Lecture 32: Concurrency with processes

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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);
}</pre>
```

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 is distinct from parallelism

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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

ightharpoonup 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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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

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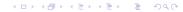
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Consider what happens if a SIGCHLD signal is received *after* the initial value of g_num_procs is read, but *before* the updated value of tmp is stored back to g_num_procs

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



Consider code implementing g_num_procs--:

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

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

Consider code implementing g_num_procs--:

```
\label{eq:continuous} \begin{split} & \text{int tmp} = \text{g\_num\_procs;} \\ & \text{tmp} = \text{tmp - 1;} \\ & \text{g\_num\_procs} = \text{tmp;} \end{split}
```

// Assume tmp is a register

SIGCHLD handled, g_num_procs decremented

```
Consider code implementing g_num_procs--:
```

```
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```

```
\label{eq:sume_tmp} \begin{subarray}{ll} // Assume tmp is a register \\ int tmp = g_num\_procs; \\ \\ tmp = tmp - 1; \\ \\ g_num\_procs = tmp; \\ \\ \hline \end{subarray} invalid count stored in g_num\_procs
```

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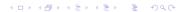
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A data race can cause data invariants to be violated (e.g., "g_num_procs accurately reflects the number of processes running")

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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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

ldea: 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!

exit(0):

close(clientfd);

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);

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

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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
- lacktriangle Too many file descriptors open ightarrow 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");
}</pre>
```

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:

