# 15-213

*"The course that gives CMU its Zip!"*

# Concurrent Programming
# November 18, 2008

**Topics**

- Event-based concurrent servers
- Shared variables
- The need for synchronization
- Synchronizing with semaphores

`lecture-23.ppt`

## 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



## Appr. #3: 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);
```

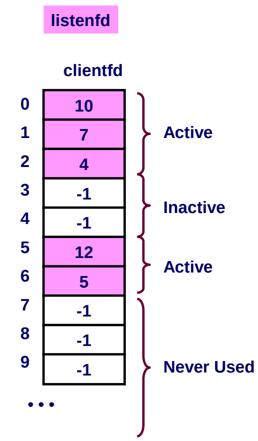
- Turn off bit `fd` in `fdset`

```
int FD_ISSET(int fd, *fdset);
```

- Is bit `fd` in `fdset` turned on?



# 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

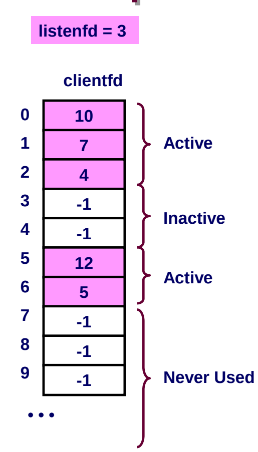


# Representing Pool of Clients

```
/*
 * 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);
    }
}
```

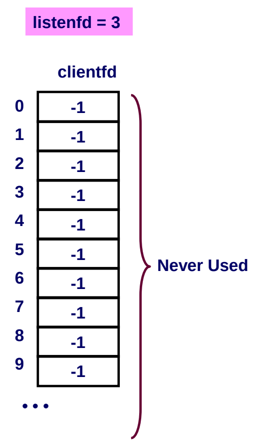


# Pool Initialization

```
/* 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 }



# Main Loop

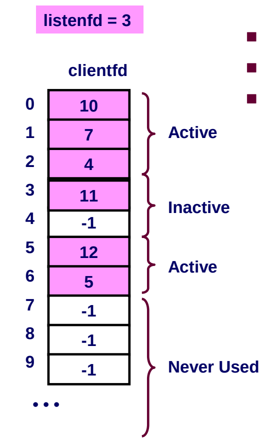
```
int main(int argc, char **argv)
{
    int listenfd, connfd, clientlen = sizeof(struct sockaddr_in);
    struct sockaddr_in clientaddr;
    static pool pool;

    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);
    }
}
```

# 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 gets stuck if partial line transmitted
- Bad to have network code that can get stuck 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

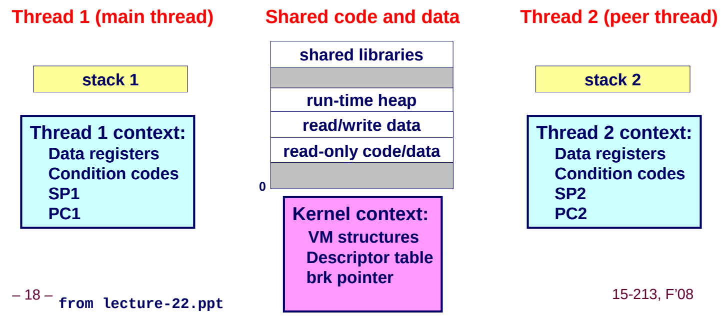
- Hard to provide fine-grained concurrency
  - E.g., our example will hang up with partial lines



# 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)






# 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)



# Shared Variables in Threaded C Programs

Question: Which variables in a threaded C program are shared variables?

- The answer is not as simple as “global variables are shared” and “stack variables are private”

Requires answers to the following questions:

- What is the memory model for threads?
- How are variables mapped to each memory instance?
- How many threads might reference each of these instances?

# Threads Memory Model

**Conceptual model:**

- Multiple threads run within the context of a single process
- Each thread has its own separate thread context
  - Thread ID, stack, stack pointer, program counter, condition codes, and general purpose registers
- All threads share the remaining process context
  - Code, data, heap, and shared library segments of the process virtual address space
  - Open files and installed handlers

**Operationally, this model is not strictly enforced:**

- While register values are truly separate and protected....
- Any thread can read and write the stack of any other thread

*Mismatch between the conceptual and operation model is a source of confusion and errors*



# Example of Threads Accessing Another Thread's Stack

```
char **ptr;  /* global */

int main()
{
    int i;
    pthread_t tid;
    char *msgs[N] = {
        "Hello from foo",
        "Hello from bar"
    };
    ptr = msgs;
    for (i = 0; i < 2; i++)
        Pthread_create(&tid,
            NULL,
            thread,
            (void *)i);
    Pthread_exit(NULL);
}
```

```
/* thread routine */
void *thread(void *vargp)
{
    int myid = (int) vargp;
    static int svar = 0;

    printf("[%d]: %s (svar=%d)\n",
         myid, ptr[myid], ++svar);
}
```

*Peer threads access main thread's stack indirectly through global ptr variable*



# Mapping Variables to Mem. Instances

*Global var*: 1 instance (`ptr` [data])

*Local automatic vars*: 1 instance (`i.m`, `msgs.m` )

*Local automatic var:* 2 instances (
`myid.p0`[peer thread 0's stack],
`myid.p1`[peer thread 1's stack]
)

```
char **ptr;  /* global */

int main()
{
    int i;
    pthread_t tid;
    char *msgs[N] = {
        "Hello from foo",
        "Hello from bar"
    };
    ptr = msgs;
    for (i = 0; i < 2; i++)
        Pthread_create(&tid,
            NULL,
            thread,
            (void *)i);
    Pthread_exit(NULL);
}
```

```
/* thread routine */
void *thread(void *vargp)
{
    int myid = (int)vargp;
    static int svar = 0;

    printf("[%d]: %s (svar=%d)\n",
         myid, ptr[myid], ++svar);
}
```

*Local static var*: 1 instance (`svar` [data])



# Shared Variable Analysis

**Which variables are shared?**

| Variable instance | Referenced by main thread? | Referenced by peer thread 0? | Referenced by peer thread 1? |
|---|---|---|---|
| `ptr` | yes | yes | yes |
| `svar` | no | yes | yes |
| `i.m` | yes | no | no |
| `msgs.m` | yes | yes | yes |
| `myid.p0` | no | yes | no |
| `myid.p1` | no | no | yes |

**Answer: A variable x is shared iff multiple threads reference at least one instance of x. Thus:**

- `ptr`, `svar`, and `msgs` are shared
- `i` and `myid` are NOT shared

## badcnt.c: An Improperly Synchronized Threaded Program

```
/* shared */
volatile unsigned int cnt = 0;
#define NITERS 100000000

int main() {
    pthread_t tid1, tid2;
    Pthread_create(&tid1, NULL,
                   count, NULL);
    Pthread_create(&tid2, NULL,
                   count, NULL);

    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    if (cnt != (unsigned)NITERS*2)
        printf("BOOM! cnt=%d\n",
               cnt);
    else
        printf("OK cnt=%d\n",
               cnt);
}
```

```
/* thread routine */
void *count(void *arg) {
    int i;
    for (i=0; i<NITERS; i++)
        cnt++;
    return NULL;
}
```

```
linux> ./badcnt
BOOM! cnt=198841183

linux> ./badcnt
BOOM! cnt=198261801

linux> ./badcnt
BOOM! cnt=198269672
```

**cnt should be equal to 200,000,000. What went wrong?!**



## Assembly Code for Counter Loop

C code for counter loop

```
for (i=0; i<NITERS; i++)
    cnt++;
```

Corresponding asm code

Head ($H_i$)

```
.L9:
        movl -4(%ebp),%eax
        cmpl $99999999,%eax
        jle .L12
        jmp .L10
```

Load cnt ($L_i$)
Update cnt ($U_i$)
Store cnt ($S_i$)

```
.L12:
        movl cnt,%eax       # Load
        leal 1(%eax),%edx   # Update
        movl %edx,cnt       # Store
```

Tail ($T_i$)

```
.L11:
        movl -4(%ebp),%eax
        leal 1(%eax),%edx
        movl %edx,-4(%ebp)
        jmp .L9
.L10:
```



## Concurrent Execution

**Key idea: In general, any sequentially consistent interleaving is possible, but some are incorrect!**

- $I_i$ denotes that thread i executes instruction I
- $\%eax_i$ is the contents of %eax in thread i's context

| i (thread) | $instr_i$ | $\%eax_1$ | $\%eax_2$ | cnt |
|---|---|---|---|---|
| 1 | $H_1$ | - | - | 0 |
| 1 | $L_1$ | 0 | - | 0 |
| 1 | $U_1$ | 1 | - | 0 |
| 1 | $S_1$ | 1 | - | 1 |
| 2 | $H_2$ | - | - | 1 |
| 2 | $L_2$ | - | 1 | 1 |
| 2 | $U_2$ | - | 2 | 1 |
| 2 | $S_2$ | - | 2 | 2 |
| 2 | $T_2$ | - | 2 | 2 |
| 1 | $T_1$ | 1 | - | 2 |

OK



## Concurrent Execution (cont)

**Incorrect ordering: two threads increment the counter, but the result is 1 instead of 2**

| i (thread) | $instr_i$ | $\%eax_1$ | $\%eax_2$ | cnt |
|---|---|---|---|---|
| 1 | $H_1$ | - | - | 0 |
| 1 | $L_1$ | 0 | - | 0 |
| 1 | $U_1$ | 1 | - | 0 |
| 2 | $H_2$ | - | - | 0 |
| 2 | $L_2$ | - | 0 | 0 |
| 1 | $S_1$ | 1 | - | 1 |
| 1 | $T_1$ | 1 | - | 1 |
| 2 | $U_2$ | - | 1 | 1 |
| 2 | $S_2$ | - | 1 | 1 |
| 2 | $T_2$ | - | 1 | 1 |

Oops!

# Concurrent Execution (cont)

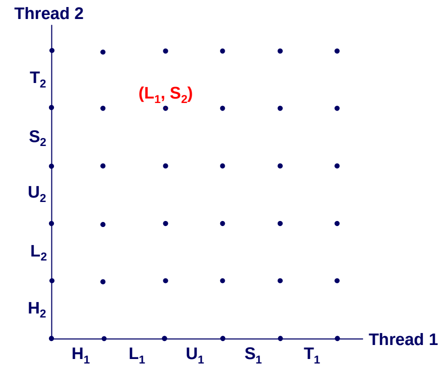
## How about this ordering?

| i (thread) | $instr_i$ | $\%eax_1$ | $\%eax_2$ | cnt |
|---|---|---|---|---|
| 1 | $H_1$ | | | |
| 1 | $L_1$ | | | |
| 2 | $H_2$ | | | |
| 2 | $L_2$ | | | |
| 2 | $U_2$ | | | |
| 2 | $S_2$ | | | |
| 1 | $U_1$ | | | |
| 1 | $S_1$ | | | |
| 1 | $T_1$ | | | |
| 2 | $T_2$ | | | |

**We can clarify our understanding of concurrent execution with the help of the *progress graph***



# Progress Graphs




**A *progress graph* depicts the discrete *execution state space* of concurrent threads.**

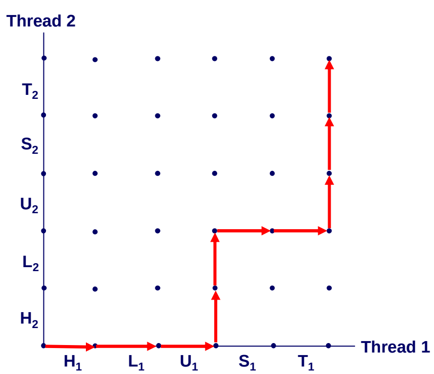
**Each axis corresponds to the sequential order of instructions in a thread.**

**Each point corresponds to a possible *execution state* $(Inst_1, Inst_2)$.**

**E.g., $(L_1, S_2)$ denotes state where thread 1 has completed $L_1$ and thread 2 has completed $S_2$.**



# Trajectories in Progress Graphs



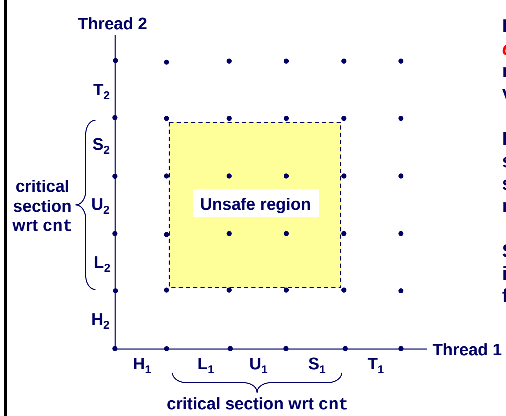

**A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.**

**Example:**

**H1, L1, U1, H2, L2, S1, T1, U2, S2, T2**



# Critical Sections and Unsafe Regions

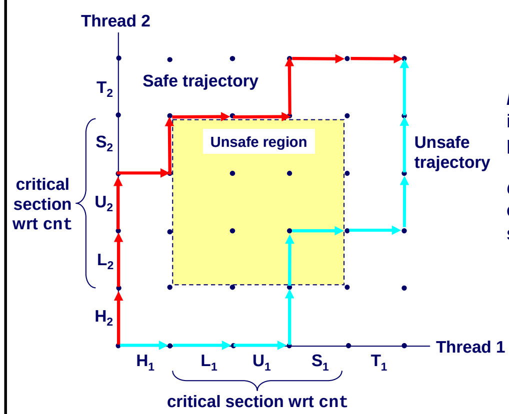



**L, U, and S form a *critical section* with respect to the shared variable `cnt`.**

**Instructions in critical sections (wrt to some shared variable) should not be interleaved.**

**Sets of states where such interleaving occurs form *unsafe regions*.**

# Safe and Unsafe Trajectories




***Def:*** A trajectory is ***safe*** iff it doesn't touch any part of an unsafe region.

***Claim:*** A trajectory is correct (wrt `cnt`) iff it is safe.



# Semaphores

***Question:*** **How can we guarantee a safe trajectory?**

- We must *synchronize* the threads so that they never enter an unsafe state.

***Classic solution*: Dijkstra's P and V operations on *semaphores*.**

- *semaphore:* non-negative integer synchronization variable.
  - P(s): [ `while (s == 0) wait(); s--;` ]
    - » Dutch for "Proberen" (test)
  - V(s): [ `s++;` ]
    - » Dutch for "Verhogen" (increment)
- OS guarantees that operations between brackets [ ] are executed indivisibly.
  - Only one P or V operation at a time can modify s.
  - When `while` loop in P terminates, only that P can decrement s.

**Semaphore invariant: *(s >= 0)***



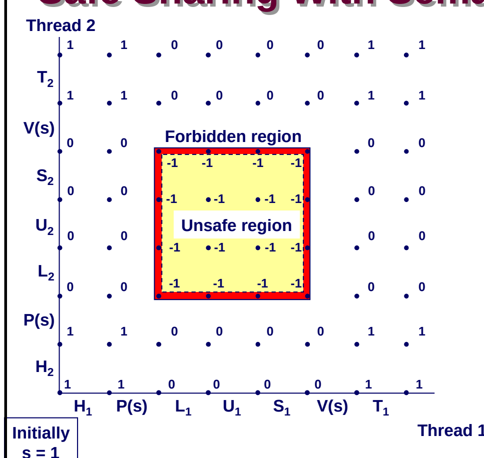
# Safe Sharing with Semaphores

**Here is how we would use P and V operations to synchronize the threads that update `cnt`.**

```
/* Semaphore s is initially 1 */

/* Thread routine */
void *count(void *arg)
{
    int i;

    for (i=0; i<NITERS; i++) {
        P(s);
        cnt++;
        V(s);
    }
    return NULL;
}
```



# Safe Sharing With Semaphores




Provide mutually exclusive access to shared variable by surrounding critical section with P and V operations on semaphore s (initially set to 1).

Semaphore invariant creates a *forbidden region* that encloses unsafe region and is never touched by any trajectory.