A Productive Framework for Generating High Performance, Portable, Scalable Applications for Heterogeneous computing

Wen-mei W. Hwu

with
Tom Jablin, Chris Rodrigues, Liwen Chang,
Steven ShengZhou Wu, Abdul Dakkak

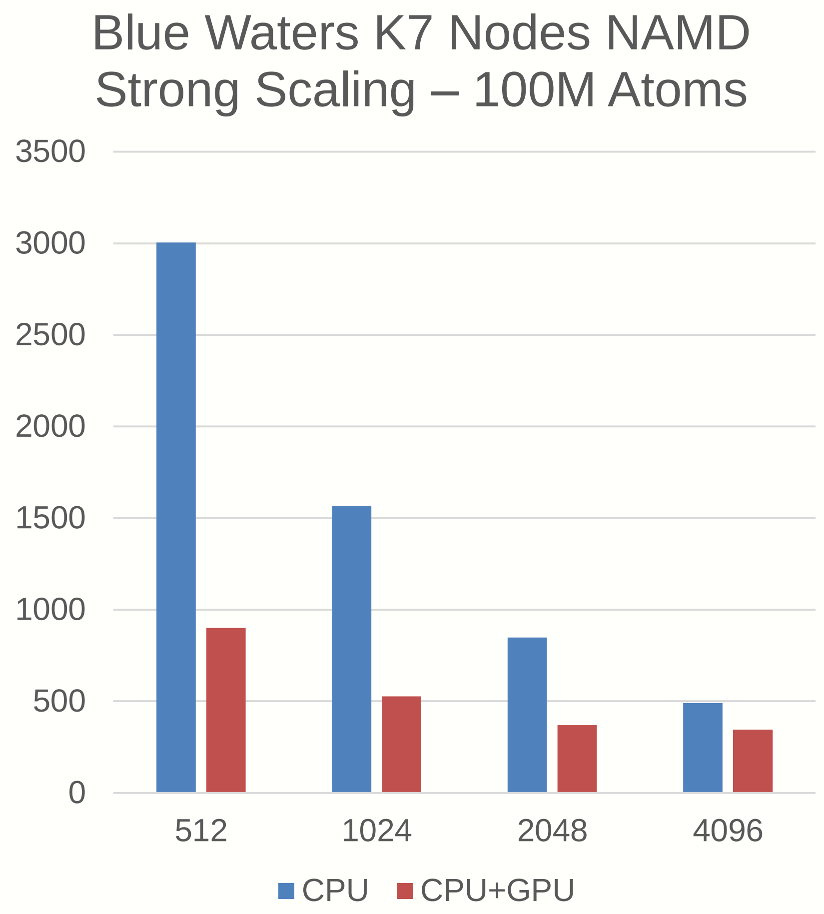
CCoE, University of Illinois at Urbana-Champaign

4,224 Kepler GPUs in Blue Waters

- NAMD
  - 100 million atom benchmark with Langevin dynamics and PME once every 4 steps, from launch to finish, all I/O included
  - 768 nodes, Kepler+Interlagos is 3.9X faster over Interlagos-only
  - 768 nodes, XK7 is 1.8X XE6
- Chroma
  - Lattice QCD parameters: grid size of 48^3 x 512 running at the physical values of the quark masses
  - 768 nodes, Kepler+Interlagos is 4.9X faster over Interlagos-only
  - 768 nodes, XK7 is 2.4X XE6
- QMCPACK
  - Full run Graphite 4x4x1 (256 electrons), QMC followed by VMC
  - 700 nodes, Kepler+Interlagos is 4.9X faster over Interlagos-only
  - 700 nodes, XK7 is 2.7X XE6

Two Current Challenges

- At scale use of GPUs
  - Communication costs dominate beyond 2048 nodes
  - E.g., NAMD Limited by PME
  - Insufficient computation work
- Programming Efforts
  - This talk



ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Writing efficient parallel code is complicated.

Tools can provide focused help

or broad help

Planning how to execute an algorithm **Implementing the plan**

- Choose data structures

- Memory allocation
- Data movement

GMAC

- Pointer operations
- Index arithmetic

DL

Triolet, X10, Chappel, Nesl, DeLite, Par4All

- Map work/data into tasks
- Schedule tasks to threads

Tangram

- Kernel dimensions
- Thread ID arithmetic

OpenACC/
C++AMP/
Thrust

- Synchronization
- Temporary data structures

Levels of GPU Programming Languages

Prototype & in development X10, Chapel, Nesl, Delite, Par4all, Triolet...

Implementation manages GPU threading and synchronization invisibly to user

Next generation OpenACC, C++AMP, Thrust, Bolt

Simplifies data movement, kernel details and kernel launch

Same GPU execution model (but less boilerplate)

Current generation CUDA, OpenCL, DirectCompute

Where should the smarts be for Parallelization and Optimization?

- General-purpose language + parallelizing compiler
  - Requires a very intelligent compiler
  - Limited success outside of regular, static array algorithms

- Domain-specific language + domain-specific compiler
  - Simplify compiler's job with language restrictions and extensions
  - Requires customizing a compiler for each domain

- Parallel meta-library + general-purpose compiler
  - Library embodies parallelization decisions
  - Uses a general-purpose compiler infrastructure
  - Extensible—just add library functions
  - Historically, library is the area with the most success in parallel computing

Triolet – Composable Library-Driven Parallelization

- EDSL-style library: build, then interpret program packages
- Allows library to collect multiple parallel operations and create an optimized arrangement
  - **Lazy evaluation** and aggressive inlining
  - **Loop fusion** to reduce communication and memory traffic
  - **Array partitioning** to reduce communication overhead
  - Library source-guided **parallelism optimization** of sequential, shared-memory, and/or distributed algorithms
- Loop-building decisions use information that is often known at compile time
  - By adding typing to Python

Example: Correlation Code

Compute f(x,y) for every x in xs and for every y in ys (Doubly nested loop)

```
def correlation(xs, ys):
  scores = (f(x,y) for x in xs for y in ys)
  return histogram(100, par(scores))
```

Compute it in parallel

Put scores into a 100-element histogram

Triolet Compiler Intermediate Representation

- List comprehension and `par` build a package containing
  1. Desired parallelism
  2. Input data structures
  3. Loop body

  for each loop level
- Loop structure and parallelism annotations are **statically known**

```
correlation xs ys =
  let i = IdxNest HintPar
                 (arraySlice xs)
                 (λx. IdxFlat HintSeq
                             (arraySlice ys)
                             (λy. f x y ) )
  in histogram 100 i
```

Outer loop

Inner loop

Body

Triolet Meta-Library

- Compiler inlines `histogram`
- `histogram` has code paths for handling different loop structures
- Loop structure is known, so compiler can remove unused code paths

```
correlation xs ys =
  case IdxNest HintPar
               (arraySlice xs)
               (λx. IdxFlat HintSeq
                            (arraySlice ys)
                            (λy. f x y )       )
  of IdxNest parhint input body.
       case parhint
       of HintSeq. code for sequential nested histogram
          HintPar. parReduce input
                             (λchunk.
                                seqHistogram 100 body chunk)
     IdxFlat parhint input body. code for flat histogram
```

Example: Correlation Code

- Result is an outer loop specialized for this application
- Process continues for inner loop

```
correlation xs ys =
  parReduce
    (arraySlice xs)
    (λchunk. seqHistogram
               100
               (λx. IdxFlat HintSeq
                            (arraySlice ys)
                            (λy. f x y )         )
               chunk)
```

Parallel reduction; each task processes a chunk of xs

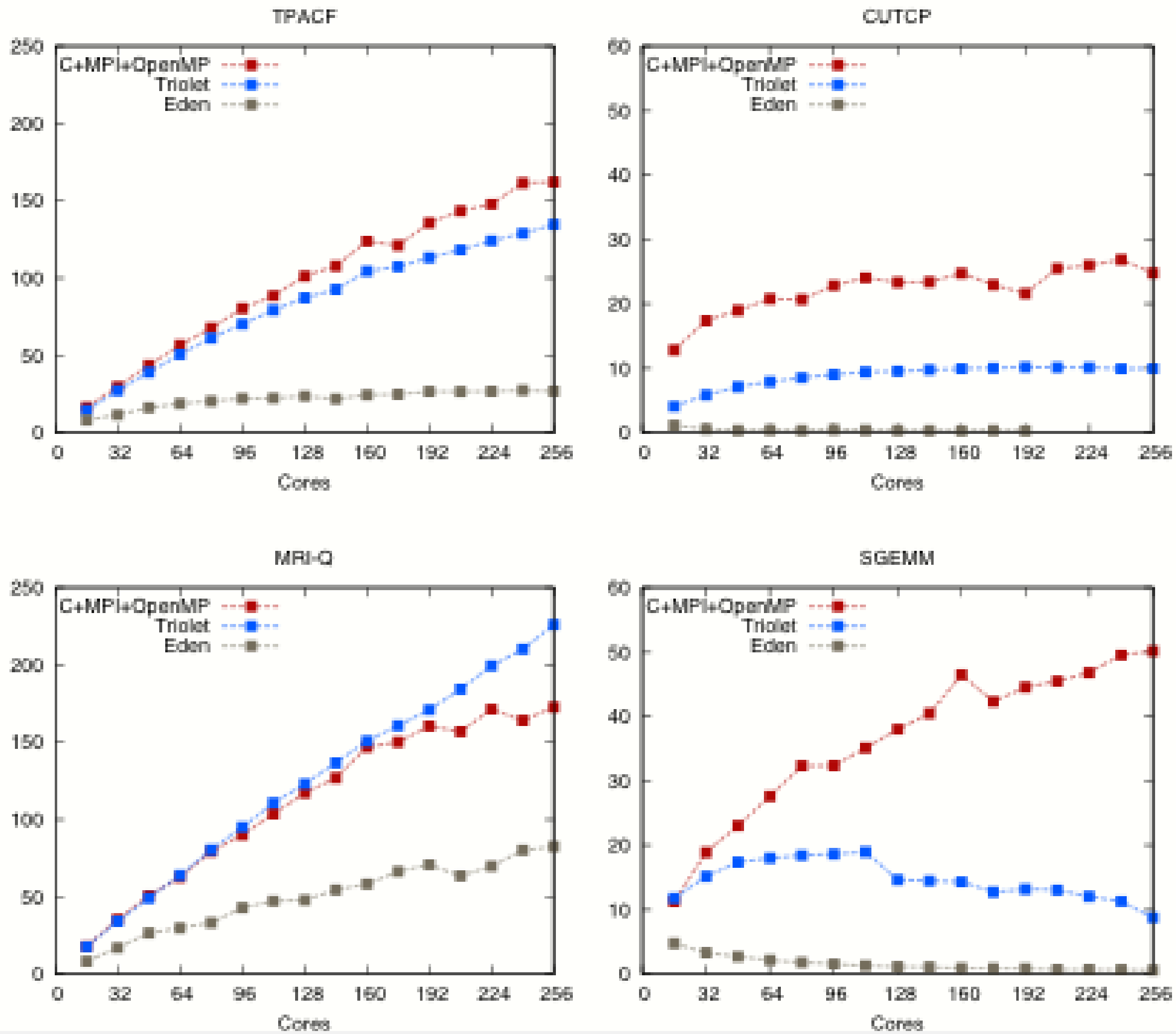
Task computes a sequential histogram

Inner loop

Body

Cluster-Parallel Performance and Scalability

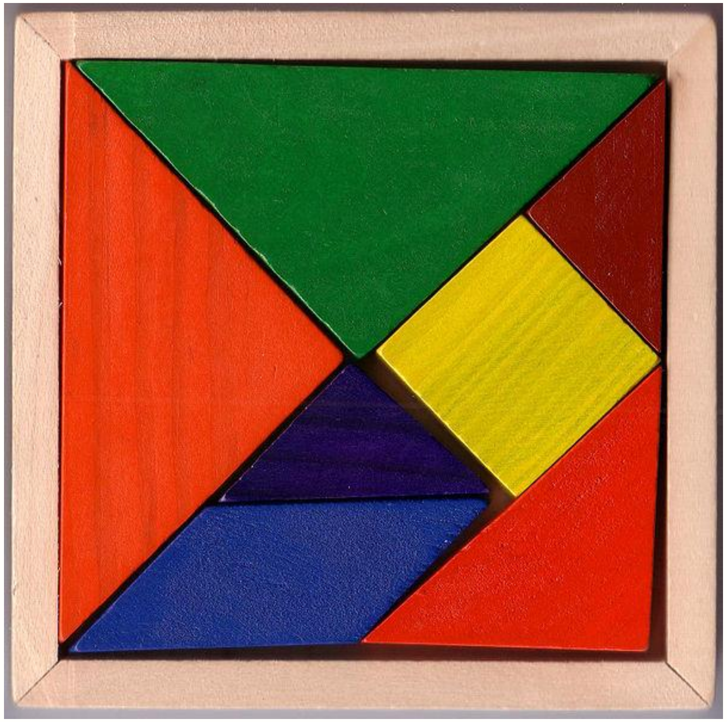
- Triolet delivers large speedup over sequential C
- On par with manually parallelized C for computation-bound code (left)
- Beats similar high-level interfaces on communication-intensive code (right)



Chris Rodriues Rodrigues, et al, PPoPP 2014

Tangram

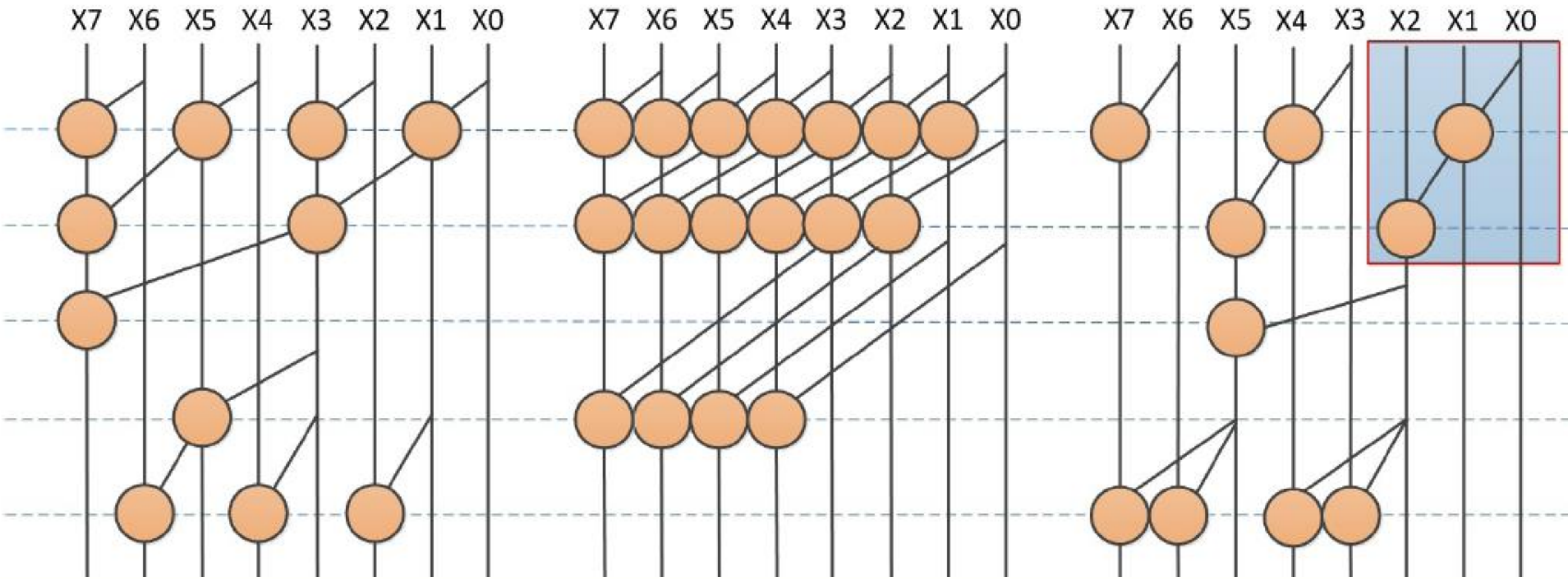
- A parallel algorithm framework for solving linear recurrence problems
  - Scan, tridiagonal matrix solvers, bidiagonal matrix solvers, recursive filters, …
  - Many specialized algorithms in literature
- Linear Recurrence - very important for converting sequential algorithms into parallel algorithms



Tangrams Linear Optimizations

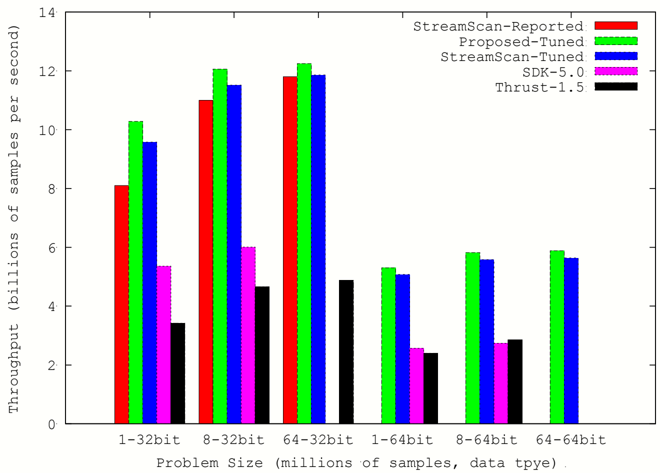
- Library operations to simplify application tiling and communication
  - Auto-tuning for each target architecture
- Unified Tiling Space
  - Simple interface for register tiling, scratchpad tiling, and cache tiling
  - Automatic thread fusion as enabler
- Communication Optimization
  - Choice/hybrid of three major types of algorithms
  - Computation vs. communication tradeoff

Linear Recurrence Algorithms and Communication

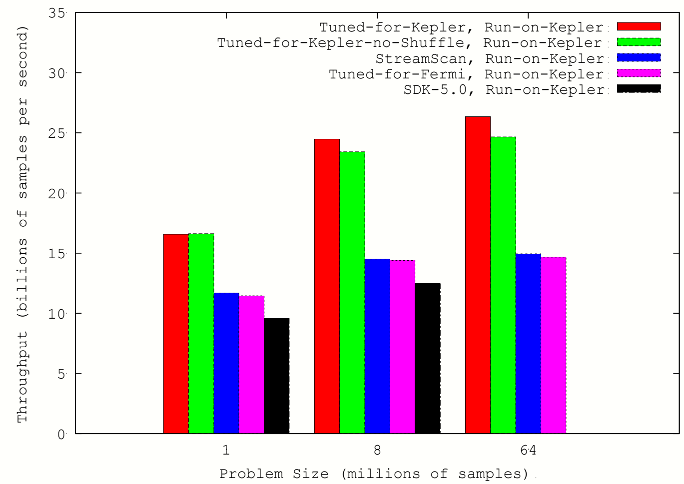


Brent-Kung Circuit   Kogge-Stone Circuit   Group Structured

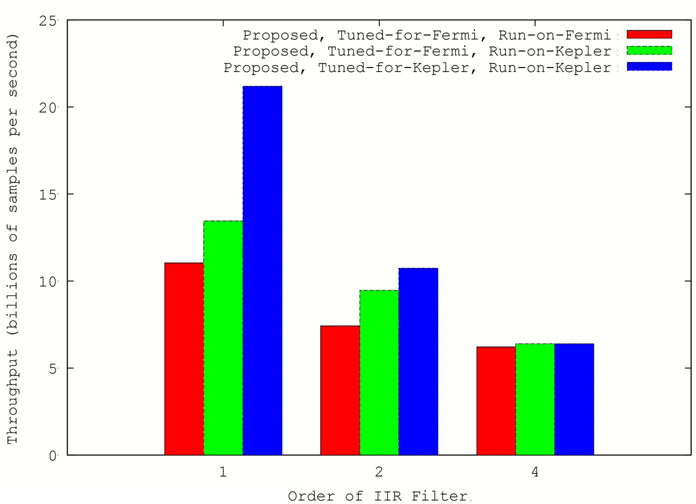
Tangram Initial Results



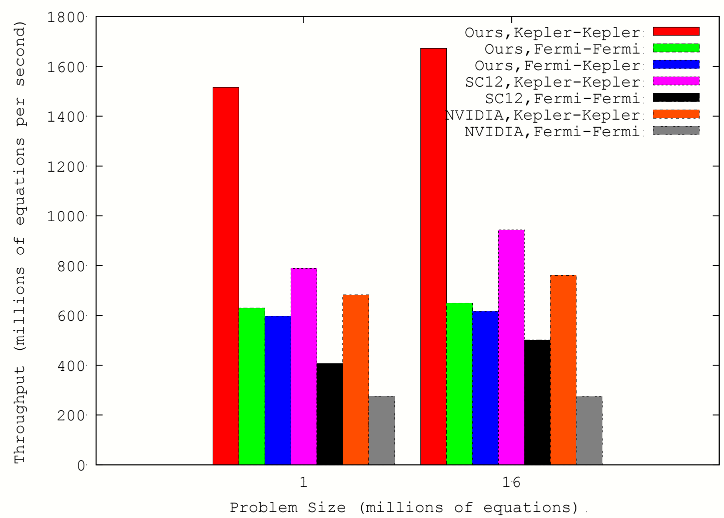
Prefix scan on Fermi (C2050)



Prefix scan on Kepler(Titan)



IIR Filter on both GPUs



Tridiagonal solver on both GPUs

Next Steps

- Triolet released as an open source project
  - Develop additional Triolet library functions and their implementations for important application domains
  - Develop Triolet library functions for GPU clusters
- Publish and release Tangram
  - Current tridiagonal solver in CUSPARSE is from UIUC based on the Tangram work
  - Integration with Triolet

THANK YOU!