# Lab 5. Simple KVS

SNU System Programming Assignment

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T-NETWORKING LABORATORY

# What You Should Do

1. Implement basic server/client
   - Use socket APIs
   - Use multiple threads
   - Use skvs helper function

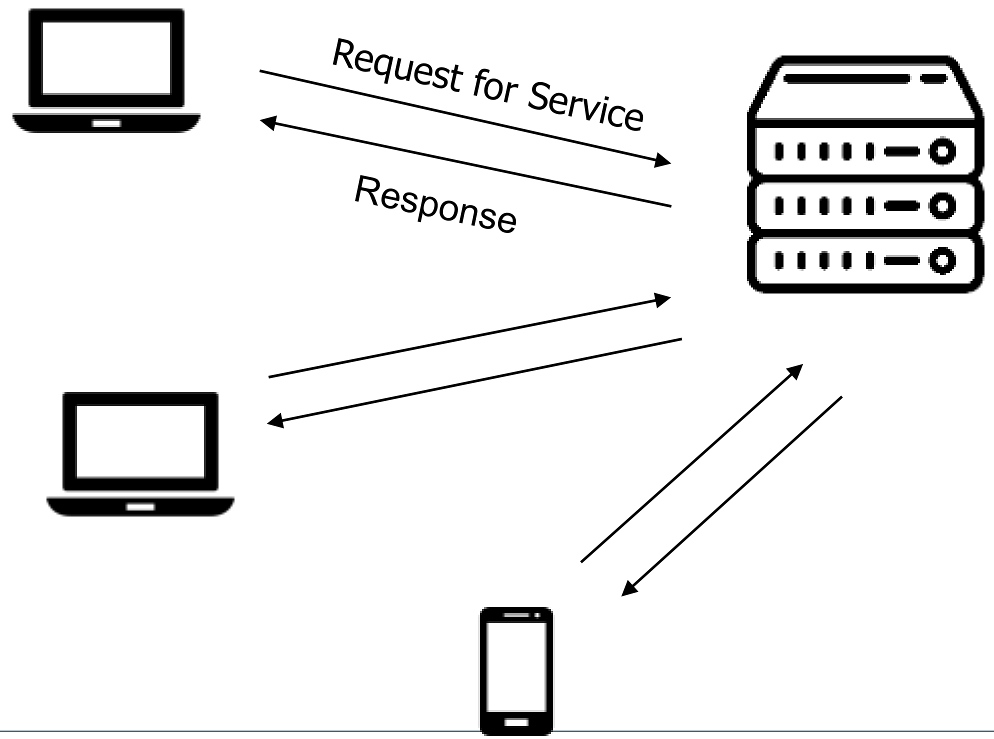
2. Implement a global hash table and rwlock
   - Multiple threads may access at the same time
   - Global hash table uses rwlock library
   - rwlock should support multiple concurrent readers when there is no writer

- Reference for socket programming in C:
  - https://beej.us/guide/bgnet/
- Reference for rwlock:
  - https://docs.oracle.com/cd/E37838_01/html/E61057/sync-124.html
  - https://www.ibm.com/docs/en/aix/7.3?topic=p-pthread-rwlock-rdlock-pthread-rwlock-tryrdlock-subroutines

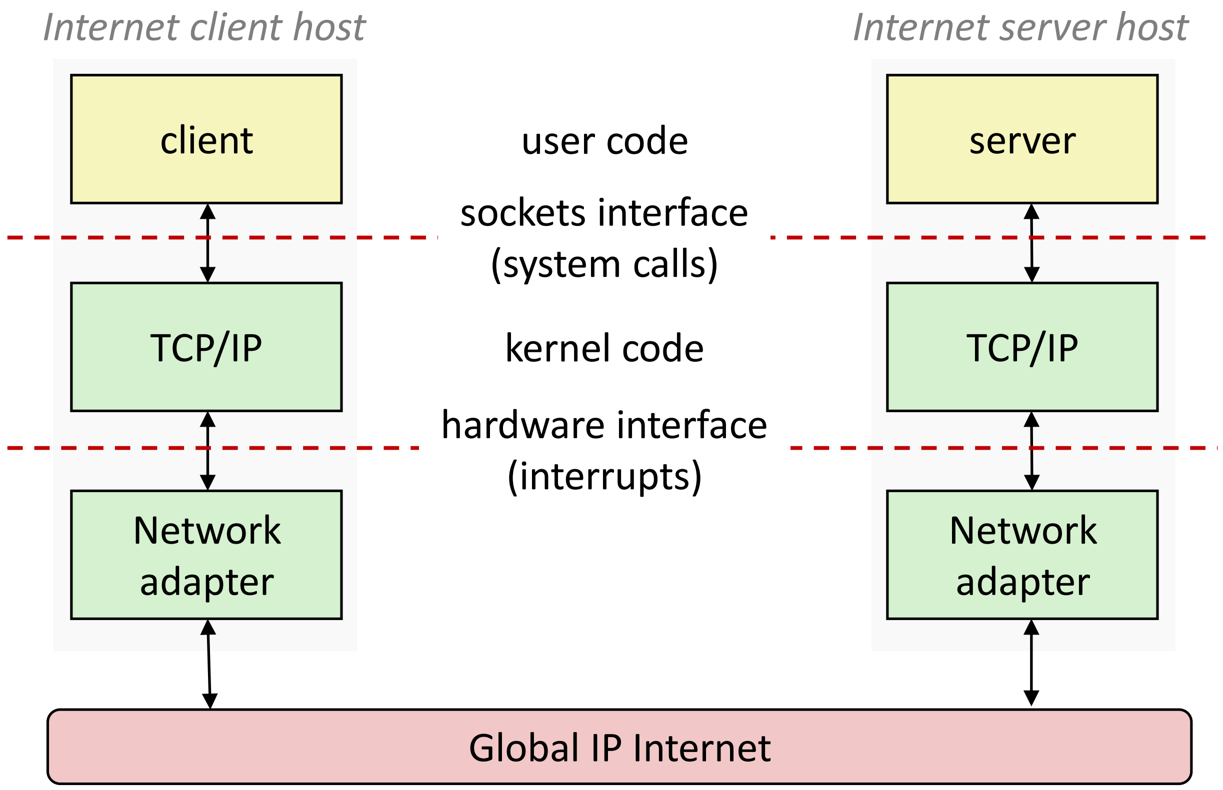
# Background 1:
# Basic Server/Client

# What is the Client-Server Model?

- **Definition**: A distributed computing architecture where a **client** requests services, and a **server** provides them.
- **Structure**: Typically involves multiple clients connecting to a centralized server.



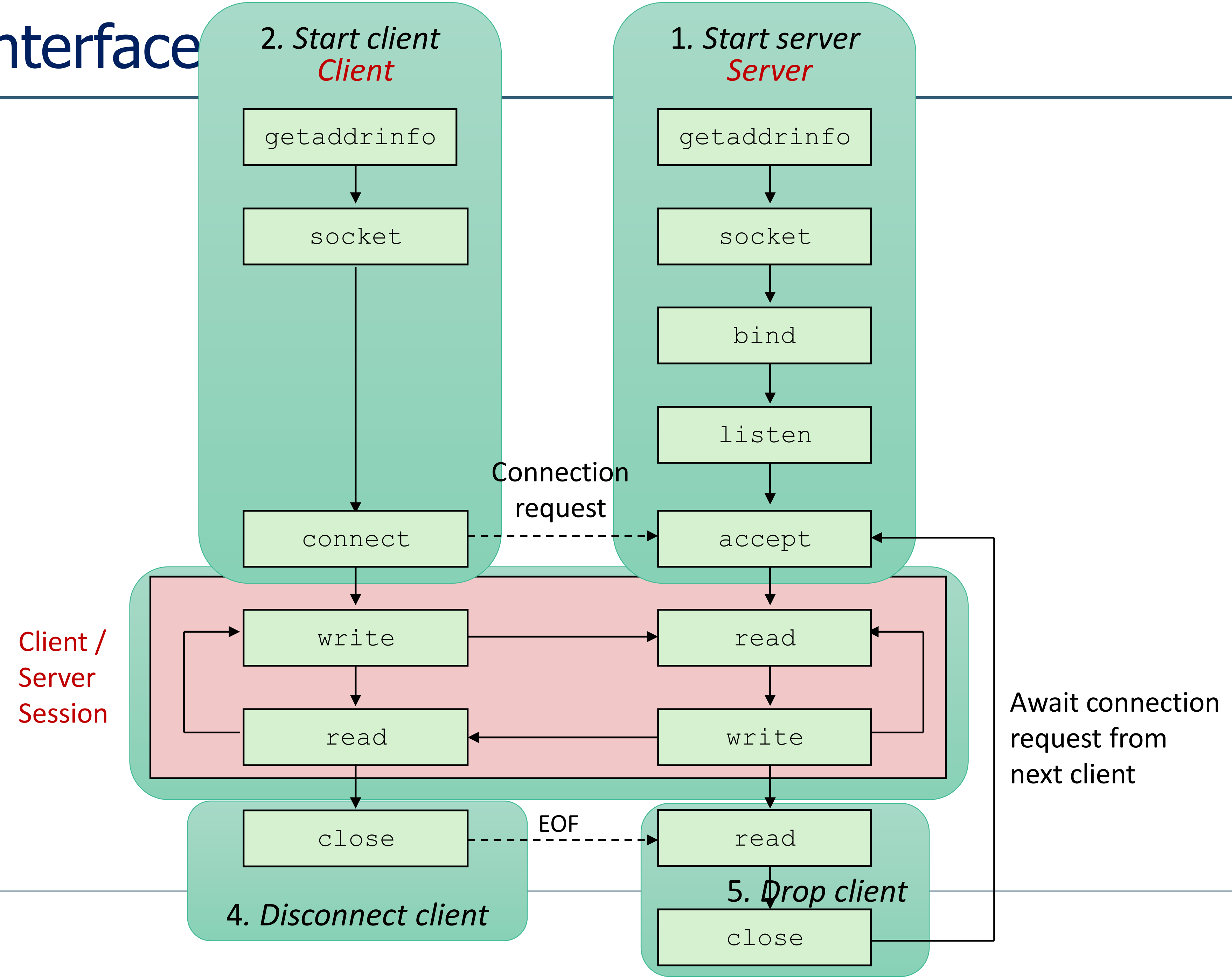
# Programmer's View




- Both client and server use socket interface!
- Not only for TCP, but also for UDP

TCP? UDP?

# TCP Socket Interface



# System Calls for Basic Server

- `getaddrinfo() & freeaddrinfo()`
  - Helper function for IP lookup
  - You may use `gethostbyname()` or `gethostbyname_r()`
  - Usually not used in server
- `socket()`
  - Makes a socket and allocates system resources for the socket
- `bind()`
  - Binds IP address and port to the socket
- `listen()`
  - Creates a connection queue to allow connections from clients
- `accept()`
  - Retrieves a connection from the connection queue and **returns a socket** for an established connection
- `read() & write()`
  - Next slide
- `close()`
  - Close the socket and cleans up resources

For this assignment, use 0.0.0.0 for binding server IP address

Socket descriptor,
Socket structure for metadata

Listen, accept: for TCP
TCP server has 2 sockets

# System Calls for Basic Client

- `getaddrinfo() & freeaddrinfo()`
  - Helper function for IP lookup
  - You may use `gethostbyname()` or `gethostbyname_r()`
- `socket()`
  - Makes a socket and allocates system resources for the socket
- `bind()`
  - Binds IP address and port to the socket
  - Usually not used in client
- `connect()`
  - Creates a connection to the specified address:port (starts TCP handshake)
- `read() & write()`
  - Next slide
- `close()`
  - Close the socket and cleans up resources

Socket descriptor,
Socket structure for metadata

connect: for TCP
TCP client has 1 socket

# read()

- `ssize_t read(int fd, void *buf, size_t nbytes)`

- `Returns`
  - # of bytes read ( > 0)
  - -1 (error, you should check `errno`)
    - No bytes read
  - 0 (closed by the peer)
- `errno == EAGAIN, EWOULDBLOCK`
  - Nothing to read from the TCP socket recv buffer, try later
- `errno == EINTR`
  - Failed due to interrupt, try again right now
- `errno == ECONNRESET`
  - The peer abruptly reset the connection

# write()

- `ssize_t write(int fd, void *buf, size_t nbytes)`

- `Returns`
  - # of bytes wrote ( > 0)
  - -1 (error, you should check `errno`)
    - No bytes wrote

- `errno == EAGAIN, EWOULDBLOCK`
  - TCP socket send buffer is full, try later
- `errno == EINTR`
  - Failed due to interrupt, try again right now
- `errno == ECONNRESET`
  - The peer abruptly reset the connection
- `errno == EPIPE`
  - The peer closed the connection

# Background 2:
# Lock

# Spin Lock vs. Mutex Lock

- Spin Lock
  - Continuously checks if the lock is available while consuming CPU cycles (busy-waiting)
  - Optimized for short wait times and multi-core environments
- Mutex Lock
  - Puts the waiting thread to sleep, releasing the CPU until the lock becomes available
  - Suitable for longer wait times or resource-intensive applications

| Aspect | Spin Lock | Mutex Lock |
|---|---|---|
| Waiting | Busy-waiting (CPU is fully utilized) | Sleep-waiting (CPU is released) |
| Overhead | Low (no context switching) | High (context switching involved) |
| Use case | Short wait times | Long wait times |
| Multi-core | Effective in multi-core systems | Works well in both single/multi-core |
| Complexity | Simple | Relies on OS support |

# Mutex Lock

- Protects shared data
- Allows only one thread to access the critical section

```c
int shared_data = 0;
void *thread_function(void* arg) {
    pthread_mutex_lock(&mutex);  // acquire mutex lock

    // critical section: access to the shared data
    shared_data++;
    printf("Thread %ld incremented data: %d\n",
           (long)arg, shared_data);

    pthread_mutex_unlock(&mutex);  // release mutex lock
    return NULL;
}
```

- What if most of the accesses are reads?

# Many Readers & Few Writers

- Contention necessary?

```
int shared_data = 0;
void *reader_function(void* arg) {
    pthread_mutex_lock(&mutex);

    printf("Reader %ld read 
data: %d\n",
           (long)arg, shared_data);

    pthread_mutex_unlock(&mutex);
    return NULL;
}
```

```
void *writer_function(void* arg) {
    pthread_mutex_lock(&mutex);

    shared_data++;
    printf("Writer %ld updated 
data: %d\n",
           (long)arg, shared_data);

    pthread_mutex_unlock(&mutex);
    return NULL;
}
```

- If there is no concurrent writer, multiple threads can concurrently read

# Reader-Writer Lock

- A specialized lock that distinguishes b/w read and write access

1. Allows concurrent multiple readers
   - Blocks writer when any readers exist
   - When there is no more readers, wake up one pending writer (Which one?)
2. Allows single writer only
   - Blocks other threads when writing
   - When there is no more writers, wake up all pending readers, then wake up one pending writer

| Aspect | Mutex Lock | Reader-Writer Lock |
|---|---|---|
| Concurrency | Only one thread (reader or writer) at a time | Multiple readers or a single writer |
| Performance | Suitable for low read-to-write ratio | Optimized for high read-to-write ratio |
| Complexity | Simpler | More complex |
| Starvation Risk | No starvation (single queue) | Writer starvation |
| Use Case | Any critical section | Scenarios with frequent reads and rare writes |

- By default, reader-writer lock is usually **reader-priority**

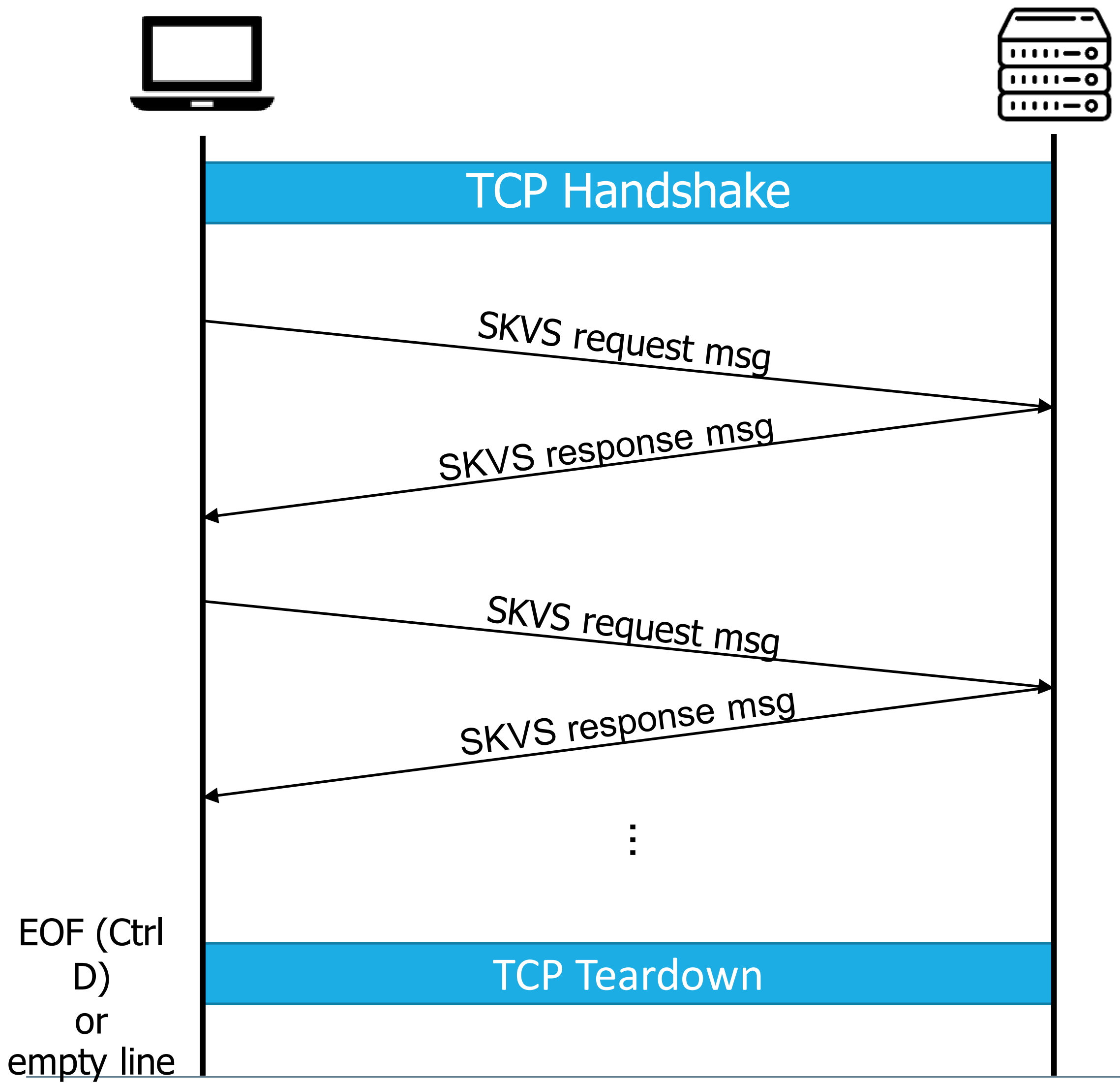
# Reader-Priority vs. Writer-Priority (Out of Scope)

- Reader-Priority RW Lock
  - A read request is granted immediately
  - A write request waits until all ongoing read operations complete
  - If new requests keep arriving, the write request can be indefinitely delayed (writer starvation)
- Writer-Priority RW Lock
  - If a write request is waiting, any new read requests are delayed
  - Once ongoing read operations finish, the write request is executed immediately
  - After the write completes, pending read requests are processed
  - Subsequent write requests continue to take precedence over new reads

| Aspect | Reader-Priority | Writer-Priority |
|---|---|---|
| Priority | Readers are prioritized | Writers are prioritized |
| Starvation Risk | Writers may starve | Readers may starve |
| Performance | Optimized for read-heavy workloads | Balances performance for both reads and writes |
| Complexity | Simpler | More complex |
| Use Case | Best for frequent reads | Suitable for fair scheduling b/w reads and writes |

# Part 1:
# Simple Key-Value Store Protocol

# SKVS Protocol




- One connection per one client
- **Keep alive** until typing empty line (\n) or EOF (Ctrl D)
- **Half-duplex**
  - After sending request, wait for the response
- **Text** based protocol
  - Key and value should be also text
  - Refer to the nest slide
- Server should be **stateful**
  - Key-value pairs should be accessible by other clients
- Default service port: 8080

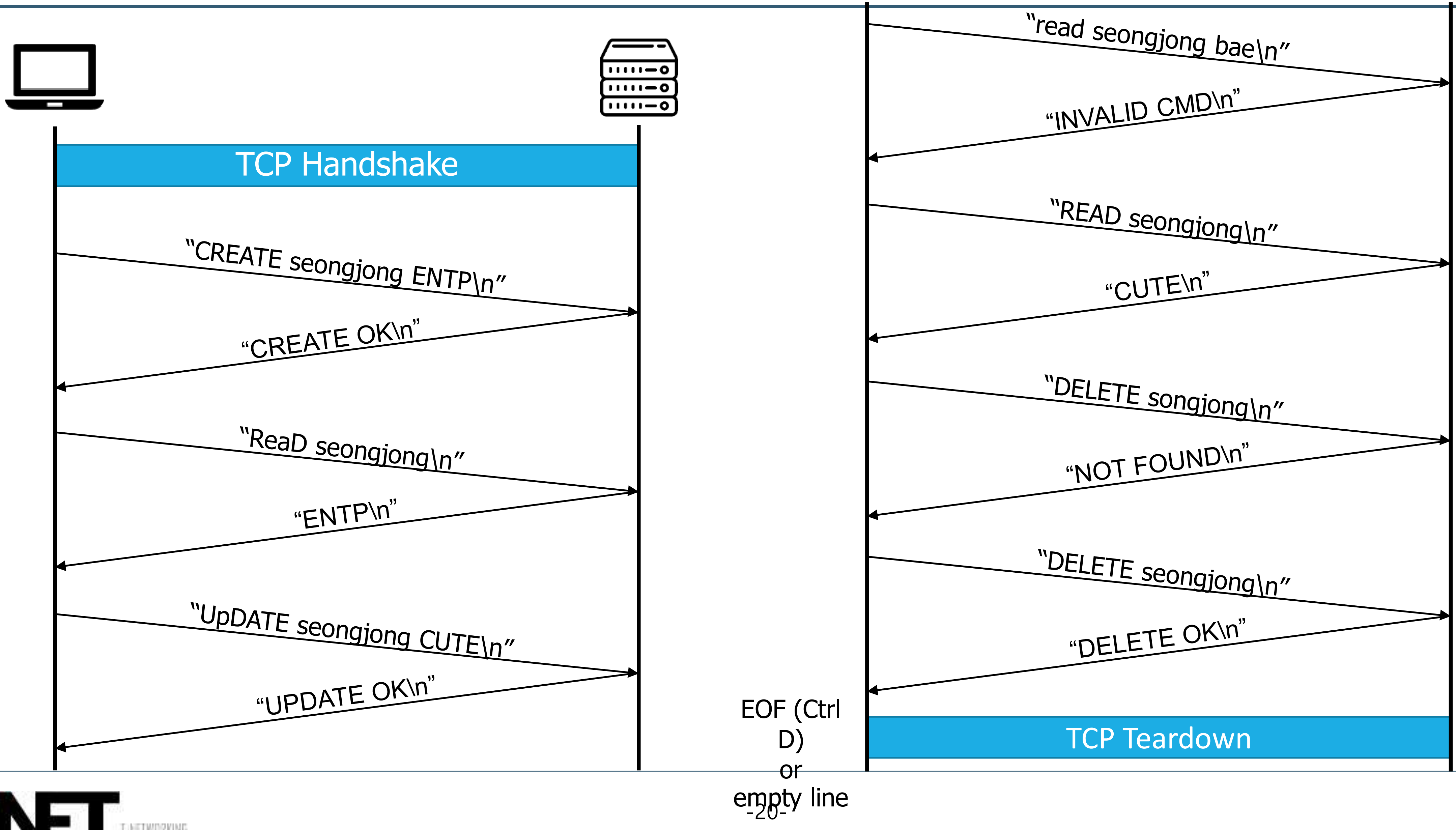
# SKVS Protocol (cont.)

- Request Msg Format:
  1. [CMD]$_s$[key]$_s$[value]$_n$
  2. [CMD]$_s$[key]$_n$
  - "$_s$": a space character
  - "$_n$": a newline character
- Examples
  - "CREATE hello world\n"
  - "READ hello\n"
  - "UPDATE hello snu\n"
  - "DELETE hello\n"
- CMD: one of CREATE, READ, UPDATE, and DELETE
  - case-insensitive (e.g., rEAd, cReAtE are okay)
- Key, value: string without $_s$ nor $_n$
  - No binary, only text, case-sensitive
  - len(key) <= 32B, len(SKVS msg) <= 4096B
    - Including $_n$

- Response Msg Format:
  - CREATE$_s$OK$_n$
  - [value]$_n$
  - UPDATE$_s$OK$_n$
  - DELETE$_s$OK$_n$
  - COLLISION$_n$
  - NOT$_s$FOUND$_n$
  - INVALID$_s$CMD$_n$
  - INTERNAL$_s$ERR$_n$

- EOF or empty line on client
  - Close the connection
  - Exit client program

# Example

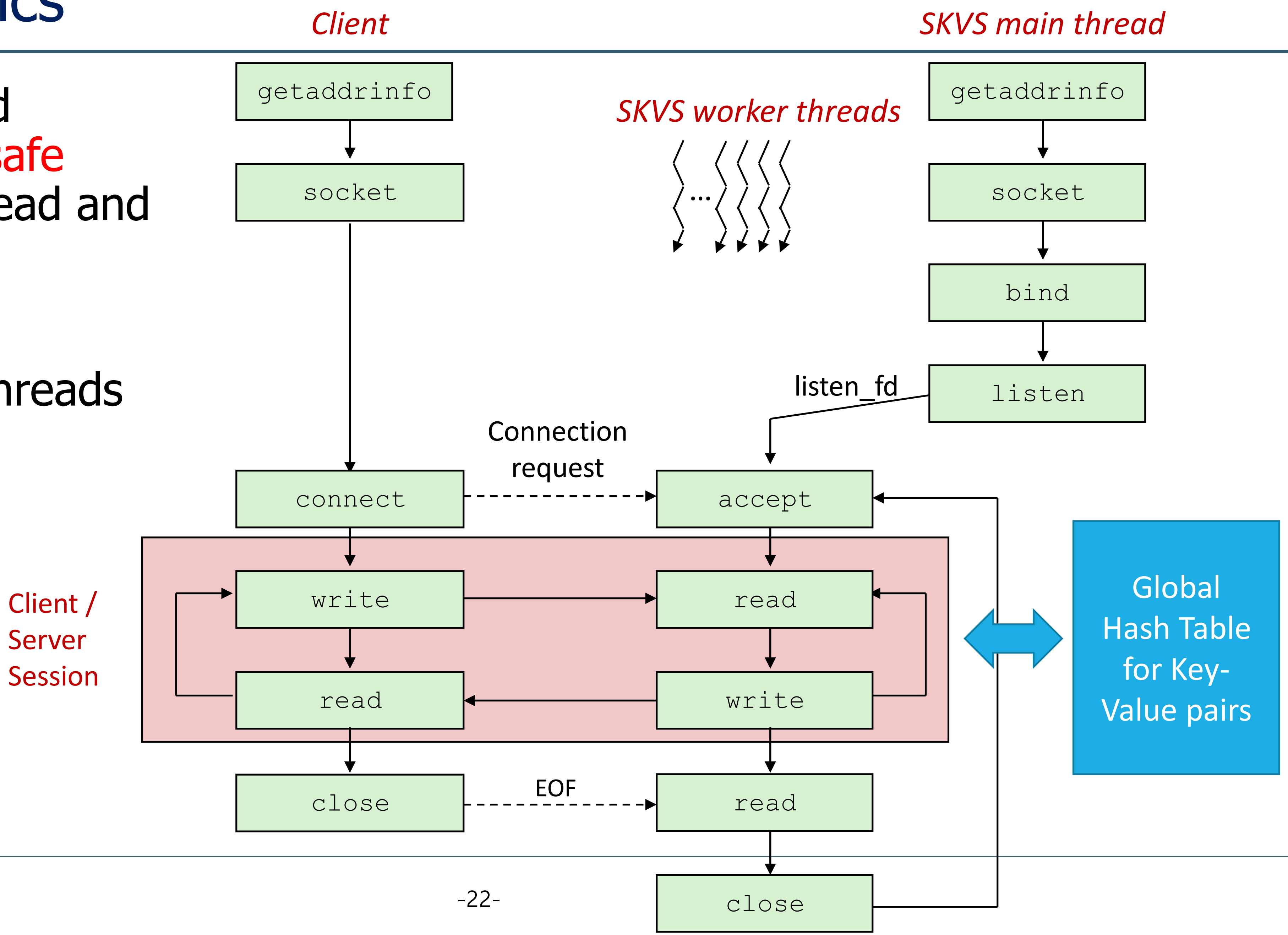

TCP Handshake
"CREATE seongjong ENTP\n"
"CREATE OK\n"
"ReaD seongjong\n"
"ENTP\n"
"UpDATE seongjong CUTE\n"
"UPDATE OK\n"
"read seongjong bae\n"
"INVALID CMD\n"
"READ seongjong\n"
"CUTE\n"
"DELETE songjong\n"
"NOT FOUND\n"
"DELETE seongjong\n"
"DELETE OK\n"
EOF (Ctrl D) or empty line
TCP Teardown

# Handling Errors

- If SKVS request is in invalid format?
  - Responds “INVALID CMD\n”
- If the length of SKVS msg > 4096
  - Responds “INVALID CMD\n”
- If the length of [key] > 32
  - Responds “INVALID CMD\n”
- Received CREATE msg, but key-value pair already exists?
  - Responds “COLLISION\n”
- Received READ/UPDATE/DELETE msg, but no such key exists?
  - Responds “NOT FOUND\n”
- If any internal error occurs, so cannot serve the request?
  - Responds “INTERNAL ERR\n”

# SKVS Semantics

- Global HT should support thread-safe access to both read and write operations
- Use 10 worker threads



# Why Static 10 Threads? Any Other Ways for Concurrency?

- What you have learned
  - `accept()`, `read()`, and `write()` are blocking..
  - What if dynamically `fork() / pthread_create()` for every clients?

  (+) Easy to implement

  (+) Easy to leverage multiple cores

- Reality..

  (--) Wastes system resources

  (--) Poor performance due to creating processes or threads

  (--) Poor performance due to context switching

  - Using `fork() / pthread_create()` for each request is inefficient (fork()/pthread_create() is heavyweight)

# Event-Driven Socket Programming (Out of Scope)

- Set the sockets non-blocking
- Use event-driven API (e.g., epoll)
- Static threads to leverage multiple cores
- Then,

  (+) Best performance
    - Supports concurrency without context switching
    - Small number of threads

  (--) Hard to implement using event-driven APIs

➔ Workaround: Simply use static threads for this assignment! ☺

# SKVS API

- Helper API for parsing and processing the SKVS requests
- `struct skvs_ctx *skvs_init(size_t hash_size, int delay)`
  - Initiates SKVS context
- `void skvs_destroy(struct skvs_ctx *ctx)`
  - Destroys SKVS context
- `const char *skvs_serve(struct skvs_ctx *ctx, char *buffer, size_t len)`
  - Serves an appropriate command for the given SKVS request
  - e.g., [value], “INVALID CMD”, “CREATE OK”, “UPDATE OK”, “COLLISION”, …
  - Notice: You should add a line feed at the end

# Client & Server Requirement

- Your client should connect remote server using domain name with arbitrary port
  - e.g., client on sp03.snucse.org → server on sp04.snucse.org:8080

```
./server [-p port (8080)] [-t num_threads (10)] [-d rwlock_delay (0)]
[-s hash_size (1024)]
./client [-i server_ip_or_domain (127.0.0.1)] [-p port (8080)] [-t]
```

  - Your server should serve ~10 concurrent clients
  - Your server and client should interoperate with reference client and server, respectively
- Your server should serve large key-value pair (~32B key, ~4096B SKVS msg)

- Reference server/client binaries will be provided
  - No support for Mac, windows
- For usage, refer to the reference server/client

# Usage Example for Interactive Mode (client w/ -t)

- Interactive mode for your better understanding and testing
  - Try it on using our reference client
- We will not use this mode for grading
  - No deduction even if your client does not support -t

```
junghan@sp01:~/lab-5-simple-kvs/assign5/ref$ ./server -p 8000 -t 5 -s 4096
Server listening on 0.0.0.0:8000
0th worker ready
1th worker ready
3th worker ready
2th worker ready
4th worker ready
```

```
junghan@sp02:~/lab-5-simple-kvs/assign5/ref$ ./client -i sp01.snucse.org -p 8000 -t
Connected to sp01.snucse.org:8000
Enter command: create hello world
Server reply: CREATE OK
Enter command: read hello
Server reply: world
```

# Usage Example for Silent Mode (client w/o -t)

- We will use this mode for grading
  - On the client, SKVS responses should be printed out to stdout
  - No any other messages allowed on the client

```
junghan@sp01:~/lab-5-simple-kvs/assign5/ref$ ./server -p 8000 -t 5 -s 4096
Server listening on 0.0.0.0:8000
1th worker ready
0th worker ready
3th worker ready
2th worker ready
4th worker ready
```

```
junghan@sp02:~/lab-5-simple-kvs/assign5/ref$ cat input
create hello world
read hello
junghan@sp02:~/lab-5-simple-kvs/assign5/ref$ ./client -i sp01.snucse.org -p 8000 < input
CREATE OK
world
```

# Part 2:
# Global Hash Table
# and
# rwlock

# hashtable.c

- SKVS library depends on hash table functions
- Hash table functions depend on rwlock functions
- Currently `hashtable.c, rwlock.c` are empty, but you should fill them

- `int hash_insert(hashtable_t *table, char *key, char *value)`
  - Needs a **write lock**
  - Duplicates key and value
  - Fills node structure and inserts node to the table
  - Returns 0 if collision, 1 if inserted, -1 if any internal error
- `int hash_search(hashtable_t *table, char *key, char **value)`
  - Needs a **read lock**
  - Returns 0 if not found, 1 (and outputs to `value`) if found, -1 if any internal error

# hashtable.c

- `int hash_update(hashtable_t *table, char *key, char *value)`
  - Needs a **write lock**
  - Duplicates value
  - Updates node->value to new one
  - Free old value
  - Returns 0 if not found, 1 if updated, -1 if any internal error
- `int hash_delete(hashtable_t *table, char *key)`
  - Needs a **write lock**
  - Frees key and value
  - Evicts from the table
  - Returns 0 if not found, 1 if deleted, -1 if any internal error

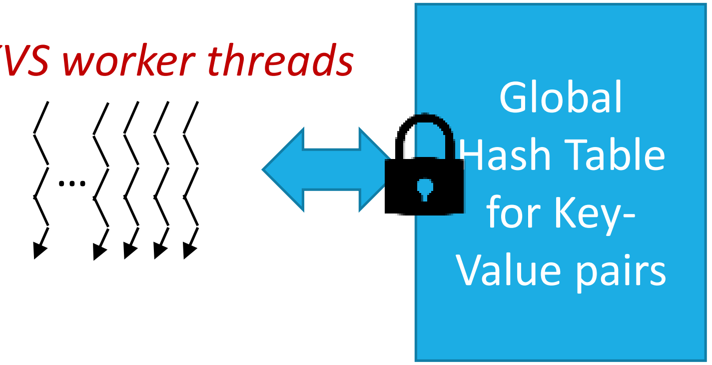
# Dumping Global Hash Table

- Your SKVS server should dump the hash table using `hash_dump()` before exit on SIGINT
- Register SIGINT handler for dump

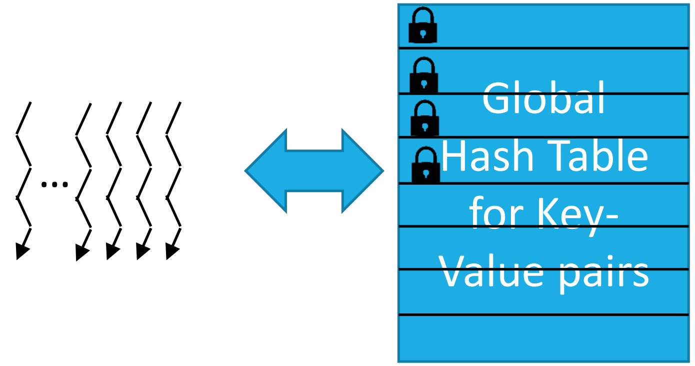
# Lock?

- SKVS uses global hashtable
  - Any threads consistently access the key-value pair
  - Accesses to the hashtable needs mutex lock
- But, lock contention leads to poor performance..

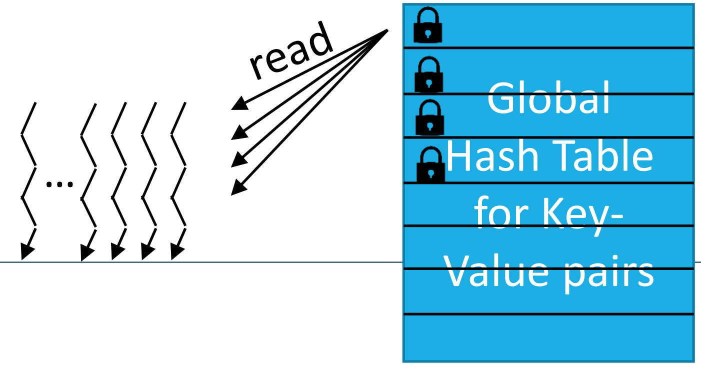
*SKVS worker threads*




1. Fine-grained lock
   - **For each bucket**
   - Less contention compared to course-grained lock




2. Reader-writer lock (reader-priority)
   - Assumes many readers, few writers
   - **Multiple readers are allowed at the same time**
   - Wakes up readers first, then the **oldest writer**



# `rwlock.c`

- Reader-priority reader-writer lock
- **Not** allowed to use `pthread_rwlock` API
- Implement your **own** one in `rwlock.c` using `pthread_mutex` and `pthread_cond` API

- `int rwlock_init(rwlock_t *rw, int delay)`
- `int rwlock_read_lock(rwlock_t *rw)`
- `int rwlock_read_unlock(rwlock_t *rw)`
- `int rwlock_write_lock(rwlock_t *rw)`
- `int rwlock_write_unlock(rwlock_t *rw)`
- `int rwlock_destroy(rwlock_t *rw)`

# Wake Up using Condition Variables

```
typedef struct {
        int read_count;          // number of current readers and waiting readers
        int write_count;         // number of current writers w/o waiting writers
        pthread_mutex_t lock;    // mutex lock for protecting other fields
        pthread_cond_t readers; // condvar for threads waiting read
        pthread_cond_t writers; // condvar for threads waiting write
        …
} rwlock_t
```

- Example for waking up other threads using condition variables

Thread 1: `pthread_cond_wait(&condvar, &mutex);`

Thread 2: `pthread_cond_signal(&condvar);`

- You should distinguish reader threads and writer threads

# rwlock_read_lock

`int rwlock_read_lock(rwlock_t *rw)`

1. Acquire mutex `lock`
2. Increment `read_count`
3. Wait if any threads are writing
   - By waiting for reader condvar `readers`

- Wake up!

4. Release mutex `lock`

```
typedef struct {
        int read_count;
        int write_count;
        pthread_mutex_t lock;
        pthread_cond_t readers;
        pthread_cond_t writers;
        …
} rwlock_t
```

# rwlock_write_lock

`int rwlock_write_lock(rwlock_t *rw)`

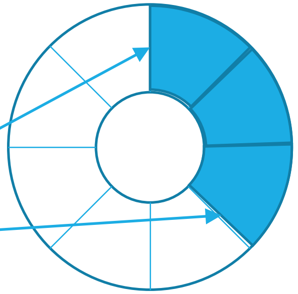
1. Acquire mutex `lock`
2. Insert this thread to `writer_ring`
3. Wait if any threads exist
   - By waiting for writer condvar `writers`

- Wake up!

4. Check if this thread is the oldest
   - If not, wait again
5. Increment `write_count`
6. Evict this thread from `writer_ring`
7. Release mutex `lock`

```
typedef struct {
        int read_count;
        int write_count;
        pthread_mutex_t lock;
        pthread_cond_t readers;
        pthread_cond_t writers;

        // pending writer ring
        pthread_t *writer_ring;
        int writer_ring_head;
        int writer_ring_tail;
} rwlock_t
```



# How to Test Write Lock?

- Before testing, check below
  1. Implement server/client first with **robust read/write**
  2. Your server **must** be ready for concurrency first
  3. `./server -d 5`
     - Add `sleep(5)` in `rwlock_write_unlock()`
     - Add `sleep(5)` in `rwlock_read_unlock()`

- Example test scenario

1. Send "CREATE hello 1\n" on client 1
   - It will hold a write lock for 5 seconds
2. Send "CREATE hello 2\n" on client 2
   - Check whether client 2 gets stuck
3. Send "CREATE hello 3\n" on client 3
   - Check whether client 3 gets stuck
4. Send "CREATE hello 4\n" on client 4
   - Check whether client 4 gets stuck

7. After 5 seconds…
   - Check whether client 1 receives "CREATE OK\n"
8. After 5 seconds…
   - Check whether client 2 receives "COLLISION\n"
9. After 5 seconds…
   - Check whether client 3 receives "COLLISION\n"
10. After 5 seconds…
    - Check whether client 4 receives "COLLISION\n"

# How to Test Read Lock?

- Before testing, check below
  1. Implement server/client first with **robust read/write**
  2. Your server **must** be ready for concurrency first
  3. `./server -d 5`
     - Add `sleep(5)` in `rwlock_write_unlock()`
     - Add `sleep(5)` in `rwlock_read_unlock()`

- Example test scenario

1. Send "CREATE hello world\n" on client 1
   - It will hold a write lock for 5 seconds
2. Send "READ hello\n" on client 2
   - Check whether client 2 gets stuck
3. Send "READ hello\n" on client 3
   - Check whether client 3 gets stuck
4. Send "READ hello\n" on client 4
   - Check whether client 4 gets stuck

simultaneously

7. After 5 seconds…
   - Check whether client 1 receives "CREATE OK\n"
8. After 5 seconds…
   - Check whether client 2 receives "world\n"
   - Check whether client 3 receives "world\n"
   - Check whether client 4 receives "world\n"

# Complex Scenario

- Before testing, check below
  1. Implement server/client first with **robust read/write**
  2. Your server **must** be ready for concurrency first
  3. `./server -d 5`
     - Add `sleep(5)` in `rwlock_write_unlock()`
     - Add `sleep(5)` in `rwlock_read_unlock()`
- Example test scenario

1. Send "CREATE hello world\n" on client 1
   - It will hold a write lock for 5 seconds
2. Send "DELETE bye\n" on client 2
   - Check whether client 2 gets stuck
3. Send "READ hello\n" on client 3
   - Check whether client 3 gets stuck
4. Send "UPDATE hello snu\n" on client 4
   - Check whether client 4 gets stuck
5. Send "DELETE hello\n" on client 5
   - Check whether client 5 gets stuck
6. Send "READ hello\n" on client 6
   - Check whether client 6 gets stuck
7. After 5 seconds…
   - Check whether client 1 receives "CREATE OK\n"
   - Check whether client 2 receives "NOT FOUND\n" (why?)
8. After 5 seconds…
   - Check whether client 3 receives "world\n"
   - Check whether client 6 receives "world\n"
9. After 5 seconds…
   - Check whether client 4 receives "UPDATE OK\n"
10. After 5 seconds…
    - Check whether client 5 receives "DELETE OK\n"

# Requirements Summary

- Your client should connect remote server using domain name with arbitrary port
  - e.g., client on sp03.snucse.org → server on sp04.snucse.org:8080

```
./server [-p port (8080)] [-t num_threads (10)] [-d rwlock_delay (0)]
[-s hash_size (1024)]
./client [-i server_ip_or_domain (127.0.0.1)] [-p port (8080)] [-t]
```

  - Your server should serve ~10 concurrent clients
  - Your server and client should interoperate with reference client and server, respectively
- Your server should serve large key-value pair (~32B key, ~4096B SKVS msg)
- Print the entries in the global hash table using `hash_dump()`
  - Do not modify this function
- Concurrent multiple readers' access to the global hash table
- Correct reader-priority RW lock semantic
- Do not modify other files than `client.c`, `server.c`, `hashtable.c`, and `rwlock.c`

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# Guidelines

# Notice

- Do not change the name and the prototype of the skeleton code

- What to submit
  - A tarball named `202412345_assign5` including `server.c client.c hashtable.c rwlock.c`.

```
cd assign5/src
make submit ID=202412345
```

- Replace `202412345` to your student ID without dash

# Deadline

- Deadline: ~ 2024. 12. 20 21:00
  - 0 Points if deadline is missed
  - 0 Points for copying
- Contact
  - Lab 5 TA e-mail: cerotyki@snu.ac.kr
  - TA mailing list: snu-sysp@googlegroups.com

# Reference Binaries for self-checking

- Reference server/client binaries will be provided
  - No support for Mac, windows
- For any ambiguities, refer to the reference server/client

- You may use `TRACE_PRINT()` and `DEBUG_PRINT()` for debugging

```
CFLAGS += -DTRACE
CFLAGS += -DDEBUG
```

# Q&A