High-Performance I/O for Computational Grid Applications

Ron Oldfield and David Kotz

{raoldfi,dfk}@cs.dartmouth.edu.

Department of Computer Science, Dartmouth College

http://www.cs.dartmouth.edu/∼dfk/armada/

Computational Grids

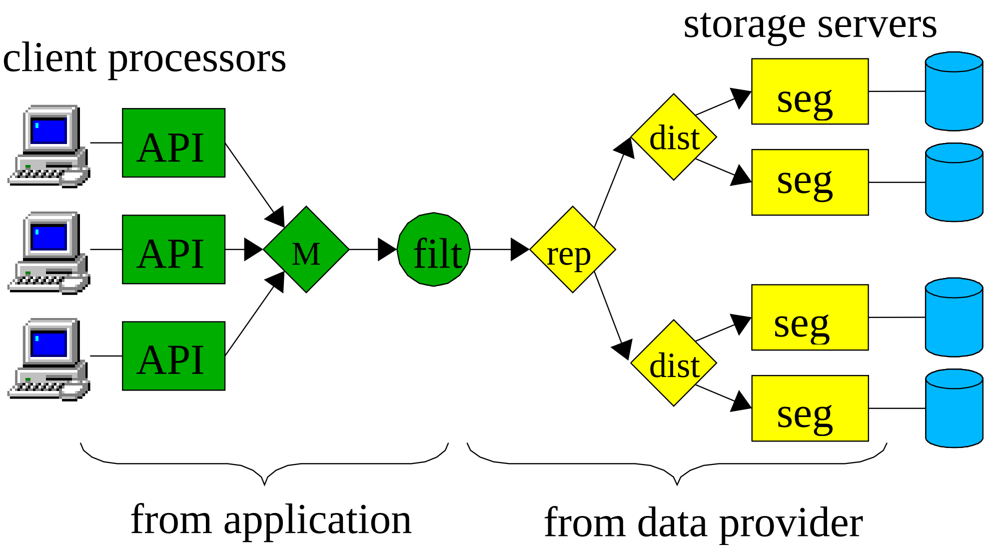
Networks of geographically distributed heterogeneous systems and devices

Data-intensive grid applications

- Access large remote datasets (terabyte–petabyte)
- Datasets often need pre/post-processesing
- Often computationally intensive
- Examples
  - Climate modeling
  - Astronomy
  - Computational Biology
  - High-energy physics

The Armada Framework

- Application deploys a graph of distributed objects (*ships*)
- Requests cause 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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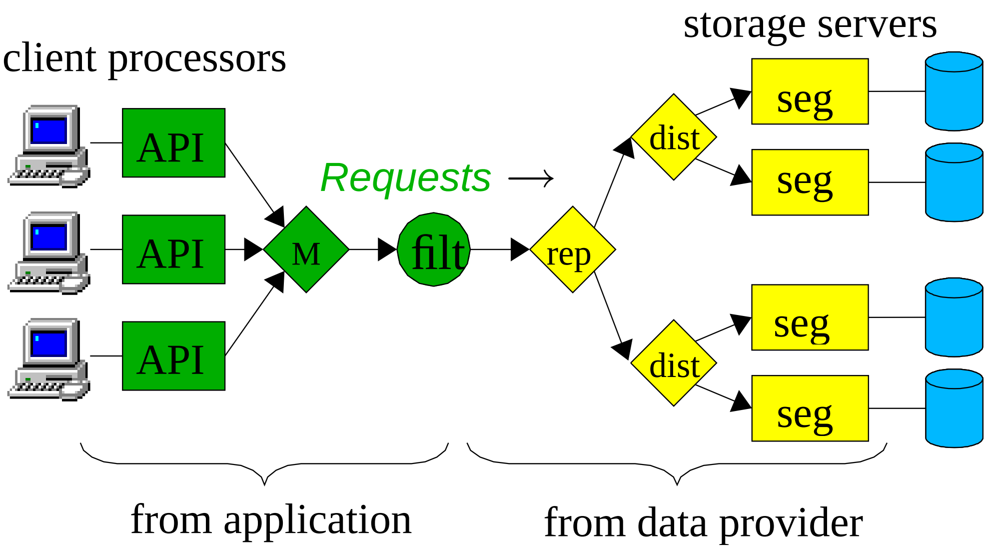

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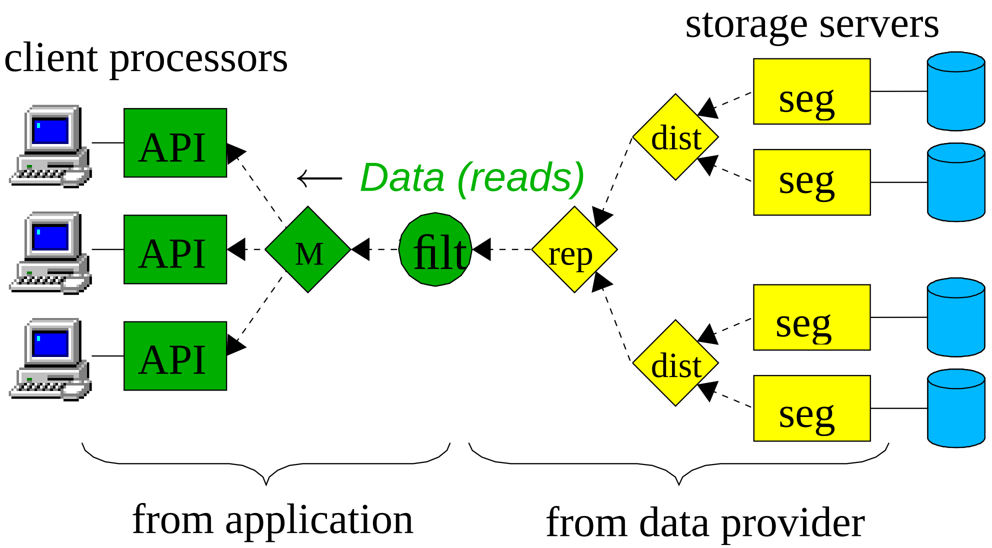

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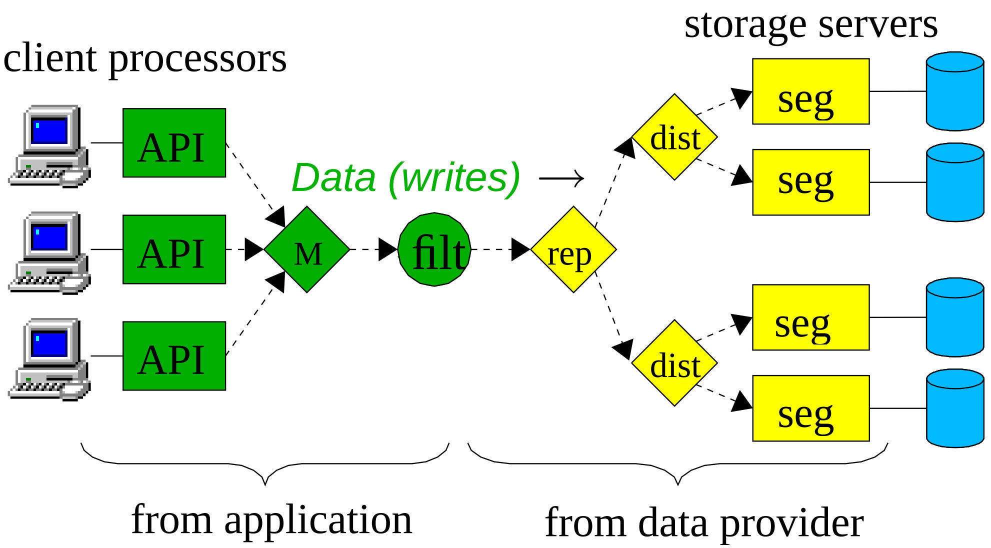


Armada

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...

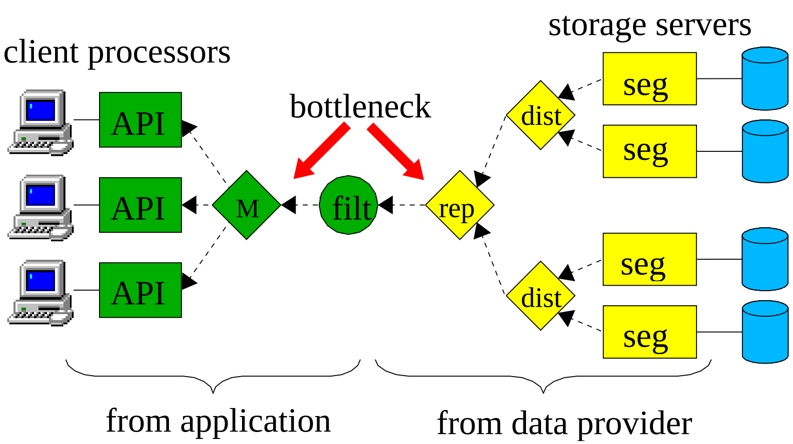
- build a graph for parallel access to a group of legacy files,
- present many similar data sets through a standard interface, and
- provide transparent access to derived “virtual” data– either cached or calculated as needed.

Restructuring

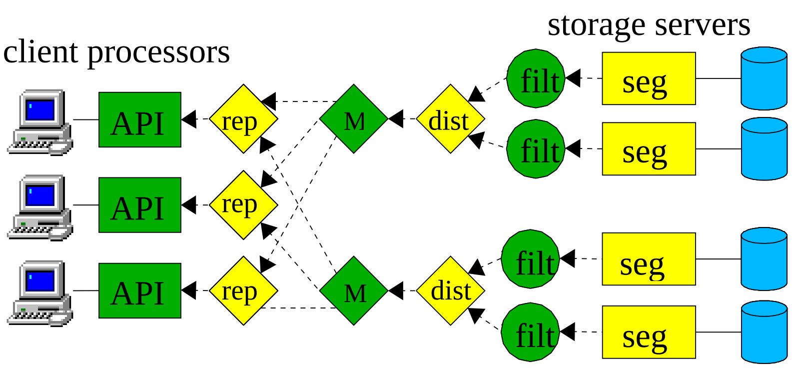
Problems with the example application:

- Potential bottlenecks in composed graph
- original graph restricts placement alternatives for filter

Original graph



Restructured graph

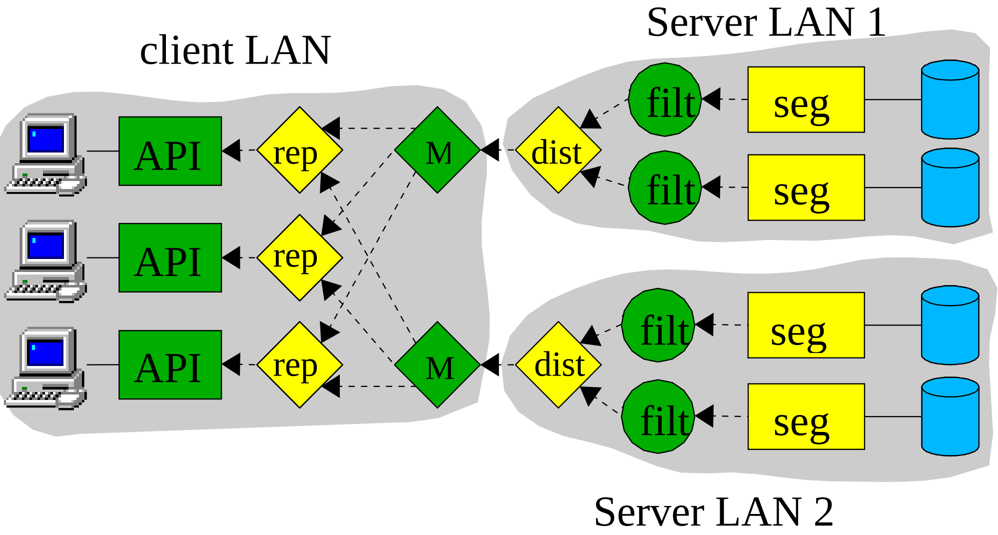


Armada restructures original graph to improve data flow.

Placement

After restructuring:

1. Armada deploys ships to appropriate administrative domains to optimize data flow, then
2. domain-level resource manager decides placement of individual ships.

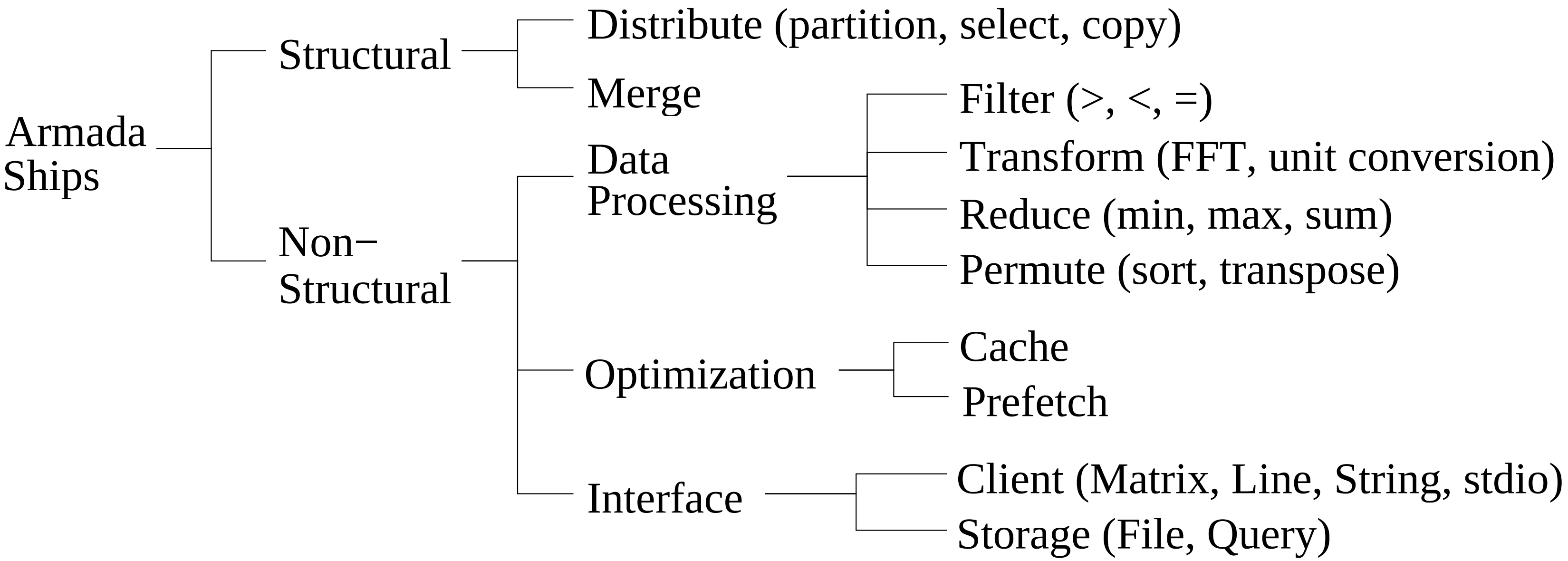


Talk Outline

- *Introduction*
- Framework details
  - Ships
  - Graph Representation
- Restructuring graphs to improve data flow
- Partitioning graphs and placing ships
- Experiments
- Conclusion

Ships

Armada includes a rich set of extensible ship classes.



- Armada Ships
  - Structural
    - Distribute (partition, select, copy)
    - Merge
  - Non−Structural
    - Data Processing
      - Filter (>, <, =)
      - Transform (FFT, unit conversion)
      - Reduce (min, max, sum)
      - Permute (sort, transpose)
    - Optimization
      - Cache
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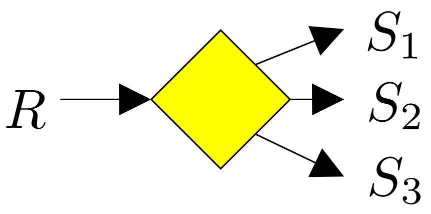
Distribute ships partition requests or data to multiple output streams.



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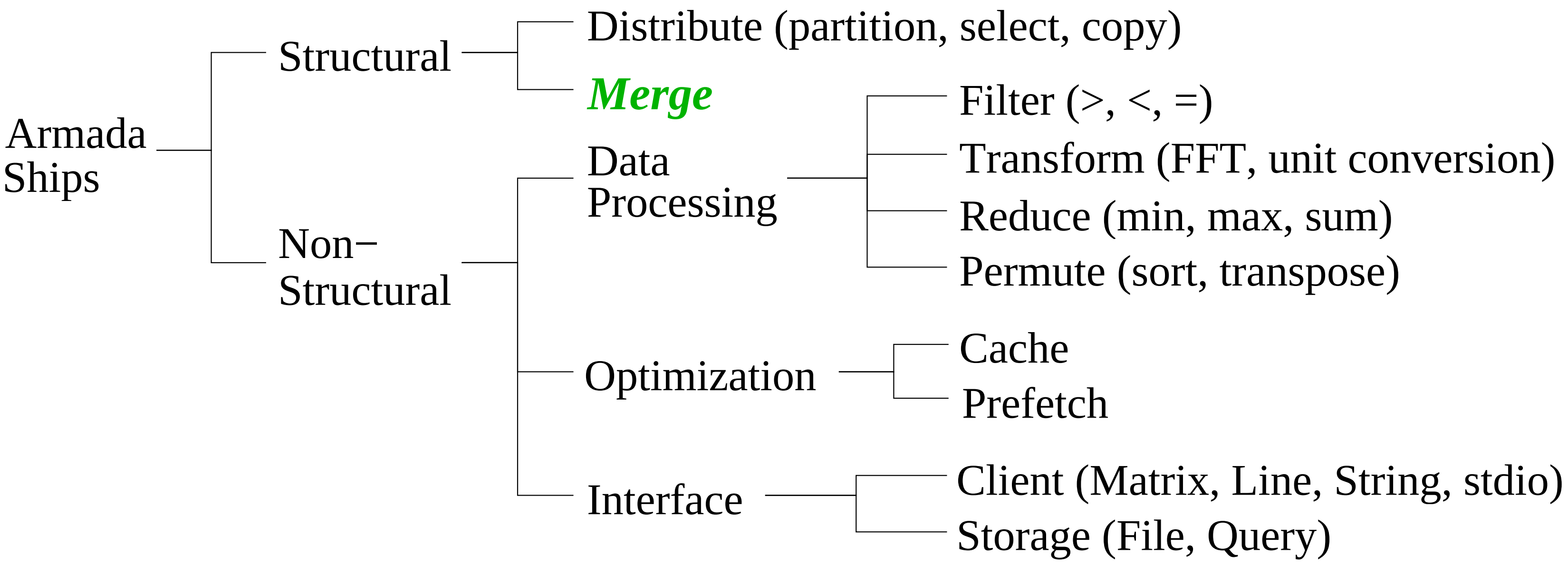

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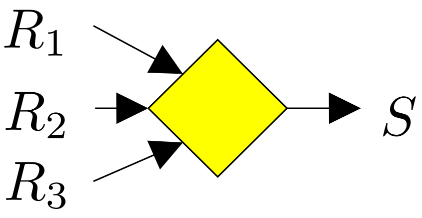
Merge ships interleave requests or data from multiple input streams.



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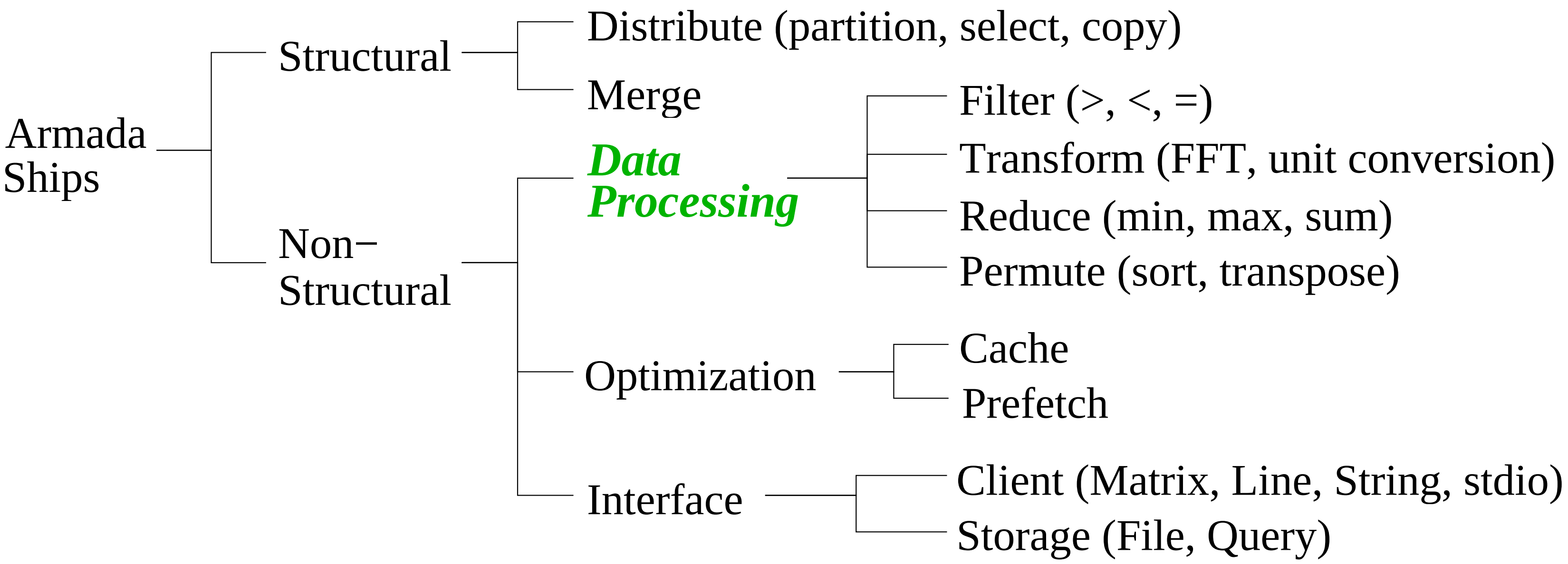

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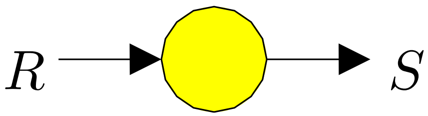
Data-processing ships manipulate data, either individually, or in groups as it passes through the ship.



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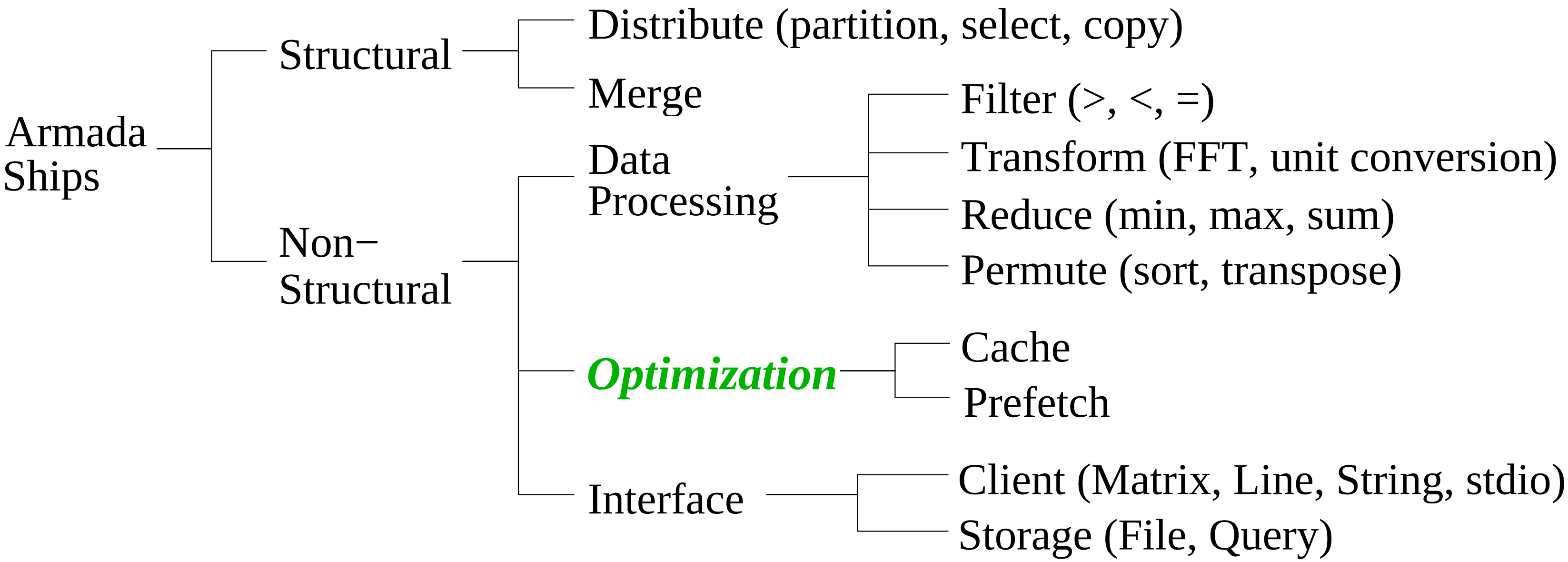

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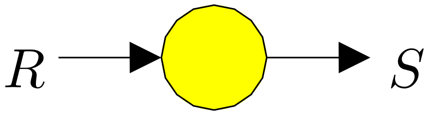
Optimization ships improve I/O performance through latency-reduction techniques like caching and prefetching.



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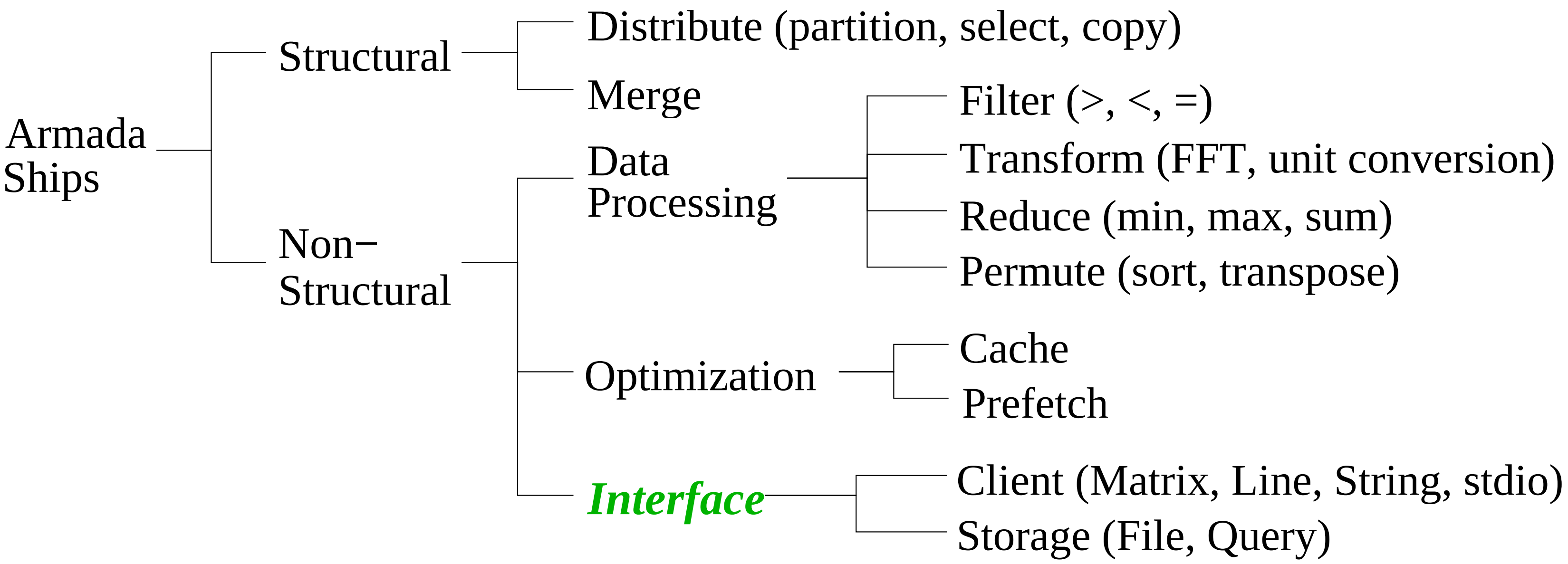

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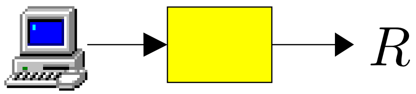
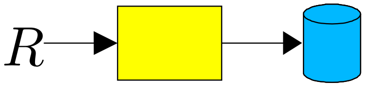
Client-interface ships
convert method calls to a set of requests for data.



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 definition

Properties identify whether a ship

- is data- or request-equivalent
- increases or decreases data flow,
- is parallelizable

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.

Examples:

$$\begin{aligned} \{1,2,3,4,5\} &\equiv \{2,3,5,1,4\} \\ \{1,2,3,4,5\} &\equiv \{\{2,3\},\{1,4,5\}\} \\ \{1,2,3,4,5\} &\equiv \{\{2,3\},\{1,5,4\}\} \end{aligned}$$

In other words, order does not matter.

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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.

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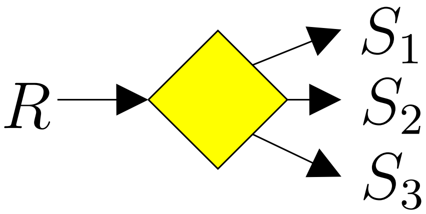
Distribution ships partition requests or data

- S_1, S_2, and S_3 are subsequences of R.
- $R \equiv \{S_1, S_2, S_3\}$



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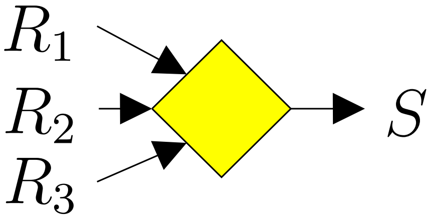
Merge ships interleave requests or data

- R_1, R_2, and R_3 are subsequences 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*

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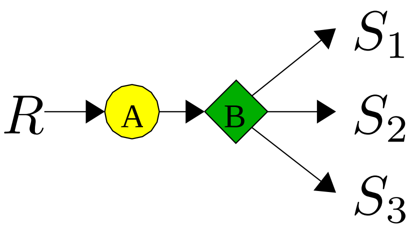
Right-parallelizable



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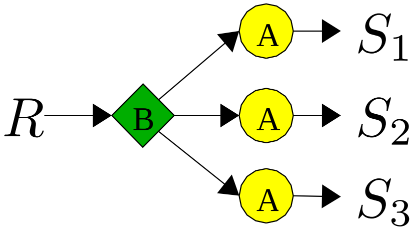
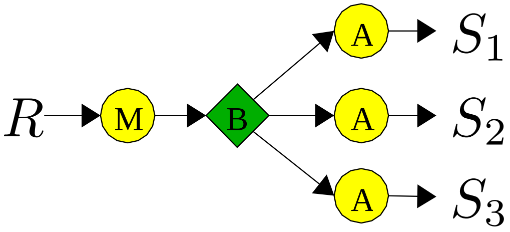


Replicated



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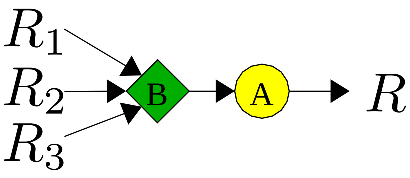
Left-parallelizable



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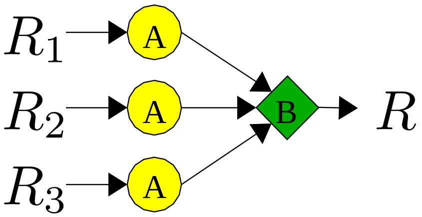

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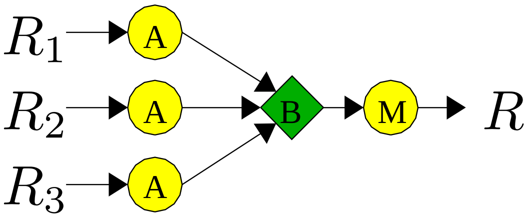
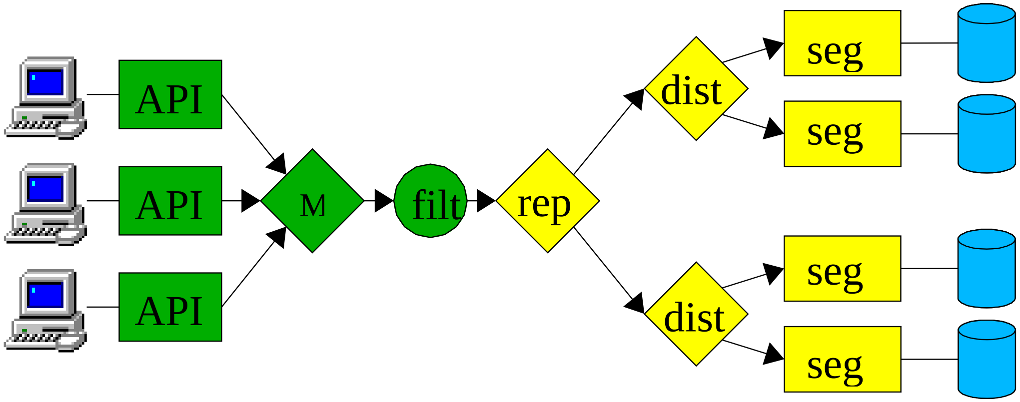


Recursed

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



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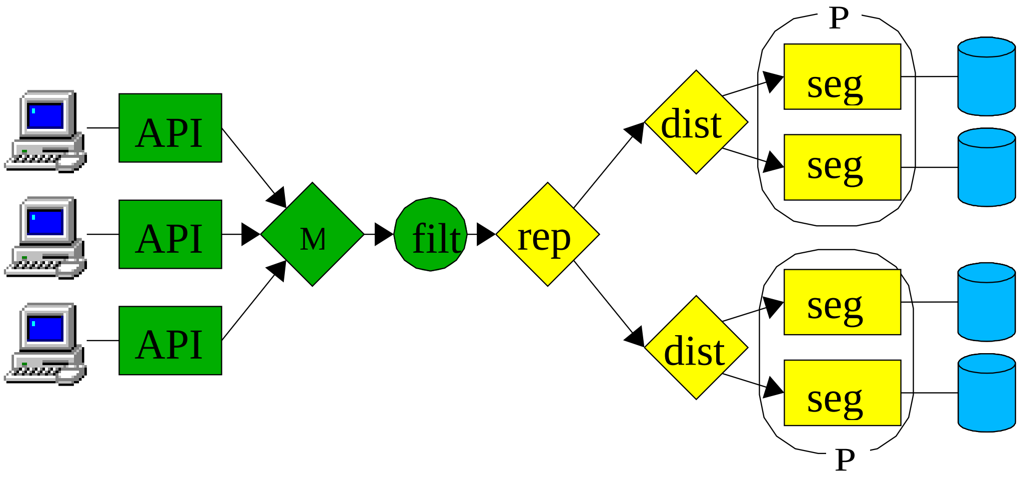

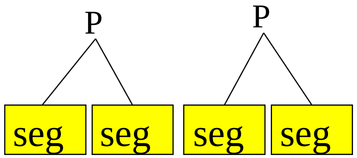

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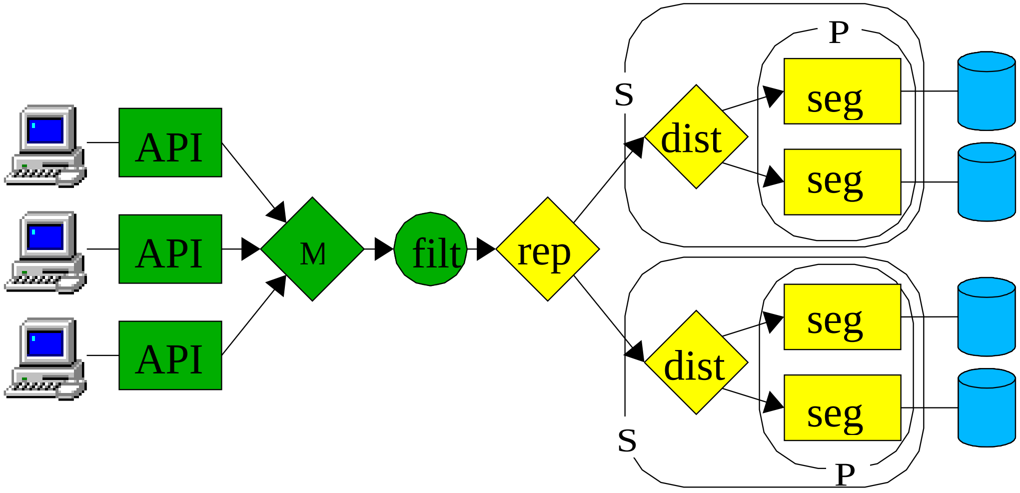

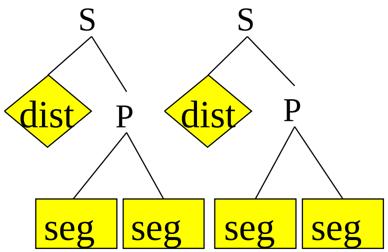

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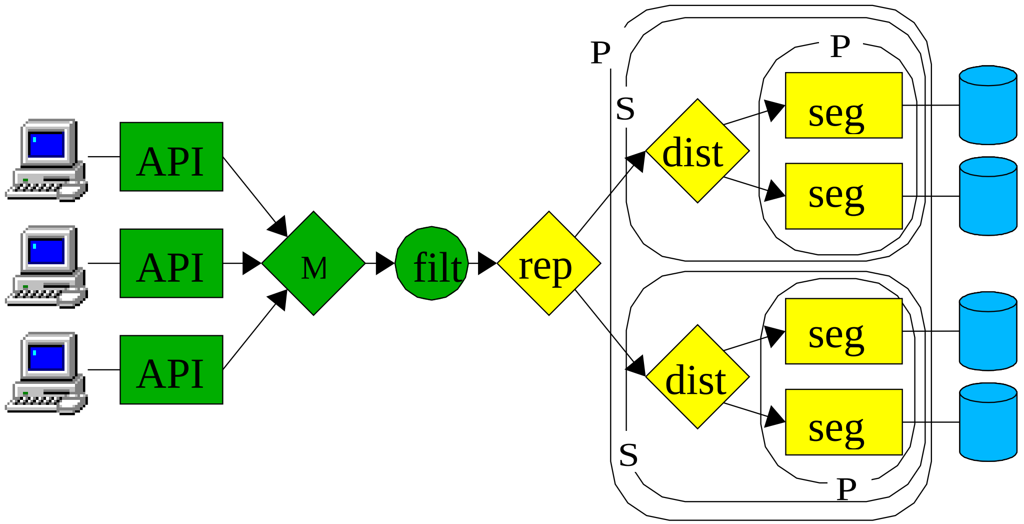

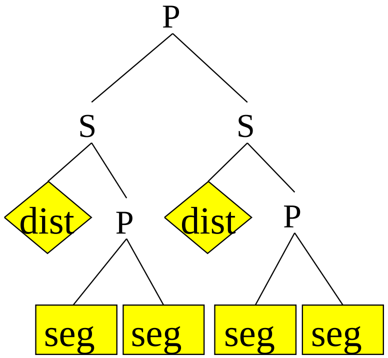

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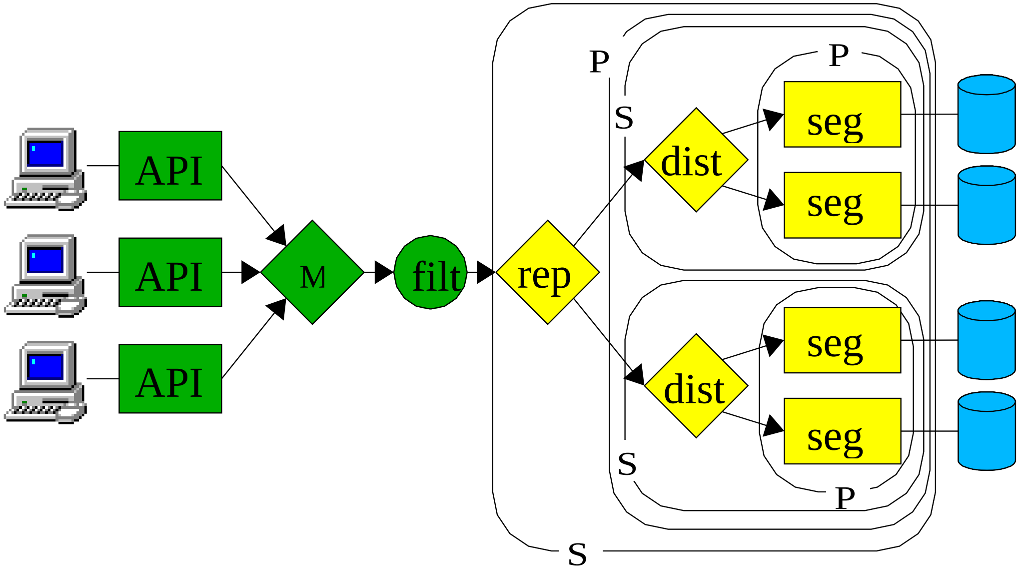

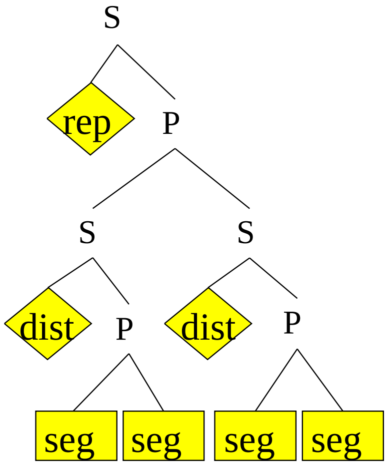

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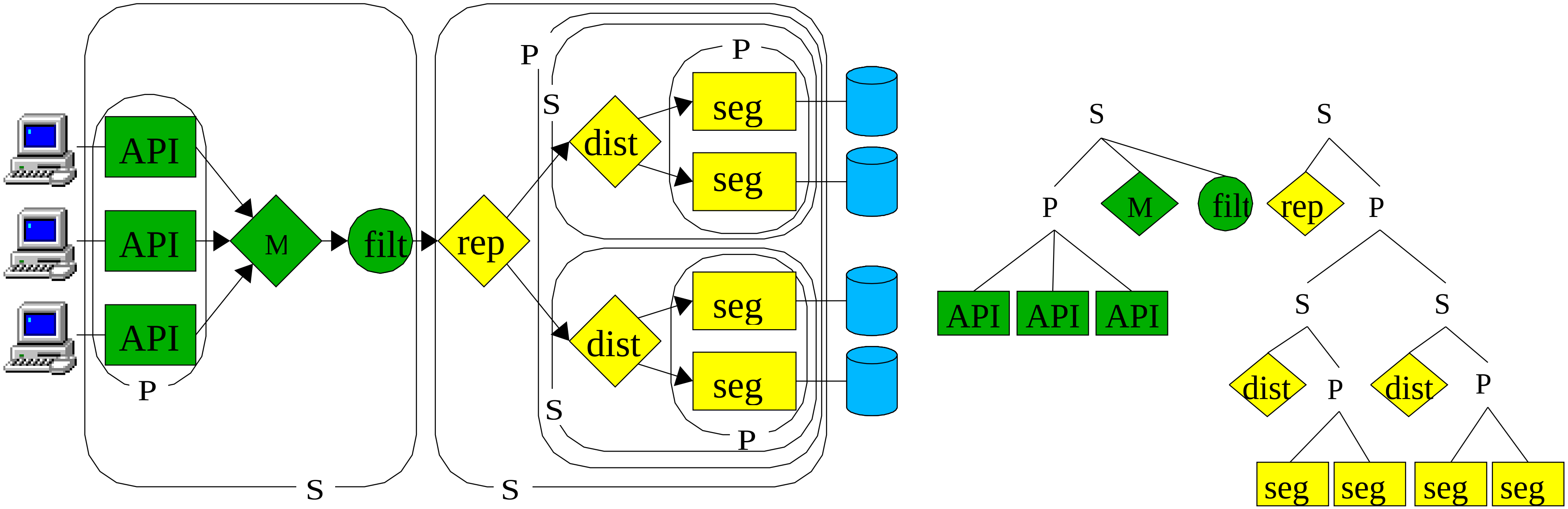

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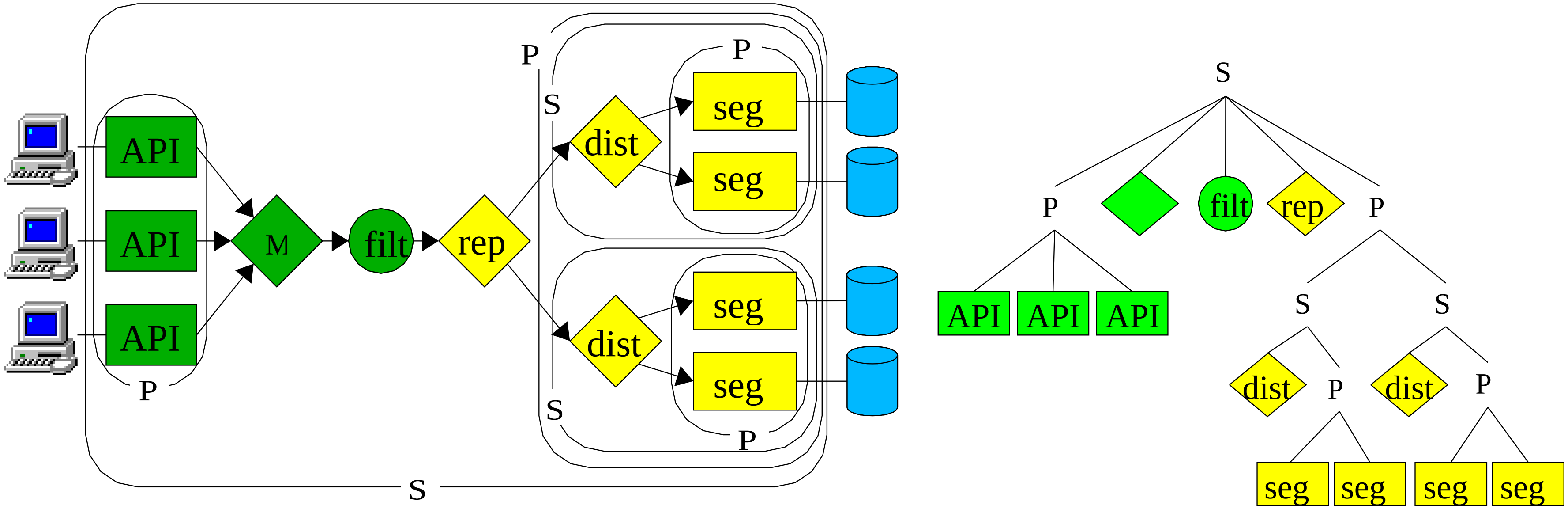

Graph Restructuring

Goals:

- remove bottlenecks (increase parallelism)
- allow effective placement of ships

We restructure by *swapping* adjacent ships 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 dest

The Restruct Algorithm

The RESTRUCT algorithm traverses the SP-tree (depth-first) from node N, revisiting when necessary (all series and parallel nodes are initially marked *dirty*).

```
1. if $N$ is a leaf or $clean$ (base case)
    (a) return
2. else if $N$ is a parallel node
    (a) RESTRUCT each child of $N$
3. else if $N$ is a series node
    (a) create a new series node $S$
    (b) while $N$ has children
        i. $child \leftarrow$remove leftmost child of $N$
        ii. append $child$ to $S$
        iii. SLIDE $child$ left
    (c) $N \leftarrow S$
4. mark $N$ $clean$
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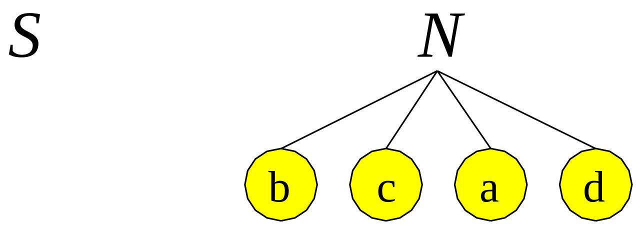

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Append c to S

The Restruct Algorithm

The RESTRUCT algorithm traverses the SP-tree (depth-first) from node N, revisiting when necessary (all series and parallel nodes are initially marked *dirty*).

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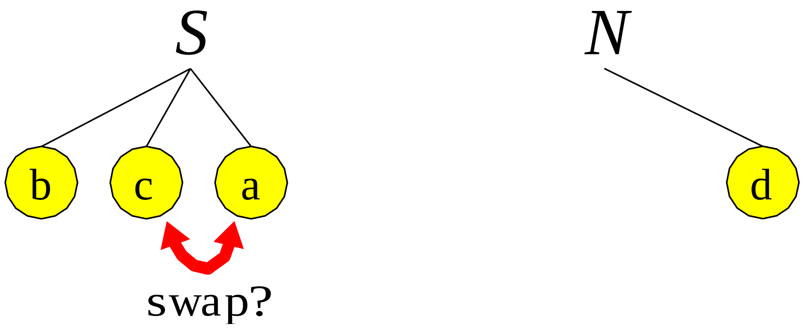

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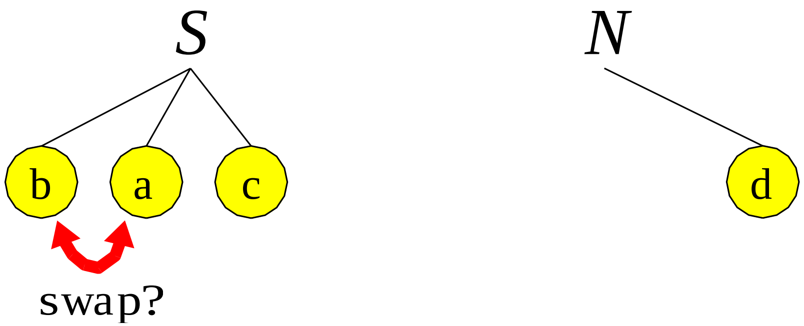

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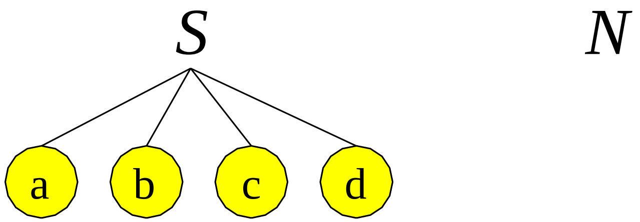

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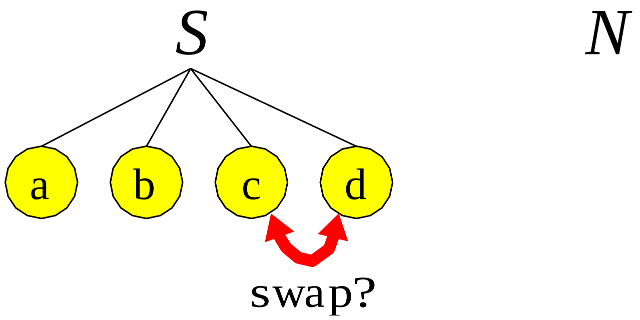

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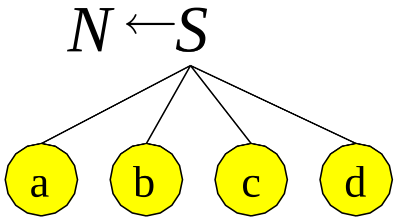
Assign S to N



Swapping Ships

Conditions for swapping two series-connected ships (labeled A and B)

- A and B are *commutative* (A or B is request-equivalent and A or B is data-equivalent)
- swapping A and B is *beneficial* to the application (see next slide), and
- the graph resulting from a swap is an SP-DAG (we allow four configurations).

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(A) Non-structural, (B) Non-structural

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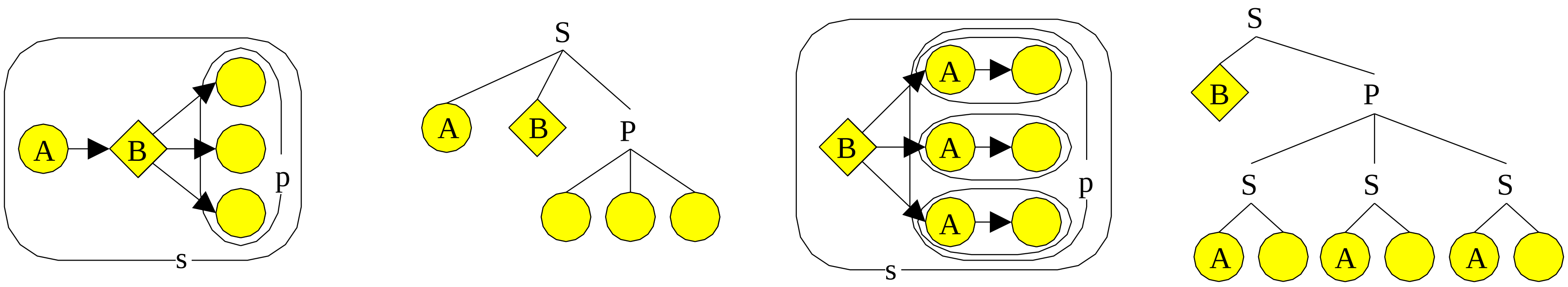
(A) Non-structural, (B) Distribution, Parallel node



PARALLELIZE right

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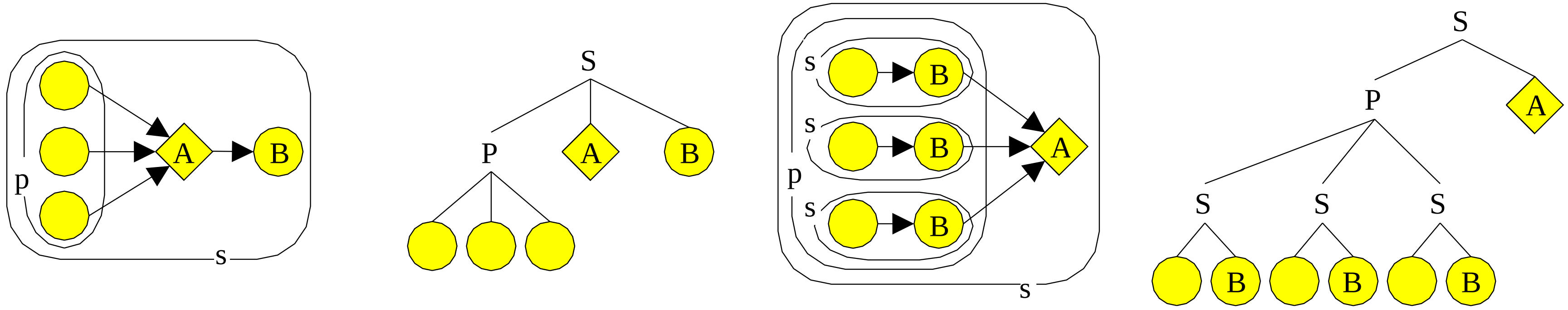
Parallel node, (A) Merge, (B) Non-structural



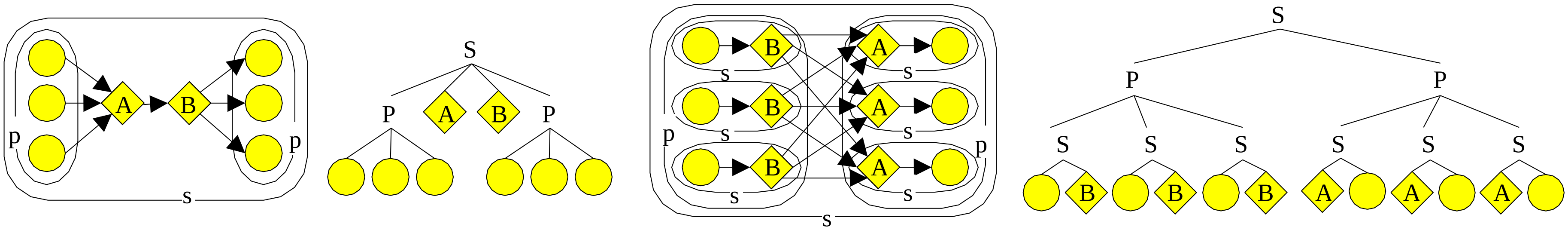
PARALLELIZE left

Swapping Ships

Conditions for swapping two series-connected ships (labeled A and B)

- A and B are *commutative* (A or B is request-equivalent and A or B is data-equivalent)
- swapping A and B is *beneficial* to the application (see next slide), and
- the graph resulting from a swap is an SP-DAG (we allow four configurations).

Parallel node, (A) Merge, (B) Distrib, Parallel node



PARALLELIZE right and left

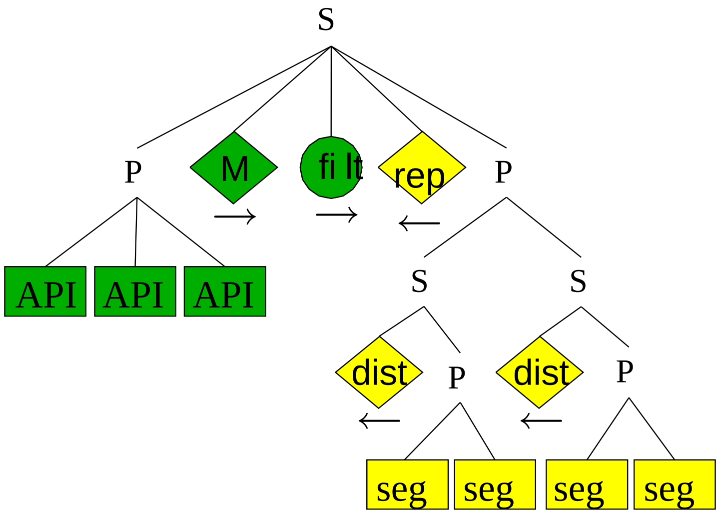
Beneficial Swap

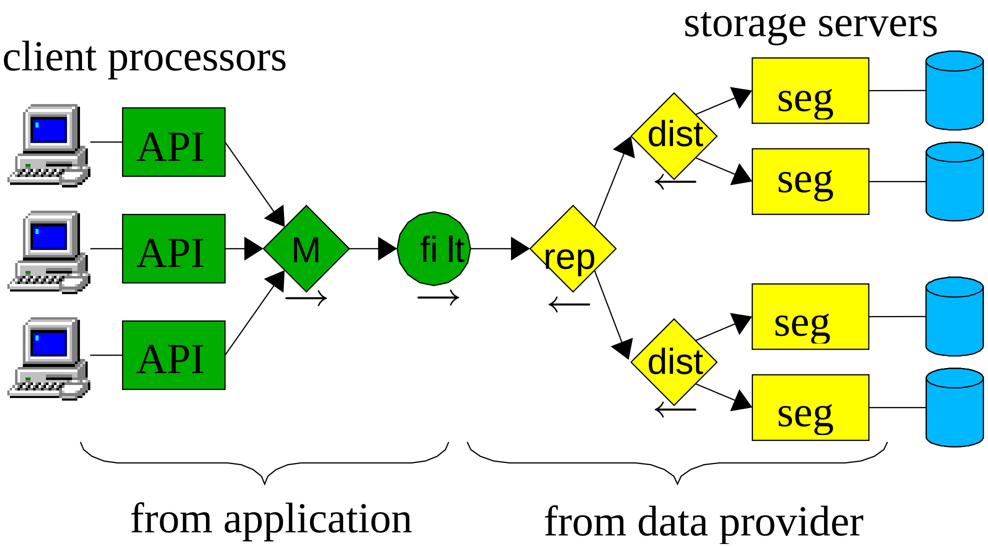
A swap is deemed *beneficial* if it increases parallelism, moves a data-reducing ship closer to the data source, or moves a data-increasing ship closer to data destination.

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, or 0)
    - 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





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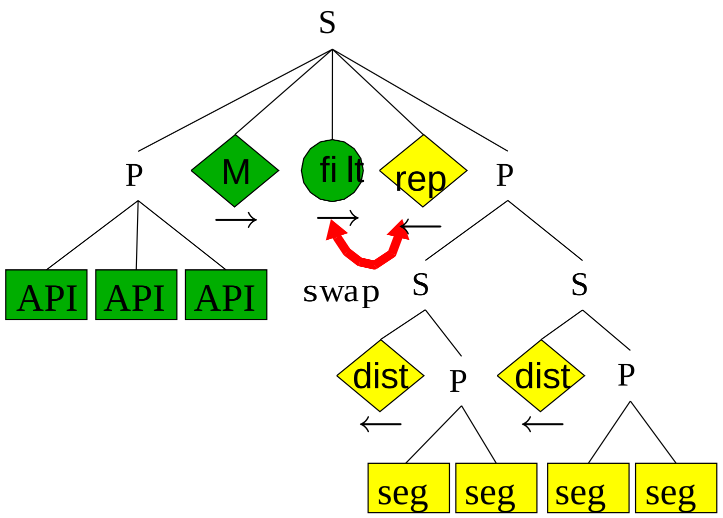

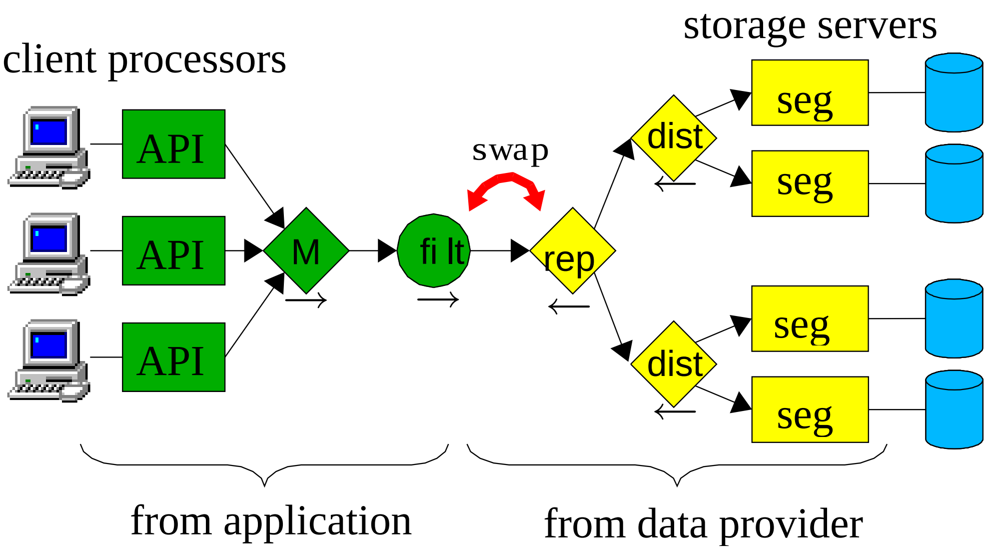

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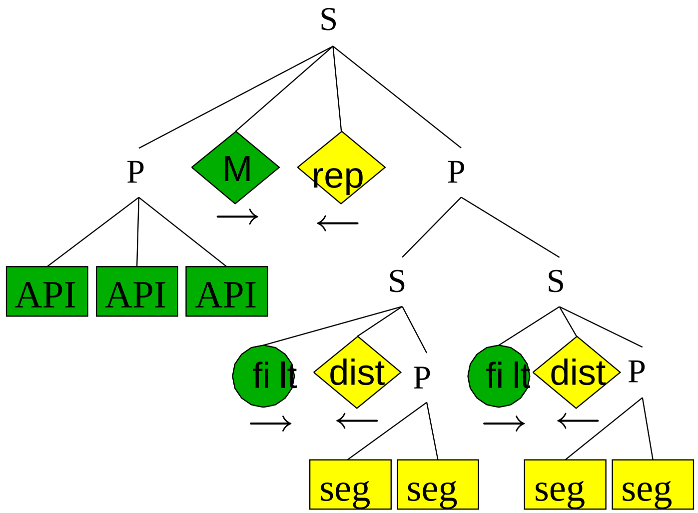

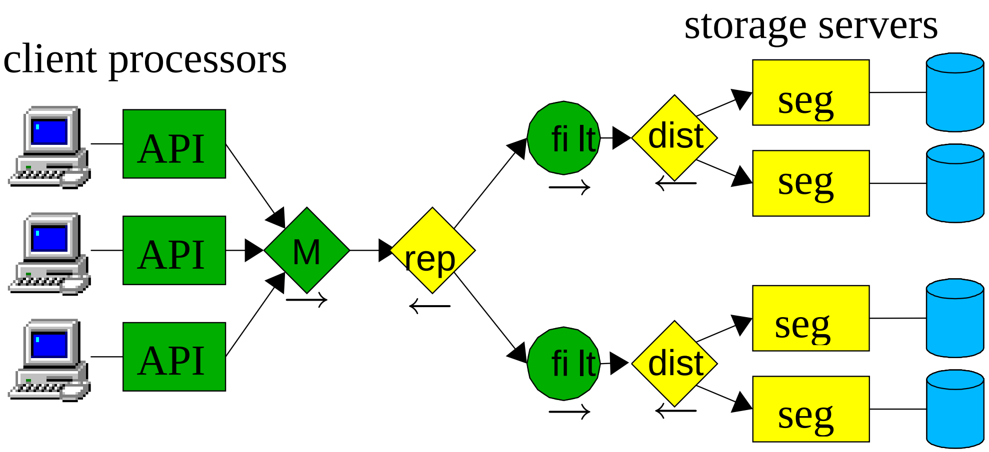

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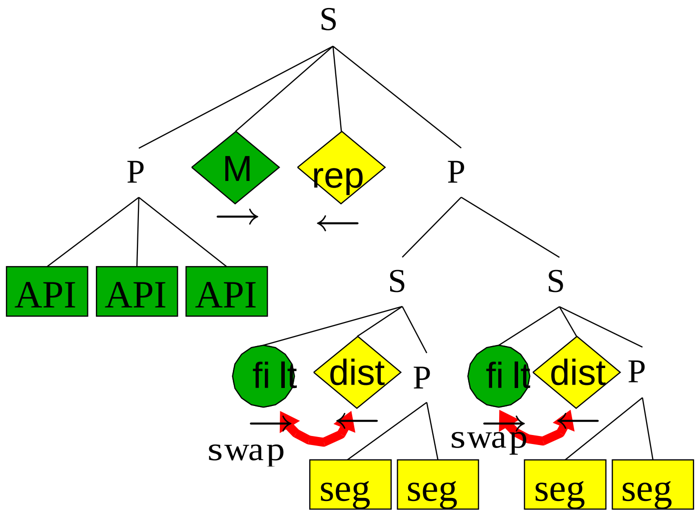

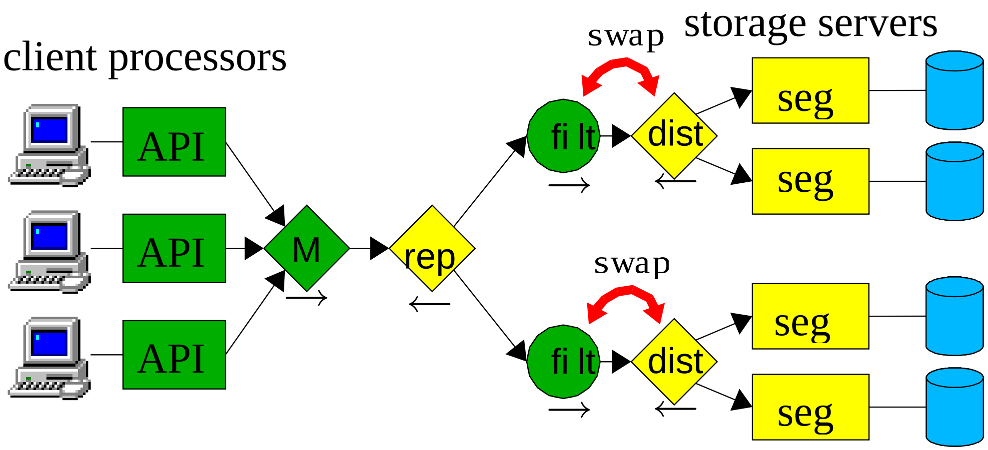

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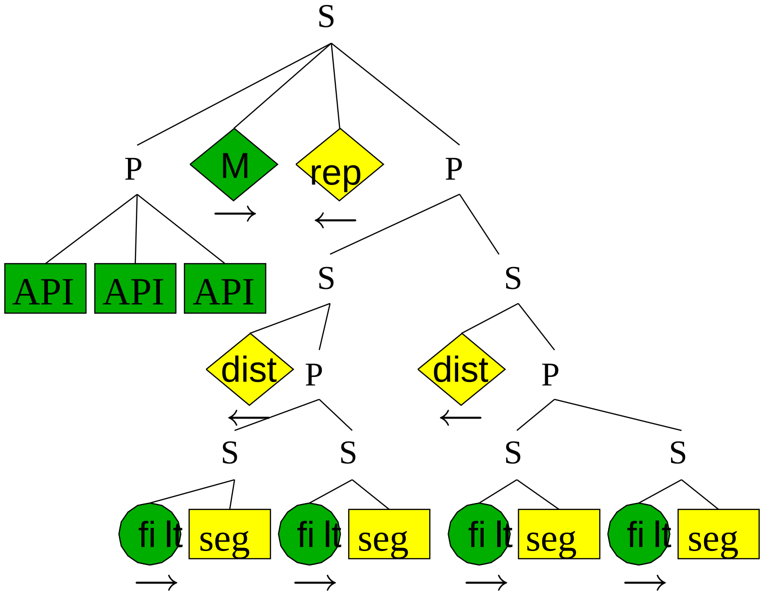

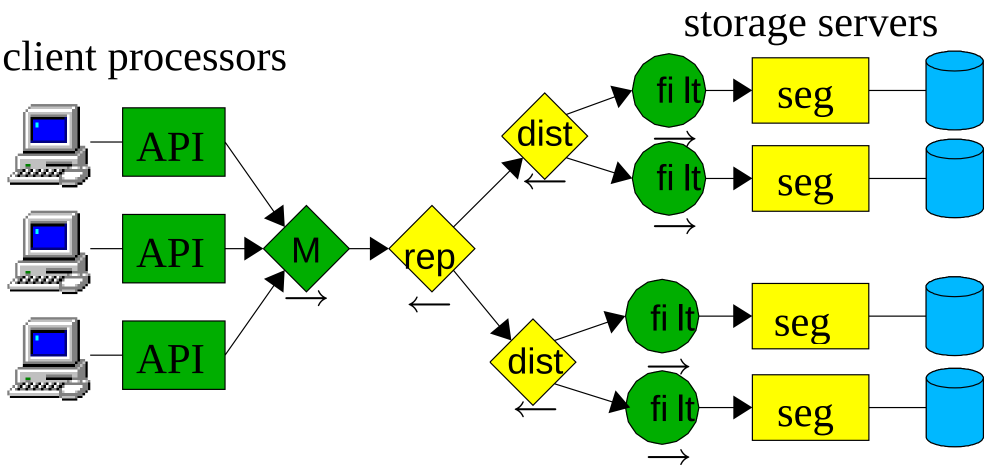

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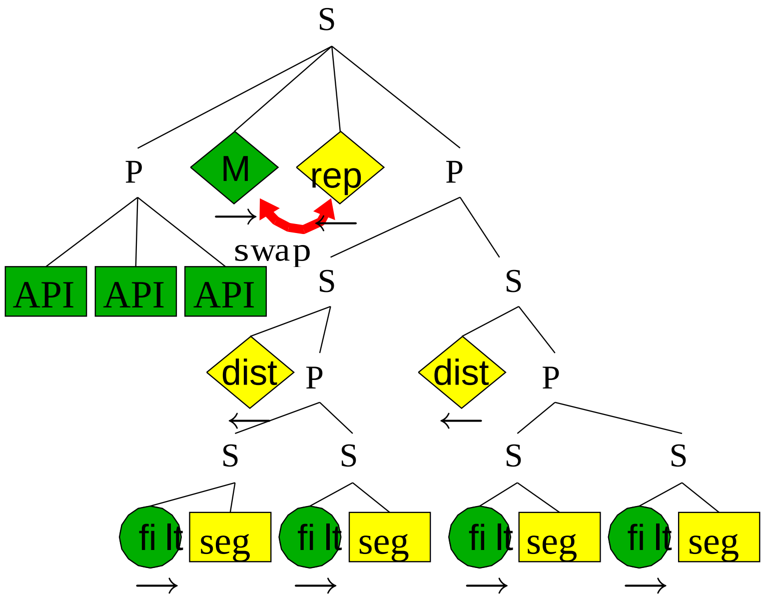

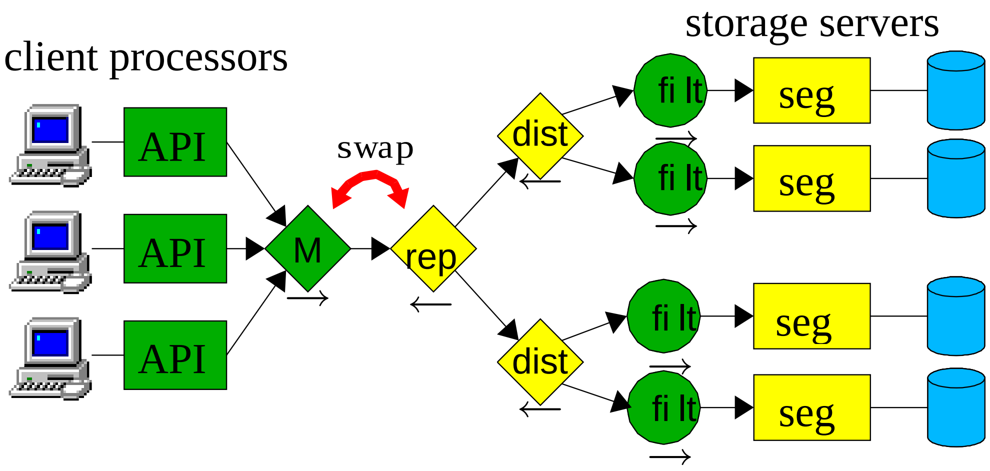

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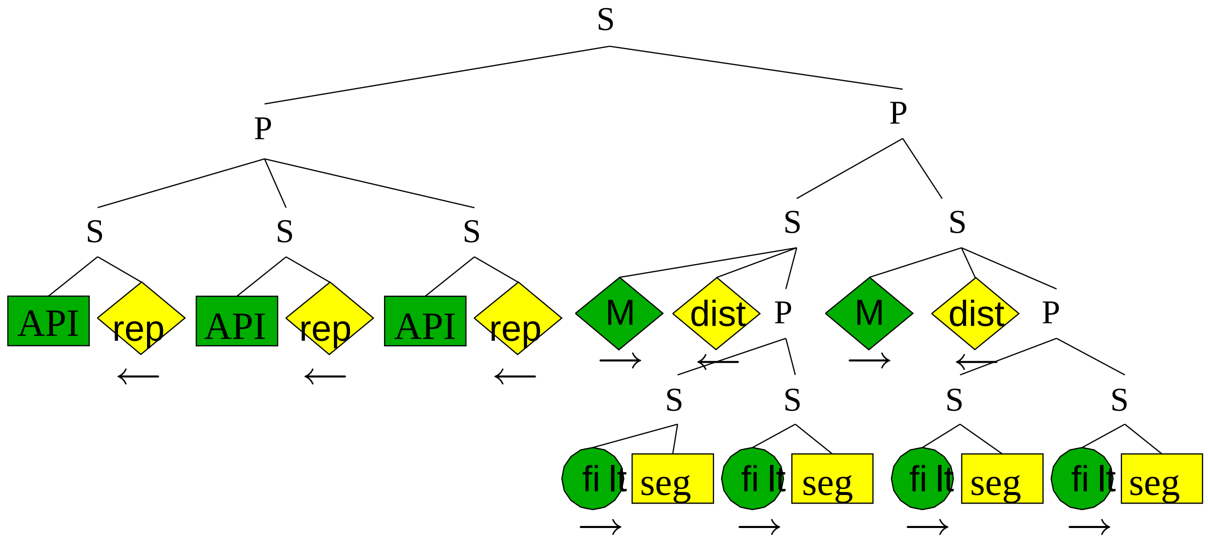
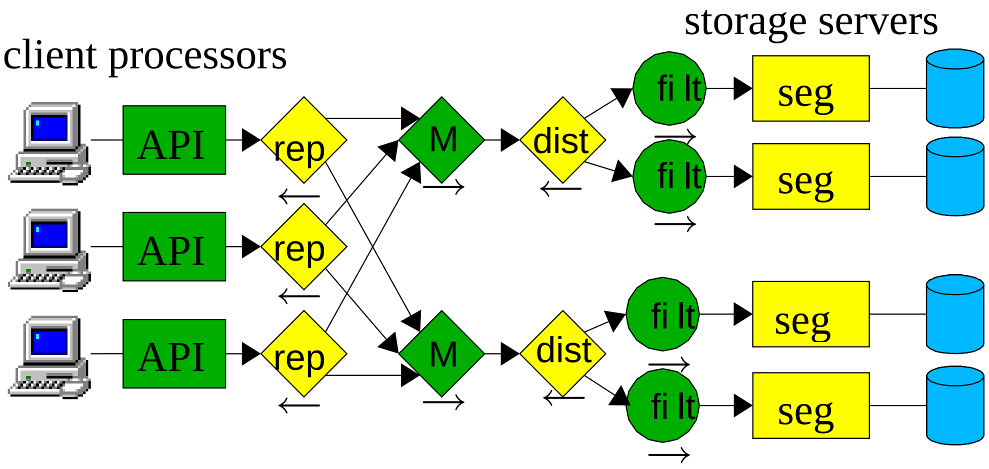




Placement

Hierarchical graph partitioning

1. Partition the ships into k sets (each set represents an administrative domain).
2. Partition the ships within each domain to processors provided by domain-level schedulers.

The Graph Partitioning Problem

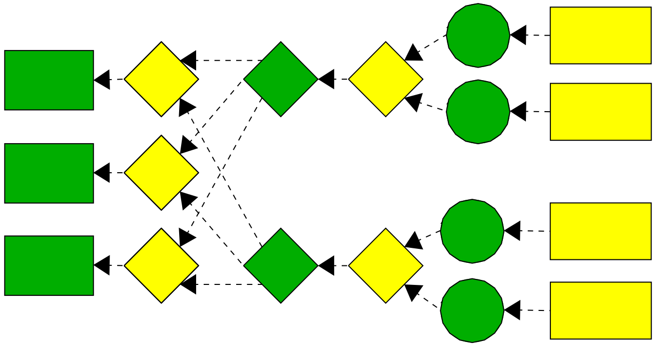
Given graph $G(V, E)$ with weighted vertices and weighted edges, partition the vertices into k sets in such a way to balance the sum of the vertices and to minimize the weights of the edge crossings between sets
(NP-hard [Garey et al., 1976]).

Partitioning an Armada Graph

Chaco Graph Partitioning Software [Hendrickson and Leland, SNL]

Algorithm for placement of Armada ships

1. Construct graph from SP-tree
2. Assign edge weights
3. Assign vertex weights
4. partition graph (using CHACO)
5. for each domain
    (a) request procs from domain
    (b) partition sub-graph



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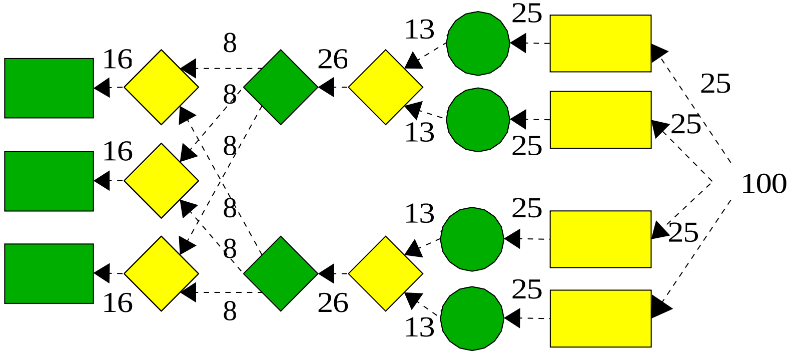

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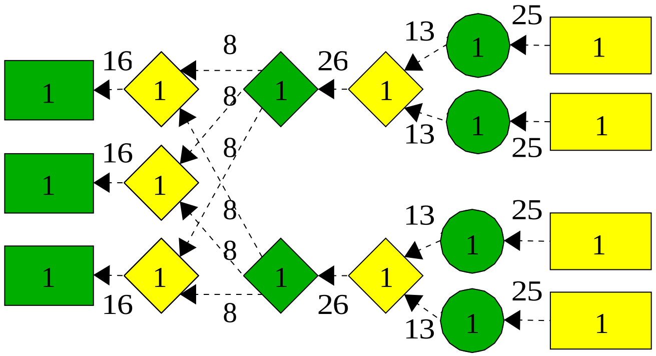

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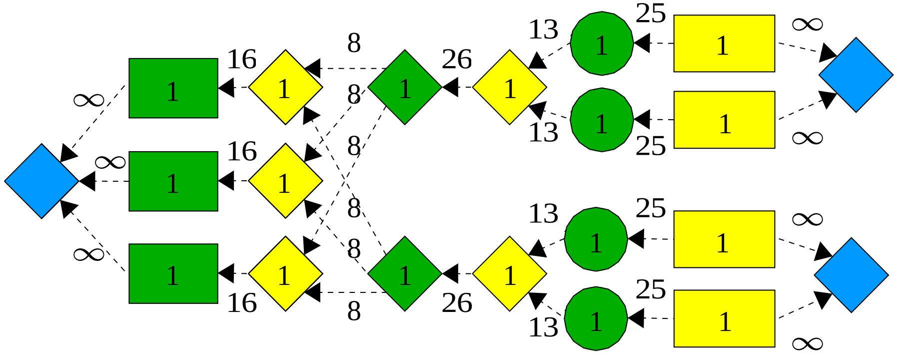

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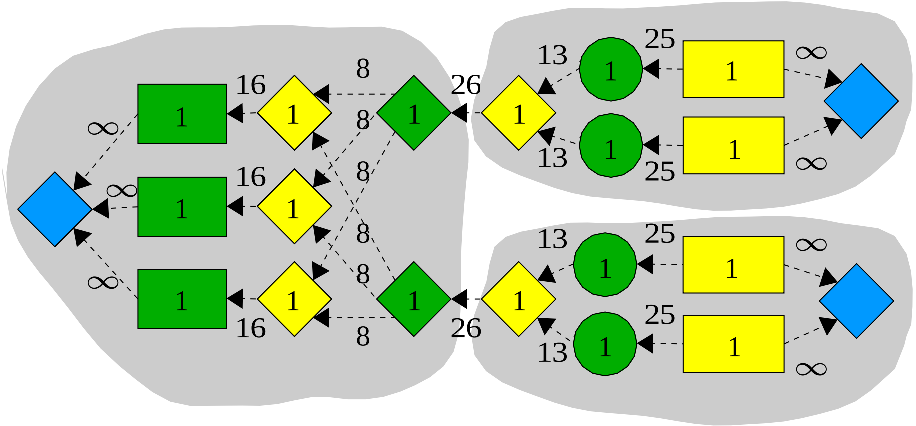

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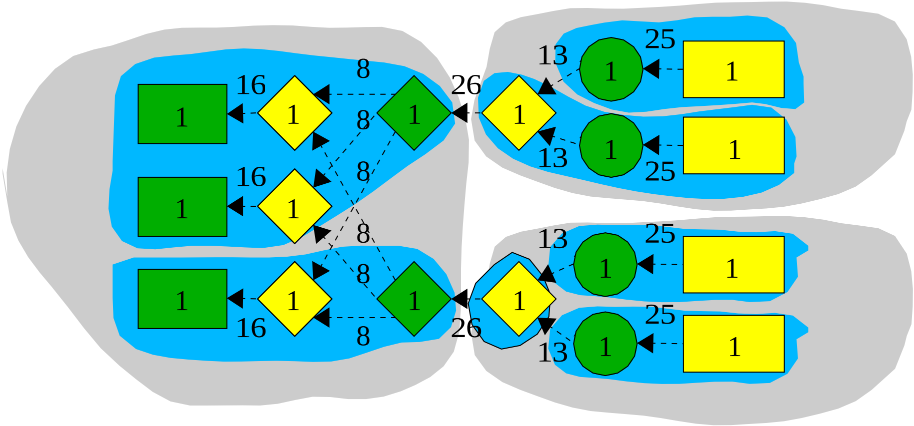
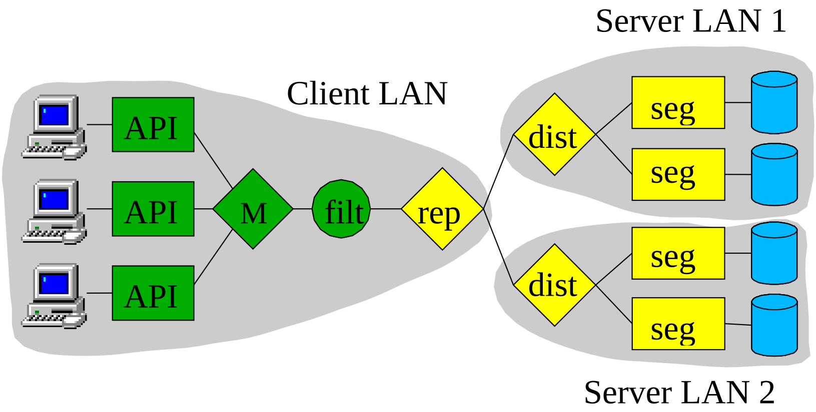
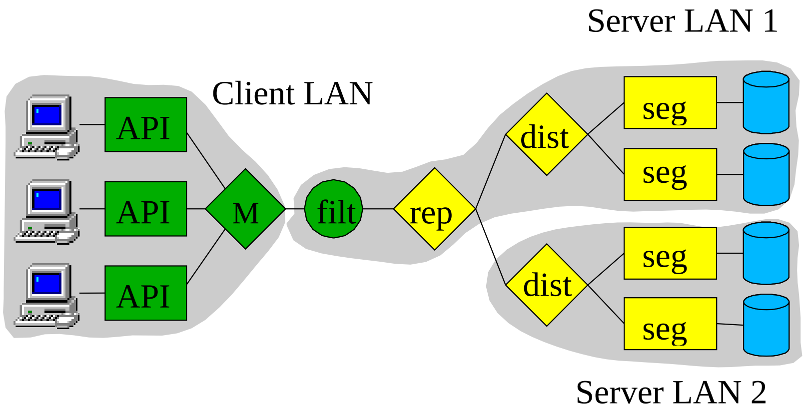


Experiments

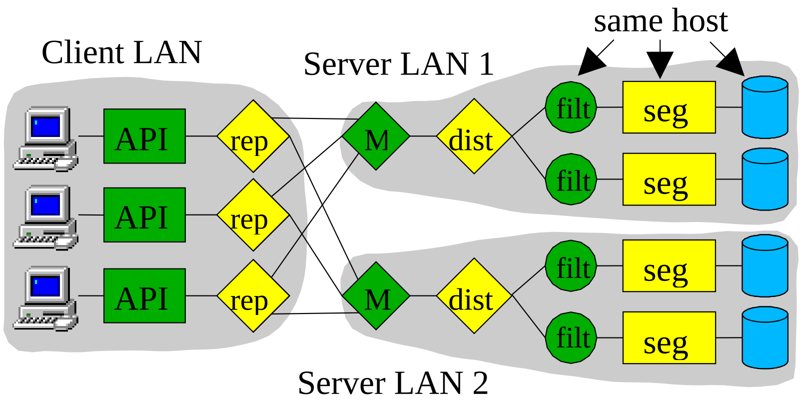
Examined four configurations of the example application with a filter that removed exactly 50% of the data.



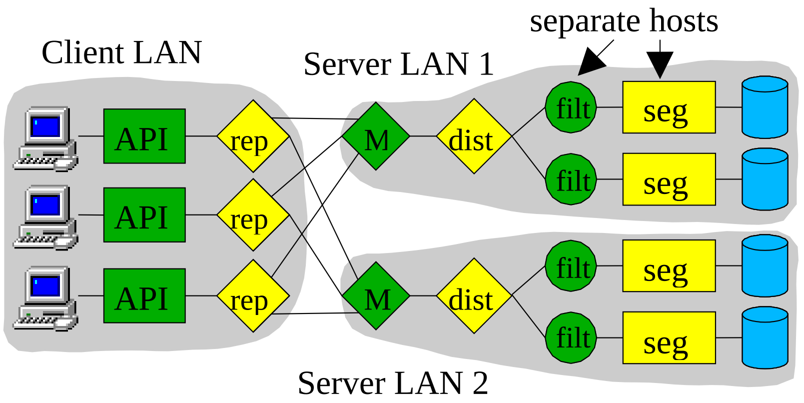
(a) orig1



(b) orig2



(c) restruct1

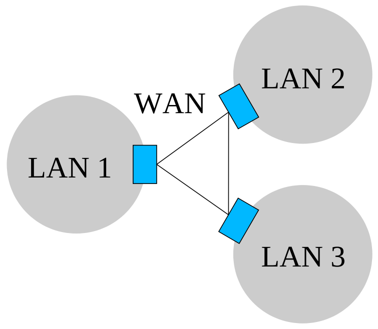


(d) restruct2

Experiment Setup

The area between the blobs represents the WAN

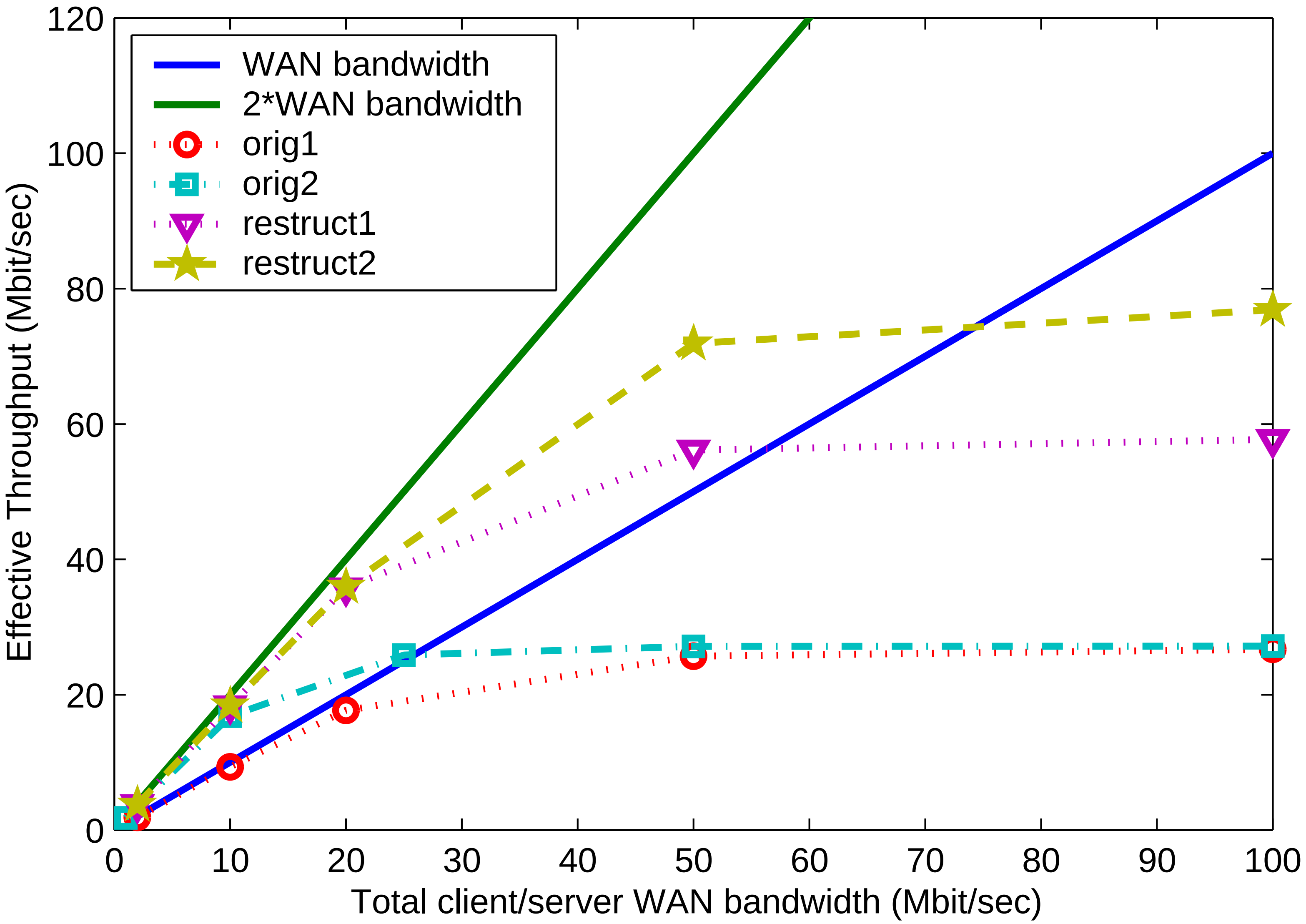
- each LAN connected to the WAN by single router
- each WAN link has limited capacity



Ran experiments on the Emulab Network Testbed

- 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 2 to 100 Mbps

Results: Effective Throughput



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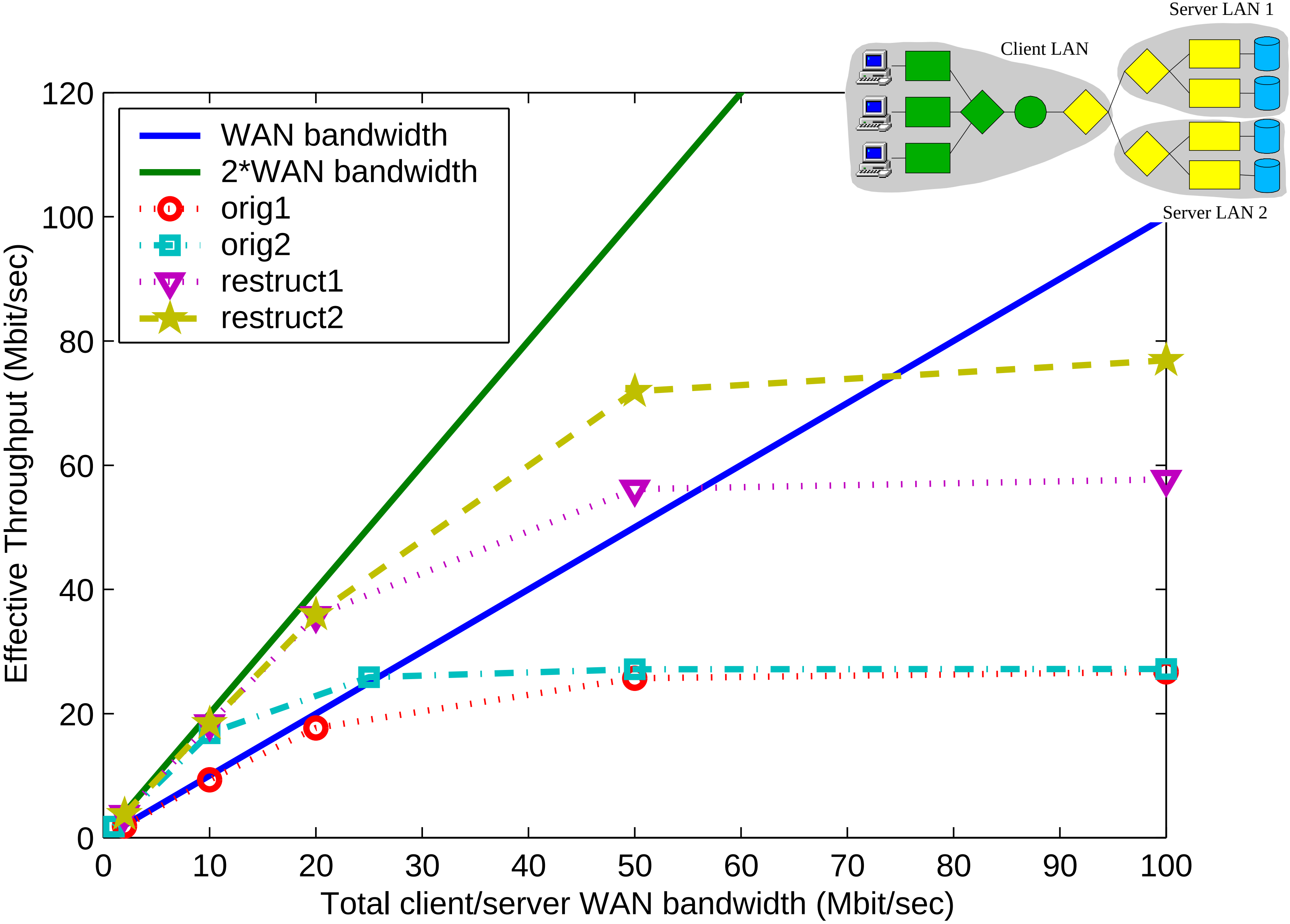

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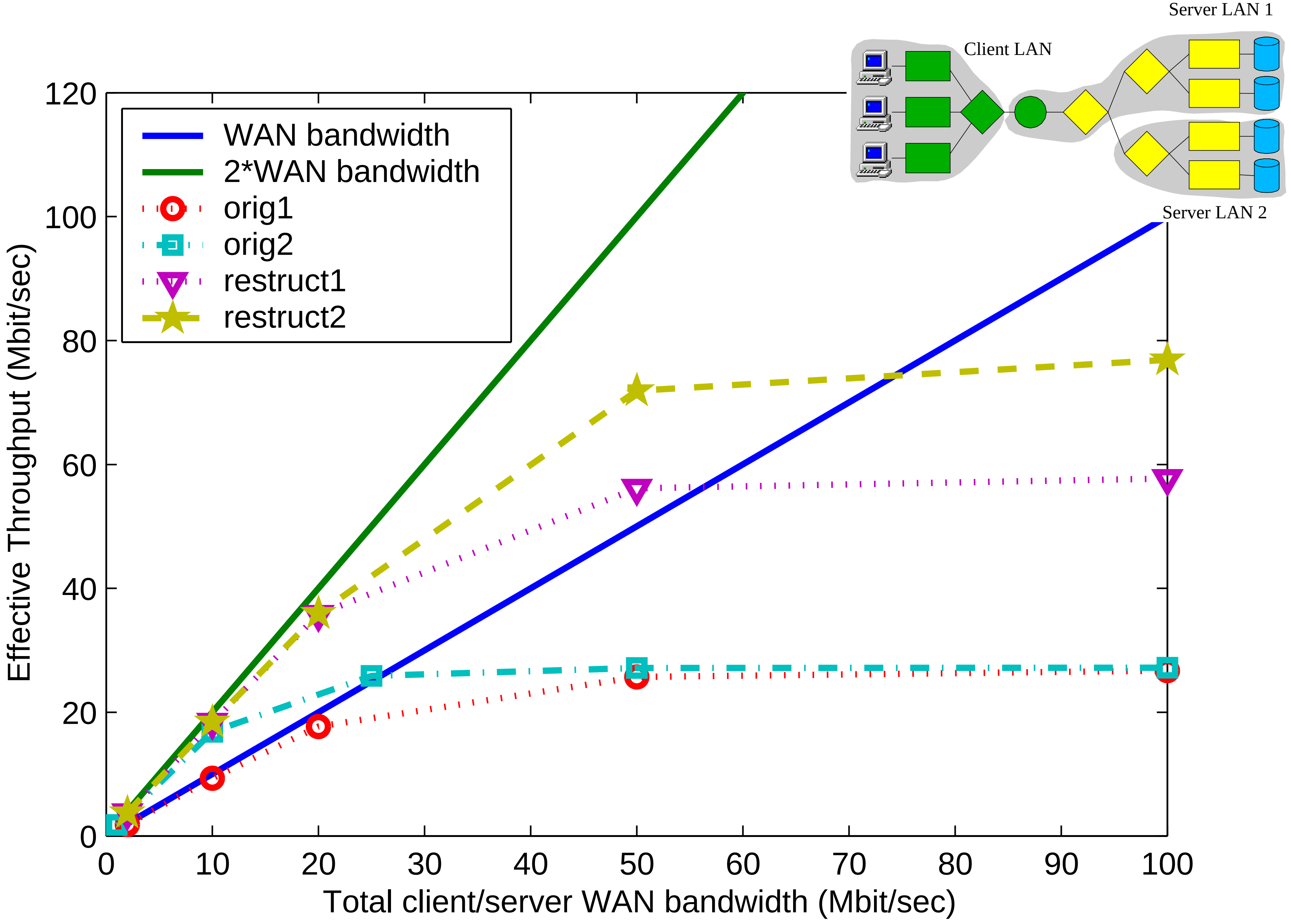

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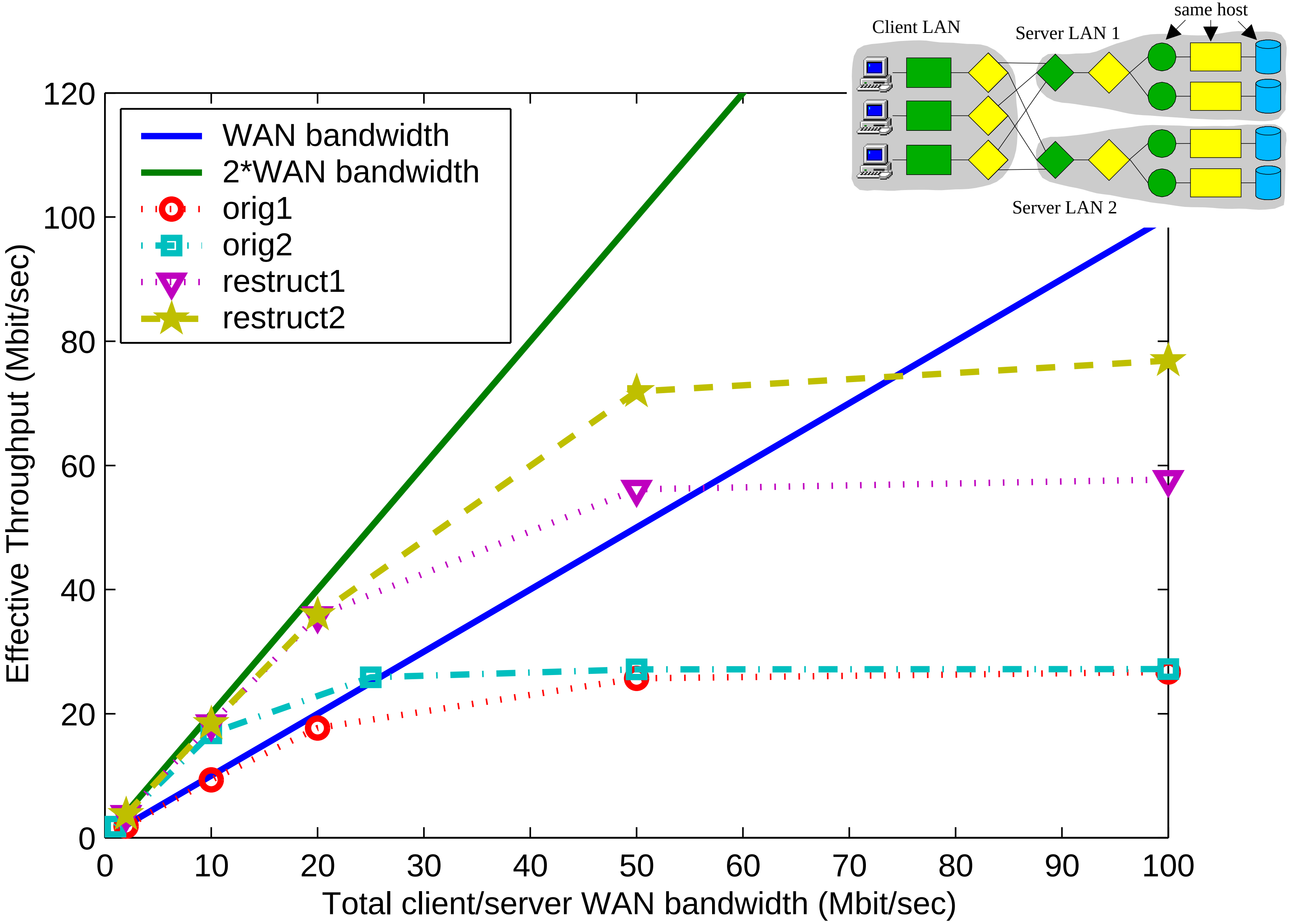

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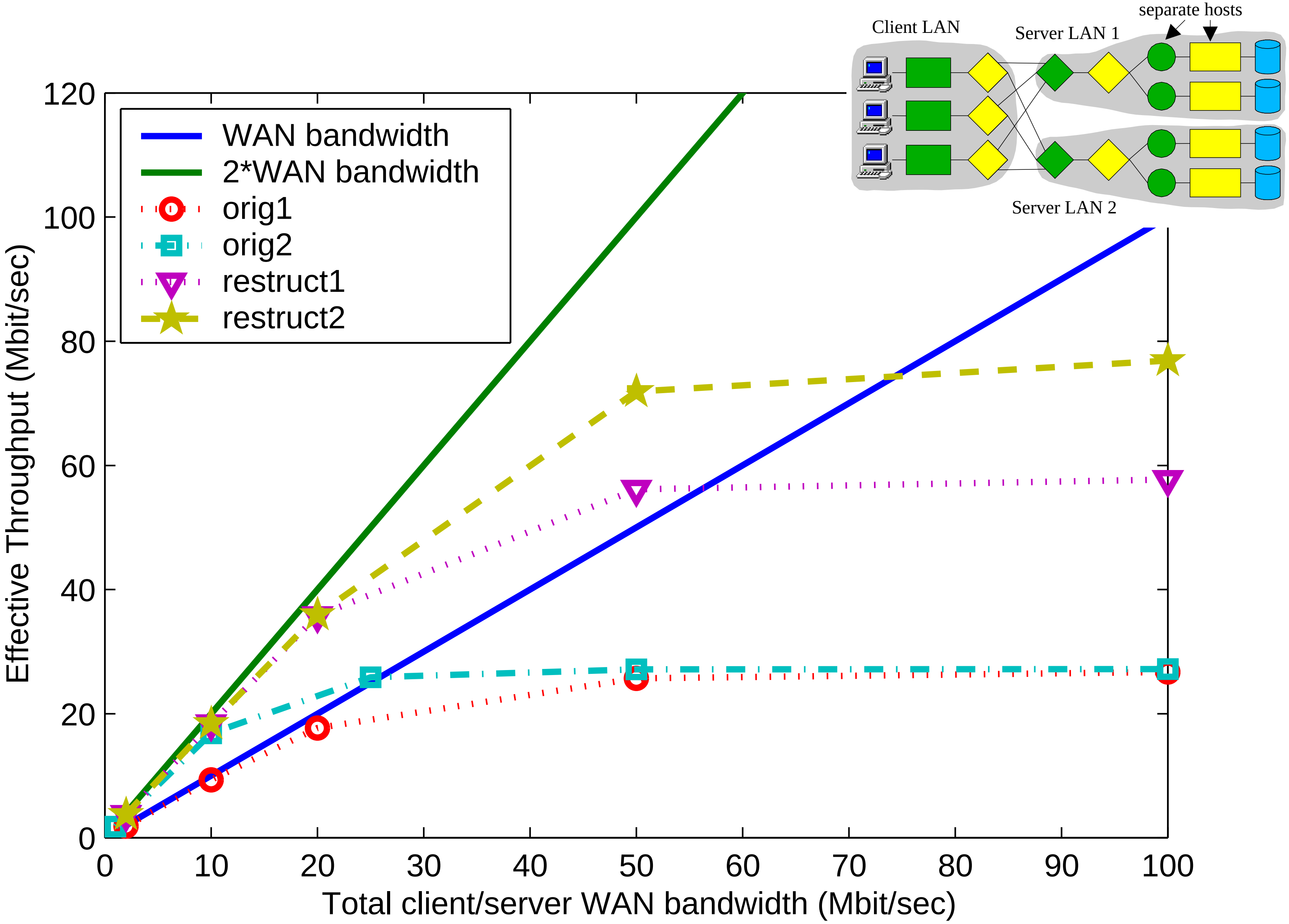

Related Work

Parallel processing of I/O streams

- PS^2[Messerli, 1999]
  - data-flow model with automatic parallelization
- DataCutter [Spencer et al., 2002]
  - component-based, analytic model to decide parallelization

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

Operation re-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

- fMRI application (80 TBytes of brain image data)
- Seismic application (3 TBytes of synthetic seismic data)
- Can components be reused between applications?
- How much can performance benefit?

Modifications to BENEFICIAL and COMMUTATIVE

Placement

- incorporate domain-specific information into the partitioner (compute capacity, memory capacity, etc...)
- dynamic re-deployment when network conditions change

Tuning for cluster computing (in addition to the grid)

Summary

The Armada framework

- allows data provider to describe complex distributed data sets
- allows the application to describe processing required before computation
- data-flow model provides a “latency-tolerant” 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

Placement

- hierarchical approach: application-level assignment to domain, domain-level assignment to processors.

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

The High-Performance I/O for Computational Grid Applications

Ron Oldfield and David Kotz

Department of Computer Science, Dartmouth College

http://www.cs.dartmouth.edu/∼dfk/armada/

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