STAPL:
A High Productivity Programming Infrastructure for Parallel and Distributed Computing

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http://parasol.tamu.edu/stapl/

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Motivation

- There is a growing need for parallel programs
  - Large scale parallel machines getting larger
  - small scale parallel machines (i.e., multicores) are becoming ubiquitous
- Challenges
  - Parallel programming is specialized & costly
  - portability
  - Scalability & Efficiency is (usually) poor
  - Composability and integration with other components

STAPL

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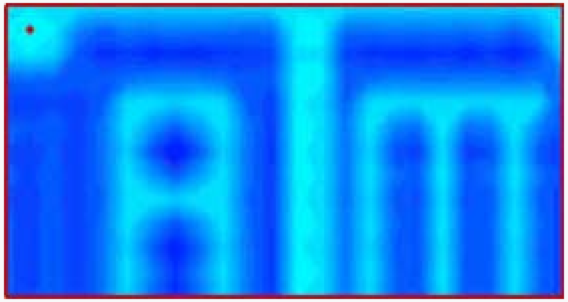
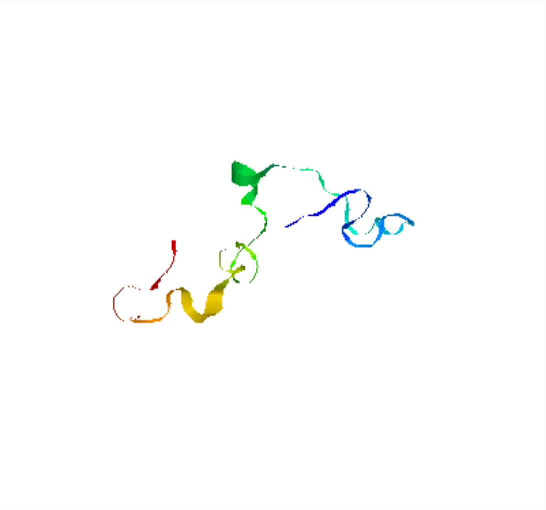
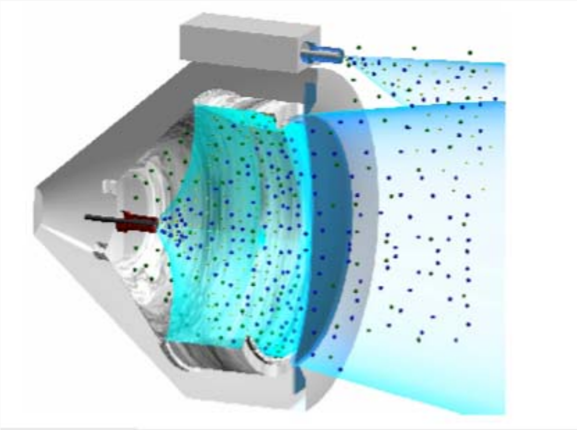
- **STAPL:** Parallel components library and development environment
  - Extensible & composable
  - Parallel superset of **STL**
  - Inter-operable with STL
- Layered architecture: User – Developer - Specialist
  - Extensible
  - Portable (only lowest layer needs to be specialized once at system installation)
- High Productivity Environment
  - components have (almost) sequential interfaces

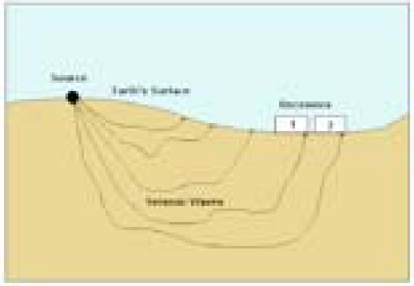
Applications Using STAPL

- Nuclear Eng. - Discrete Ordinates Particle Transport
- Bioinformatics - Protein Folding
- Geophysics - Seismic Ray Tracing
- Aerospace - Lattice Boltzman Method









Outline

- Motivation
- STAPL: Standard Template Adaptive Parallel Library
  - Philosophy & Design Overview
  - Components for Program Development
    - pContainers, Views, pRange, pAlgorithms
  - Portability and Optimization
    - RTS & ARMI Communication Library
    - Adaptive Components, Adaptive Algorithm Selection
  - Applications developed using STAPL
- Summary & Future Work

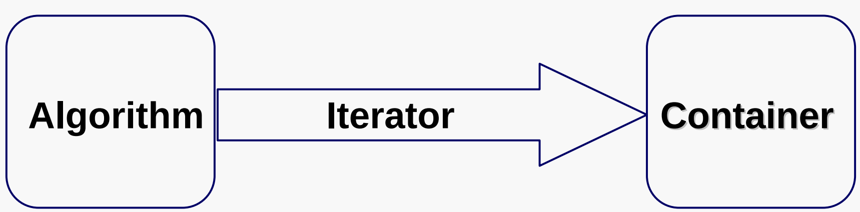
STAPL Specification

- Adopts STL Philosophy: Generic Programming
  - composable (unlike STL)
  - Interoperable with other libraries and packages
- Shared Object View
  - User Layer: No explicit communication
  - Machine Layer: Architecture dependent code
- Distributed Objects
  - no replication (visible to the user)
  - no software coherence (visible to the user)
- Portable efficiency
  - Adaptation to environment
  - Runtime System virtualizes underlying architecture
- Compiles with any standard C++ compiler (GCC) (It's a library – not a language)

STL: Standard Template Library

Generic programming components using C++ templates.

- **Containers - collection of other objects**
  - vector, list, deque, set, multiset, map, multi_map, hash_map
  - Templated by data type: vector<int> v(50);
- **Algorithms - manipulate the data stored in containers**
  - count(), reverse(), sort(), accumulate(), for_each(), reverse()
- **Iterators - Decouple algorithms from containers**
  - Provide generic ***elementary access*** to data in containers
  - can define custom ***traversal*** of container (e.g., every other element)
  - count(vector.begin(), vector.end(), 18);



STAPL: Standard Template Adaptive Parallel Library

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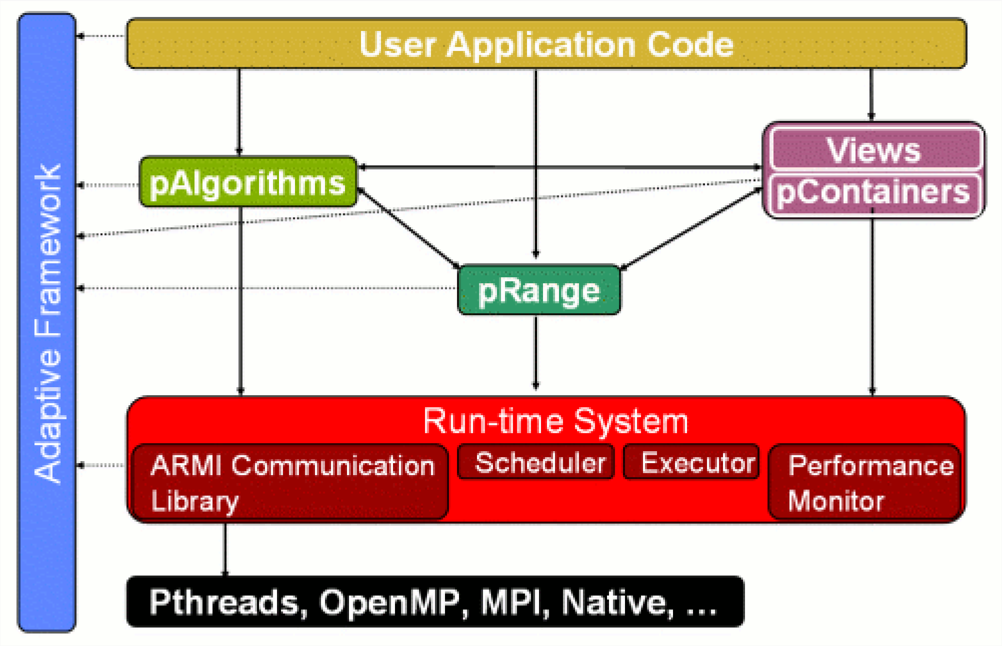
STAPL: A library of parallel, generic constructs based on the C++ Standard Template Library (STL)

- **Components for Program Development**
  - pAlgorithms, pContainers, Views, pRange
- **Portability and Optimization**
  - STAPL RTS and Adaptive Remote Method Invocation (ARMI) Communication Library
  - Framework for Algorithm Selection and Tuning (FAST)



Usage Model

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- Two Models:

Application Programmer	**Library Developer**
Single threaded	Multithreaded
Shared Memory	PGAS
Implicit Synchronizations	Explicit Communications
Thread Safe Operations	

- Data and Task Parallelism co-exist
- programmers can use library developer options, if desired

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pContainers

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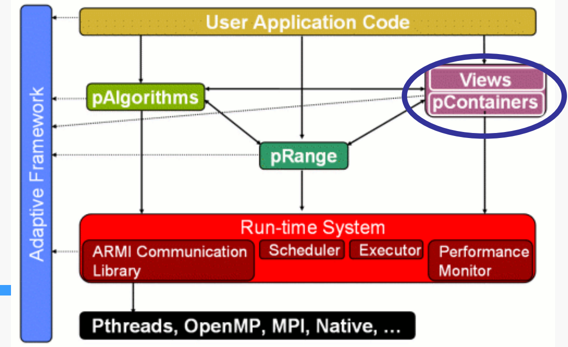
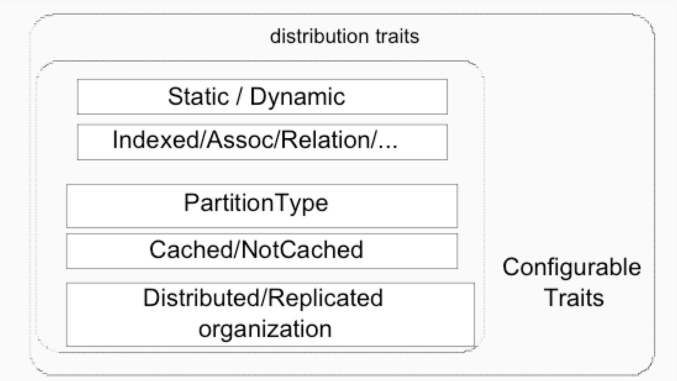


Generic, distributed data structures with parallel methods

- Usability
  - Shared object view
  - Generic access mechanism through Views
  - Handle data distribution and remote data access internally
  - Interface compatible with sequential counterpart
- Extendability & Composability
  - New (user defined) pContainers extend Base classes
  - pContainers of pContainers
- Efficiency & Adaptability
  - OO design to optimize specific containers
  - Optional user customization of each pContainer instance template parameters & traits
    - Enable/Disable Performance Monitoring, thread safety, ..
    - Select Partition Strategies, consistency models, …



- pContainers currently available in STAPL
  - pVector, pList, pMap, pSet, pMultiMap, pMultiSet, pHashMap, pHashSet, pArray, pGraph, pMatriix

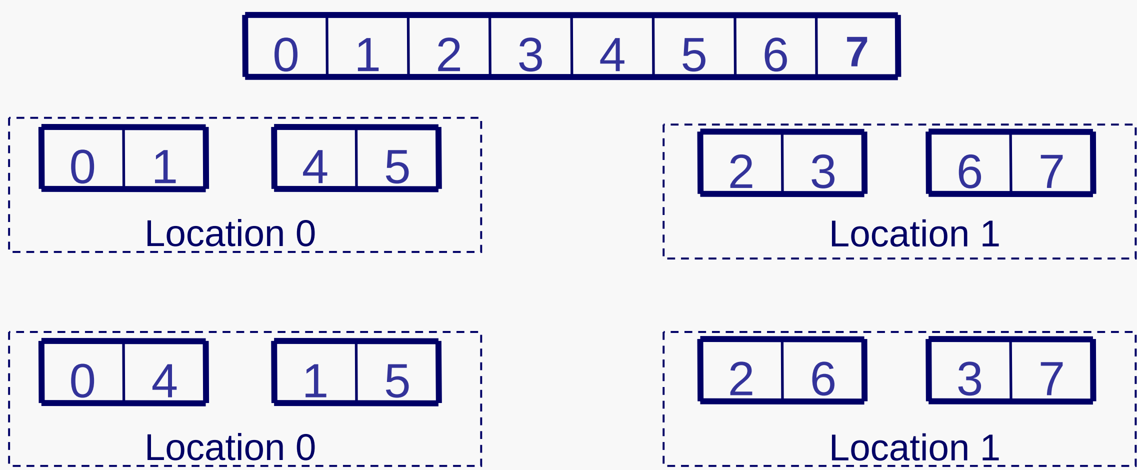
Example: pArray

- pArray is an ordered sequence of elements accessed using indices
- The domain (unique identifiers of pContainer elements) is a range of integers, e.g., [0,7]
- STAPL provides common
  - Logical Partitions of elements (e.g., Blocked, Balanced, BlockCyclic, …)
  - PartitionMappers to map subdomains to locations (e.g., Blocked, Cyclic, …)
  - Users can extend existing & implement new Partitions and Mappers

pArray

Ex 1: Blocked Partition
Cyclic Mapper

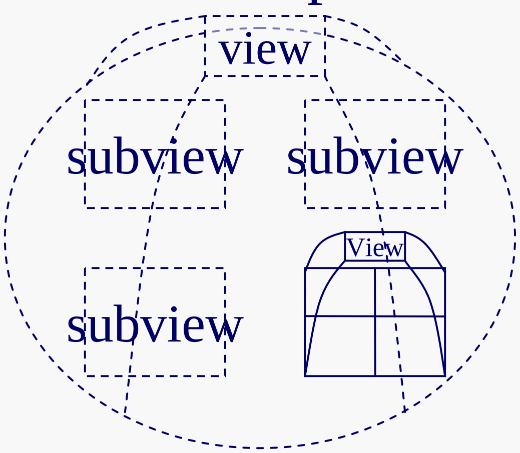
Ex 2: Cyclic Partition
Blocked Mapper



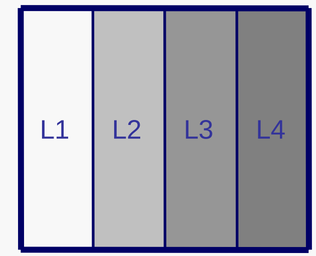
Views

- Views provide generic access mechanism for pContainer
  - STAPL equivalent of STL iterator, extended to allow for efficient parallelism
  - Focus on processing range of items, instead of single item
  - Specify different partitions and data traversal for the data in a pContainer
  - Hierarchically defined to control locality and granularity of parallelism

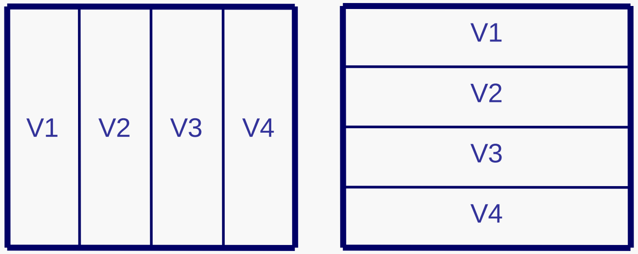
Data Space



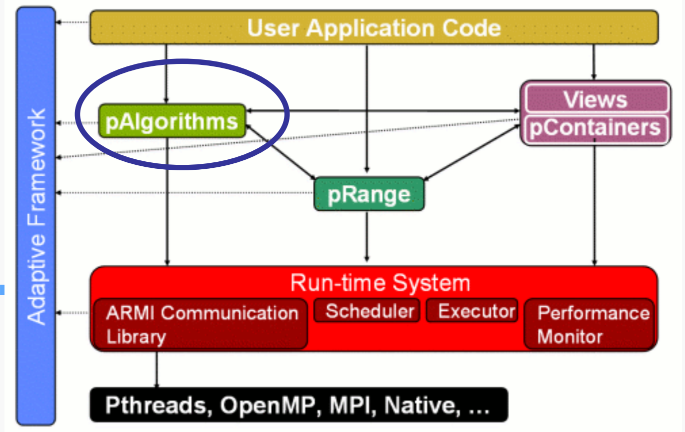
pContainer
Physical
partition



Two logical views - one (left) aligned with physical partition



pAlgorithms



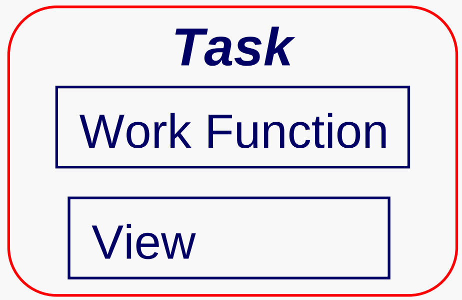
- pAlgorithms in STAPL
  - Parallel counterparts of STL algorithms
  - Additional parallel algorithms
    - Common parallel algorithms:
      - Prefix sums
      - List ranking
    - pContainer specific algorithms:
      - Strongly Connected Components (pGraph)
      - Euler Tour (pGraph)
      - Matrix multiplication (pMatrix)
  - Composable
    - pAlgorithms may invoke pAlgorithms
  - multiple algorithms exist for a particular operation (e.g., sorting) and STAPL adaptively selects which to use

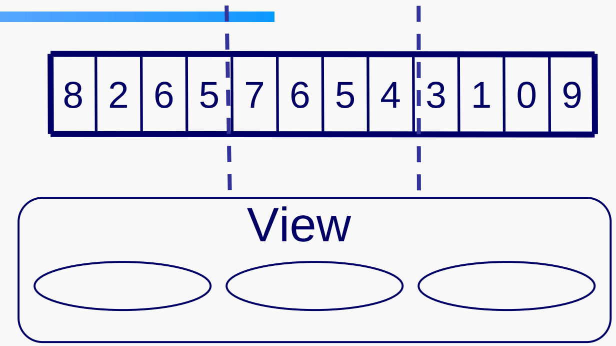
pAlgorithms and Views

- Views are inputs for pAlgorithms
  - Input views specify parallelism the algorithm can exploit
- A pAlgorithm may operate on views before beginning to optimize the computation
  - Refining (subdividing) a sub-view may increase parallelism and locality
    - Views may be adjusted to match data boundary
    - Different views may be adjusted differently to allow easier algorithm specification
- Optimized access methods when all the data of a sub-view is local and contiguous

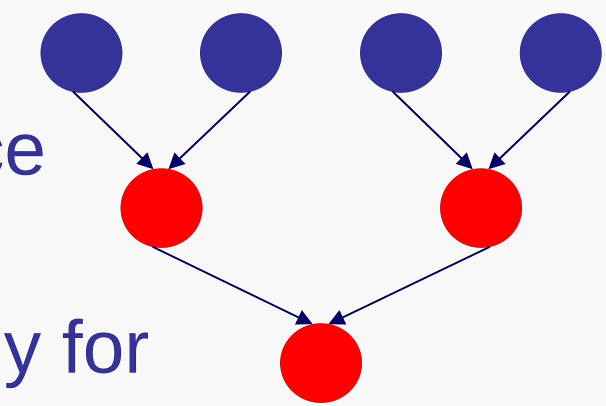
pRange - Task Graphs in STAPL

- Task
  – Work function
  – Data to process





- Task dependencies
  – Expressed in Task Dependence Graph (TDG)
  – TDG queried to find tasks ready for execution

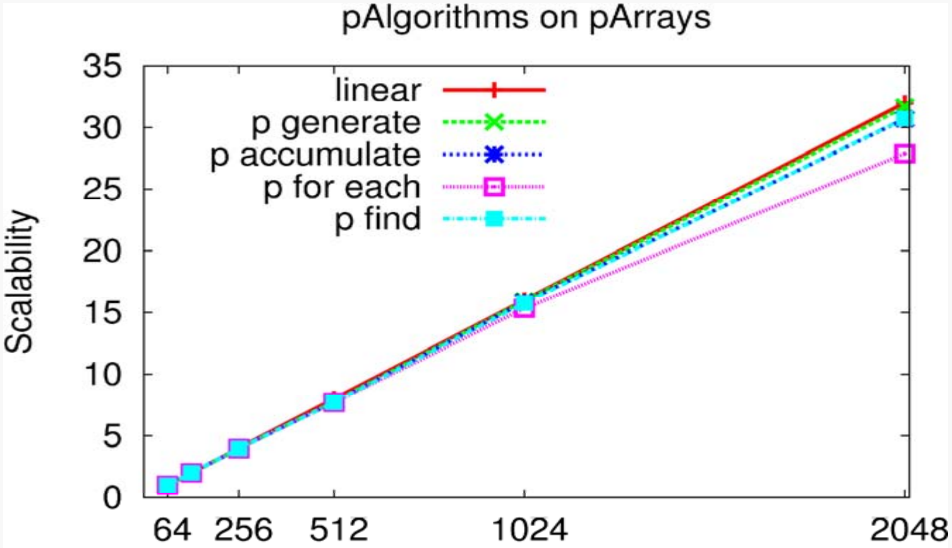


pRange: Simple Dependence Specification

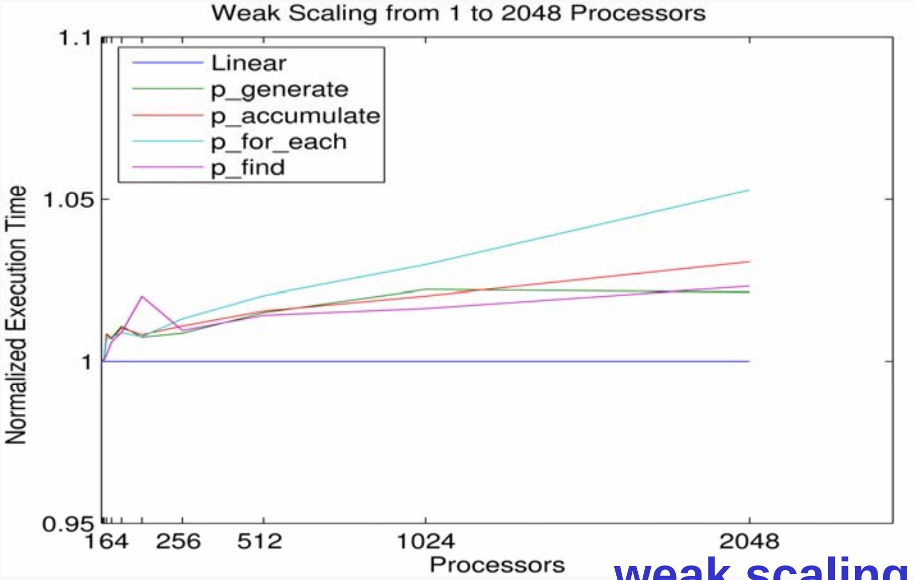
- Goal: Developer expresses dependencies concisely
  - If needed, full enumeration of dependencies is supported

- Common patterns supported in pRange
  - Sequential – sources depend on sinks
  - Independent – no new dependencies needed in composed graph
  - Pipelined – dependencies follow a regular pattern
    - Wave front, tree-based reductions, etc.

Scalability of pAlgorithms



strong scaling



weak scaling

- Results obtained on an IBM P3 machine at NERSC
  - Strong scaling: same problem size as increase #procs
    - Results show scalability relative to 64 processors
  - Weak scaling: increase problem size as increase #procs, keep work per processor constant

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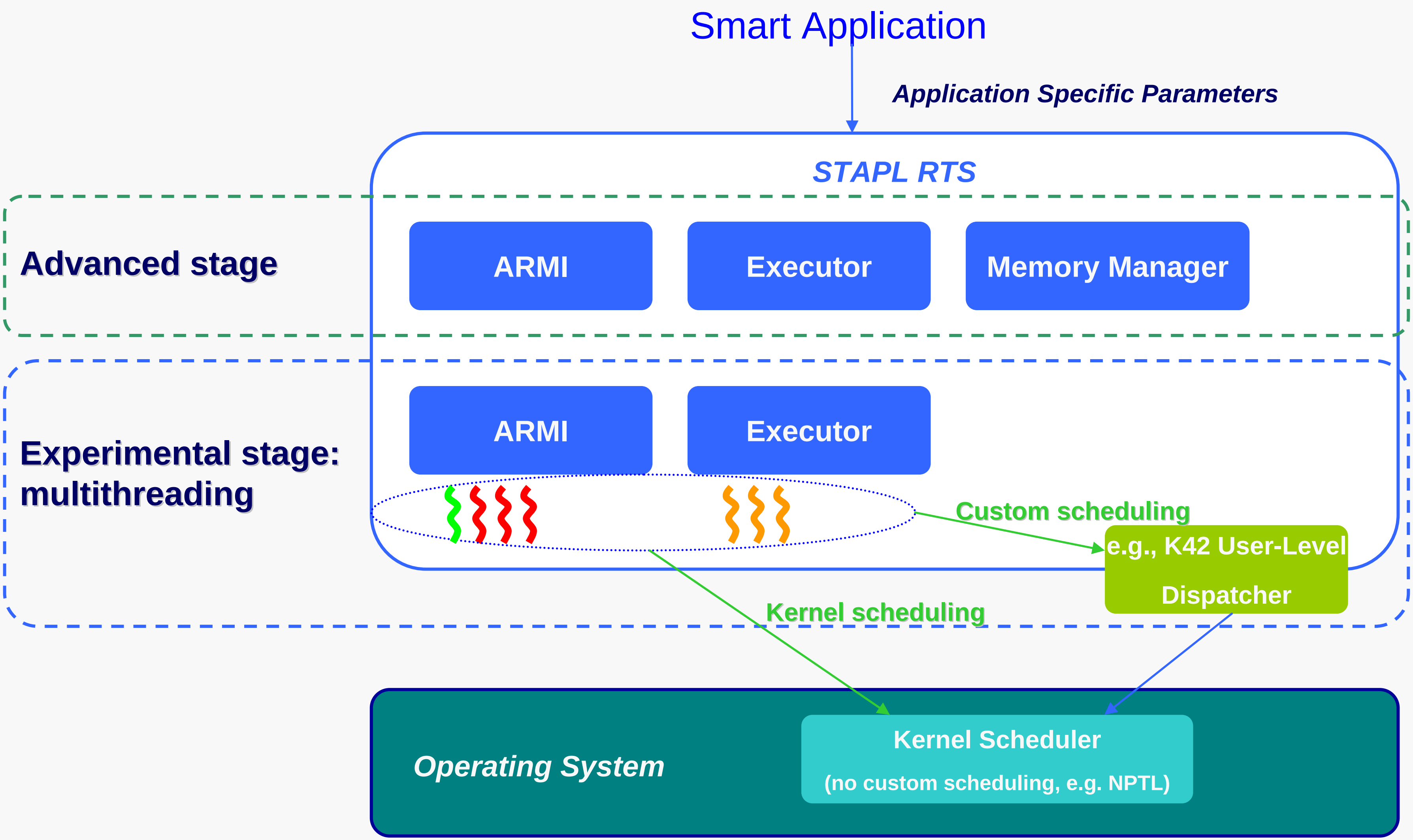
Run Time System



STAPL RTS

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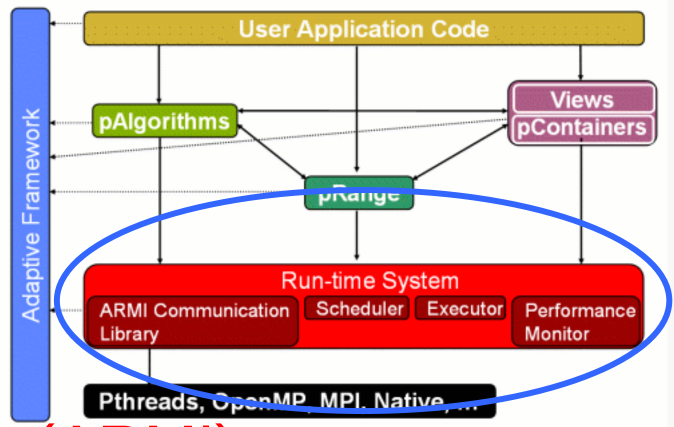

- Adaptive Remote Method Invocation (ARMI) Communication Library
  - Synchronous and Asynchronous RMI
  - Support for message aggregation
  - Synchronization primitives
    - Fence, Global Distributed Locks, Group-Based Synchronization
- Executor/Scheduler - execute pRange tasks
  - Customized task scheduling & load balancing for every pRange instance
  - RTS selects default policy, but can be user specified
- Performance monitor for feedback to the user and the adaptive framework
- Multithreaded RTS
  - RMI servers, Task executors, Comm. threads, …

RTS Consistency Models

- Processor Consistency (default)
  - Accesses from a processor on another's memory are sequential
  - Requires in-order processing of RMIs
    - Limited parallelism
- Object Consistency
  - Accesses to different objects can happen out of order
  - Uncovers fine-grained parallelism
    - Accesses to different objects are concurrent
    - Potential gain in scalability
  - Can be made default for specific computational phases
- Mixed Consistency
  - Use Object Consistency on select objects
    - Selection of objects fit for this model can be:
      - Elective – the application can specify that an object's state does not depend on others' states.
      - Detected – if it is possible to assert the absence of such dependencies
  - Use Processor Consistency on the rest

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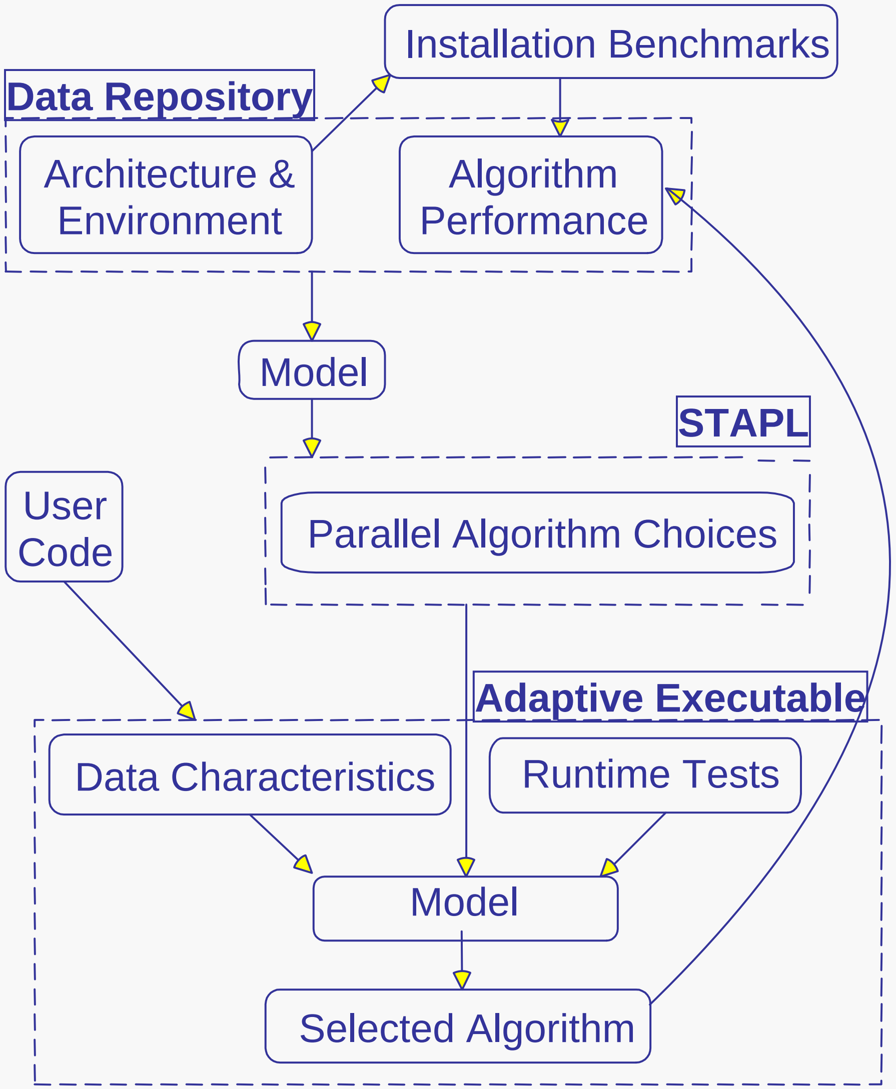
Support for Adaptivity in STAPL

- pAlgorithms
  - Algorithm Selection and Tuning (FAST)
  - Parametric Algorithms
- pContainers
  - Consistency model may vary for each instance, or even over time for the same instance
  - Data distribution can be selected/modified at runtime
- ARMI Communication Library
  - Message passing and\or shared memory communication modes
  - Aggregation of messages to tolerate latency

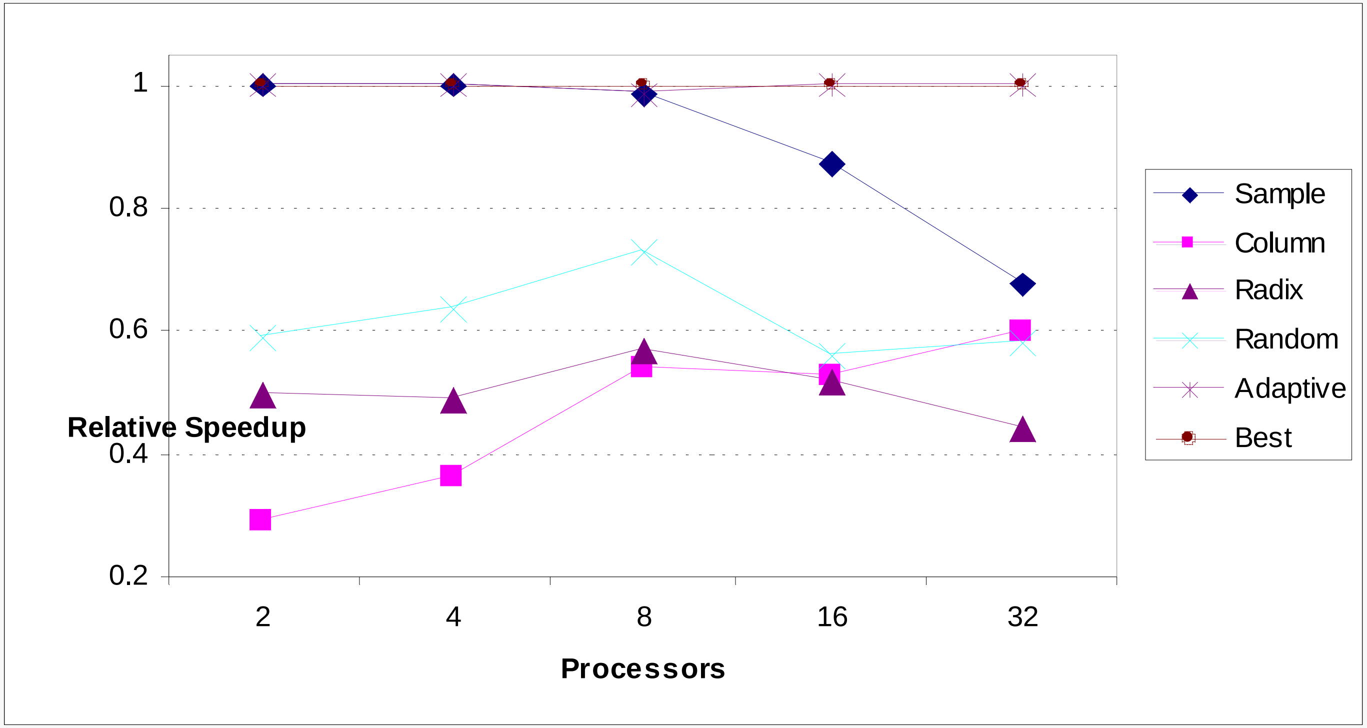
Adaptive Algorithm Selection
(ICS 00, IWACT 01, PPoPP 05)

Overview of Approach

- Given
  Multiple algorithmic choices for the same high level operation
- At STAPL installation (& refine later)
  Analyze each pAlgorithm's performance on system and create a selection model
- Program execution
  Gather parameters, query model, and select pAlgorithm to use

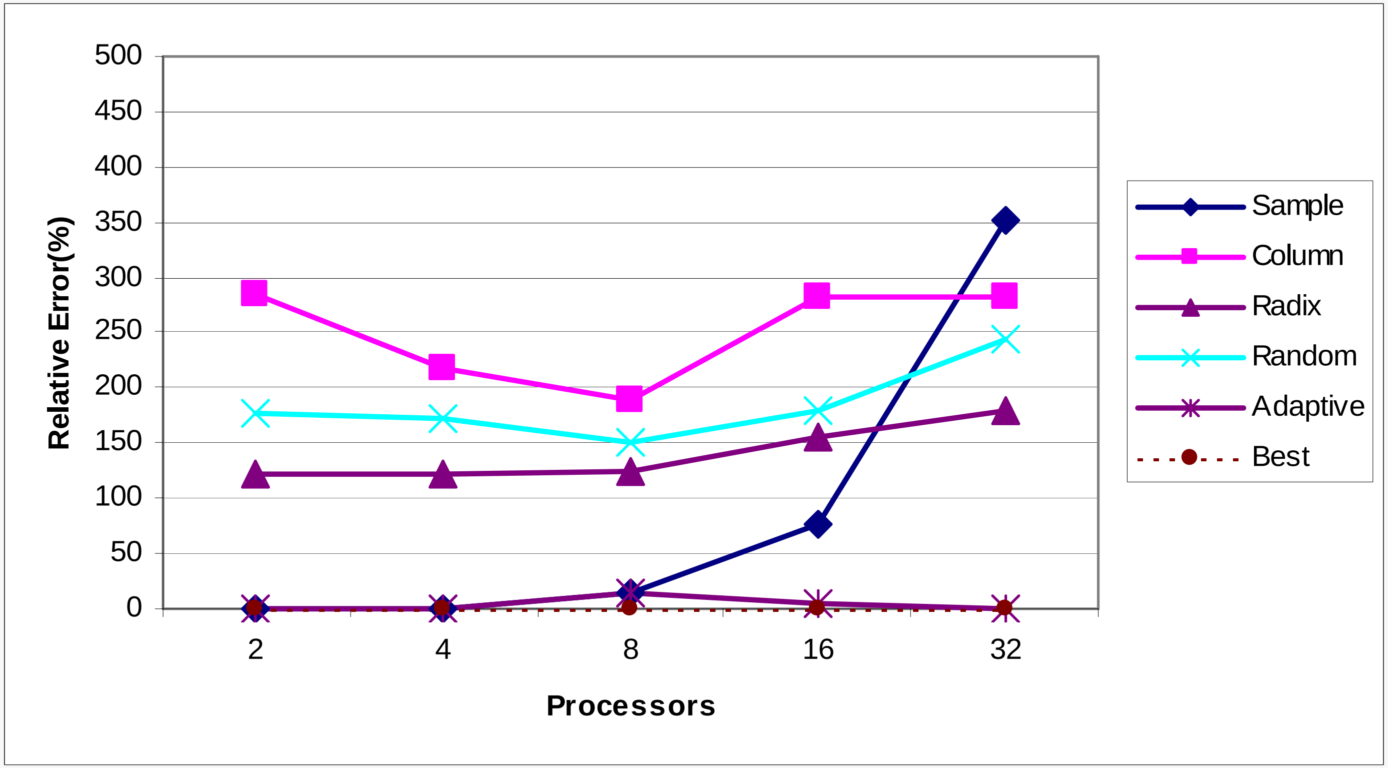


Parallel Sorting - Relative Performance



- Relative performance of parallel sorting algorithms on SGI Altix
- Adaptive algorithm selection model obtains 99.7% of the possible performance.
- Next best algorithm (sample sort) provides only 90.4%.

Parallel Sorting - performance penalty



- Relative performance penalty of parallel sorting algorithms on SGI Altix
- Adaptive algorithm selection model incurs 12% average penalty on misprediction
- Next best algorithm (sample sort) averages 132% penalty

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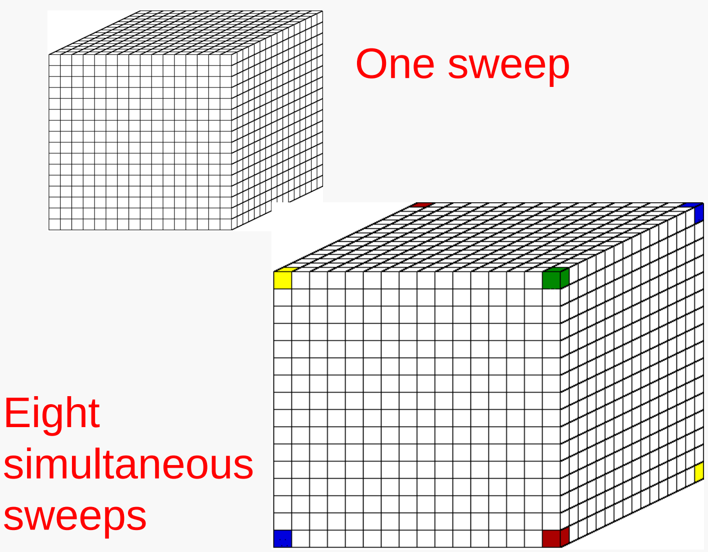
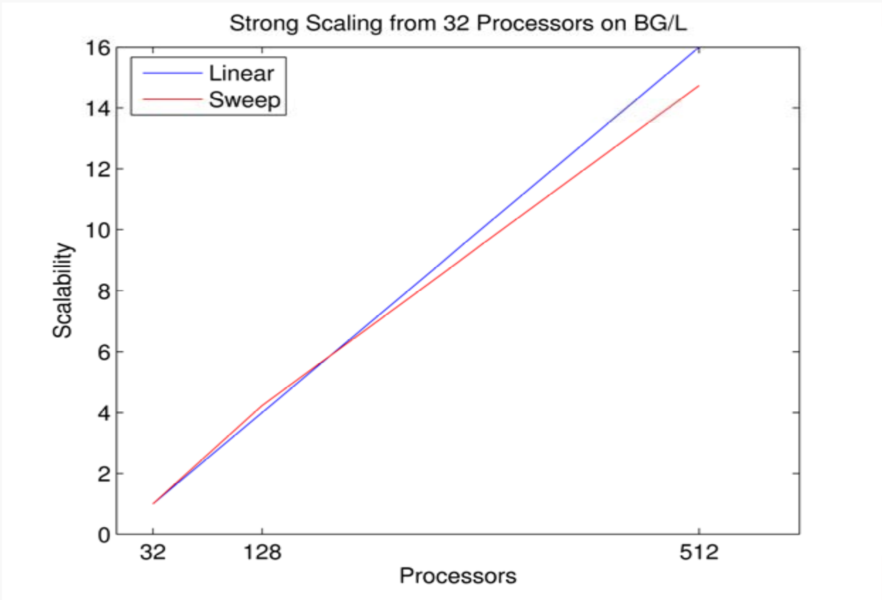
Discrete Ordinates Particle Transport Computation

- Important application for DOE
  - E.g., Sweep3D and UMT2K
  - Large, on-going DOE project at TAMU to develop application in STAPL (TAXI)
    - Spatial sweep for each direction of particle transport, each represented by a pRange where the sweep is encoded in the pRange's TDG (task dependence graph)





Related work

Features\Project	STAPL	Charm++	PSTL	HTA	POOMA	Titanium	TBB
Language/Library	Lib	Lang	Lib	Lib	Lib	Lang	Lib
Memory Address Space	Shared	Shared/ Part	Shared	Shared	Shared	Shared/ Part	Shared
Programming Model	SPMD/ MPMD	MPMD	SPMD	SPMD	SPMD	SPMD/ MPMD	MPMD
Generic Data Type/ Generic Algorithms	Y/Y	Y/N	Y/Y	Y/N	Y/N	Y/Y	Y/Y
Reuse Seq Containers	Y	N	Y	N	N	Y	Y
Framework for pContainers	Y	N	N	N	N	N	Y
Data Structures (Array, Vector,List, Graph, Matrix)	A,V,L,G, M	V	V,L	M	A	A	V,H,Q
Views	Y	N	N	Y	N	Y	N
Data Partition/ Mapping	Y/Y	Y	N	Y	Y	N	N
Adaptive	Y	Y	N	N	N	N	N

Conclusion

- STAPL has been used successfully on several large-scale, complex applications
  - STAPL has influenced Intel's TBB
- We plan to release a version soon to friendly users
- More info at http://parasol.tamu.edu/stapl/
- STAPL Team:
  - Faculty: Lawrence Rauchwerger (PI), Nancy Amato, Bjarne Stroustrup
  - Postdoc: Mauro Bianco
  - Students: Antal Buss, Olga Pearce, Antoniu Pop, Ioannis Papadopoulos, Timmie Smith, Gabriel Tanase, Nathan Thomas
  - Sponsors: DOE, NSF, IBM, Intel, HP