Carnegie Mellon University Software Engineering Institute

Research Review 2021

Spiral AI/ML: Co-optimization for High-Performance, Data-Intensive Computing in Resource-Constrained Environments

November 2021

Scott McMillan

Software Engineering Institute
Carnegie Mellon University
Pittsburgh, PA 15213

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DM21-0887

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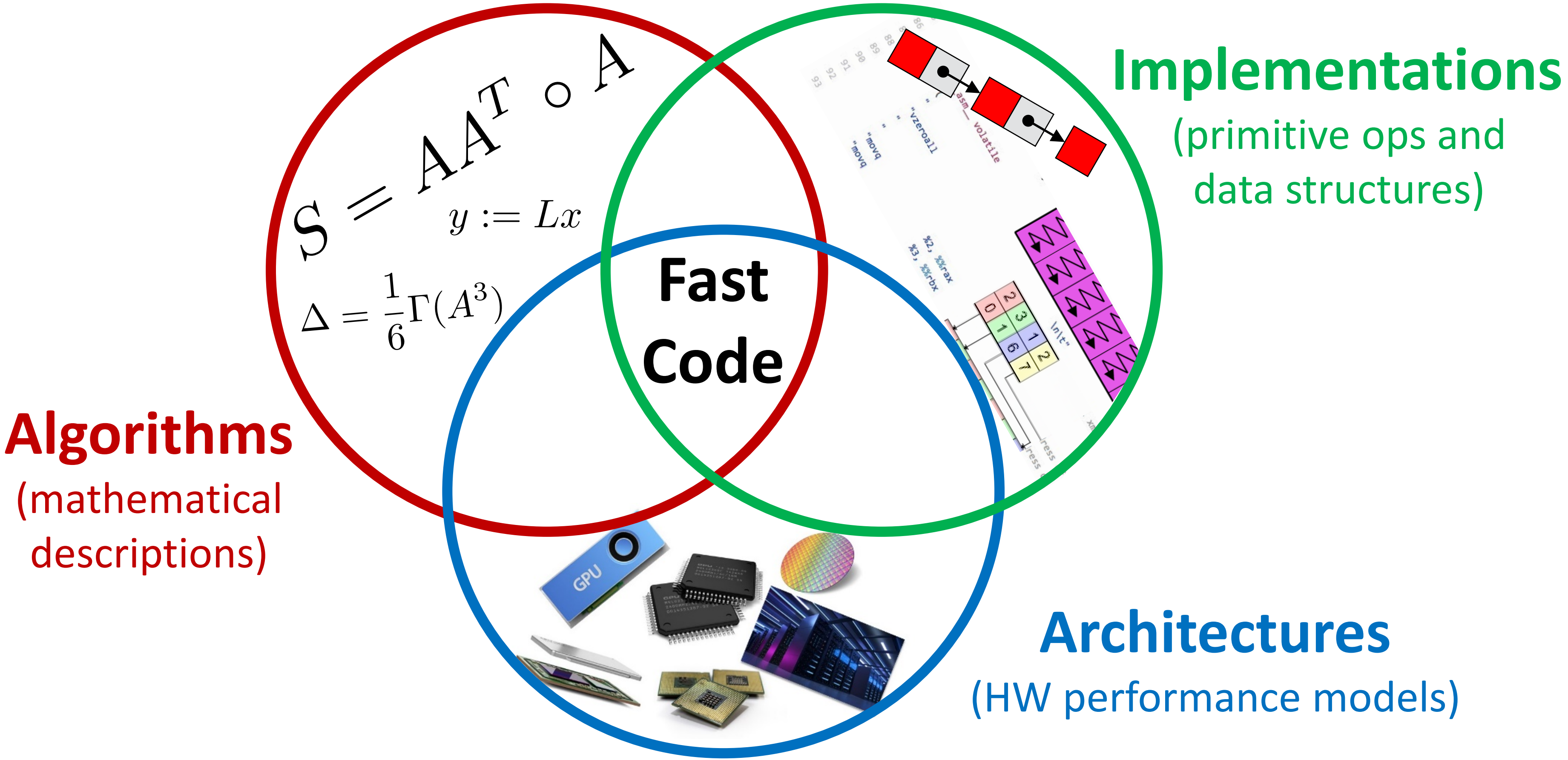
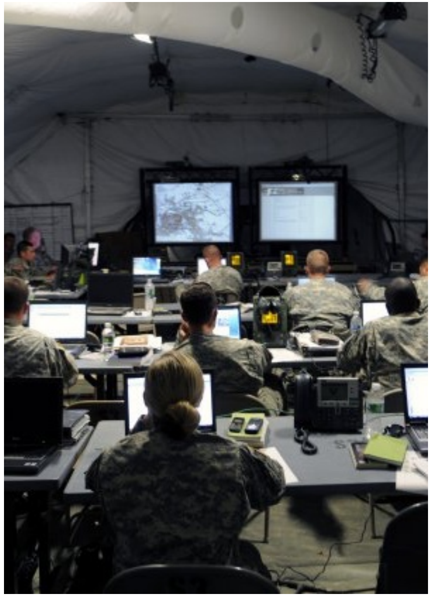
Fast code depends on three interdependent ingredients



Spiral/AIML: Co-Optimization for High-Performance, Data-Intensive Computing in Resource-Constrained Environments



"Rapidly delivering artificial intelligence to a combat zone won't be easy." Col. Drew Cukor, USMC.

Problem(s)

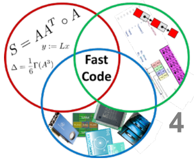
- Increasing complexity in computing architectures.
- Mission cost, size, weight, and power (CSWAP) constraints drive increasing use of FPGAs and ASICs (more complexity).
- Achieving performance from these platforms is *hard*.
- Achieving performance from **data-intensive applications** (graphs, ML, AI) is *hard*.

Solution

- Automatic code generation for data-intensive computations.
- Simultaneous, automatic co-optimization of hardware within CSWAP constraints.

Approach

- Identify common AI/ML/Graph computational primitives and their ***mathematical descriptions***.
- Develop ***hardware performance models*** allowing Spiral to choose between components satisfying CSWAP requirements.
- Encode knowledge about ***efficient implementations*** of graph, ML, and AI computational primitives into **Spiral code-generation technology**.



What is Spiral?

Traditionally

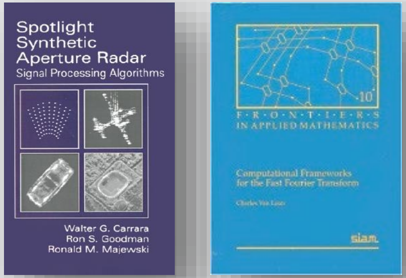
High performance library optimized for given platform

Spiral Approach

High performance library optimized for given platform

What is Spiral?

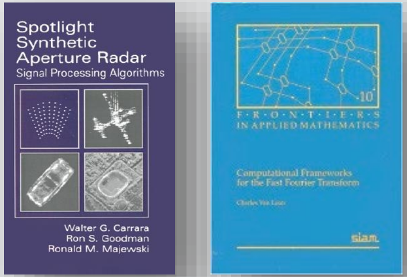
Traditionally



High performance library optimized for given platform

Comparable performance

Spiral Approach



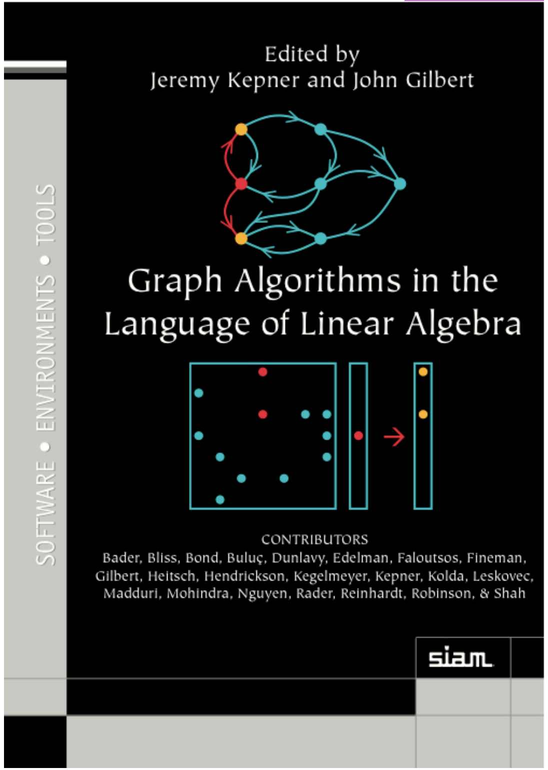
Spiral

High performance library optimized for given platform

Previous Work Addressed Spiral for Graphs

- Spiral understands the rules of linear algebra.
- Much research in graph algorithms using linear algebra
- However, it involves *sparse* and *irregular* data.
- FY2016-2018: working to "teach" the data structures, operations, and optimizations used in graph algorithms
  - Needed a mathematical specification of common operations
  - Led to involvement in the **GraphBLAS** community

2011



Foundational GraphBLAS References

Mathematical Foundations of the GraphBLAS

IEEE HPEC 2016

Jeremy Kepner (MIT Lincoln Laboratory Supercomputing Center), Peter Aaltonen (Indiana University), David Bader (Georgia Institute of Technology), Aydın Buluç (Lawrence Berkeley National Laboratory), Franz Franchetti (Carnegie Mellon University), John Gilbert (University of California, Santa Barbara), Dylan Hutchison (University of Washington), Manoj Kumar (IBM), Andrew Lumsdaine (Indiana University), Henning Meyerhenke (Karlsruhe Institute of Technology), Scott McMillan (CMU Software Engineering Institute), Jose Moreira (IBM), John D. Owens (University of California, Davis), Carl Yang (University of California, Davis), Marcin Zalewski (Indiana University), Timothy Mattson (Intel)

Design of the GraphBLAS API for C

IEEE HPEC 2017

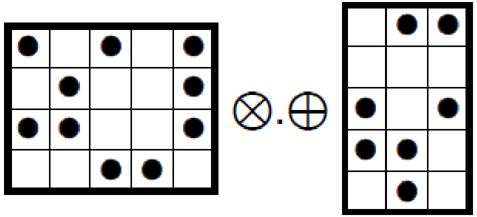
Aydın Buluç[†], Tim Mattson[‡], Scott McMillan[§], José Moreira[¶], Carl Yang[*,†]

[†]*Computational Research Division, Lawrence Berkeley National Laboratory*
[‡]*Intel Corporation* §*Software Engineering Institute, Carnegie Mellon University* ¶*IBM Corporation*
[*]*Electrical and Computer Engineering Department, University of California, Davis, USA*

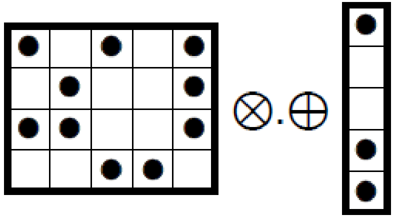
GraphBLAS Primitives

- Basic objects (opaque types)
  - Matrices (sparse or dense), vectors (sparse or dense), algebraic operators (semirings)
- Fundamental operations over these objects

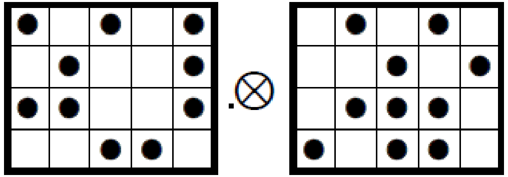
Sparse matrix times sparse matrix



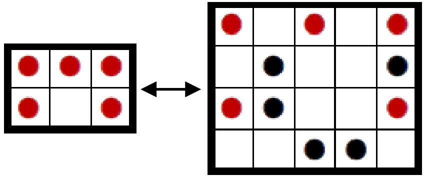
Sparse matrix times sparse vector



Element-wise multiplication (and addition)



Sparse matrix extraction (and assignment)



…plus reduction, transpose, Kronecker product, filtering, transform, etc.

Buluc, A.; Mattson, T.; McMillan, S.; Moreira, J.; &Yang, C. "The GraphBLAS C API Specification," v1.0 May 2017, v1.1 May 2018, v1.3 Sep 2019. **v2.0 Nov 2021 (at SC21).** http://graphblas.org

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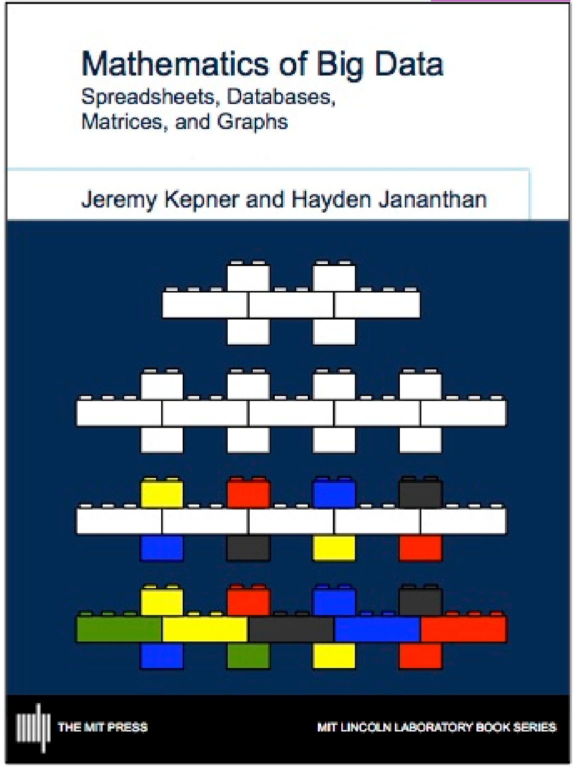
GraphBLAS Is Not Just for Graphs

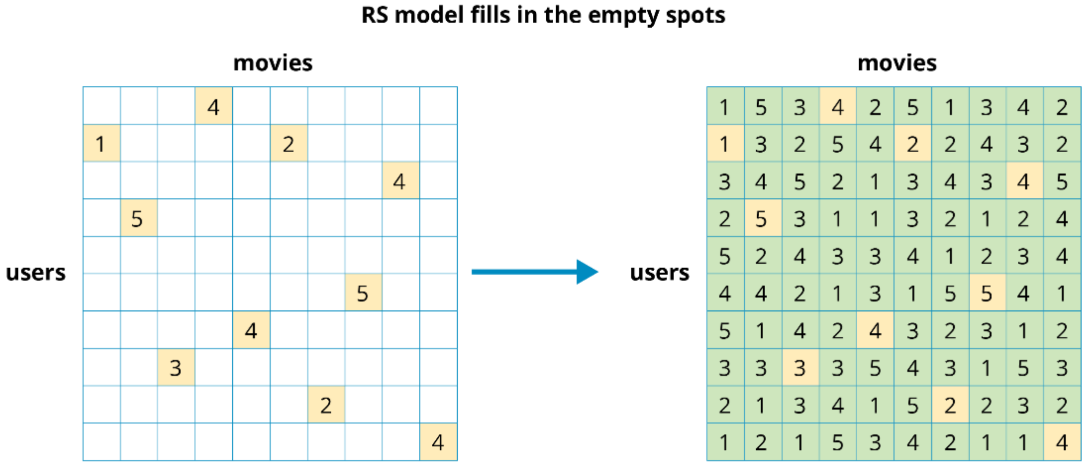
- It is a general linear algebra specification with a rich set of operations on any type of matrix and vector data.
- Recent work has shown applicability of GraphBLAS for operations on data in tabular form.
- **AI, specifically ML, workloads use both sparse and dense data…**

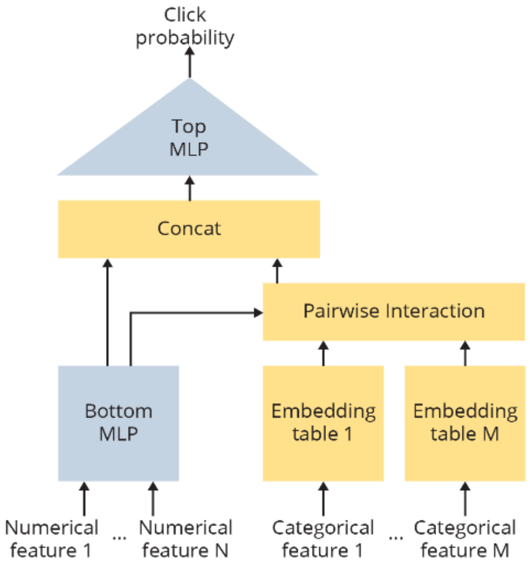
2018



GraphBLAS Operations Can Also Perform ML

- Recommender Systems predict broad information from sparse data
- Deep Learning Recommendation Models (DLRM) has a mixed sparse-dense workloads

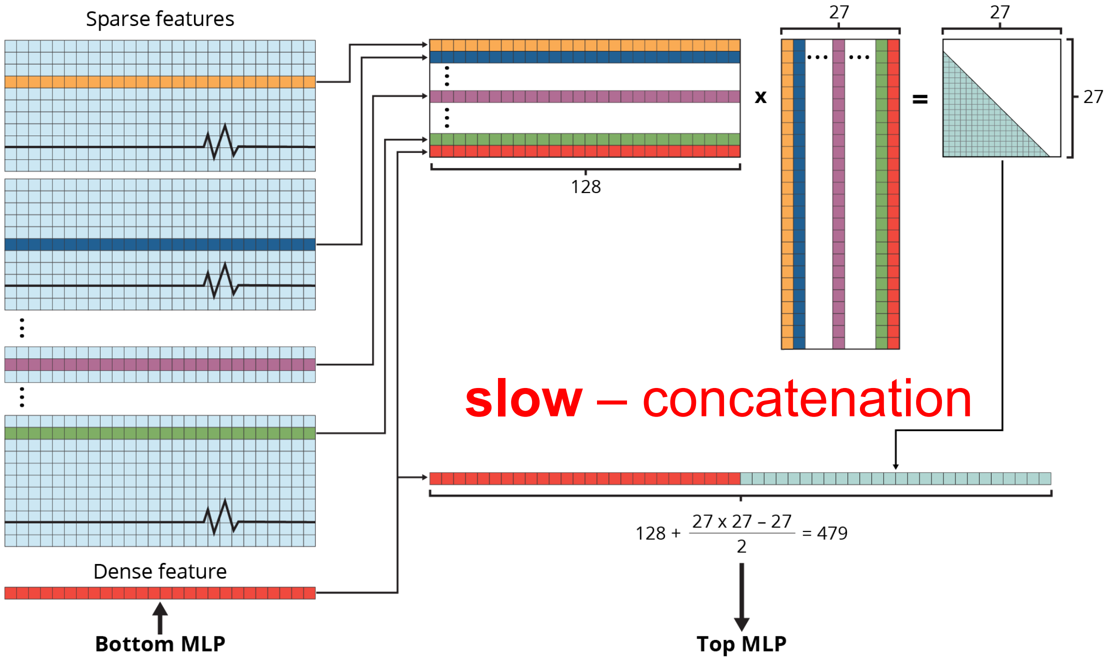




Deep Learning Recommendation Model (DLRM)

Co-Funded by DARPA SDH

slow – DRAM Access

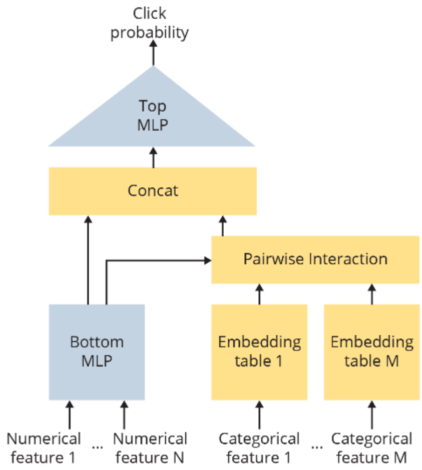


slow – concatenation

fast – Vector Math

fast – Vector Math

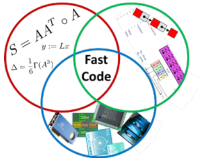
fast – Vector Math



FY19-21: Adding More GraphBLAS for ML to Spiral

Three primary lines of R&D

- **Algorithms**
  - Analyzing graph, ML and AI workloads
  - Identifying computational kernels
  - Developing data structures
- **Implementations**
  - Expanding the GraphBLAS API
  - Optimizing GraphBLAS Template Library
  - Developing the Graph Kernel Collection
- **Architectures**
  - Developing performance models for GPU and multi-core CPU



Spiral Approach

Spiral

High performance library optimized for given platform

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SPIRAL is an Advanced Source-to-Source Compiler

Compiler Analogies

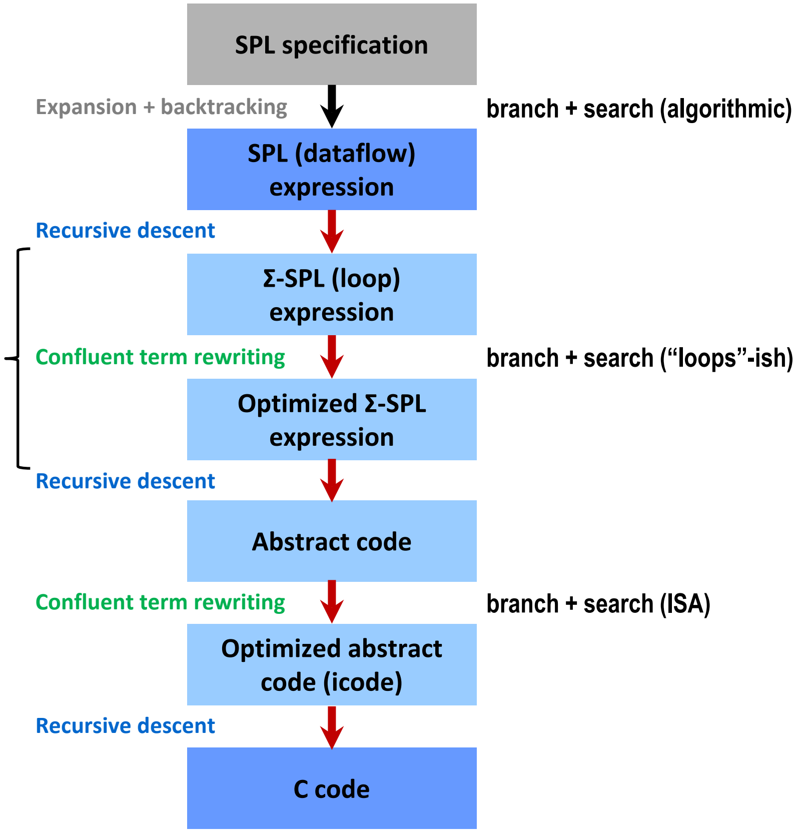
AST

Finest grained AST
algorithm breakdown, and some architecture-specific features; e.g., SIMD vs. warp, number of threads, etc.

Optimization Phase

IR
of a compiler

IR
mapping to HW specific instruction sets



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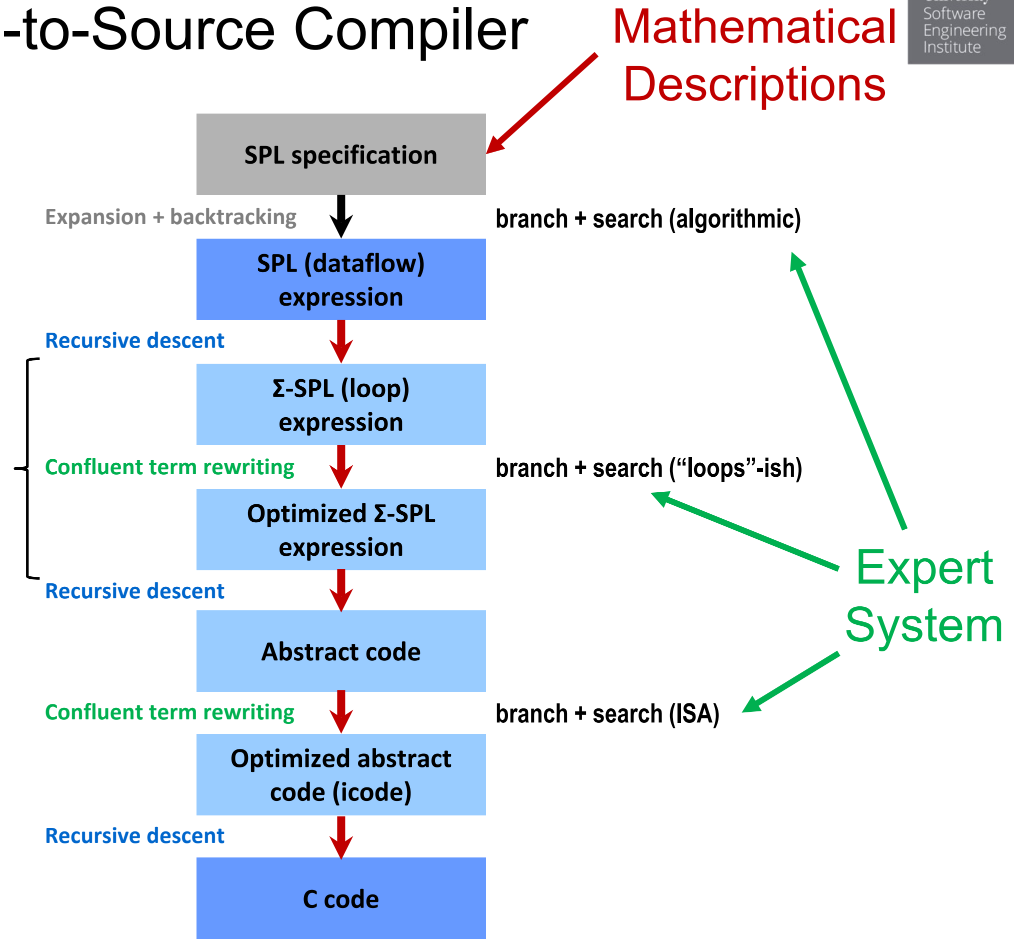
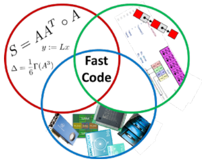
Optimization Phase

Performance Models

IR
of a compiler

IR
mapping to HW specific instruction sets





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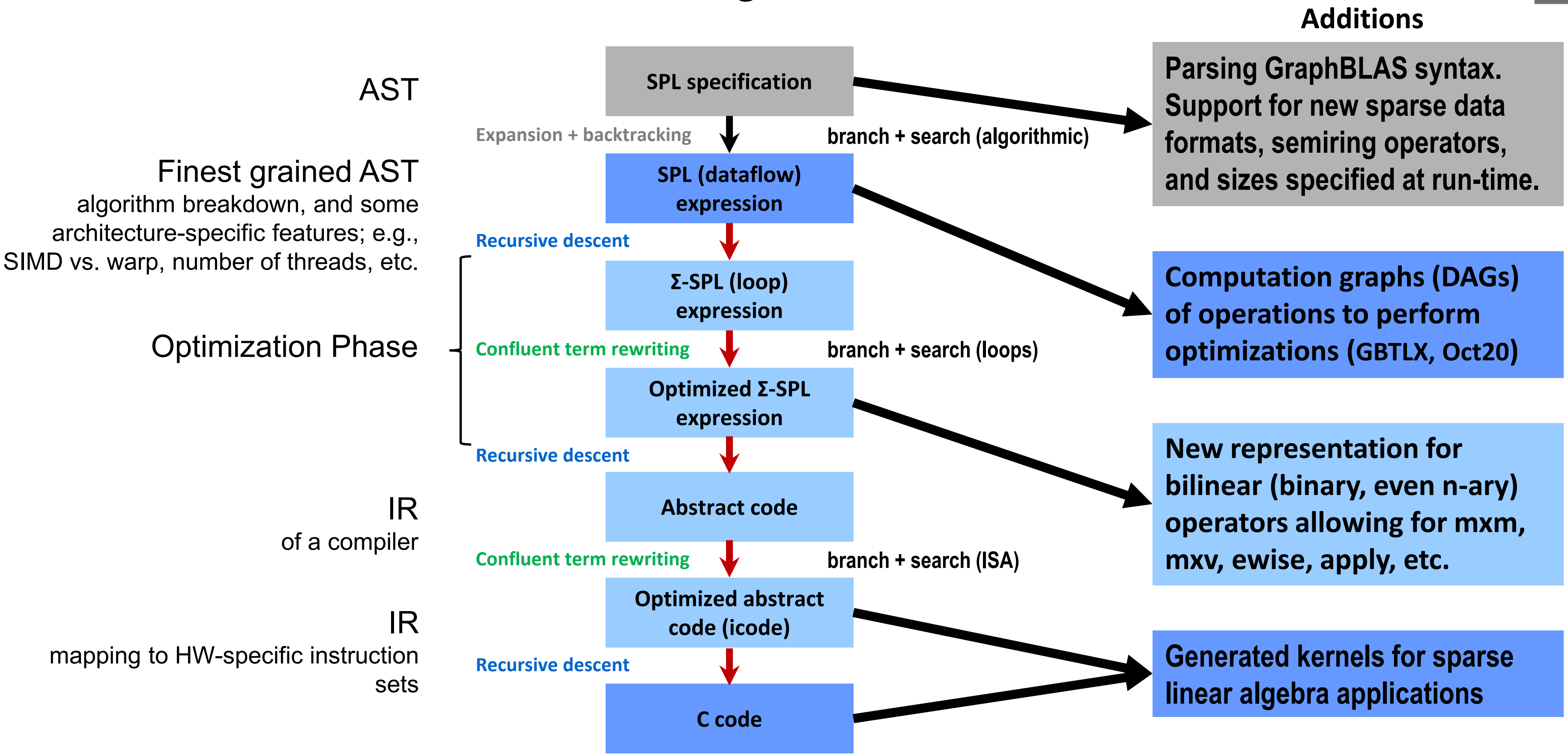
SPIRAL: Code Generation Stages/Additions



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Artifact Highlights: Algorithms

Publications and Implementations

1. **LAGraph: a community effort to curate algorithms built on top of GraphBLAS (IPDPSW'19)**
2. Linear algebraic formulation of edge-centric k-truss algorithms with adjacency matrices (HPEC'18)
3. Graph signal processing and deep learning (Signals'20)
4. Delta-stepping SSSP: from vertices and edges to GraphBLAS implementations (IPDPSW'19)
5. Linear algebraic depth-first search (ARRAY'19)
6. Linear algebraic Louvain clustering algorithm (IPDPSW'20)
7. Edge entropy as an indicator of effectiveness of Graph Neural Networks for node classification (SSC'20)
8. Bipartite graph generation using Kronecker product (IPDPSW'20)
9. **The design of LAGraph (SIAM CSE'21)**
10. **LAGraph: Linear Algebra, Network Analysis Libraries, and the Study of Graph Algorithms (IPDPSW'21)**
11. GraphSAINT, graph neural networks
12. Deep Learning Recommender Models
13. GAP Benchmark algorithms
14. Triangle Centrality analysis

LAGraph: Linear Algebra, Network Analysis Libraries, and the Study of Graph Algorithms

Gábor Szárnyas[*], David A. Bader[†], Timothy A. Davis[‡], James Kitchen[§], Timothy G. Mattson[¶], Scott McMillan[‖], Erik Welch[§]

[*]CWI Amsterdam [†]New Jersey Institute of Technology [‡]Texas A&M University [§]Anaconda, Inc. [¶]Intel Corp. [‖]Software Engineering Institute, Carnegie Mellon University

Download and/or contribute code at:
https://github.com/GraphBLAS/LAGraph

Artifact Highlights: Implementations

APIs:

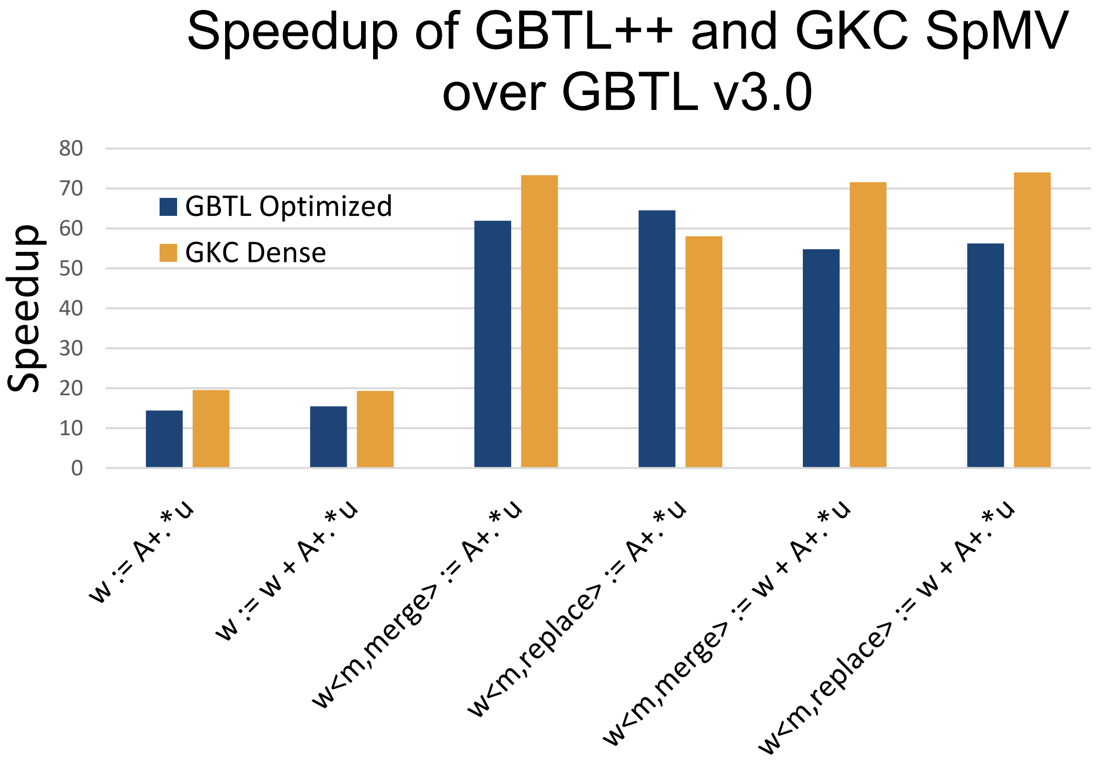
15. GraphBLAS C API Spec v1.3 (9/19)
16. GraphBLAS C API Spec v2.0 for multithreading (IPDPSW'21)
17. GraphBLAS C++ API Spec (draft, IPDPSW'20)
18. Distributed GraphBLAS API (IPDPSW'20)
19. Spiral/GBTLX source-to-source translator, (HPEC'20)

Open-source code:

20. **GraphBLAS Template Library (GBTL) v3.0**
21. **Graph Kernel Collection**
22. LAGraph Algorithms Repository, v1.0: a community effort to curate algorithms built on top of GraphBLAS
23. NWGraph: A Library of Generic Graph Algorithms and Data Structure in C++20 (with PNNL/UW)

Tutorials:

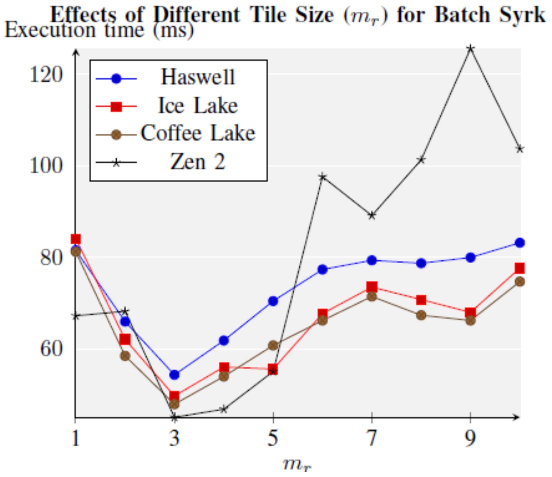
- "A Hands-on Introduction to GraphBLAS"
  24. Tutorial in C (HPEC'18, '19)
  25. Tutorial in python (SIAM CSE'21, ICS'21, HPEC'21)

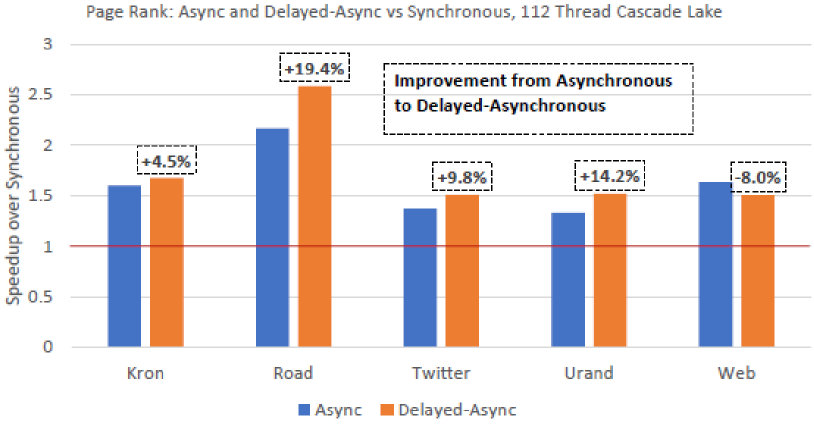


Artifact Highlights: Architectures

Analyses and Publications:

26. PageRank acceleration for large graphs with scalable hardware (FPGA) and 2-step SpMV (HPEC'18)
27. Preliminary exploration of large-scale triangle counting on shared-memory, multicore systems (HPEC'18)
28. Exploration of fine-grained parallelism for load balancing eager k-truss on GPU and CPU (HPEC'19)
29. Efficient SpMV operation for large and highly sparse matrices using scalable multi-way merge parallelization (Micro'19)
30. FESIA: Fast, efficient set intersection approach on modern CPUs (ICDE'20)
31. Toward an objective metric for exact triangle count (HPEC'20)
32. Triangle counting with cyclic distribution (HPEC'20)
33. Evaluation of graph analytic frameworks using the GAP benchmark suite (IISWC'20)
34. **Analytical models for portable Deep Learning Recommender Model (DLRM) implementations (manuscript)**
35. A method for fusing non-element-wise layers in DNNs (HPEC'21)
36. Modeling matrix engines for portability and performance (manuscript)
37. **Delayed asynchronous iterative graph algorithms (HPEC'21)**





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External Collaborators

Andrew Lumsdaine/PNNL/UW
Jesun Firoz/PNNL
Tony Liu/UW
Kevin Deweese/UW

Tim Mattson/Intel Research

Michel Pelletier/Graphegon

Ben Brock/UCB
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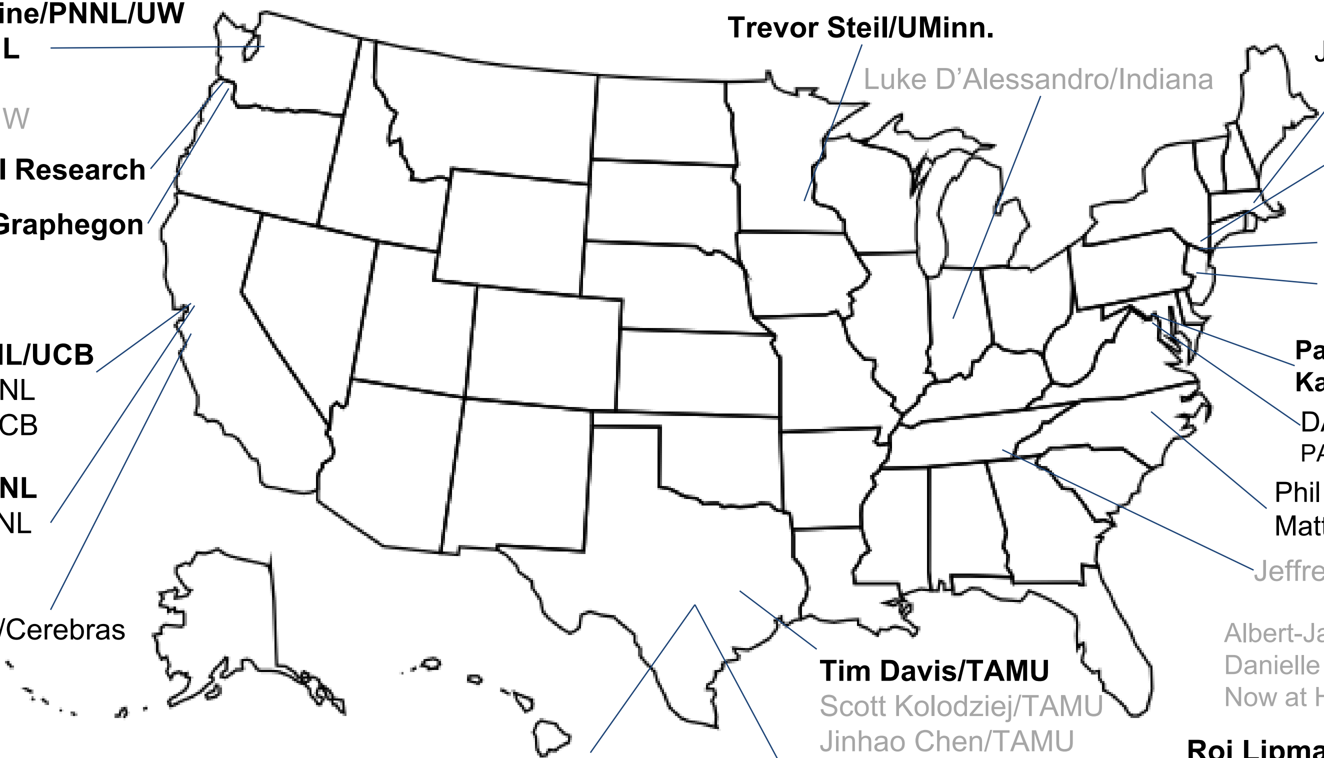

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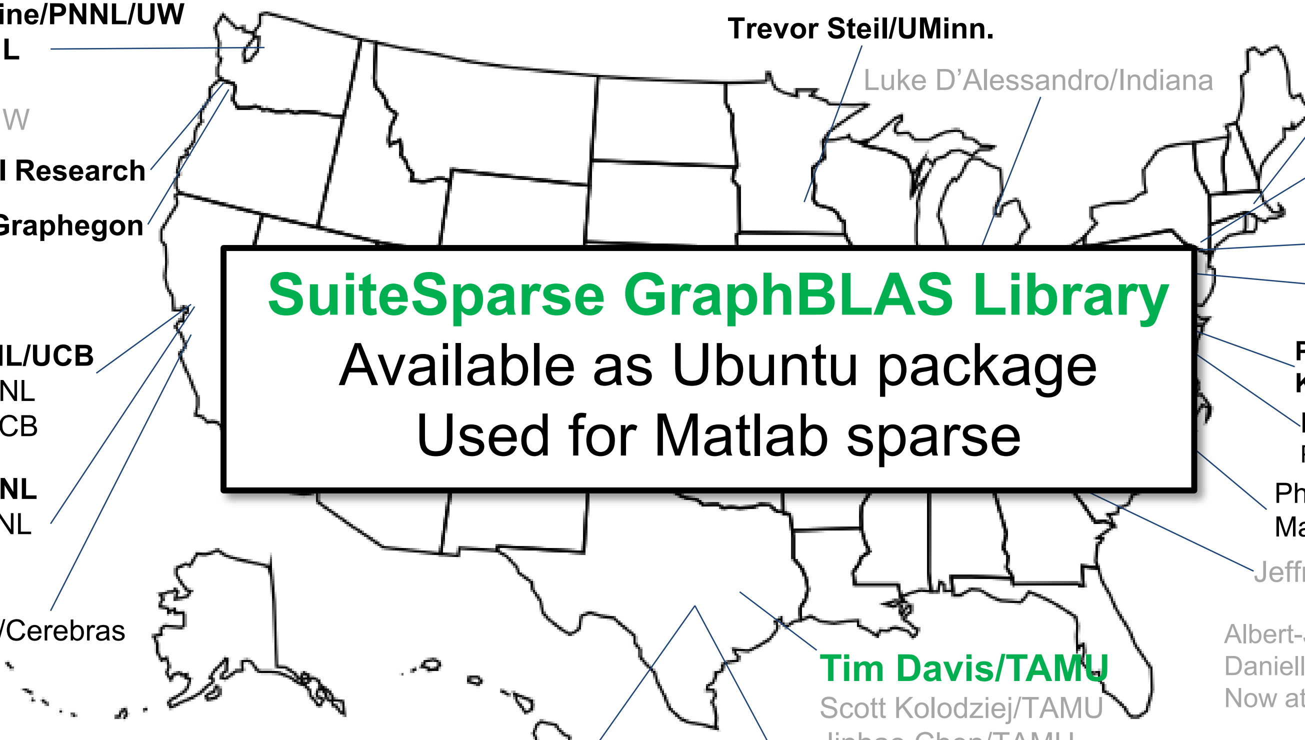

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SuiteSparse GraphBLAS Library
Available as Ubuntu package
Used for Matlab sparse

Tim Davis/TAMU
Scott Kolodziej/TAMU
Jinhao Chen/TAMU
Et al.

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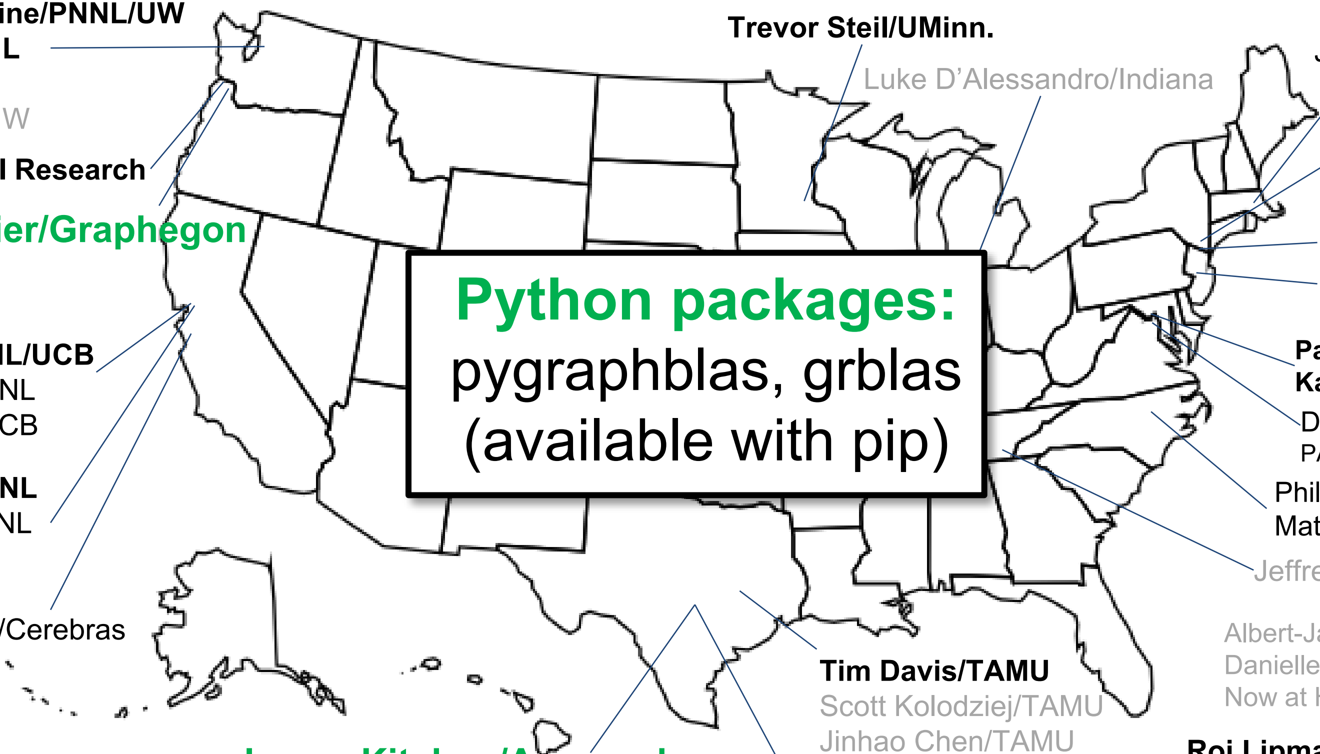

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Ben Priest/LLNL

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Trevor Steil/UMinn.

Luke D'Alessandro/Indiana

Python packages:
pygraphblas, grblas
(available with pip)

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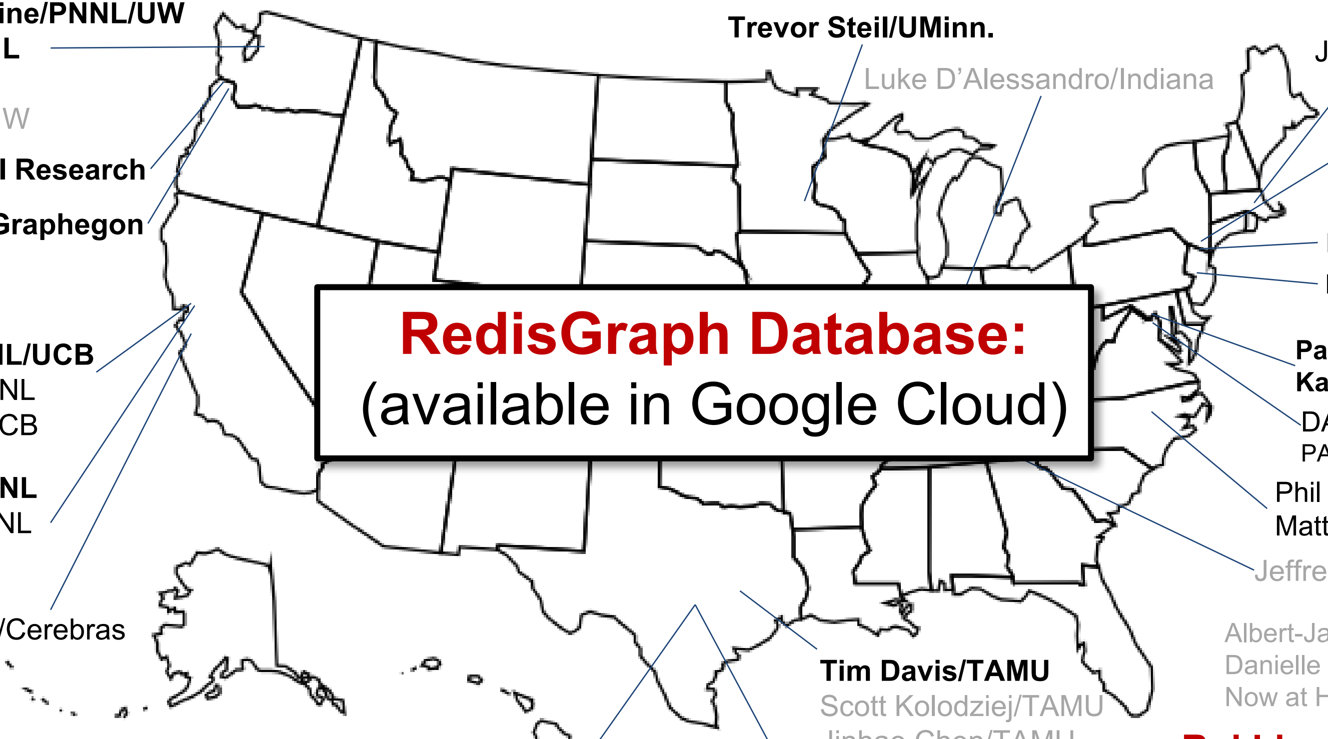

Trevor Steil/UMinn.
Luke D'Alessandro/Indiana

RedisGraph Database:
(available in Google Cloud)

Jeremy Kepner/MIT/LL

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David Bader/NJIT

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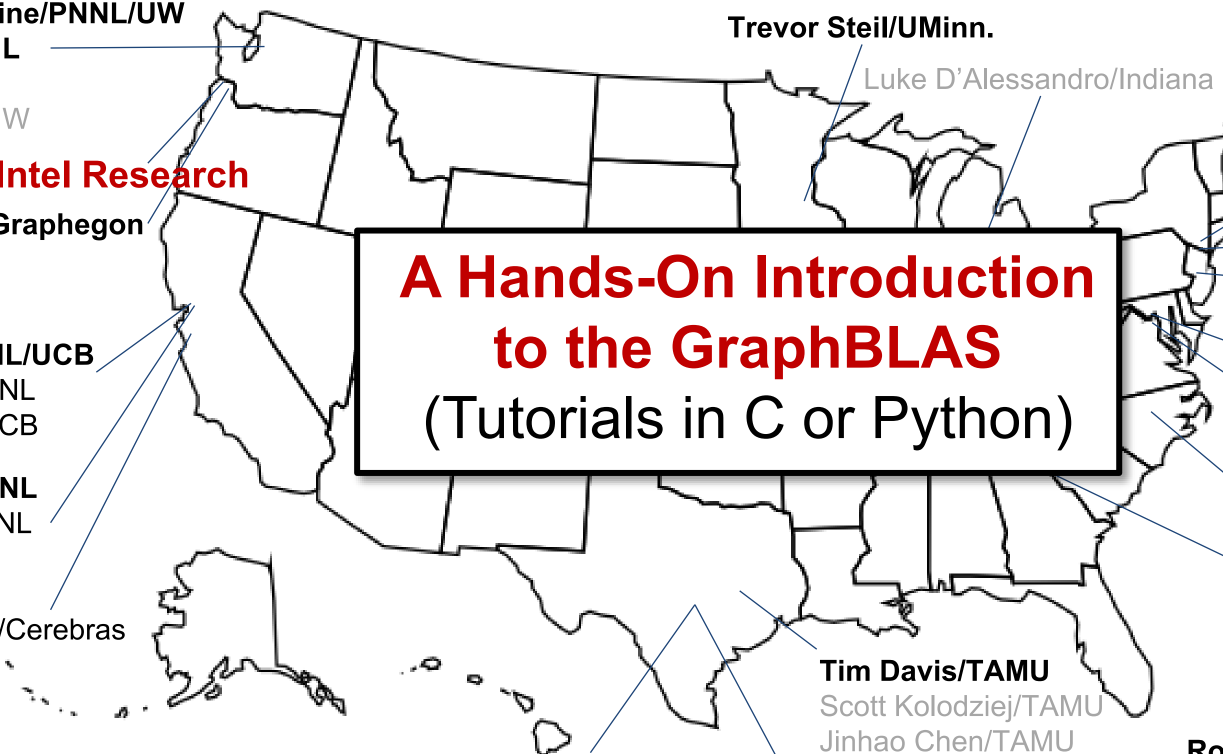

A Hands-On Introduction to the GraphBLAS

(Tutorials in C or Python)

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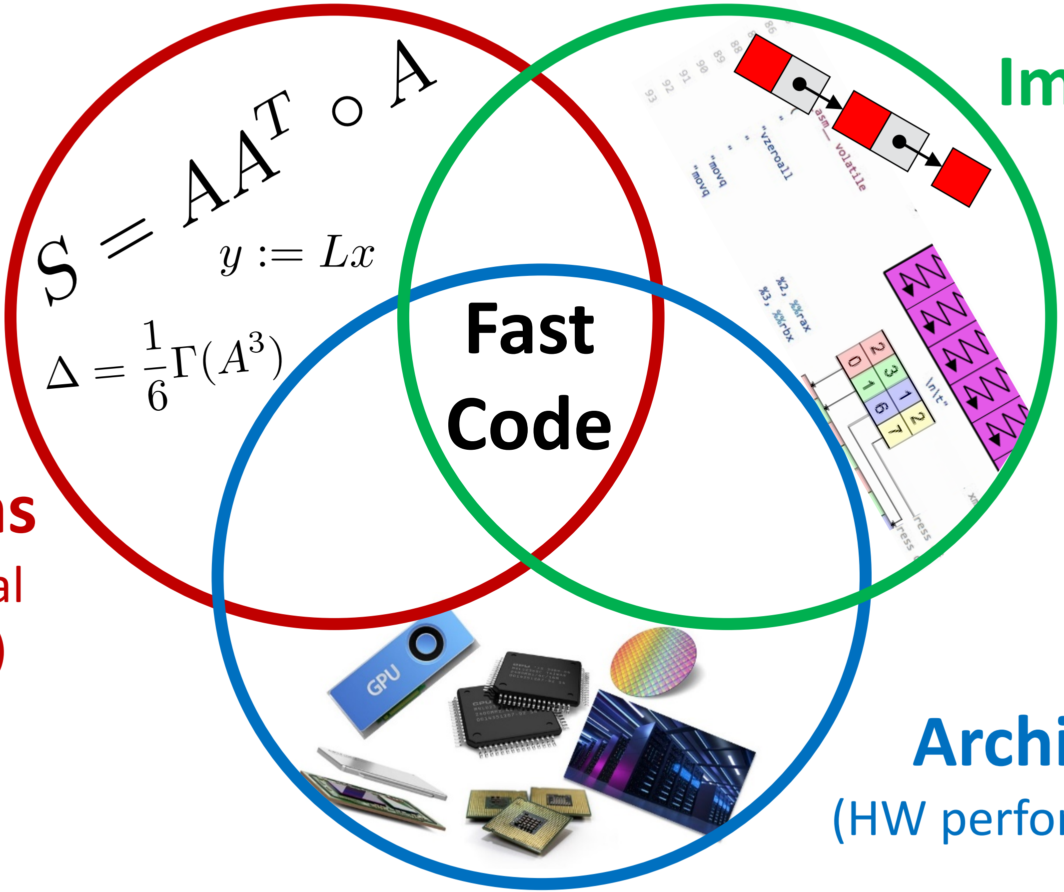

Implementations
(primitive ops and data structures)

Algorithms
(mathematical descriptions)

Architectures
(HW performance models)

Team Members

Carnegie Mellon University Software Engineering Institute

SEI

Scott McMillan
Principal Engineer
The AI Division
Software Engineering Institute

John Wohlbier
Senior Research Scientist
The AI Division
Software Engineering Institute

Oren Wright
Senior Researcher
The AI Division
Software Engineering Institute

Jason Larkin
Senior Researcher
The AI Division
Software Engineering Institute

CMU ECE

Franz Franchetti
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Team Members

CMU Staff

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Dr. Daniele Spampinato
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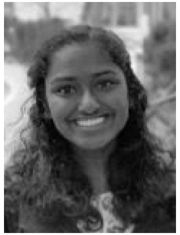
SEI Interns

Courtney Rankin



Sandra Sanjeev
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CMU Students

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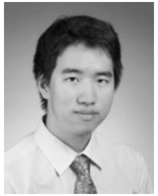
Mark Blanco

Peter Oostema

Sanil Rao

Upasana Sridhar



Mark Cheung

Guanglin Xu

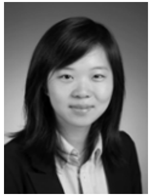
George Ralph

Arvind Srinivasan

John Shi

Dr. Fazle Sadi
(Intel)

Dr. Anuva Kulkarni
(Motional)



Dr. Jiyuan Zhang
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