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Using OpenMP from C++
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Justification

OpenMP has the opportunity to exploit features of modern C++ that are no present in C. In this course we will explore:

- range-based iteration,
- differences in treatment between vectors and arrays, and various sophisti reduction schemes.

Basic stuff

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1. Output streams in parallel

The use of *cout* may give jumbled output:
lines can break at each <<.
Use `stringstream` to form a single stream to output.

```
1  // hello.cxx
2  #pragma omp parallel
3    {
4      int t = omp_get_thread_num();
5      stringstream proctext;
6      proctext << "Hello world from " << t << endl;
7      cerr << proctext.str();
8    }
```

2. Parallel regions in lambdas

OpenMP parallel regions can be in functions, including lambda expressions.

```
1  const int s = [] () {
2    int s;
3  #   pragma omp parallel
4  #   pragma omp master
5    s = 2 * omp_get_num_threads();
6    return s; }();
```

('Immediately Invoked Function Expression')

3. Dynamic scope for class methods

Dynamic scope holds for class methods as for any other function:

Code:

```
// nested.cxx
class c {
public:
  void f() {
    cout
      << omp_get_num_threads()
      << '\n';
  };
};
int main() {
  c my_object;
#pragma omp parallel
  my_object.f();
```

Output:

```
executing: OMP_MAX_ACTIVE_LEVELS=2
    ↪OMP_PROC_BIND=true
    ↪OMP_NUM_THREADS=2 ./nested
2
2
```

4. Privatizing class members

Class members can only be privatized from (non-static) class methods:

```
      class foo {
        private:
        int x;
        public:
        void f() {
#pragma omp parallel private x
g()
        }
      }

```

So `f` can not be `static`, and

```
      class foo { public: int x; }
      foo x;
      #pragma omp parallel private thing.x // NOPE

```

5. Vectors are copied, unlike arrays, 1

C arrays: private pointer, but shared array:

Code:

```
// alloc.c
int *array =
  (int*) malloc(nthreads*sizeof(int));
for (int i=0; i<nthreads; i++)
  array[i] = 0;

#pragma omp parallel firstprivate(array)
{
  int t = omp_get_thread_num();
  array += t;
  array[0] = t;
}
// ... print the array
```

Output:

```
Array result:
0:0, 1:1, 2:2, 3:3,
```

6. Vectors are copied, unlike arrays, 2

C++ vectors: copy constructor also copies data:

Code:

```
// alloc.cxx
vector<int> array(nthreads);

#pragma omp parallel firstprivate(array)
{
  int t = omp_get_thread_num();
  array[t] = t+1;
}
// ... print the array
```

Output:

```
Array result:
0:0, 1:0, 2:0, 3:0,
```

Parallel loops

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7. Range syntax

Parallel loops in C++ can use range-based syntax as of OpenMP-5.0:

```
1  // vecdata.cxx
2  #pragma omp parallel for
3      for ( auto& elt : values ) {
4        elt = 5.f;
5      }
6      float sum{0.f};
7  #pragma omp parallel for reduction(+:sum)
8      for ( auto elt : values ) {
9        sum += elt;
10     }
```

Tests not reported here show exactly the same speedup as the C code.

8. C++ ranges header

The C++20 ranges library is also supported:

```
1  // range.cxx
2  #     pragma omp parallel for reduction(+:count)
3        for ( auto e : data )
4          count += e;
5  #     pragma omp parallel for reduction(+:count)
6        for ( auto e : data
7                | std::ranges::views::drop(1) )
8          count += e;
9  #     pragma omp parallel for reduction(+:count)
10       for ( auto e : data
11               | std::ranges::views::transform
12               ( []( auto e ) { return 2*e; } ) )
13         count += e;
```

9. C++ ranges speedup

```
==== Run range on 1 threads ====
sum of vector: 50000005000000 in 6.148
sum w/ drop 1: 50000004999999 in 6.017
sum times 2  : 100000010000000 in 6.012
==== Run range on 25 threads ====
sum of vector: 50000005000000 in 0.494
sum w/ drop 1: 50000004999999 in 0.477
sum times 2  : 100000010000000 in 0.489
==== Run range on 51 threads ====
sum of vector: 50000005000000 in 0.257
sum w/ drop 1: 50000004999999 in 0.248
sum times 2  : 100000010000000 in 0.245
==== Run range on 76 threads ====
sum of vector: 50000005000000 in 0.182
sum w/ drop 1: 50000004999999 in 0.184
sum times 2  : 100000010000000 in 0.185
==== Run range on 102 threads ====
sum of vector: 50000005000000 in 0.143
sum w/ drop 1: 50000004999999 in 0.139
sum times 2  : 100000010000000 in 0.134
==== Run range on 128 threads ====
sum of vector: 50000005000000 in 0.122
```

10. Custom iterators, 0

Recall that

Short hand:

```
1  vector<float> v;
2  for ( auto e : v )
3     ... e ...
```

for:

```
1  for ( vector<float>::iterator
2        e=v.begin();
3        e!=v.end(); e++ )
4     ... *e ...
```

If we want

```
1  for ( auto e : my_object )
2       ... e ...
```

we need a sub-class for the iterator with methods such as *begin*, *end*, * and ++

11. Custom iterators, 1

OpenMP can parallelize any range-based loop with a random-access iterator.

Class:

```
1  // iterator.cxx
2  class NewVector {
3  protected:
4    int *storage;
5    int s;
6  public:
7  // iterator stuff
8    class iter;
9    iter begin();
10   iter end();
11 };
```

Main:

```
1  NewVector v(s);
2  #pragma omp parallel for
3  for ( auto e : v )
4    cout << e << " ";
```

12. Custom iterators, 2

Required iterator methods:

```
1  NewVector::iter& operator++();
2  int& operator*();
3  bool operator==( const NewVector::iter &other ) const;
4  bool operator!=( const NewVector::iter &other ) const;
5  // needed to OpenMP
6  int operator-( const NewVector::iter& other ) const;
7  NewVector::iter& operator+=( int add );
```

13. Custom iterators, exercise

Write the missing iterator methods.
Here's something to get you started.

```
1  class NewVector::iter {
2  private: int *searcher;
3  };
4  NewVector::iter::iter( int *searcher )
5    : searcher(searcher) {};
6  NewVector::iter NewVector::begin() {
7    return NewVector::iter(storage); };
8  NewVector::iter NewVector::end()   {
9    return NewVector::iter(storage+NewVector::s); };
```

14. Custom iterators, solution

```
1  NewVector::iter& NewVector::iter::operator++() {
2    searcher++; return *this; };
3  int&  NewVector::iter::operator*() {
4    return *searcher; };
5  bool  NewVector::iter::operator==( const NewVector::iter &other ) const {
6    return searcher==other.searcher; };
7  bool  NewVector::iter::operator!=( const NewVector::iter &other ) const {
8    return searcher!=other.searcher; };
9  // needed to OpenMP
10 int   NewVector::iter::operator-( const NewVector::iter& other ) const {
11   return searcher-other.searcher; };
12 NewVector::iter& NewVector::iter::operator+=( int add ) {
13   searcher += add; return *this; };
```

15. OpenMP vs standard parallelism

Application: prime number marking (load unbalanced)

```
#pragma omp parallel for schedule(guided,8)
 for (int i=0; i<nsize; i++) {
   results[i] = one_if_prime( number(i) );
 }
```

```
// primepolicy.cxx
transform( std::execution::par,
           numbers.begin(),numbers.end(),
           results.begin(),
           [] (int n ) -> int {
             return one_if_prime(n); }
           );
```

Standard parallelism uses Thread Building Blocks (TBB) as backend

16. Timing

```
1  OMP: Time:     8591 msec (threads= 5)
2  TBB: Time:     8335 msec
3  OMP: Time:     4298 msec (threads=10)
4  TBB: Time:     4160 msec
5  OMP: Time:     2150 msec (threads=20)
6  TBB: Time:     2082 msec
7  OMP: Time:     1078 msec (threads=40)
8  TBB: Time:     1138 msec
9  OMP: Time:      771 msec (threads=56)
10 TBB: Time:      885 msec
```

TBB slightly better on one socket, worse on two.

Reductions

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17. Reductions on vectors

Use the *data* method to extract the array on which to reduce. Also, the reduc
clause wants a variable, not an expression, for the array, so you need an extra
pointer:

```
1  // reductarray.cxx
2  vector<int> data(nthreads,0);
3  int *datadata = data.data();
4  #pragma omp parallel for schedule(static,1) \
5    reduction(+:datadata[:nthreads])
6  for (int it=0; it<nthreads; it++) {
7    for (int i=0; i<nthreads; i++)
8          datadata[i]++;
9  }
```

18. Reduction on class objects

Reduction can be applied to any class for which the reduction operator is def
as *operator+* or whichever operator the case may be.

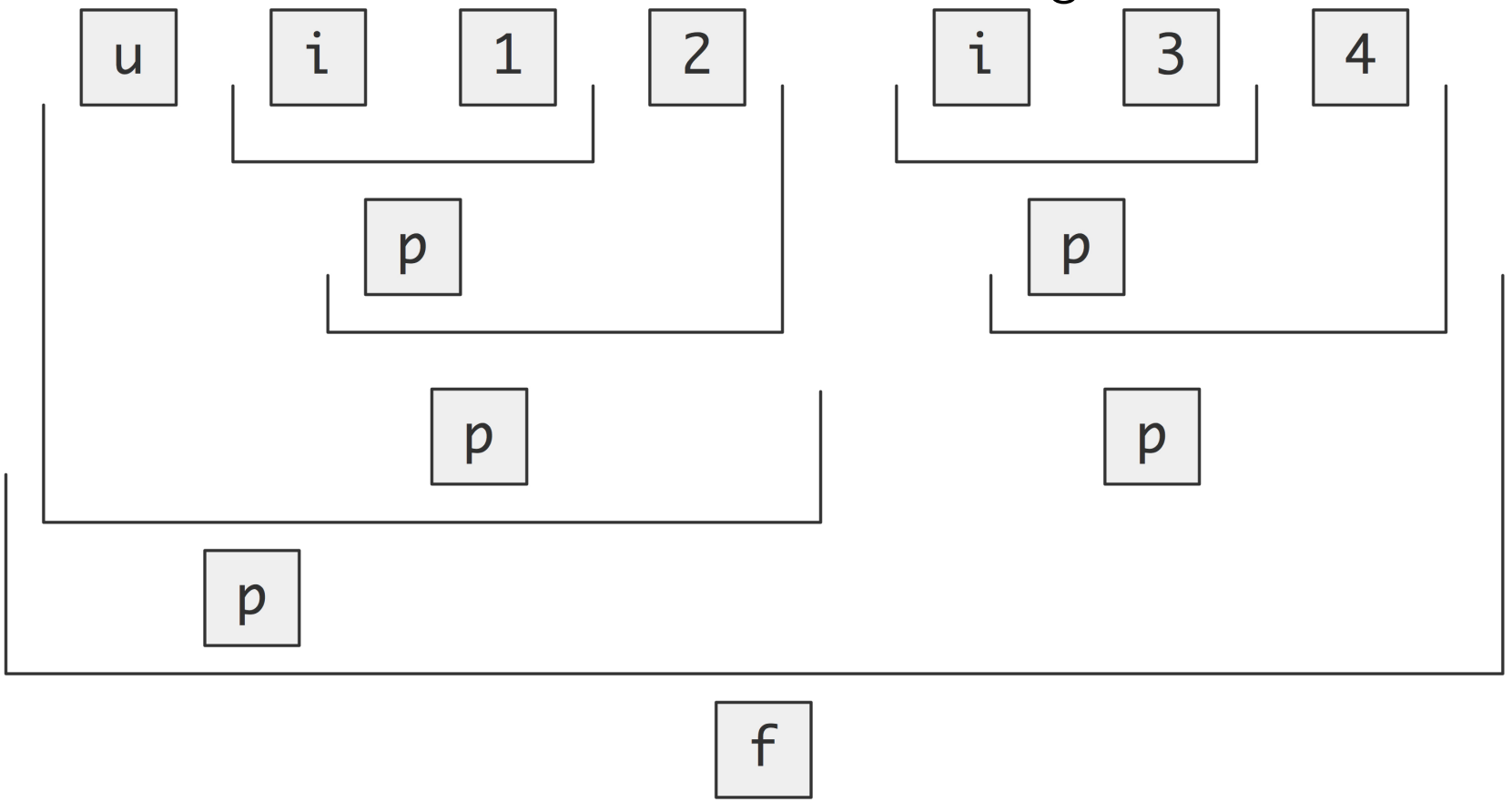
```
1  // reductcomplex.cxx
2  class Thing {
3  private:
4    float x;
5  public:
6    Thing() : Thing( 0.f ) {};
7    Thing( float x ) : x(x) {};
8    Thing operator+( const Thing&
       ↪other ) {
9      return Thing( x + other.x );
10   };
11 };
```

```
1  vector< Thing >
       ↪things(500,Thing(1.f) );
2  Thing result(0.f);
3  #pragma omp parallel for reducti
       ↪+:result )
4  for ( const auto& t : things )
5    result = result + t;
```

A default constructor is required for the internally used init value; see figure 2

19. Reduction illustrated

Reduction of four items on two threads, taking into account initial values.



20. User-defined reductions, syntax

```
1       #pragma omp declare reduction
2       ( identifier : typelist : combiner )
3       [initializer(initializer-expression)]
4
```

21. Reduction over iterators

Support for *C++ iterators*

```
1  #pragma omp declare reduction (merge : std::vector<int>
2       : omp_out.insert(omp_out.end(), omp_in.begin(), omp_in.end()))
```

22. Lambda expressions in declared reductions

You can use lambda expressions in the explicit expression:

```
1  // reductexpr.cxx
2  #pragma omp declare reduction\
3    (minabs : int : \
4     omp_out = \
5         [] (int x,int y) -> int { \
6            return abs(x) > abs(y) ? abs(y) : abs(x); } \
7         (omp_in,omp_out) ) \
8    initializer (omp_priv=limit::max())
```

You can not assign the lambda expression to a variable and use that, because *omp_in/out* are the only variables allowed in the explicit expression.

23. Example category: histograms

```
1       for ( auto e : some_range )
2         histogram[ value(e)]++;
3
```

Collisions are possible, but unlikely, so critical section is very inefficient

24. Histogram: intended main program

```
1  using CharCounter = bincounter<char>;
2  #pragma omp declare reduction\
3  (       \
4          +:CharCounter:omp_out += omp_in \
5          ) \
6  initializer( omp_priv = CharCounter{} )
7  CharCounter charcount;
8  #pragma omp parallel for reduction(+ : charcount)
9  for ( int i=0; i<text.size(); i++ )
10   charcount.inc( text[i] );
```

Q: why does the *inc* not have to be atomic?

25. Histogram: reduction operator

```
1  // mapreduce.cxx
2  template<typename key>
3  class bincounter : public map<key,int> {
4  public:
5  // merge this with other map
6    void operator+=( const bincounter<key>& other ) {
7      for ( auto [k,v] : other )
8        if ( map<key,int>::contains(k) ) // c++20
9          this->at(k) += v;
10       else
11         this->insert( {k,v} );
12   };
13 // insert one char in this map
14   void inc(char k) {
15     if ( map<key,int>::contains(k) )
16       this->at(k) += 1;
17     else
18       this->insert( {k,1} );
19   };
20 };
```

26. Histogram in native C++

Use atomics because there is no reduction mechanism:

```
1  // mapreduceatomic.cxx
2  class CharCounter : public array<atomic<int>,26> {
3  public:
4    CharCounter() {
5      for ( int ic=0; ic<26; ic++ )
6        (*this)[ic] = 0;
7    };
8  // insert one char in this map
9    void inc(char k) {
10     if (k==' ') return;
11     int ik = k-'a';
12     (*this)[ik]++;
13   };
14 };
```

27. Histogram in native C++, comparison

OpenMP reduction on *array*<*int*,26>:

```
1  Using atomics    on 1 threads: time= 20.19 msec
2  OpenMP reduction on 1 threads: time= 1.966 msec
3  Using atomics    on 5 threads: time= 315.855 msec
4  OpenMP reduction on 5 threads: time= 0.52 msec
5  Using atomics    on 10 threads: time= 91.968 msec
6  OpenMP reduction on 10 threads: time= 0.364 msec
7  Using atomics    on 30 threads: time= 249.171 msec
8  OpenMP reduction on 30 threads: time= 0.556 msec
9  Using atomics    on 50 threads: time= 164.177 msec
10 OpenMP reduction on 50 threads: time= 0.904 msec
```

28. Example category: list filtering

The sequential code is as follows:

```
1  vector<int> data(100);
2  // fil the data
3  vector<int> filtered;
4  for ( auto e : data ) {
5    if ( f(e) )
6      filtered.push_back(e);
7  }
```

29. List filtering, solution 1

Let each thread have a local array, and then to concatenate these:

```
#pragma omp parallel
{
  vector<int> local;
# pragma omp for
  for ( auto e : data )
    if ( f(e) ) local.push_back(e);
  filtered += local;
}
```

where we have used an append operation on vectors:

```
// filterreduct.cxx
template<typename T>
vector<T>& operator+=( vector<T>& me, const vector<T>& other ) {
  me.insert( me.end(),other.begin(),other.end() );
  return me;
};
```

30. List filtering, not quite solution 2

We could use the plus-is operation to declare a reduction:

```
1  #pragma omp declare reduction\
2    (     \
3          +:vector<int>:omp_out += omp_in \
4          ) \
5    initializer( omp_priv = vector<int>{} )
```

Problem: OpenMP reductions can not be declared non-commutative, so the contributions from the threads may not appear in order.

Code:

```
#pragma omp parallel \
  reduction(+ : filtered)
  {
    vector<int> local;
#   pragma omp for
    for ( auto e : data )
      if ( f(e) )
        local.push_back(e);
    filtered += local;
  }
```

Output:

```
1  Mod 5: 80 85 90 95 100
       ↪10 15 20 25 30
       ↪40 45 50 55 60
       ↪70 75
```

31. List filtering, task-based solution

With a task it becomes possible to have a spin-wait loop:

Code:

```
// filtertask.cxx
#   pragma omp task \
      shared(filtered,ithread)
    {
// wait your turn
      while (threadnum>ithread) {
#       pragma omp taskyield
      }
// merge
      filtered += local;
      ithread++;
    }
```

Output:

```
1  Mod 5: 5 10 15 20 25 3
       ↪35 40 45 50 55
       ↪65 70 75 80 85
       ↪95 100
```

32. Templated reductions

You can reduce with a templated function if you put both the declaration and reduction in the same templated function:

```
template<typename T>
T generic_reduction( vector<T> tdata ) {
#pragma omp declare reduction                                          \
  (rwzt:T:omp_out=reduce_without_zero<T>(omp_out,omp_in))               \
  initializer(omp_priv=-1.f)

  T tmin = -1;
#pragma omp parallel for reduction(rwzt:tmin)
  for (int id=0; id<tdata.size(); id++)
    tmin = reduce_without_zero<T>(tmin,tdata[id]);
  return tmin;
};
```

which is then called with specific data:

```
auto tmin = generic_reduction<float>(fdata);
```

More topics

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33. Threadprivate random number generators

The new C++ *random* header has a threadsafe generator, by virtue of the statement in the standard that no STL object can rely on global state. The u idiom can not be made threadsafe because of the initialization:

```
1  static random_device rd;
2  static mt19937 rng(rd);
```

However, the following works:

```
1  // privaterandom.cxx
2  static random_device rd;
3  static mt19937 rng;
4  #pragma omp threadprivate(rd)
5  #pragma omp threadprivate(rng)
6
7  int main() {
8
9  #pragma omp parallel
10   rng = mt19937(rd());
```

You can then use the generator safely and independently:

```
1  #pragma omp parallel
```

34. Uninitialized containers

Multi-socket systems:
parallel initialization instantiates pages on sockets:
'first touch'

```
1       double *x = (double*)malloc( N*sizeof(double));
2       #pragma omp parallel for
3       for (int i=0; i<N; i++)
4         x[i] = f(i);
5
```

This does not work with

```
1       std::vector<double> x(N);
2       #pragma omp parallel for
3       for (int i=0; i<N; i++)
4         x[i] = f(i);
5
```

because of value initialization in the `vector` container.

35. Uninitialized containers, 2

Trick to create a vector of uninitialized data:

```
1  // heatalloc.cxx
2  template<typename T>
3  struct uninitialized {
4    uninitialized() {};
5    T val;
6    constexpr operator T() const {return val;};
7    T operator=( const T&& v ) { val = v; return val; };
8  };
```

so that we can create vectors that behave normally:

```
1  vector<uninitialized<double>> x(N),y(N);
2
3  #pragma omp parallel for
4  for (int i=0; i<N; i++)
5    y[i] = x[i] = 0.;
6  x[0] = 0; x[N-1] = 1.;
```

36. Atomic updates

Pragma `atomic` only works for simple cases. Can you atomically do more complicated updates?

- Make an object that has data plus a lock;
- Disable copy and copy-assignment operators;
- Destructor does `omp_destroy_lock`;
- Overload arithmetic operator.

37. Atomic updates: class with OMP lock

```
1  // lockobject.cxx
2  class atomic_int {
3  private:
4    omp_lock_t the_lock;
5    int _value{0};
6  public:
7    atomic_int() {
8      omp_init_lock(&the_lock);
9    };
10   atomic_int( const atomic_int& )
11       = delete;
12   atomic_int& operator=( const atomic_int& )
13       = delete;
14   ~atomic_int() {
15     omp_destroy_lock(&the_lock);
16   };
```

38. Atomic updates: atomic ops

```
1  int operator +=( int i ) {
2  // atomic increment
3    omp_set_lock(&the_lock);
4    _value += i; int rv = _value;
5    omp_unset_lock(&the_lock);
6    return rv;
7  };
```

39. Atomic updates: usage

```
1  atomic_int my_object;
2  vector<std::thread> threads;
3  for (int ithread=0; ithread<NTHREADS; ithread++) {
4    threads.push_back
5      ( std::thread(
6        [=,&my_object] () {
7          for (int iop=0; iop<nops; iop++)
8            my_object += 1; } ) );
9  }
10 for ( auto &t : threads )
11   t.join();
```

40. Atomic updates, comparison to native

Timing comparison on simplest case:

Object with built-in lock:

```
1   atomic_int my_object;
2   vector<std::thread> threads;
3   for (int ithread=0; ithread<NTHREADS;
        ↪ithread++) {
4     threads.push_back
5       ( std::thread(
6         [=,&my_object] () {
7           for (int iop=0; iop<nops; iop++)
8             my_object += 1; } ) );
9   }
10  for ( auto &t : threads )
11    t.join();
```

Native C++ atomics:

```
1   std::atomic<int> my_object{0};
2   #pragma omp parallel for
3   for ( size_t update=0;
4         update<NTHREADS*nops;
5         update++) {
6     my_object += 1;
7   }
8   result = my_object;
```

Native solution is 10x faster.

41. False sharing prevention

```
1       #include <new>
2
3       #ifdef __cpp_lib_hardware_interference_size
4       const int spread = std::hardware_destructive_interference_size
5               / sizeof(datatype);
6       #else
7       const int spread = 8;
8       #endif
9
10      vector<datatype> k(nthreads*spread);
11      #pragma omp parallel for schedule( static, 1 )
12      for ( datatype i = 0; i < N; i++ ) {
13        k[ (i%nthreads) * spread ] += 2;
14
```

42. Beware vector-of-bool!

Does not compile:

```
1  // boolrange.cxx
2  vector<bool> bits(1000000);
3  for ( auto& b : bits )
4    b = true;
```

More subtle:

Code:

```
1  // booliter.cxx
2  vector<bool> bits(3000000);
3  #pragma omp parallel for schedule(static,4)
4  for ( int i=0; i<bits.size(); i++ )
5    bits[i] = ( i%3==0 );
```

Output:

```
1  #threads=1; should be
       ↪million: 100000
2  #threads=2; should be
       ↪million: 100000
3  #threads=3; should be
       ↪million: 999964
4  #threads=4; should be
       ↪million: 999659
```

Different `bits[i]` are falsely shared.

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43. CMake

```
1  cmake_minimum_required( VERSION 3.12 )
2  project( ${PROJECT_NAME} VERSION 1.0 )
3
4  find_package(OpenMP)
5  if(OpenMP_CXX_FOUND)
6  else()
7          message( FATAL_ERROR "Could not find OpenMP for CXX" )
8  endif()
9
10 add_executable( ${PROJECT_NAME} ${PROJECT_NAME}.cxx )
11 target_link_libraries( ${PROJECT_NAME} PUBLIC OpenMP::OpenMP_CXX)
12
13 install( TARGETS ${PROJECT_NAME} DESTINATION . )
```