

## Lab 4: the summit (TCP in full)

**Due:** Wednesday, Nov. 6, 5 p.m.

**Lab sessions:** Tuesday, Oct. 29 & Nov. 5, 7:30–10 p.m. in STLC114

## 0 Collaboration Policy

**The programming assignments must be your own work:** You must write all the code you hand in for the programming assignments, except for the code that we give you as part of the assignment. Please do not copy-and-paste code from Stack Overflow, GitHub, or other sources. If you base your own code on examples you find on the Web or elsewhere, cite the URL in a comment in your submitted source code.

**Working with others:** You may not show your code to anyone else, look at anyone else's code, or look at solutions from previous years. You may discuss the assignments with other students, but do not copy anybody's code. If you discuss an assignment with another student, please name them in a comment in your submitted source code. Please refer to the course administrative handout for more details, and ask on Piazza if anything is unclear.

**Piazza:** Please feel free to ask questions on Piazza, but please don't post any source code.

## 1 Overview

In Lab 0, you implemented the abstraction of a *flow-controlled byte stream* (`ByteStream`).

In Labs 1, 2, and 3, you implemented tools that translate between that abstraction and the one the Internet provides: unreliable datagrams (IP or UDP).

Now, you are nearing the summit: a working `TCPConnection` that combines your `TCPSender` and `TCPReceiver` and can talk to other implementations at a speed of at least 100 Mbit/s. Figure 1 shows the overall design.

## 2 Getting started

Your implementation of a `TCPConnection` will use the same Sponge library that you used in Labs 0–3, with additional classes and tests. We're giving you support code that reads and writes TCP segments into the payloads of user datagrams ("TCP-over-UDP") and Internet datagrams ("TCP/IP"). We're also giving you a class (`CS144TCPSocket`) that wraps your `TCPConnection` and makes it behave like a normal stream socket, just like the `TCPSocket` you used to implement `webget` back in Lab 0. By the end of this lab, you will slightly modify your `webget` to use *your* TCP implementation. To get started:

1. Make sure you have committed all your solutions to Lab 3. Please don't modify any

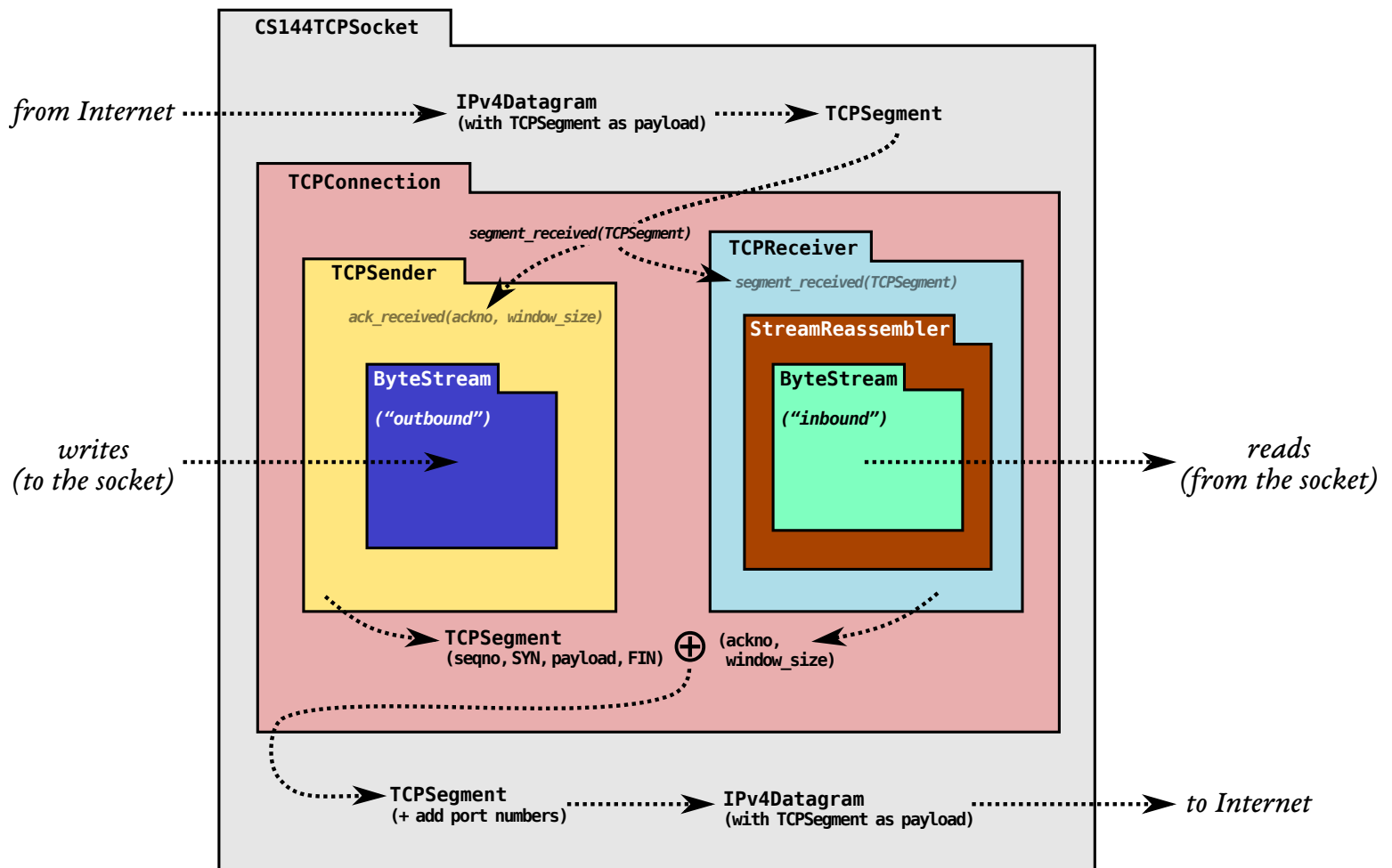


Figure 1: The arrangement of modules and dataflow in your TCP implementation.

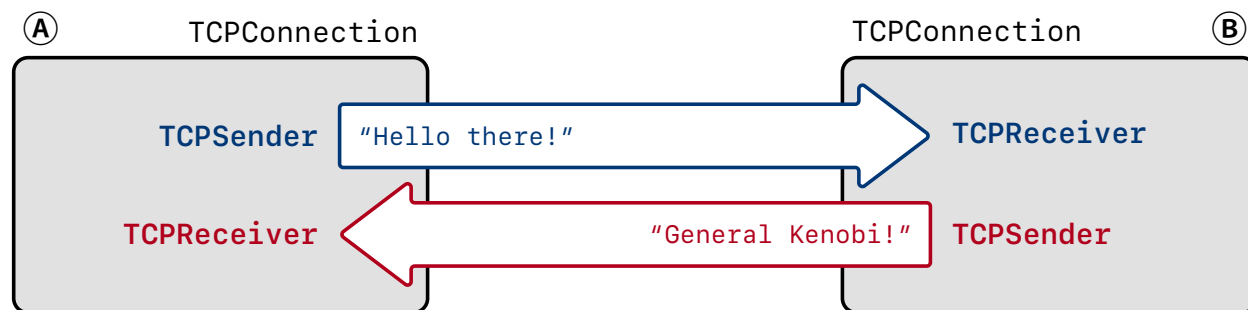
files outside the top level of the `libsponge` directory, or `webget.cc`. You may have trouble merging the Lab 4 starter code otherwise.

2. While inside the repository for the lab assignments, run `git fetch` to retrieve the most recent version of the lab assignments.
3. Download the starter code for Lab 3 by running `git merge origin/lab4-startercode`.
4. Within your `build` directory, compile the source code: `make` (you can run, e.g., `make -j4` to use four processors when compiling).
5. Outside the `build` directory, open and start editing the `writeups/lab4.md` file. This is the template for your lab writeup and will be included in your submission.

### 3 Lab 4: The TCP connection

This week, you'll finish building a working TCP implementation that's compatible with literally billions of computers and mobile devices on the Internet. You've already done most of the work to get there: you've implemented the sender and the receiver. Your job this week is to “wire them up” together into one object (a `TCPConnection`) and handle some housekeeping tasks that are global to the connection.

Recall: TCP reliably conveys a *pair* of flow-controlled byte streams, one in each direction. Two parties participate in the TCP connection, and *each party* acts as both “sender” (of its own outbound byte-stream) and “receiver” (of an inbound byte-stream) at the same time:



The two parties (“A” and “B” in the above diagram) are called the “endpoints” of the connection, or the “peers.” Your `TCPConnection` acts as *one* of the peers. It’s responsible for receiving and sending segments, making sure the sender and receiver are informed about and have a chance to contribute to *the fields they care about* for incoming and outgoing segments.

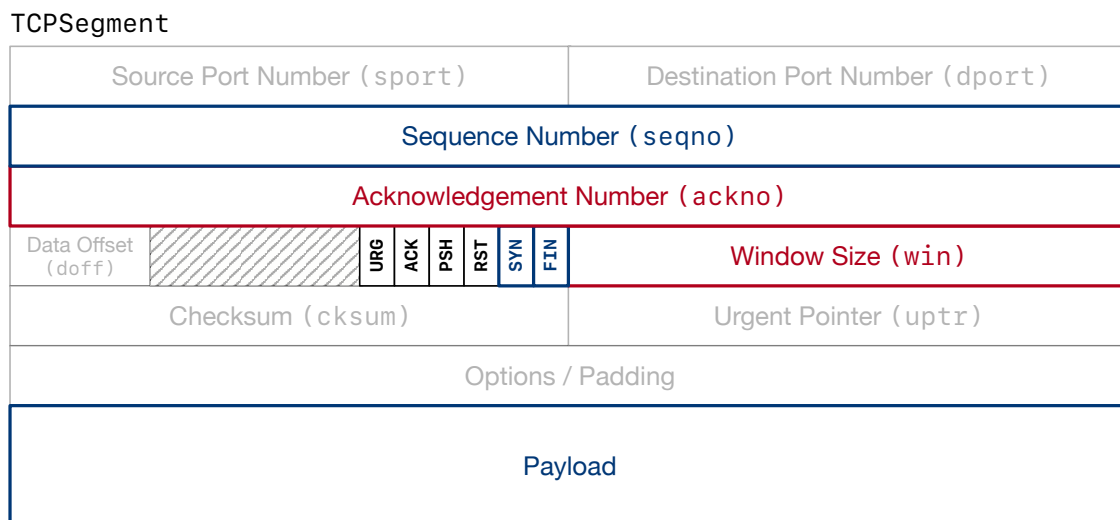
**Receiving segments.** The `TCPConnection` will receive `TCPSegments` from the Internet, and

- if the `ACK` flag is set, tell the `TCPSender` about the fields it cares about on incoming segments: `ackno` and `window.size`, and
- give the segment to the `TCPReceiver` so it can inspect the fields it cares about on incoming segments: `seqno`, `SYN`, `payload`, and `FIN`.

**Sending segments.** The `TCPConnection` will send `TCPSegments` over the Internet:

- whenever the `TCPSender` pushes a segment onto its outgoing queue, having set the fields it's responsible for on outgoing segments: (`seqno`, `SYN`, `payload`, and `FIN`).
- Before sending the segment, the `TCPConnection` will ask the `TCPReceiver` for the fields it's responsible for on outgoing segments: `ackno` and `window_size`. If there is an `ackno`,<sup>1</sup> it will set the `ACK` flag and the fields in the `TCPSegment`.

As a result, the overall structure of each `TCPSegment` looks like this, with “sender” and “receiver” fields shown in different colors:



The full interface for the `TCPConnection` is [in the class documentation](#). Please take some time to read through this. **Much** of your implementation will involve “wiring up” the public API of the `TCPConnection` to the appropriate routines in the `TCPSender` and `TCPReceiver`. As much as possible, you want to defer any heavy lifting to the sender and receiver that you’ve already implemented. That said, not everything will be that simple, and there are some subtleties that involve the “global” behavior of the overall connection. The hardest part will be deciding when to fully terminate a `TCPConnection` and declare it no longer “active.”

What follows are some FAQs and details of edge cases that you’ll need to handle.

## 4 FAQs and special cases

- *How much code are you expecting?*

Overall, we expect the implementation (in `tcp_connection.cc`) will require about 100–150 lines of code in total. When you’re done, the test suite will extensively test your interoperability with your own implementation as well as the Linux kernel’s implementation of TCP.

<sup>1</sup>Remember that `TCPReceiver::ackno()` returns an optional value.

- *How should I get started?*

Probably the best way to start is by wiring up some of the “ordinary” methods to the appropriate calls in `TCPSender` and `TCPReceiver`. This may include stuff like `remaining_outbound_capacity()`, `bytes_in_flight()`, and `unassembled_bytes()`.

Then you may choose to implement the “writer” methods: `connect()`, `write()`, and `end_input_stream()`. Some of these methods may need to do something to the outbound `ByteStream` (owned by the `TCPSender`) **and** tell the `TCPSender` about it.

You might choose to start running the test suite (`make check`) before you have fully implemented every method; the test failure messages can give you a clue or a guide about what to tackle next.

- *How does the application read from the inbound stream?*

`TCPConnection::inbound_stream()` is implemented in the header file already.

- *Does the `TCPConnection` need any fancy data structures or algorithms?*

No, it really doesn’t. The heavy lifting is all done by the `TCPSender` and `TCPReceiver` that you’ve already implemented. The work here is really just about wiring everything up, and dealing with some lingering connection-wide subtleties that can’t easily be factored in to the sender and receiver.

- *How does the `TCPConnection` actually send a segment?*

Similar to the `TCPSender`—push it on to the `_segments_out` queue. As far as your `TCPConnection` is concerned, consider it sent as soon as you push it on to this queue. Soon the owner will come along and pop it (using the public `segments_out()` accessor method) and really send it.

- *How does the `TCPConnection` learn about the passage of time?*

Similar to the `TCPSender`—the `tick()` method will be called periodically. Please don’t use any other way of telling the time—the tick method is your only access to the passage of time. That keeps things deterministic and testable.

- *What does the `TCPConnection` do if an incoming segment has the `RST` flag set?*

This flag (“reset”) means instant death to the connection. If you receive a segment with `RST`, you should set the error flag on the inbound and outbound `ByteStreams`, and any subsequent call to `TCPConnection::active()` should return false.

- *When should I **send** a segment with the `RST` flag set?*

There are two situations where you’ll want to abort the entire connection:

1. If the sender has sent too many consecutive retransmissions without success (more than `TCPConfig::MAX_RETX_ATTEMPTS`, i.e., 8).
2. If the `TCPConnection` destructor is called while the connection is still active (`active()` returns true).

Sending a segment with `RST` set has a similar effect to receiving one: the connection is dead and no longer `active()`, and both `ByteStreams` should be set to the error state.

- *Wait, but how do I even make a segment that I can set the `RST` flag on? What's the sequence number?*

Any outgoing segment needs to have the proper sequence number. You can force the `TCPSender` to generate an empty segment with the proper sequence number by calling its `send_empty_segment()` method. Or you can make it fill the window (generating segments *if* it has outstanding information to send, e.g. bytes from the stream or SYN/FIN) by calling its `fill_window()` method.

- *What's the purpose of the `ACK` flag? Isn't there always an `ackno`?*

**Almost** every `TCPSegment` has an `ackno`, and has the `ACK` flag set. The exceptions are just at the very beginning of the connection, before the receiver has anything to acknowledge.

**On outgoing segments**, you'll want to set the `ackno` and the `ACK` flag whenever possible. That is, whenever the `TCPReceiver`'s `ackno()` method returns a `std::optional<WrappingInt32>` that has a value, which you can test with `has_value()`.

**On incoming segments**, you'll want to look at the `ackno` only if the `ACK` field is set. If so, give that `ackno` (and window size) to the `TCPSender`.

- *On receiving a segment, what should I do if the `TCPReceiver` complains that the segment didn't overlap the window and was unacceptable (`segment_received()` returns false)?*

In that situation, the `TCPConnection` needs to make sure that a segment is sent back to the peer, giving the current `ackno` and `window_size`. This can help correct a confused peer.

- *Okay, fine. How about if the `TCPConnection` received a segment, and the `TCPSender` complains that an `ackno` was invalid (`ack_received()` returns false)?*

Same answer!

- *How about if the `TCPConnection` received a segment, and everything was great? Do I still need to reply?*

**If the segment occupied any sequence numbers**, then you need to make sure it gets acknowledged—at least one segment needs to be sent back to the peer with an appropriate sequence number and the new `ackno` and `window_size`. You might not need to do anything to force this, because the `TCPSender` will often decide to send a new segment in `ack_received()` (because more space has opened up in the window). But even if the `TCPSender` doesn't have more data to send, you need to make sure the incoming segment gets acknowledged somehow.

- *How about if the `TCPConnection` just acknowledges **every** segment, even if it doesn't occupy any sequence numbers?*

Not a great idea! The two peers would end up sending an infinite number of acks ping-ponging back and forth.

- *How do I decipher these “state” names (like “stream started” or “stream ongoing”)?*  
Check out the [libsponge/tcp\\_helpers/tcp\\_state.hh](#) and [tcp\\_state.cc](#) files.
- *What window size should I send if the `TCPReceiver` wants to advertise a window size that’s bigger than will fit in the `TCPSegment::header().win` field?*  
Send the biggest value you can. You might find the `std::numeric_limits` class helpful.
- *When is the TCP connection finally “done”? When can `active()` return false?*  
Please see the next section.
- *Where can I read if there are more FAQs after this PDF comes out?*  
Please check the website ([https://cs144.github.io/lab\\_faq.html](https://cs144.github.io/lab_faq.html)) and Piazza regularly.

## 5 The end of a TCP connection: consensus takes work

One important function of the `TCPConnection` is to decide when the TCP connection is fully “done.” When this happens, the implementation releases its exclusive claim to a local port number, stops sending acknowledgments in reply to incoming segments, considers the connection to be history, and has its `active()` method return false.

There are two ways a connection can end. In an **unclean shutdown**, the `TCPConnection` either sends or receives a segment with the `RST` flag set. In this case, the outbound and inbound `ByteStreams` should both be in the `error` state, and `active()` can return false immediately.

A **clean shutdown** is how we get to “done” (`active() = false`) without an error. This is more complicated, but it’s a beautiful thing because it ensures as much as possible that *each* of the two `ByteStreams` has been reliably delivered *completely* to the receiving peer. In the next section (§§5.1), we give the practical upshot for when a clean shutdown happens, so feel free to skip ahead if you like.

Cool, you’re still here. Because of the [Two Generals Problem](#), it’s *impossible to guarantee* that both peers can achieve a clean shutdown, but TCP gets pretty close. Here’s how. From the perspective of one peer (one `TCPConnection`, which we’ll call the “local” peer), there are four prerequisites to having a clean shutdown in its connection with the “remote” peer:

**Prereq #1** The **inbound** stream has been fully assembled and has ended.

**Prereq #2** The **outbound** stream has been ended by the local application *and* fully sent (including the fact that it ended, i.e. a segment with `FIN`) to the remote peer.

**Prereq #3** The **outbound** stream has been fully acknowledged by the remote peer.

**Prereq #4** The **local** `TCPConnection` is confident that the **remote** peer can satisfy prerequisite #3. This is the brain-bending part. There are two alternative ways this can happen:

- **Option A: lingering after both streams end.** Prerequisites #1 through #3 are true, and the remote peer *seems* to have gotten the local peer's acknowledgments of the entire stream. The local peer doesn't know this for sure—TCP doesn't deliver acks reliably (it doesn't ack acks). But the local peer is pretty confident that the remote peer has gotten its acks, because the remote peer doesn't seem to be retransmitting anything, and the local peer has waited a while to make sure.

In specific, a connection is done when prereqs #1 through #3 are satisfied and **it has been at least 10 times the initial retransmission timeout** (`_cfg.rt.timeout`) **since the local peer has received *any* segments from the remote peer**. This is called “lingering” after both streams finish, to make sure the remote peer isn't trying to retransmit anything that we need to acknowledge. It does mean that a `TCPConnection` needs to stay alive for a while,<sup>2</sup> keeping an exclusive claim on a local port number and possibly sending acks in response to incoming segments, even after the `TCPSender` and `TCPReceiver` are completely done with their jobs and both streams have ended.

- **Option B: passive close.** Prerequisites #1 through #3 are true, and the local peer is 100% certain that the remote peer can satisfy prerequisite #3. How can this be, if TCP doesn't acknowledge acknowledgments? Because the remote peer was **the first one to end its stream**.

*★Why does this rule work?* This is the brain-bender and you don't need to read further to complete this lab, but it's fun to think about and gets to the deep reasons for the Two Generals Problem and the inherent constraints on reliability across an unreliable network. The reason this works is that *after* receiving and assembling the remote peer's `FIN` (prerequisite #1), the local peer sent a segment with a greater sequence number than it had ever sent before (at the very least, it had to send its own `FIN` segment to satisfy prerequisite #2), and that segment also had an `ackno` that acknowledged the remote peer's `FIN` bit. The remote peer acknowledged that segment (to satisfy prerequisite #3), which means that the remote peer *must have also seen the local peer's ack of the remote peer's* `FIN`. Which guarantees that the **remote peer** must be able to satisfy its own prerequisite #3. All this means the local peer can satisfy prerequisite #4 without having to linger.

Whew! We said it's a brain-bender. *Extra credit in your lab writeup: can you find a better way of explaining this?*

The bottom line is that **if the `TCPConnection`'s inbound stream ends before the `TCPConnection` has ever sent a `FIN` segment, then the `TCPConnection` doesn't need to linger after both streams finish**.

<sup>2</sup>In a production TCP implementation, the linger timer (also known as the TIME-WAIT timer or twice the Maximum Segment Lifetime (MSL)) is typically something like 60 or 120 seconds. That can be long time to keep a port number reserved after a connection is effectively done, especially if you want to start a new server that binds to the same port number—nobody wants to wait two minutes. The `SO_REUSEADDR` socket option essentially makes Linux ignore the reservation and can be handy for debugging or testing.



## 5.1 The end of a TCP connection (practical summary)

Practically what all this means is that your `TCPConnection` has a member variable called `_linger_after_streams_finish`, exposed to the testing apparatus through the `state()` method. The variable starts out `true`. If the inbound stream ends before the `TCPConnection` has reached EOF on its outbound stream, this variable needs to be set to `false`.

At any point where prerequisites #1 through #3 are satisfied, the connection is “done” (and `active()` should return `false`) if `_linger_after_streams_finish` is false. Otherwise you need to linger: the connection is only done after enough time ( $10 \times \text{\_cfg.rt\_timeout}$ ) has elapsed since the last segment was received.

## 6 Performance

After you’ve finished your TCP implementation, and after you are passing all of the tests run by `make check`, please commit! Then, measure the performance of your system and bring it up to at least 100 megabits per second.

From the build directory, run `./apps/tcp_benchmark`. If all goes well, you’ll see output that looks like this:

```
user@computer:~/sponge/build$ ./apps/tcp_benchmark
CPU-limited throughput           : 1.78 Gbit/s
CPU-limited throughput with reordering: 1.21 Gbit/s
```

**To receive full credit on the lab, your performance needs to be at least “0.10 Gbit/s” (100 megabits per second) on both lines.** You may need to profile your code or reason about where it is slow, and you may have to improve your implementation of some of the critical modules (e.g., `ByteStream` or `StreamReassembler`) to get to this point.

**In your writeup**, please report the speed figures you achieved (with and without reordering).

If you would like, you’re welcome to try to optimize your code as much as you want, but *please do not do this at the expense of other parts of CS144*, including other parts of this lab. We won’t give extra points for performance that’s faster than 100 Mbit/s—any improvements you do beyond this minimum are for your own satisfaction and learning only. If you achieve an implementation that’s faster than ours<sup>3</sup> without changing any public interfaces, we would love to learn from you about how you did it.

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<sup>3</sup>We ran our reference implementation on a 2011 Intel Core i7-2600K CPU @ 4.40GHz with Ubuntu 19.04, Linux 5.0.0-31-generic #33-Ubuntu with default mitigations against Meltdown/Spectre/etc., and g++ 8.3.0 with the default compiler flags for a default (“Release”) build. The CPU-limited throughput (first line) was 7.18 Gbit/s, and (second line) 6.84 Gbit/s with reordering.

## 7 webget revisited

Time to take a victory lap! Remember your `webget.cc` that you wrote in Lab 0? It used a TCP implementation (`TCPSocket`) provided by the Linux kernel. We'd like you to switch it to use your own TCP implementation without changing anything else. We think that all you'll need to do is:

- Replace `#include "socket.hh"` with `#include "tcp_sponge_socket.hh"`.
- Replace the `TCPSocket` type with `CS144TCPSocket`.
- At the end of your `get_URL()` function, add a call to `socket.wait_until_closed()`.

★*Why am I doing this?* Normally the Linux kernel takes care of waiting for TCP connections to reach “clean shutdown” (and give up their port reservations) even after user processes have exited. But because your TCP implementation is all in user space, there's nothing else to keep track of the connection state except your program. Adding this call makes the socket wait until your `TCPConnection` reports `active() = false`.

Recompile, and run `make check_webget` to confirm that you've gone full-circle: you've written a basic Web fetcher on top of *your own complete TCP implementation*, and it still successfully talks to a real webserver. If you have trouble, try running the program manually: `./apps/webget cs144.keithw.org /hasher/xyzyzy`. You'll get some debugging output on the terminal that may be helpful.

## 8 Development and debugging advice

1. Implement the `TCPConnection`'s public interface (and any private methods or functions you'd like) in the file `tcp_connection.cc`. You may add any private members you like to the `TCPConnection` class in `tcp_connection.hh`.
2. We are expecting about 100–150 lines of code in total. You won't need any fancy data structures or algorithms;
3. You can test your code (after compiling it) with `make check`. This will run a fairly comprehensive test suite (159 tests). Many of the tests confirm that your TCP implementation can transfer files error-free with Linux's TCP implementation, or with itself, over various combinations of packet loss and data transfer in each direction.<sup>4</sup>

<sup>4</sup>In the test names, “c” means your code is the client (peer that sends the first `SYN`), and “s” means your code is the server. The letter “u” means it is testing TCP-over-UDP, and “i” is testing TCP-over-IP (TCP/IP). The letter “n” means it is trying to interoperate with Linux's TCP implementation. “S” means

4. Please re-read the section on “using Git” in the Lab 0 document and [in the online FAQs](#), and remember to keep the code in the Git repository it was distributed in on the `master` branch. Make small commits, using good commit messages that identify what changed and why.
5. Please work to make your code readable to the CA who will be grading it for style. Use reasonable and clear naming conventions for variables. Use comments to explain complex or subtle pieces of code. Use “defensive programming”—explicitly check preconditions of functions or invariants, and throw an exception if anything is ever wrong. Use modularity in your design—identify common abstractions and behaviors and factor them out when possible. Blocks of repeated code and enormous functions will make it hard to follow your code.
6. Please also keep to the “Modern C++” style described in the Lab 0 document. The `cppreference` website (<https://en.cppreference.com>) is a great resource, although you won’t need any sophisticated features of C++ to do these labs. (You may sometimes need to use the `move()` function to pass an object that can’t be copied.)
7. If you get a segmentation fault, something is really wrong! We would like you to be writing in a style where you use safe programming practices to make segfaults extremely unusual (no `malloc()`, no `new`, no pointers, safety checks that throw exceptions where you are uncertain, etc.). That said, to debug you can configure your build directory with `cmake .. -DCMAKE_BUILD_TYPE=RelASan` to enable the compiler’s “sanitizers” to detect memory errors and undefined behavior and give you a nice diagnostic about when they occur. You can also use the `valgrind` tool. You can also configure with `cmake .. -DCMAKE_BUILD_TYPE=Debug` and use the GNU debugger (`gdb`). Remember to use these settings for debugging only—they dramatically slow down both compilation and execution of your programs. The most reliable/foolproof way to revert to “Release” mode is just to blow away the `build` directory and create a new one.

## 9 Submit

1. In your submission, please only make changes to the `.hh` and `.cc` files in the top level of `libsponge`. Within these files, please feel free to add private members as necessary, but please don’t change the *public* interface of any of the classes.
2. Before handing in any assignment, please run these in order:
  - (a) `make format` (to normalize the coding style)
  - (b) `git status` (to check for un-committed changes—if you have any, commit!)
  - (c) `make` (to make sure the code compiles)

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your code is sending data; “R” means your code is receiving data, and “D” means data is being sent in both directions. At the end of a test name, a lowercase “l” means there is packet loss on the receiving (incoming segment) direction, and uppercase “L” means there is packet loss on the sending (outgoing segment) direction.

- (d) `make check` (to make sure the automated tests pass)
3. Write a report in `wriateups/lab4.md`. This file should be a roughly 20-to-50-line document with no more than 80 characters per line to make it easier to read. The report should contain the following sections:
    - (a) **Program Structure and Design.** Describe the high-level structure and design choices embodied in your code. You do not need to discuss in detail what you inherited from the starter code. Use this as an opportunity to highlight important design aspects and provide greater detail on those areas for your grading TA to understand. You are strongly encouraged to make this writeup as readable as possible by using subheadings and outlines. Please do not simply translate your program into an paragraph of English.
    - (b) **Implementation Challenges.** Describe the parts of code that you found most troublesome and explain why. Reflect on how you overcame those challenges and what helped you finally understand the concept that was giving you trouble. How did you attempt to ensure that your code maintained your assumptions, invariants, and preconditions, and in what ways did you find this easy or difficult? How did you debug and test your code?
    - (c) **Remaining Bugs.** Point out and explain as best you can any bugs (or unhandled edge cases) that remain in the code.
  4. Please also fill in the number of hours the assignment took you and any other comments.
  5. When ready to submit, please follow the instructions at <https://cs144.github.io/submit>. Please make sure you have committed everything you intend before submitting.
  6. Please let the course staff know ASAP of any problems at the Tuesday-evening lab sessions, or by posting a question on Piazza. Good luck!