Processes, I/O Multiplexing

David Hovemeyer

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Web server

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

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

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

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

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

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

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

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

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!

Data race

A *data race* is a (potential) bug where two concurrently-executing 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 sequencing

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

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: $\boxed{\texttt{man signal-safety}}$ on Linux

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

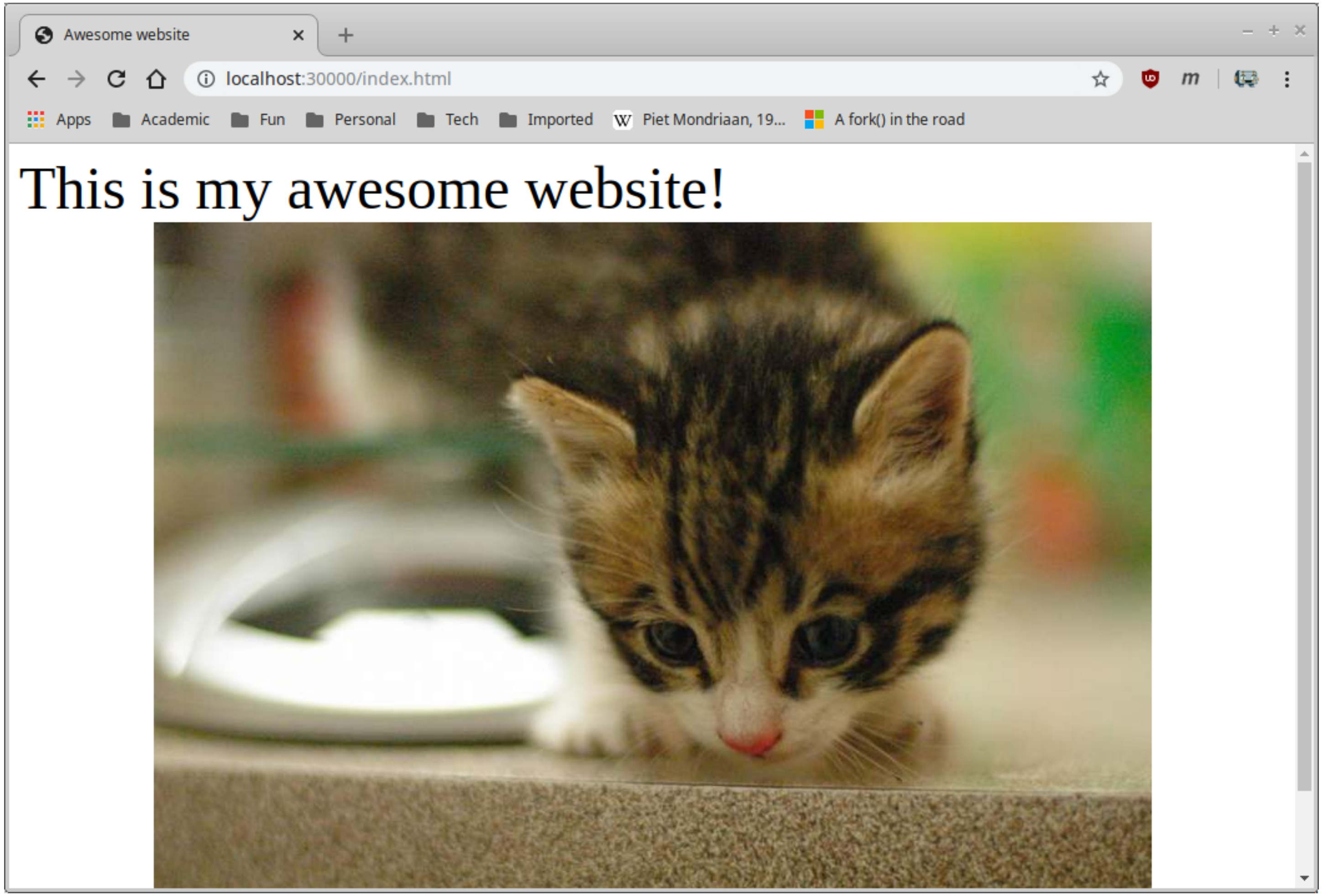
Putting it together

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

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 real or write can be performed without blocking

Compared to using processes or threads for concurrency:

- Advantage: higher performance
- Disadvantage: higher code complexity

select system call

The select system call:

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

int select(int nfds, 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/or 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!

Coroutines

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

- But with runtime cost closer to function call overhead

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