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

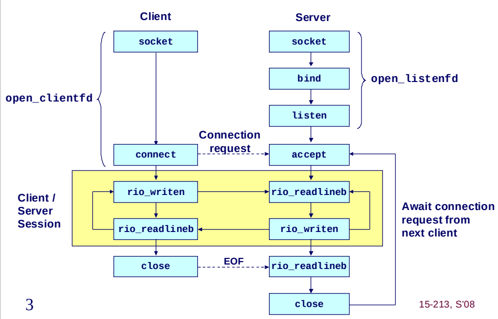
Thinking about all possible sequences of events in a computer system is at least error prone and frequently impossible

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

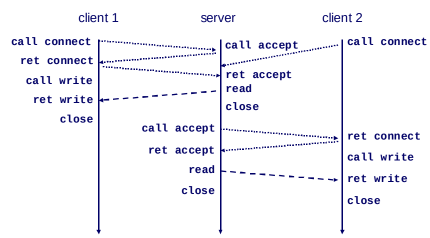
Many aspects of concurrent programming are beyond the scope of 15-213

Echo Server Operation

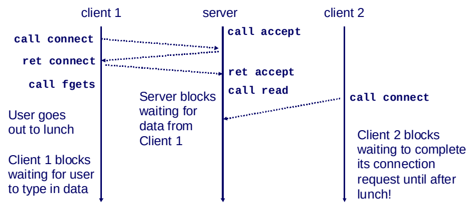


Iterative Servers

Iterative servers process one request at a time.



Fundamental Flaw of Iterative Servers

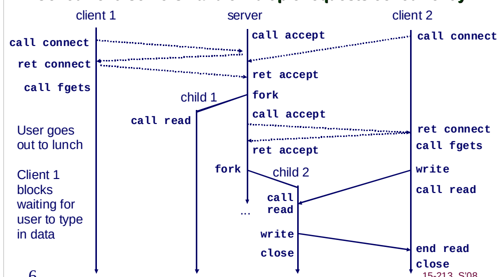


Solution: use *concurrent servers* instead.

- Concurrent servers use multiple concurrent flows to serve multiple clients at the same time.

Concurrent Servers: Multiple Processes

Concurrent servers handle multiple requests concurrently.



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

```
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);
}
```

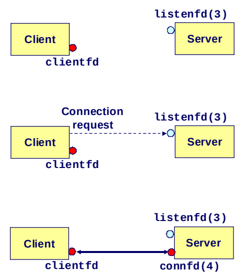
- Accept a connection request
- Handle echo requests until client terminates

Inner Echo Loop

```
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);
    }
}
```

- Server reads lines of text
- Echos them right back

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

```
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!) */
    }
}
```

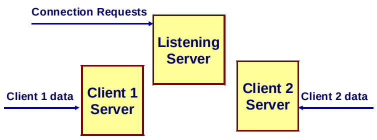
Fork separate process for each client
Does not allow any communication between different client handlers

Process-Based Concurrent Server (cont)

```
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, `refcnt(connfd) = 2`.
- Connection will not be closed until `refcnt(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.

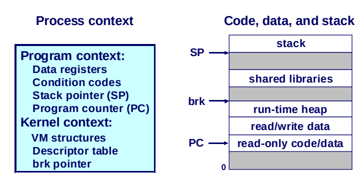
- Additional overhead for process control.

- Nontrivial to share data between processes.

- Requires IPC (interprocess communication) mechanisms
  - FIFO's (named pipes), System V shared memory and semaphores

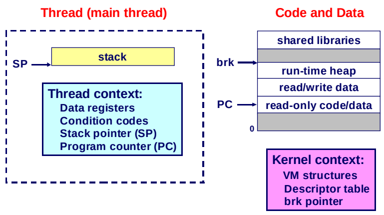
Traditional View of a Process

Process = process context + code, data, and stack



Alternate View of a Process

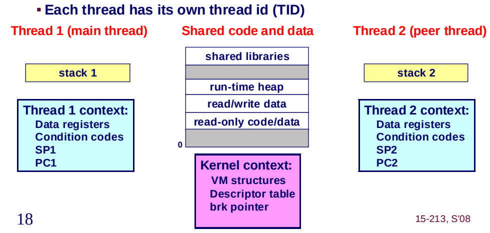
Process = thread + code, data, and kernel context



A Process With Multiple Threads

Multiple threads can be associated with a process

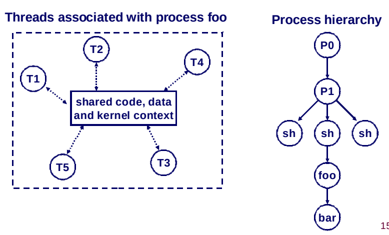
- Each thread has its own logical control flow
- Each thread shares the same code, data, and kernel context
  - Share common virtual address space
- Each thread has its own thread id (TID)



Logical View of Threads

Threads associated with process form a pool of peers.

- Unlike processes which form a tree hierarchy



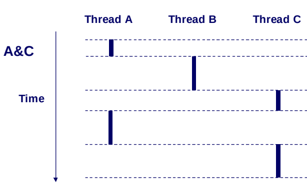
Concurrent Thread Execution

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

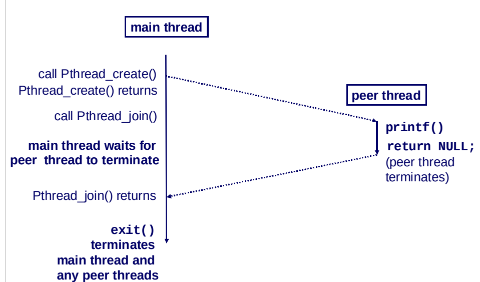
```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"

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;
}
```

Thread attributes (usually NULL)

*Thread arguments (void *p)*

*return value (void **p)*

Execution of Threaded"hello, world"



Thread-Based Concurrent Echo Server

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

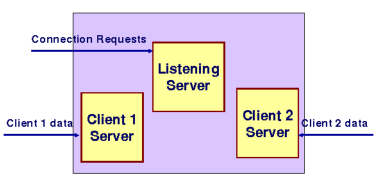
- Spawn new thread for each client
- Pass it copy of connection file descriptor
- Note use of Malloc()!
  - Without corresponding Free()

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

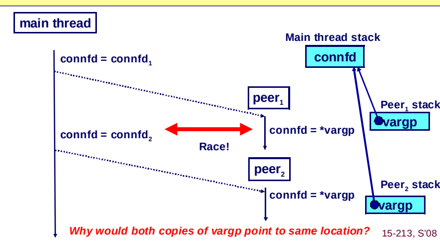
Threaded-Process Execution Model



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

Potential Form of Unintended Sharing

```
    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)

Event-Based Concurrent Servers Using I/O Multiplexing

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.

```
#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`.

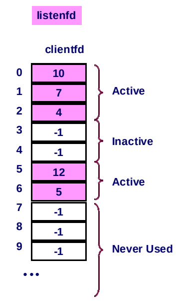
`void FD_CLR(int fd, fd_set *fdset);`

- 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

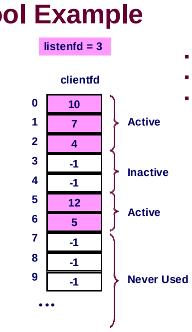
Required Activities

- 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 }

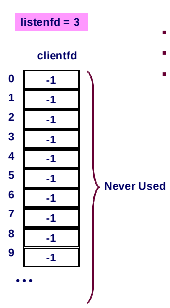
Main Loop

```
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

```
/* 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

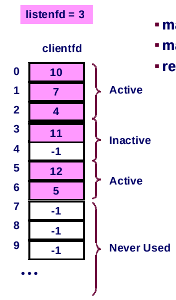


- maxfd = 3
- maxi = -1
- read_set = { 3 }

Adding Client

```
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



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

Checking Clients

```
void check_clients(pool *p) { /* echo line from ready descs 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->ready_set))) {
            p->nready--;
            if ((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
                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

```
        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

- 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

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