The Armada Parallel I/O framework for Computational Grids

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Computational Grids

Networks of geographically distributed heterogeneous systems and devices.

Properties of computational grids

- Dynamic resources
- Heterogeneous components
- Multiple administrative domains
- High-latency networks

An important challenge facing grid computing is efficient I/O for data-intensive applications.
Grid Applications

- *Computationally intensive*: may require supercomputers
- Many are also *data intensive*:
  - Access large remote datasets (terabytes)
  - Datasets often need pre, and/or post-processing
- Examples
  - Seismic processing
  - Climate modeling
  - Astronomy
  - Computational Biology
  - High-energy physics
The Armada Framework

- Application deploys a graph of distributed objects (*ships*)
- Data request causes pipelined data flow through graph
- Graph has two distinct portions:
  - from the data provider (describes layout of data set)
  - from the application programmer (pre/post-processing)
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Armada

Armada is not a data storage system. 
Armada is not a parallel file system.

The data segments that make up a data set are stored in conventional data servers as files, databases, or the like. 

The Armada graph encodes most functionality provided by the I/O system: 

- programmers interface, 
- data layout, 
- caching and prefetching policies, 
- interfaces to heterogeneous data servers. 

Armada can...

With Armada, one can

• build a graph for parallel access to a group of legacy files,
• present many similar data sets through a standard interface, and
• provide transparent access to derived “virtual” data—either cached or calculated as needed.
Restructuring

Problems with the example application:

- potential bottlenecks in the composed graph
- original graph restricts placement alternatives for filter

Original graph

Restructured graph

Armada restructures original graph to improve data flow.
Placement

After restructuring:

1. Armada deploys ships to appropriate administrative domains to optimize data flow, then

2. domain-level resource managers decide placement of individual ships.

Work in progress...
Armada includes a rich set of extensible ship classes.

- Structural
  - Distribute (partition, select, copy)
  - Merge
  - Data Processing
    - Filter (>, <, =)
    - Transform (FFT, unit conversion)
    - Reduce (min, max, sum)
    - Permute (sort, transpose)
  - Optimization
    - Cache
    - Prefetch
  - Interface
    - Client (Matrix, Line, String, stdio)
    - Storage (File, Query)
Ships

Armada includes a rich set of extensible ship classes.

Distribute (partition, select, copy)

Distribute ships partition requests or data to multiple output streams.
Armada includes a rich set of extensible ship classes.

Merge ships interleave requests or data from multiple input streams.
Armada includes a rich set of extensible ship classes.

Data-processing ships manipulate data, either individually, or in groups as it passes through the ship.
Armada includes a rich set of extensible ship classes.

Optimization ships improve I/O performance through latency-reduction techniques like caching and prefetching.
Armada includes a rich set of extensible ship classes.

**Client-interface** ships convert method calls to a set of requests for data.

**Storage-interface** ships access storage devices to process requests.
Properties of Ships

Properties of ships are

- used by restructuring and placement algorithms
- assigned by the programmer
- encoded in the ship’s description

Properties identify whether a ship

- is data- or request-equivalent
- increases or decreases data flow
- is parallelizable
A sequence $A$ is *equivalent* to sequence $B$ (denoted $A \equiv B$) if $B$ is a permutation of $A$, or if $B$ is a set of subsequences that partition $A$.

Examples:

\[
\{1, 2, 3, 4, 5\} \equiv \{2, 3, 5, 1, 4\}
\]

\[
\{1, 2, 3, 4, 5\} \equiv \{\{2, 3\}, \{1, 4, 5\}\}
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In other words, order does not matter.
Request- and Data-Equivalent Ships

A sequence $A$ is *equivalent* to sequence $B$ (denoted $A \equiv B$) if $B$ is a permutation of $A$, or if $B$ is a set of subsequences that partition $A$.

A *request-equivalent* ship produces request sequence equivalent to its input. A *data-equivalent* ship produces data sequence equivalent to its input.

*Most structural ships are both request and data-equivalent.*
A sequence $A$ is *equivalent* to sequence $B$ (denoted $A \equiv B$) if $B$ is a permutation of $A$, or if $B$ is a set of subsequences that partition $A$.

Distribution ships partition requests or data

- $S_1$, $S_2$, and $S_3$ are disjoint subsets of $R$.
- $R \equiv \{S_1, S_2, S_3\}$
Request- and Data-Equivalent Ships

A sequence $A$ is *equivalent* to sequence $B$ (denoted $A \equiv B$) if $B$ is a permutation of $A$, or if $B$ is a set of subsequences that partition $A$.

Merge ships interleave requests or data

- $R_1$, $R_2$, and $R_3$ are disjoint subsets of $S$.
- $\{R_1, R_2, R_3\} \equiv S$
Ships that Change Data Flow

Data-reducer: a ship that decreases the data flow
- filter
- compress
- reduce (min, max, sum)

Data-increaser: a ship that increases the data flow
- cache
- decompress
Parallelizable Ships

*Parallelizable:* a ship that can transform into multiple ships

- process requests and data in parallel
- parallelized by “swapping” with structural ships
- parallel version produces *equivalent* output

Types of parallelizable ships: *replicatable, recursive*
Parallelizable Ships

*Parallelizable:* a ship that can transform into multiple ships

- process requests and data in parallel
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Types of parallelizable ships: *replicatable*, *recursive*

Right-parallelizable

![Diagram showing Original, Replicated, and Recursed ships](Armada -- p.13)
Parallelizable Ships

*Parallelizable*: a ship that can transform into multiple ships

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- parallel version produces *equivalent* output

Types of parallelizable ships: *replicatable, recursive*

Left-parallelizable

*Original*  

*Replicated*  

*Recursed*
Graph Representation

We use a *series-parallel tree* (SP-tree) to describe the composition of an Armada graph.

- Syntactically easy to describe (we use XML)
- Easy to manipulate internally
- Constrains the graph to be an SP-DAG (important for restructuring)
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Graph Restructuring

Goals:

- remove bottlenecks (increase parallelism)
- allow better placement to reduce network traffic

We restructure by *swapping* adjacent nodes in the SP-tree

- increase parallelism by swapping *parallelizable* ships with *structural* ships
- reduce network traffic on slow links by
  - moving *data-reducing* ships toward data source,
  - moving *data-increasing* ships toward data destination
The Restruct Algorithm

All series and parallel nodes are initially marked *dirty*.

The *Restruct* algorithm traverses the SP-tree (depth-first), revisiting when necessary

1. if node is a leaf or clean (base case)
   (a) do nothing
2. if node is a dirty parallel node
   (a) recursively call *Restruct* on each child
   (b) mark node *clean*
3. if node is a dirty series node
   (a) call the *RestructSeries* algorithm
   (b) mark node *clean*
The RestructSeries Algorithm

1. Partition node into two disjoint series nodes $Head$ and $Tail$
2. Recursively call $Restruct$ on both partitions
3. If it is legal and beneficial to swap last child of $Head$ ($A$) with first child of $Tail$ ($B$)
   (a) Swap $A$ and $B$
   (b) Mark $Head$ and $Tail$ dirty (force restructuring)
4. else
   (a) Append $B$ to $Head$
5. If $Tail$ has children, goto 2
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Original

\[ S \]

A B \cdots

(1) Partitioned

\[ Head \]

A B \cdots

(3) If swap

\[ Tail \]

swap?

B A \cdots
The RestructSeries Algorithm

1. Partition node into two disjoint series nodes *Head* and *Tail*
2. Recursively call *Restruct* on both partitions
3. If it is *legal* and *beneficial* to swap last child of *Head* (*A*) with first child of *Tail* (*B*)
   (a) Swap *A* and *B*
   (b) Mark *Head* and *Tail* dirty (force restructuring)
4. else
   (a) Append *B* to *Head*
5. If *Tail* has children, goto 2
Legal Swap

It is legal to swap adjacent ships $A$ and $B$ if

1. the swap must produce an equivalent sequence
   - that is, ship $A$ and $B$ are *commutative*
   - $A$ or $B$ is request-equivalent and $A$ or $B$ is data-equivalent

2. the swap must produce an SP-tree (we allow four configs)
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2. the swap must produce an SP-tree (we allow four configs)
   - $A$ (non-structural) — $B$ (non-structural)
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2. the swap must produce an SP-tree (we allow four configs)
   - $A$ (non-structural) — $B$ (distribution) — parallel node

![Original](image1.png) ![Swapped](image2.png)
Legal Swap

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1. the swap must produce an equivalent sequence
   - that is, ship $A$ and $B$ are *commutative*
   - $A$ or $B$ is request-equivalent and $A$ or $B$ is data-equivalent
2. the swap must produce an SP-tree (we allow four configs)

Parallel node — $A$ (merge) — $B$ (non-structural)
Legal Swap

It is legal to swap adjacent ships $A$ and $B$ if

1. the swap must produce an equivalent sequence
   - that is, ship $A$ and $B$ are *commutative*
   - $A$ or $B$ is request-equivalent and $A$ or $B$ is data-equivalent

2. the swap must produce an SP-tree (we allow four configs)
   - Parallel node — $A$ (merge) — $B$ (distribution) — parallel node

![Original Swapped Armada](image-url)
Beneficial Swap

A swap is deemed *beneficial* if it increases parallelism, moves a data-reducing ship closer to the data source, or moves a data-increasing ship closer to data destination.

Algorithm to decide a beneficial swap of adjacent ships $A$ and $B$

1. Assign a preferred direction to each ship (1 for right, $-1$ for left)
   - Merge ships prefer to go right (increase parallelism)
   - Distribution ships prefer to go left (increase parallelism)
   - Data-reducing ships prefer to swap toward the data destination
   - Data-increasing ships prefer to swap toward the data source

2. return *true* if preferred direction of $A$ is greater than preferred direction of $B$

3. else return *false*
Restructuring the Example Graph

client processors

storage servers

from application

from data provider

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Restructuring the Example Graph

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Restructuring the Example Graph
Restructuring the Example Graph

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Experiments

Examined four configurations of the example application with a filter that removed exactly 50% of the data.
Experiment Setup

The area between the blobs represents the WAN

- each LAN connected to the WAN by single router
- each WAN link has limited capacity

Ran experiments on the Emulab Network Testbed (Univ. Utah)

- Three LANs, each with
  - five 850 MHz Pentium III processors
  - 100 Mbps switched network (0.15 msec latency)
- WAN consisted of
  - three network links with 2.0 msec latency
  - bandwidth ranged from 1 to 50 Mbps (available between client/servers 2-100 Mbps)
Results: Timings

![Graph showing execution time vs. total client/server WAN bandwidth (Mbit/sec) for different configurations: orig1, orig2, restruct1, restruct2.](Armada -- p.23)
Results: Timings

![Graph showing execution time vs. total client/server WAN bandwidth for different configurations.](image-url)
Results: Effective Throughput

- **WAN bandwidth**
- **2*WAN bandwidth**
- **orig1**
- **orig2**
- **restruct1**
- **restruct2**

Effective Throughput (Mbit/sec) vs. Total client/server WAN bandwidth (Mbit/sec)
Discussion

- Below 25 Mbps, all configurations limited by WAN
- Above 25 Mbps, computation associated with Java serialization and the filter code became the bottleneck
- When network bound, placement of filter is critical
  - restruct1 and restruct2 achieve nearly twice the effective throughput
- When compute bound, parallelization of filter is beneficial
  - restruct1 and restruct2 achieve 2-3 times the effective throughput as orig1 and orig2
Related Work

Parallel processing of I/O streams

- PS\(^2\) [Messerli 1999]
  - data-flow model with automatic parallelization
- TPIE [Vengroff et al. 1996 and 2002]
  - data-flow model for I/O-optimal algorithms

Armada does not force whole application into data-flow model
Armada widens data flow for parallel clients and parallel servers

Operation ordering to improve data flow, e.g., in databases

- dQUOB [Plale et al. 2000]
  - optimize query tree to move high-filtering portions close to data
  - exploit well-defined properties associated with query processing

Armada provides a more general approach
Future Work

• Real applications
  – How to push some application function into Armada framework?
  – Can components (ships) be re-used between applications?
  – How much can performance benefit?

• Analytic model of “beneficial”

• Placement algorithm
  – Static: deploy graph at start
  – Dynamic: re-deploy when network conditions change
Conclusion

The Armada framework

- allows data provider to describe complex distributed data sets
- allows the application to describe processing required before computation
- provides a latency-tolerant data-flow approach useful for wide-area computing

Restructuring algorithm

- arranges graph to provide end-to-end parallel I/O
- enables effective placement of data-processing components to reducing network traffic over slow network links

Experiments show that restructuring is beneficial in both low and high-bandwidth environments.
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