15-213
"The course that gives CMU its Zip!"

Concurrent Programming
April 27, 2004

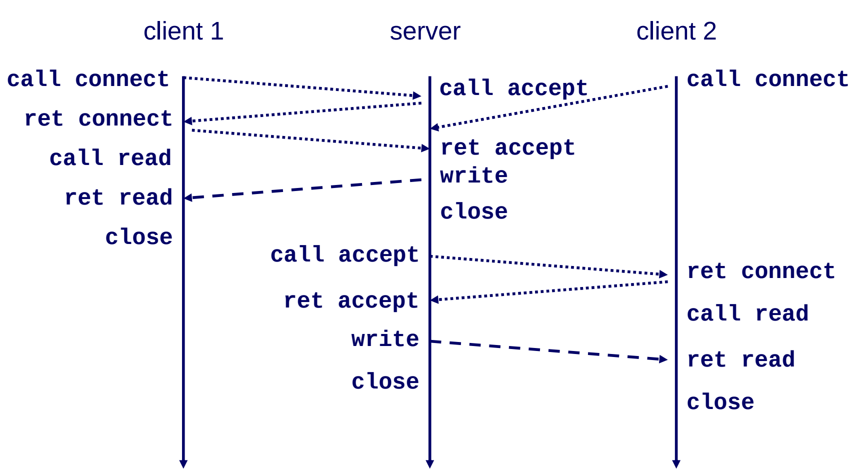
Topics
- Limitations of iterative servers
- Process-based concurrent servers
- Event-based concurrent servers
- Threads-based concurrent servers

Concurrent Programming is Hard!

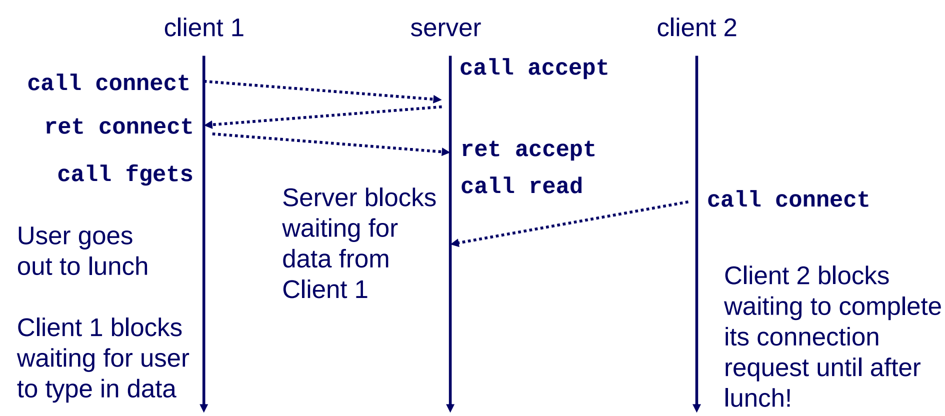
- The human mind tends to be sequential
- The notion of time is often misleading
- Thinking about all possible sequences of events in a computer system is at least error prone and frequently impossible
- Classical problem classes of concurrent programs:
  - Races: outcome depends on arbitrary scheduling decisions elsewhere in the system
  - Deadlock: improper resource allocation prevents forward progress
  - Lifelock / Starvation / Fairness: external events and/or system scheduling decisions can prevent sub-task progress
- Many aspects of concurrent programming are beyond the scope of 15-213

Iterative Servers

Iterative servers process one request at a time.



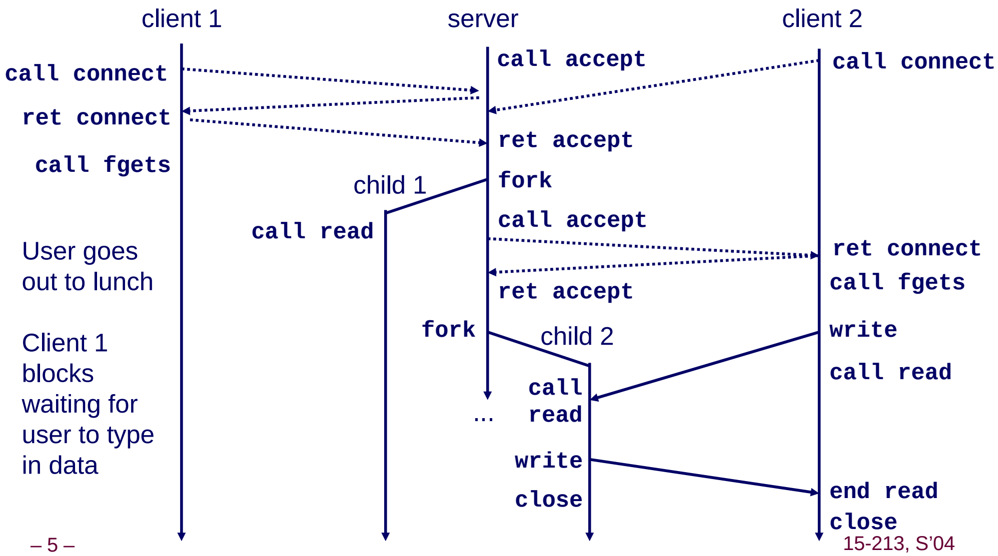
Fundamental Flaw of Iterative Servers



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. I/O multiplexing with `select()`

- User manually interleaves multiple logical flows.
- Each flow shares the same address space.
- Popular for high-performance server designs.

3. Threads

- Kernel automatically interleaves multiple logical flows.
- Each flow shares the same address space.
- Hybrid of processes and I/O multiplexing!

Process-Based Concurrent Server

```
/*
 * echoserverp.c - A concurrent echo server based on processes
 * Usage: echoserverp <port>
 */
#include <ics.h>
#define BUFSIZE 1024
void echo(int connfd);
void handler(int sig);

int main(int argc, char **argv) {
  int listenfd, connfd;
  int portno;
  struct sockaddr_in clientaddr;
  int clientlen = sizeof(struct sockaddr_in);

  if (argc != 2) {
    fprintf(stderr, "usage: %s <port>\n", argv[0]);
    exit(0);
  }
  portno = atoi(argv[1]);
  listenfd = open_listenfd(portno);
```


Process-Based Concurrent Server (cont)

```
 Signal(SIGCHLD, handler); /* parent must reap children! */

  /* main server loop */
  while (1) {
    connfd = Accept(listenfd, (struct sockaddr *) &clientaddr,
                    &clientlen));
    if (Fork() == 0) {
      Close(listenfd); /* child closes its listening socket */
      echo(connfd);    /* child reads and echoes input line */
      Close(connfd);   /* child is done with this client */
      exit(0);         /* child exits */
    }
    Close(connfd); /* parent must close connected socket! */
  }
}
```

Process-Based Concurrent Server (cont)

```
/* handler - reaps children as they terminate */
void handler(int sig) {
  pid_t pid;
  int stat;

  while ((pid = waitpid(-1, &stat, WNOHANG)) > 0)
    ;
  return;
}
```


Implementation Issues With Process-Based Designs

Server should restart `accept` call if it is interrupted by a transfer of control to the SIGCHLD handler

- Not necessary for systems with POSIX signal handling.
  - Our `Signal` wrapper tells kernel to automatically restart `accept`
- Required for portability on some older Unix systems.

Server must reap zombie children

- to avoid fatal memory leak.

Server must `close` its copy of `connfd`.

- Kernel keeps reference for each socket.
- 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

I/O multiplexing provides more control with less overhead...

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` are 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?

`select` Example

```
/*
 * main loop: wait for connection request or stdin command.
 * If connection request, then echo input line
 * and close connection. If stdin command, then process.
 */
 printf("server> ");
 fflush(stdout);

 while (notdone) {
    /*
     * select: check if the user typed something to stdin or
     * if a connection request arrived.
     */
    FD_ZERO(&readfds);          /* initialize the fd set */
    FD_SET(listenfd, &readfds); /* add socket fd */
    FD_SET(0, &readfds);        /* add stdin fd (0) */
    Select(listenfd+1, &readfds, NULL, NULL, NULL);
```


`select` Example (cont)

First we check for a pending event on stdin.

```
   /* if the user has typed a command, process it */
   if (FD_ISSET(0, &readfds)) {
      fgets(buf, BUFSIZE, stdin);
      switch (buf[0]) {
      case 'c': /* print the connection count */
         printf("Received %d conn. requests so far.\n", connectcnt);
         printf("server> ");
         fflush(stdout);
         break;
      case 'q': /* terminate the server */
         notdone = 0;
         break;
      default: /* bad input */
         printf("ERROR: unknown command\n");
         printf("server> ");
         fflush(stdout);
      }
   }
```

select Example (cont)

Next we check for a pending connection request.

```
  /* if a connection request has arrived, process it */
  if (FD_ISSET(listenfd, &readfds)) {
     connfd = Accept(listenfd,
                    (struct sockaddr *) &clientaddr, &clientlen);
     connectcnt++;

     bzero(buf, BUFSIZE);
     Rio_readn(connfd, buf, BUFSIZE);
     Rio_writen(connfd, buf, strlen(buf));
     Close(connfd);
  }
} /* while */
```


Event-based Concurrent Echo Server

```
/*
 * 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 */
```


Event-based Concurrent Server (cont)

```
int main(int argc, char **argv)
{
    int listenfd, connfd, clientlen = si
    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);
    }
}
```

```
typedef struct {
   int maxfd;
   fd_set read_set;
   fd_set ready_set;
   int nready;
   int maxi;
   int clientfd[FD_SETSIZE];
   rio_t clientrio[FD_SETSIZE];
} pool;
```


Event-based Concurrent Server (cont)

```
/* 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);
}
```

```
typedef struct {
   int maxfd;
   fd_set read_set;
   fd_set ready_set;
   int nready;
   int maxi;
   int clientfd[FD_SETSIZE];
   rio_t clientrio[FD_SETSIZE];
} pool;
```

Event-based Concurr t)

```
typedef struct {
   int maxfd;
   fd_set read_set;
   fd_set ready_set;
   int nready;
   int maxi;
   int clientfd[FD_SETSIZE];
   rio_t clientrio[FD_SETSIZE];
} pool;
```

```
void add_client(int connfd, 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");
}
```


Event-based Concurrent Server (cont)

```
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;
            }
        }
    }
}
```

```
typedef struct {
   int maxfd;
   fd_set read_set;
   fd_set ready_set;
   int nready;
   int maxi;
   int clientfd[FD_SETSIZE];
   rio_t clientrio[FD_SETSIZE];
} pool;
```

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.

- Can be vulnerable to denial of service attack
  - How?

Threads provide a middle ground between processes and I/O multiplexing...

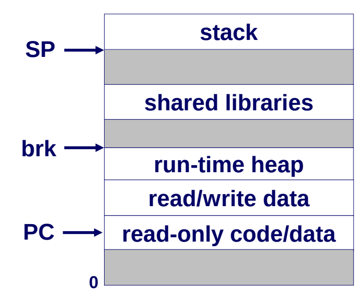
Traditional View of a Process

Process = process context + code, data, and stack

Process context

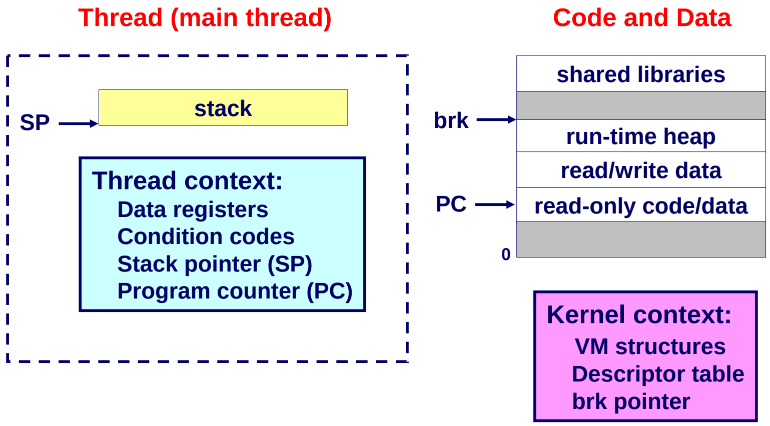
Program context:
Data registers
Condition codes
Stack pointer (SP)
Program counter (PC)
Kernel context:
VM structures
Descriptor table
brk pointer

Code, data, and stack



Alternate View of a Process

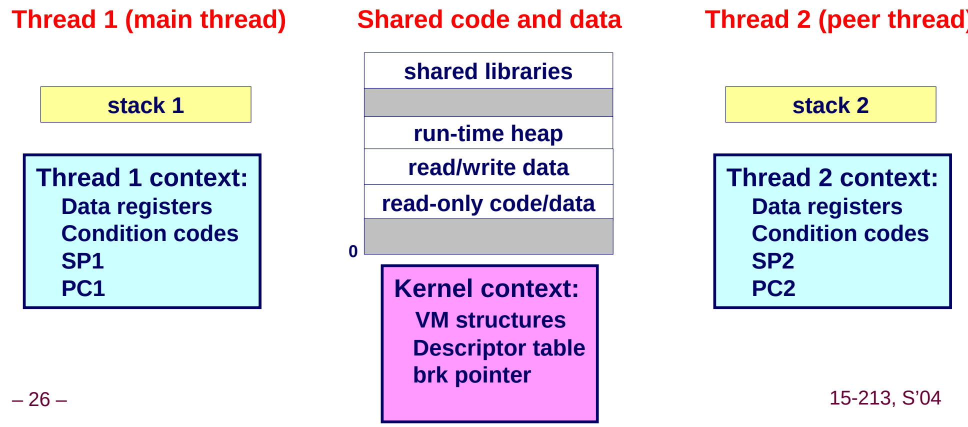
Process = thread + code, data, and kernel context



A Process With Multiple Threads

Multiple threads can be associated with a process

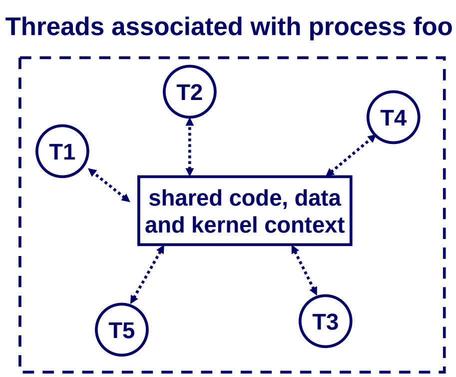
- Each thread has its own logical control flow (sequence of PC values)
- Each thread shares the same code, data, and kernel context
- Each thread has its own thread id (TID)

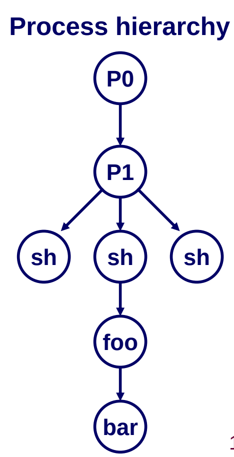


Logical View of Threads

Threads associated with a process form a pool of peers.

- Unlike processes which form a tree hierarchy





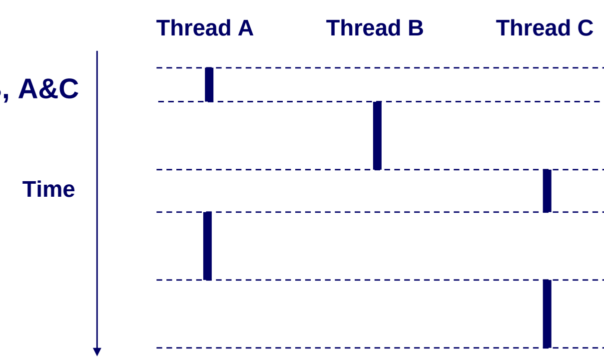
Concurrent Thread Execution

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 *(next lecture)*
  - `pthread_mutex_init`
  - `pthread_mutex_[un]lock`
  - `pthread_cond_init`
  - `pthread_cond_[timed]wait`

The Pthreads "hello, world" Program

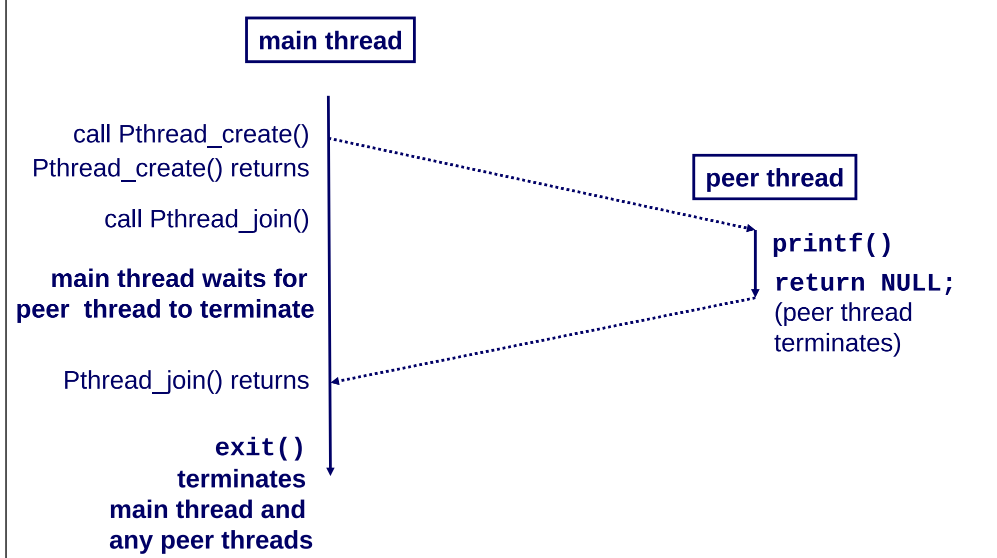
```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"

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 listenfd, *connfdp, port, clientlen;
    struct sockaddr_in clientaddr;
    pthread_t tid;

    if (argc != 2) {
        fprintf(stderr, "usage: %s <port>\n", argv[0]);
        exit(0);
    }
    port = atoi(argv[1]);

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


Thread-Based Concurrent Server (cont)

```
* thread routine */
void *thread(void *vargp)
{
    int connfd = *((int *)vargp);

    Pthread_detach(pthread_self());
    Free(vargp);

    echo_r(connfd); /* reentrant version of echo() */
    Close(connfd);
    return NULL;
}
```


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)