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

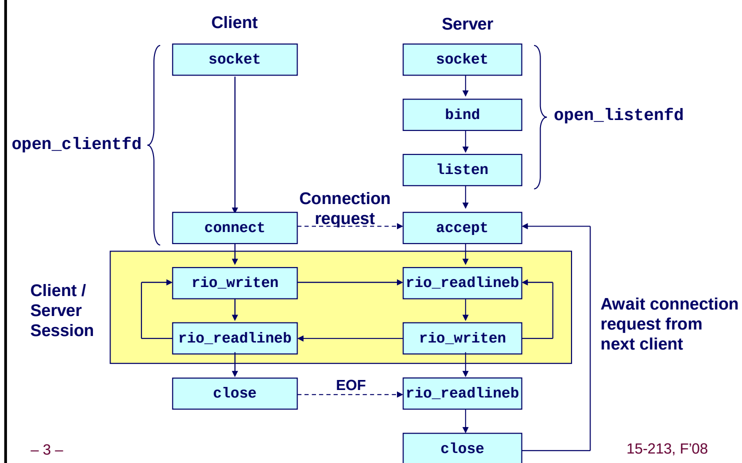
Concurrent Programming
November 13, 2008

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

Concurrent Programming is Hard!

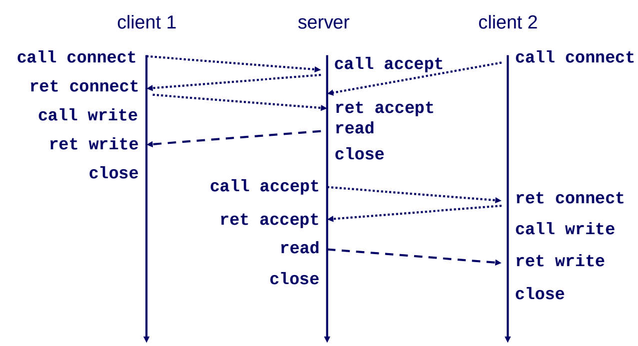
- The human mind tends to be sequential
- The notion of time is often misleading
- Thinking about all possible sequences of events in a computer system is at least error prone and frequently impossible
- Classical problem classes of concurrent programs:
  - Races: outcome depends on arbitrary scheduling 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

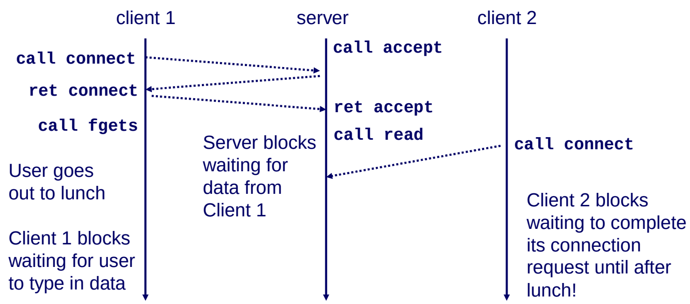


Iterative Servers

Iterative servers process one request at a time



Fundamental Flaw of Iterative Servers

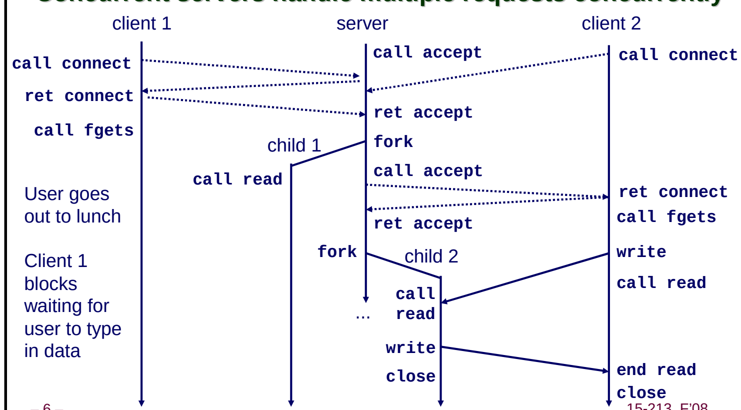


Solution: use *concurrent servers* instead

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

Concurrent Servers (approach #1): 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
- Each flow shares 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 Echo 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

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!) */
    }
}
```

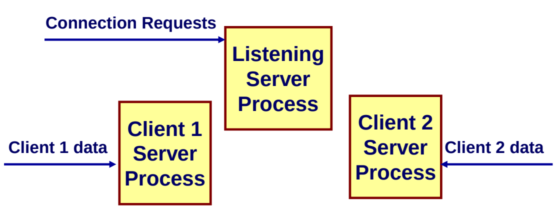
Fork separate process for each client
Does not allow any communication between different client handlers

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 have copies of listenfd and connfd
  - Parent must close connfd, child must close listenfd

Implementation Must-dos With Process-Based Designs

Listening server process must reap zombie children

- to avoid fatal memory leak

Listening server process must `close` its copy of `connfd`

- Kernel keeps reference 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

+ Handle multiple connections concurrently

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

+ Simple and straightforward

- Additional overhead for process control

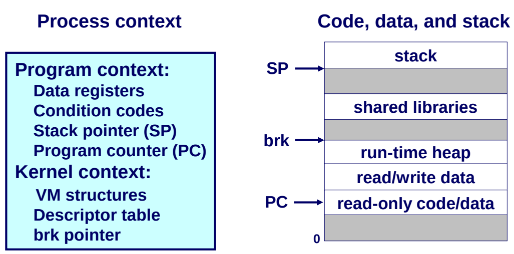
- Nontrivial to share data between processes
  - Requires IPC (interprocess communication) mechanisms
    - FIFO's (named pipes), System V shared memory and semaphores

Approach #2: Multiple Threads

Very similar to approach #1 (multiple processes)
- but, with threads instead of processes

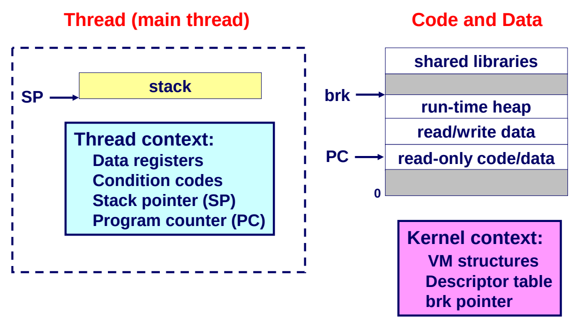
Traditional View of a Process

Process = process context + code, data, and stack



Alternate View of a Process

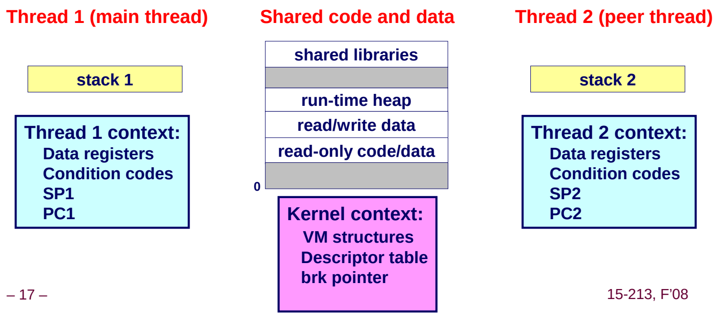
Process = thread + code, data, and kernel context



A Process With Multiple Threads

Multiple threads can be associated with a process

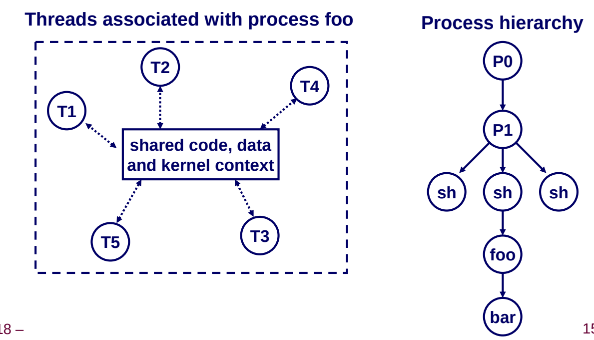
- Each thread has its own logical control flow
- Each thread shares the same code, data, and kernel context
  - Share common virtual address space (inc. stacks)
- Each thread has its own thread id (TID)



Logical View of Threads

Threads associated with process form a pool of peers

- Unlike processes which form a tree hierarchy



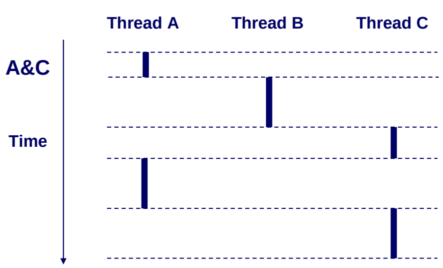
Concurrent Thread Execution

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 with others
- 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 (or less) 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

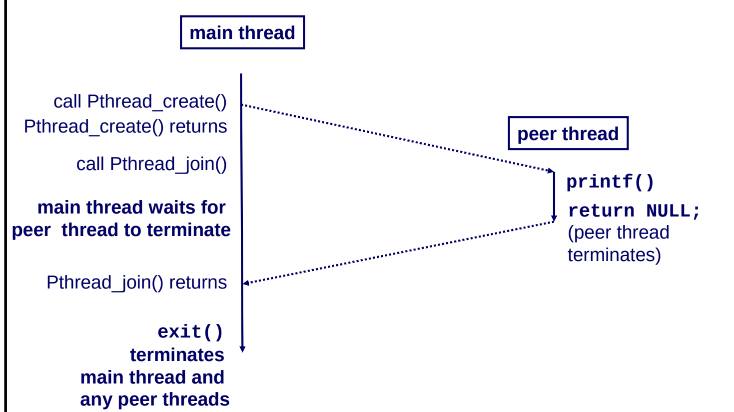
```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"

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);
    }
}
```

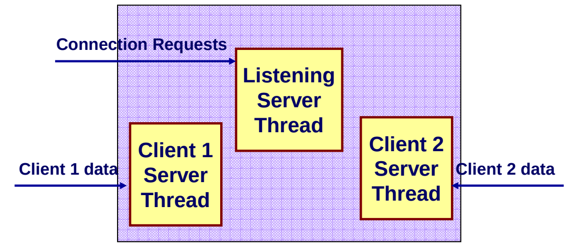
- Spawn new thread for each client
- Pass it copy of connection file descriptor
- Note use of Malloc()!
  - Without corresponding Free()

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

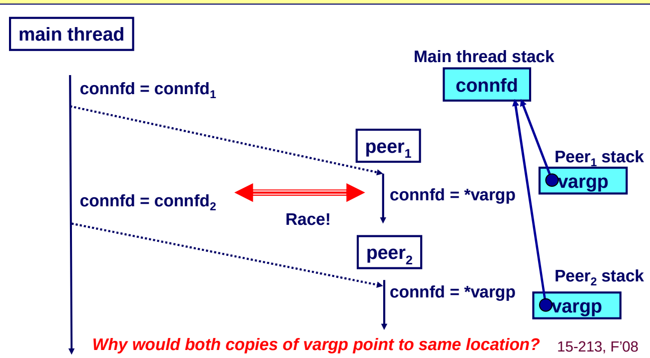
Process Execution Model



- 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)

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