C++ and OpenMP

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Agenda

- OpenMP and object-oriented programming
- Thread Safety and the STL
- OpenMP and C++ libraries
- Conclusion
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- OpenMP and object-oriented programming
  - Scoping variables of class-type
  - Parallelization of non-conforming loops
  - Remark on Parallelization of oo-codes

- Thread Safety

- OpenMP and C++ libraries

- Conclusion
Scoping variables of class-type

Simple class for demonstration purposes:

```cpp
class Object1 {
public:
    Object1(); // constr.
    ~Object1(); // destr.
    Object1(const Object1& o); // copy constr.
    Object1 & operator=(const Object1& o); // assignm. op.
};
```

- What happens, if instances of such an object are scoped in a parallel region using the different scoping attributes
  1. as `shared`
  2. as `private`
  3. as `firstprivate`
  4. as `lastprivate`

- What happens, if instances of such an object are declared
  5. as `threadprivate`
  6. as `threadprivate + copyin`
Scoping variables of class-type

Let's assume we have declared an instance of Object1

```cpp
Object1 o;
```

and it is *shared* in a parallel region:

```cpp
#pragma omp parallel shared(o)
{
    ... 
}
```

• Simplified excerpt of the C++ standard:
  • The lifetime of an object begins when appropriate storage is obtained and the constructor call (if not non-trivial) has completed
  • Thus, the object’s lifetime begins sometime before the parallel region, and ends sometime after it

• OpenMP specification:
  • *Shared variable*: a variable whose name provides access to the same block of storage for all threads in a team

• Conclusion for *shared*:
  • Only the C++ rules for object lifetime apply
Scoping variables of class-type

- What if the variable is *privatized* in a parallel region:
  
  #pragma omp parallel private(o)

- OpenMP specification:
  
  - *Private variable*: a variable whose name provides access to a different block of storage for all threads
  
  - *Private clause*: a new list item of the same type, with automatic storage duration, is allocated for the construct

- Simplified excerpt of the C++ standard:
  
  - The storage for these objects lasts until the block in which they are created exits

- Conclusion for *private*:
  
  - Each thread has its own instance of the object, the default constructor is called
  
  - At the end of the parallel region, the destructor is called
  
  - The order of constructor calls and destructor calls is undefined
Scoping variables of class-type

- What about `firstprivate` and `lastprivate` variables:
  
  ```
  #pragma omp parallel do firstprivate(o) / lastprivate(o)
  ```

- OpenMP specification:
  - `Firstprivate clause`: ... list items private to a thread, initializes each of them with the value that the corresponding original item has ...
  - C/C++: For class types, a copy constructor is invoked to perform the initialization, the order in which copy constructors for different objects are called is unspecified
  - `Lastprivate clause`: ... list items private to a thread, and causes the corresponding original list item to be updated after the end of the region
  - C/C++: For class types, a copy assignment operator is invoked to perform the operation, the order is unspecified again
Scoping variables of class-type

• Conclusion for *firstprivate* and *lastprivate*:
  • Each thread has its own instance of the object, a copy constructor is called for initialization with *firstprivate*, a copy assignment operator is called to save the value back with *lastprivate*
  • The functions have to be declared conforming and accessible

• What about *threadprivate* variables:
  #pragma omp threadprivate(o)
• OpenMP specification:
  • *Threadprivate directive*: ... specifies that named global-lifetime objects are replicated, each thread has its own copy
• Conclusion for *threadprivate*:
  • The constructor is called sometime before the first access to the object, the destructor is called sometime after the last access to the object
Scoping variables of class-type

- Last but not least: `threadprivate + copyin`, OpenMP specification:
  - The copy assignment operator is invoked

- Now, do the compilers behave as explained?
  - All compilers do fine for `shared`
  - Most compilers do fine for `private, firstprivate, lastprivate`
    - Some fail: objects are neither constructed nor initialized
  - The tested compilers differ in how they handle `threadprivate and threadprivate with copyin/copyprivate`
    - Objects are not initialized
    - Objects are not destructed

- Proposed workaround:
  - Use private pointers instead of object types, construct and destruct objects using these pointers inside the parallel region
OpenMP and classes

- What is missing in the OpenMP specification:
  - Privatization of (static) class member variables is not possible

- What is bothering in the OpenMP specification:
  - Loop index variables must be of signed integer type, therefore `size_t` is not allowed (depending on the compiler no error is thrown, but parallel region is serialized)

- What you have to care about:
  - If an exception is thrown inside a parallel region, it must be caught inside that parallel region, otherwise the behavior is undefined
  - Using pointers you can get access to everything – but that is not allowed by the OpenMP specification and therefore the behavior is undefined
Parallelization of non-conforming loops

- Parallelization of non-conforming loops:
  - Pointer arithmetic
  - Loops using STL iterators

- Simple example:
  ```
  for (it = list1.begin(); it != list1.end(); it++) {
      it->compute();
  }
  ```

- We will now consider three possible solutions …
Parallelization of non-conforming loops

- Construction of a parallelizable loop:

```cpp
long l = 0, lSize = 0;
for (it = list1.begin(); it != list1.end(); it++)
    lSize++;
valarray<CComputeItem*> items(lSize);
for (it = list1.begin(); it != list1.end(); it++) {
    items[l] = &(*it); l++;
}
#pragma omp parallel for default(shared)
for (long l = 0; l < lSize; l++) {
    items[l]->compute();
}
```
Parallelization of non-conforming loops

• Intel's Taskqueuing

```c++
#pragma intel omp parallel taskq
{
    for (it = list2.begin(); it != list2.end(); it++) {
        #pragma intel omp task
        {
            it->compute();
        }
    // end for
    } // end omp parallel
```

• A similar concept will be available in OpenMP 3.0!
Parallelization of non-conforming loops

- **single-nowait trick:**

```cpp
#pragma omp parallel private(it)
{
    for (it = list3.begin(); it != list3.end(); it++) {
        #pragma omp single nowait
        {
            it->compute();
        }
    } // end for
} // end omp parallel
```

- Performance of these three techniques
  - depends on the number of loop iterations
  - depends on the amount of work in the loop body
  - depends on the compiler

- Construction of parallelizable loop should be preferred at the moment
Parallelization of oo-codes

- Parallelization of High-Level C++ codes:
  - Internal parallelization
  - External parallelization
  - Thread-safety (next section)
- Internal parallelization: complete parallel region inside member functions
  - Main pro argument: no change to the interface
  - Main contra argument: parallel region can not span multice member functions, overhead can not be reduced by enlarging the region
- External parallelization: orphaned OpenMP directives inside member functions
  - Main pro argument: parallel region can be enlarged
  - Main contra argument: interface is changed implicitly
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• OpenMP and object-oriented programming

• Thread Safety and the STL

• OpenMP and C++ libraries

• Conclusion
Thread-Safety

- A function is *reentrant*, if
  - it only uses variables from the stack
  - it only depends on its actual arguments
  - and all its callees fulfill these claims

- A code is *thread-safe*, if it behaves *correct* when run with or called by multiple threads

- Current STL implementations claim to be thread-safe, but what does that mean? Examination of:
  - Sun C++ libCstd
  - Sun C++ stlport4
  - GNU C++ STL since gcc 3.4
  - Intel C++ since 8.1 (partly building on gcc‘s STL)
Thread-Safety

- Two scenarios:
  - Multiple threads accessing one instance of an STL datatype
  - Multiple threads accessing multiples instances of an STL datatype, but not more than one thread access one instance
- As all STL provided functions and operations are reentrant, one can draw the conclusion that:
  - Only read access: safe
  - Multiple threads accessing distinct instances: safe
  - Multiple threads accessing on instance, at least one thread writes: potential race condition. Application is required to implement locking
  - With respect to the universe of different application scenarios, this behavior is probably optimal.
- Sun's libCstd und stlport4 contain some allocators with static data (access secured by internal locking)
Agenda

• OpenMP and object-oriented programming

• Thread Safety

• OpenMP and C++ libraries
  • STL: std::valarray and ccNUMA architectures

• Conclusion
std::valarray and NUMA architectures

- Some datatypes are not suited for NUMA architectures because of properties not visible at first sight
- Example: STL datatype std::valarray, elements are guaranteed to be initialized with zero
- Initialization (first time touching the data) leads to physical memory distribution – or no “distribution“ on NUMA architectures

- Two approaches for optimization:
  - Employment of operating system features (Sun Solaris)
  - Employment of C++ language constructs with OpenMP

- Solaris feature madvise with MADV_ACCESS_LWP advice:
  
  ```c
  int madvise(caddr_t addr, size_t len, int advice)
  ```

- Problem: portability
std::valarray and NUMA architectures

- Usage of C++ language features and OpenMP: first-touch initialization of datatypes with same access pattern as in computation

- Three choices:
  - Modification of std::valarray: zero-initialization is done by internal methods which can be modified easily
    - Pro: good performance, low effort
    - Con: solution not portable between compilers and platforms
  - Usage of other datatype (e.g. std::vector) which allows for using a custom allocator which can initialize the memory in a distributed fashion
    - Pro: good performance, portable
    - Con: one-time effort for allocator-implementation
  - Usage of other datatype without initialization (e.g. TNTs Array1D)
    - Con: multiple modifications in the program code
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Conclusion

• One can combine high level abstractions and performance! (not discussed today)

• The combination of OpenMP and C++ works, but the *portability of performance* depends on
  • Platform
  • Operating System
  • Compiler

• There are deficiencies in the current OpenMP specification regarding C++, but they will hopefully be addressed in 3.0.

• The C++ language and programming style might arise special problems – but it also might offer “elegant” solutions.
End

Thank you for your attention.

Questions?
Designing data types

• Can C++ abstraction features be implemented efficiently?

```cpp
la_vector<double> s(_dimension), r(_dimension), ...;
la_matrix_crs<double> A(_rows, _cols, _vals);

while (iter < max_iter && sqrt(sigma) > tol)
{
    p = r + p * beta;    q = s + beta * q;
    x = x + alpha * p;   r = r - q * alpha;

    s = A * r;

    [...]  
}
```

• Yes, if done the right way
  • Avoid temporaries and repeated initializations
Designing data types

- Some advises to achieve high performance with C++:
  - Pass by reference: always try to pass arguments by reference rather than by value:

    ```cpp
    template<class T> la_vector<T> operator*(la_matrix_crs<T> & lhs,
                                             la_vector<T> & rhs)
    {
        // throw exception, if dimensions do not fit
        // efficient implementation of the actual operation
        // ...
    }
    
    // Together with
    la_vector<T> & la_vector::operator=(la_vector<T> & rhs)
    {
        ...     
    }
    
    the sparse matrix vector multiplication $s = A \times r$ does not introduce any overhead over the „plain C“ implementation
Designing data types

- Wherever possible initialize variables just once, e.g. at the declaration or by initialization lists:

```cpp
la_vector(size_t stDimension):
    m_stDimension(stDimension), m_vaData((T)0, stDimension)
{
    ...
}
```

- Make local functions `static`, declare small functions inline:

```cpp
inline const size_t getDimension() const {
    ...
}
```

- If there is something `const`, tell the compiler

- Wherever possible, use nameless objects:

```cpp
foo(TMyClass("abc"));
```

    is faster than

```cpp
TMyClass x("abc");
foo(x);
```

    because parameter and object share memory