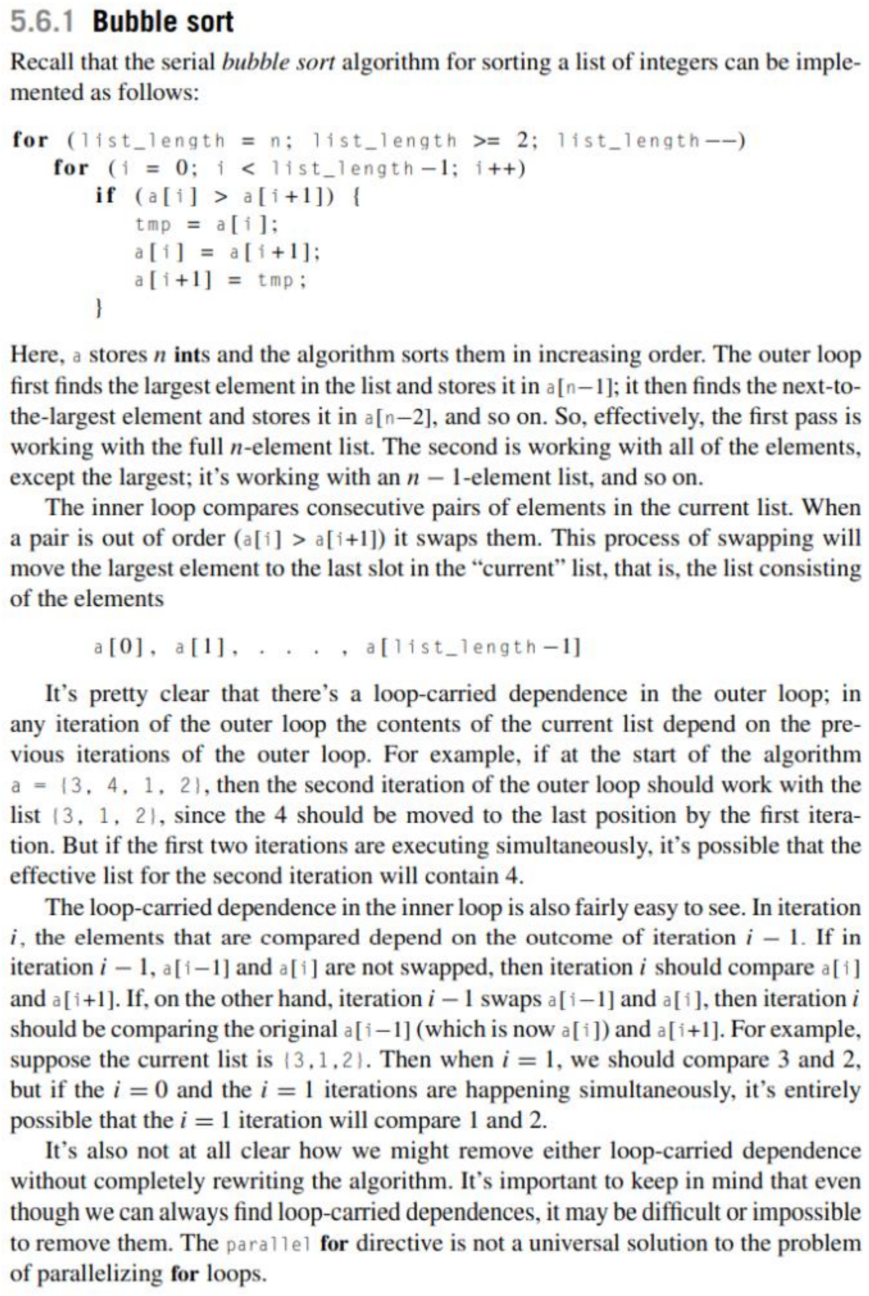
More about loops in OpenMP: sorting

Sometimes it is hard or impossible to find a solution to loop carried dependence problems in algs:
Bubble Sort example



5.6.1 Bubble sort

Recall that the serial *bubble sort* algorithm for sorting a list of integers can be implemented as follows:

```
for (list_length = n; list_length >= 2; list_length--)
   for (i = 0; i < list_length-1; i++)
      if (a[i] > a[i+1]) {
         tmp = a[i];
         a[i] = a[i+1];
         a[i+1] = tmp;
      }
```

Here, a stores n **int**s and the algorithm sorts them in increasing order. The outer loop first finds the largest element in the list and stores it in a[n−1]; it then finds the next-to-the-largest element and stores it in a[n−2], and so on. So, effectively, the first pass is working with the full n-element list. The second is working with all of the elements, except the largest; it's working with an $n-1$-element list, and so on.

The inner loop compares consecutive pairs of elements in the current list. When a pair is out of order (a[i] > a[i+1]) it swaps them. This process of swapping will move the largest element to the last slot in the "current" list, that is, the list consisting of the elements

```
a[0], a[1], . . . , a[list_length-1]
```

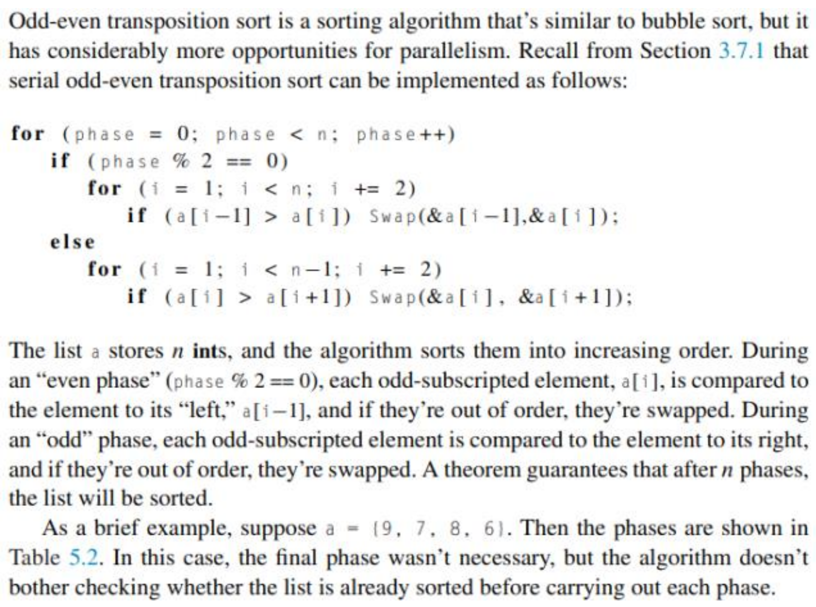
It's pretty clear that there's a loop-carried dependence in the outer loop; in any iteration of the outer loop the contents of the current list depend on the previous iterations of the outer loop. For example, if at the start of the algorithm a = {3, 4, 1, 2}, then the second iteration of the outer loop should work with the list {3, 1, 2}, since the 4 should be moved to the last position by the first iteration. But if the first two iterations are executing simultaneously, it's possible that the effective list for the second iteration will contain 4.

The loop-carried dependence in the inner loop is also fairly easy to see. In iteration i, the elements that are compared depend on the outcome of iteration $i-1$. If in iteration $i-1$, a[i−1] and a[i] are not swapped, then iteration i should compare a[i] and a[i+1]. If, on the other hand, iteration $i-1$ swaps a[i−1] and a[i], then iteration i should be comparing the original a[i−1] (which is now a[i]) and a[i+1]. For example, suppose the current list is {3,1,2}. Then when $i=1$, we should compare 3 and 2, but if the $i=0$ and the $i=1$ iterations are happening simultaneously, it's entirely possible that the $i=1$ iteration will compare 1 and 2.

It's also not at all clear how we might remove either loop-carried dependence without completely rewriting the algorithm. It's important to keep in mind that even though we can always find loop-carried dependences, it may be difficult or impossible to remove them. The parallel **for** directive is not a universal solution to the problem of parallelizing **for** loops.

- The parallel for directive is not a universal solution to the problem of parallelizing for loops

Odd even transportation sort example:
- Summary of how the alg works:



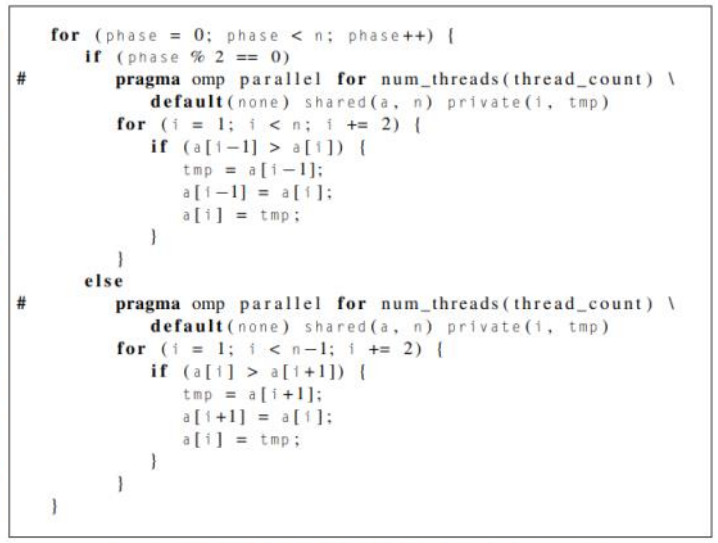
Odd-even transposition sort is a sorting algorithm that's similar to bubble sort, but it has considerably more opportunities for parallelism. Recall from Section 3.7.1 that serial odd-even transposition sort can be implemented as follows:

```
for (phase = 0; phase < n; phase++)
   if (phase % 2 == 0)
      for (i = 1; i < n; i += 2)
         if (a[i-1] > a[i]) Swap(&a[i-1],&a[i]);
   else
      for (i = 1; i < n-1; i += 2)
         if (a[i] > a[i+1]) Swap(&a[i], &a[i+1]);
```

The list a stores *n* **ints**, and the algorithm sorts them into increasing order. During an "even phase" (phase % 2 == 0), each odd-subscripted element, a[i], is compared to the element to its "left," a[i-1], and if they're out of order, they're swapped. During an "odd" phase, each odd-subscripted element is compared to the element to its right, and if they're out of order, they're swapped. A theorem guarantees that after *n* phases, the list will be sorted.

As a brief example, suppose a = {9, 7, 8, 6}. Then the phases are shown in Table 5.2. In this case, the final phase wasn't necessary, but the algorithm doesn't bother checking whether the list is already sorted before carrying out each phase.

- Where is there an loop carried dependence in this alg?
    - It's not hard to see that the outer loop has a loop-carried dependence. As an example, suppose as before that a = {9, 7, 8, 6}. Then in phase 0 the inner loop will compare elements in the pairs (9, 7) and (8, 6), and both pairs are swapped. So for phase 1, the list should be {7, 9, 6, 8}, and during phase 1 the elements in the pair (9, 6) should be compared and swapped. However, if phase 0 and phase 1 are executed simultaneously, the pair that's checked in phase 1 might be (7, 8), which is in order. Furthermore, it's not clear how one might eliminate this loop-carried dependence, so it would appear that parallelizing the outer for loop isn't an option.
- The inner for loops, however, don't appear to have any loop-carried dependences. For example, in an even phase loop variable i will be odd, so for two distinct values of i, say i = j and i = k, the pairs {j —1, j } and {k — 1, k} will be disjoint.
    - The comparison and possible swaps of the pairs (a[j—1], a[j]) and (a[k—1], a[k]) can therefore proceed simultaneously.
    - Our alg for even odd sort can now look like this:

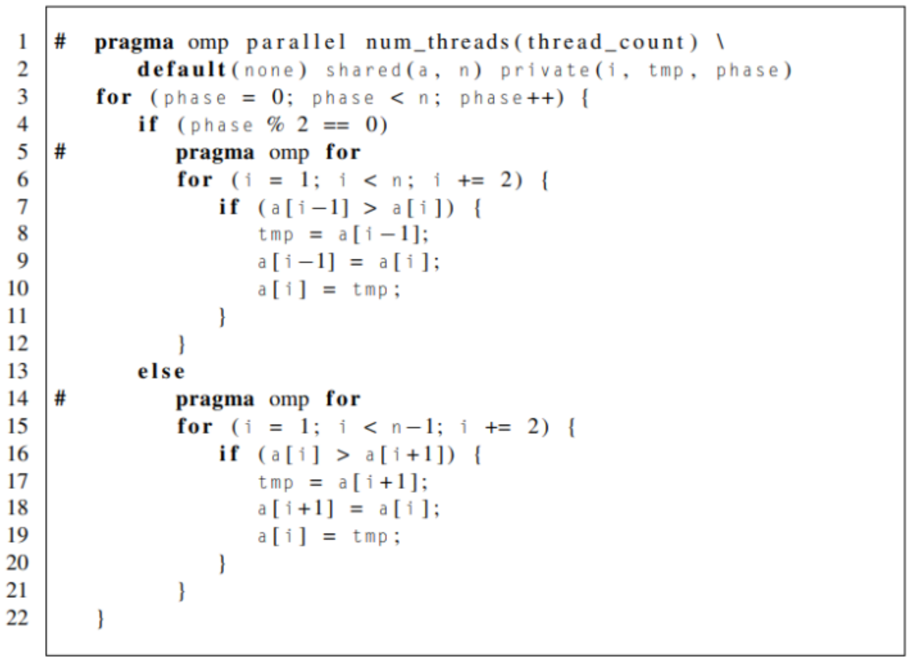


```
for (phase = 0; phase < n; phase++) {
   if (phase % 2 == 0)
#     pragma omp parallel for num_threads(thread_count) \
         default(none) shared(a, n) private(i, tmp)
      for (i = 1; i < n; i += 2) {
         if (a[i-1] > a[i]) {
            tmp = a[i-1];
            a[i-1] = a[i];
            a[i] = tmp;
         }
      }
   else
#     pragma omp parallel for num_threads(thread_count) \
         default(none) shared(a, n) private(i, tmp)
      for (i = 1; i < n-1; i += 2) {
         if (a[i] > a[i+1]) {
            tmp = a[i+1];
            a[i+1] = a[i];
            a[i] = tmp;
         }
      }
}
```

Program 5.4: First OpenMP implementation of odd-even sort.

    - There are some issues we must handle as well with this implementation
        - First, although any iteration of, say, one even phase doesn't depend on any other iteration of that phase, we've already noted that this is not the case for iterations in phase p and phase p + 1.
            - We need to be sure that all the threads have finished phase p before any thread starts phase p + 1.

    - However, like the parallel directive, the parallel for directive has an implicit barrier at the end of the loop, so none of the threads will proceed to the next phase, phase p +1, until all of the threads have completed the current phase, phase p
        - openMP handles this for us
- A second potential problem is the overhead associated with forking and joining the threads.
    - In this implementation we would be asking for threads to be built for us each time for each phase which is too costly, can we do better?
    - Each time we execute one of the inner loops, we use the same number of threads, so it would seem to be superior to fork the threads once and reuse the same team of threads for each execution of the inner loops.
    - Not surprisingly, OpenMP provides directives that allow us to do just this. We can fork our team of thread_count threads before the outer loop with a parallel directive.
        - Then, rather than forking a new team of threads with each execution of one of the inner loops, we use a for directive, which tells OpenMP to parallelize the for loop with the existing team of threads.
            - Note that the parallel for directive is different from the "solo" for directive
        - First we use the parrallel directive to initiate the threads and other stuff and then right before each for loop we call on the for directive
        - Our new odd even sort alg would look like this:



```
#   pragma omp parallel num_threads(thread_count) \
       default(none) shared(a, n) private(i, tmp, phase)
    for (phase = 0; phase < n; phase++) {
       if (phase % 2 == 0)
#         pragma omp for
          for (i = 1; i < n; i += 2) {
             if (a[i-1] > a[i]) {
                tmp = a[i-1];
                a[i-1] = a[i];
                a[i] = tmp;
             }
          }
       else
#         pragma omp for
          for (i = 1; i < n-1; i += 2) {
             if (a[i] > a[i+1]) {
                tmp = a[i+1];
                a[i+1] = a[i];
                a[i] = tmp;
             }
          }
    }
```

Program 5.5: Second OpenMP implementation of odd-even sort.

        - The for directive, unlike the parallel for directive, doesn't fork any threads. It uses whatever threads have already been forked in the enclosing parallel block.
        - When we're using two or more threads, the version that uses two for directives is at least 17% faster than the version that uses two parallel for directives, so for this system the slight effort involved in making the change is well worth it.