Purpose

The goal of this assignment is to get you programming with strings, iteration, and dynamic memory.

Preliminaries

Login to the server of your choice and cd to the directory where you keep your CS 211 work. Then download and unarchive the starter code, and change into the project directory:

% cd cs211
% curl $HW211/hw02.tgz | tar zvxf
...
% cd hw02

If you have correctly downloaded and configured everything then the project should build cleanly:

% make all
...
cc -fsanitize=address,undefined -l211 -o test_translate.
%

Background

In this project, you will implement a clone of the standard Unix utility \texttt{tr(1)}, which is a filter that performs transliteration. Given two equal-length sequences of characters, \texttt{from} and \texttt{to}, it replaces all occurrences of characters appearing in \texttt{from} with the character in the corresponding position in \texttt{to}.

The \texttt{tr} program takes the \texttt{from} and \texttt{to} character sequences as command-line arguments. In the simplest case, they are strings of the same length:

% ./tr abc xyz
a
x
FUNCTION signatures for src/translate.c are provided for you in src/translate.h; since the grading tests expect to interface with your code via

orientations: As in Homework 1, your code is divided into three .c files:

• Most significant functionality will be defined in the “translate library,” src/translate.c.

• Tests for those functions will be written in test/test_translate.c.

• The main() function that implements the tr program will be def-

This means press Control-D.

characters that have special meaning for the shell, such as
space, !, *, ?, $, and \, need to be quoted in arguments.

Fish’s function command defines a new shell command in
terms of other shell commands. Here we use it to define rot13 as shorthand for ./tr a-zA-Z n-za-mN-Za-M.

The above examples won’t work until you’ve finished the assign-ment, but if you replace ./tr with just tr, you should get the system’s /usr/bin/tr, which will do the same thing.
this header file, you must not modify src/translate.h in any way. All of your code will be written in the three .c files.

The project also provides a Makefile with several targets:

<table>
<thead>
<tr>
<th>target</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>builds everything * &amp;</td>
</tr>
<tr>
<td>test</td>
<td>builds and runs the tests &amp;</td>
</tr>
<tr>
<td>test_translate</td>
<td>builds (but doesn’t run) the tests</td>
</tr>
<tr>
<td>tr</td>
<td>builds the tr program</td>
</tr>
<tr>
<td>clean</td>
<td>removes all build products &amp;</td>
</tr>
</tbody>
</table>

* default & phony

Specifications

The project comprises two functional components, which are specified in this section. First, though, we define charseqs (character sequences).

Character sequences

The tr program uses charseqs to specify which characters to replace and what to replace them with. The C type of a charseq is just char*—that is, a C string—but they can be represented in two forms having different interpretations:

- A literal charseq is just a sequence of characters, each standing for itself. For example, interpreted as a literal charseq, the string “a-e” contains the three characters ‘a’, ‘-’, and ‘e’ at indices 0, 1, and 2, respectively. In a literal charseq, no character has special meaning.

- An unexpanded charseq may contain ranges, written “c-d”, and escape sequences, written “\c”.
  - The range “c-d” stands for the interval of characters from ‘c’ to ‘d’, inclusive. (This means that if ‘c’ > ‘d’ then the range is empty, and if ‘c’ == ‘d’ then the range contains only ’c’.)
  - If the escape “\c” is valid C string literal escape sequence, then it has the same meaning for tr as in C; otherwise it just stands for character ’c’ itself.

Here is a table showing several unexpanded charseqs along with their literal expansions:

In C (but not C++) those literals don’t actually have type char!—they have type int for obscure historical reasons. That is, ’A’ is an alterative way of writing the int value 65. Try printing sizeof ’A’ and see…

We have provided you a function mapping character ’c’ to the meaning of \c, so you don’t have to figure that part out.
The *tr* program takes charseqs in unexpanded form, and must expand them to literal form before it can do its work.

### The translate library

The *translate* library is responsible for expanding charseqs from unexpanded to literal form, and for using a pair of literal charseqs to translate a string. It provides a function for each of these purposes that will be used in src/tr.c. Additionally, the header file exposes two helper functions to facilitate testing. Thus, src/translate.c defines four functions:

- Function `expand_charseq(const char*)` takes a charseq in unexpanded form and expands it, returning it in literal form.

  The returned charseq is allocated by `malloc(3)`, which means that the caller is responsible for deallocating it with `free(3)` when finished with it.

  **Error case:** If `expand_charseq()` is unable to allocate memory then it returns the special pointer value `NULL`.

- Function `charseq_length(const char*)` is a helper to `expand_charseq()` that determines how long the literal result of expanding its argument will be.

- Function `translate(char* s, const char* from, const char* to)` takes a string to modify (*s*) and two literal charseqs (*from* and *to*). Each character in string *s* that appears in charseq *from* is replaced by the character at the same index in charseq *to*.

  To be precise: For each index *i* in *s*, if there is some *j* such that *s*[*i*] == *from*[*j*] (and there is no *k* < *j* such that *s*[*i*] == *from*[*k*]), then *s*[*i*] is replaced by *to*[*j*].

  **Undefined behavior:** Function `translate()` has an *unchecked precondition* whose violation will result in undefined behavior. In particular, for it to work properly, *from* must not be a longer string than *to*. However, `translate()` **should not** check this condition, as ensuring it is the caller’s responsibility.

- Function `translate_char(char c, const char* from, const char* to)` is a helper to function `translate()`. It takes a character

---

<table>
<thead>
<tr>
<th>unexpanded</th>
<th>literal</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;abc&quot;</td>
<td>&quot;abc&quot;</td>
</tr>
<tr>
<td>&quot;a-e&quot;</td>
<td>&quot;abcde&quot;</td>
</tr>
<tr>
<td>&quot;a-e_&quot;</td>
<td>&quot;abcde_&quot;</td>
</tr>
<tr>
<td>&quot;a-df-i&quot;</td>
<td>&quot;abcdfghi&quot;</td>
</tr>
</tbody>
</table>
to translate \((c)\) and two literal charseqs \((\text{from} \text{ and } \text{to})\). It returns the translation of character \(c\) as given by the two charseqs.

To be precise: If there is some \(j\) such that \(c = \text{from}[j]\) (and there is no \(k < j\) such that \(c = \text{from}[k]\)), then this function returns \(\text{to}[j]\); but if there is no such \(j\) then it returns \(c\) unchanged.

**Undefined behavior:** Function translate_char() has the same unchecked precondition as function translate(), with the same results if violated. (This is a natural consequence of translate() calling translate_char().)

An additional unchecked precondition for all four of the above functions is that all \texttt{char*}s that they are given as arguments must be non-null pointers to 0-terminated character arrays—that is, valid C strings. If this precondition is violated then the functions’ behaviors are undefined. (This means that these functions should not check whether their arguments are null.)

*The tr program*

The tr program must be run with two command-line arguments. If run with more or fewer than two, it prints the message

Usage: \(tr \text{ FROM } \text{ TO } < \text{ INPUT\_FILE}\)

to stderr, where \(tr\) is replaced by argv[0] (the actual name that the program was called with), and then exits with error code 1.

The arguments FROM (argv[1]) and TO (argv[2]) are unexpanded charseqs, so tr must expand them to literal charseqs. If the lengths of the two literal charseqs differ (post-expansion, that is) then it prints the message

\(tr: \text{ error: lengths of FROM and TO differ}\)

to stderr, where again \(tr\) is replaced by argv[0], and then exits with error code 2.

Now that argument checking has succeeded, \(tr\) begins filtering. For each line read from the standard input, it translates the line according to the literal expansions of FROM and TO and prints the result. When there is no more input to process, the program terminates successfully.

*Reference*

*Accepting command-line arguments*

When running a C program from the command line, the user can supply it with command-line arguments, which the program’s main()
function then receives as an array of strings. In particular, main() can be declared to accept two function arguments, as follows:

```c
int main(int argc, char* argv[]);
```

Then argc will contain the number of command-line arguments (including the name of the program itself in argv[0]), and argv will contain the command line arguments themselves.

For example, if a C program is run like

```
% my_prog foo bar baz
```

then argc is 4 and argv is the array

```c
{ "my_prog", "foo", "bar", "baz" }
```

**Reading input a line at a time**

The C programming language doesn’t provide an easy way to read a line of input whose length is unknown, so I have provided you a small library, lib211, on the Unix login machines. The library exports a function `read_line()` for this purpose. Here is its signature:

```c
char* read_line(void);
```

The `read_line` function returns a character array allocated by `malloc()`, which means that the caller is responsible for deallocating it with `free()` when finished with it. See the next subsection for more on this topic, and see the `read_line` manual page on the lab machines for information on the `read_line()` function.

**Managing memory with malloc() and free()**

In Homework 1, all memory used by your program was allocated and deallocated automatically. But to work with strings, especially strings whose length is not known when the program is written, we need a different technique.

Function `malloc()` (from `<stdlib.h>`) takes the number of bytes that you need and attempts to allocate that much memory. For example, we can allocate enough memory for one `int`, or for an array of `N` `ints`:

```c
int* just_one = malloc(sizeof(int));
int* several = malloc(N * sizeof(int));
```

It provides `gets()`, which is easy to use but inherently unsafe, and `fgets()`, which can be used safely but requires you to specify a limit on the length of the line.

The result of `malloc()` has type `void*`, which is the type of a pointer whose referent type is unknown. In C (but not C++), `void*` converts automatically to and from any other pointer type.
If malloc() succeeds, it returns a pointer to the newly allocated memory, which can be used to hold any type that fits. The memory this pointer points to is uninitialized, so you must initialize it to avoid undefined behavior. When you are done with this memory, you must free it by passing the pointer to free().

If malloc() fails to find sufficient memory, which it can, it returns the special pointer value NULL, which is a valid pointer that points nowhere. Dereferencing NULL is undefined behavior, but you can compare it using the == operator. Consequently, every call to malloc() must be followed by a NULL check. We provide this call to malloc() and the obligatory NULL check in src/translate.c:

```c
char* result = malloc(charseq_length(src) + 1);
char* dst = result;
if (result == NULL) return NULL;
```

Two things to note about the above malloc() call:

- We are allocating one more byte than the length that src will expand to, because we need an extra byte to store the string’s \0 terminator.

- There is no need to multiply the desired number of chars by sizeof(char) because sizeof(char) is always 1.

**Working with C strings**

When testing your functions, you might be tempted to write assertions like this:

```c
assert(expand_charseq("a-e") == "abcde");
```

But there are three problems with this:

1. It leaks memory.
2. It compares the addresses of the strings rather than the characters in them.
3. In rare cases, it might cause undefined behavior.

It leaks memory because expand_charseq() allocates memory and the code above doesn’t free it. To fix that, we need to store the result of expand_charseq() in a variable, which lets us refer to it twice:

```c
char* actual_result = expand_charseq("a-e");
assert(actual_result == "abcde");
free(actual_result);
```

Failure to free memory that you no longer need can lead to a memory leak, which causes your program to use more memory than it should, or even run out. But worse things can happen: freeing a pointer twice, or dereferencing a pointer that has already been freed, causes undefined behavior.
However, this still won’t work, because when you use == to compare pointers, it compares the addresses, not the pointed-to values. And the address returned by `expand_charseq()` will never be the same as the address of a string literal.

Instead, to compare strings, we need to use the `strcmp()` function (from `<string.h>`), which compares them character by character. You may expect that `strcmp()` would return true for equal strings and false for unequal strings, but actually it does something more useful: `strcmp(s1, s2)` determines the lexicographical ordering for `s1` and `s2`. If `s1` should come before `s2` when sorting then it returns a negative int; if `s1` should come after `s2` then it returns a positive int. If they are equal, it returns 0. Thus we should write:

```c
char* actual_result = expand_charseq("a-e");
assert( strcmp(actual_result, "abcde") == 0 );
free(actual_result);
```

This almost works! In fact, it usually will work. But to be completely correct, we need to deal with the possibility that `expand_charseq()` fails to allocate memory and returns `NULL`. In that case, `strcmp()` will dereference `NULL`, which is undefined behavior. Thus, we need to ensure that `actual_result` is not `NULL` before we try to use the string that it points to:

```c
char* actual_result = expand_charseq("a-e");
assert( actual_result);
assert( strcmp(actual_result, "abcde") == 0 );
free(actual_result);
```

Here are some more functions from `<string.h>` that you may find useful:

```c
char* strchr(const char* s, int c)  
    searches string `s` for the first occurrence of `(char)c`, returning a pointer to the occurrence if found or `NULL` if not

char* strcpy(char* dst, const char* src)  
    copies string pointed to by `src` into string pointed to by `dst` (which must have sufficient capacity, or you’ll get UB)

size_t strlen(const char*)  
    computes the length of a string (not including the 0)
```

**Better testing assertions**

In Homework 1 you used `assert()` for testing. It works to catch errors, but it isn’t very helpful when it catches one, since it doesn’t tell you what’s wrong. It also doesn’t tell you anything when it

---

**Lexicographical order** is a generalization of alphabetical order to sequences of non-letters (or more than just letters). `strcmp()` compares the numeric values of `chars`, which means that 'a' < 'b' and 'A' < 'B', but also 'B' < 'a' and '$' < ','.

Why does `strchr()` take an `int` rather than a `char`? Many C functions take a character as type `int` for obscure historical reasons.
succeeds, which an makes it difficult to see if your tests are actually running and working.

Starting with this homework, when you \#include <lib211.h>, you get access to a somewhat more helpful—but still pretty simple—testing framework. Here’s what writing test assertions with these macros looks like:

```c
static void example_checks(void)
{
    CHECK_INT( 2 * 3, 6);
    CHECK_SIZE( sizeof(double), 8);
    CHECK_CHAR( toupper('a'), 'A');
    CHECK( islower('a'));
}
```

The provided checks are summarized here:

<table>
<thead>
<tr>
<th>Form...</th>
<th>checks that...</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHECK_CHAR(x, y);</td>
<td>x and y are equal chars</td>
</tr>
<tr>
<td>CHECK_INT(x, y);</td>
<td>x and y are equal ints</td>
</tr>
<tr>
<td>CHECK_UINT(x, y);</td>
<td>x and y are equal unsigned ints</td>
</tr>
<tr>
<td>CHECK_SIZE(x, y);</td>
<td>x and y are equal size_t</td>
</tr>
<tr>
<td>CHECK_DOUBLE(x, y);</td>
<td>x and y are equal doubles</td>
</tr>
<tr>
<td>CHECK_STRING(x, y);</td>
<td>x and y point to equal '0'-terminated strings</td>
</tr>
<tr>
<td>CHECK_POINTER(x, y);</td>
<td>x and y point to the same object</td>
</tr>
<tr>
<td>CHECK(x);</td>
<td>x is true, non-zero, or non-null</td>
</tr>
</tbody>
</table>

**Hints**

In this section, we provide suggestions, such as algorithms, for writing the necessary functions. These hints are given in what we expect will be the best order of implementation. It’s a very good idea to test each function as you write it, rather than testing them all at the end, because you will find bugs sooner that way.

**Algorithm for the charseq_length() function**

The charseq_length() function scans its argument string (an unexpanded character sequence) while counting how many characters it will take when expanded. Thus, you need two variables: one to count, and one to keep track of the position while scanning the string. Start the count at 0 and the position at the beginning of the argument string. Then iterate and evaluate the following conditions for each iteration:

To scan a string you can use either an index size_t i or pointer char* p. If you hold onto the original string s then the two approaches are interchangeable, since p == s + i, or equivalently i == p - s.
• If the character at the current position is 0, then you’ve reached the end and should return the count.

• If the character at the next position is ‘-’, and the character at the position after that is not 0, then you’ve found a range. If we call the character before the hyphen start and the character after the hyphen end, then we can determine the length of the range by comparing the two characters: If start > end then the range is empty; otherwise the length of the range is end - start + 1. Add this to the count, and then advance the current position by 3 to get to the first character past the right side of the range.

• If the character at the current position is ‘\’ (a single backslash), and the character at the next position is not 0 then you have found an escape sequence. Its expanded length is 1, so add that much to the count, and advance the current position by 2 to get to the first character after the escape sequence.

• Otherwise, the character at the current position will be copied as is, so increment the count by 1 and advance the current position to the next character.

Algorithm for the expand_charseq() function

Like charseq_length(), the expand_charseq() function scans its argument string (an unexpanded character sequence), but instead of counting, it copies the characters into a fresh string, expanding ranges and escape characters into their literal meanings.

The first thing it must do is allocate memory for its result. We have provided you code that calls charseq_length() to find out how much memory is needed, allocates the memory, and checks that the allocation succeeded. Then the algorithm works by scanning the argument string while storing characters into the result string. To do this, you will likely need three variables: one to remember the start of the result string in order to return it; one to keep track of your position in the unexpanded character sequence being scanned (the source); and one to keep track of your position in the result string being filled in (the destination).

The control logic of the scanning-and-copying loop is the same as in the charseq_length() function, but the actions at each step differ:

• If the character at the current source position is 0, then you’ve reached the end. Don’t forget to store a 0 at the destination position (which should be the end of the result string) before returning.

This implies that a hyphen at the beginning or end of the string, or immediately following the end of a character range, is interpreted literally rather than denoting a range.

This case should be checked after the range case, which implies that the literal expansion of unexpanded charseq “\-” is “\[^_]”, not “-”. 

This function is probably the trickiest part of the whole homework. One way to develop your code would be to hold off writing this function and move forward, while temporarily considering all input charseqs to be literal. It’s not hard to add a call to expand_charseq() to src/tc’s main() function once you get it working.
• If the character at the next source position is \texttt{‘-’}, and the character at the position after that is not \texttt{0}, then you’ve found a range. If we call the character before the hyphen start and the character after the hyphen end, then we can generate the range by iteration, incrementing start until it passes end. That is, so long as start \(\leq\) end, we want to store start to the destination position, advance the destination position, and increment start. Once we’ve fully expanded the range, we advance the source position past it (by adding 3).

• If the character at the current source position is \texttt{‘\textbackslash\textbackslash’}, and the character at the next source position is not \texttt{0} then you have found an escape sequence. Its expansion is given by \texttt{interpret_escape(c)} (provided in \texttt{src/translate.c}), where \texttt{c} is the character following the backlash. Store the expansion to the destination position, advance the destination position, and advance the source position past the escape sequence (by adding 2).

• Otherwise, the character at the current position stands for itself, so store it at the current destination position and then advance both the source and destination positions by 1.

\textit{Algorithm for the translate_char() function}

The \texttt{translate_char()} function takes a character to translate \texttt{(c)} and two literal charseqs \texttt{(from and to)}. The idea is to scan charseq \texttt{from} searching for \texttt{c}. If we find \texttt{c} at some index \texttt{i} then return \texttt{to[i]}. If we get to the end of \texttt{from} without finding \texttt{c} then return \texttt{c} unchanged.

\textit{Algorithm for the translate() function}

The \texttt{translate()} function takes a string to translate in place \texttt{(s)} and two literal charseqs \texttt{(from and to)}. The idea is to iterate through each position in \texttt{s}, replacing each character with its translation according to \texttt{translate_char()}.

\textit{Algorithm for the tr program}

The \texttt{tr} program has three phases: first it validates and interprets its arguments, then it transforms its input to its output, and then it cleans up its resources.

We’ve provided you with the first check, for the correct number of arguments. This serves as an example of how to use \texttt{fprintf(3)} and \texttt{stderr(4)} for printing error messages.

Next, use \texttt{expand_charseq()} to expand both command-line arguments \texttt{argv[1]} and \texttt{argv[2]} into literal charseqs. Since \texttt{expand_charseq()} means you will need two calls to \texttt{free()} in order to clean up in the end.

To avoid undefined behavior here, you should store start and end as \texttt{ints}, not \texttt{chars}.

To understand why, consider what would happen if end were \texttt{CHAR_MAX}.

The traditional C way to do this is \texttt{*dst++ = *src++;}.
returns **NULL** if it cannot allocate memory, you need to **NULL**-check both results; if it fails, print the error message (using **OOM_MESSAGE** and **argv[0]**) and exit with error code 10.

If character sequence expansion succeeds but the charseqs, once expanded, don’t have the same length, it is an error; print the specified error message (**LENGTH_MESSAGE**) to **stderr** and exit with error code 2.

Now, if there are no errors then we are ready to iterate over the input lines until **read_line()** returns **NULL**, translating each line and printing the result. Since each input line read by **read_line()** is allocated by **malloc()**, you need to free each line with **free()** when you are done with it. This should be straightforward because you process one line at a time and never need to hold onto one longer.

**Deliverables and evaluation**

For this homework you must:

1. Implement the specification for the **translate** library from the previous section in **src/translate.c**.
2. Implement the specification for the **tr** program from the previous section in **src/tr.c**.
3. Add more test cases to **test/test_translate.c** in order to test the four functions that you defined in **src/translate.c**.

The file **test/test_convert.c** already contains two tests cases for each of the four functions, and helper functions to facilitate testing for two of them. Because the functions you are implementing are complex and have many corner cases, you need to add many more tests for each. Try to cover all the possibilities, because for this week’s self evaluation we will spot-check your test coverage by asking for just a few particular test cases. You can’t anticipate which we’ll ask about, so you should try to cover everything.

Grading will be based on:

- the correctness of your implementations with respect to the specifications,
- the presence of sufficient test cases to ensure your code’s correctness, and
- adherance to the CS 211 Style Manual.

**Submission**

Homework submission and grading will use the GSC grading server. You must include any files that you create or change. For this home-
work, that will include src/translate.c, src/tr.c, and test/test_translate.c. 
(You should not need to modify Makefile and you must not modify 
src/translate.h.)

Submit using the command-line GSC client gsc(1). Instructions 
are available in the submit211(7) manual page on the Unix login and 
lab machines. To view the manual page, run:

% man submit211

Partners

If you work with a partner then you must register your partnership 
before uploading to GSC. There are two steps to this: one partner 
must create a partner request (referring to their intended partner by 
NetID), and then the other partner must accept that request for it to 
take effect.

Partner requests are created with the gsc partner request command and accepted using using the gsc partner accept command. You can list outstanding partner requests with the gsc status command and cancel them with the gsc partner cancel command. See the gsc(1) manual page for details.

Before a partner request can be accepted, the files in the two 
submissions must be disjoint. (The system will not choose whose 
file to delete if you both have files with the same name.) Once a 
partner request is accepted, you and your partner’s submissions are 
joined together: when one partner uploads files to the GSC server or 
performs self evaluation, the results will be visible to both.