15-213

"The course that gives CMU its Zip!"

Concurrent Servers

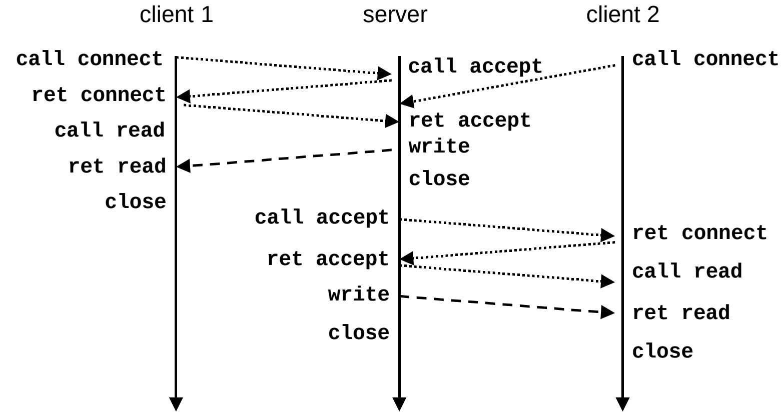
December 4, 2001

Topics

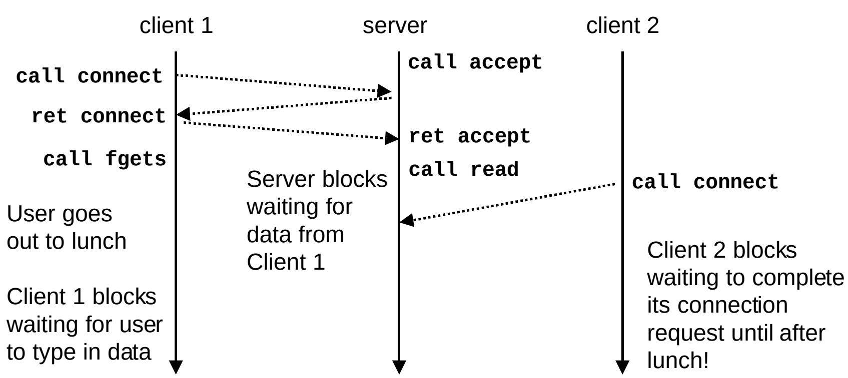
- **Limitations of iterative servers**
- **Process-based concurrent servers**
- **Threads-based concurrent servers**
- **Event-based concurrent servers**

Iterative servers

Iterative servers process one request at a time.



The fundamental flaw of iterative servers

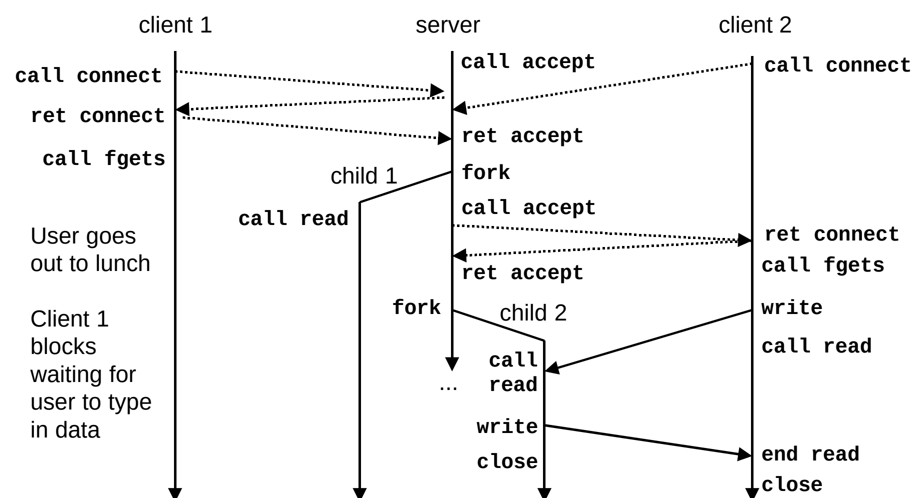


Solution: use *concurrent servers* instead.

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

Concurrent servers

Concurrent servers handle multiple requests concurrently.



Three basic mechanisms for creating concurrent flows

1. Processes
   - Kernel provides multiple control flows with separate address spaces.
   - Standard Unix process control and signals.
2. Threads
   - Kernel provides multiple control flows (threads) running in one process.
     - Each thread has its own stack and register values.
     - All threads share the same address space and open files.
   - POSIX threads (Pthreads) interface.
3. I/O multiplexing with `select()`
   - Manually interleave the processing of multiple open connections.
   - Use Unix `select()` function to notice pending socket activity.
   - Form of manual, application-level concurrency.
   - Popular for high-performance server designs.

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`.

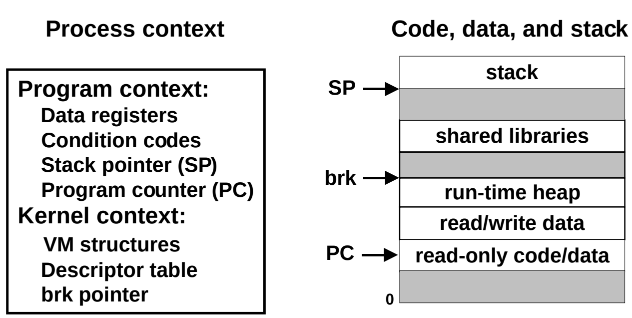
Pros and cons of process-based designs

- \+ 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

Threads provide more efficient flows with easier sharing of data between the flows

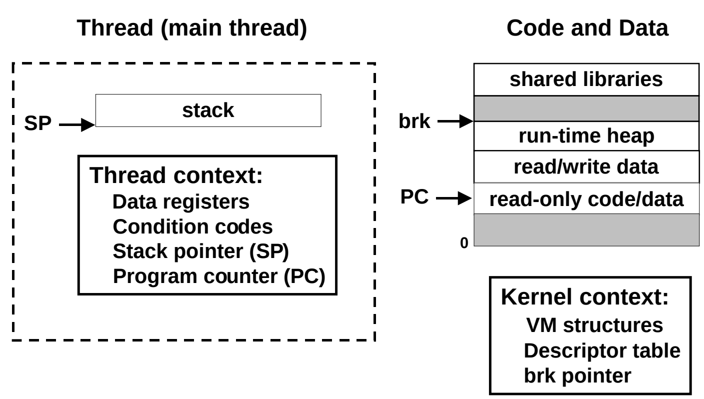
Traditional view of a process

Process = process context + code, data, and stack



Alternate view of a process

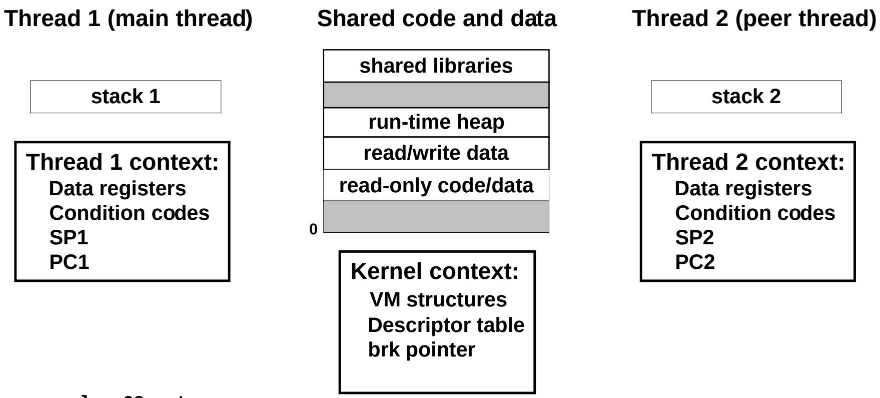
Process = thread + code, data, and kernel context



A process with multiple threads

Multiple threads can be associated with a process

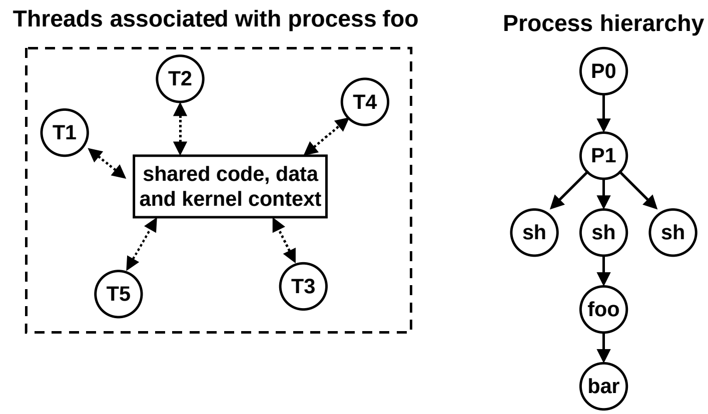
- Each thread has its own logical control flow (sequence of PC values)
- Each thread shares the same code, data, and kernel context
- Each thread has its own thread id (TID)



Logical view of threads

Threads associated with a process form a pool of peers.

- Unlike processes which form a tree hierarchy



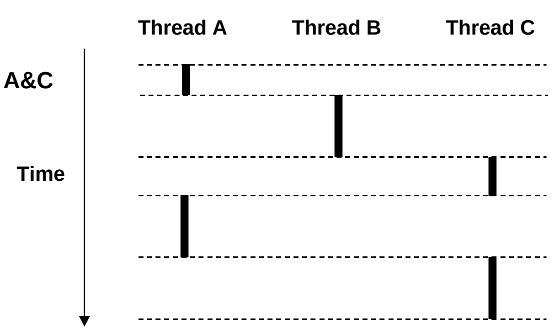
Concurrent thread execution

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**
  - `pthread_mutex_init`
  - `pthread_mutex_[un]lock`
  - `pthread_cond_init`
  - `pthread_cond_[timed]wait`

The Pthreads "hello, world" program

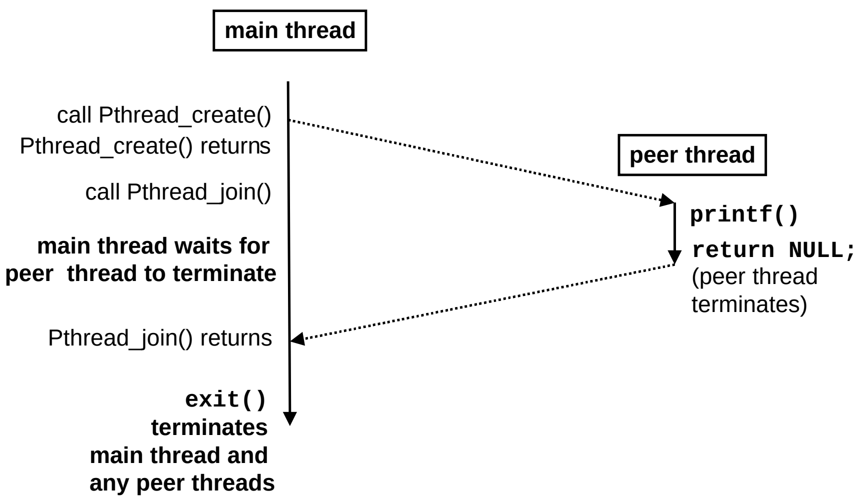
```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"

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 "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)*

Event-based concurrent servers

An event-based approach to concurrency:

- 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.

Writing an event-based server is akin to implementing your own application-specific threads package.

`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);
     Readn(connfd, buf, BUFSIZE);
     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"
#define BUFSIZE 1024

void echo(int connfd);

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

  fd_set allset; /* descriptor set for select */
  fd_set rset;   /* copy of allset for select */
  int maxfd;     /* max descriptor value for select */

  int client[FD_SETSIZE]; /* pool of connected descriptors */
  int maxi;      /* highwater index into client pool */
  int nready;    /* number of ready descriptors from select */
  int i, sockfd; /* misc */
```


Event-based concurrent server (cont)

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

  /* open the listening socket */
  listenfd = open_listenfd(portno);

  /* initialize the pool of active client connections */
  maxi = -1;
  maxfd = listenfd;
  for (i=0; i< FD_SETSIZE; i++)
    client[i] = -1;
  FD_ZERO(&allset);
  FD_SET(listenfd, &allset);
```


Event-based concurrent server (cont)

```
  /* main server loop */
  while (1) {
    rset = allset;

    /* Wait until one or more descriptors are ready to read */
    nready = Select(maxfd+1, &rset, NULL, NULL, NULL);
    ...
```

Event-based concurrent server (cont)

```
    /* PART I: a new connection request has arrived, so
       add a new connected descriptor to the pool */
    if (FD_ISSET(listenfd, &rset)) {
      connfd = Accept(listenfd, (struct_sockaddr *)
                      &clientaddr, &clientlen);
      nready--;

      /* update the client pool */
      for (i=0; i<FD_SETSIZE; i++)
        if (client[i] < 0) {
           client[i] = connfd;
           break;
        }
      if (i == FD_SETSIZE)
         app_error("Too many clients\n");

      /* update the read descriptor set */
      FD_SET(connfd, &allset);
      if (connfd > maxfd)
        maxfd = connfd;
      if (i > maxi)
         maxi = i;
    }
```


Event-based concurrent server (cont)

```
    /* PART II: check the pool of connected descriptors for
       client data to read */
    for (i = 0; (i <= maxi) && (nready > 0); i++) {
      sockfd = client[i];
      if ((sockfd > 0) && (FD_ISSET(sockfd, &rset))) {
        echo(sockfd);
        Close(sockfd);
        FD_CLR(sockfd, &allset);
        client[i] = -1;
        nready--;
      }
    } /* for */
  } /* while(1) */

} /* main */
```


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?**