Lecture 32: Concurrency with processes

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April 23, 2025

601.229 Computer Systems Fundamentals

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?

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```

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

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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

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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

Clicker quiz!

Clicker quiz omitted from public slides

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

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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`

A data race

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

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- 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

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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`

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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;
g_num_procs = tmp;
```

tmp (old value of g_num_procs) decremented

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"

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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")

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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

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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

File descriptor sharing

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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 $\rightarrow$ 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`: