THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

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PRQA
Programming Research

How to avoid bottlenecks when converting serial code to multithreaded

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REPHRASE

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Background

- The RePhrase Project is an EU Horizon 2020 research project
- New software engineering tools that help tackle multi-core computing
- PRQA's contributions
  - Rule set facilitating parallel programming
  - Qualitative analysis of sources before and after transformations

Outline

- Review a code sample
- Identify code constructs that interfere with parallelism
- Check relevant constraints in the C++ standard
- Formulate coding rule(s)
- Rinse and repeat
- Come away with coding guidelines for parallel ready code

Simple Accumulator

```
#include <vector>

int reentrantFunc (int);

int simpleAcc (std::vector <int> const & data)
{
  int result = 0;

  for (int i = 0; i < data.size (); ++i)
  {
    result += reentrantFunc (data [i]);
  }

  return result;
}
```

Simple Accumulator – range for

```
#include <vector>

int reentrantFunc (int);

int simpleAcc2 (std::vector <int> const & data)
{
  int result = 0;

  for (auto d : data)
  {
    result += reentrantFunc (d);
  }

  return result;
}
```

Simple Accumulator – STL algorithm

```
#include <vector>
#include <numeric>

int reentrantFunc (int);

int simpleAcc3 (std::vector <int> const & data)
{
  auto ftor = [] (int sum, int d) {
    return sum + reentrantFunc (d);
  };

  return std::accumulate (std::execution::par
    , data.cbegin (), data.cend (), 0, ftor);
}
```

Simple Accumulator – C++17

```
#include <vector>
#include <numeric>
#include <execution>

int reentrantFunc (int);

int simpleAcc4 (std::vector <int> const & data)
{
  return std::transform_reduce (std::execution::par
                // or switch to std::execution::seq
    , data.cbegin ()
    , data.cend ()
    , 0               // initialisation of sum
    , std::plus <> () // reduce operation
    , reentrantFunc); // transform operation
}
```

Simple Accumulator – C++ constraints

- Data races [intro.races]

  "(2) Two expression evaluations conflict if one of them modifies a memory location and the other one reads or modifies the same memory location."

  "(3) The library defines a number of atomic operations and operations on mutexes that are specially identified as synchronization operations..."

Simple Accumulator – rules

- no access to objects visible outside of the loop/functor
  - data races when parallelised
    - need synchronisation
- use range for or an STL algorithm where possible
  - easier conversion between serial and parallel execution with C++17 parallel algorithms
    - limited compiler support
      - Intel System Studio 2018
      - Visual C++ 2017

Simple Accumulator – VC++ 2017

```
#include <vector>
#include <numeric>
#include <algorithm>
#include <execution>

int reentrantFunc (int);

int simpleAcc4 (std::vector <int> const & data)
{
  std::vector <int> temp (data.size ());
  std::transform (std::execution::par
    , data.cbegin ()
    , data.cend ()
    , temp.begin ()
    , reentrantFunc);

  return std::reduce (std::execution::par
    , temp.cbegin ()
    , temp.cend ());
}
```

Has Negative

```
#include <vector>

int reentrantFunc (int);

bool hasNegative (std::vector <int> const & data)
{
  for (auto d : data)
  {
    auto v = reentrantFunc (d);
    if (v < 0)
    {
      return true;
    }
  }
  return false;
}
```

Has Negative – fixed number of iterations

```
#include <vector>

int reentrantFunc (int);

bool hasNegative2 (std::vector <int> const & data)
{
  bool result = false;

  for (auto d : data)
  {
// is short-circut really wanted: variable number of calls
    result = result || (reentrantFunc (d) < 0);
//  result = (reentrantFunc (d) < 0) || result;
  }
  return result;
}
```

Has Negative – C++17 – everything OK?

```
#include <vector>
#include <algorithm>
#include <execution>

int reentrantFunc (int);

bool hasNegative4 (std::vector <int> const & data)
{
  auto ftor = [] (int d) { return reentrantFunc (d) < 0; };

  return std::any_of (std::execution::par
    , data.cbegin ()
    , data.cend ()
    , ftor);
}
```

Has Negative – all singing and dancing

```
bool hasNegative5 (std::vector <int> const & data)
{
  auto ftor = [] (int d) noexcept {
    bool result = true; // or perhaps false?
    try
    {
      result = reentrantFunc (d) < 0;
    }
    catch (...) {}

    return result;
  };

  return std::any_of (std::execution::par
    , data.cbegin ()
    , data.cend ()
    , ftor);
}
```

Has Negative – C++ constraints

- Uncaught exceptions in functors
  - The std::terminate() function [except.terminate]

“(1.11) — for a parallel algorithm whose ExecutionPolicy specifies such behavior, when execution of an element access function of the parallel algorithm exits via an exception”

Has Negative – rules

- no break, goto, return, throw, or other non-returning statement/function call inside a loop
  - hard/impossible to parallelise
- no uncaught exception or a non-returning statement/function call inside a functor

Nested algorithms – what have we missed?

```
// #includes
int reentrantFunc (int) noexcept;

void nested (std::vector <std::vector <int> > & data)
{
  std::for_each (std::execution::par
    , data.begin ()
    , data.end ()
    , [] (auto & inner) noexcept {
    std::transform (std::execution::par
      , inner.cbegin ()
      , inner.cend ()
      , inner.begin ()
      , reentrantFunc); // transform operation
  });
}
```

Nested algorithms – fixed

```
void nested2 (std::vector <std::vector <int> > & data)
{
  bool hadException = std::find_if (std::execution::par
    , data.begin ()
    , data.end ()
    , [] (auto & inner) noexcept {
    bool result = false;
    try
    {
      std::transform (std::execution::par
        , inner.cbegin ()
        , inner.cend ()
        , inner.begin ()
        , reentrantFunc);
    }
    catch (std::bad_alloc const & e)
    {
      result = true;
    }
    return result;
  }) != data.end ();
}
```

Nested algorithms – C++ constraints

- Parallel algorithm exceptions [algorithms.parallel.exceptions]
  - “(1) During the execution of a parallel algorithm, if temporary memory resources are required for parallelization and none are available, the algorithm throws a bad_alloc exception.”

Nested algorithms – rules

- Handle a std::bad_alloc exception that can be thrown by a parallel algorithm

Random Accumulator

```
#include <vector>
#include <cstdlib>

int reentrantFunc (int) noexcept;

int randomAccumulator (std::vector <int> const & data)
{
  int result = 0;

  for (auto d : data)
  {
    auto random = std::rand ();
    auto v = reentrantFunc (d);
    if (v > random)
    {
      result += v;
    }
  }

  return result;
}
```

Random Accumulator – fixed

```
int randomAccumulator2 (std::vector <int> const & data)
{
  std::vector <int> test (data.size ());

  // The rand function is not required to avoid data races with other calls to
  // pseudo-random sequence generation functions.
  // serial execution only
  std::generate (test.begin (), test.end (), std::rand);

  int result = 0;
  auto it = test.cbegin ();
  for (auto d : data) // potential parallel execution
  {
    auto v = reentrantFunc (d);
    if (v > *it)
    {
      result += v;
    }
    ++it;
  }

  return result;
}
```

Random Accumulator – C++17

```cpp
int randomAccumulator3 (std::vector <int> const & data)
{
  std::vector <int> test (data.size ());

  // serial execution only
  std::generate (test.begin (), test.end (), std::rand);

  auto ftor = [] (int d, int randNum) {
    auto v = reentrantFunc (d);
    return (v > randNum) ? v : 0;
  };

  return std::transform_reduce (std::execution::par // or switch to
   std::execution::seq
    , data.cbegin ()
    , data.cend ()
    , test.cbegin ()
    , 0
    , std::plus <> () // reduce op
    , ftor);          // transform op
}
```

Random Accumulator – C++ constraints

- The C++ standard library has data race guarantees [res.on.data.races]
  - the implementation will not implicitly introduce data races
  - arguments passed may cause data races
- non-reentrant functions in the C standard library
  - asctime, ctime, gmtime, and localtime [ctime.syn]
  - strerror and strtok [cstring.syn]
  - multibyte / wide string and character conversion functions [c.mb.wcs]
  - <locale> and <clocale> functions [locales] & [c.locales]
  - rand [c.math.rand]
  - tmpnam [cstdio.syn]

Random Accumulator – rules

- no call to a non-reentrant function inside a loop or functor
  - data races when parallelised

Recursive

```
int recursiveHelper (int i, std::vector <int> & data)
{
  data [i] = reentrantFunc (data [i]);
  if (i > 0)
  {
    data [i] += recursiveHelper (i - 1, data);
  }
  return data [i];
}

void recursive (std::vector <int> & data)
{
  if (! data.empty ())
  {
    recursiveHelper (data.size () - 1, data);
  }
}
```

Recursive – rules

- no direct or indirect recursion
  - needs to be converted to loop(s) before parallelisation

Iterative – better?

```
void iterative (std::vector <int> & data)
{
  int num = data.size ();

  data [0] = reentrantFunc (data [0]);

  for (int i = 1; i != num; ++i)
  {
    data [i] = reentrantFunc (data [i]);
    data [i] += data [i - 1];
  }
}
```

Iterative – C++17 – everything OK?

```
void iterative3 (std::vector <int> & data)
{
  std::transform (std::execution::par
    , data.cbegin ()
    , data.cend ()
    , data.begin ()
    , reentrantFunc);

  // serial execution only
  int num = data.size ();
  for (int i = 1; i != num; ++i)
  {
    data [i] += data [i - 1]; // loop carried dependence
  }
}
```

Iterative – fixed

```
void iterative4 (std::vector <int> & data)
{
  std::transform_inclusive_scan (
    std::execution::par
    , data.cbegin ()
    , data.cend ()
    , data.begin ()
    , std::plus <> () // prefix sum
    , reentrantFunc); // transform op
}
```

Iterative – C++ constraints

- Container data races [container.requirements.dataraces]

  “2 ... implementations are required to avoid data races when the contents of the contained object in different elements in the same container, excepting vector<bool>, are modified concurrently.”

Iterative – rules

- avoid/isolate loop carried dependences
  - When a statement in one iteration of a loop depends in some way on a statement in a different iteration of the same loop

Mean – is it correct?

```
#include <numeric>
#include <execution>

int mean (std::vector <int> const & data)
{
  auto ftor = [] (int i, int j) {
    return (i + j) / 2;
  };

  return std::reduce (std::execution::par
    , data.cbegin ()
    , data.cend ()
    , 0
    , ftor);
}
```

Mean – fixed

```
int mean2 (std::vector <int> const & data)
{
  return std::reduce (std::execution::par
    , data.cbegin ()
    , data.cend ()
    , 0
    , std::plus <> ()) / data.size ();
}
```

Mean – C++ constraints

- Non-determinism
  - Reduce [reduce]
  - Transform reduce [transform.reduce]

"(8) [Note: The difference between reduce and accumulate is that reduce applies binary_op in an unspecified order, which yields a nondeterministic result for non-associative or non-commutative binary_op such as floating-point addition. —end note]"

Mean – rules

- Only use an associative and commutative binary op with std::reduce or std::transform reduce

Parallelisation Blockers: control flow

- Complex loops
  - Cannot be easily represented as STL algorithms or range-for
  - break/goto/return/throw/other non-returning statement
- Complex functors
  - Uncaught exceptions or a non-returning statement/function call
    - functor should always return
- Recursion
  - Convert into a loop first

Parallelisation Blockers: control flow - continued

- Prefer an STL algorithm with a functor/lambda that always returns
  - RePhrase rules 2.7, 4.1, 4.5, and 4.6
  - Easy conversion to a parallel algorithm
- std::bad_alloc exception can be thrown by a parallel algorithm
  - RePhrase rule 4.7

Parallelisation Blockers: data races

- Access to objects visible outside of the loop/functor
- Calling non-reentrant library functions
  - strtok/rand etc.
- Loop carried dependence
  - Evaluation of an iteration depends on the result of another
- Require synchronisation to prevent races
  - reduce performance gains from parallelisation
- RePhrase rules 4.2 and 4.9

Parallelisation Blockers: non-determinism

- Non-associative or non-commutative binary op used with std::reduce or std::transform_reduce
- RePhrase rule 4.8

Useful concurrency sources

- C++17 Draft
  - http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2017/n4659.pdf
- Anthony Williams
  - C++ Concurrency in Action 2nd Ed
- Scott Meyers
  - Effective Modern C++
- Herb Sutter
  - Effective Concurrency
  - www.herbsutter.com/2010/09/24/effective-concurrency-know-when-to-use-an-active-object-instead-of-a-mutex/

Multi-threading misuse rules

- HIC++ Coding Standard
  - www.codingstandard.com/section/18-concurrency/
  - C++11 Thread support library issues
- CWE and CERT C++ concurrency rules
  - wiki.sei.cmu.edu/confluence/pages/viewpage.action?pageId=88046460
  - data race
  - deadlock
  - use of non-reentrant functions
- RePhrase Coding Standard
  - rephrase-eu.weebly.com/uploads/3/1/0/9/31098995/hicppmp.pdf
  - Completely focused on concurrency
  - More rules than presented here

Concurrent – what’s wrong

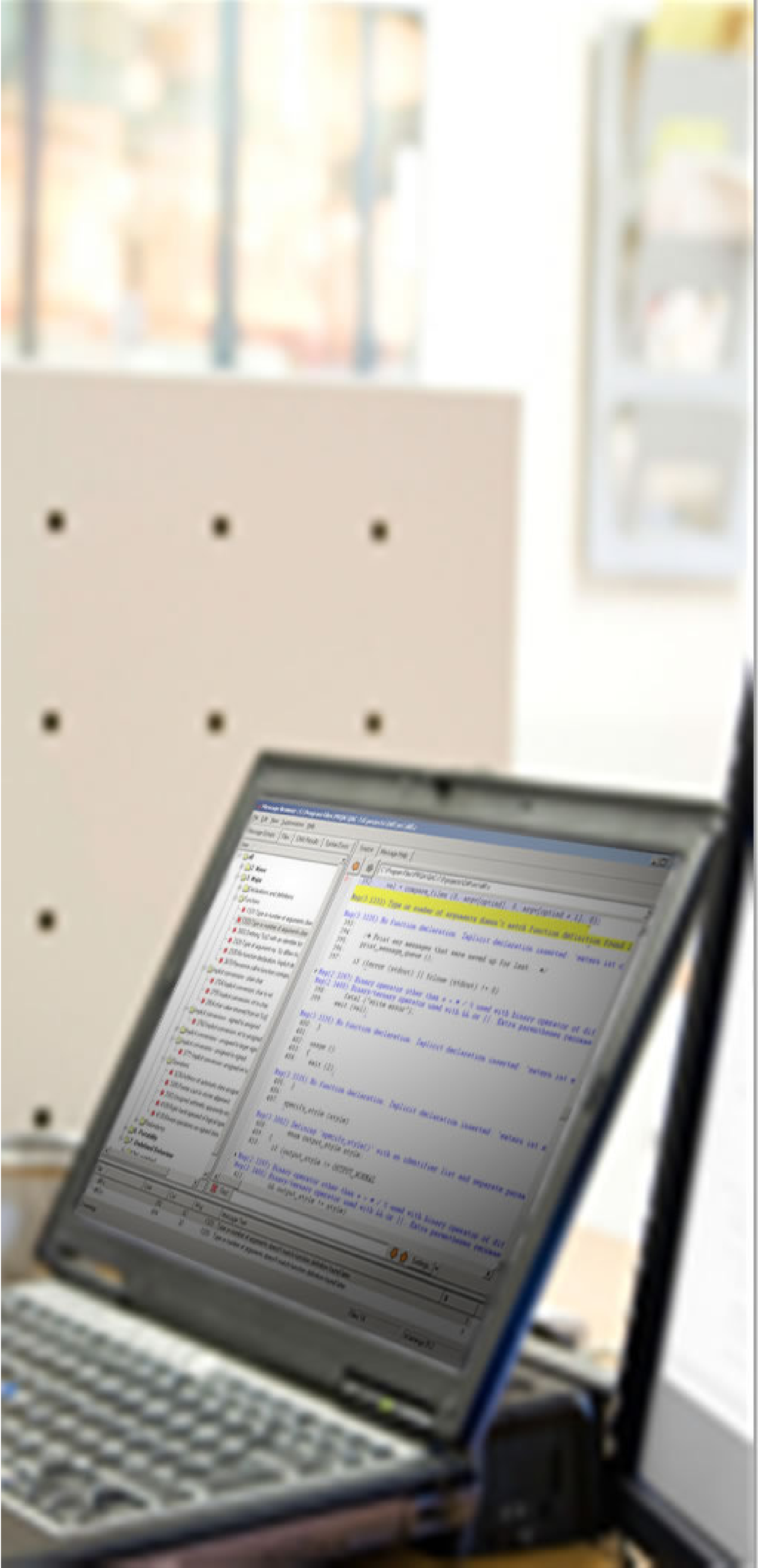
```
void concurrent () {
  std::mutex m; std::condition_variable cond; std::queue<int> data;

  auto f = std::async ([&m, &cond, &data] () {
    for (unsigned i = 0; i != 10; ++i) {
      const int value = reentrantFunc (i);
      std::lock_guard<std::mutex> guard (m);
      data.push (value);
      cond.notify_one ();
    }
  });

  for (unsigned i = 0; i != 10; ++i) {
    std::unique_lock<std::mutex> lock (m);
    cond.wait (lock, [&data] () { return ! data.empty(); });
    int result = data.front ();
    data.pop ();
    lock.unlock ();
    // do something with ‘result’
  }
  f.wait();
}
```

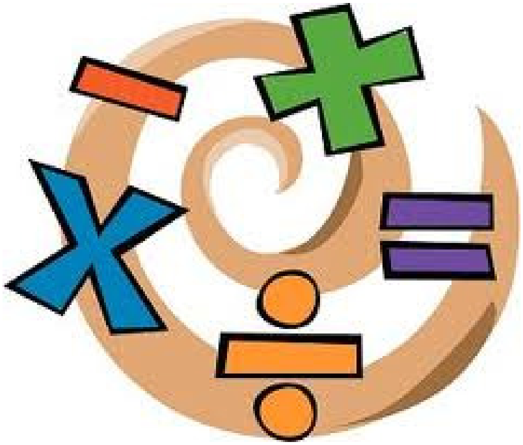
Concurrent – fixed

```
void concurrent () {
  std::mutex m; std::condition_variable cond; std::queue<int> data;

  auto f = std::async (std::launch::async, [&m, &cond, &data] () {
    for (unsigned i = 0; i != 10; ++i) {
      const int value = reentrantFunc (i);
      std::lock_guard<std::mutex> guard (m);
      data.push (value);
      cond.notify_one ();
    }
  });

  for (unsigned i = 0; i != 10; ++i) {
    std::unique_lock<std::mutex> lock (m);
    cond.wait (lock, [&data] () { return ! data.empty(); });
    int result = data.front ();
    data.pop ();
    lock.unlock ();
    // do something with ‘result’
  }
  f.wait();
}
```

Concurrent – rules

- Explicitly specify a launch policy for std::async
  - RePhrase rule 3.3
  - Default is std::launch::async | std::launch::deferred
- …





Questions?

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