15-213
“The course that gives CMU its Zip!”

Concurrent Programming
April 24, 2008

Topics
- Limitations of iterative servers
- Process-based concurrent servers
- Threads-based concurrent servers
- Event-based concurrent servers
Concurrent Programming is Hard!

The human mind tends to be sequential

The notion of time is often misleading

Thinking about all possible sequences of events in a computer system is at least error prone and frequently impossible

Classical problem classes of concurrent programs:

- Races: outcome depends on arbitrary scheduling decisions elsewhere in the system
  - Example: who gets the last seat on the airplane?
- Deadlock: improper resource allocation prevents forward progress
  - Example: traffic gridlock
- Livelock / Starvation / Fairness: external events and/or system scheduling decisions can prevent sub-task progress
  - Example: people always jump in front of you in line

Many aspects of concurrent programming are beyond the scope of 15-213
Echo Server Operation

Client / Server Session

open_clientfd

Client

socket

connect

rio_readlineb

rio_writen

close

Server

socket

bind

listen

accept

rio_readlineb

rio_writen

close

open_listenfd

Connection request

Await connection request from next client

EOF
Iterative Servers

Iterative servers process one request at a time.

client 1

- call connect
- ret connect
- call write
- ret write
- close

server

- call accept
- ret accept
- read
- close
- call accept
- ret accept
- read
- close

client 2

- call connect
- ret connect
- call write
- ret write
- close
- ret connect
- call write
- ret write
- close
Fundamental Flaw of Iterative Servers

Solution: use **concurrent servers** instead.

- Concurrent servers use multiple concurrent flows to serve multiple clients at the same time.
Concurrent Servers: Multiple Processes

Concurrent servers handle multiple requests concurrently.

- User goes out to lunch
- Client 1 blocks waiting for user to type in data

Client 1
- call connect
- ret connect
- call fgets
- User goes out to lunch
- Client 1 blocks waiting for user to type in data

Server
- call accept
- ret accept
- fork
- child 1
  - call read
- child 2
  - call read
  - write
  - close
  - end read
  - close

Client 2
- call connect
- ret connect
- call fgets
- write
- call read
- close
Three Basic Mechanisms for Creating Concurrent Flows

1. Processes
   - Kernel automatically interleaves multiple logical flows.
   - Each flow has its own private address space.

2. Threads
   - Kernel automatically interleaves multiple logical flows.
   - All flows share the same address space.

3. I/O multiplexing with `select()`
   - Programmer manually interleaves multiple logical flows.
   - All flows share the same address space.
   - Popular for high-performance server designs.
Review: Sequential Server

```c
int main(int argc, char **argv) {
    int listenfd, connfd;
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen = sizeof(clientaddr);
    listenfd = Open_listenfd(port);
    while (1) {
        connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
        echo(connfd);
        Close(connfd);
    }
    exit(0);
}
```

- Accept a connection request
- Handle echo requests until client terminates
void echo(int connfd)
{
    size_t n;
    char buf[MAXLINE];
    rio_t rio;

    Rio_readinitb(&rio, connfd);
    while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
        printf("server received %d bytes\n", n);
        Rio_writen(connfd, buf, n);
    }
}
Echo Server: accept Illustrated

1. Server blocks in accept(), waiting for connection request on listening descriptor listenfd.

2. Client makes connection request by calling and blocking in connect().

3. Server receives connfd from accept(). Client returns from connect(). Connection is now established between clientfd and connfd.
Process-Based Concurrent Server

```c
int main(int argc, char **argv) {
    int listenfd, connfd;
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen = sizeof(clientaddr);

    Signal(SIGCHLD, sigchld_handler);
    listenfd = Open_listenfd(port);
    while (1) {
        connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
        if (Fork() == 0) {
            Close(listenfd); /* Child closes its listening socket */
            echo(connfd); /* Child services client */
            Close(connfd); /* Child closes connection with client */
            exit(0); /* Child exits */
        }
        Close(connfd); /* Parent closes connected socket (important!) */
    }
}
```

Fork separate process for each client
Does not allow any communication between different client handlers
Process-Based Concurrent Server (cont)

```c
void sigchld_handler(int sig) {
    while (waitpid(-1, 0, WNOHANG) > 0)
        ;
    return;
}
```

- Reap all zombie children
Process Execution Model

- Each client handled by independent process
- No shared state between them
- When child created, each has copies of listenfd and connfd
  - Parent must close connfd, child must close listenfd
Implementation Issues With Process-Based Designs

Server must reap zombie children
  - to avoid fatal memory leak.

Server must close its copy of connfd.
  - Kernel keeps reference count for each socket/open file.
  - After fork, $\text{refcnt} (\text{connfd}) = 2$.
  - Connection will not be closed until $\text{refcnt} (\text{connfd}) == 0$. 
Pros and Cons of Process-Based Designs

+ Handles multiple connections concurrently

+ Clean sharing model
  - descriptors (no)
  - file tables (yes)
  - global variables (no)

+ Simple and straightforward.

- Additional overhead for process control.

- Nontrivial to share data between processes.
  - Requires IPC (interprocess communication) mechanisms
    FIFO’s (named pipes), System V shared memory and semaphores
Traditional View of a Process

Process = process context + code, data, and stack

Process context

Program context:
- Data registers
- Condition codes
- Stack pointer (SP)
- Program counter (PC)

Kernel context:
- VM structures
- Descriptor table
- brk pointer

Code, data, and stack

- Stack
- Shared libraries
- Run-time heap
- Read/write data
- Read-only code/data
Alternate View of a Process

**Process = thread + code, data, and kernel context**

Thread (main thread):
- Stack
- Thread context:
  - Data registers
  - Condition codes
  - Stack pointer (SP)
  - Program counter (PC)

Code and Data:
- Shared libraries
- Run-time heap
- Read/write data
- Read-only code/data

Kernel context:
- VM structures
- Descriptor table
- Brk pointer
A Process With Multiple Threads

Multiple threads can be associated with a process

- Each thread has its own logical control flow
- Each thread shares the same code, data, and kernel context
  - Share common virtual address space
- Each thread has its own thread id (TID)

Thread 1 (main thread)                      Shared code and data                      Thread 2 (peer thread)

Thread 1 context:
Data registers
Condition codes
SP1
PC1

stack 1

shared libraries
run-time heap
read/write data
read-only code/data

0

Kernel context:
VM structures
Descriptor table
brk pointer

stack 2

Thread 2 context:
Data registers
Condition codes
SP2
PC2
Logical View of Threads

Threads associated with process form a pool of peers.

- Unlike processes which form a tree hierarchy

Threads associated with process foo

shared code, data and kernel context

Process hierarchy

P0

P1

sh

sh

sh

foo

bar
Concurrent Thread Execution

Two threads run concurrently (are concurrent) if their logical flows overlap in time.
Otherwise, they are sequential.

Examples:
- Concurrent: A & B, A&C
- Sequential: B & C
Threads vs. Processes

How threads and processes are similar
- Each has its own logical control flow.
- Each can run concurrently.
- Each is context switched.

How threads and processes are different
- Threads share code and data, processes (typically) do not.
- Threads are somewhat less expensive than processes.
  - Process control (creating and reaping) is twice as expensive as thread control.
  - Linux/Pentium III numbers:
    - ~20K cycles to create and reap a process.
    - ~10K cycles to create and reap a thread.
Posix Threads (Pthreads) Interface

Pthreads: Standard interface for ~60 functions that manipulate threads from C programs.

- Creating and reaping threads.
  - pthread_create()
  - pthread_join()
- Determining your thread ID
  - pthread_self()
- Terminating threads
  - pthread_cancel()
  - pthread_exit()
  - exit() [terminates all threads], RET [terminates current thread]
- Synchronizing access to shared variables
  - pthread_mutex_init
  - pthread_mutex_[un]lock
  - pthread_cond_init
  - pthread_cond_[timed]wait
The Pthreads "Hello, world" Program

/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"

void *thread(void *vargp);

int main() {
    pthread_t tid;
    Pthread_create(&tid, NULL, thread, NULL);
    Pthread_join(tid, NULL);
    exit(0);
}

/* thread routine */
void *thread(void *vargp) {
    printf("Hello, world!\n");
    return NULL;
}
Execution of Threaded “hello, world”

main thread

call Pthread_create()
Pthread_create() returns

call Pthread_join()

main thread waits for peer thread to terminate

Pthread_join() returns

ext() terminates main thread and any peer threads

peer thread

printf() return NULL;
(peer thread terminates)
int main(int argc, char **argv) {
    int port = atoi(argv[1]);
    struct sockaddr_in clientaddr;
    int clientlen = sizeof(clientaddr);
    pthread_t tid;

    int listenfd = Open_listenefd(port);
    while (1) {
        int *connfdp = Malloc(sizeof(int));
        *connfdp = Accept(listenfd, (SA *) &clientaddr, &clientlen);
        Pthread_create(&tid, NULL, echo_thread, connfdp);
    }
}

- Spawn new thread for each client
- Pass it copy of connection file descriptor
- Note use of Malloc()!
  - Without corresponding Free()
Thread-Based Concurrent Server (cont)

/* thread routine */
void *echo_thread(void *vargp) {
    int connfd = *((int *)vargp);
    Pthread_detach(pthread_self());
    Free(vargp);
    echo(connfd);
    Close(connfd);
    return NULL;
}

- Run thread in “detached” mode
  - Runs independently of other threads
  - Reaped when it terminates
- Free storage allocated to hold clientfd
  - “Producer-Consumer” model
Threaded-Process Execution Model

- Multiple threads within single process
- Some state between them
  - File descriptors (in this example; usually more)
Potential Form of Unintended Sharing

```c
while (1) {
    int connfd = Accept(listenfd, (SA *) &clientaddr, &clientlen);
    Pthread_create(&tid, NULL, echo_thread, (void *) &connfd);
}
```

Why would both copies of vargp point to same location?
Issues With Thread-Based Servers

Must run “detached” to avoid memory leak.

- At any point in time, a thread is either joinable or detached.
  - Joinable thread can be reaped and killed by other threads.
    - must be reaped (with pthread_join) to free memory resources.
  - Detached thread cannot be reaped or killed by other threads.
    - resources are automatically reaped on termination.
- Default state is joinable.
  - use pthread_detach(pthread_self()) to make detached.

Must be careful to avoid unintended sharing.

- For example, what happens if we pass the address of connfd to the thread routine?
  - Pthread_create(&tid, NULL, thread, (void *)&connfd);

All functions called by a thread must be thread-safe

- (next lecture)
Pros and Cons of Thread-Based Designs

+ Easy to share data structures between threads
  - e.g., logging information, file cache.

+ Threads are more efficient than processes.

--- Unintentional sharing can introduce subtle and hard-to-reproduce errors!
  - The ease with which data can be shared is both the greatest strength and the greatest weakness of threads.
  - (next lecture)
Maintain a pool of connected descriptors.

Repeat the following forever:

- Use the Unix `select()` function to block until:
  
  (a) New connection request arrives on the listening descriptor.
  
  (b) New data arrives on an existing connected descriptor.

- If (a), add the new connection to the pool of connections.

- If (b), read any available data from the connection
  
  - Close connection on EOF and remove it from the pool.
The `select()` Function

`select()` sleeps until one or more file descriptors in the set `readset` ready for reading.

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

int select(int maxfdp1, fd_set *readset, NULL, NULL, NULL);
```

**readset**
- Opaque bit vector (max FD_SETSIZE bits) that indicates membership in a descriptor set.
- If bit k is 1, then descriptor k is a member of the descriptor set.

**maxfdp1**
- Maximum descriptor in descriptor set plus 1.
- Tests descriptors 0, 1, 2, ..., maxfdp1 - 1 for set membership.

select() returns the number of ready descriptors and sets each bit of `readset` to indicate the ready status of its corresponding descriptor.
Macros for Manipulating Set Descriptors

void FD_ZERO(fd_set *fdset);
  ▪ Turn off all bits in fdset.

void FD_SET(int fd, fd_set *fdset);
  ▪ Turn on bit fd in fdset.

void FD_CLR(int fd, fd_set *fdset);
  ▪ Turn off bit fd in fdset.

int FD_ISSET(int fd, *fdset);
  ▪ Is bit fd in fdset turned on?
Overall Structure

**Manage Pool of Connections**
- **listenfd:** Listen for requests from new clients
- **Active clients:** Ones with a valid connection

**Use select to detect activity**
- New request on listenfd
- Request by active client

**Required Activities**
- Adding new clients
- Removing terminated clients
- Echoing
Representing Pool of Clients

/*
 * echoservers.c - A concurrent echo server based on select
 */
#include "csapp.h"

typedef struct { /* represents a pool of connected descriptors */
    int maxfd;        /* largest descriptor in read_set */
    fd_set read_set;  /* set of all active descriptors */
    fd_set ready_set; /* subset of descriptors ready for reading */
    int nready;       /* number of ready descriptors from select */

    int maxi;         /* highwater index into client array */
    int clientfd[FD_SETSIZE]; /* set of active descriptors */
    rio_t clientrio[FD_SETSIZE]; /* set of active read buffers */
} pool;

int byte_cnt = 0; /* counts total bytes received by server */
Pool Example

- maxfd = 12
- maxi = 6
- read_set = { 3, 4, 5, 7, 10, 12 }

| clientfd | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |...
|----------|---|---|---|---|---|---|---|---|---|---|---|
|          | 10| 7 | 4 | -1| -1| 12| 5 | -1| -1| -1|...

- Active
- Inactive
- Never Used

listenfd = 3
Main Loop

```c
int main(int argc, char **argv) {
    int listenfd, connfd, clientlen = sizeof(struct sockaddr_in);
    struct sockaddr_in clientaddr;
    static pool pool;

    listenfd = Open_listenfd(argv[1]);
    init_pool(listenfd, &pool);

    while (1) {
        pool.ready_set = pool.read_set;
        pool.nready = Select(pool.maxfd+1, &pool.ready_set,
                              NULL, NULL, NULL);

        if (FD_ISSET(listenfd, &pool.ready_set)) {
            connfd = Accept(listenfd, (SA *)&clientaddr,&clientlen);
            add_client(connfd, &pool);
        }
        check_clients(&pool);
    }
}
```
Pool Initialization

```c
/* initialize the descriptor pool */
void init_pool(int listenfd, pool *p) {
    /* Initially, there are no connected descriptors */
    int i;
    p->maxi = -1;
    for (i=0; i< FD_SETSIZE; i++)
        p->clientfd[i] = -1;

    /* Initially, listenfd is only member of select read set */
    p->maxfd = listenfd;
    FD_ZERO(&p->read_set);
    FD_SET(listenfd, &p->read_set);
}
```
Initial Pool

- \text{listenfd} = 3
- \text{maxfd} = 3
- \text{maxi} = -1
- \text{read\_set} = \{ 3 \}

\begin{array}{c|c}
0 & -1 \\
1 & -1 \\
2 & -1 \\
3 & -1 \\
4 & -1 \\
5 & -1 \\
6 & -1 \\
7 & -1 \\
8 & -1 \\
9 & -1 \\
\vdots & \text{Never Used} \\
\end{array}
void add_client(int connfd, pool *p) /* add connfd to pool p */
{
    int i;
    p->nready--;

    for (i = 0; i < FD_SETSIZE; i++) /* Find available slot */
        if (p->clientfd[i] < 0) {
            p->clientfd[i] = connfd;
            Rio_readinitb(&p->clientrio[i], connfd);

            FD_SET(connfd, &p->read_set); /* Add desc to read set */

            if (connfd > p->maxfd) /* Update max descriptor num */
                p->maxfd = connfd;
            if (i > p->maxi) /* Update pool high water mark */
                p->maxi = i;
            break;
        }
    if (i == FD_SETSIZE) /* Couldn't find an empty slot */
        app_error("add_client error: Too many clients");
}
Adding Client with fd 11

- `listenfd = 3`
- `maxfd = 12`
- `maxi = 6`
- `read_set = { 3, 4, 5, 7, 10, 11, 12 }`

<table>
<thead>
<tr>
<th>clientfd</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>7</td>
<td>4</td>
<td>11</td>
<td>-1</td>
<td>12</td>
<td>5</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
</tbody>
</table>

- Active
- Inactive
- Active
- Never Used
void check_clients(pool *p) { /* echo line from ready descrs in pool p */
    int i, connfd, n;
    char buf[MAXLINE];
    rio_t rio;

    for (i = 0; (i <= p->maxi) && (p->nready > 0); i++) {
        connfd = p->clientfd[i];
        rio = p->clientrio[i];

        /* If the descriptor is ready, echo a text line from it */
        if (((connfd > 0) && (FD_ISSET(connfd, &p->read_set)))
            && ((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0)) {
            p->nready--;
            byte_cnt += n;
            Rio_writen(connfd, buf, n);
        } else /* EOF detected, remove descriptor from pool */
            Close(connfd);
            FD_CLR(connfd, &p->read_set);
            p->clientfd[i] = -1;
    }
}
Concurrency Limitations

- Current design will hang up if partial line transmitted
- Bad to have network code that can hang up if client does something weird
  - By mistake or maliciously
- Would require more work to implement more robust version
  - Must allow each read to return only part of line, and reassemble lines within server

```c
if ((connfd > 0) && (FD_ISSET(connfd, &p->ready_set))) {
    p->nready--;
    if ((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
        byte_cnt += n;
        Rio_writen(connfd, buf, n);
    }
}
```

Does not return until complete line received
Pro and Cons of Event-Based Designs

+ One logical control flow.
+ Can single-step with a debugger.
+ No process or thread control overhead.
  ▪ Design of choice for high-performance Web servers and search engines.

- Significantly more complex to code than process- or thread-based designs.
- Hard to provide fine-grained concurrency
  ▪ E.g., our example will hang up with partial lines.
Approaches to Concurrency

**Processes**
- Hard to share resources: Easy to avoid unintended sharing
- High overhead in adding/removing clients

**Threads**
- Easy to share resources: Perhaps too easy
- Medium overhead
- Not much control over scheduling policies
- Difficult to debug
  - Event orderings not repeatable

**I/O Multiplexing**
- Tedious and low level
- Total control over scheduling
- Very low overhead
- Cannot create as fine grained a level of concurrency