# Component Integration and Optimization

## For High Productivity and Performance

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http://lacsi.rice.edu/review/slides_2006/

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# Outline

- Component Integration Systems
  - —Support for the maintenance and optimization of component libraries
  - —High-productivity languages
- Retargetable High Performance Components
  - —Automatic tuning of components for specific computing platforms
  - —Design of adaptive components
- Application Drivers from LANL Weapons Program
  - —Marmot, Telluride, Ajax programming system (FLAG)
- Previous Projects, Renewed Relevance
  - —High-level Java optimization
  - —Program Preparation for Heterogenous Computing Environments (e.g., Grids)

# Some Previous Accomplishments

- JaMake Java Framework
  - Collaboration with CartaBlanca Project
  - Performs object inlining on arrays of objects
    - Overcomes the cost of using full OO polymorphism
    - Achieved 80% improvement on the LANL Parsek code
    - Critical to CartaBlanca R&D 100 Award
  - Results apply to C++ and Python (and Ajax?)
  - Attracted NSF funding, published 7 refereed papers
- Grid Research
  - Drove performance prediction research
  - Effective performance-model based scheduling
  - VGrADS: NSF ITR (Large)
  - Ideas for Grid in a box
    - Many future supercomputers will have heterogeneous computing components: good scheduling will be critical for performance

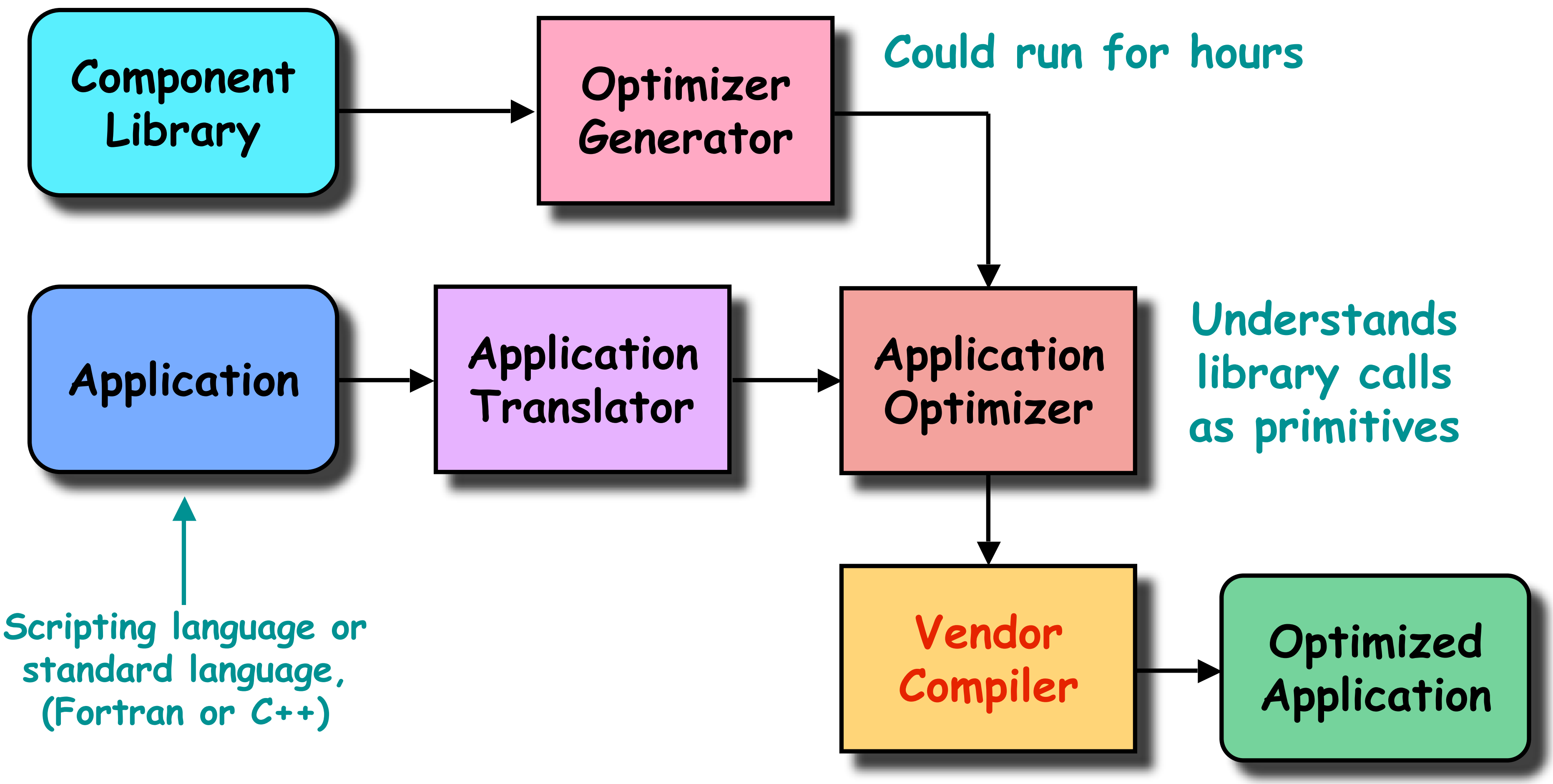
# Component Integration

- **Supporting Technologies for Component Integration**
  - Transformation systems to eliminate overheads due to abstraction
  - Component integration systems to automate specialization
    - Key problem: integration of data structure components with functional components
- **Continue Collaborations with LANL Code Projects**
  - Marmot
    - Pursue directions in the draft collaboration plan (later)
    - Application of object-oriented optimization strategies (from JaMake, applied to C++ via ROSE infrastructure)
  - New LANL Contact from X Division
    - Hank Alme
- **Challenge Applications**
  - Export-restricted codes including hydro and transport
  - Representative of ASC code styles

# Participants

- LANL Contacts
  - Staff: Hank Alme, Craig Rasmussen
- Rice
  - Faculty/Staff: Ken Kennedy, Bradley Broom*, Zoran Budimlic, Keith Cooper, Arun Chauhan*, Rob Fowler, Guohua Jin, Tim Harvey, Chuck Koelbel, John Mellor-Crummey, Steve Reeves, Linda Torczon
  - Students: Raj Bandyopadhyay, Jason Eckhardt, Mary Fletcher, Alex Grosul, Mack Joyner, Cheryl McCosh, Apan Qasem, Todd Waterman, Anna Youssefi, Rui Zhang, Yuan Zhao
- Tennessee
  - Faculty/Staff: Jack Dongarra, Shirley Moore, Graham Fagg, George Bosilca
  - Students: Haihang You, Jelena Pjesivac-Grbovic, and Jeffery Chen

# Telescoping Languages

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# Telescoping Language Advantages

- Optimized script compilation times can be reasonable
  - Investment in library analysis speeds script optimization
- High-level optimizations possible
  - Exploit library designer's knowledge of routine properties
  - Specialize library routines during optimizer generation to exploit expected calling sequences
    - Apply high-level transformations based on identities
    - Factor and/or fuse library primitives as appropriate
- User retains substantive control over performance
  - Mature code can be built into a library, annotated with properties to aid optimization and fed to library compiler
- Reliability can be improved
  - No hand coding to context

# Component Integration System

- Component integration systems are important productivity tools
- Programs constructed from them can be slow
  - —No context-based code improvements can be applied
  - —Component crossing overheads are high
    - – Result: heavyweight components, insufficient separation of concerns
- Claim: Telescoping languages can address this problem
  - —Can be applied to construct component integration systems that yield high-performance applications
  - —Can make components usable in contexts that have been previously considered impractical
- ASC Relevance
  - —Component-based software is critical for productivity and reliability
  - —Performance must be high for software to be usable
  - —Useful to prototype in high-productivity language (Python, Matlab)

# Component Integration Challenge

- **Integration of different component libraries that**
  - —Implement data structures (e.g., sparse matrices)
  - —Implement functions on data structures (e.g., linear algebra)
- **Problem: Performance**
  - —High function overhead for data structure access (frequently invoked)
  - —Need optimization for special contexts
    - – e.g., invocation in loops
- **Claim: Telescoping languages can handle this well**
  - —Advance generation of specialized entries
  - —Transformation pass to perform substitution

# What We Have Done

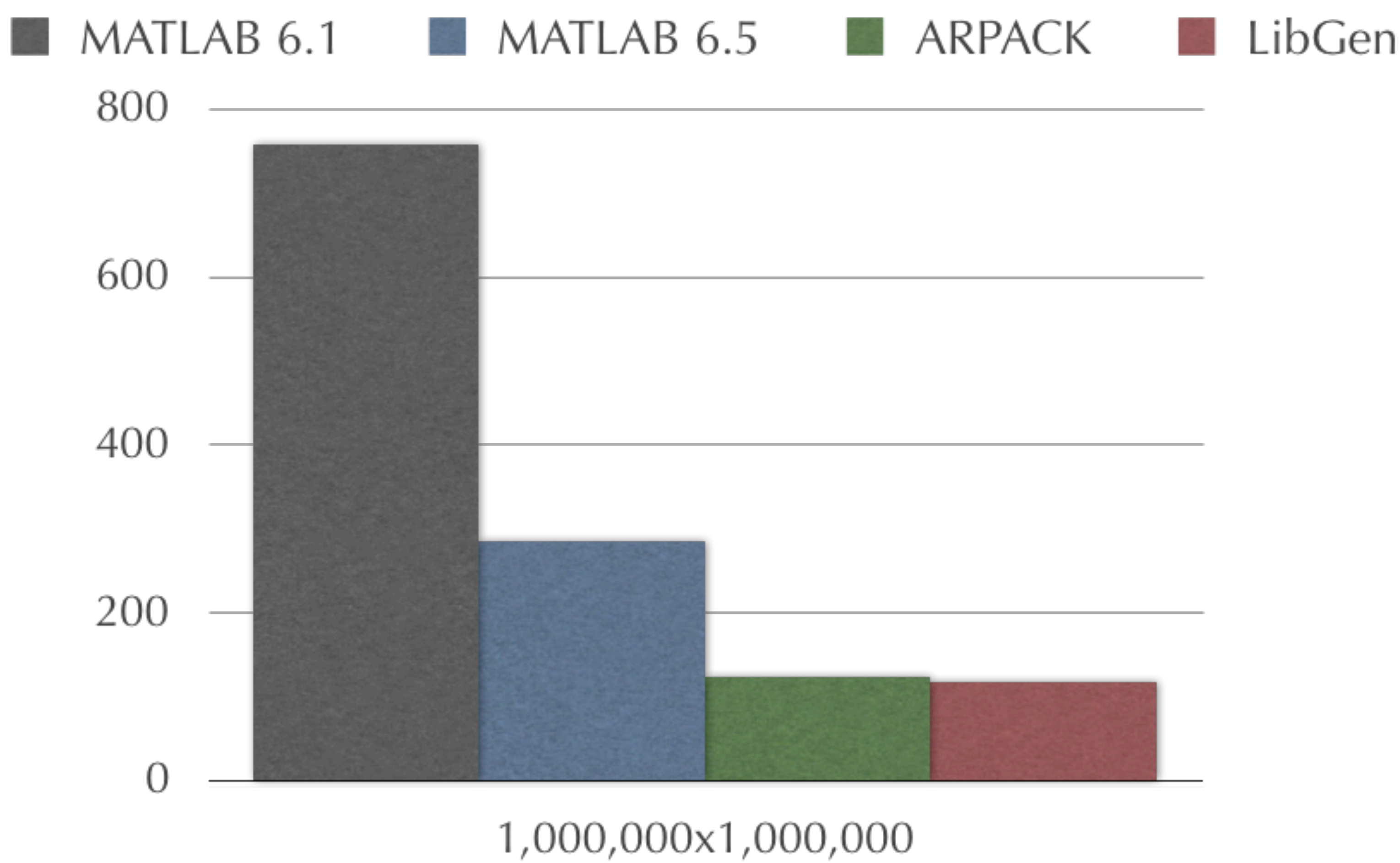
- **Developed base-language compiler technology**
  - Type inference: Key to generation of C or Fortran from Matlab, S, or Python
    - Useful even if C++ or Fortran is your scripting language
- **Conducted preliminary studies**
  - Matlab SP (Signal Processing), LibGen (library generation)
    - Six papers, one Ph.D., two Master's
  - R compilation (funded separately by DOD)
- **Demonstrated benefits of telescoping languages as component integration system (via LibGen)**
- **Developed strategy for generalized data structures**
  - Including addition of parallelism to scripting languages (funded by ST-HEC program from NSF/DARPA)
- **Met with Marmot team to explore collaboration opportunities**
- **Begun examination of applicability to codes written using Ajax Programming System (e.g., FLAG)**

# Library Generator (LibGen)

- **ARPACK**
  - Prof Dan Sorensen (Rice CAAM) maintains ARPACK, a large-scale eigenvalue solver
- **Methodology**
  - He prototypes the algorithms in Matlab, then generates 8 variants in Fortran by hand:
    - {Real, Complex} x {Symmetric, Nonsymmetric} x {Single,Double}
    - Dense vs Sparse handled by special interface
- **Could this hand generation step be eliminated?**
  - Answer: YES
  - Key technology: Constraint-based type inference
    - Polynomial time algorithm to compute type jump functions

      Map input types to variable types

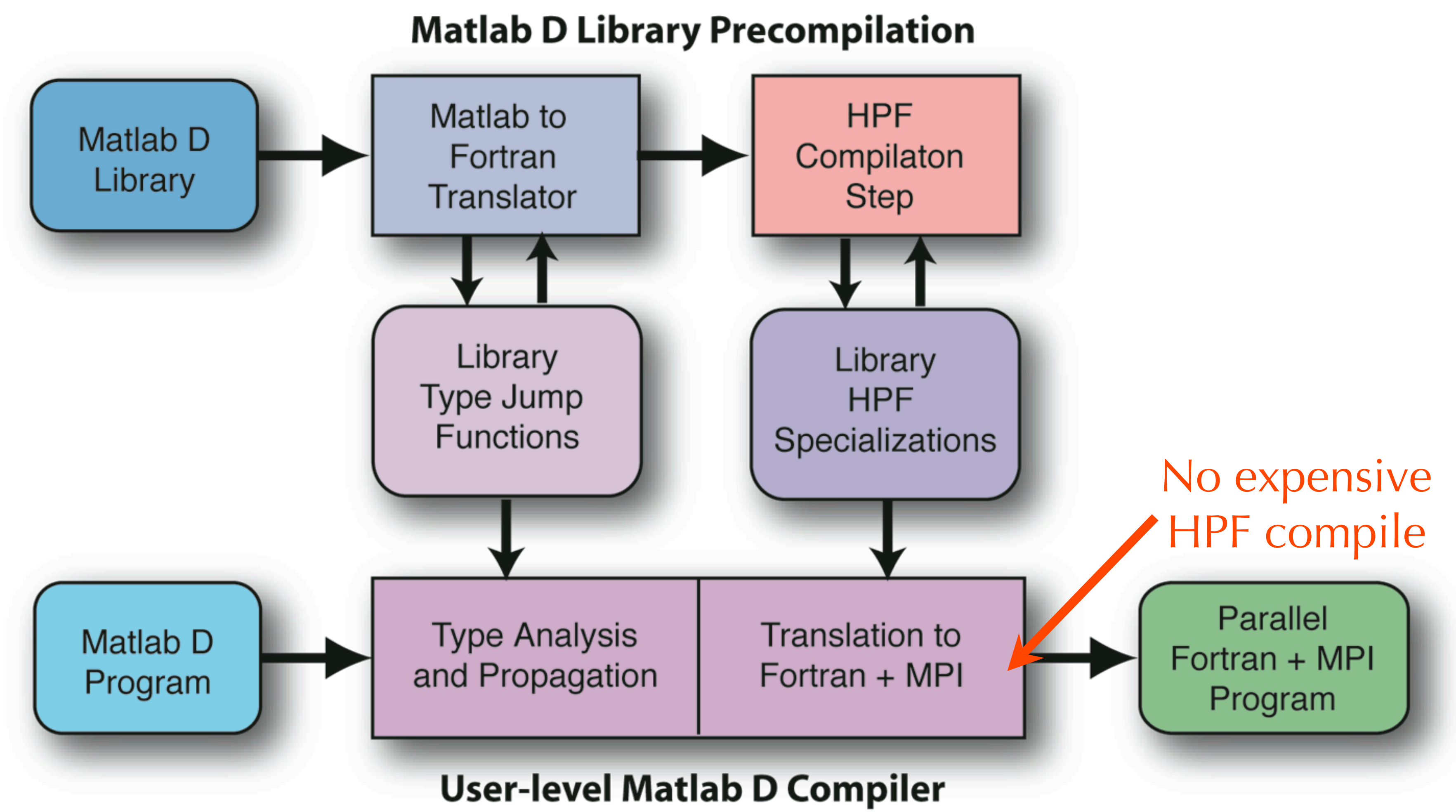
# LibGen Performance



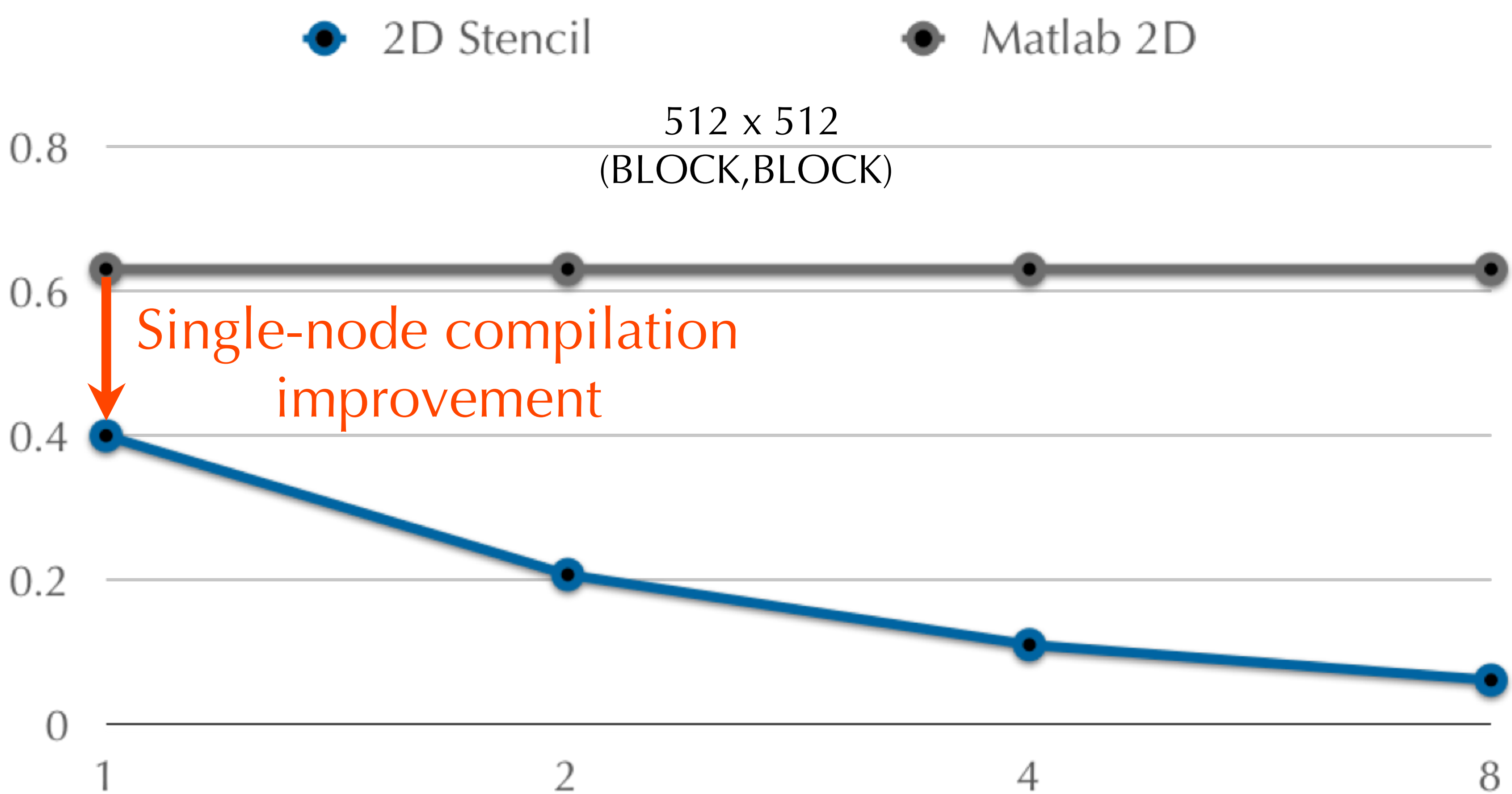
# Parallelism in Scripting Languages

- **Tennessee Approach**
  - Global arrays resident on parallel ScaLAPACK server
    - Operations executed local to data
  - Accessible from Matlab, Python, Mathematica clients
    - R should be an easy extension
  - Working now
- **Rice Approach**
  - Support for multiple distributions
    - Standard plus user-defined
  - Compilation to Fortran 90 + MPI
    - Runs on back end server
  - Telescoping languages + HPF technology for specialization
    - Specialize each operation for each distribution
    - Specialize communication for each distribution pair
  - Funded by NSF ST-HEC (DARPA HPCS)

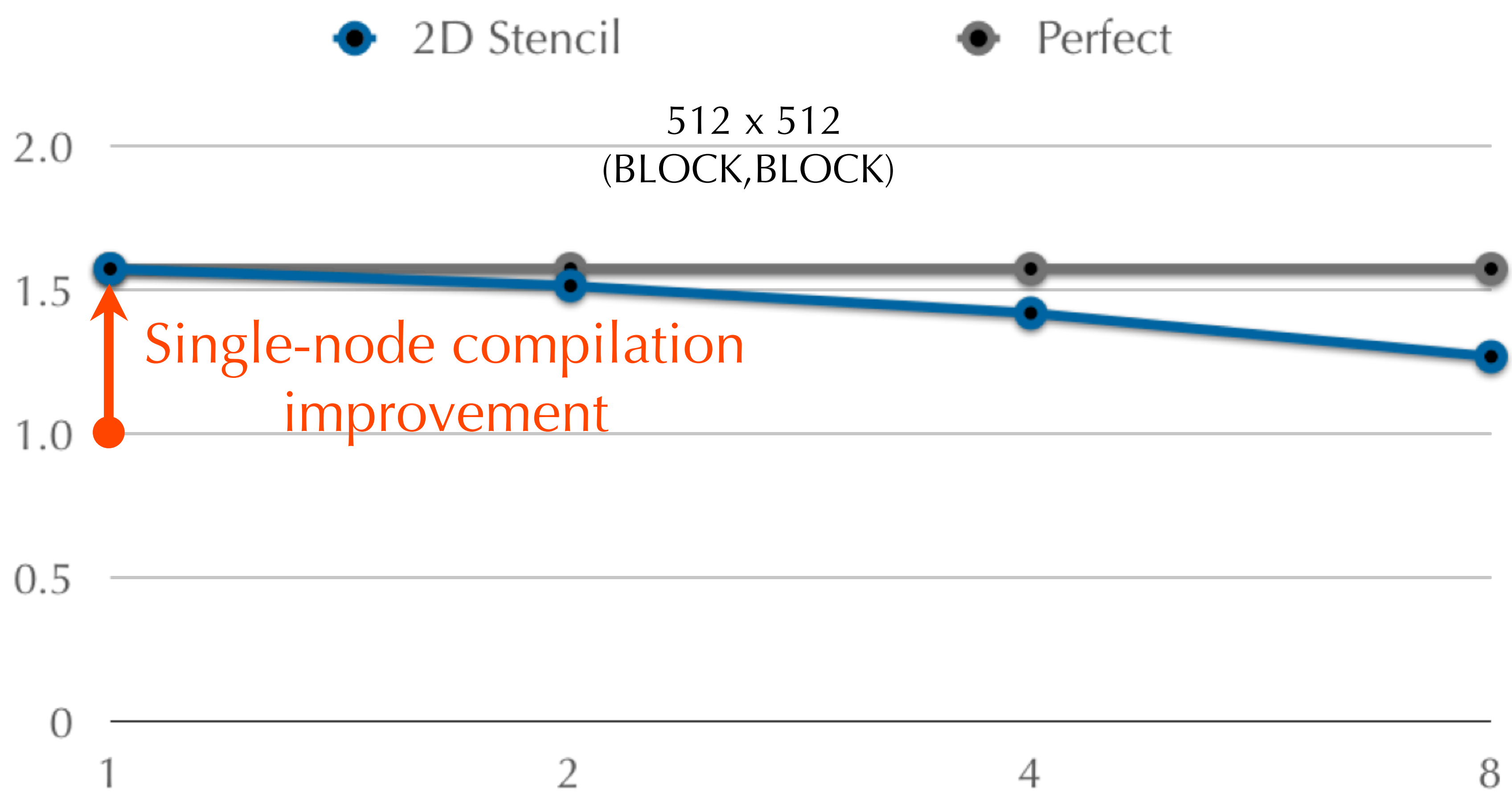
# Rice Parallel Matlab



# Performance: 2D Stencil



# Parallel Efficiency: 2D Stencil



# LACSI Interactions

- **Priorities and Strategies Meetings**
  - Inputs from Steven Lee and Ken Koch led to direction change
- **Attended Workshops**
  - Common Component Architecture, LACSI Symposium 2002
  - Initial Components Workshop (April 16-17, 2003)
- **Discussions with Marmot Group**
  - Monterrey Methods Workshop (March 16-18, 2004)
  - Components Workshop at LANL (June 24, 2004)
    - Developed an outline plan for collaboration
  - Additional meetings during LACSI visit Oct 31-Nov 3, 2005
- **Meetings with Code Performance Team (Alme)**
  - October-November 2005 visit, December 2005
    - Leading to focus on Ajax (Scott Runnels)

# What We Plan to Do

- Seek (and solve) component integration challenge problem
  - Emphasis on efficiency of frequent component-crossing
    - Integration of data structure and function
- Explore opportunities in other ASC codes
  - Initiating new project to explore improvements in Ajax programming system (on FLAG)
    - Telescoping languages and object-oriented optimizations
- Continue interactions with Marmot Project
  - Goal: build tools to help them on their second or third iteration
- Explore application of parallel Matlab and R to V&V codes from D1 (Dave Higdon)
- Relevance to ASC
  - Success will make it easier to use modern component-based software development strategies in ASC codes
    - Without sacrificing performance

# Specific Topics

- Specialization Strategies
  - Specialized handling of multiple materials in cells
  - Compiler-based specialization to sparse data structures
  - Combined telescoping languages and dynamic code selection
    - Optimization by limited computation reorganization
- Improved Translation within Ajax
- Tools for Preoptimization of Libraries
  - Pre-specialization of library codes to expected calling contexts
  - Potential source of components: Trillinos
- Mining of Traditional Applications
  - Construction of libraries for inclusion in domain languages
- Rapid Prototyping Support
  - Compilation of scripting languages (Python, Matlab) to Fortran/C

# Automatic Component Tuning

- **Participants: Four Groups within LACSI**
  - Tennessee: Jack Dongarra
    - Collaboration with LLNL ROSE Group (Dan Quinlan, Qing Yi)
  - Rice: Ken Kennedy and John Mellor Crummey
    - Students Apan Qasem and Yuan Zhao
    - Also collaborating with ROSE Group
  - Rice: Keith Cooper, Devika Subramanian, and Linda Torczon
    - Students Todd Waterman and Alex Grosul

# Automatic Component Tuning

- Goal: Pretune components for high performance on different computing platforms (in advance)
  - Models: ATLAS, FFTW, UHFFT
  - Generate tuned versions automatically
- Strategy: View as giant optimization problem with code running time as objective function
  - For each critical loop nest:
    - Parameterize the search space
    - Prune using compiler models based on static analysis
    - Employ heuristic search to find optimal point and generate optimal code version
  - Typical optimizations:
    - Loop blocking, unroll, unroll-and-jam, loop fusion, storage reduction, optimization of target compiler settings, inlining, optimization of function decomposition

# New Autotuning Work

- Combination of three optimizations (student: Apan Qasem)
  - Cache tiling, register blocking, and loop fusion (new)
- Loop fusion
  - Critical for performance, particularly on Fortran 90 codes
    - Array assignments are “scalarized” in multiple dimensions
    - Fusion can dramatically enhance memory performance
  - Problems:
    - too much fusion can lead to conflict misses
    - fusion and tiling interactions can degrade performance
  - Strategy:
    - Strategy: construct combined model that predicts “effective cache size” (fewer than 2.5% conflict misses) then fuse and tune to that size
    - Advantage: many fewer evaluations, basically same performance

# Automatic Tuning

- **Successes**
  - Experimental infrastructure
    - LoopTool, MSCP, ATLAS2, CODELAB
  - Large-scale experiments
  - Principles demonstrated
    - Effectiveness of heuristic search (including parallel search)
    - Importance of search-space pruning using compiler models
  - Papers published
    - Ten refereed publications and one technical report (see web site)
  - Established an Autotuning Community
    - LACSI Workshop 2005
- **Relevance**
  - Dramatically increases productivity of scientific programming
- **Connections to ASC**
  - Sweep3D (1.3x on Alpha), ASC performance group, Marmot, Truchas

# Summary

- **Component integration languages and frameworks**
  - —High Level: Matlab, S, Python plus component libraries
  - —Low Level: C, C++, Fortran
- **Compilation technology**
  - —Type inferencing to drive translation to C or Fortran
  - —Telescoping languages to pre-optimize libraries
  - —Parallelism in scripting languages
    - – Parallelism based on distribution
- **Component Autotuning**
  - —Goal: ATLAS-style automatic tuning for generalized applications, UHFFT-style automatic tuning for decomposable (library) components
  - —Exploring heuristic search and static search-space pruning
- **Technology Transfer**
  - —Focus component integration on problems arising from ASC code projects
  - —Automatic tuning applicable to general languages