Automated Characterization of Parallel Application Communication Patterns

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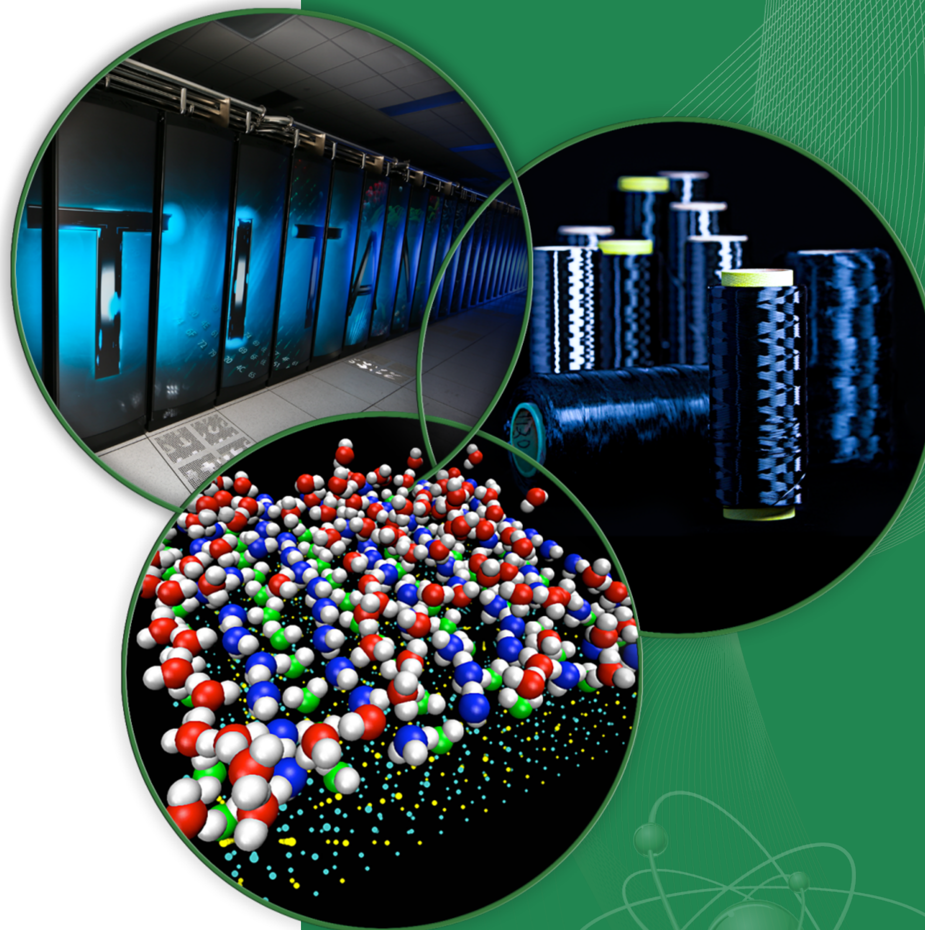

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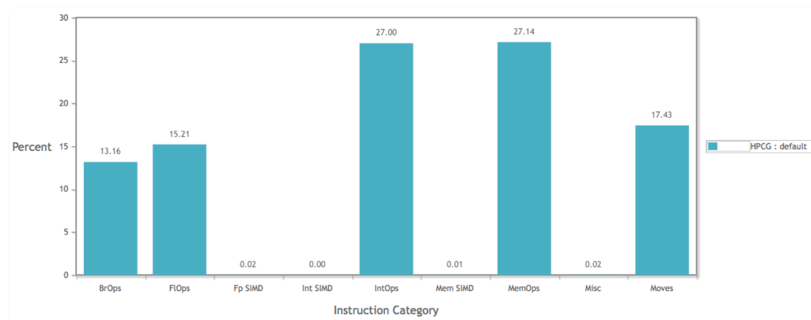
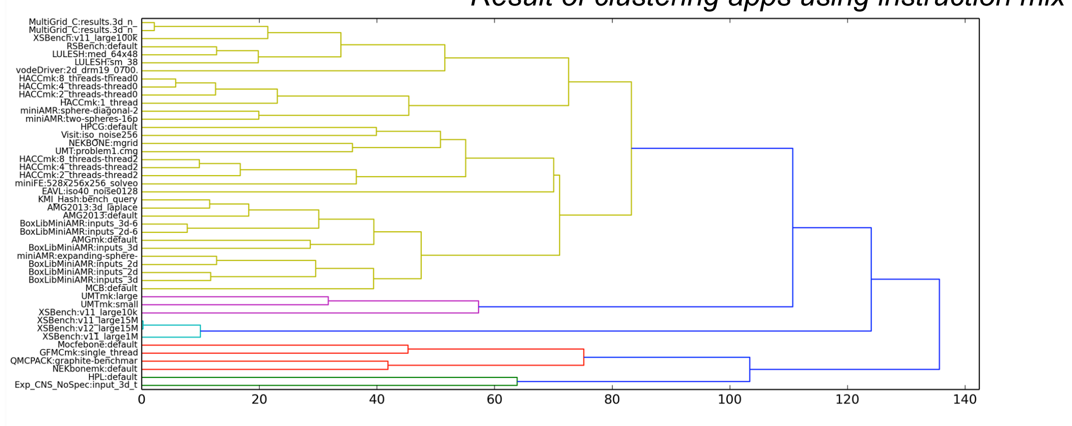
Background: Oxbow

- Characterize application demands independent of performance
  - System design
  - Representativeness of proxy apps
- Characterization on several axes:
  - Communication (topology, volume)
  - Computation (instruction mix)
  - Memory access (reuse distance)
- Online database for results with web portal including analytics support
- http://oxbow.ornl.gov

Instruction Mix, HPCG, 64 processes



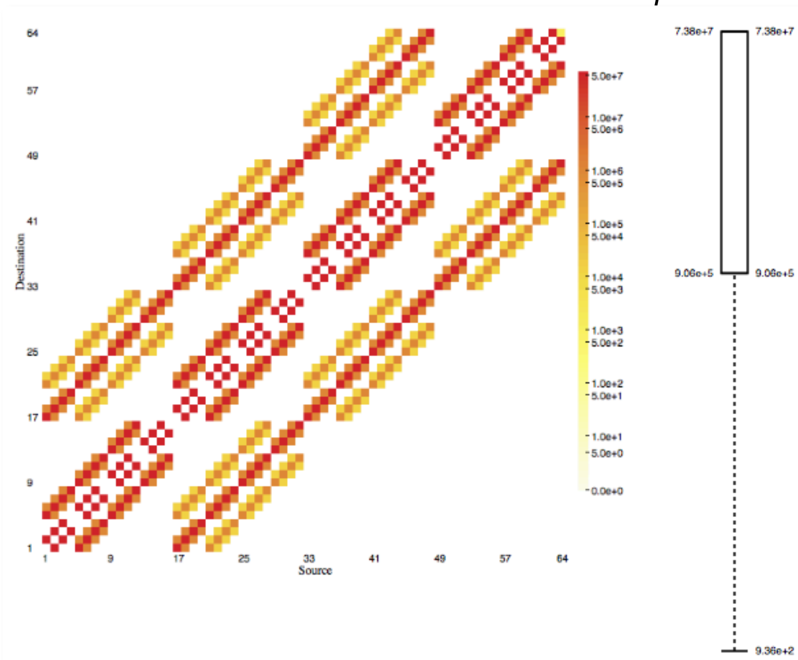
Result of clustering apps using instruction mix



Background: mpiP

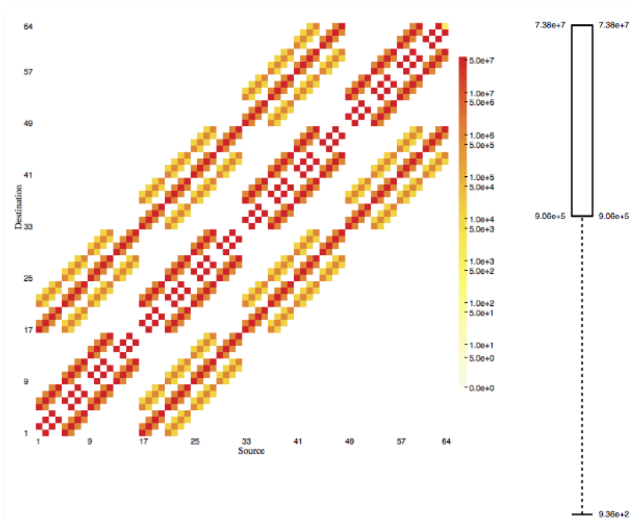
- Lightweight communication and I/O profiler for MPI programs
- Interposes instrumentation using PMPI interface
- For Oxbow, we modified mpiP to track:
  – Sender, receiver, volume for point to point operations
  – Root, destination(s) and volume for rooted collectives
  – Processes involved, volume for rootless collectives

Communication matrix for HPCG, 64 processes



The Problem

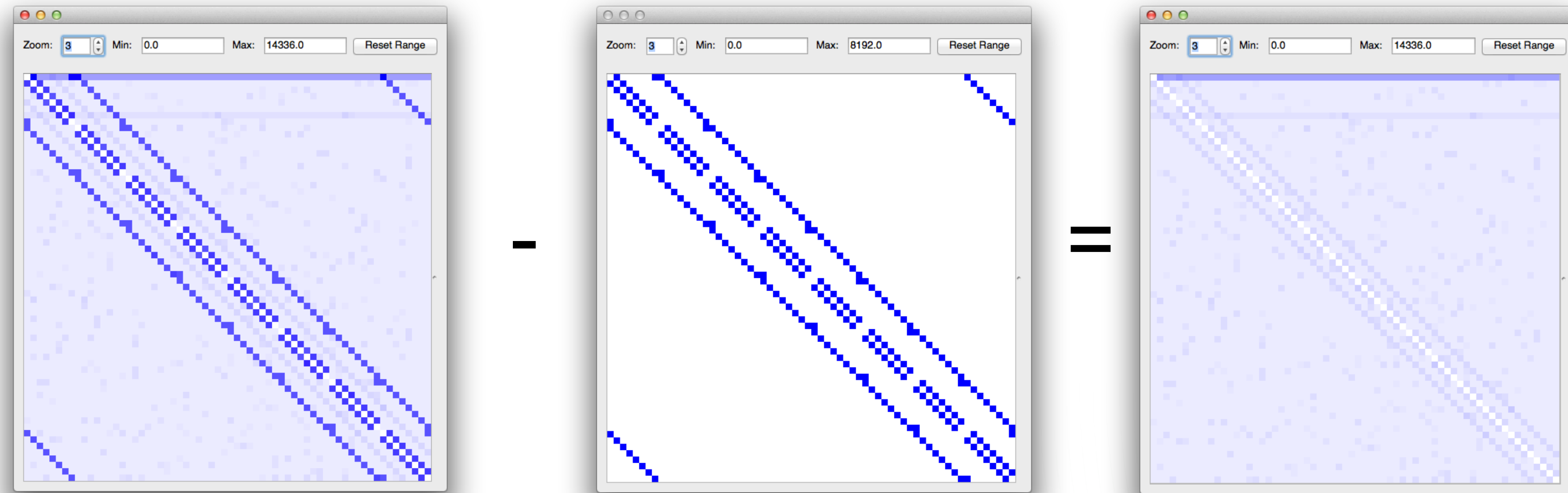
- We want concise way to express application communication demands
- E.g., “3D Nearest Neighbor plus broadcast and reduce” instead of:



- But…expertise needed to identify patterns from communication matrices

Inspiration: Sky Subtraction

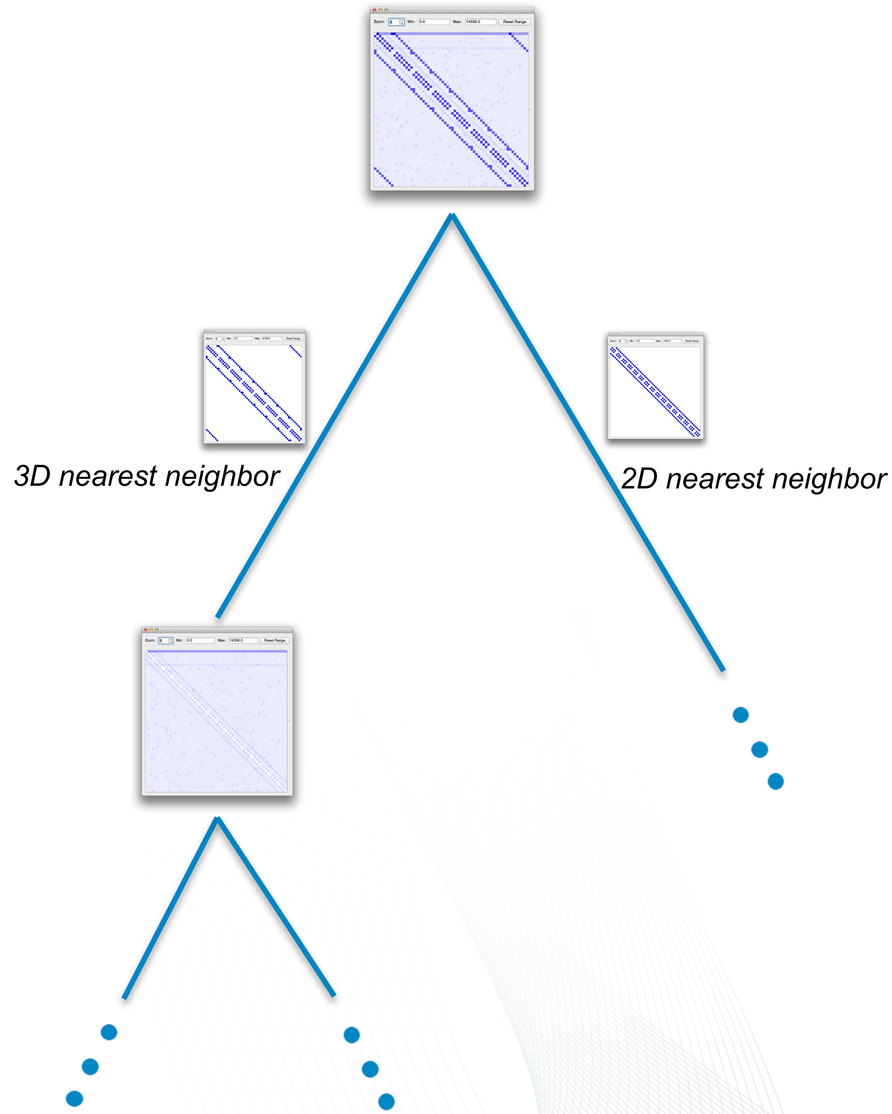
- Inspired by sky subtraction: *given an image, remove the known to make it easier to identify the unknown*



Recognizing and removing the contribution of a 2D nearest neighbor pattern in a synthetic communication matrix. This represents ***one step*** *in a search-based approach.*

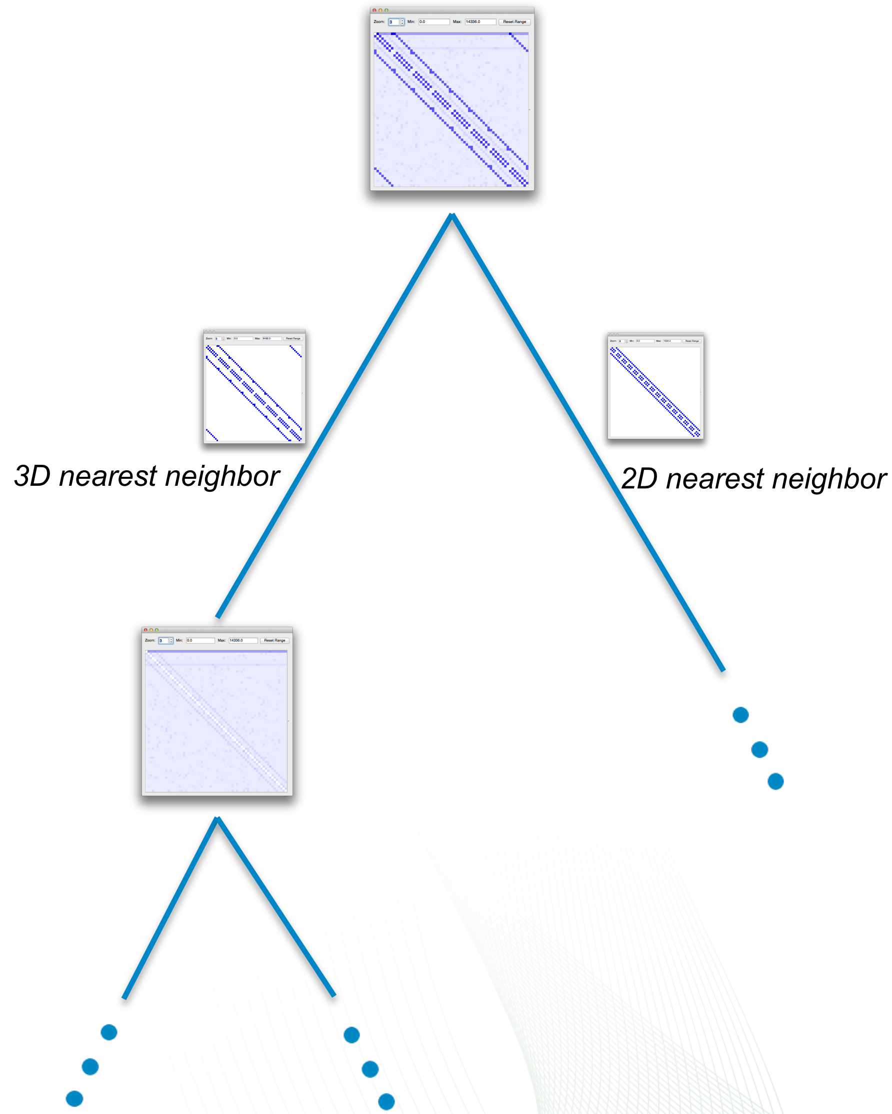
Our Approach: Search Results Tree

- Automated search using a library of patterns
- Search results tree
  - Each node represents a communication matrix with an associated *residual* that captures how much volume is represented by the matrix
  - Each edge represents a recognized pattern in parent node's matrix; subtracting that pattern results in child node's matrix



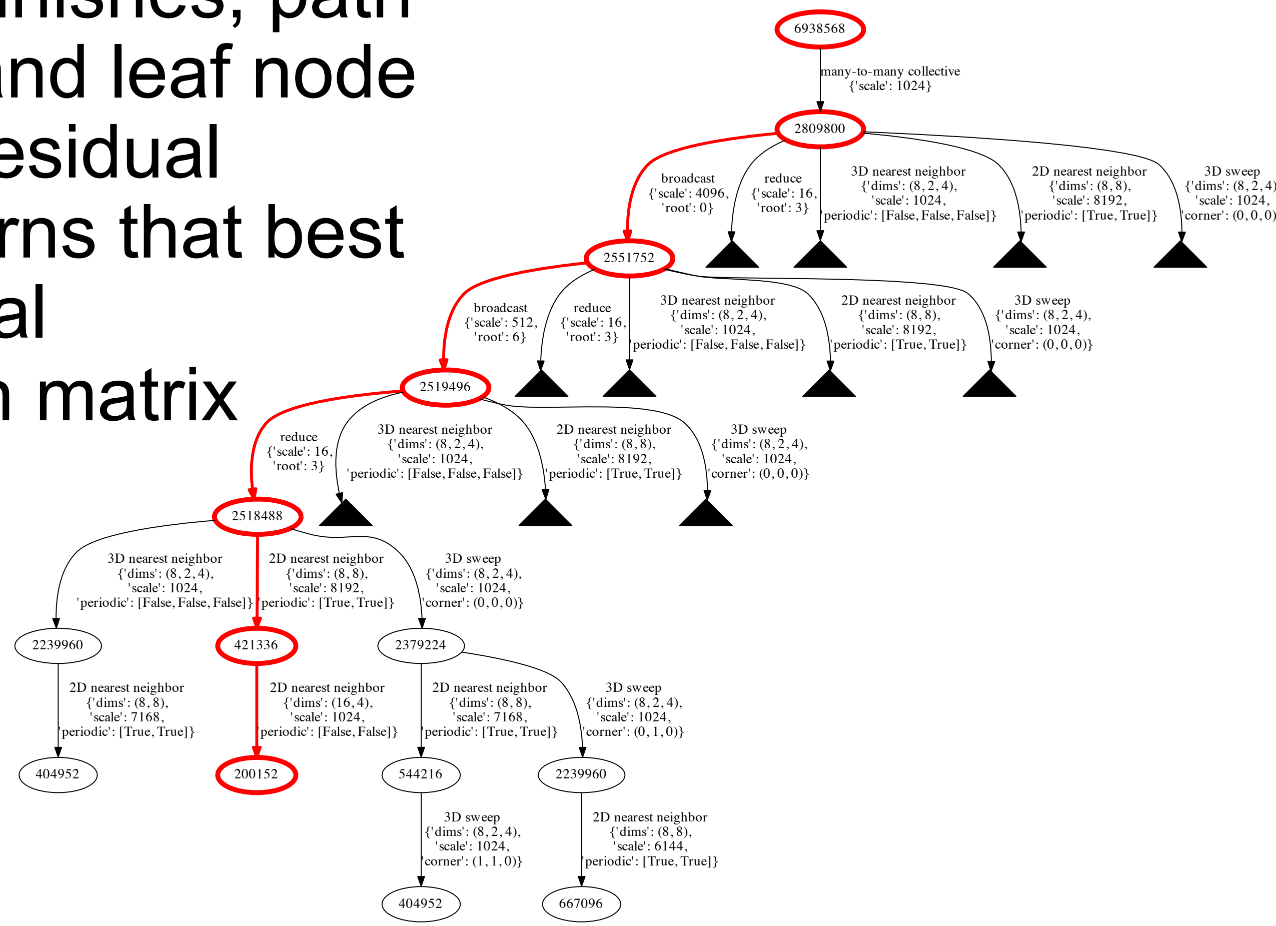
Our Approach: Algorithm Overview

- Associate original communication matrix with root node
- For each pattern in pattern library
  - Attempt to recognize the pattern in node's matrix
  - If recognized, add child node and edge to search result tree
- For each child node added, recursively apply search starting at child node



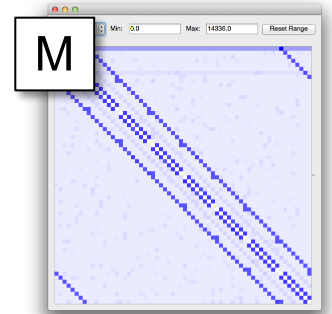
Our Approach: Final Result

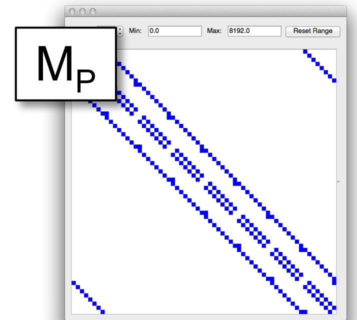
- When search finishes, path between root and leaf node with smallest residual indicates patterns that best explains original communication matrix



Pattern Recognition

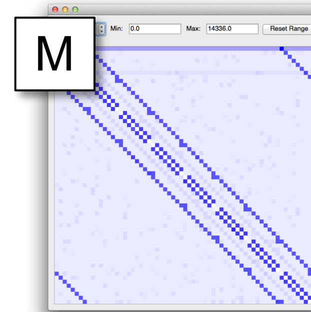
- Library of scale-independent pattern generators and recognizers
- Given matrix M and recognizer for pattern P
  - Determines number of processes represented in M
  - Checks entries in M that should be non-zero, keeping track of smallest non-zero value seen (for computing scale)
    - Detects 2D and 3D pattern dimensions based on non-zero diagonals
    - Detects root process for broadcasts and reduce
    - Detects origin corner for 3D wavefront
  - If all entries that should be non-zero are non-zero, reports that pattern is recognized and provides the scale

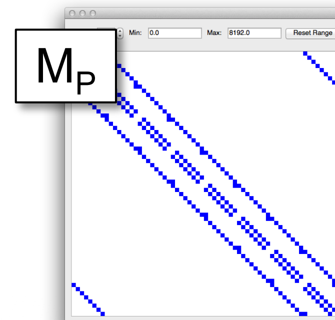


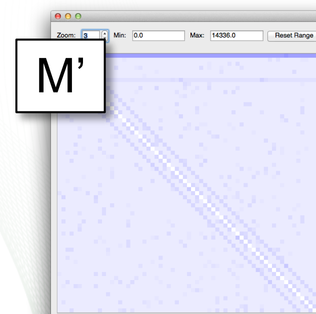


Pattern Removal

- When pattern P is recognized in M at scale S
  - Generator for P generates matrix M_P with scale 1
  - Search forms $M - SM_P = M'$, computes residual of M', and adds child node for M' with edge labeled with P and S



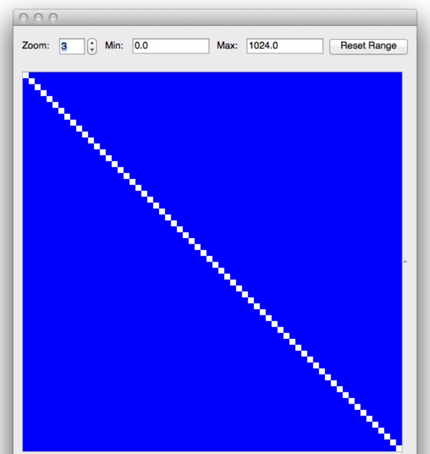


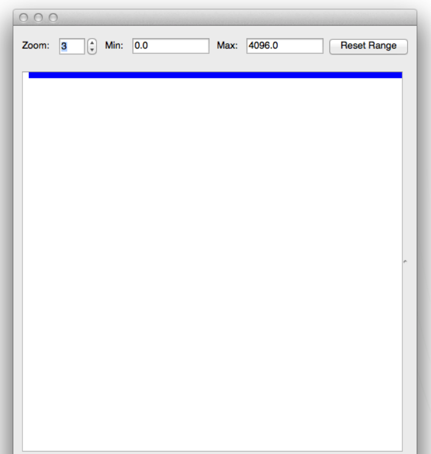


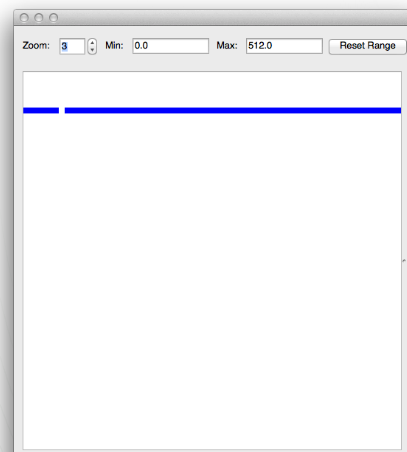
Recognition Order

- Recognition order matters
  - E.g., search recognizes and removes pattern for a broadcast, but doing so precludes subsequent recognition of all-to-all
- At each node in search results tree search attempts to recognize all patterns so search considers all permutations of pattern orderings
- As search speed optimization, always considers rootless collectives first
  - Otherwise, will recognize a long sequence of rooted collectives
  - Rooted collective sequence is equivalent from a topology/message volume perspective

Rootless collective pattern







Broadcast patterns from root 0 (left) and root 6 (right)

Residual

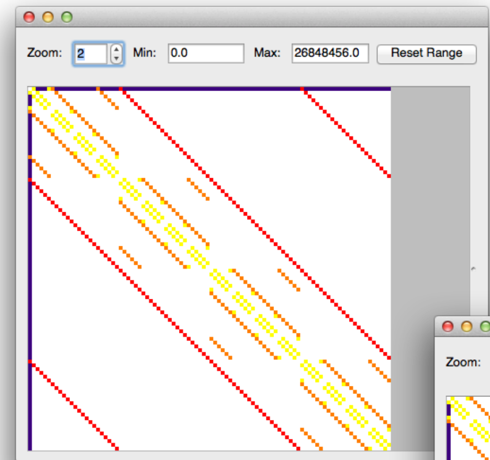
- Current residual definition is sum of values in matrix, representing amount of traffic to be explained
  - Lower is better
  - Simple to understand
  - Simple to compute
  - But, absolute values can be very large, even for modest-sized programs
- Alternatives possible
  - Keep definition and express as percentage of original message volume
  - Statistics (e.g., average volume across all processes)

Implementation

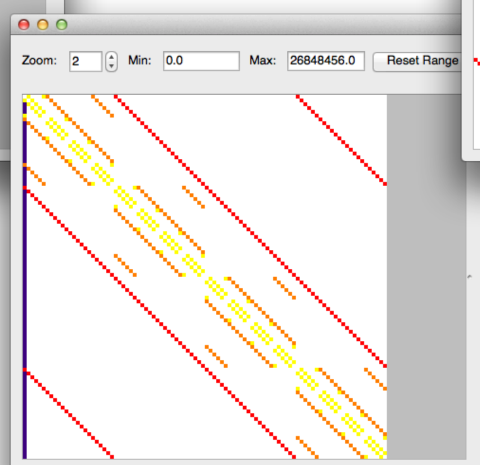
- AChax, implemented in Python using NumPy and SciPy matrix support
- Each pattern is a Python class with Recognize and Generate methods
  - Many-to-many
  - Broadcast
  - Reduce
  - 2D Nearest Neighbor
  - 3D Nearest Neighbor
  - 3D Wavefront (sweep) from a corner
  - Random (generate only)
- AChax search engine reports collection of patterns and their scale that best explains original communication matrix, and optionally:
  - Matrix identified as having smallest residual
  - Log of search actions
  - Search results tree in format that can be visualized by GraphViz
  - Sequence of files containing intermediate matrices on path between tree root and leaf with lowest residual

Example: LAMMPS

- Communication matrix collected using mpiP from 96 process run on Keeneland Initial Delivery System, EAM benchmark problem
- Basically a 3D Nearest Neighbor pattern, but imperfect pattern (red circle in last figure)

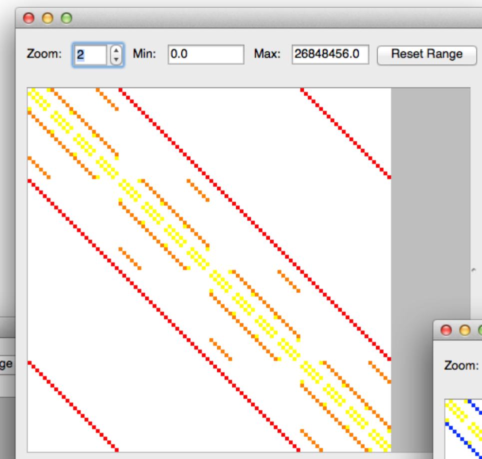


Original matrix

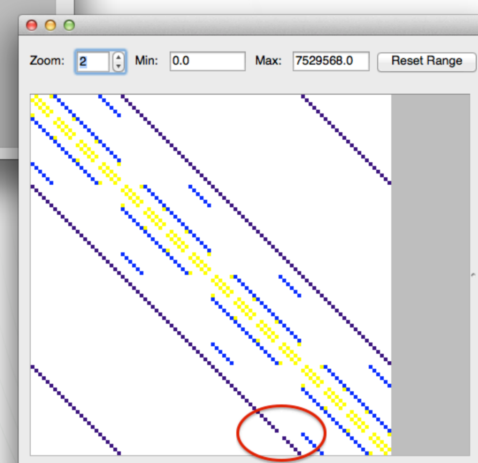


After removing broadcast

After removing reduce



After removing 3D nearest neighbor, dimensions (4,4,6), periodic



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LAMMPS: Expressing Search Results

- Search results trees are useful but not particularly concise
- We use an expression using parameterized pattern names with scale coefficients, e.g.,

$$
\begin{aligned}
C_{LAMMPS} = {} & 13354 \cdot Broadcast(root : 0) + \\
& 700 \cdot Reduce(root : 0) + \\
& 19318888 \cdot 3DNearestNeighbor(\\
& \quad dims : (4, 4, 6), \\
& \quad periodic : True)
\end{aligned}
$$

Future Directions

- Expand pattern library
  - Always more patterns to support
  - Irregular patterns
- Handle imperfect patterns (e.g., LAMMPS example) with nearness score
- Add better support for operation identification
  - We can recognize an all-to-all pattern, but cannot discern which rootless MPI operation was used using just the matrix, nor say whether it was truly an all-to-all or a naïve sequence of broadcasts
  - Incorporating tracing and/or profiling data may help
- Truly scale-independent expressions
  - Modeling integration (e.g., ASPEN)

Future Directions (II)

- Search optimizations
  - Parallelize the search
  - Prune the search by recognizing search path prefixes that are permutations
    - Recognition order matters, but having recognized A, B, C on one path results in same matrix as other path that recognized C, A, B as long as scales match – don't need to continue search from both
- Phase-aware characterization
  - mpiP can generate per-phase communication matrices
- Using image recognition algorithms for pattern matching

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Summary

- We are researching an approach for automatically characterizing communication patterns of message passing applications
- We look for combination of simple patterns that best explains observed communication behavior using:
  - Automated search through large search space
  - Pattern generator library
  - "Subtraction" of recognized patterns from observed communication
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- http://ft.ornl.gov/~rothpc