Concurrent Programming
November 18, 2008

Topics

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

```c
#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

<table>
<thead>
<tr>
<th>listenfd</th>
</tr>
</thead>
<tbody>
<tr>
<td>clientfd</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
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<td>4</td>
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<td>6</td>
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<td>7</td>
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<tr>
<td>8</td>
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<tr>
<td>9</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

### 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 \}

\[\begin{array}{c|cccccc}
\text{clientfd} & 0 & 1 & 2 & 3 & 4 & 5 \\
\hline
0 & 10 & 7 & 4 & -1 & -1 & 12 \\
1 & -1 & -1 & 5 & 12 & 8 & 9 \\
2 & 5 & 12 & 8 & 9 & 10 & 11 \\
3 & 7 & 4 & -1 & -1 & -1 & -1 \\
4 & 12 & 8 & 9 & 10 & 11 & 12 \\
5 & 8 & 9 & 10 & 11 & 12 & 13 \\
6 & 9 & 10 & 11 & 12 & 13 & 14 \\
7 & 10 & 11 & 12 & 13 & 14 & 15 \\
8 & 11 & 12 & 13 & 14 & 15 & 16 \\
9 & 12 & 13 & 14 & 15 & 16 & 17 \\
\end{array}\]
int main(int argc, char **argv)
{
    int listenfd, connfd, clientlen = sizeof(struct sockaddr_in);
    struct sockaddr_in clientaddr;
    static pool pool;

    listenfd = Open_listendfd(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);
    }
}

Main Loop
/* 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

- \( \text{listenfd} = 3 \)
- \( \text{maxfd} = 3 \)
- \( \text{maxi} = -1 \)
- \( \text{read\_set} = \{3\} \)

<table>
<thead>
<tr>
<th>clientfd</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>-1</td>
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<tr>
<td>1</td>
</tr>
<tr>
<td>-1</td>
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<tr>
<td>2</td>
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<td>6</td>
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<td>8</td>
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<td>-1</td>
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<tr>
<td>9</td>
</tr>
<tr>
<td>-1</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

Never Used
Main Loop

```c
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

```c
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 \}

<table>
<thead>
<tr>
<th>clientfd</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>
| 3        | 11
| 4        | -1
| 5        | 12
| 6        | 5
| 7        | -1
| 8        | -1
| 9        | -1
| ...      |

- Active
- Inactive
- Never Used
void check_clients(pool *p) { /* echo line from ready desc 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

- 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

```
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
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)

Thread 1 (main thread)  
Shared code and data  
Thread 2 (peer thread)

<table>
<thead>
<tr>
<th>Thread 1 context:</th>
<th>Shared code and data</th>
<th>Thread 2 context:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data registers</td>
<td></td>
<td>Data registers</td>
</tr>
<tr>
<td>Condition codes</td>
<td></td>
<td>Condition codes</td>
</tr>
<tr>
<td>SP1</td>
<td></td>
<td>SP2</td>
</tr>
<tr>
<td>PC1</td>
<td></td>
<td>PC2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stack 1</th>
<th>Stack 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>shared libraries</td>
<td>run-time heap</td>
</tr>
<tr>
<td>read/write data</td>
<td>read-only code/data</td>
</tr>
</tbody>
</table>

Kernel context:
- VM structures
- Descriptor table
- brk pointer

from lecture-22.ppt
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**

```c
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*
```c
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);
}
```

**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])

**Local static var:** 1 instance (svar [data])
Shared Variable Analysis

Which variables are shared?

<table>
<thead>
<tr>
<th>Variable instance</th>
<th>Referenced by main thread?</th>
<th>Referenced by peer thread 0?</th>
<th>Referenced by peer thread 1?</th>
</tr>
</thead>
<tbody>
<tr>
<td>ptr</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>svar</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>i.m</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>msgs.m</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>myid.p0</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>myid.p1</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

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

```c
/* 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;
}
```

```bash
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

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

Corresponding asm code

```
.L9:
    movl -4(%ebp),%eax
    cmpl $99999999,%eax
    jle .L12
    jmp .L10
.L12:
    movl cnt,%eax  # Load
    leal 1(%eax),%edx  # Update
    movl %edx,cnt  # Store
    jmp .L9
```

Head (H_i)

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

Tail (T_i)
Concurrent Execution

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

- $l_i$ denotes that thread $i$ executes instruction $l$
- $%eax_i$ is the contents of $%eax$ in thread $i$’s context

<table>
<thead>
<tr>
<th>i (thread)</th>
<th>instr$_i$</th>
<th>$%eax_1$</th>
<th>$%eax_2$</th>
<th>cnt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$H_1$</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>$L_1$</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>$U_1$</td>
<td>1</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>$S_1$</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>$H_2$</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>$L_2$</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>$U_2$</td>
<td>-</td>
<td>2</td>
<td>1</td>
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<td>2</td>
<td>$S_2$</td>
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<td>2</td>
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<tr>
<td>2</td>
<td>$T_2$</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>$T_1$</td>
<td>1</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>i (thread)</th>
<th>instr_i</th>
<th>%eax_1</th>
<th>%eax_2</th>
<th>cnt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H_1</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>L_1</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>U_1</td>
<td>1</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>H_2</td>
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<td>-</td>
<td>0</td>
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<tr>
<td>1</td>
<td>S_1</td>
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<td>1</td>
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<tr>
<td>1</td>
<td>T_1</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>U_2</td>
<td>-</td>
<td>1</td>
<td>1</td>
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<tr>
<td>2</td>
<td>S_2</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>T_2</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Oops!
Concurrent Execution (cont)

How about this ordering?

<table>
<thead>
<tr>
<th>i (thread)</th>
<th>instr_j</th>
<th>%eax_i</th>
<th>%eax_j</th>
<th>cnt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H_1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>L_1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>H_2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>L_2</td>
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<td>2</td>
<td>U_2</td>
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<td>2</td>
<td>S_2</td>
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<tr>
<td>1</td>
<td>U_1</td>
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<tr>
<td>1</td>
<td>S_1</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>T_1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>T_2</td>
<td></td>
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</tr>
</tbody>
</table>

We can clarify our understanding of concurrent execution with the help of the progress graph.
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 \((\text{Inst}_1, \text{Inst}_2)\).

E.g., \((L_1, S_2)\) denotes state where thread 1 has completed \(L_1\) and thread 2 has completed \(S_2\).
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
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.
  - \( P(s): [\text{while } (s == 0) \text{ wait()}; s--; ] \)
    - 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 \texttt{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 \( \text{cnt} \).

```c
/* 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.

Initially
s = 1

<table>
<thead>
<tr>
<th></th>
<th>H_1</th>
<th>P(s)</th>
<th>L_1</th>
<th>U_1</th>
<th>S_1</th>
<th>V(s)</th>
<th>T_1</th>
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</thead>
<tbody>
<tr>
<td>H_2</td>
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<td>0</td>
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<td>1</td>
</tr>
<tr>
<td>P(s)</td>
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<td>1</td>
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<td>1</td>
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<td>L_1</td>
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<td>T_1</td>
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<td>1</td>
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