Parallel Sparse Tensor Decomposition in Chapel

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Outline

1. Motivation and Background
2. Porting SPLATT to Chapel
3. Performance Evaluation: Experiments, modifications and optimizations
4. Conclusions

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Motivation and Background

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1.) Motivation: Tensors + Chapel

- Why focus on Chapel for this work?
  - Tensor decompositions algorithms are complex and immature
    - Expressiveness and simplicity of Chapel would promote maintainable and extensible code
    - High performance is crucial as well

1.) Motivation: Tensors + Chapel

- Why focus on Chapel for this work?
  - Tensor decompositions algorithms are complex and immature
    - Expressiveness and simplicity of Chapel would promote maintainable and extensible code
    - High performance is crucial as well
  - Existing tensor tools are based on C/C++ and OpenMP+MPI
    - No implementations within Chapel (or similar framework)

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1.) Background: **Tensors**

- Tensors: Multidimensional arrays
  - Typically very large and sparse
    - Can have billions of non-zeros and densities on the order of 10^{-10}

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1.) Background: Tensors

- Tensors: Multidimensional arrays
  - Typically very large and sparse
    - Can have billions of non-zeros and densities on the order of 10^{-10}
- Tensor Decomposition:
  - Higher-order extension of matrix singular value decomposition (SVD)
  - CP-ALS: Alternating Least Squares
    - Critical routine: Matricized tensor times Khatri-Rao product (MTTKRP)

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1.) Background: SPLATT

- SPLATT: The Surprisingly ParalleL spArse Tensor Toolkit
  - Developed by University of Minnesota (Smith, Karypis)
  - Written in C with OpenMP+MPI hybrid parallelism
- Current state of the art in tensor decomp.
- We focus on SPLATT's the shared-memory (single locale) implementation of CP-ALS for this work
- Porting SPLATT to Chapel serves as a "stress test" for Chapel
  - File I/O, BLAS/LAPACK interface, custom data structures and non-trivial parallelized routines

Porting SPLATT to Chapel

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2.) Porting SPLATT to Chapel: Overview

- **Goal**: simplify SPLATT code when applicable but preserve original implementation and design
- Single-locale port
  - Multi-locale port left for future work
- Mostly a straightforward port
  - However, there were some cases that required extra effort to port: **mutex/locks**, work sharing constructs, jagged arrays

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2.) Porting SPLATT to Chapel:

Mutex Pool

- SPLATT uses a mutex pool for some of the parallel MTTKRP routines to synchronize access to matrix rows
- Chapel currently does not have a native lock/mutex module
  - Can recreate behavior with **sync** or **atomic** variables
  - We originally used **sync** variables, but later switched to **atomic** (see Performance Evaluation section).

```
proc set(pool : [] atomic bool, lockID : int) {
  while pool[lockID].testAndSet() {
    chpl_task_yield();
  }
}
proc unset(pool : [] atomic bool, lockID : int) {
  pool[lockID].clear();
}
```

Performance Evaluation

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4.) Performance Evaluation: **Set Up**

- Compare performance of Chapel port of original C/OpenMP code
- Default Chapel 1.16 build (Qthreads, jemalloc)
- OpenBLAS for BLAS/LAPACK
- Ensured both C and Chapel code utilize same # of threads for each trial
  - OMP_NUM_THREADS
  - CHPL_RT_NUM_THREADS_PER_LOCALE

4.) Performance Evaluation : Datasets

Name	Dimensions	Non-Zeros	Density	Size on Disk
YELP	**41k x 11k x 75k**	**8 million**	**1.97E-7**	**240 MB**
RATE-BEER	27k x 105k x 262k	62 million	8.3E-8	1.85 GB
BEER-ADVOCATE	31k x 61k x 182k	63 million	1.84E-7	1.88 GB
NELL-2	**12k x 9k x 29k**	**77 million**	**2.4E-5**	**2.3 GB**
NETFLIX	480k x 18k x 2k	100 million	5.4E-6	3 GB

See paper for more details on data sets

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4.) Performance Evaluation: Summary

- Profiled and analyzed Chapel code
  - Initial code exhibited very poor performance
- Identified 3 major bottlenecks
  - MTTKRP: up to **163x slower** than C code
  - Matrix inverse: up to **20x slower** than C code
  - Sorting (refer to paper for details)
- After modifications to initial code
  - Achieved competitive performance to C code

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4.) Performance Evaluation :

MTTKRP Optimizations: Matrix Row Accessing

```
double *mat = ...; // row-major 1D array
double *row = mat + (i*cols);
for(int j = 0; j < cols; j++) {
   row[j]...
}
```

Original C: number of cols is small (35) but number of rows is large (tensor dims)

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```

Original C: number of cols is small (35) but number of rows is large (tensor dims)

```
var mat [0..rows-1,0..cols-1] = ...;
ref row = mat[i,0..cols-1];
for j in 0..cols-1 {
   row[j]...
}
```

Initial Chapel: use slicing to get row reference → very slow since cost of slicing is not amortized by computation on each slice

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2D Index: use (i,j) index into original matrix instead of getting row reference → 17x speed up over initial MTTKRP code

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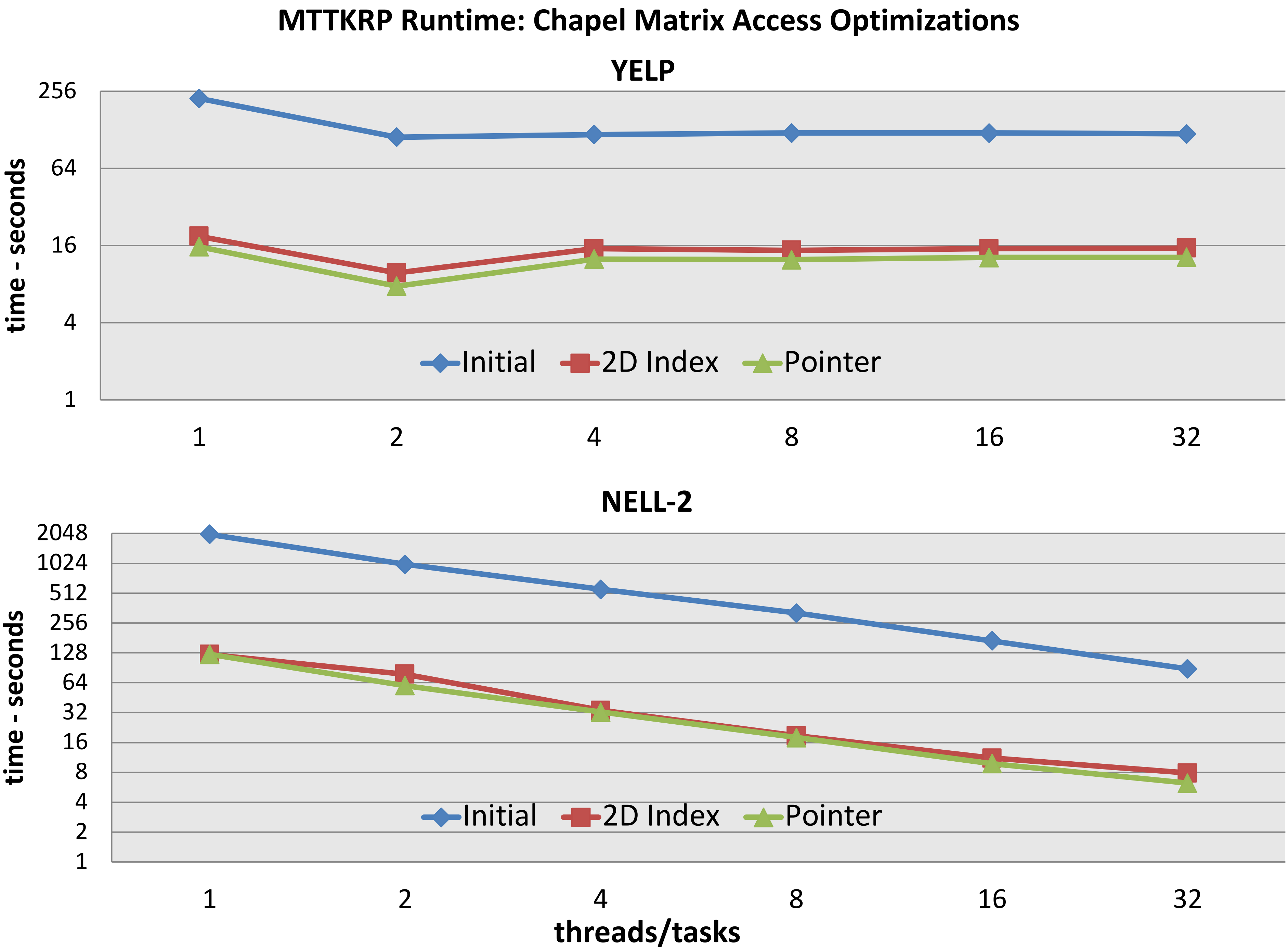
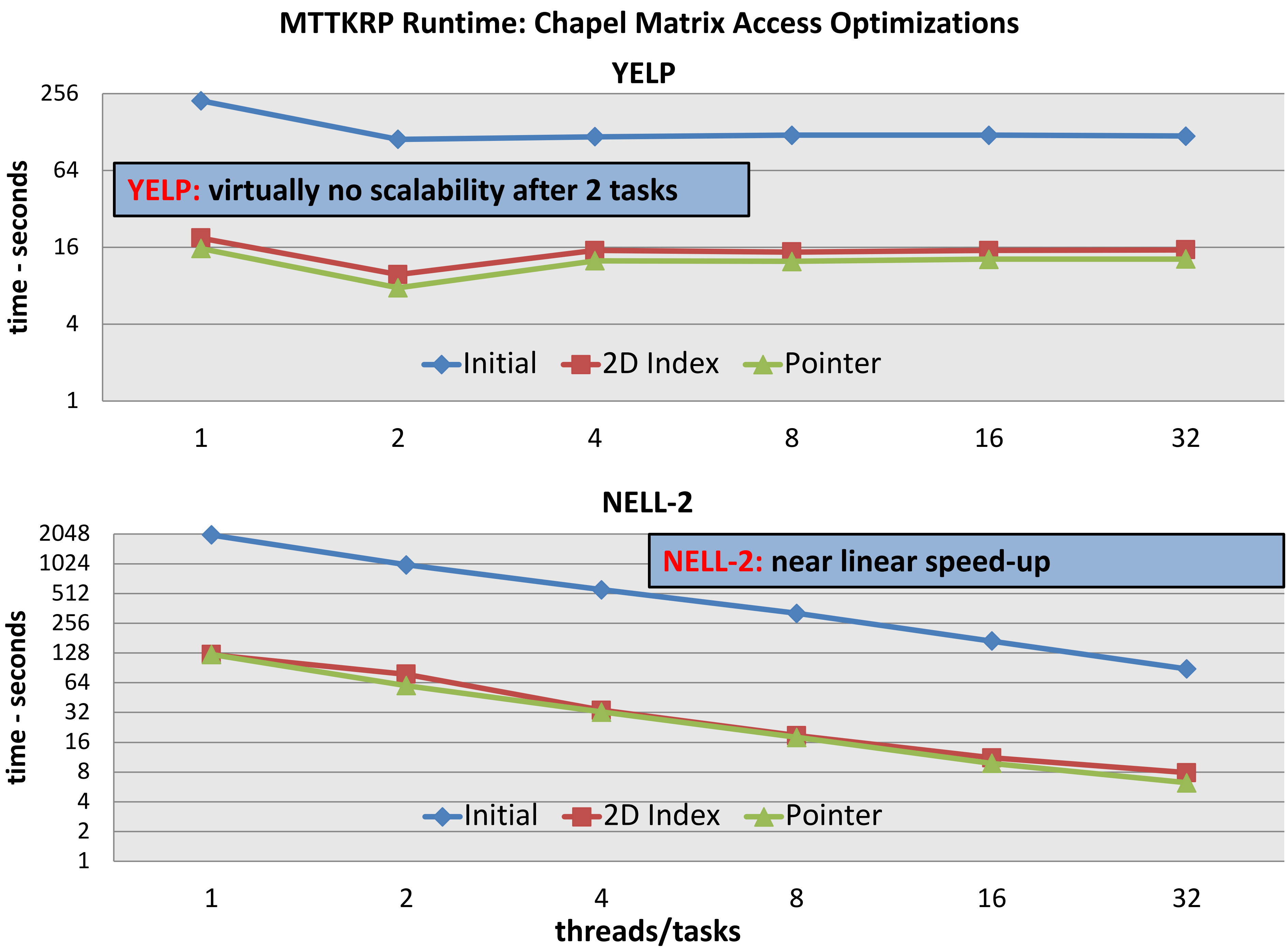
```

2D Index: use (i,j) index into original matrix instead of getting row reference → 17x speed up over initial MTTKRP code

```
var mat [0..rows-1,0..cols-1] = ...;
var matPtr = c_ptrTo(mat);
var row = matPtr + (i*cols);
for j in 0..cols-1 {
   row[j]...
}
```

Pointer: more direct C translation → 1.26x speed up over 2D indexing


MTTKRP Runtime: Chapel Matrix Access Optimizations
YELP
256
64
16
4
1
time - seconds
Initial
2D Index
Pointer
1
2
4
8
16
32
NELL-2
2048
1024
512
256
128
64
32
16
8
4
2
1
time - seconds
Initial
2D Index
Pointer
1
2
4
8
16
32
threads/tasks



MTTKRP Runtime: Chapel Matrix Access Optimizations
YELP
time - seconds
256
64
16
4
1
YELP: virtually no scalability after 2 tasks
Initial
2D Index
Pointer
1
2
4
8
16
32
NELL-2
NELL-2: near linear speed-up
2048
1024
512
256
128
64
32
16
8
4
2
1
Initial
2D Index
Pointer
threads/tasks

4.) Performance Evaluation :

MTTKRP Optimizations: **Mutex/Locks**

- YELP requires the use of locks during the MTTKRP and NELL-2 does not
  - Decision whether to use locks is highly dependent on tensor properties and number of threads used

4.) Performance Evaluation : MTTKRP Optimizations: Mutex/Locks

- YELP requires the use of locks during the MTTKRP and NELL-2 does not
  - Decision whether to use locks is highly dependent on tensor properties and number of threads used
- Initially used **sync** vars
  - MTTKRP critical regions are short and fast
    - Not well suited for how **sync** vars are implemented in Qthreads
  - Switched to **atomic** vars
    - Up to **14x** improvement on YELP

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- Initially used **sync** vars
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    - Not well suited for how **sync** vars are implemented in Qthreads
  - Switched to **atomic** vars
    - Up to **14x** improvement on YELP
- FIFO w/ **sync** vars competitive with Qthreads w/ **atomic** vars
  - Troubling: just recompiling the code can drastically alter performance

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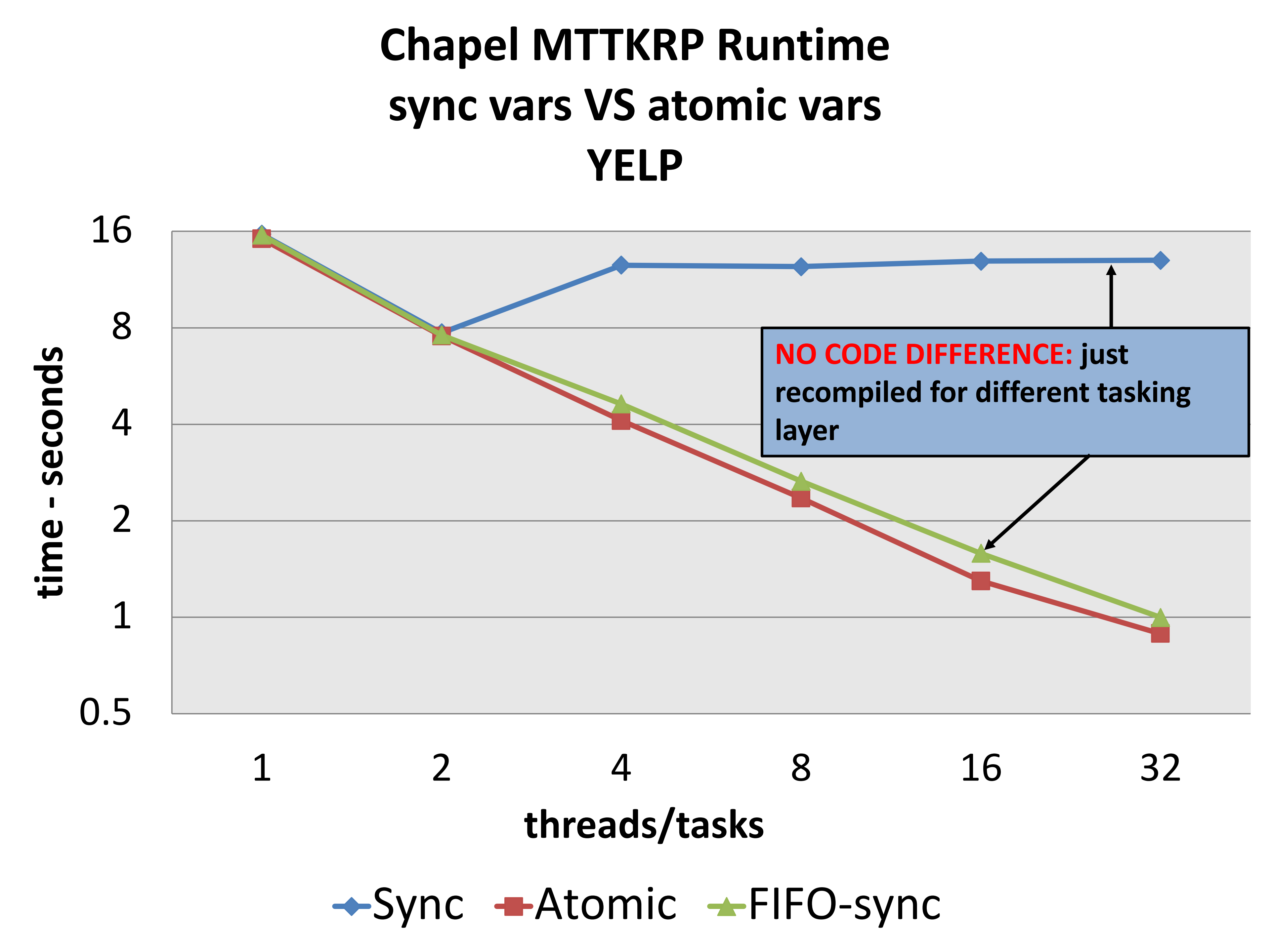

Chapel MTTKRP Runtime
sync vars VS atomic vars
YELP
16
8
4
2
1
0.5
time - seconds
1
2
4
8
16
32
threads/tasks
NO CODE DIFFERENCE: just recompiled for different tasking layer
Sync
Atomic
FIFO-sync

4.) Performance Evaluation :
Matrix Inverse (OpenBLAS/OpenMP)

- SPLATT uses LAPACK routines to compute matrix inverse
  - Experiments used OpenBLAS, parallelized via OpenMP

4.) Performance Evaluation : Matrix Inverse (OpenBLAS/OpenMP)

- SPLATT uses LAPACK routines to compute matrix inverse
  - Experiments used OpenBLAS, parallelized via OpenMP
- Observed **15x slow down** in matrix inverse runtime for Chapel when using 32 threads (OpenMP and Qthreads)
- **Issue:** interaction of Qthreads and OpenMP is messy

4.) Performance Evaluation :

Matrix Inverse (OpenBLAS/OpenMP) cont.

- **Problem:** OpenMP and Qthreads stomp over each other
- **Reason:** Default → Qthreads pinned to cores
  - OpenMP threads all end up on 1 core due to how Qthreads uses sched_setaffinity
- **Result**: Huge performance loss for OpenMP routine

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4.) Performance Evaluation :

Matrix Inverse (OpenBLAS/OpenMP) cont.

- **Try:** Explicitly bind OpenMP threads to cores
- **Result:** Chapel will fall back to only using 1 thread

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- **Reason:** Same as OpenMP in previous slide
  - Difference: Chapel detects this over subscription and will prevent it by only using 1 thread

4.) Performance Evaluation :

Matrix Inverse (OpenBLAS/OpenMP) cont.

- **Try:** Explicitly bind OpenMP threads to cores
- **Result:** Chapel will fall back to only using 1 thread
- **Reason:** Same as OpenMP in previous slide
  - Difference: Chapel detects this over subscription and will prevent it by only using 1 thread
- **Problem:** Not always clear to users
  - If CHPL_RT_NUM_THREADS_PER_LOCALE is set, then a warning is displayed about falling back to 1 thread
  - If not, users expect default (# threads == # cores) but only a single thread is used and **no warning given**

4.) Performance Evaluation :

Matrix Inverse (OpenBLAS/OpenMP) cont.

- **Attempted solutions:**
  - 1.) QT_AFFINITY=no, QT_SPINCOUNT=300
  - 2.) Remove Chapel over subscription warning/check and allow both Qthreads and OpenMP threads to bind to cores

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4.) Performance Evaluation :

Matrix Inverse (OpenBLAS/OpenMP) cont.

- **Attempted solutions:**
  - 1.) QT_AFFINITY=no, QT_SPINCOUNT=300
  - 2.) Remove Chapel over subscription warning/check and allow both Qthreads and OpenMP threads to bind to cores
- **Overall Results:**
  - (1) and (2) provided roughly equal improvement of OpenMP runtime but still **4x slower** than the C code

4.) Performance Evaluation :

Matrix Inverse (OpenBLAS/OpenMP) cont.

- **Another issue**:
  - Improving OpenMP runtime caused a **7 to 13x slow down** in a Chapel routine that followed
  - Still resource contention on cores

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4.) Performance Evaluation :

Matrix Inverse (OpenBLAS/OpenMP) cont.

- **Another issue**:
  - Improving OpenMP runtime caused a **7 to 13x slow down** in a Chapel routine that followed
  - Still resource contention on cores
- No clear solution to overcome issues
  - We set OMP_NUM_THREADS=1 for Chapel runs since OpenMP runtime is generally negligible

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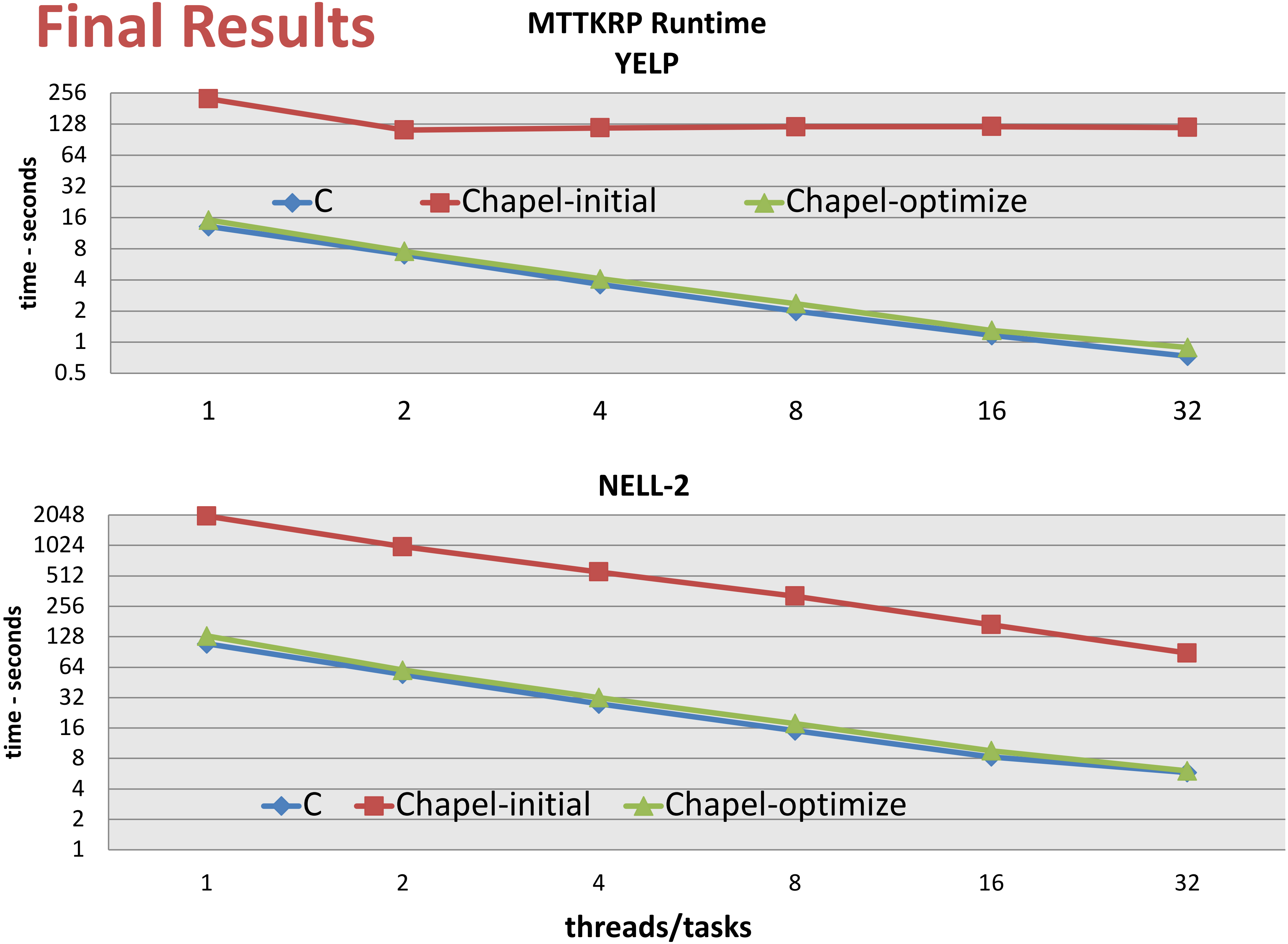
4.) Performance Evaluation :

Matrix Inverse (OpenBLAS/OpenMP) cont.

- **Another issue**:
  - Improving OpenMP runtime caused a **7 to 13x slow down** in a Chapel routine that followed
  - Still resource contention on cores
- No clear solution to overcome issues
  - We set OMP_NUM_THREADS=1 for Chapel runs since OpenMP runtime is generally negligible
- Brings up crucial question regarding library integration:
  - **When does it make sense to provide native Chapel implementations rather than integrate with existing libraries?**

Final Results



5.) Conclusions

- Implemented parallel sparse tensor decomposition in Chapel
- Identified bottlenecks in code
  - Array slicing
  - **sync** vs **atomic** variables for locks
  - Conflicts between OpenMP and Qthreads
- Achieved 83-96% of the original C/OpenMP performance after modifications to initial port
- Suggestions for Chapel:
  - Create a mutex/lock library
  - More documentation/experiments with integrating 3rd party code that utilize different threading libraries
- Future work:
  - Multi-locale version
  - Closer inspection of code to make it more Chapel-like
    - Will the performance suffer or improve?

Questions

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Back up Slides

Matricizing a Tensor

$$\mathbf{X}_1 = \begin{bmatrix} 1 & 4 & 7 & 10 \\ 2 & 5 & 8 & 11 \\ 3 & 6 & 9 & 12 \end{bmatrix}, \quad \mathbf{X}_2 = \begin{bmatrix} 13 & 16 & 19 & 22 \\ 14 & 17 & 20 & 23 \\ 15 & 18 & 21 & 24 \end{bmatrix}$$

$$\mathbf{X}_{(1)} = \begin{bmatrix} 1 & 4 & 7 & 10 & 13 & 16 & 19 & 22 \\ 2 & 5 & 8 & 11 & 14 & 17 & 20 & 23 \\ 3 & 6 & 9 & 12 & 15 & 18 & 21 & 24 \end{bmatrix},$$

$$\mathbf{X}_{(2)} = \begin{bmatrix} 1 & 2 & 3 & 13 & 14 & 15 \\ 4 & 5 & 6 & 16 & 17 & 18 \\ 7 & 8 & 9 & 19 & 20 & 21 \\ 10 & 11 & 12 & 22 & 23 & 24 \end{bmatrix},$$

$$\mathbf{X}_{(3)} = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 & \cdots & 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 & 17 & \cdots & 21 & 22 & 23 & 24 \end{bmatrix}$$

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Kronecker and Khatri-Rao Prodcuts

Kronecker Product

$$\mathbf{A} \otimes \mathbf{B} = \begin{bmatrix} a_{11}\mathbf{B} & a_{12}\mathbf{B} & \cdots & a_{1J}\mathbf{B} \\ a_{21}\mathbf{B} & a_{22}\mathbf{B} & \cdots & a_{2J}\mathbf{B} \\ \vdots & \vdots & \ddots & \vdots \\ a_{I1}\mathbf{B} & a_{I2}\mathbf{B} & \cdots & a_{IJ}\mathbf{B} \end{bmatrix}$$
$$= \begin{bmatrix} \mathbf{a}_1 \otimes \mathbf{b}_1 & \mathbf{a}_1 \otimes \mathbf{b}_2 & \mathbf{a}_1 \otimes \mathbf{b}_3 & \cdots & \mathbf{a}_J \otimes \mathbf{b}_{L-1} & \mathbf{a}_J \otimes \mathbf{b}_L \end{bmatrix}$$

Khatri-Rao Product

$$\mathbf{A} \odot \mathbf{B} = \begin{bmatrix} \mathbf{a}_1 \otimes \mathbf{b}_1 & \mathbf{a}_2 \otimes \mathbf{b}_2 & \cdots & \mathbf{a}_K \otimes \mathbf{b}_K \end{bmatrix}$$

4.) Performance Evaluation :

Sorting Optimizations

- Profiled customized sorting routine in Chapel code and found two bottlenecks:
  - Creation of small array in recursive routine
    - Created millions of times due to recursion and large tensors: consumed up to 10% of the sorting runtime
    - **Solution**: just declare local ints rather than an array (possible since this array was only of length 2)
  - Reassignment of array of arrays
    - C code: array of pointers → simple pointer assignment
    - Chapel code:
      - Initially 2D matrix → used slicing for reassignment (slow due to large size of slices)
      - Changed to array of arrays → whole array assignment (slow due to copying the arrays)
      - **Final**: get pointer to arrays and use pointer reassignment (similar to C code)
- Modifications resulted in roughly **4x** improvement

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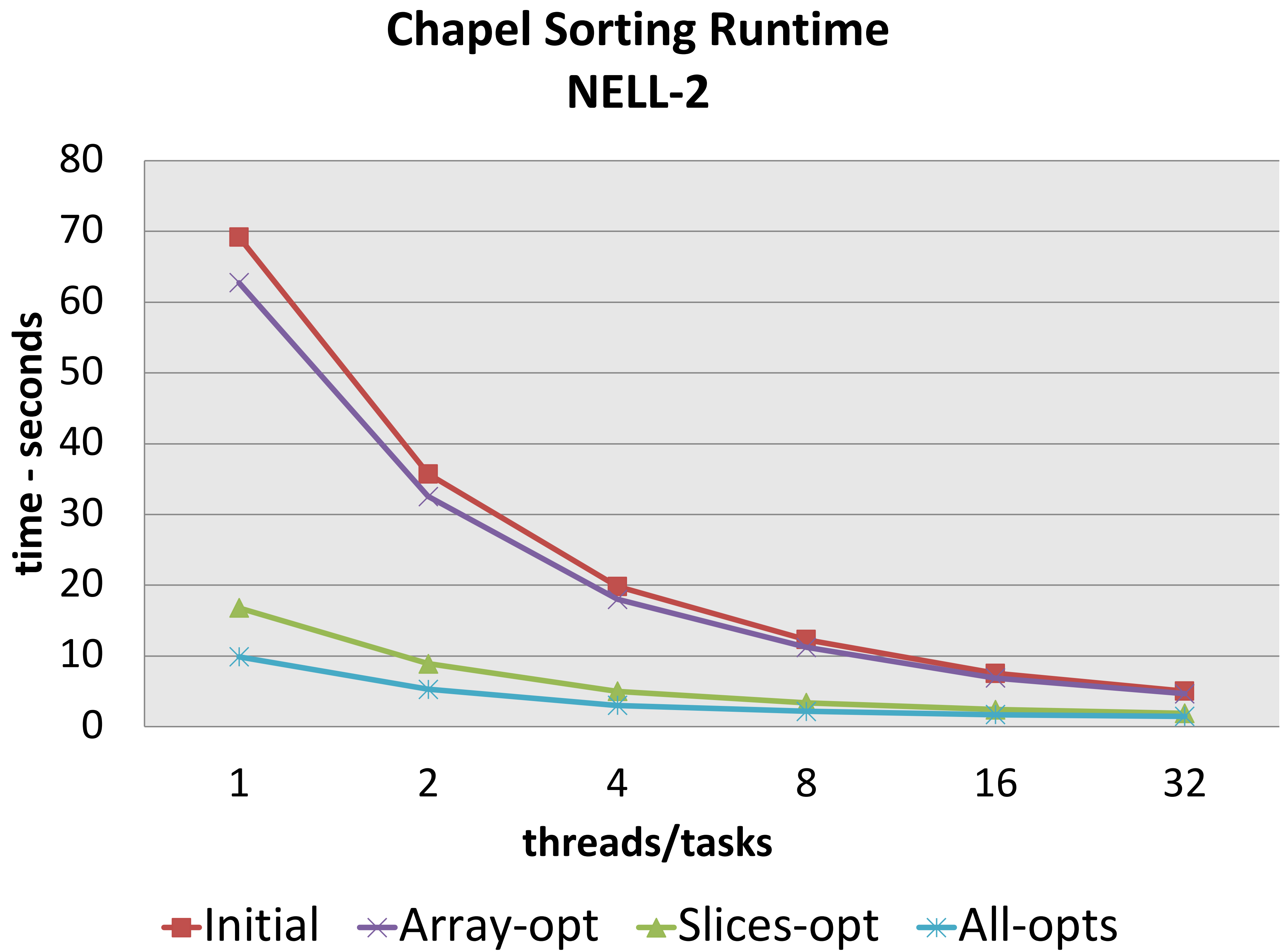
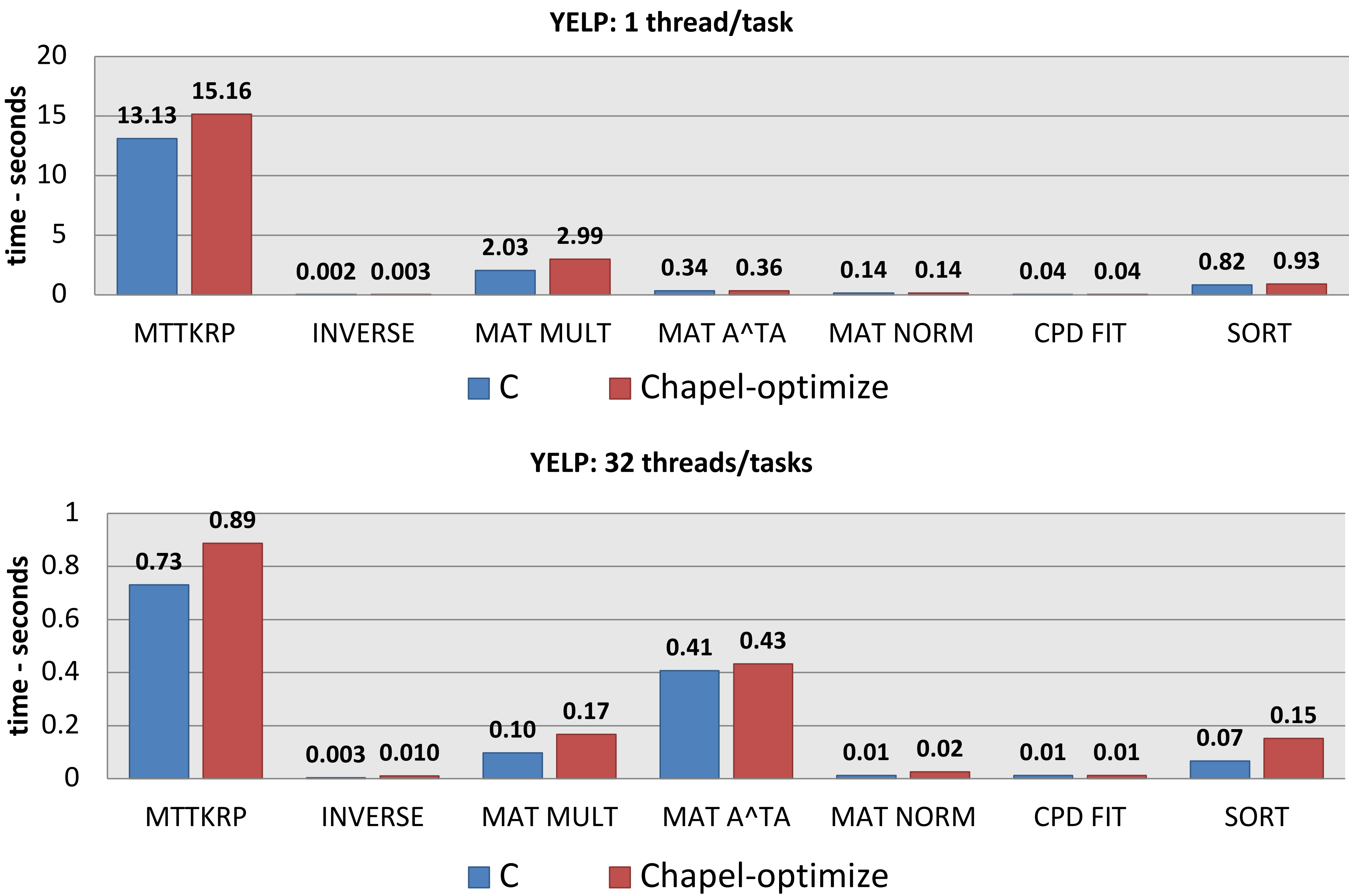
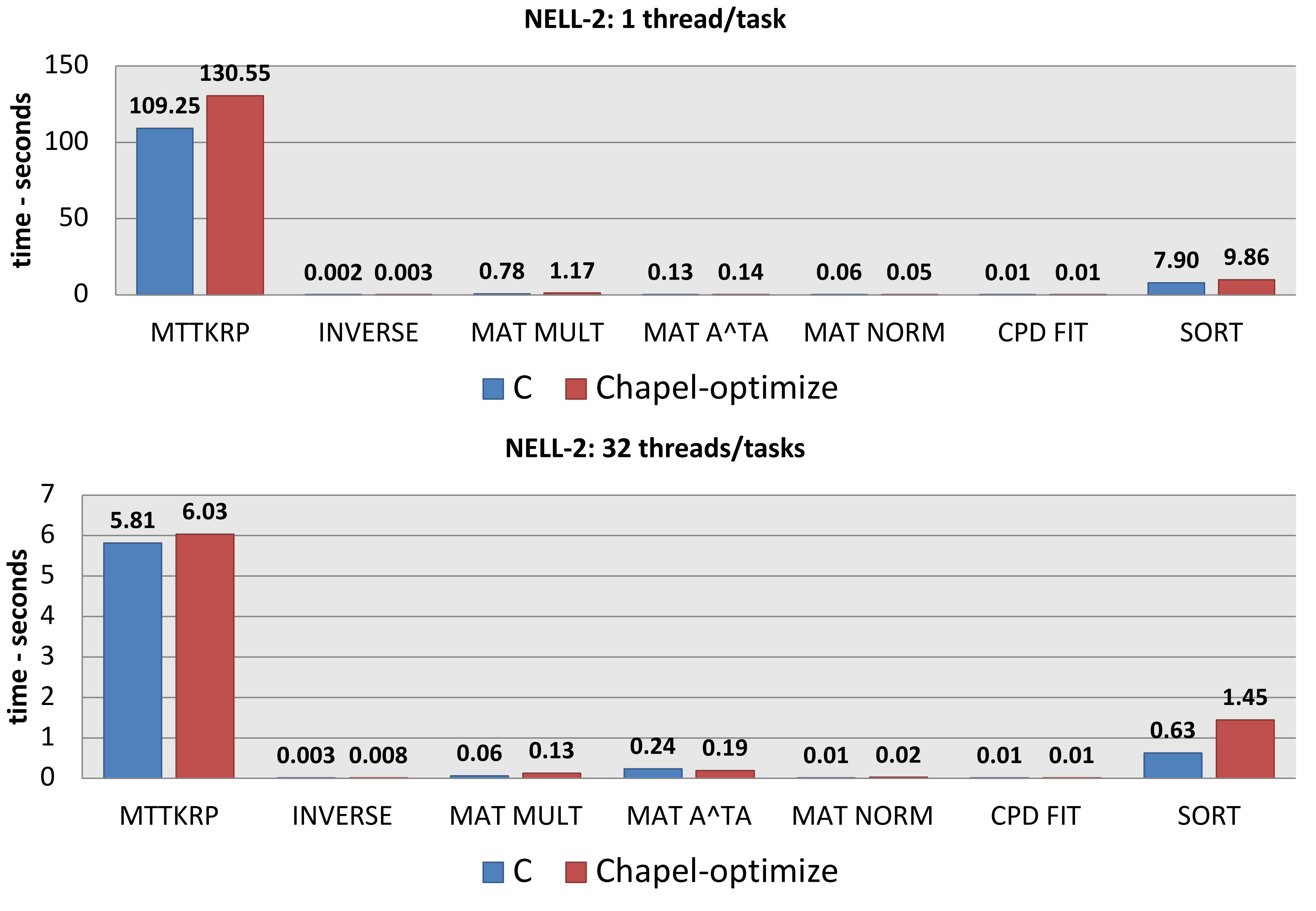

Chapel Sorting Runtime
NELL-2
time - seconds
80
70
60
50
40
30
20
10
0
1
2
4
8
16
32
threads/tasks
Initial
Array-opt
Slices-opt
All-opts

Runtimes for CP-ALS Routines



Runtimes for CP-ALS Routines



4.) Performance Evaluation :

Initial Results: CP-ALS Routines Runtimes

Data set	Threads/tasks	Code	MTTKRP	Sort	Mat A^TA	Mat Norm	CPD Fit	Inverse
YELP	1	C	13.31	0.82	0.34	0.14	0.04	0.94
		Chapel-Initial	225.11	7.21	0.36	0.14	0.04	0.98
	32	C	0.73	0.07	0.41	0.01	0.01	0.05
		Chapel-Initial	118.93	0.47	0.56	0.06	0.01	0.98
NELL-2	1	C	109.25	7.9	0.13	0.06	0.01	0.37
		Chapel-Initial	1999	69.04	0.14	0.06	0.01	0.39
	32	C	5.81	0.63	0.24	0.01	0.01	0.04
		Chapel-Initial	88.3	5.01	0.19	0.02	0.01	0.39

Times shown in seconds

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4.) Performance Evaluation :

MTTKRP Optimizations: Mutex/Locks

- YELP requires the use of locks during the MTTKRP and NELL-2 does not
  - Decision whether to use locks is highly dependent on tensor properties and number of threads used

Sync vars (Qthreads)	Atomic vars (Qthreads)	Sync vars (FIFO)
- Tasks put to sleep - Suitable for long-held heavily contended locks	- Tasks spin-wait - Suitable for short, non-intensive critical reigions	- Tasks spin-wait, similar to atomic vars in Qthreads

- Initially used **sync** vars
  - MTTKRP critical regions are short and fast
  - Switching to **atomic** vars gave huge improvement for YELP
- FIFO w/ **sync** vars competitive with Qthreads w/ **atomic** vars
  - troubling: simple recompilation of code can drastically alter performance

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Initial Results: CP-ALS Routines Runtimes

Data set	Threads/tasks	Code	MTTKRP	Inverse
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	32	C	0.73	0.05
		Chapel	118.93→0.88	0.98
NELL-2	1	C	109.25	0.37
		Chapel	1999→130.54	0.39
	32	C	5.81	0.04
		Chapel	88.3→6.03	0.39

Times shown in seconds

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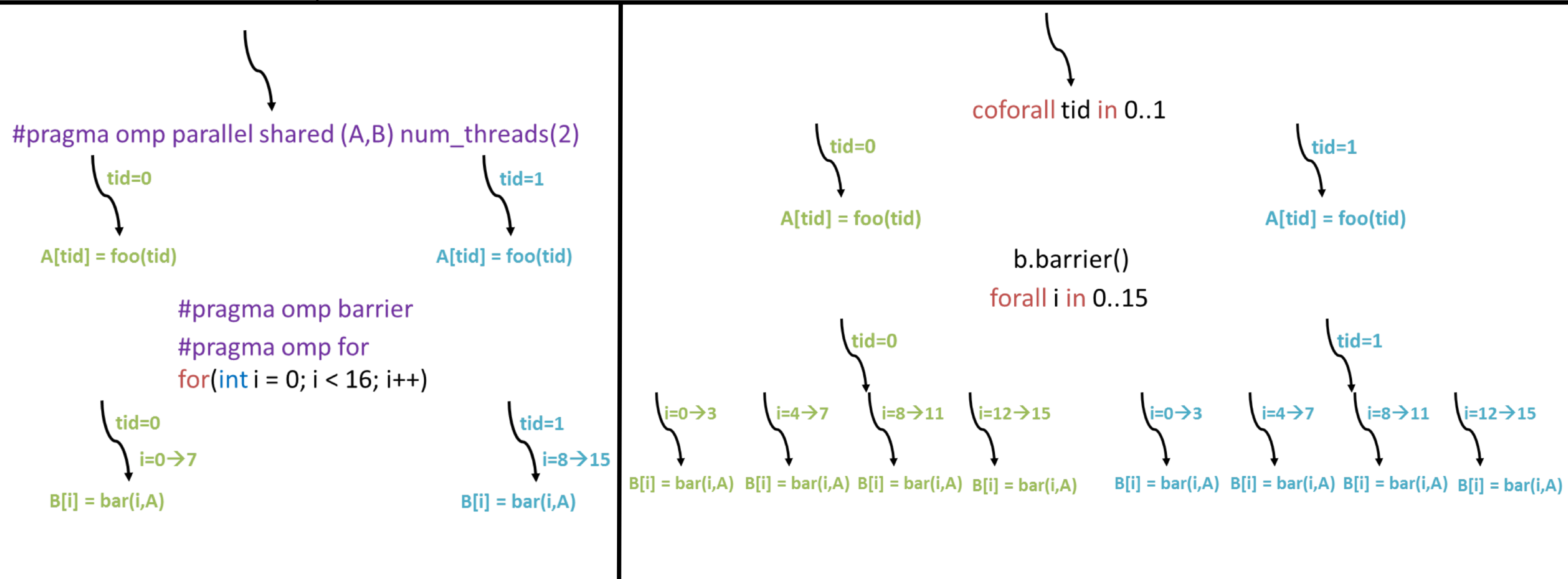
3.) Porting SPLATT to Chapel: Work Sharing Constructs

```
#pragma omp parallel shared(A,B) num_threads(2)
   int tid = omp_get_thread_num();
   A[tid] = foo(tid);
   #pragma omp barrier
   #pragma omp for
   for(int i = 0; i < 16; i++) {
      B[i] = bar(i, A);
   }
}
```

≠

```
coforall tid in 0..1 {
   A[tid] = foo(tid);
   b.barrier();
   forall i in 0..15 {
      B[i] = bar(i, A);
   }
}
```



3.) Porting SPLATT to Chapel:

Work Sharing Constructs

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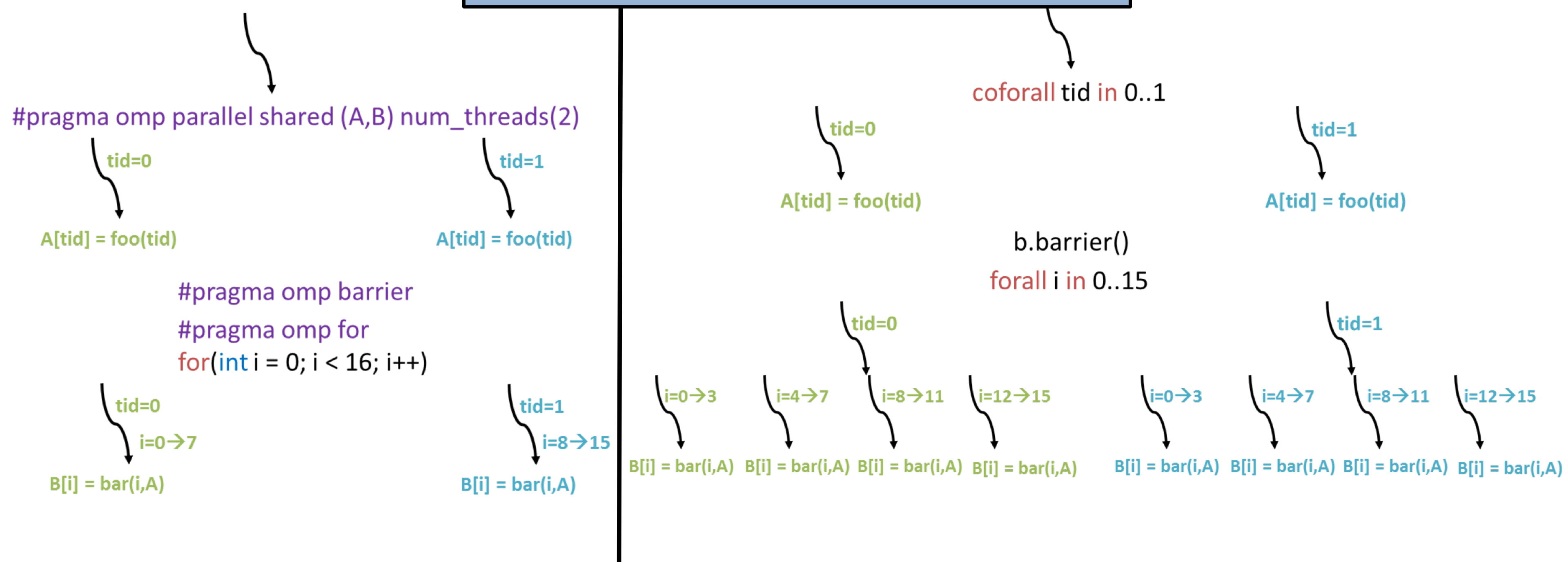
   }
```

Solution: Manually compute loop bounds for each task



3.) Porting SPLATT to Chapel:
Work Sharing Constructs (cont.)

```
#pragma omp parallel
{
  int tid = omp_get_thread_num();
  double *myVals = thdData[tid];
  #pragma omp for
  for (int i = 0; i < rows; i++) {
    for (int j = 0; j < cols; j++) {
      myVals[j] += vals[i][j] * 2;
    }
  }
  // do reduction on myVals
}
```

↓

```
var myVals: [cols] real;
forall r in rows with (+ reduce myVals) do
  for c in cols do
    myVals[c] += vals[r,c] * 2
```

Specific case of perfectly nested loops and partial reduction → clean and concise Chapel translation