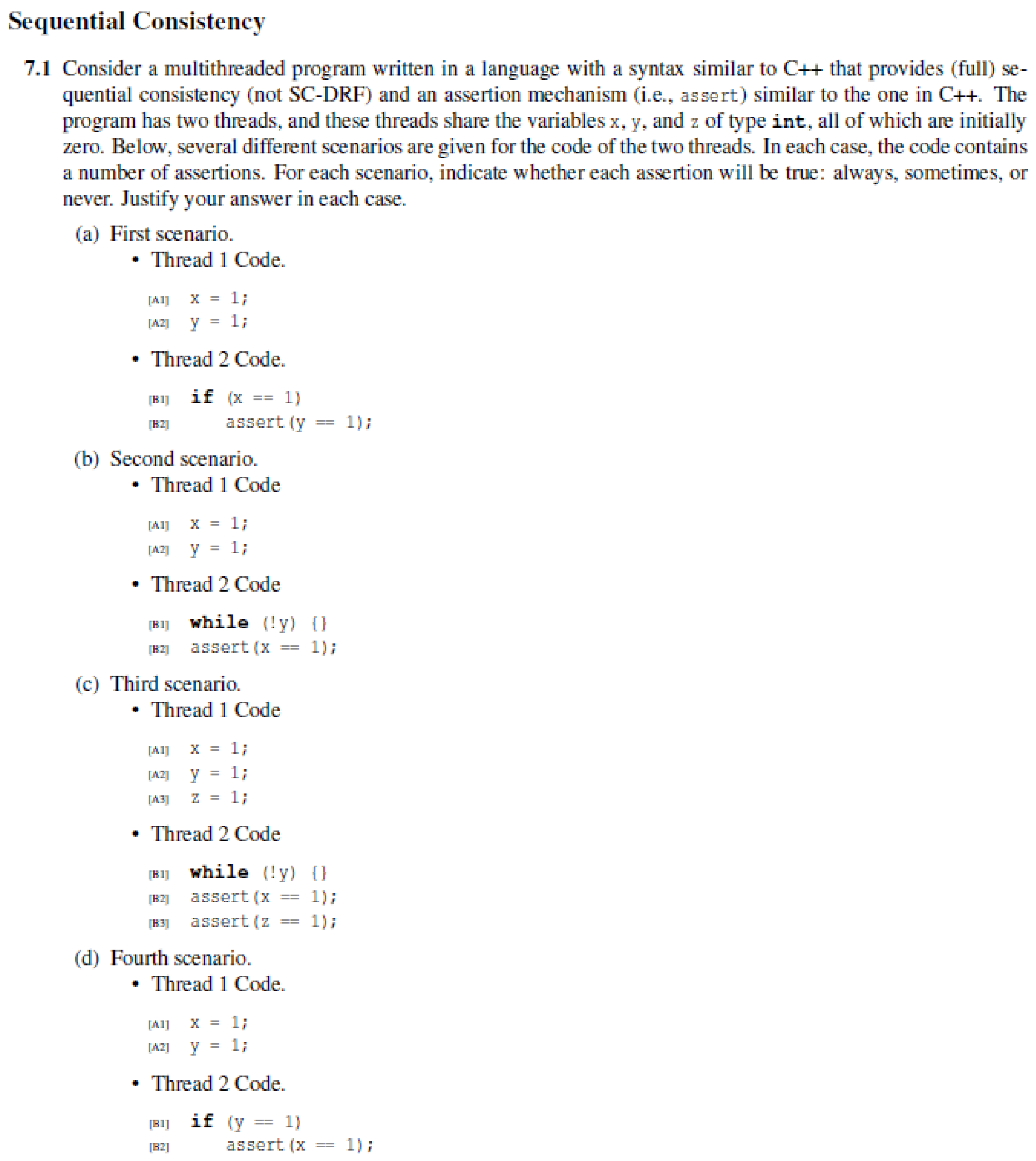


Sequential Consistency

7.1 Consider a multithreaded program written in a language with a syntax similar to C++ that provides (full) sequential consistency (not SC-DRF) and an assertion mechanism (i.e., `assert`) similar to the one in C++. The program has two threads, and these threads share the variables x, y, and z of type **int**, all of which are initially zero. Below, several different scenarios are given for the code of the two threads. In each case, the code contains a number of assertions. For each scenario, indicate whether each assertion will be true: always, sometimes, or never. Justify your answer in each case.

(a) First scenario.

- Thread 1 Code.

```
[A1]  x = 1;
[A2]  y = 1;
```

- Thread 2 Code.

```
[B1]  if (x == 1)
[B2]      assert(y == 1);
```

(b) Second scenario.

- Thread 1 Code

```
[A1]  x = 1;
[A2]  y = 1;
```

- Thread 2 Code

```
[B1]  while (!y) {}
[B2]  assert(x == 1);
```

(c) Third scenario.

- Thread 1 Code

```
[A1]  x = 1;
[A2]  y = 1;
[A3]  z = 1;
```

- Thread 2 Code

```
[B1]  while (!y) {}
[B2]  assert(x == 1);
[B3]  assert(z == 1);
```

(d) Fourth scenario.

- Thread 1 Code.

```
[A1]  x = 1;
[A2]  y = 1;
```

- Thread 2 Code.

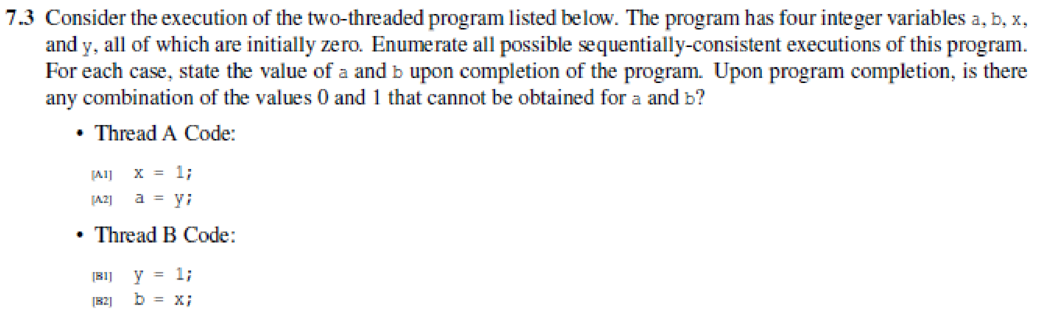
```
[B1]  if (y == 1)
[B2]      assert(x == 1);
```

First scenario: Sometimes true. One possible of sequentially-consistent executions would be A1-B1-B2-A2. In this case, the assertion will be false.

Second scenario: Always true.

Third scenario: Sometime true. In the case of A1-A2-B1-B2-B3-A3 the assertion will be false.

Fourth scenario: Sometimes true. If the execution in the order that B1 executes before A2, the assertion will not be executed.



7.3 Consider the execution of the two-threaded program listed below. The program has four integer variables a, b, x, and y, all of which are initially zero. Enumerate all possible sequentially-consistent executions of this program. For each case, state the value of a and b upon completion of the program. Upon program completion, is there any combination of the values 0 and 1 that cannot be obtained for a and b?

- Thread A Code:

```
[A1]  x = 1;
[A2]  a = y;
```

- Thread B Code:

```
[B1]  y = 1;
[B2]  b = x;
```

Case 1: A1-A2-B1-B2, a = 0, b = 1.

Case 2: A1-B1-A2-B2, a = 1, b = 1.

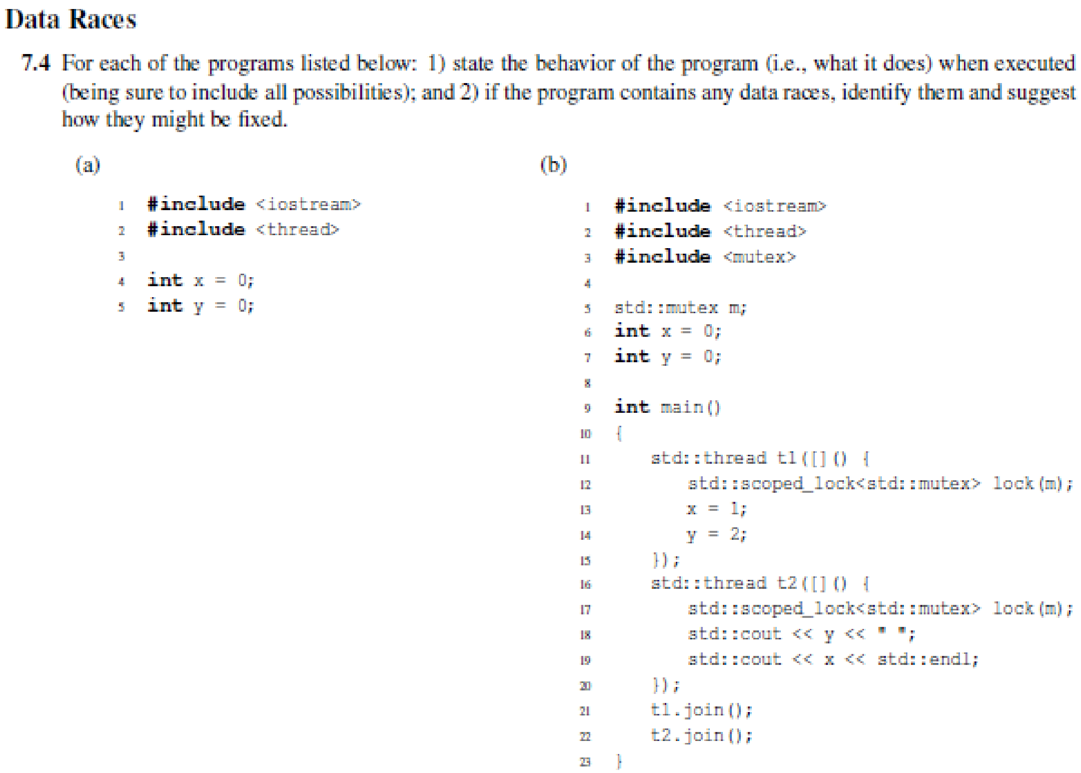
Case 3: A1-B1-B2-A2, a = 1, b = 1.

Case 4: B1-B2-A1-A2, a = 1, b = 0.

Case 5: B1-A1-B2-A2, a = 1, b = 1.

Case 6: B1-A1-A2-B2, a = 1, b = 1.

No sequentially-consistent execution can result in both `a` and `b` being 0.



Data Races

7.4 For each of the programs listed below: 1) state the behavior of the program (i.e., what it does) when executed (being sure to include all possibilities); and 2) if the program contains any data races, identify them and suggest how they might be fixed.

(a)

```cpp
#include <iostream>
#include <thread>

int x = 0;
int y = 0;
```

(b)

```cpp
#include <iostream>
#include <thread>
#include <mutex>

std::mutex m;
int x = 0;
int y = 0;

int main()
{
    std::thread t1([] () {
        std::scoped_lock<std::mutex> lock(m);
        x = 1;
        y = 2;
    });
    std::thread t2([] () {
        std::scoped_lock<std::mutex> lock(m);
        std::cout << y << " ";
        std::cout << x << std::endl;
    });
    t1.join();
    t2.join();
}
```

(a)

1) Assigns 0 to `x`, then assigns 0 to `b`. Or assigns 0 to `b`, then assigns 0 to `x` if reording appled.

2) Not contains data race.

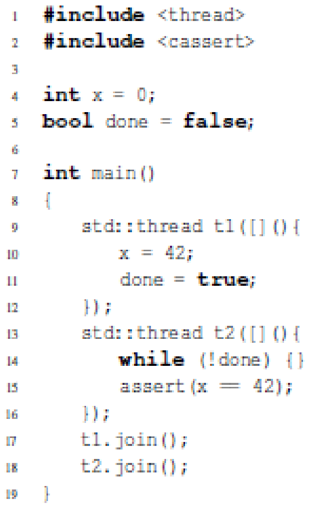
(b)

1) The program creates two threads, one is initializing the variables `x` and `y`, the other thread prints out the value of `y` and `x`.

```
- Possible output: "2 1" or "0 0".
```

2) Not contains data race.

(g)

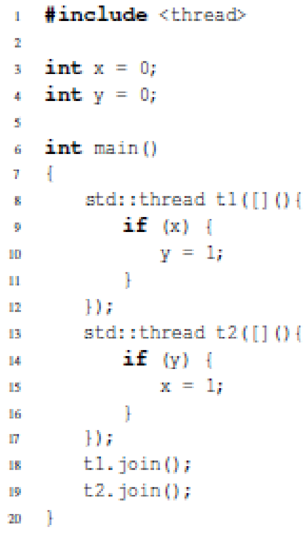


```cpp
#include <thread>
#include <cassert>

int x = 0;
bool done = false;

int main()
{
    std::thread t1([](){
        x = 42;
        done = true;
    });
    std::thread t2([](){
        while (!done) {}
        assert(x == 42);
    });
    t1.join();
    t2.join();
}
```

(i)



```cpp
#include <thread>

int x = 0;
int y = 0;

int main()
{
    std::thread t1([](){
        if (x) {
            y = 1;
        }
    });
    std::thread t2([](){
        if (y) {
            x = 1;
        }
    });
    t1.join();
    t2.join();
}
```

(g)

1) `t1` assigns 42 to `x` and sets `done` to true, `t2` has a while loop and assertion for `x == 42`.

```
- Possible outcome: `x == 42` and assertion true.
```

2) Not contains data race.

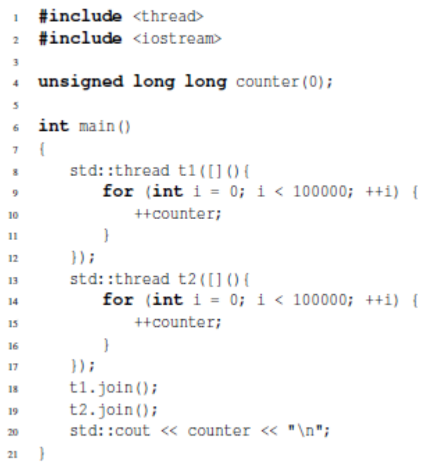
(i)

1) `t1` assigns 1 to `y` if `x` greater than 0, `t2` assigns 1 to `x` if `y` greater than 0.

```
- Possible outcome: Both threads do nothing.
```

2) Not contains data race.

(l)

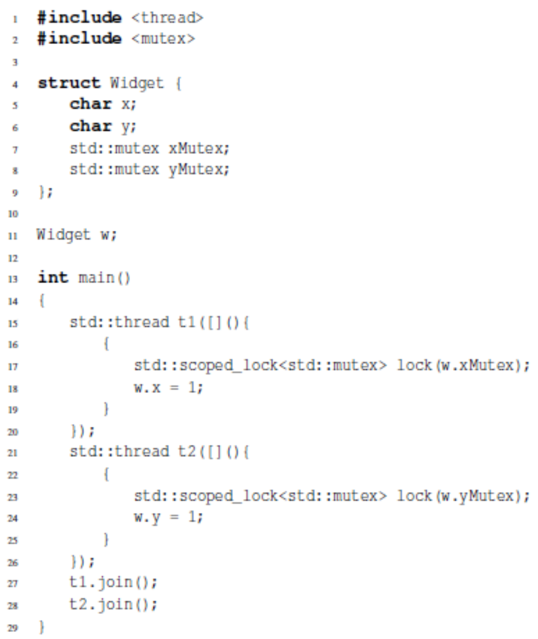


```cpp
#include <thread>
#include <iostream>

unsigned long long counter(0);

int main()
{
    std::thread t1([](){
        for (int i = 0; i < 100000; ++i) {
            ++counter;
        }
    });
    std::thread t2([](){
        for (int i = 0; i < 100000; ++i) {
            ++counter;
        }
    });
    t1.join();
    t2.join();
    std::cout << counter << "\n";
}
```

(m)



```cpp
#include <thread>
#include <mutex>

struct Widget {
    char x;
    char y;
    std::mutex xMutex;
    std::mutex yMutex;
};

Widget w;

int main()
{
    std::thread t1([](){
        {
            std::scoped_lock<std::mutex> lock(w.xMutex);
            w.x = 1;
        }
    });
    std::thread t2([](){
        {
            std::scoped_lock<std::mutex> lock(w.yMutex);
            w.y = 1;
        }
    });
    t1.join();
    t2.join();
}
```

(l)

1) Both thread `t1` and thread `t2` increase the `counter` 100000 times respectively, then prints out `counter`.

```
- Possible outcome: the value of `counter` is not 200000.
```

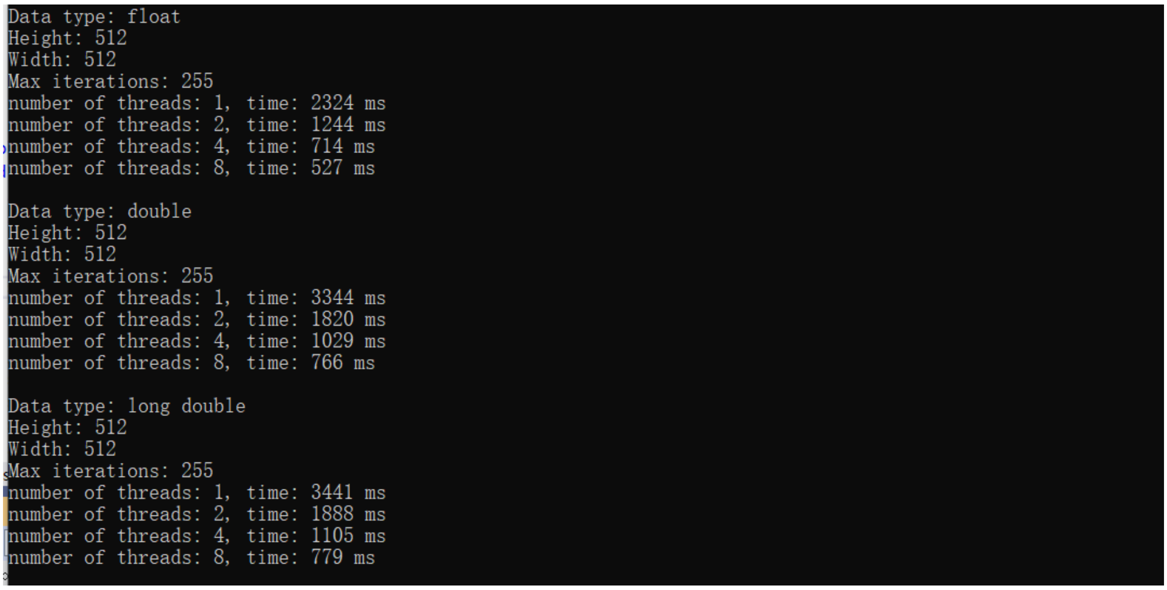
2) Data race may happen since both threads try to increase the `counter`. We can use mutex to avoid this problem.

(m)

1) The program creates a Wiget object `w`, and create two threads `t1` and `t2`. Thread `t1` creates a scoped_lock object `lock` and sets `w.x` to 1, `t2` creates a scoped_lock object `lock` and sets `w.y` to 1.

```
- Possible outcome: `w.x == 1` and `w.y == 1`.
```

2) Not contains data race.



```
Data type: float
Height: 512
Width: 512
Max iterations: 255
number of threads: 1, time: 2324 ms
number of threads: 2, time: 1244 ms
number of threads: 4, time: 714 ms
number of threads: 8, time: 527 ms

Data type: double
Height: 512
Width: 512
Max iterations: 255
number of threads: 1, time: 3344 ms
number of threads: 2, time: 1820 ms
number of threads: 4, time: 1029 ms
number of threads: 8, time: 766 ms

Data type: long double
Height: 512
Width: 512
Max iterations: 255
number of threads: 1, time: 3441 ms
number of threads: 2, time: 1888 ms
number of threads: 4, time: 1105 ms
number of threads: 8, time: 779 ms
```

Base on the result, the preformance seems reasonable since more workers doing the same amount of job, the time they need will be shorter.