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Characterizing the Performance of Task Reductions in OpenMP 5.X Implementations

Jan Ciesko, Stephen Olivier

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UT, Chattanooga, Tennessee,

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Agenda

- Reductions in OpenMP
- Implementations in LLVM/Clang and GCC
- Benchmarks
- Evaluation
- Conclusion

Reductions in OpenMP

- OpenMP supports reductions since V1.0
- Tasking since V3.0 in 2008
- Demand for task-parallel reductions
- I started working on this in 2013
- Presented to OMP LC in 2015.
- Proposal made it into the spec in 2018 (OpenMP 5.0)
- Task reductions are conceptually concurrent and are orthogonal to the depend clause
- Compiler support evaluation is important for performance portability
  - How well did we do in the spec?
  - Did implementers implement the spec?

OpenMP C and C++ Application Program Interface

Version 1.0 – October 1998

2.3 `parallel` Construct

The following directive defines a *parallel region*, which is a region of the program that is to be executed by multiple threads in parallel. This is the fundamental construct that starts parallel execution.

```
#pragma omp parallel [clause[ clause] ...] new-line
        structured-block
```

The *clause* is one of the following:

`if(`*scalar-expression*`)`

`private(`*list*`)`

`firstprivate(`*list*`)`

`default(shared | none)`

`shared(`*list*`)`

`copyin(`*list*`)`

`reduction(`*operator*`:` *list*`)`

Reductions in OpenMP

- Task reductions allow reductions computed by arbitrary task graphs
- Challenge: definition of participating tasks and of the scope of the reduction computations
- Clauses for task reductions:

Clause	Semantic	Description
reduction(task, op: var)	Scoping, Participation	Scopes a task reduction for a **parallel or work-sharing region***.
reduction(op: var)	Scoping, Participation	Scopes a task reduction for a **taskloop** region and makes created tasks participants.
task_reduction(op: var)	Scoping	Scopes a task reduction for a **taskgroup** region.
in_reduction(op: var)	Participation	Denotes participation of a **task**, **target task**, or **taskloop** in a task reduction.

- ‘task’ reduction modifier on construct only for ‘parallel’, ‘for’, ‘sections’ or ‘scope

Rule of Thumb:

1. Participating tasks must have a enclosing scope that defines a task reduction
2. The reduction computation completes by the time the scope ends

Implementations in GCC and LLVM/Clang

- Privatization and data reuse

```
void func(int &sum) {
#pragma omp taskgroup task_reduction(+ : sum)
#pragma omp task in_reduction(+ : sum)
     sum++;
}
```

gcc -fopenmp -c task.c -fdump-tree-optimized -o task.o.gcc

```
void func (int & sum) {
  struct .omp_data_s.0 .omp_data_o.1;
  ...
  .omp_data_o.1.sum = sum_2(D);
  __builtin_GOMP_task (_Z4funcRi._omp_fn.0, &.omp_data_o.1, 0B, 8, 8, 1,
     0, 0B, 0, 0B);
  return;
}

void _Z4funcRi._omp_fn.0 (struct .omp_data_s.0 & restrict .omp_data_i) {
  ...
  void * D.2516[1];    // new double pointer
  _3 = .omp_data_i_2(D)->sum; // reference to original reduction storage location
  D.2516[0] = _3;
  __builtin_GOMP_task_reduction_remap (1, 0, &D.2516);   // redirect
  sum_6 = D.2516[0]; // dereference
  _10 = *sum_6;
  _11 = _10 + 1;   // use
  *sum_6 = _11;
  return;
}
```

clang -Xclang -S -emit-llvm -Xpreprocessor -fopenmp -c task.c -o task.o.s.llvm (not shown)

*GCC Version 13, 20220518

Benchmarks

Applications*

- Fibonacci
- Powerset
- Powerset-UDR
- Dot-product

6 implementations each:

- Parallel task-reduction
- Taskloop reduction
- Taskgroup reduction
- Manual per-thread data privatization
- Atomics
- Stack

README.md

OMP Task Bench (OMP-TB)

OMP-TB is a collection of benchmarks to measure tasking performance and tasking-related features in OpenMP. Currently it includes benchmark as listed below. Benchmarks in the `reductions` sub-directory target task-parallel reduction support. In general, such benchmarks are useful to evaluate compiler language support as well as its efficient implementation.

OMP-TB Benchmarks

- reductions/dot (Dot Product)
- reductions/fib (Fibonacci)
- reductions/powerset (Powerset Permutations)
- reductions/powerset-final (Powerset Permutations using the final OpenMP clause)
- reductions/powerset-UDR (Powerset Permutations using user-defined reductions)
- reductions/others/array_sum (Array Sum)
- reductions/others/knapsack (Knapsack)
- reductions/others/knightstour (Knights Tour)
- reductions/others/max_height_tree (Max Height)
- reductions/others/nbinarywords (n-Permutations)
- reductions/others/nqueens (N-Queens)
- reductions/others/TSP (Travelling Salesman Problem)

[1] https://github.com/sandialabs/openmp_task_bench

* OMP-TB [1] contains further examples

Implementation: Fibonacci

- Parallel task reduction using manual cut-off

In results: “parallel-red”

main

```
...
#pragma omp parallel reduction(task, + : sum) \
                       num_threads(conf.num_threads)
#pragma omp single
#pragma omp task firstprivate(n) in_reduction(+ : sum)
    fib(n, sum);
```

task

```
void fib(int n, int &sum) {
  if (n < 2)
    sum += n;
  else {
    if (n < cut_off) {
      fib(n - 1, sum);
      fib(n - 2, sum);
    } else {
#pragma omp task firstprivate(n) in_reduction(+ : sum)
      fib(n - 1, sum);

#pragma omp task firstprivate(n) in_reduction(+ : sum)
      fib(n - 2, sum);
    }
  }
}
```

Note: we avoided the use of final

Implementation: Fibonacci

- Taskgroup reductions using manual cut-off

In results: “taskgroup-red”

```
...
#pragma omp parallel shared(n, sum) num_threads(conf.num_threads)
#pragma omp single
#pragma omp taskgroup task_reduction(+ : sum)
#pragma omp task firstprivate(n) in_reduction(+ : sum)
  fib(n, sum);
```

main

```
void fib(int n, int &sum) {
  if (n < 2)
    sum += n;
  else {
    if (n < cut_off) {
      fib(n - 1, sum);
      fib(n - 2, sum);
    } else {
#pragma omp task firstprivate(n) in_reduction(+ : sum)
      fib(n - 1, sum);

#pragma omp task firstprivate(n) in_reduction(+ : sum)
      fib(n - 2, sum);
    }
  }
}
```

task

Implementation: Fibonacci

- Using the stack and manual cut-off

In results: “stack”

```
int fib(int n) {
  int x, y;

  if (n < 2)
    return n;
  else {
    if (n < cut_off) {
      x = fib(n - 1);
      y = fib(n - 2);
    } else {
#pragma omp task shared(x) firstprivate(n)
      x = fib(n - 1);

#pragma omp task shared(y) firstprivate(n)
      y = fib(n - 2);

#pragma omp taskwait
    }
    return x + y;
  }
}
```

task

```
...
#pragma omp parallel shared(sum) num_threads(conf.num_threads)
#pragma omp single
#pragma omp task shared(sum) firstprivate(n)
    sum = fib(n);
```

main

Implementation: Fibonacci

- Using explicit threadprivate and manual cut-off

task

```c
#pragma omp threadprivate(mysum)
void fib(int n) {
  if (n < 2)
    mysum += n;
  else {
    if (n < cut_off) {
      fib(n - 1);
      fib(n - 2);
    } else {
#pragma omp task firstprivate(n)
      fib(n - 1);

#pragma omp task firstprivate(n)
      fib(n - 2);
    }
  }
}
```

In results: “threadpriv”

main

```c
...
#pragma omp parallel num_threads(conf.num_threads)
{
      mysum = 0;
#pragma omp single
#pragma omp task
      fib(n);
}

#pragma omp parallel num_threads(conf.num_threads)
{
#pragma omp single
      nthreads = omp_get_num_threads();
#pragma omp for reduction(+ : sum)
      for (int i = 0; i < nthreads; i++)
        sum += mysum;
}
```

Evaluation

System configuration:

- **LLVM/Clang 14.0 (release)**
- **GCC 13 (code version dated 20220518)**
- Intel® Xeon® Skylake Platinum 8160 Processor, dual-socket, 48 cores, (blake.sandia.gov)
- 192GB RAM
- Flags: -fopenmp, -Wall, -Wextra, -pedantic, -Werror, -O3.
- Env: OMP_PROC_BIND = close, OMP_PLACES = cores (one thread per core with incremental core IDs)

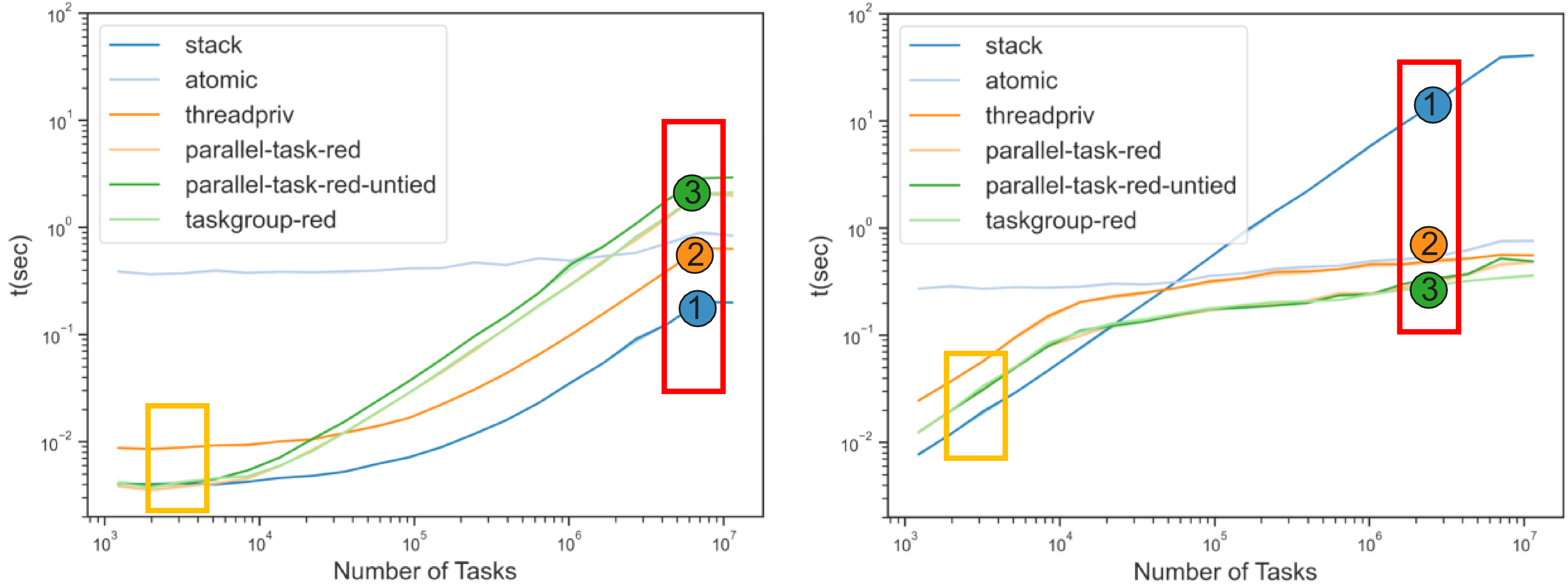
Methodology

- Each benchmark ran 5x, average time and standard deviation recorded
- Generate very large task counts to accumulate overheads
- Downside: tasking vs reduction overheads blend together

Evaluation: Fibonacci

1) Stack has lowest OH, OH with # tasks, has TW
2) TP has low OH but requires manual reduction
3) Comparable performance

- Time over number of tasks, N=33, 48 threads, variable cut-off, **1.2k – 11405k tasks**

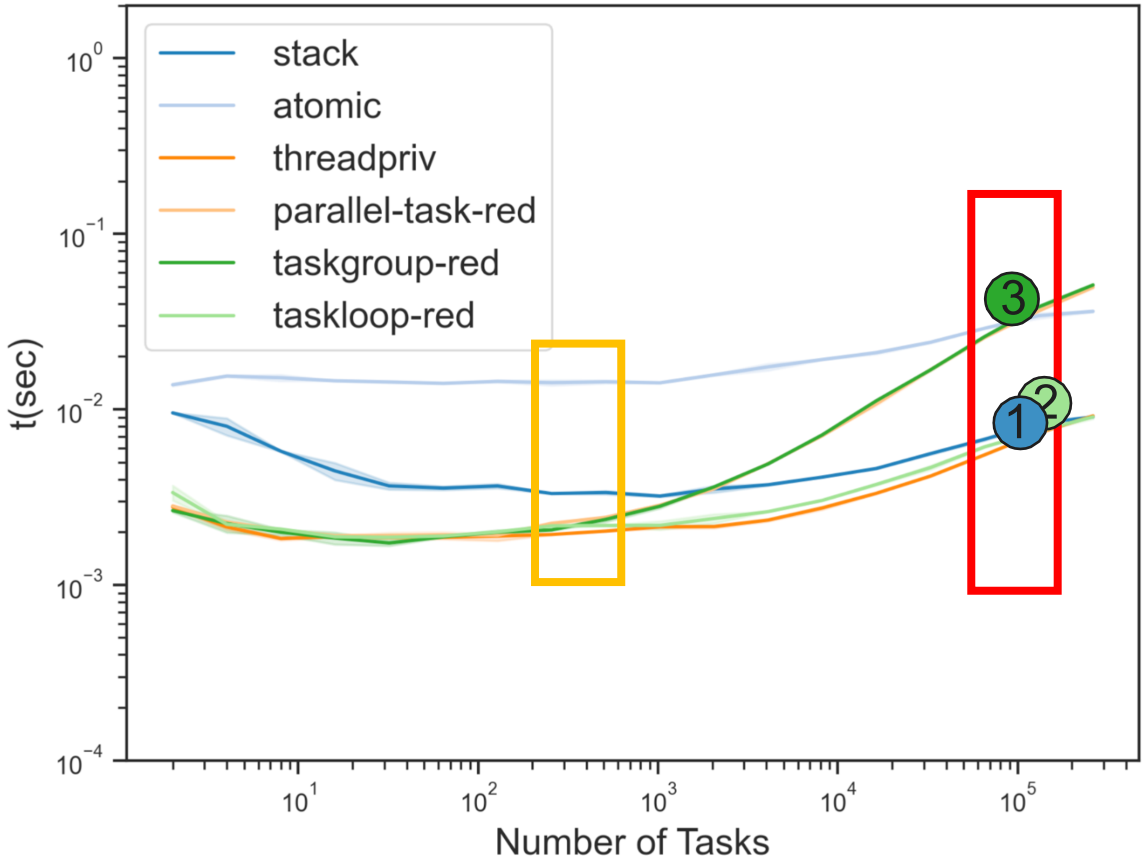


(a) LLVM/Clang (b) GCC/g++

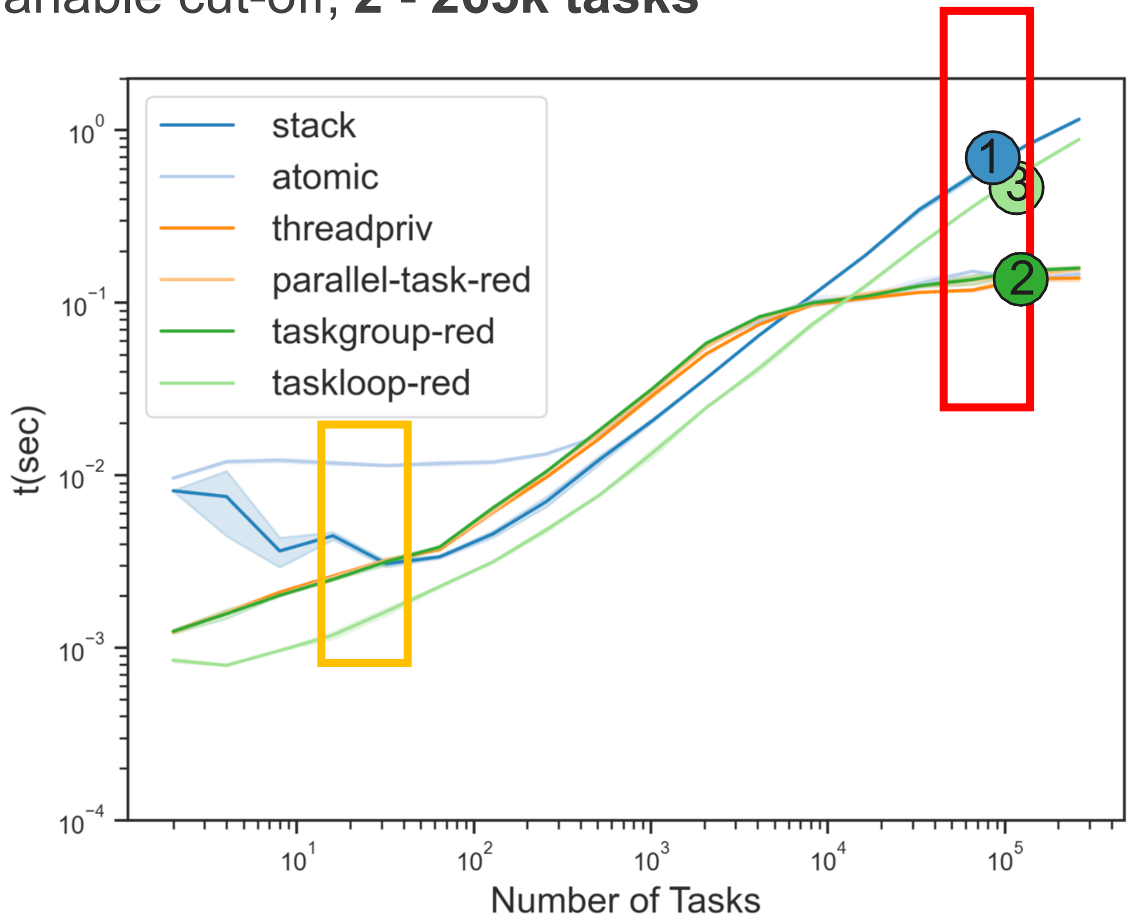
Evaluation: Powerset

1) Similar behavior of taskwait to Fib
2) Taskgroup and taskloop diverge (3), due to differences in reduction list item lookup and explicit task creation (taskloop)

- Time over number of tasks, N=18, 48 threads, variable cut-off, **2 - 265k tasks**



(a) LLVM/Clang

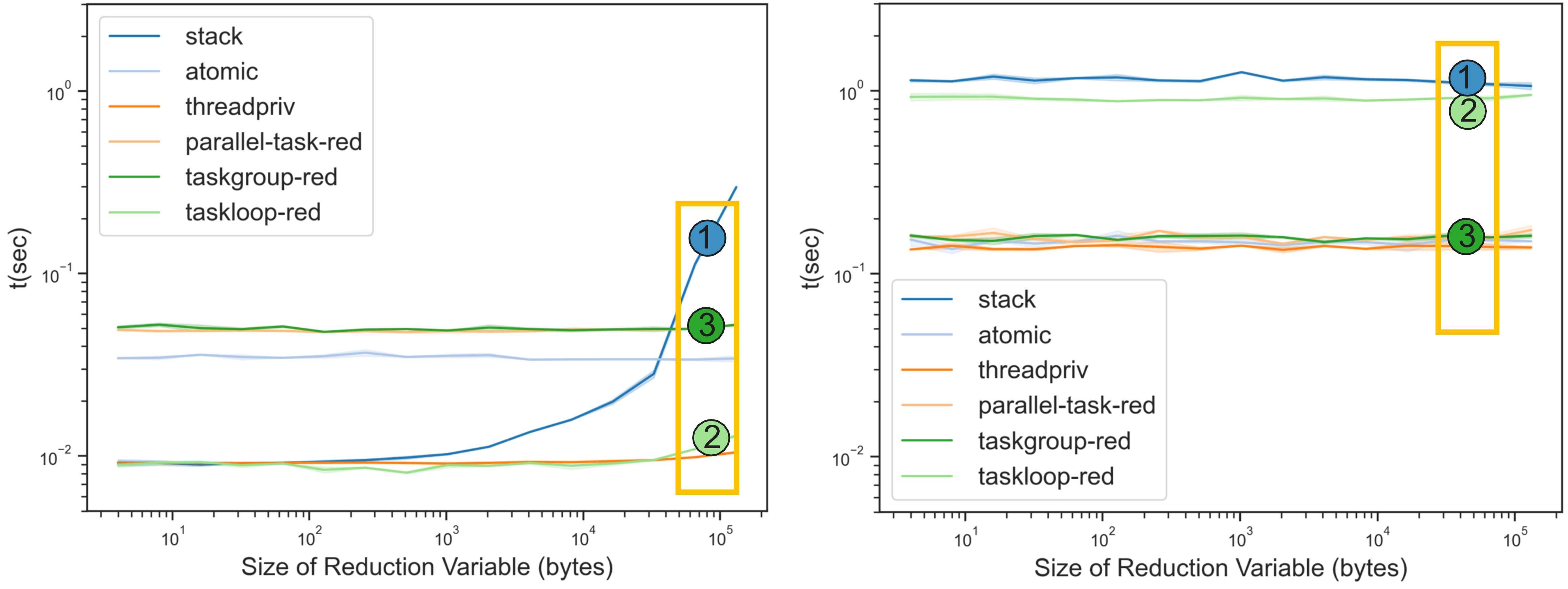


(b) GCC/g++

Evaluation: Powerset **UDR**

1) Stack accesses causing cache faults (LLVM)
2) Differences in reduction list item look-up and explicit task creation (taskloop)

- Time over reduction size (UDR), **4B – 131kB**, 48 threads, 262k tasks

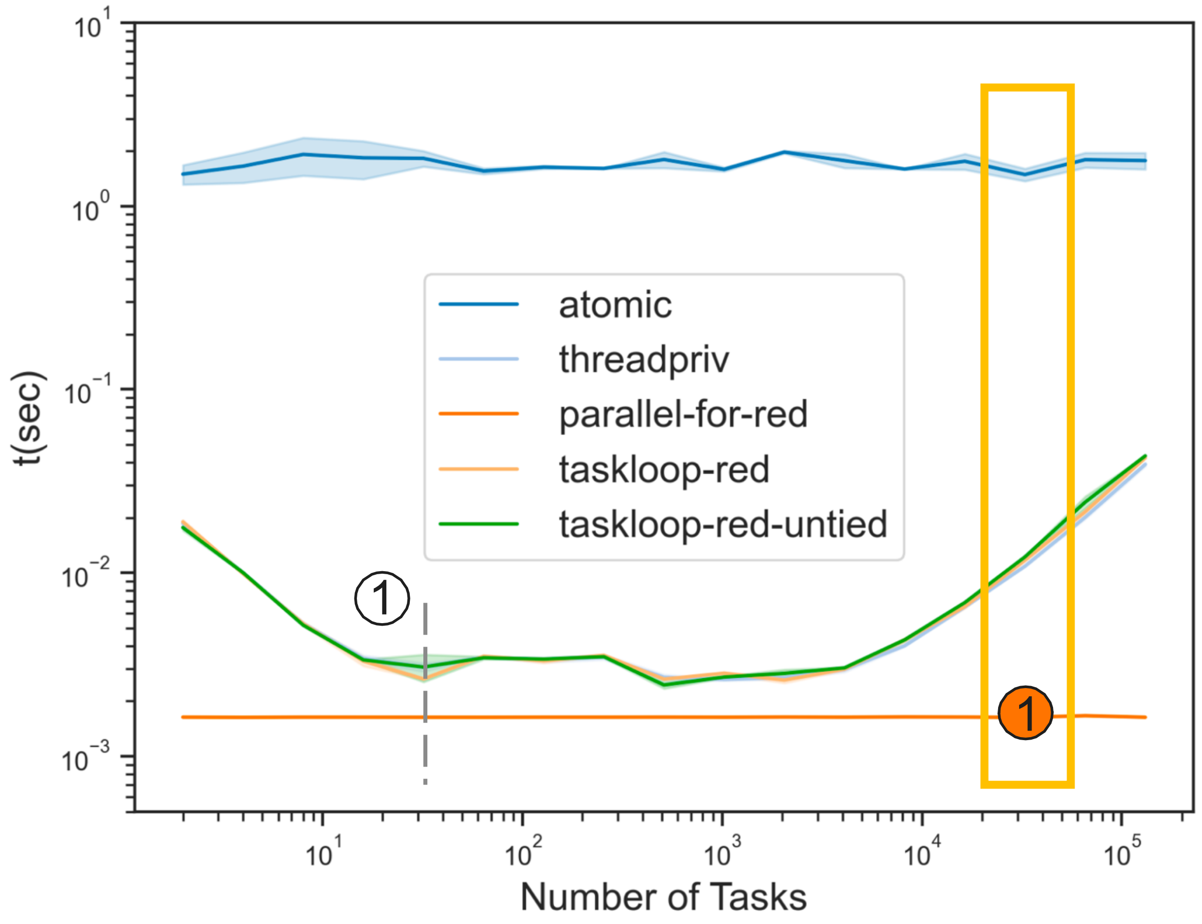


(a) LLVM/Clang (b) GCC/g++

Evaluation: Dot-product (not recursive)

1) Execution with work for 48 threads
2) Parallel for is invariant as it does not use tasks

- Time over number of tasks, N=2^{24}, 128MB, 48 threads, variable cut-off, **2 - 131k tasks**



Conclusion

- Both compilers support task-parallel reductions as in the spec
- Performance is comparable to manually implemented and optimized reductions
- For large task counts, tasking overheads dominate (incl. taskwait)
- We recommend the use of these constructs

Future work

- Evaluation of tasking implementations in LLVM/Clang and GCC

Links:

[1] https://github.com/sandialabs/openmp_task_bench