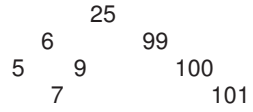
CS 343 Fall 2023 – Assignment 2
Instructor: Peter Buhr
Due Date: Wednesday, October 4, 2023 at 22:00
Late Date: Friday, October 6, 2023 at 22:00

September 27, 2023

This assignment examines complex semi-coroutines, and introduces full-coroutines and concurrency in μC++. 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 receives little or no marks. (You may freely use the code from these example programs.)

1. Write a *semi-coroutine* to sort a set of values, which may contain duplicate 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:



   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. (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):

```
template<typename T> _Coroutine Binsertsort {
    T value;                        // communication: value passed down/up 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 is 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 unnecessarily. Let *leaf* mean a node that has received a pivot value but no further values. Ensure a leaf node does not contain left/right coroutines because both would be unused. However, unused coroutine nodes are allowed in non-leaf nodes.

   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, by calling its retrieve, passes these sorted values up the tree as the return value its retrieve call, and does so 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, passes these values up the tree as it did for the left branch, and does so 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; hence, *all* coroutines must raise the Sentinel exception before terminating. (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 in the coroutine versus special cases in the program main, i.e., a Sentinel exception is raised as the first or second action to the sort coroutine.

The executable program is named binsertsort 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 variable 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. See uIO.cc for an example of μC++ command-line parsing and file I/O.

Because Binsertsort is a template, show an example of it sorting a *non-basic* type, e.g., a structure with multiple values that provides operators ==, <, >> and <<, respectively. Include this example type in the same file as the program main. Note, string *is* a basic type and must be sortable by Binsertsort.

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.

2. Write a *full coroutine* that simulates the game of Hot Potato. What makes the potato *hot* is that it explodes after its internal count-down timer reaches zero. The game consists of N players linked in a circle, where one of the players also acts as the umpire. The umpire (or special case in the program main for the first toss) starts a *game* by randomly tossing the *hot* potato to a player on their left or right. The potato is then randomly tossed left or right among the players until the timer goes off and it explodes. The player holding the potato when the timer goes off (potato explodes) is removed from the game (circle) and deleted. A player cannot delete itself, so the umpire must perform this action. The last remaining player is the winner.

   Should the potato explode for the umpire, a new umpire is *elected* among the remaining players. An election involves traversing the circle using exceptions to find the remaining player with the highest id; this player becomes the new umpire.

   The potato contains a count-down timer that goes off after a random number of clock ticks. The interface for the Potato is (you may only add a public destructor and private members):

```
class Potato {
    // YOU ADD MEMBERS HERE
  public:
    _Event Explode {};
    Potato( PRNG & prng, unsigned int maxTicks = 10 );
    void reset( unsigned int maxTicks = 10 );
    void countdown();
};
```

   The constructor is passed a PRNG and optionally the *maximum* number of ticks until the timer goes off. The potato chooses a random value between 1 and the maximum for the number of ticks, inclusive. Member reset is called by the umpire to reinitialize the timer for the next set. The constructor resets the potato. Member countdown is called by the players, and throws exception Explode, if the timer has reached zero. Rather than absolute time to implement the potato's timer, each call to countdown is one tick of the clock (relative time).

   Figure 1 shows the interface for a Player (you may only add a public destructor and private members). The exception Terminate is raised at the umpire and contains the player to be deleted. The exception Election is raised at the player on the right to run an election and contains the highest player id seen so far in the circle.

   The array partner contains the left/right partners of a player. **You may *not* change the array into a C++ vector.** The vote member is called to vote in an election (discussed below). The terminate member is only called for the umpire after a player receives the Explode exception from the potato. The terminating player first raises the Terminate exception at the umpire, and calls the umpire's terminate member to cause propagation of the nonlocal exception; the call to terminate never returns. When the umpire handles the Terminate exception, it unlinks the player given in the exception from the circle, deletes it, resets the potato, and continues the game by randomly tossing the potato to its left/right player.

   The **static** variable umpire is the player currently acting as the umpire. This variable allows a player (and program main) to communicate with the umpire. The variable umpire is updated after electing a new umpire.

   The constructor is passed a PRNG, an identification number (0 to $N-1$), and the potato created by the main program. The init member receives a player's left and right partners from the program main. The getId member returns a player's id. The toss member is called to conceptually pass the potato to another player.

   When a terminated player is also the umpire, it raises an Election exception at the player on the right, and calls that player's vote member to cause propagation of the nonlocal exception. Each resumed player handles the Election exception, updating the election id in the exception and raising it at the player on the right. After the election finishes and a new umpire is set, control returns to the old umpire. The old umpire raises the Terminate exception at the new umpire, to tell the new umpire to terminate it, and calls the new umpire's terminate member to cause propagation of the nonlocal exception. The new umpire handles the Terminate exception as defined above. This toss counts with respect to the timer in the potato. Note, good software engineering encapsulates calls to resume only in interface members, rather than directly calling resume for another player.

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

```
_Coroutine Player {
    _Event Terminate {
      public:
        Player & victim;                        // delete player
        Terminate( Player & victim ) : victim( victim ) {}
    };
    _Event Election {
      public:
        Player * player;                        // highest player id seen so far
        Election( Player * player ) : player( player ) {}
    };
    Player * partner[2];                        // left and right player
    // YOU ADD MEMBERS HERE
    void main();
    void vote();                                // resume partner to vote
    void terminate();                           // resume umpire
  public:
    static Player * umpire;                     // current umpire

    Player( PRNG & prng, unsigned int id, Potato & potato );
    void init( Player & lp, Player & rp );      // supply partners
    int getId();                                // player id
    void toss();                                // tossed potato
};
```

Figure 1: Player Interface

```
hotpotato [ games | 'd' [ players | 'd' [ seed | 'd' ] ] ]
```

(Square brackets indicate optional command line parameters, and do not appear on the actual command line.)

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

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

seed is the starting seed for the random number generator to allow reproducible results (> 0). If d or no value for seed is specified, initialize the random number generator with an arbitrary seed value (e.g., getpid() or time()), so each run of the program generates different output.

Check all command arguments for correct form (integers or d) 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 (see Appendix C). There are up to four calls to get random numbers: up to two in program main (only one if a value for players is specified on the command line), one in potato::reset, and one in Player::main.

The program main creates three PRNGs, seeding them all with the same seed value. The program main uses the first PRNG, passes second to potato, and passes the third to each player, so all players use the same PRNG. Then the potato and players are created in increasing order of player id, but the umpire *deletes* the players during the game. After creating the players, generate a random player index, between 1 and players − 1, and swap that position with position 0; hence players may not be in increasing order by player id. To form the ring of players, the program main calls the init member for each player to link the players together into a circle. The init member also resumes the player to set the program main as its starter so the last player can get back to the program main at the end the game. The main member of each player suspends back immediately so the next player can be started. Finally, the program main sets the global umpire variable to the player with id 0 (located at the random position), and tosses the potato to it to start the game. Figure 2 shows the output of a game, where U means umpire and E means election.

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

```
$ hotpotato 1 6 1005
6 players in the game
  POTATO goes off after 6 ticks
U 0 -> 2 -> 0 -> 1 -> 5 -> 4 is eliminated
  POTATO goes off after 5 ticks
U 0 -> 2 -> 3 -> 2 -> 3 is eliminated
  POTATO goes off after 9 ticks
U 0 -> 1 -> 0 -> 1 -> 5 -> 2 -> 0 -> 2 -> 0 is eliminated
E 0 -> 2 -> 5 -> 1 : umpire 5
  POTATO goes off after 7 ticks
U 5 -> 2 -> 5 -> 2 -> 1 -> 5 -> 2 is eliminated
  POTATO goes off after 3 ticks
U 5 -> 1 -> 5 is eliminated
E 5 -> 1 : umpire 1
  POTATO goes off after 2 ticks
U 1 wins the Match!
```

Figure 2: Sample Output

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. Compile the program in Figure 3 using the u++ command with compilation flag -multi, and 1 and 2 processors.

   (a) Perforamnce the following experiments.

   - Run the program 10 times with command line argument 1000000000 1 on a multi-core computer with at least 2 CPUs (cores).
   - Show the 10 results.
   - Run the program 10 times with command line argument 1000000000 2 on a multi-core computer with at least 2 CPUs (cores).
   - Show the 10 results.

   (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 100000000? Explain your answers. (**Hint:** one of the obvious answers is wrong.)

   (d) **BONUS:** Explain any subtle difference between the size of the values for 1 processor and 2 processors.

Submission Guidelines

Follow these guidelines carefully. Review the Assignment Guidelines and C++ Coding Guidelines *before* starting each assignment. **Each text or test-document file, e.g., *.{txt,testdoc} file, must be ASCII text and not exceed 500 lines in length, using the command fold -w120 *.testdoc | wc -l.** 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. q1binsertsort.h, q1*.{h,cc,C,cpp} – code for question 1, p. 1. **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.**

2. q1*.testdoc – test documentation for question 1, p. 1, 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.**

3. q2*.{h,cc,C,cpp} – code for question 2, p. 3. **Program documentation must be present in your submitted code. No test documentation is submitted for this question. Output for this question is checked via a marking program, so it must match exactly with the given program.**

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

static volatile long int shared = 0;            // volatile to prevent dead-code removal
static intmax_t iterations = 500000000;

_Task increment {
    void main() {
        for ( decltype(iterations) i = 0; i < iterations; i += 1 ) {
            shared += 1;                        // multiple increments to increase pipeline size
            shared += 1;
        } // for
    } // increment::main
}; // increment

int main( int argc, char * argv[] ) {
    intmax_t processors = 1;
    struct cmd_error {};
    try {                                       // process command-line arguments
        switch ( argc ) {
          case 3: processors = convert( argv[2] ); if ( processors <= 0 ) throw cmd_error{};
          case 2: iterations = convert( argv[1] ); if ( iterations <= 0 ) throw cmd_error{};
          case 1: break;                        // use defaults
          default: throw cmd_error{};
        } // switch
    } catch( ... ) {
        cout << "Usage: " << argv[0] << " [ iterations (> 0) [ processors (> 0) ] ]" << endl;
        exit( EXIT_FAILURE );                   // TERMINATE!
    } // try

    uProcessor p[processors - 1];               // create additional kernel threads
    {
        increment t[processors == 1 ? 2 : processors];
    } // wait for tasks to finish
    cout << "shared:" << shared << endl;
} // main
```

Figure 3: Interference

4. q3*.txt – contains the information required by question 3.

5. Modify the following Makefile to compile the programs for question 1, p. 1 and 2, p. 3 by inserting the object-file names matching your source-file names.

```
TYPE:=int

CXX = u++                                       # compiler
CXXFLAGS = -g -Wall -Wextra -MMD -O2 -DTYPE="${TYPE}"
MAKEFILE_NAME = ${firstword ${MAKEFILE_LIST}} # makefile name

.SUFFIXES : .cfa                                # CFA default rules
.cfa.o :
    ${CXX} ${CXXFLAGS} -c $<

OBJECTS1 = # object files forming 1st executable with prefix "q1"
EXEC1 = binsertsort

OBJECTS2 = # object files forming 2nd executable with prefix "q2"
EXEC2 = hotpotato

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

.PHONY : all clean
.ONESHELL :

all : ${EXECS}                                  # build all executables
#################################################################

-include BinsertImpl

ifeq (${IMPLTYPE},${TYPE})                      # same implementation type as last time ?
${EXEC1} : ${OBJECTS1}
    ${CXX} $^ -o $@
else                                            # implementation type has changed => rebuilt
.PHONY : ${EXEC1}
${EXEC1} :
    rm -f BinsertImpl
    touch q1binsertsort.h
    sleep 1
    ${MAKE} ${EXEC1} TYPE="${TYPE}"
endif

BinsertImpl :
    echo "IMPLTYPE=${TYPE}" > BinsertImpl
    sleep 1

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

${OBJECTS} : ${MAKEFILE_NAME}                   # OPTIONAL : changes to this file => recompile

-include ${DEPENDS}                             # include *.d files containing program dependences

clean :                                         # remove files that can be regenerated
    rm -f *.d *.o BinsertImpl ${EXECS}
```

This makefile is used as follows:

```
$ make binsertsort TYPE=int
$ ./binsertsort intdata
$ make binsertsort TYPE=double
$ ./binsertsort doubledata
$ make hotpotato
$ ./hotpotato ...
```

Put this Makefile in the directory with the programs, name the source files as specified above, and then type make binsertsort or make hotpotato 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!