Server Performance

Computer Systems

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Based on slides by:

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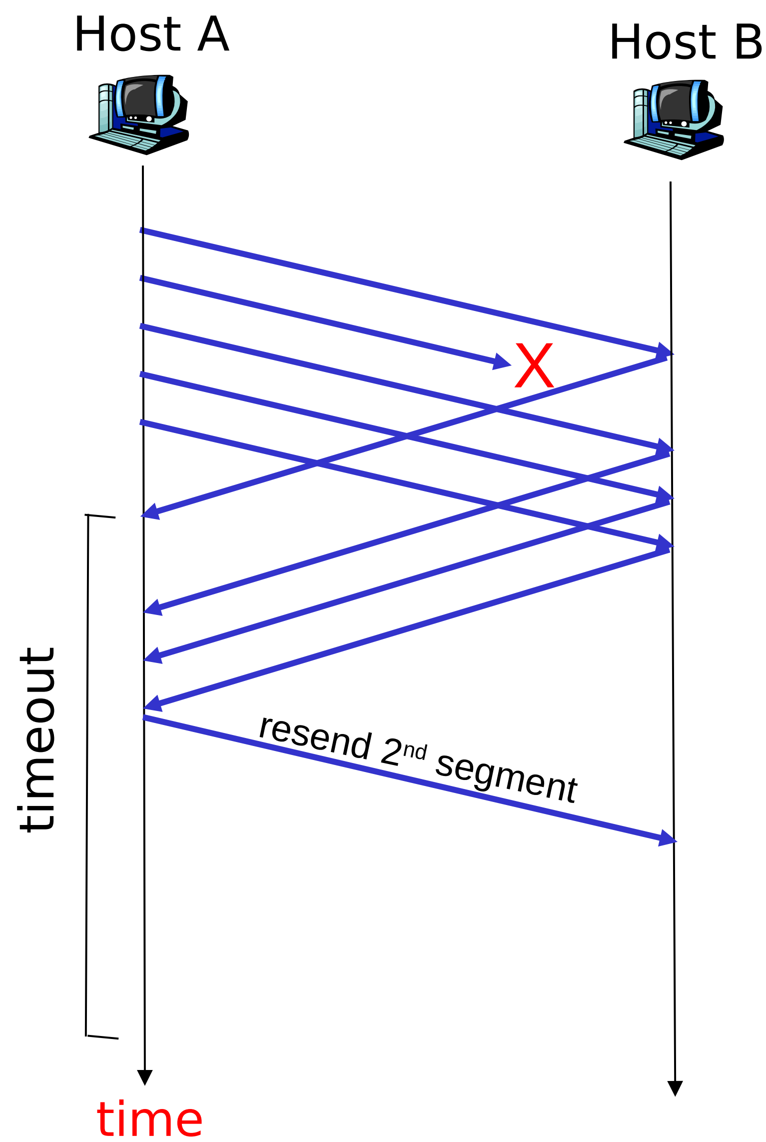
A Recap

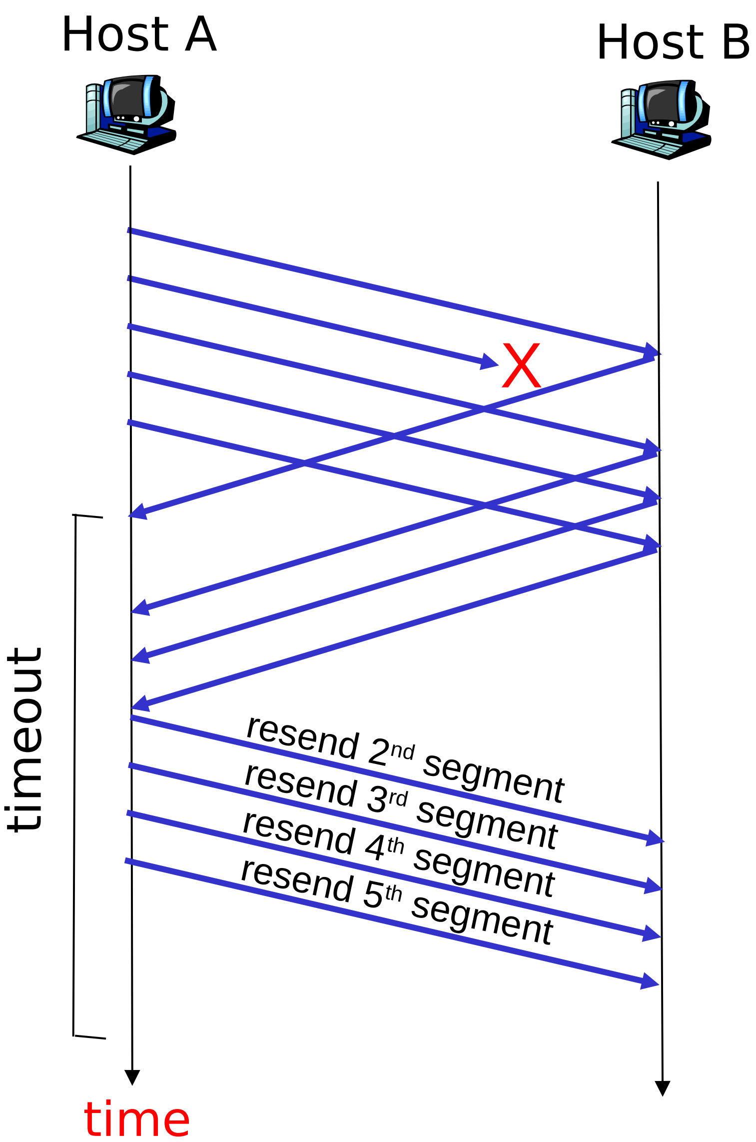
- We need to fill in some gaps that got lost in the last lecture
- Recall the triple acknowlegdement, identifying missing packets quickly
- Two responses here, GBN or SR



Source: Kurose & Ross (partial)

Go Back N (GBN)

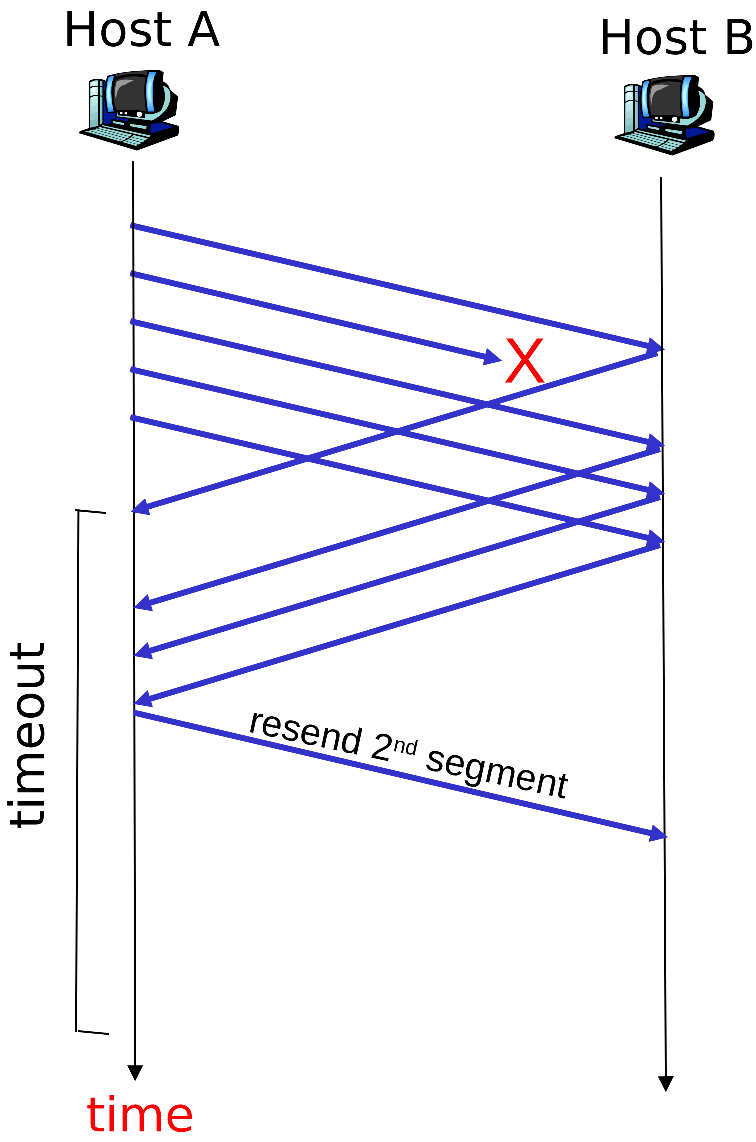
- Go back to the missed packet and start again from there
- Simple, lightweight strategy that requires little management or additional buffers
- Can acknowledge packets cumulatively
- Will reject packets received out of order



Source: Kurose & Ross (partial)

Selective Repeat (SR)

- Only resend missed packets
- More complex to implement
- Requires individual acknowledgement of packets
- Can accept packets received out of order



Source: Kurose & Ross (partial)

Some reminders...

- **Threads & Processes:** Both can mainting concurrent logical control through context switching. Threads are lighter weight and share more data.

- **Concurrency & Parrallel:** Parallel means running different processing at the literal same time. Concurrency can simulate this by interweaving

- **Semaphores & Mutex:** Synchronisation tools to ensure that we don’t encounter concurrency problems such as race conditions or deadlock

Approaches for Writing Concurrent Servers

Allow server to handle multiple clients concurrently

1. Process-based **(Intro to Network Programming Lecture)**

- Kernel automatically interleaves multiple logical flows
- Each flow has its own private address space

2. Event-based

- Programmer manually interleaves multiple logical flows
- All flows share the same address space
- Uses technique called *I/O multiplexing*.

3. Thread-based **(Intro to Network Programming Lecture)**

- Kernel automatically interleaves multiple logical flows
- Each flow shares the same address space
- Hybrid of of process-based and event-based.

Pros and Cons of Process-based Servers

- **+ 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

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
  - Hard to know which data shared & which private
  - Hard to detect by testing
    - Probability of bad race outcome very low
    - But nonzero!
  - Future lectures

Approach #2: Event-based Servers

- **Server maintains set of active connections**
  - Array of connfd's
- **Repeat:**
  - Determine which descriptors (connfd's or listenfd) have pending inputs
    - e.g., using `select` or `epoll` functions
    - arrival of pending input is an *event*
  - If listenfd has input, then `accept` connection
    - and add new connfd to array
  - Service all connfd's with pending inputs

How does this help us?

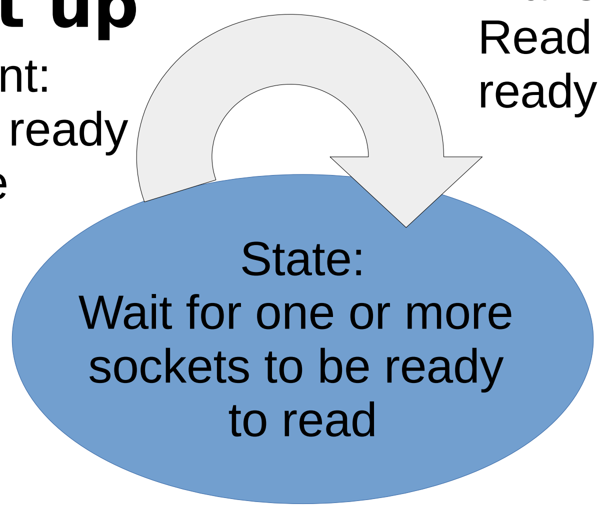
```
int main(int argc, char **argv)
{
    /* Boring declarations go here */

    listenfd = Open_listenfd(argv[1]);
    while (1) {
      clientlen = sizeof(struct sockaddr_storage);
      connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);

      Rio_readinitb(&rio, connfd);
      while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
        printf("server received %d bytes\n", (int)n);
        Rio_writen(connfd, buf, n);
      }
    }
}
```

The key issue is that we want to wait on these two lines at the same time

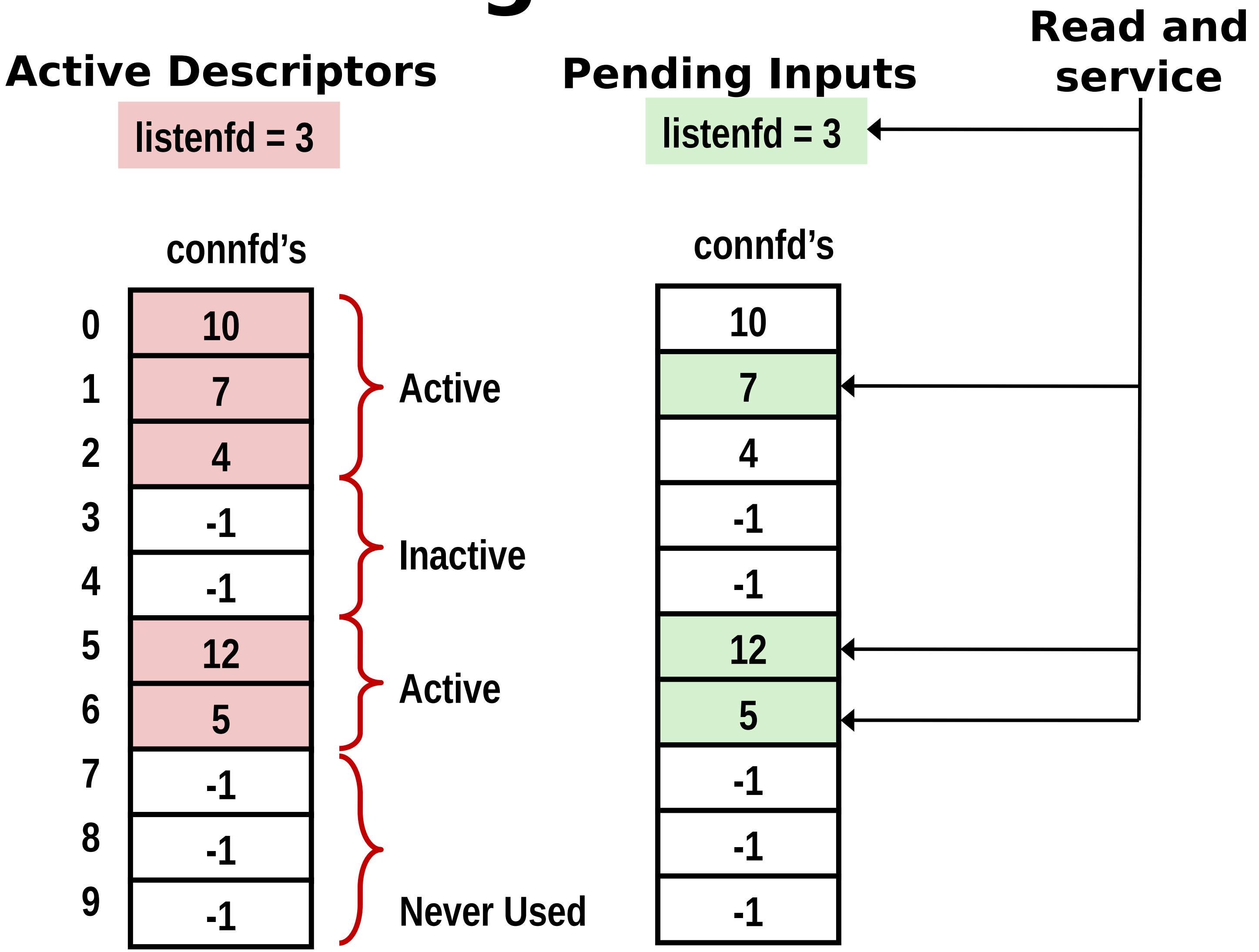
I/O Multiplexing

- **Use a** `select` **command to combine multiple events into a set, then wait for at least one of them to occur**

- **Our set of waitable events will be input through listenfd, plus any connfd’s that have been set up**



I/O Multiplexed Event Processing



Abridged Example (from book, pg 1015)

```
int main(int argc, char **argv) {
  // More boring declarations go here
  fd_set all_socks_set, ready_set;

  listenfd = Open_listenfd(PORT);

  FD_ZERO(&all_socks_set);                // Clear all_socks_set
  FD_SET(STDIN_FILENO, &all_socks_set); // Add stdin to all_socks_set
  FD_SET(listenfd, &all_socks_set);     // +listenfd to all_socks_set

  while (1) {
    ready_set = all_socks_set;
    Select(listenfd+1, &ready_set, NULL, NULL, NULL);
    if (FD_ISSET(STDIN_FILENO, &ready_set))
      command(); // Read command line from stdin
    if (FD_ISSET(listenfd, &ready_set)) {
      clientlen = sizeof(struct sockaddr_storage);
      connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
      echo(connfd); /* Echo client input until EOF */
      Close(connfd);
}}}
```

Abridged Example (from book, pg 1015)

```
void command(void) {
    char buf[MAXLINE];
    if (!Fgets(buf, MAXLINE, stdin))
        exit(0); /* EOF */
    printf("%s", buf); /* Process the input command */
}
```

```
void echo(int connfd) {
    size_t n;
    char buf[MAXLINE];
    rio_t rio;

    Rio_readinitb(&rio, connfd);
    while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
        printf("server received %d bytes\n", (int)n);
    Rio_writen(connfd, buf, n);
    }
}
```

- **Do remember this code is heavily abridged so will not work as is, full code on pg 1015 of BOH**

Abridged Example (from book, pg 1015)

```
int main(int argc, char **argv) {
  // More boring declarations go here
  fd_set all_socks_set, ready_set;

  listenfd = Open_listenfd(PORT);

  FD_ZERO(&all_socks_set);                // Clear all_socks_set
  FD_SET(STDIN_FILENO, &all_socks_set); // Add stdin to all_socks_set
  FD_SET(listenfd, &all_socks_set);     // listenfd to all_socks_set

  while (1) {
    ready_set = all_socks_set;
    Select(listenfd+1, &ready_set, NULL, NULL, NUL
    if (FD_ISSET(STDIN_FILENO, &ready_set))
      command(); // Read command line from stdin
    if (FD_ISSET(listenfd, &ready_set)) {
      clientlen = sizeof(struct sockaddr_storage);
      connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
      echo(connfd); /* Echo client input until EOF */
      Close(connfd);
}}}
```

Our server blocks here but in such a way that we can wait for multiple things to happen and respond accordingly

I/O Multiplexing

- **Thats all well and good, but it doesn’t show an example of how we’d actually run a server. . .**
- **Example on page 1018-20 does though**
- **Its going to be a lot of code, so we’re going to present it slightly differently . . . .**

I/O Multiplexing example overview

```
#include "csapp.h"

typedef struct { /* Represents a pool of connected descriptors */
    int maxfd;        /* Largest descriptor in all_socks_set */
    fd_set all_socks_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;

void init_pool(int listenfd, pool *p);
void add_client(int connfd, pool *p);
void check_clients(pool *p);

int byte_cnt = 0; /* Counts total bytes received by server */
```

I/O Multiplexing example overview

```
int main(int argc, char **argv){
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;
    static pool pool;
    if (argc != 2) {
        fprintf(stderr, "usage: %s <port>\n", argv[0]);
        exit(0);
    }
    listenfd = Open_listenfd(argv[1]);
    init_pool(listenfd, &pool);
    while (1) {
        /* Wait for listening/connected descriptor(s) to be ready */
        pool.ready_set = pool.all_socks_set;
        pool.nready = Select(pool.maxfd+1, &pool.ready_set, NULL, NULL, NULL);
        /* If listening descriptor ready, add new client to pool */
        if (FD_ISSET(listenfd, &pool.ready_set)) {
            clientlen = sizeof(struct sockaddr_storage);
            connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
            add_client(connfd, &pool);
        }
        check_clients(&pool); /* Echo line from each ready descriptor */
    }
}
```

I/O Multiplexing example overview

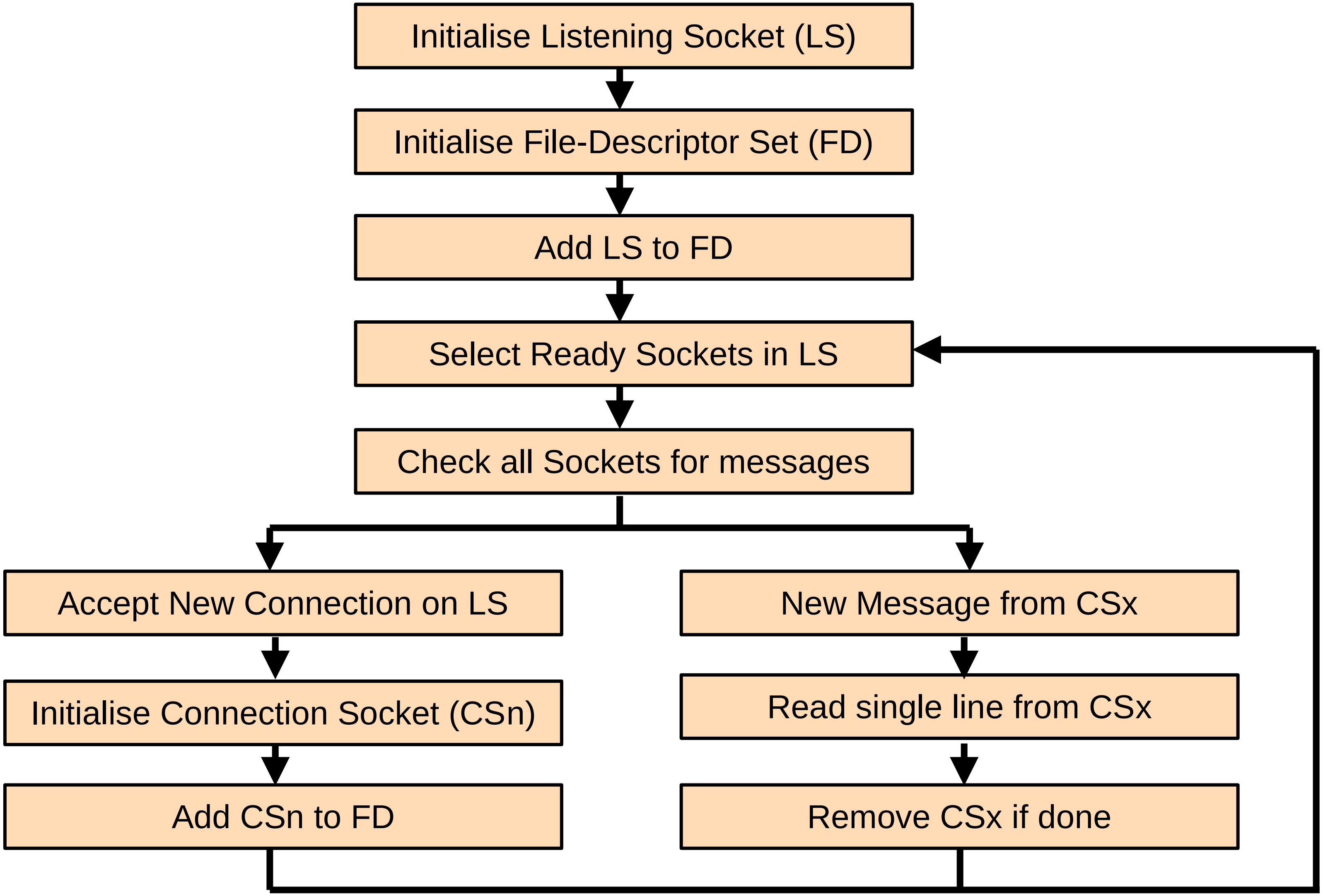
```
void init_pool(int listenfd, pool *p) {
    /* Initially, there are no connected descriptors */
    int i;
    p->maxi = -1;
    for (i=0; i< FD_SETSIZE; i++)
        p->clientfd[i] = -1;

    /* Initially, listenfd is only member of select read set */
    p->maxfd = listenfd;
    FD_ZERO(&p->all_socks_set);
    FD_SET(listenfd, &p->all_socks_set);
}
```

I/O Multiplexing example overview

```
void add_client(int connfd, pool *p) {
    int i;
    p->nready--;
    for (i = 0; i < FD_SETSIZE; i++)  /* Find an available slot */
        if (p->clientfd[i] < 0) {
            /* Add connected descriptor to the pool */
            p->clientfd[i] = connfd;
            Rio_readinitb(&p->clientrio[i], connfd);

            /* Add the descriptor to descriptor set */
            FD_SET(connfd, &p->all_socks_set);

            /* Update max descriptor and pool highwater mark */
            if (connfd > p->maxfd)
                p->maxfd = connfd;
            if (i > p->maxi)
                p->maxi = i;
            break;
        }
    if (i == FD_SETSIZE) /* Couldn't find an empty slot */
        app_error("add_client error: Too many clients");
}
```

I/O Multiplexing example overview

```
void check_clients(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;
                printf("Server received %d (%d total) bytes on fd %d\n",
                   n, byte_cnt, connfd);
                Rio_writen(connfd, buf, n);
            }
            /* EOF detected, remove descriptor from pool */
            else {
                Close(connfd);
                FD_CLR(connfd, &p->all_socks_set);
                p->clientfd[i] = -1;
            }}}}
```


Initialise Listening Socket (LS)
Initialise File-Descriptor Set (FD)
Add LS to FD
Select Ready Sockets in LS
Check all Sockets for messages
Accept New Connection on LS
Initialise Connection Socket (CSn)
Add CSn to FD
New Message from CSx
Read single line from CSx
Remove CSx if done

I/O Multiplexing example overview

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} pool;

void init_pool(int listenfd, pool *p);
void add_client(int connfd, pool *p);
void check_clients(pool *p);

int byte_cnt = 0; /* Counts total bytes received by server */
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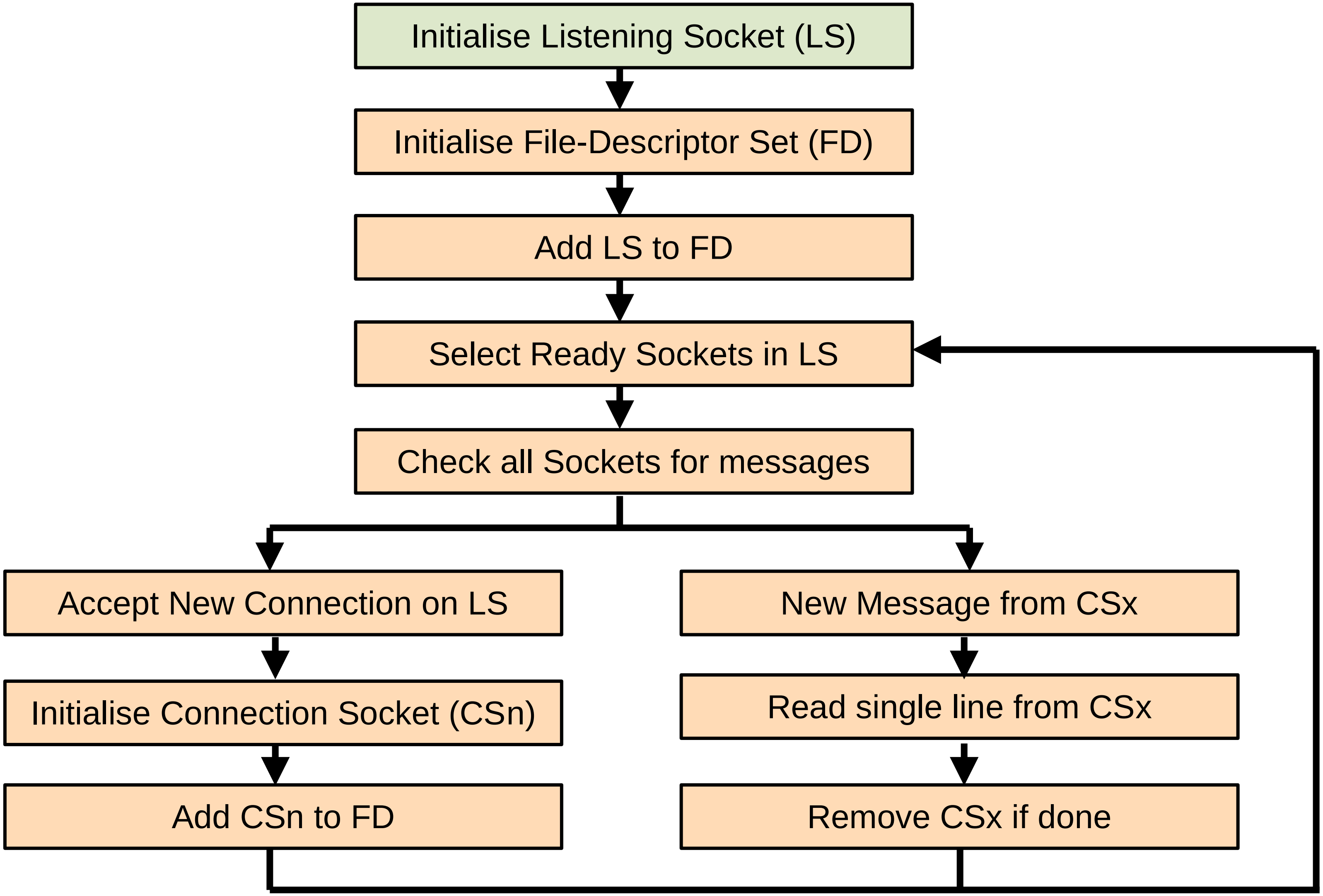
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I/O Multiplexing example overview

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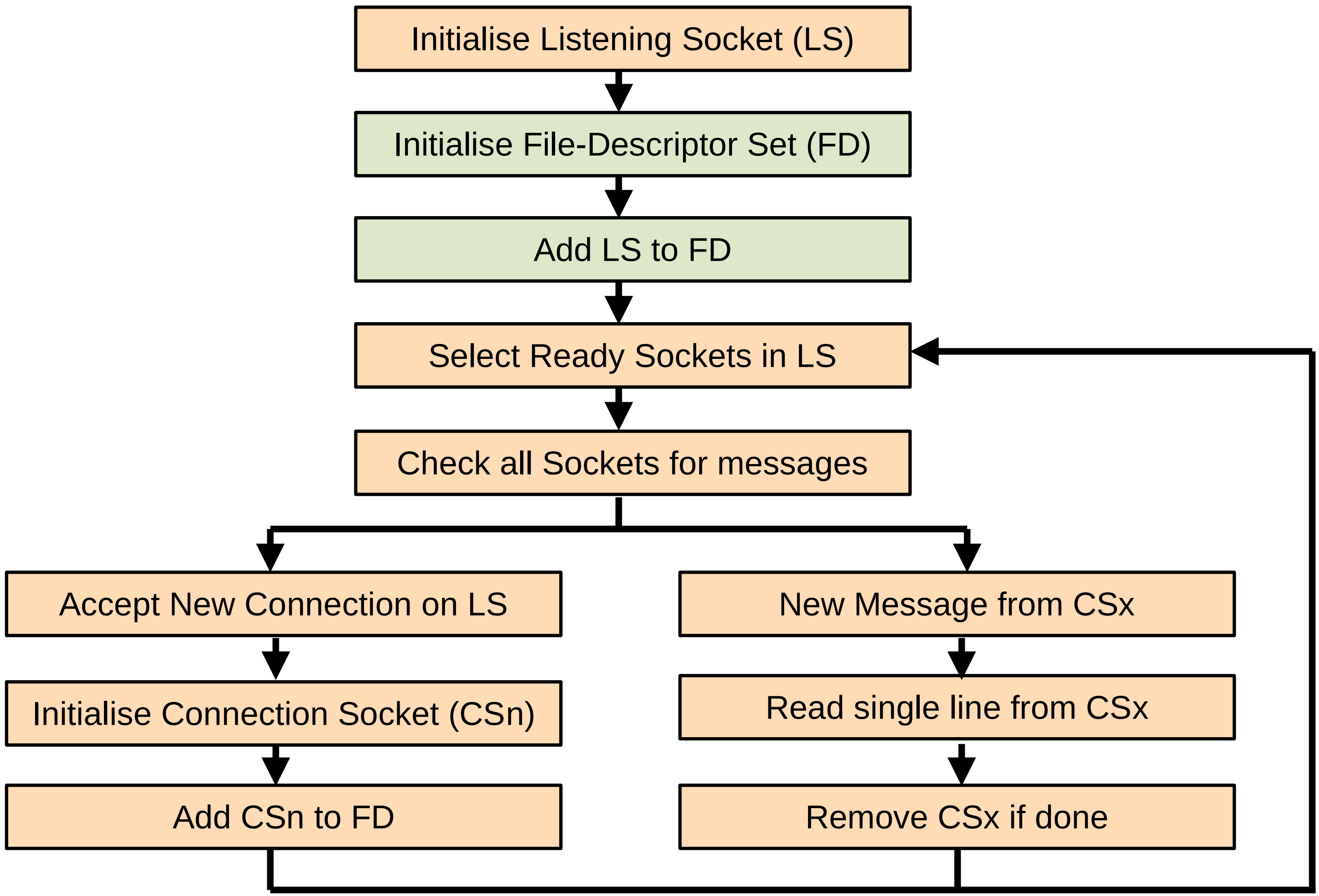
int main(int argc, char **argv){
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;
    static pool pool;
    if (argc != 2) {
        fprintf(stderr, "usage: %s <port>\n", argv[0]);
        exit(0);
    }
    listenfd = Open_listenfd(argv[1]);
    init_pool(listenfd, &pool);
    while (1) {
        /* Wait for listening/connected descriptor(s) to be ready */
        pool.ready_set = pool.all_socks_set;
        pool.nready = Select(pool.maxfd+1, &pool.ready_set, NULL, NULL, NULL);
        /* If listening descriptor ready, add new client to pool */
        if (FD_ISSET(listenfd, &pool.ready_set)) {
            clientlen = sizeof(struct sockaddr_storage);
            connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
            add_client(connfd, &pool);
        }
        check_clients(&pool); /* Echo line from each ready descriptor */
    }
}
```

IGNORE FOR NOW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New Message from CSx
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I/O Multiplexing example overview

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        pool.ready_set = pool.all_socks_set;
        pool.nready = Select(pool.maxfd+1, &pool.ready_set, NULL, NULL, NULL);
        /* If listening descriptor ready, add new client to pool */
        if (FD_ISSET(listenfd, &pool.ready_set)) {
            clientlen = sizeof(struct sockaddr_storage);
            connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
            add_client(connfd, &pool);
        }
        check_clients(&pool); /* Echo line from each ready descriptor */
    }
}
```

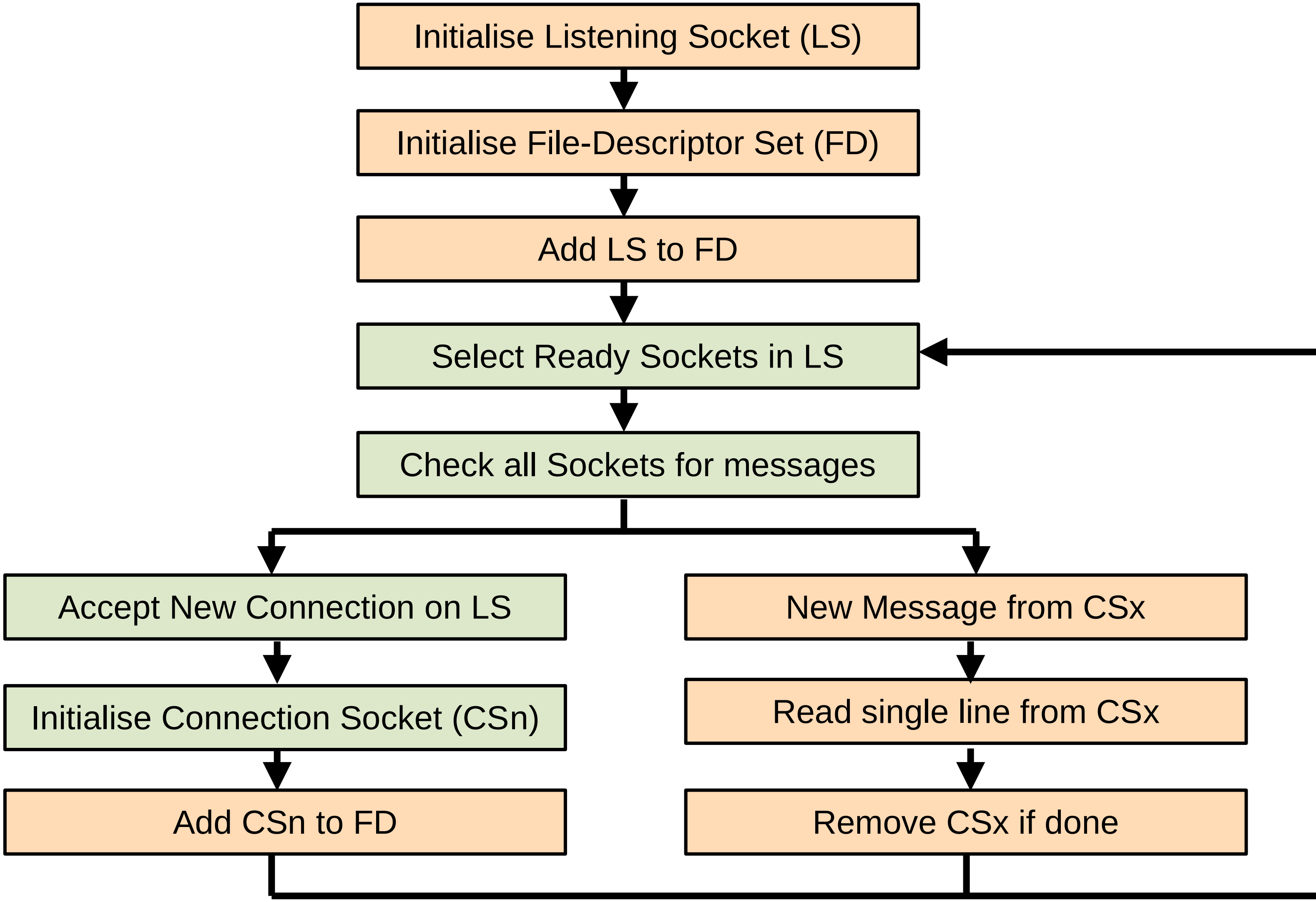
ALREADY COVERED

KEEP IGNORING ME

I/O Multiplexing example overview

```
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->all_socks_set);
    FD_SET(listenfd, &p->all_socks_set);
}
```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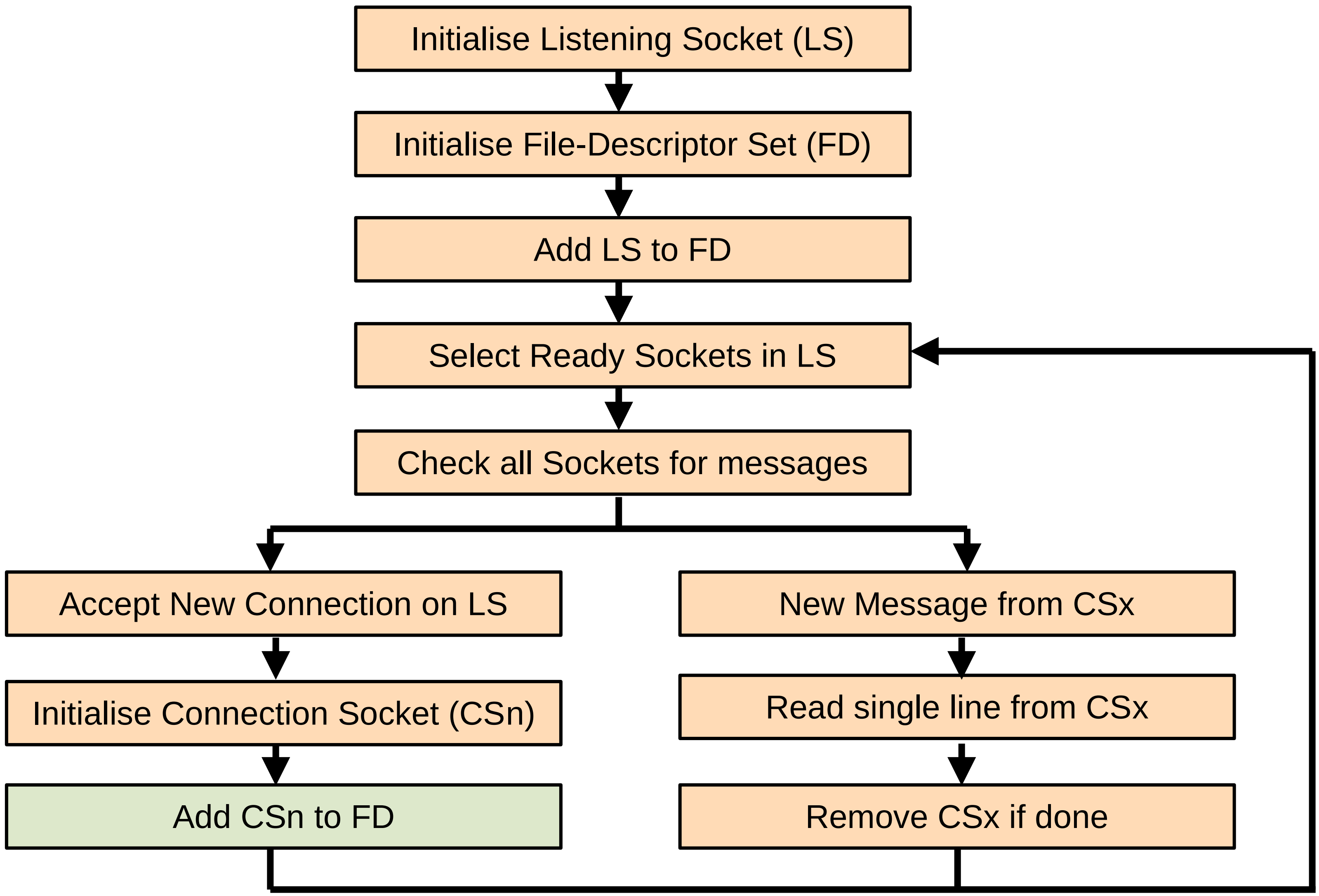
Read single line from CSx
Remove CSx if done

I/O Multiplexing example overview

NOT RELEVANT HERE

```
int main(int argc, char **argv){
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr;
    static pool pool;
    if (argc != 2) {
        fprintf(stderr, "usage: %s <port>\n", argv[0]);
        exit(0);
    }
    listenfd = Open_listenfd(argv[1]);
    init_pool(listenfd, &pool);
    while (1) {
        /* Wait for listening/connected descriptor(s) to be ready */
        pool.ready_set = pool.all_socks_set;
        pool.nready = Select(pool.maxfd+1, &pool.ready_set, NULL, NULL, NULL);
        /* If listening descriptor ready, add new client to pool */
        if (FD_ISSET(listenfd, &pool.ready_set)) {
            clientlen = sizeof(struct sockaddr_storage);
            connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
            add_client(connfd, &pool);
        }
        check_clients(&pool); /* Echo line from each ready descriptor */
    }
}
```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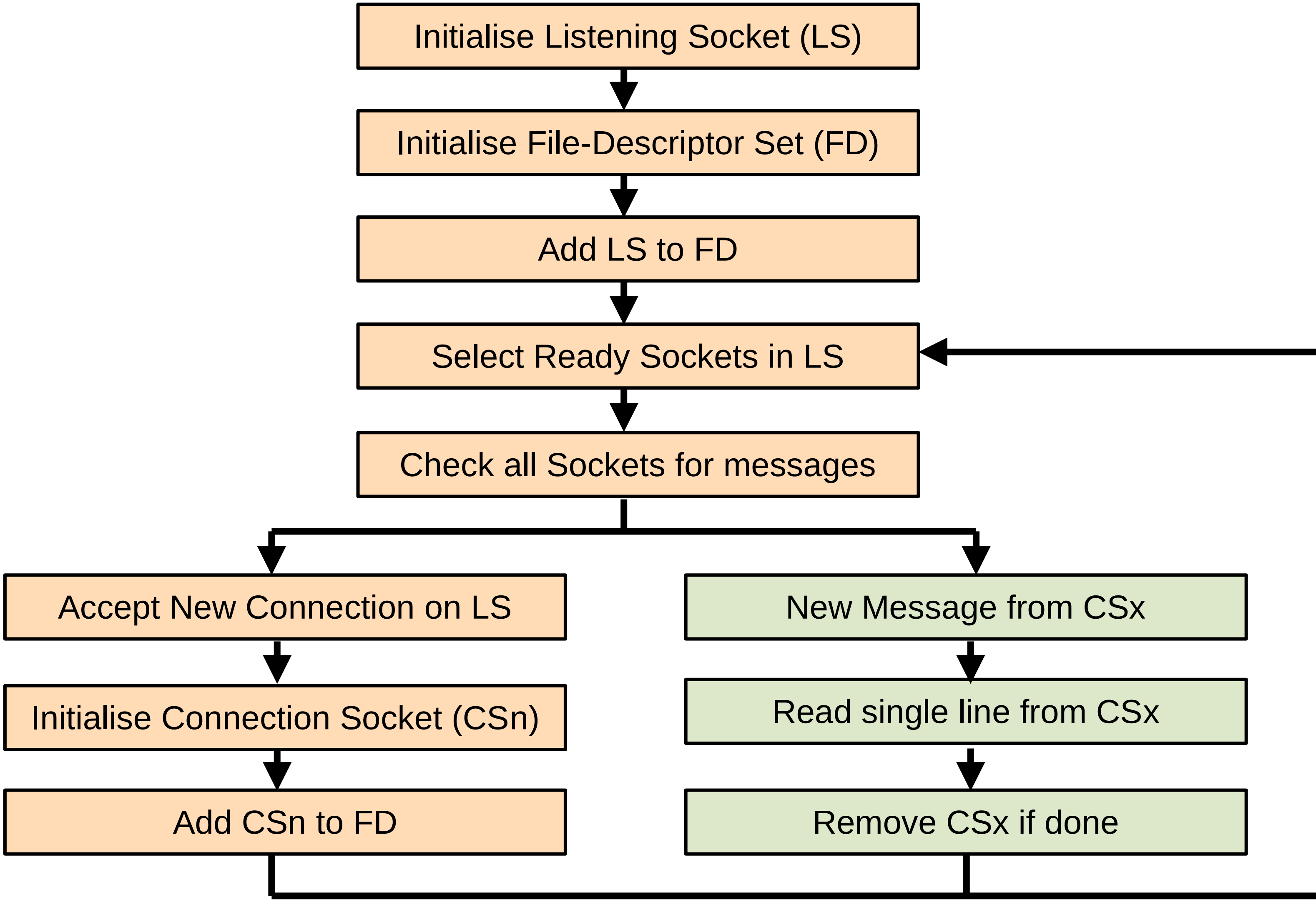
I/O Multiplexing example overview

```
void add_client(int connfd, pool *p) {
    int i;
    p->nready--;
    for (i = 0; i < FD_SETSIZE; i++)  /* Find an available slot */
        if (p->clientfd[i] < 0) {
            /* Add connected descriptor to the pool */
            p->clientfd[i] = connfd;
            Rio_readinitb(&p->clientrio[i], connfd);

             /* Add the descriptor to descriptor set */
             FD_SET(connfd, &p->all_socks_set);

            /* Update max descriptor and pool highwater mark */
            if (connfd > p->maxfd)
                p->maxfd = connfd;
            if (i > p->maxi)
                p->maxi = i;
            break;
        }
    if (i == FD_SETSIZE) /* Couldn't find an empty slot */
        app_error("add_client error: Too many clients");
}
```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I/O Multiplexing example overview

```
void check_clients(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;
                printf("Server received %d (%d total) bytes on fd %d\n",
                   n, byte_cnt, connfd);
                Rio_writen(connfd, buf, n);
            }
            /* EOF detected, remove descriptor from pool */
            else {
                Close(connfd);
                FD_CLR(connfd, &p->all_socks_set);
                p->clientfd[i] = -1;
            }}}}
```

Pros and Cons of Event-based Servers

- + One logical control flow and address space.
- + Can single-step with a debugger.
- + No process or thread control overhead.
  - Design of choice for high-performance Web servers and search engines. e.g., Node.js, nginx, Tornado

- – Significantly more complex to code than process- or thread-based designs.
- – Hard to provide fine-grained concurrency
  - E.g., how to deal with partial HTTP request headers
- – Cannot take advantage of multi-core
  - Single thread of control

Summary: Approaches to Concurrency

- **Process-based**
  - Hard to share resources: Easy to avoid unintended sharing
  - High overhead in adding/removing clients
- **Event-based**
  - Tedious and low level
  - Total control over scheduling
  - Very low overhead
  - Cannot create as fine grained a level of concurrency
  - Does not make use of multi-core
- **Thread-based**
  - Easy to share resources: Perhaps too easy
  - Medium overhead
  - Not much control over scheduling policies
  - Difficult to debug
    - Event orderings not repeatable

One worry: Races

- A *race* occurs when correctness of the program depends on one thread reaching point x before another thread reaches point y

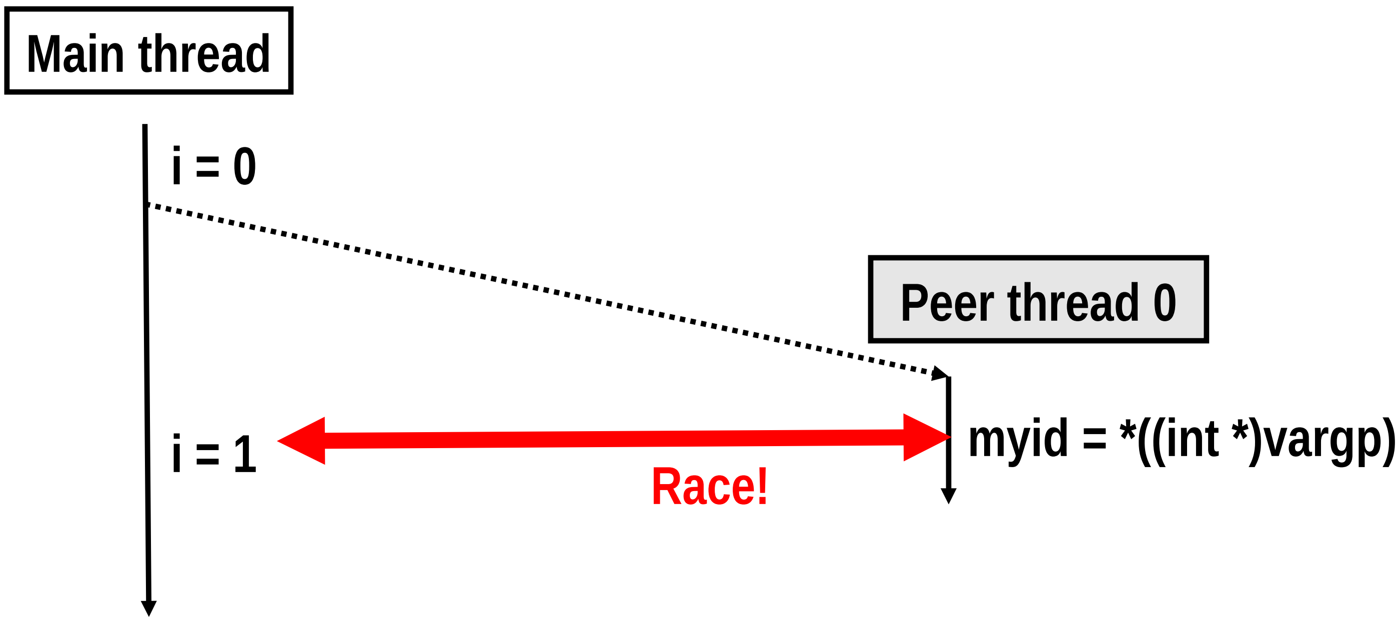
```
/* A threaded program with a race */
int main()
{
    pthread_t tid[N];
    int i;

    for (i = 0; i < N; i++)
        Pthread_create(&tid[i], NULL, thread, &i);
    for (i = 0; i < N; i++)
        Pthread_join(tid[i], NULL);
    exit(0);
}

/* Thread routine */
void *thread(void *vargp)
{
    int myid = *((int *)vargp);
    printf("Hello from thread %d\n", myid);
    return NULL;
}
```

N threads are sharing i

race.c

Race Illustration

```
for (i = 0; i < N; i++)
    Pthread_create(&tid[i], NULL, thread, &i);
```



- **Race between increment of i in main thread and deref of vargp in peer thread:**
  - If deref happens while i = 0, then OK
  - Otherwise, peer thread gets wrong id value

Could this race really occur?

Main thread

```
int i;
for (i = 0; i < 100; i++) {
    Pthread_create(&tid, NULL,
                   thread,&i);
}
```

Peer thread

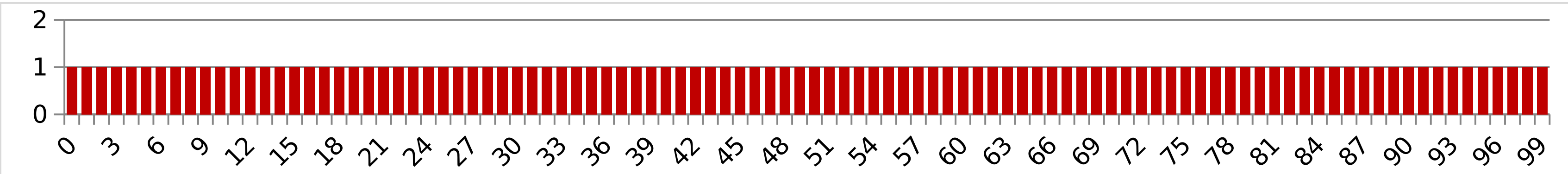
```
void *thread(void *vargp) {
    Pthread_detach(pthread_self());
    int i = *((int *)vargp);
    save_value(i);
    return NULL;
}
```

race.c

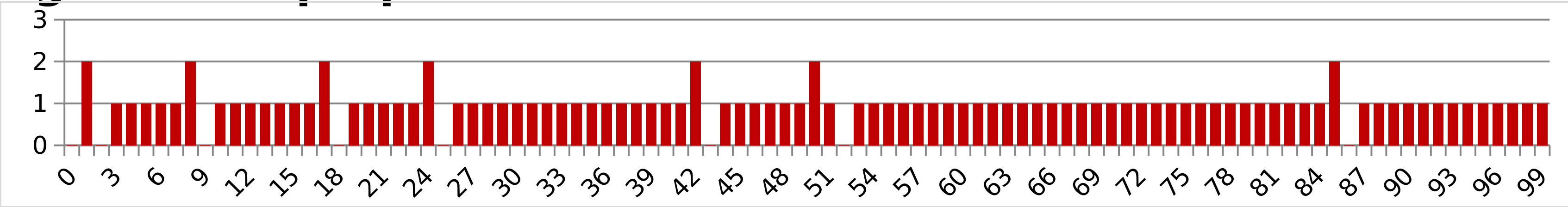
- **Race Test**
  - If no race, then each thread would get different value of i
  - Set of saved values would consist of one copy each of 0 through 99

Experimental Results

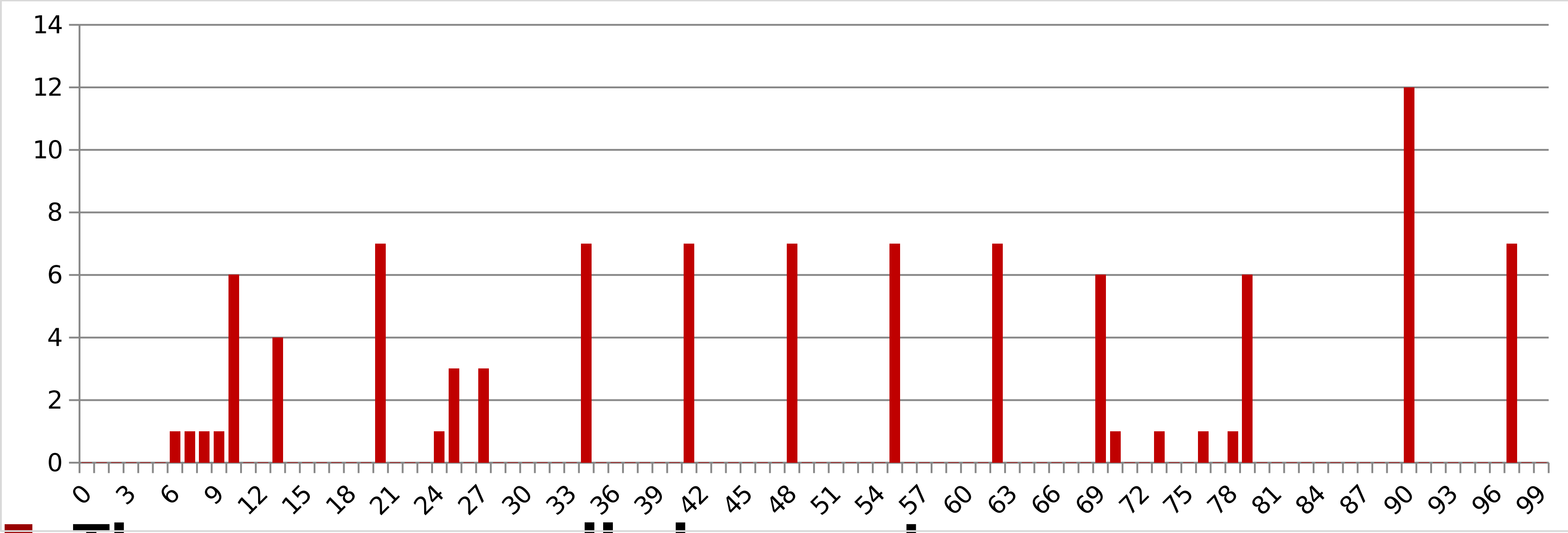
No Race



Single core laptop



Multicore server



- **The race can really happen!**

Race Elimination

```
/* Threaded program without the race */
int main()
{
    pthread_t tid[N];
    int i, *ptr;

    for (i = 0; i < N; i++) {
        ptr = Malloc(sizeof(int));
        *ptr = i;
        Pthread_create(&tid[i], NULL, thread, ptr);
    }
    for (i = 0; i < N; i++)
        Pthread_join(tid[i], NULL);
    exit(0);
}

/* Thread routine */
void *thread(void *vargp)
{
    int myid = *((int *)vargp);
    Free(vargp);
    printf("Hello from thread %d\n", myid);
    return NULL;
}
```

norace.c

- **Avoid unintended sharing of state**

Deadlocking With Semaphores

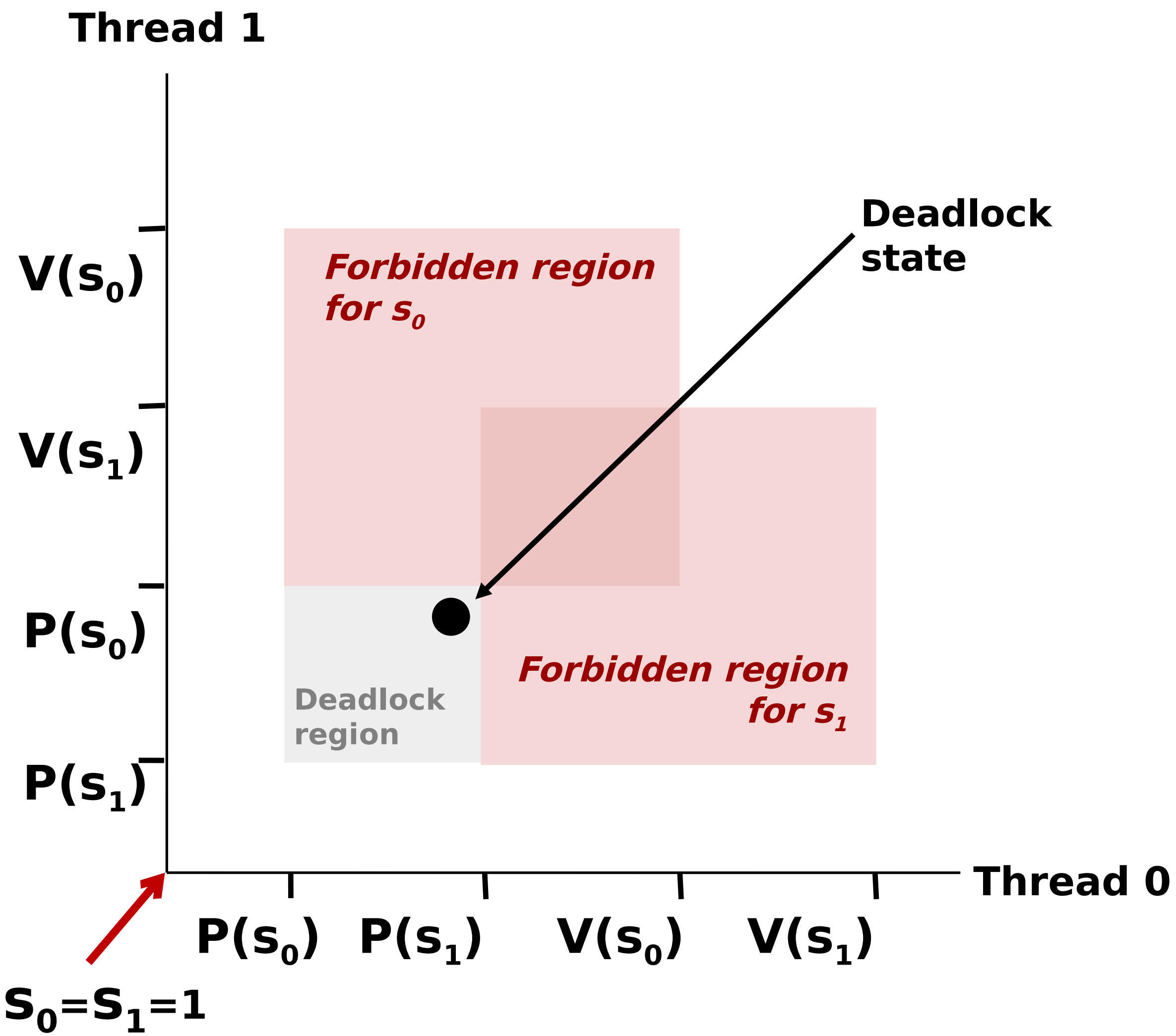
```
int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 0 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], NULL);
    printf("cnt=%d\n", cnt);
    exit(0);
}
```

```
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
      P(&mutex[id]); P(&mutex[1-id]);
      cnt++;
      V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}
```

Tid[0]:
$P(s_0)$;
$P(s_1)$;
cnt++;
$V(s_0)$;
$V(s_1)$;

Tid[1]:
$P(s_1)$;
$P(s_0)$;
cnt++;
$V(s_1)$;
$V(s_0)$;

Deadlock Visualized in Progress Graph



Locking introduces the potential for *deadlock:* waiting for a condition that will never be true

Any trajectory that enters the *deadlock region* will eventually reach the *deadlock state,* waiting for either S_0 or S_1 to become nonzero

Other trajectories luck out and skirt the deadlock region

Unfortunate fact: deadlock is often nondeterministic (race)

Avoiding Deadlock

Acquire shared resources in same order

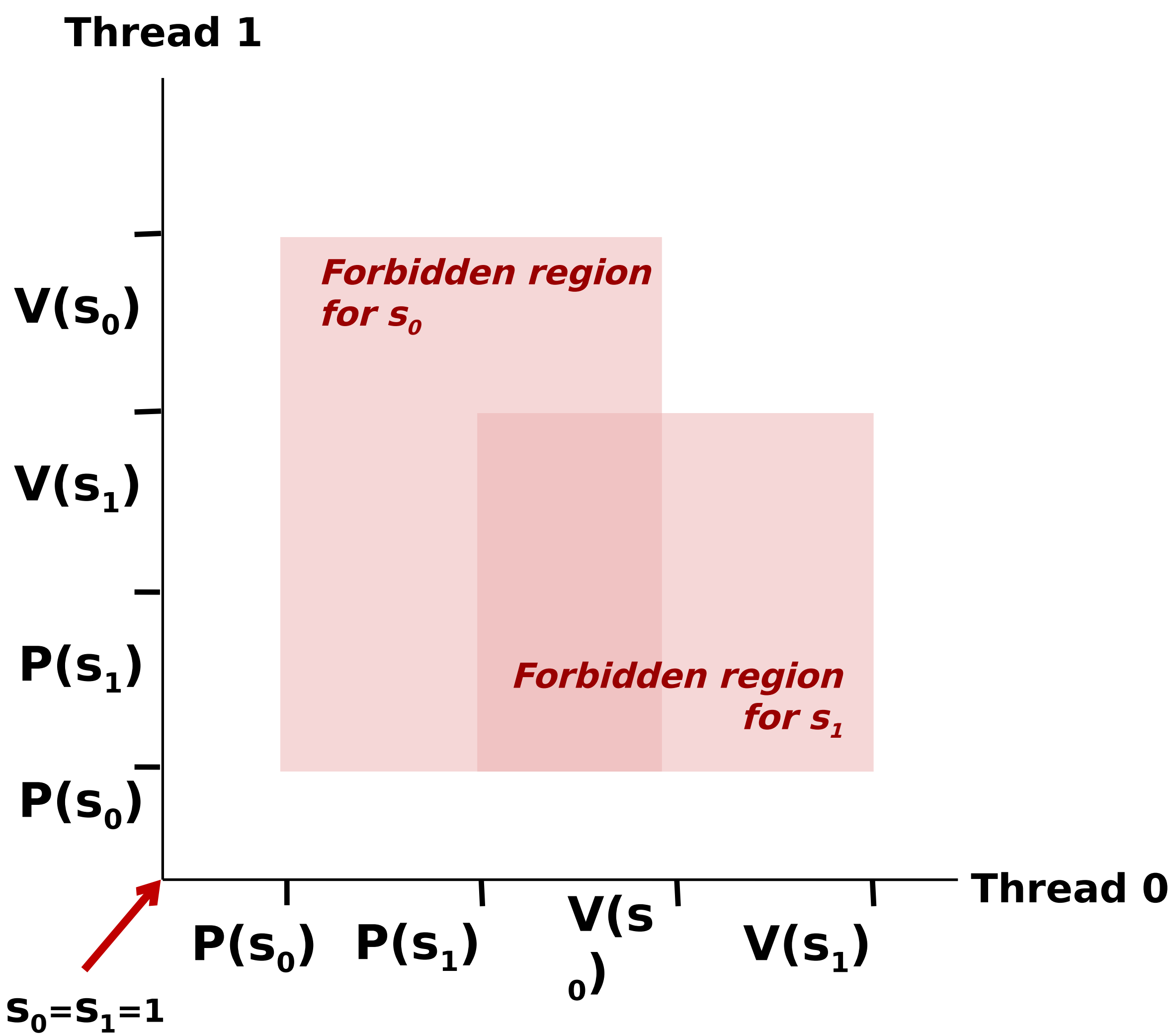
```
int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 0 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 0 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], NULL);
    printf("cnt=%d\n", cnt);
    exit(0);
}
```

```
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
        P(&mutex[0]); P(&mutex[1]);
    cnt++;
    V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}
```

Tid[0]:
P(s0);
P(s1);
cnt++;
V(s0);
V(s1);

Tid[1]:
P(s0);
P(s1);
cnt++;
V(s1);
V(s0);

Avoided Deadlock in Progress Graph

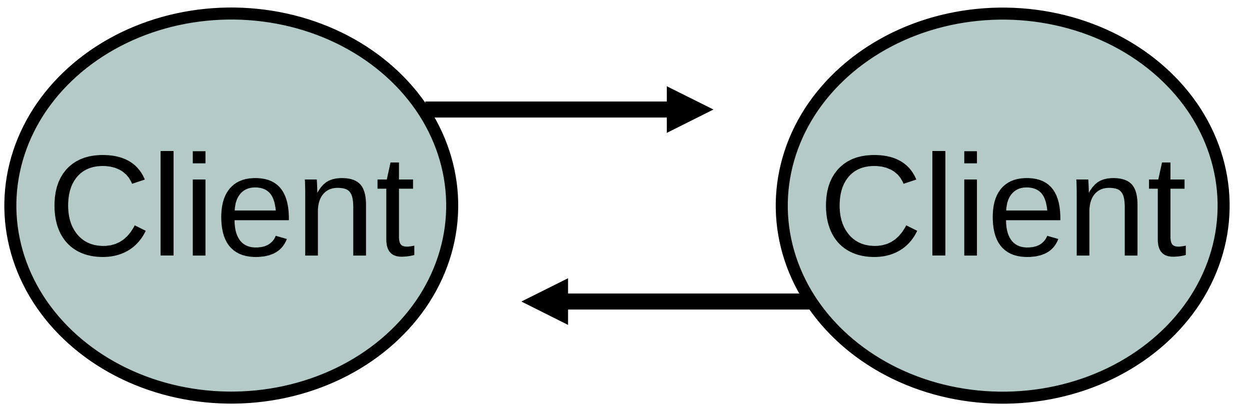


No way for trajectory to get stuck

Processes acquire locks in same order

Order in which locks released immaterial

What about Deadlock between hosts?



What about Deadlock between hosts?

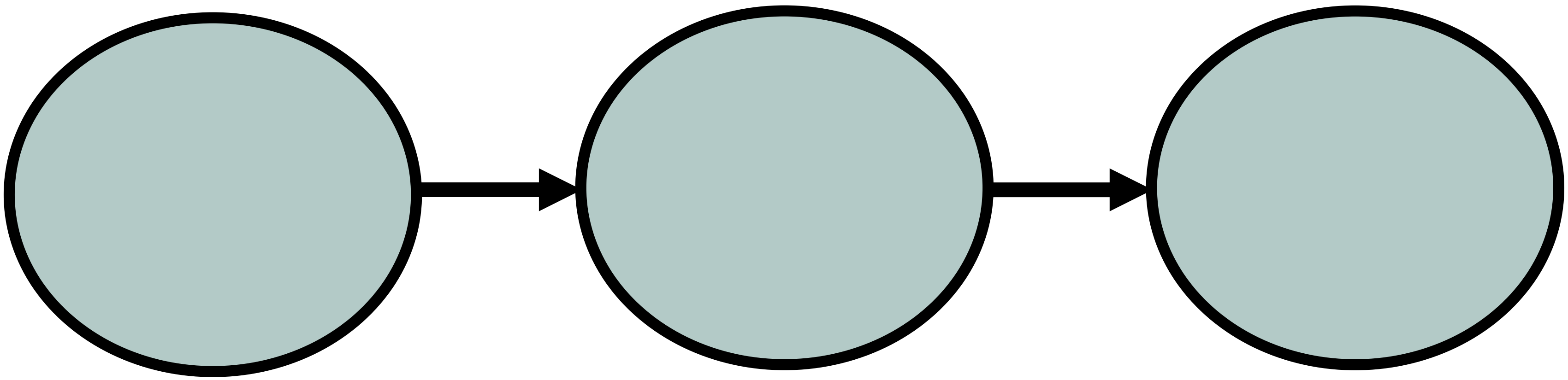
Deadlock can occur when two processes/threads/hosts try to act as clients at the same time.

Or if they both act as servers at the same time

To solve this we can use process diagrams to draw interactions

As long as they is no loop, theres no deadlock

What about Deadlock between hosts?



No deadlock

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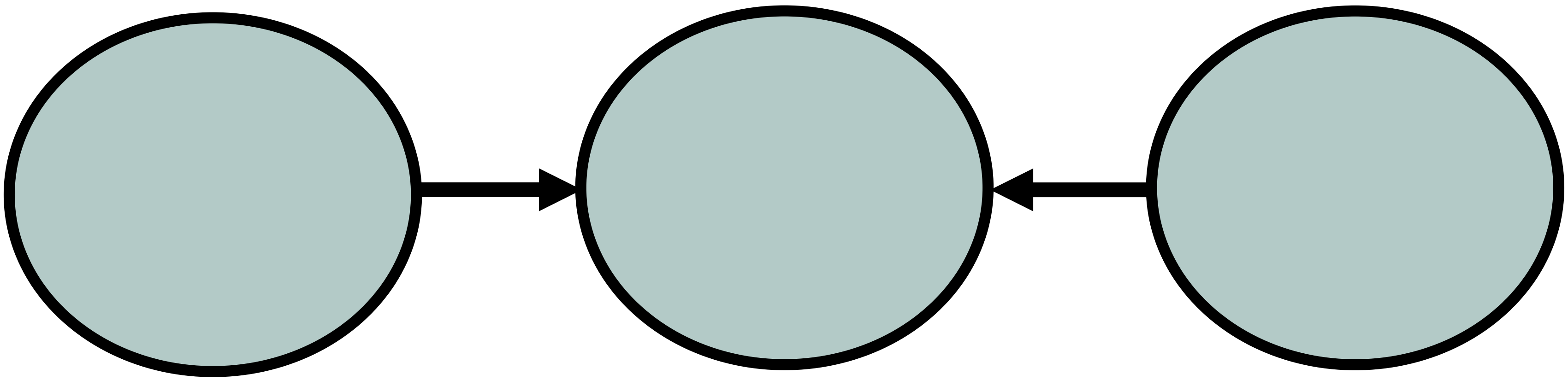

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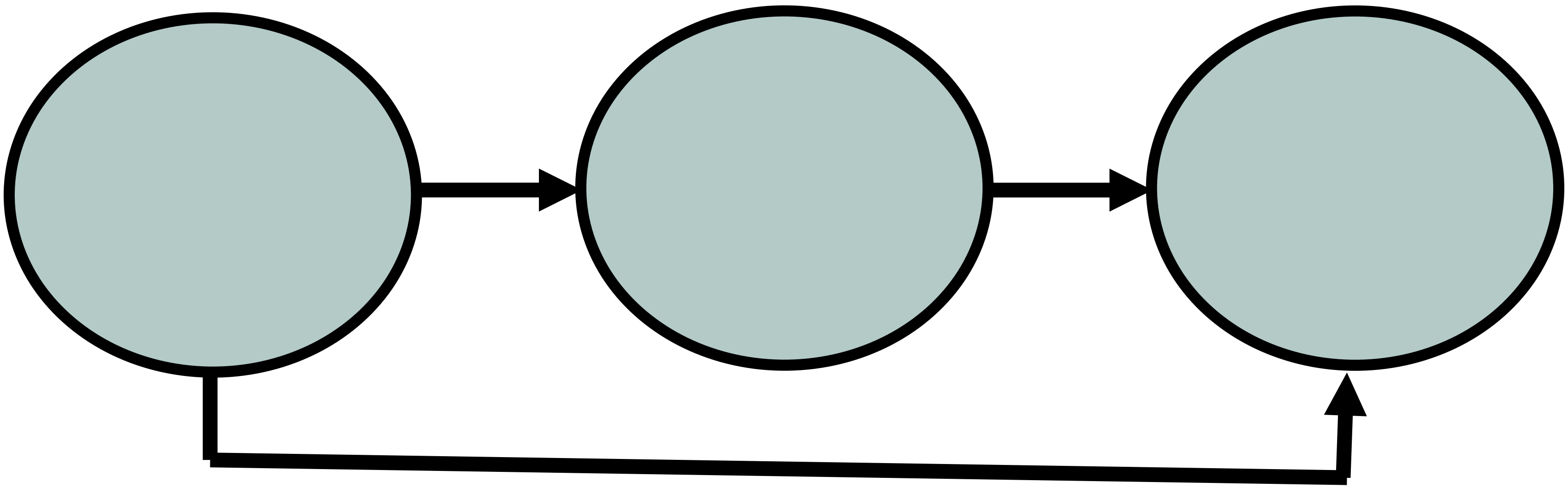

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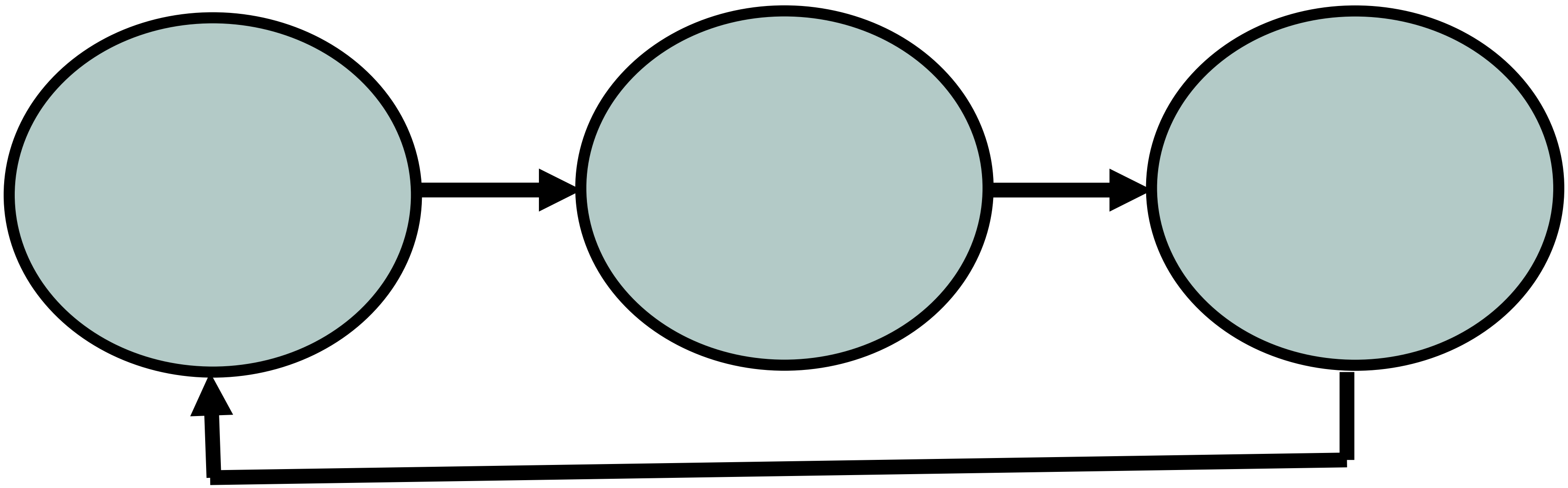

Deadlock

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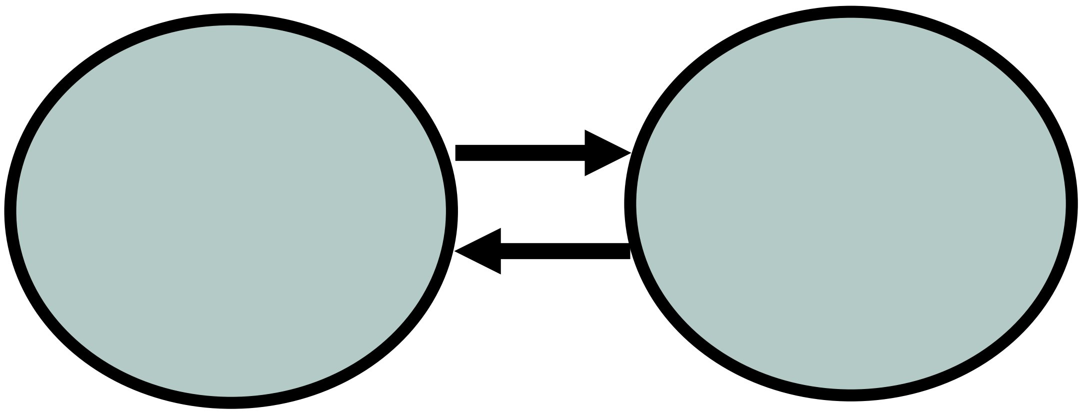
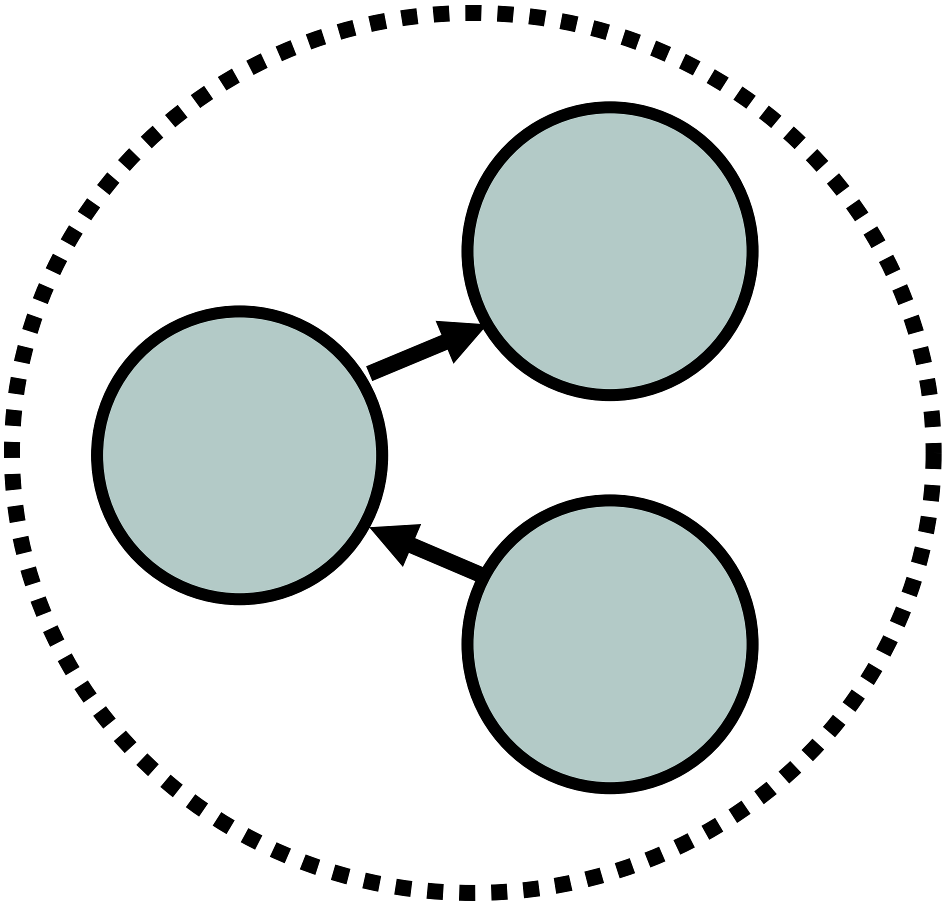


Deadlock

Didn't we solve this already?



No deadlock

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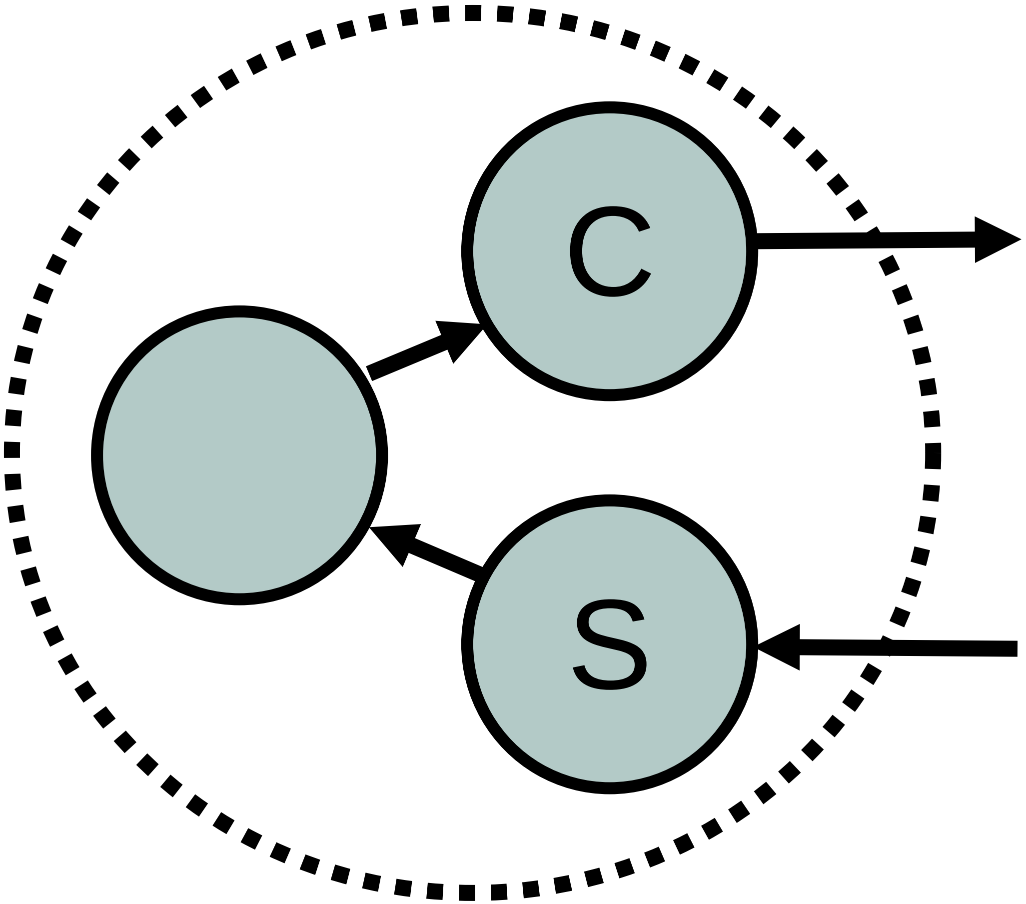
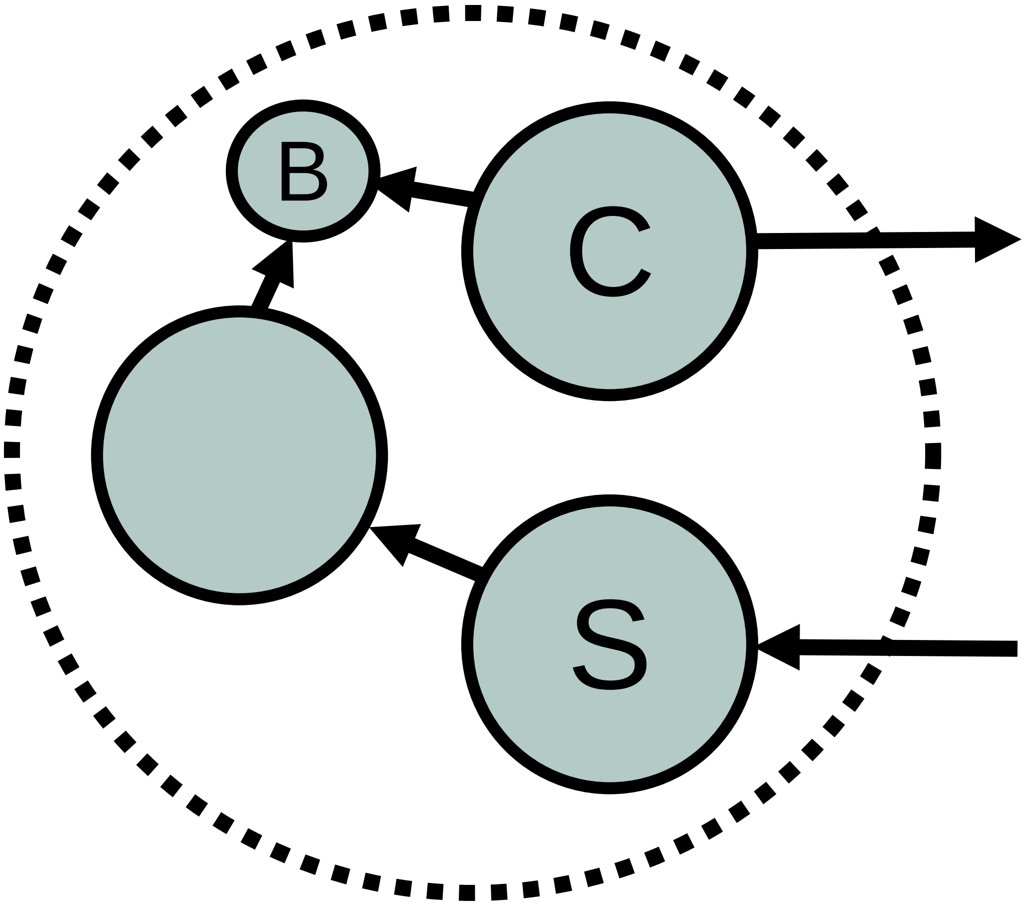


Maybe deadlock?

Deadlock

Didn’t we solve this already?



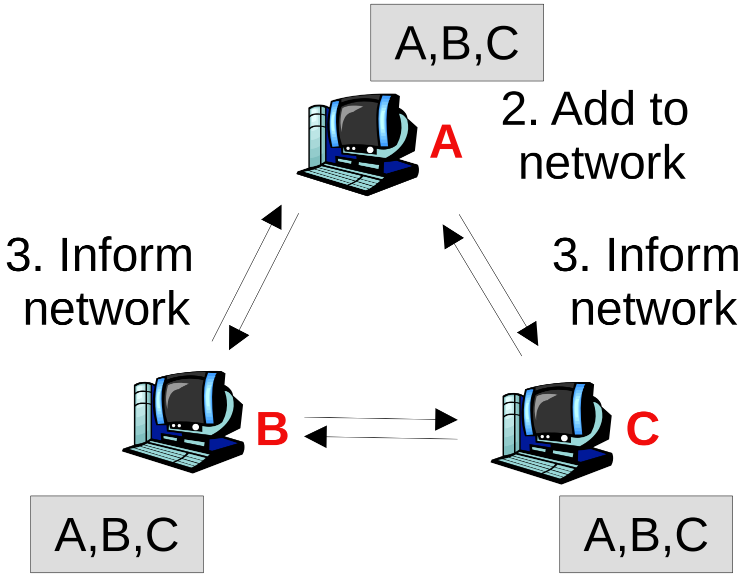
No deadlock

Summary: Approaches to Concurrency

- **Process-based**
  - Hard to share resources: Easy to avoid unintended sharing
  - High overhead in adding/removing clients
- **Event-based**
  - Tedious and low level
  - Total control over scheduling
  - Very low overhead
  - Cannot create as fine grained a level of concurrency
  - Does not make use of multi-core
- **Thread-based**
  - Easy to share resources: Perhaps too easy
  - Medium overhead
  - Not much control over scheduling policies
  - Difficult to debug
    - Event orderings not repeatable

Peer to Peer Network in A4

- P2P is a way to share data files
- Peers connect to a network by registering with someone already on it
- Each Peer will attempt to maintain a list of everyone on the network
- If a peer gets a request to join, it will inform all the peers it knows about



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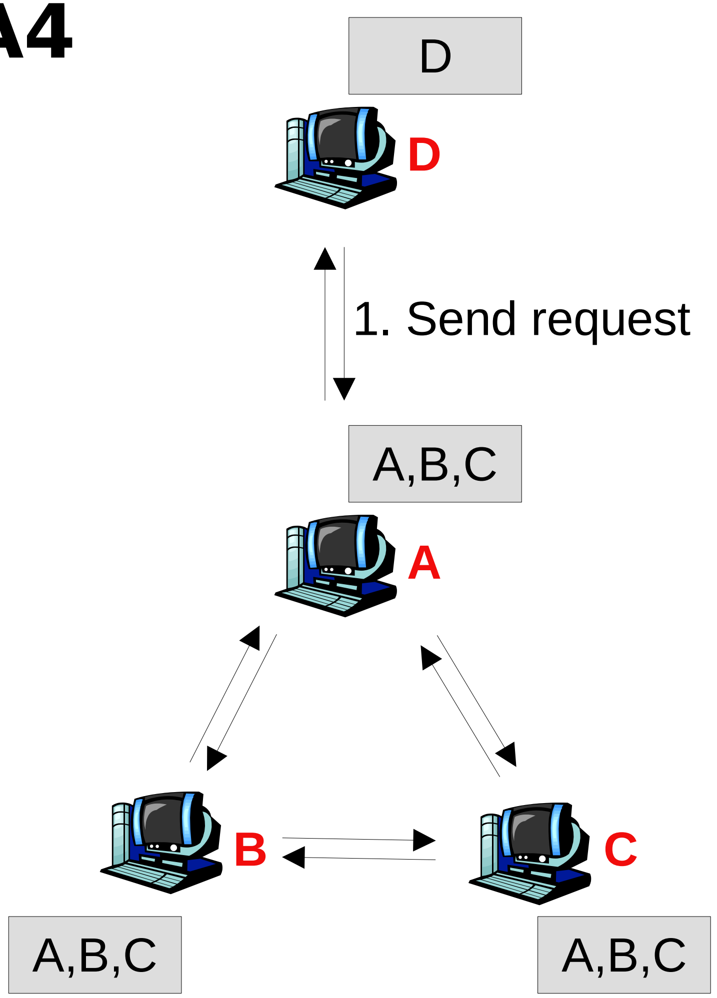

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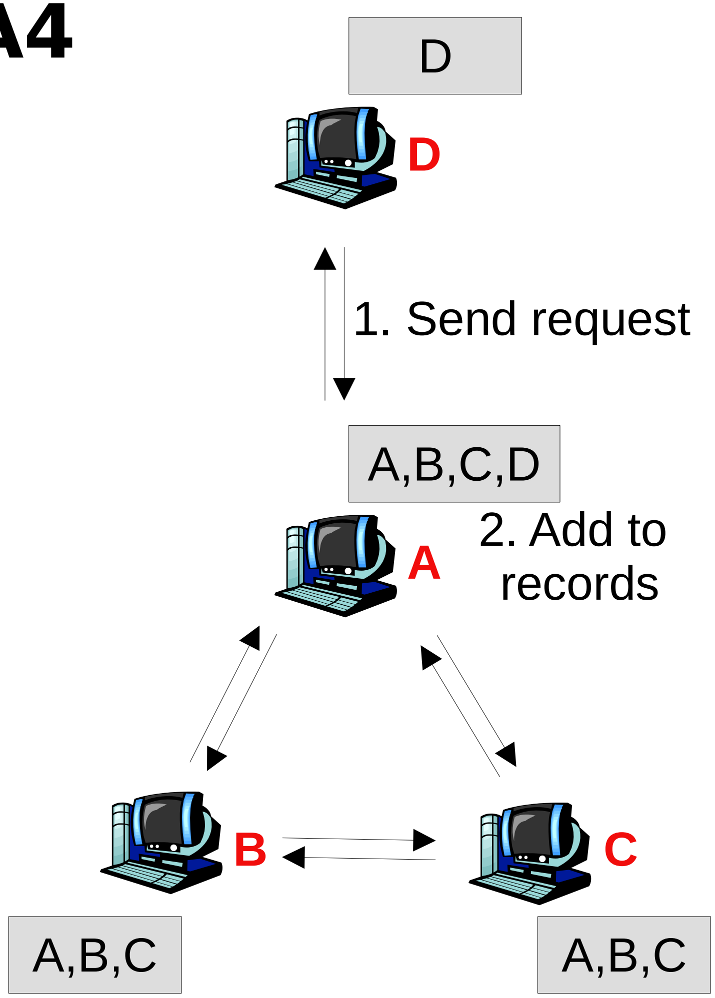

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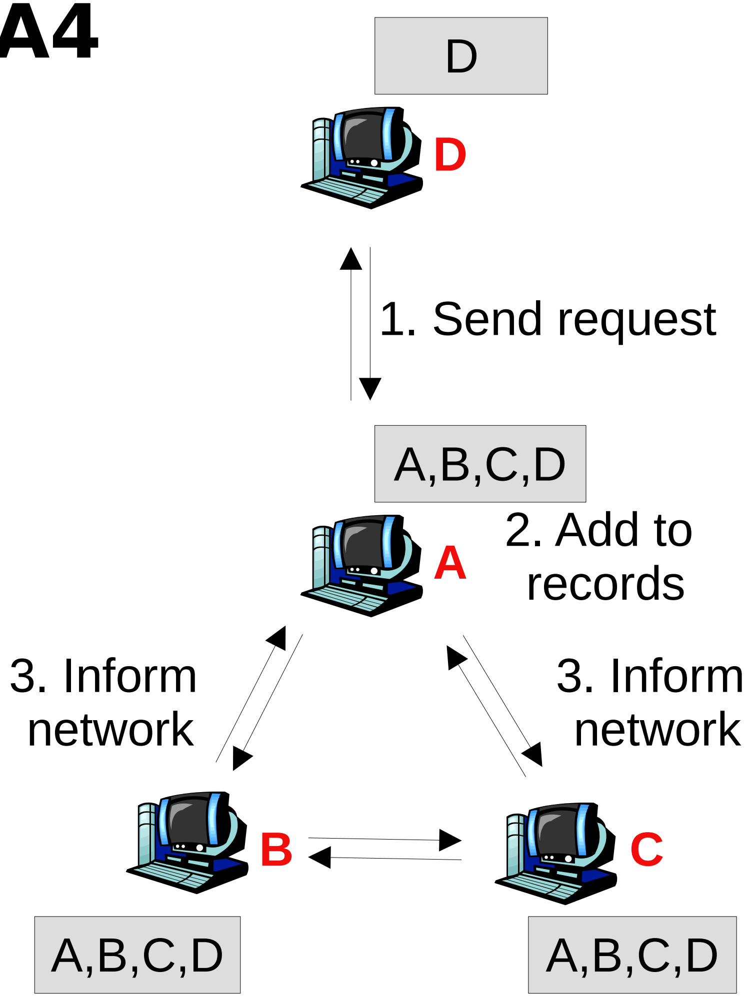

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