This assignment has complex semi-coroutines, and introduces full-coroutines and concurrency in \( \mu \text{C++} \). Use it to become familiar with these new facilities, and ensure you use these concepts in your assignment solution. Unless otherwise specified, writing a C-style solution for questions is unacceptable, and will receive little or no marks. (You may freely use the code from these example programs.)

1. Given the C++ program in Figure 1, compare buffering using internal-data versus external-data format. Redirect the program output to /dev/null to discard the output; otherwise, the output distorts the performance measurements.

(a) Compare the two versions of the program with respect to performance by doing the following:

- Run the program with and without the preprocessor option -DSTRT.

```cpp
#include <iostream>
using namespace std;

int main( int argc, char *argv[] ) {
    int times = 1000000, size = 40; // defaults

    try {
        switch ( argc ) {
            case 3: size = stoi( argv[2] ); if ( size <= 0 ) throw 1;
            case 2: times = stoi( argv[1] ); if ( times <= 0 ) throw 1;
            case 1: break; // use defaults
            default: throw 1;
        } // switch
    } catch ( ... ) {
        cout << /*Usage: */ " << argv[0] << " [ times (> 0) [ size (> 0) ] ]" " << endl;
        exit( 1 );
    } // try

    for ( int i = 0; i < times; i += 1 ) {
        #if defined( INTERNAL )
            int intbuf[size]; // internal-data buffer
            for ( int i = 0; i < size; i += 1 ) intbuf[i] = i;
        #elif defined( EXTERNAL )
            string strbuf; // external-data buffer
            for ( int i = 0; i < size; i += 1 ) strbuf += to_string( i ) + ' '; // external buffering
        #else
            #error unknown buffering style
        #endif
    } // for
}
```

Figure 1: Internal versus External Buffering
• Time the executions using the `time` command:
  
  ```bash
  $ /usr/bin/time -f "%Uu %Ss %E" ./a.out > /dev/null  # ignore program output
  3.21u 0.02s 0:03.32
  ```

  (Output from `time` differs depending on the shell, so use the system `time` command.) Compare the `user` time (3.21u) only, which is the CPU time consumed solely by the execution of user code (versus system and real time).

• Use the program command-line arguments (as necessary) to adjust program execution into the range 1 to 100 seconds. (Timing results below 1 second are inaccurate.) Use the same command-line values for all experiments, if possible; otherwise, increase/decrease the arguments as necessary and scale the difference in the answer.

• Run both the experiments again after recompiling the programs with compiler optimization turned on (i.e., compiler flag `-O2`).

• Include 4 timing results to validate the experiments.

(b) State the performance difference (larger/smaller/by how much) between the two versions of the program, and what caused the difference.

(c) State the performance difference (larger/smaller/by how much) between the original and transformed programs when compiler optimization is used.

(d) For interest, change `endl` to `\n` to see if there is any performance difference.

2. Write a **semi-coroutine** to sort a set of values into ascending order using a binary-tree insertion method. This method constructs a binary tree of the data values, which can subsequently be traversed to retrieve the values in sorted order. Construct a binary tree without balancing it, so that the values 25, 6, 9, 5, 99, 100, 101, 7 produce the tree:

```
     25
    / \
   6   99
   / \  / \
  5   9 100
   \   \ \
    7   101
```

By traversing the tree in infix order — go left if possible, return value, go right if possible — the values are returned in sorted order. Instead of constructing the binary tree with each vertex having two pointers and a value, build the tree using a coroutine for each vertex. Hence, each coroutine in the tree contains two other coroutines and a value. (A coroutine must be self-contained, i.e., it cannot access any global variables in the program.)

The coroutine has the following interface (you may only add a public destructor and private members):

```cpp
  template<typename T>
  _Coroutine Binsertsort {
    T value;  // communication: value being passed down/up the tree
    void main();  // YOU WRITE THIS ROUTINE
  public:
    _Event Sentinel {};
    void sort( T value ) {  // value to be sorted
      Binsertsort::value = value;
      resume();
    }
    T retrieve() {  // retrieve sorted value
      resume();
      return value;
    }
  };
```

Assume type `T` has operators `==`, `<`, `>>` and `<<`, and public default and copy constructors.

Each value for sorting is passed to the coroutine via member `sort`. When passed the first value, `v`, the coroutine stores it in a local variable, `pivot`. Each subsequent value is compared to `pivot`. If `v < pivot`, a `Binsertsort` coroutine called `less` is resumed with `v`; if `v => pivot`, a `Binsertsort` coroutine called `greater` resumed with `v`. Each of the two coroutines, `less` and `greater`, creates two more coroutines in turn. The result is a binary tree of identical coroutines. The coroutines `less` and `greater` must be created on the stack not by calls to new, i.e., no
dynamic allocation is necessary in this coroutine. Also, do not create coroutines less and greater for a leaf node, i.e., at least one of coroutines less and greater must be used. Hence, the start of the coroutine looks similar to:

```
pivot = value;
try {
suspend(); // get next value
} catch(Sentinel &) {
  // leaf retrieval finished
  // implies leaf node
}
// implies vertex node
Bin<insertsort<T> less, greater; // create less and greater
```

The end of the set of values is indicated by raising the Sentinel exception at the root coroutine to start retrieval. The Sentinel exception indicates the end of unsorted values, and a coroutine that catches a Sentinel exception raises a Sentinel exception at its left branch, prepares to receive the sorted values from its left branch, and passes these values up the tree until it receives a Sentinel exception from the child coroutine on that branch. The coroutine then passes up its pivot value. Then the coroutine raises a Sentinel exception at its right branch, prepares to receive the sorted values from its right branch, and passes these values up the tree until it receives a Sentinel exception from the child coroutine on that branch. Finally, the coroutine raises the Sentinel exception at its resumer to indicate the end of sorted values and terminates. (Note, the coroutine does not print out the sorted values — it simply returns them to its resumer.)

Handle a set of 0 or 1 values, e.g., a Sentinel exception is raised as the first or second action to the sort coroutine, in the coroutine versus special cases in the program main.

The executable program is named bin<insertsortsort and has the following shell interface:

```
binsertsort unsorted-file [ sorted-file ]
```

(Square brackets indicate optional command line parameters, and do not appear on the actual command line.) The type of the input values is specified externally by preprocessor variables TYPE.

- If the unsorted input file is not specified, print an appropriate usage message and terminate. The input file contains lists of unsorted values. Each list starts with the number of values in that list. For example, the input file:

```
8 25 6 8 5 99 100 101 7
3 1 3 5
0
10 9 8 7 6 5 4 3 2 1 0
```

contains 4 lists with 8, 3, 0 and 10 values in each list. (The line breaks are for readability only; values can be separated by any white-space character and appear across any number of lines.) Assume the first number in the input file is always present and correctly specifies the number of following values. Assume all following values are correctly formed so no error checking is required on the input data.

- If no output file name is specified, use standard output. Print the original input list followed by the sorted list, as in:

```
25 6 8 5 99 100 101 7
5 6 7 8 25 99 100 101
1 3 5
1 3 5
blank line from list of length 0 (not actually printed)
blank line from list of length 0 (not actually printed)
9 8 7 6 5 4 3 2 1 0
0 1 2 3 4 5 6 7 8 9
```

for the previous input file. End each set of output with a blank line.
Print an appropriate error message and terminate the program if unable to open the given files.

Because BInsertsort is a template, show an example where it can sort any non-basic type (string is a basic type; a structure with multiple values and a key is not a basic type) that provides operators ==, <, >> and <<, respectively. Include this example type in the same file as the program main.

**WARNING:** When writing coroutines, try to reduce or eliminate execution “state” variables and control-flow statements using them. A state variable contains information that is not part of the computation and exclusively used for control-flow purposes (like flag variables). Use of execution state variables in a coroutine usually indicates you are not using the ability of the coroutine to remember prior execution information. Little or no marks will be given for solutions explicitly managing “state” variables. See Section 3.1.3 in the Course Notes for details on this issue. Also, make sure a coroutine’s public methods are used for passing information to the coroutine, but not for doing the coroutine’s work, which must be done in the coroutine’s main.

3. Write a full coroutine that plays the following card game. If a player is not the only player, they take a number of cards from a deck of cards and pass the remaining deck to the player on the left if the number of remaining cards is odd, or to the right if the number of remaining cards is even. A player must take at least one card and no more than a certain maximum. **After making a play,** a player checks to see if they received a deck that is a multiple of 7 (“death deck”); if so, that player must remove themself from the game. (A player always makes a play, otherwise the death deck would be passed to all players.) The player who takes the last cards or is the only player remaining wins the game.

At random times, 1 in 10 plays, a player takes a drink and raises the Schmilblick *resumption* exception at the player on their right. In the handler for the Schmilblick exception of the player on the right, they take a drink and raise the Schmilblick resumption exception at the player on their right, and so on, until the handler is invoked for the player who started the Schmilblick. After all the players have had a drink, the game continues exactly where it left off. Note, a player that received a death deck cannot start or participate in a Schmilblick!

The interface for a *Player* is (you may only add a public destructor and private members):

```cpp
Coroutine Player {
    // YOU MAY ADD PRIVATE MEMBERS, INCLUDING STATICS
    public:
        enum { DEATH_DECK_DIVISOR = 7 };  
        static void players( unsigned int num );  
        Player( Printer &printer, unsigned int id );  
        void start( Player &lp, Player &rp );  
        void play( unsigned int deck );  
        void drink();  
};
```

The `players` routine is called before any players are created to set the total number of players in the game. The constructor is passed a reference to a printer object and an identification number assigned by the main program. (Use values in the range 0 to \( N - 1 \) for identification values.) To form the circle of players, the `start` routine is called for each player from the program main to pass a reference to the player on the left and right; the `start` routine also resumes the player coroutine to set the program main as its starter (needed during termination). The `play` routine receives the deck of cards passed among the players. The `drink` routine resumes the coroutine to receive the non-local exception.

*All* game output must be generated by calls to a printer class. Two blank lines are printed between games and may be printed by the printer or main driver loop, but there must NOT be blank lines following the last game.

The interface for the printer is (you may add only a public destructor and private members):

```cpp
class Printer {
    // YOU MAY ADD PRIVATE MEMBERS
    public:
        Printer( const unsigned int NoOfPlayers, const unsigned int NoOfCards );
        void prt( unsigned int id, int took, int RemainingPlayers );
};
```

The printer attempts to reduce output by condensing the play along a line. Figure 2 shows example outputs from different runs of the program. Each column is assigned to a player, and a column entry indicates a player is
drinking or making a play “taken:remaining:direction”:

a) the number of cards taken by a player,
b) the number of cards remaining in the deck,
c) the direction the remaining deck is passed, where “<” means to the left, “>” means to the right, “X” means the player terminated, and “#” means the game is over. If a game ends because a player takes the last cards, the output has a single “#” appended. If a game ends because there are no more players, the output is “#deck-size#”, where “deck-size” is the number of cards last passed to this player. It is possible for a player to simultaneously receive a death deck and win the game. In these cases, the output indicates both the win and the death, e.g., 7:0#X or #14#X.

Player information is buffered in the printer until a play would overwrite a buffer value. At that point, the buffer is flushed (written out) displaying a line of player information. The buffer is cleared by a flush so previously stored values do not appear when the next player flushes the buffer and an empty column is printed. All column spacing can be accomplished using the standard 8-space tabbing, i.e., do NOT use spaces to align columns. Store information in internal format for flushing; do NOT build and store C/C++ strings of text for output.

The main program plays games sequentially, i.e., one game after the other, where games is a command line parameter. For each game, \( N \) players are created, a deck containing \( M \) cards is created, and a random player is chosen and passed the deck of cards. The player passed the deck of cards begins the game, and each player follows the simple strategy of taking \( C \) cards, where \( C \) is a random integer in the range from 1 to 8 inclusive. Do not spend time developing strategies to win.

At the end of each game, it is unnecessary for a player’s coroutine-main to terminate but ensure each player is deleted before starting the next game.

The executable program is named cardgame and has the following shell interface:

```
    cardgame [ games | "d" | players | "d" | cards | "d" | seed | "d" ] ] ]
```

games is the number of card games to be played (\( \geq 0 \)). If no value for games is specified or \( d \), assume 5.

players is the number of players in the game (\( \geq 2 \)). If no value for players is specified or \( d \), generate a random integer in the range from 2 to 10 inclusive for each game.

cards is the number of cards in the game (\( > 0 \)). If no value for cards is specified or \( d \), generate a random integer in the range from 10 to 200 inclusive for each game.

seed is the starting seed for the random number generator to allow reproducible results (\( > 0 \)). If no value for seed is specified or \( d \), initialize the random number generator with an arbitrary seed value (e.g., getpid() or time).

Check all command arguments for correct form (integers) and range; print an appropriate usage message and terminate the program if a value is missing or invalid.

To obtain repeatable results, all random numbers are generated using class PRNG. There are up to five calls to obtain random values in the program. Three calls in the main routine, depending on the command-line arguments, to obtain: the number of players for a game, the number of cards in the initial deck of cards, and the random player to start the game (in that order). Two calls in Player to make a random play and start a Schmilblick (in that order).

WARNING: When writing coroutines, try to reduce or eliminate execution “state” variables and control-flow statements using them. A state variable contains information that is not part of the computation and exclusively
```cpp
#include <iostream>
using namespace std;

volatile int iterations = 10000000, shared = 0; // volatile to prevent dead-code removal

_Task increment { 
    void main() {
        for ( int i = 1; i <= iterations; i += 1 ) {
            shared += 1; // two increments to increase pipeline size
            shared += 1;
        }
    }
};

int main( int argc, char * argv[] ) {
    try {
        // process command-line arguments
        switch ( argc ) {
            case 2: iterations = stoi( argv[1] ); if ( iterations <= 0 ) throw 1;
            case 1: break; // use defaults
            default: throw 1;
        } // switch
    } catch( . . . ) {
        cout << "Usage: " << argv[0] << " [ iterations (> 0) ]" << endl;
        exit( 1 );
    } // try

    #ifdef __U_MULTI__
        uProcessor p; // create 2nd kernel thread
    #endif // __U_MULTI__
    {
        increment t[2];
        // wait for tasks to finish
        cout << "shared:" << shared << endl;
    }
}
```

Figure 3: Interference

used for control-flow purposes (like flag variables). Use of execution state variables in a coroutine usually indicates you are not using the ability of the coroutine to remember prior execution information. *Little or no marks will be given for solutions explicitly managing "state" variables.* See Section 3.1.3 in the [Course Notes](#) for details on this issue. Also, make sure a coroutine’s public methods are used for passing information to the coroutine, but not for doing the coroutine’s work, which must be done in the coroutine’s main.

4. Compile the program in Figure 3 using the `u++` command, without and with compilation flag `-multi` and *no optimization*, to generate a uniprocessor and multiprocessor executable. Run both versions of the program 10 times with command line argument `10000000` on a multi-core computer with at least 2 CPUs (cores).

   (a) Show the 10 results from each version of the program.
   (b) Must all 10 runs for each version produce the same result? Explain your answer.
   (c) In theory, what are the smallest and largest values that could be printed out by this program with an argument of `10000000`? Explain your answers. *(Hint: one of the obvious answers is wrong.)*
   (d) Explain the difference in the size of the values between the uniprocessor and multiprocessor output.

**Submission Guidelines**

Please follow these guidelines very carefully. Review the [Assignment Guidelines](#) and [C++ Coding Guidelines](#) before starting each assignment. Each text or document file, e.g., `*.txt` file, must be ASCII text and not exceed 500 lines in length, where a line is a maximum of 120 characters. Programs should be divided into separate compilation units, i.e., `*.h,cc,C,cpp` files, where applicable. Use the submit command to electronically copy the following files to the course account.

1. `q1*.txt` – contains the information required by question 1, p. 1.
2. q2binsertsort.h, q2*.{h,cc,C,cpp} – code for question 2, p. 2. **Program documentation must be present in your submitted code. Output for this question is checked via a marking program, so it must match exactly with the given program.**

3. q2*.doc – test documentation for question 2, p. 2, which includes the input and output of your tests. **Poor documentation of how and/or what is tested can results in a loss of all marks allocated to testing.**

4. PRNG.h – random number generator (provided)

5. q3*.{h,cc,C,cpp} – code for question 3, p. 4. **Program documentation must be present in your submitted code. Output for this question is checked via a marking program, so it must match exactly with the given program.**


7. Modify the following Makefile to compile the programs for question 2, p. 2 and 3, p. 4 by inserting the object-file names matching your source-file names.

```makefile
TYPE:=int
CXX = ++
CXXFLAGS = -g -Wall -Wextra -MMDD -DTYPE="${TYPE}"
MAKEFILE_NAME = ${firstword ${MAKEFILE_LIST}} # makefile name
OBJECTS1 = # object files forming 1st executable with prefix "q2"
EXEC1 = binsertsort

OBJECTS2 = # object files forming 2st executable with prefix "q3"
EXEC2 = cardgame

OBJECTS = ${OBJECTS1} ${OBJECTS2} # all object files
DEPENDS = ${OBJECTS:.o=.d} # substitute ".o" with ".d"
EXEC = ${EXEC1} ${EXEC2} # all executables

.PHONY : all clean
all : ${EXEC}
# build all executables

# same implementation type as last time ?
ifeq ($(IMPLTYPE),${TYPE})
${EXEC} : ${OBJECTS1}
  $(CXX) $(CXXFLAGS) $^ -o $@
else
# no implementation type specified ?
  TYPE=$(IMPLTYPE)
  $(EXEC1) : ${OBJECTS1}
  $(CXX) $(CXXFLAGS) $^ -o $@
else
  # implementation type has changed
  PHONY : $(EXEC1)
  $(EXEC1) :
  rm -f ImplType
  touch q2binsertsort.h
  sleep 1
  $(MAKE) $(EXEC1) TYPE="${TYPE}"
endif
endif
```
ImplType:
   echo "IMPLTYPE=${TYPE}" > ImplType
   sleep 1

$(EXEC2) : $(OBJECTS2)
   $(CXX) $(CXXFLAGS) $^ -o $@
   # link step 2nd executable

#########################################################################

$(OBJECTS) : $(MAKEFILE_NAME)
   # OPTIONAL : changes to this file => recompile
   -include $(DEPENDS)
   # include *.d files containing program dependences

clean :
   rm -f *.d *.o $(EXECS) ImplType
   # remove files that can be regenerated

This makefile is used as follows:

$ make binsertsort
$ binsertsort ...
$ make cardgame
$ cardgame ...

Put this Makefile in the directory with the programs, name the source files as specified above, and then type
make binsertsort or make cardgame in the directory to compile the programs. This Makefile must be submitted
with the assignment to build the program, so it must be correct. Use the web tool Request Test Compilation to
ensure you have submitted the appropriate files, your makefile is correct, and your code compiles in the testing
environment.

Follow these guidelines. Your grade depends on it!