:

```
// Assume tmp is a register
int tmp = g_num_procs;    value of g_num_procs loaded to tmp

tmp = tmp - 1;
g_num_procs = tmp;
```


Data race explained

16



Consider code implementing `g_num_procs--`:

```
// Assume tmp is a register
```

```
int tmp = g_num_procs;
```

SIGCHLD handled, g_num_procs decremented

```
tmp = tmp - 1;
```

```
g_num_procs = tmp;
```

Data race explained

Consider code implementing `g_num_procs--`:

```
// Assume tmp is a register  
int tmp = g_num_procs;
```

```
tmp = tmp - 1;           tmp (old value of g_num_procs) decremented  
g_num_procs = tmp;
```

Data race explained

Consider code implementing `g_num_procs--`:

```
// Assume tmp is a register
```

```
int tmp = g_num_procs;
```

```
tmp = tmp - 1;
```

```
g_num_procs = tmp;           invalid count stored in g_num_procs
```

Data race explained

Consider code implementing `g_num_procs--`:

```
// Assume tmp is a register  
int tmp = g_num_procs;
```

```
tmp = tmp - 1;  
g_num_procs = tmp;
```

Oops!

A *data race* is a (potential) bug where two execution concurrent paths access a shared variable, and at least one path writes to the variable

- Paths ‘‘race’’ to access shared data, outcome depends on which one ‘‘wins’’

Data race is a special case of a *race condition*, a situation where an execution outcome depends on unpredictable event timing

A data race can cause data invariants to be violated (e.g., ‘‘g_num_procs accurately reflects the number of processes running’’)

Solution: *synchronization*

- Implement a protocol to avoid uncontrolled access to shared data

sigprocmask to the rescue

21



Signal handler functions are a potential cause of data races because they execute asynchronously with respect to normal program execution

- OS kernel could deliver a signal at any time

`sigprocmask`: allows program to block and unblock a specific signal or signals

Idea: block `SIGCHLD` whenever `g_num_procs` is being accessed by program code

- Prevent `sigchld_handler` from unexpectedly modifying `g_num_procs`

blocking/unblocking SIGCHLD

toggle_sigchld function:

```
void toggle_sigchld(int how) {  
    sigset_t sigs;  
    sigemptyset(&sigs);  
    sigaddset(&sigs, SIGCHLD);  
    sigprocmask(how, &sigs, NULL);  
}
```

Use to protect accesses to g_num_procs:

```
toggle_sigchld(SIG_BLOCK);  
g_num_procs++;  
toggle_sigchld(SIG_UNBLOCK);
```

Back to the web server!

Web server main loop:

```
while (1) {
    wait_for_avail_proc();
    int clientfd = accept connection from client
    toggle_sigchld(SIG_BLOCK);
    g_num_procs++;
    toggle_sigchld(SIG_UNBLOCK);
    pid_t pid = fork();
    if (pid < 0) {
        fatal("fork failed");
    } else if (pid == 0) { /* in child */
        server_chat_with_client(clientfd, webroot);
        close(clientfd);
        exit(0);
    }
    close(clientfd);
}
```


File descriptor sharing

When a subprocess is forked, the child process inherits the parent process's file descriptors

In the web server, the forked child process inherits `clientfd`, the socket connected to the client

- Convenient, since we want the child process to handle the client's request

Important: the *parent* process must close `clientfd`, otherwise the web server will have a file descriptor leak

- OS kernel imposes limit on number of open files per process
- Too many file descriptors open → can't open any more files or sockets

Limiting number of processes

Before calling fork, web server calls wait_for_avail_proc:

```
void wait_for_avail_proc(void) {
    toggle_sigchld(SIG_BLOCK);
    while (g_num_procs >= MAX_PROCESSES) {
        int wstatus;
        wait(&wstatus);
        if (WIFEXITED(wstatus) || WIFSIGNALED(wstatus)) {
            g_num_procs--;
        }
    }
    toggle_sigchld(SIG_UNBLOCK);
}
```

Calls wait if too many processes are currently running

Interrupted system calls

When a program receives a signal, it can interrupt the currently-executing system call

Special handling is required for accept system call to wait for connection from client:

```
int clientfd;
do {
    clientfd = accept(serverfd, NULL, NULL);
} while (clientfd < 0 && errno == EINTR);
if (clientfd < 0) {
    fatal("Error accepting client connection");
}
```

When `errno` is `EINTR`, it indicates that the system call was interrupted

Async-signal safety

While we're talking about signals...

Because of the potential of signal handlers to introduce data races into the program, some library functions aren't safe to call from a signal handler

Good idea to know these: `man signal-safety` on Linux

Standard I/O routines (`printf`, `scanf`, etc.) are not async-signal safe ☹

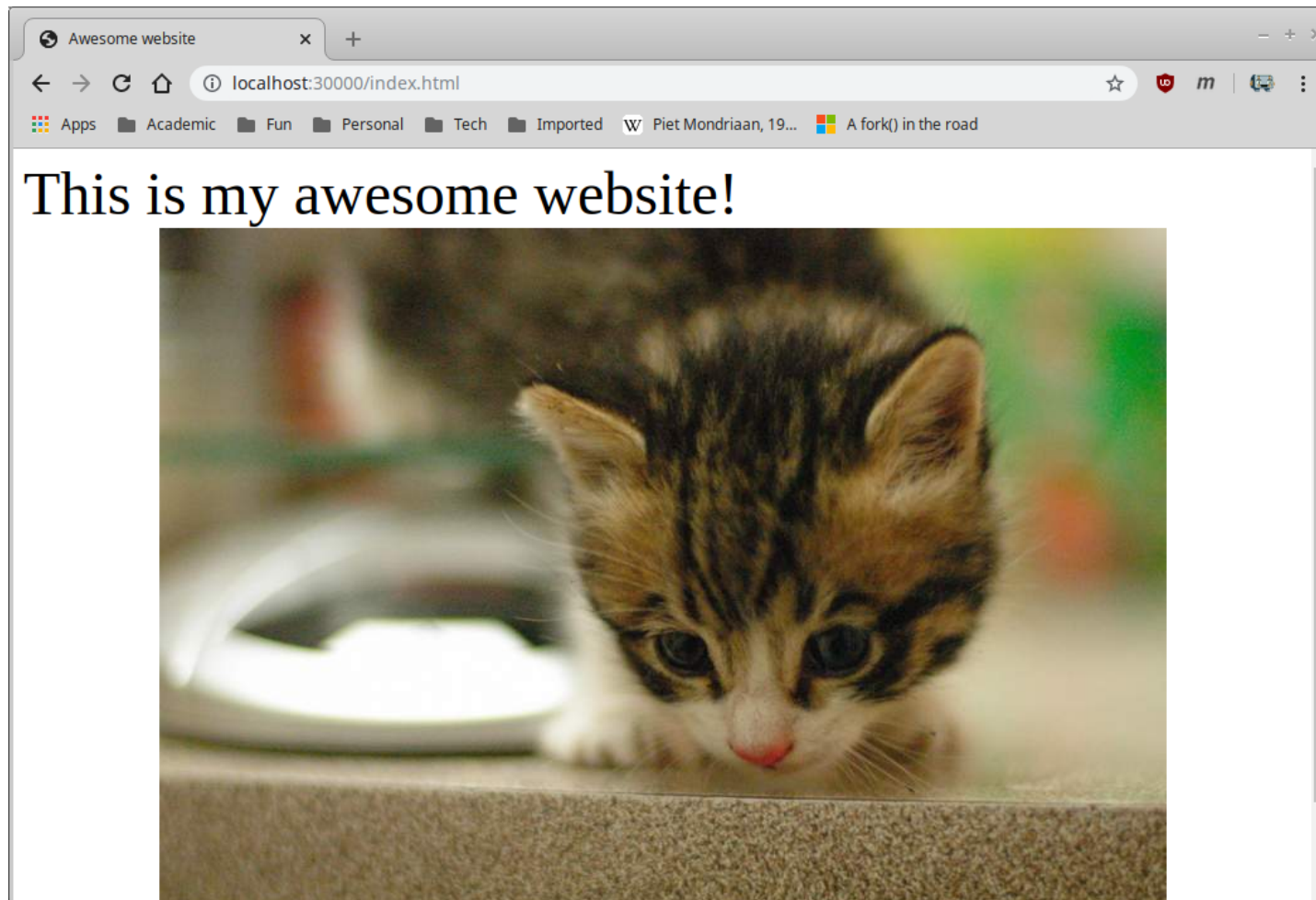
Putting it together

In the mp_webserver directory:

```
$ gcc -o mp_webserver main.c webserver.c csapp.c -lpthread  
$ ./mp_webserver 30000 ./site
```

Result

Visiting URL <http://localhost:30000/index.html>:





I/O multiplexing

I/O multiplexing

31



Alternative approach for supporting multiple simultaneous client connections

Basic idea: server maintains sets of active file descriptors (mostly client connections, but also for file I/O)

Main server loop uses `select` or `poll` system call to check which file descriptors are *ready*, meaning that a read or write can be performed without blocking

Compared to using processes or threads for concurrency:

- Advantage: higher performance
- Disadvantage: more code complexity

select system call

The select system call:

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

int select(int nfd, fd_set *readfds, fd_set *writefds,
           fd_set *exceptfds, struct timeval *timeout);
```

readfds, writefds, and exceptfds are sets of file descriptors

select waits until at least one file descriptor has become ready for reading or writing, or has an exceptional condition

- readfds, writefds, and exceptfds are *modified* to indicate the specific file descriptors that are ready
- timeout specifies maximum amount of time to wait, NULL means indefinitely

I/O multiplexing main loop

Pseudo-code:

```
create server socket, add to active fd set
```

```
while (1) {
```

```
    wait for fd to become ready (select or poll)
```

```
    if server socket ready
```

```
        accept a connection, add it to set
```

```
    for fd in client connections
```

```
        if fd is ready for reading, read and update connection state
```

```
        if fs is ready for writing, write and update connection state
```

```
}
```

Updating connection state

The main difficulty of using I/O multiplexing is that communication with clients is *event-driven*

When data is read from the client, event-processing code must figure out what to do with it

- Data read might be a partial message

Similar issue when sending data to client: data might need to be sent in chunks

Maintaining and updating state of client connections is much more complicated compared to code for process- or thread-based concurrency

- With these approaches, we can just use normal loops and control flow

Example: echo server

CS:APP textbook presents implementation of an echo server using I/O multiplexing

3x code compared to simple echo server!

Couroutines

One way to reduce the complexity of I/O multiplexing is to implement communication with clients using *coroutines*

Coroutines are, essentially, a lightweight way of implementing threads

Each client connection is implemented as a coroutine

When a client file descriptor finds that a client fd is ready for reading or writing, it *yields* to the client coroutine

The client corouting does the read or write (which won't block), updates state, and then yields back to the server control loop