Improving a High Productivity Data Analytics Chapel Framework

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Introduction

Arkouda

- Cutting edge Python data science library
- Interactive Python client
- Powerful Chapel-backed server

Many message exchanges

- Client and server's form of communication
- Inefficient and costly in some cases

Optimized client architecture

- Supports lazy evaluation
- Caches/reuses arrays and function results
- Eliminates common subexpressions
- Reduces unnecessary message exchanges

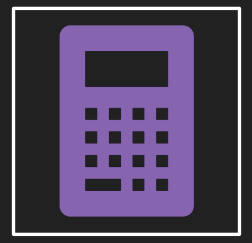
Section 1

Arkouda Overview

What is Arkouda?

Software package whose purpose is to **optimize data science operations** on large distributed data sets using **parallel computations** and a **NumPy-like** syntax

Ties **exploratory data analysis** with **high-performance computing** models to complement existing frameworks such as **Pandas**



Supports **multi-locale processing** of linear algebra data sets and graphs

More information: **https://github.com/Bears-R-Us/arkouda**

Arkouda Architecture

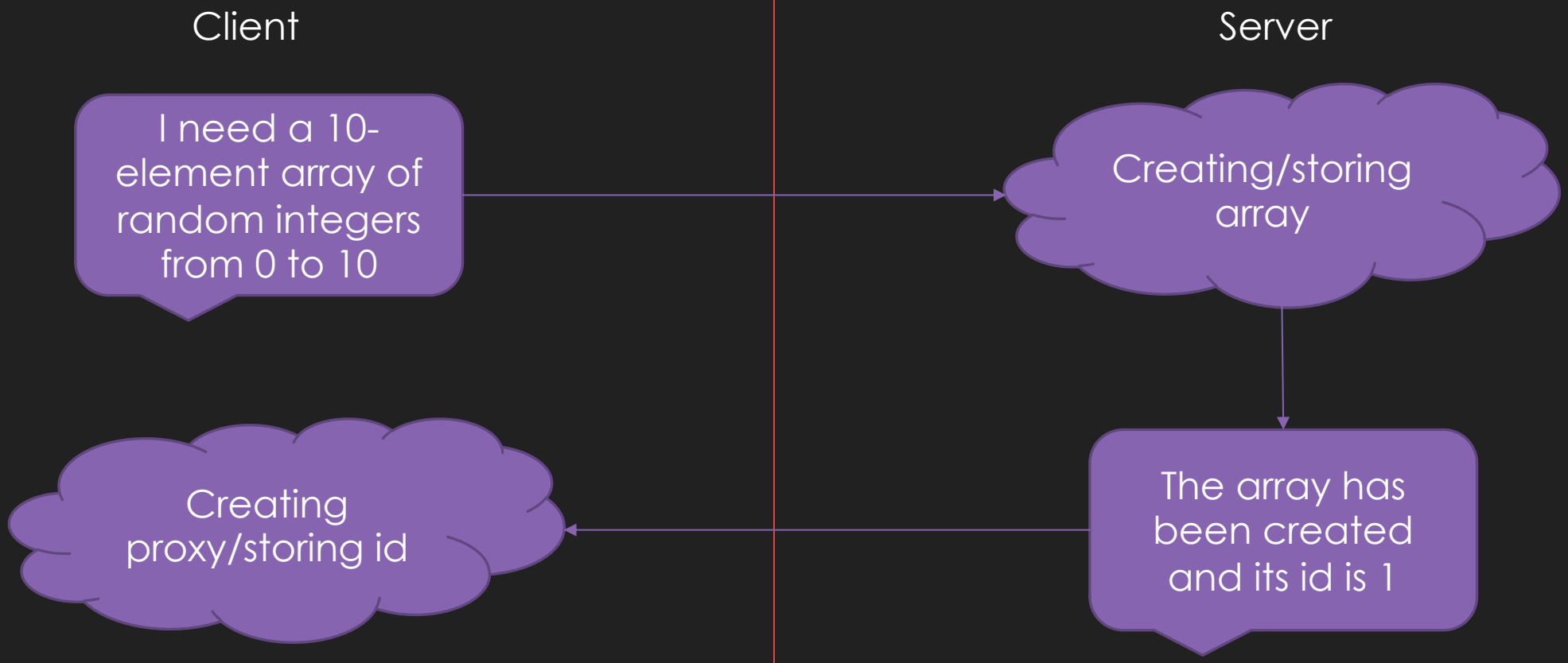
Python Client

- Exposes simple API to parallel operations
- Communicates with server using single command protocol

Chapel-backed server

- Implements set of data operations
- Receives and replies to messages
- Performs computations in parallel
- Stores data

Client-Server Interaction



Pdarray Specifics

Class which overloads common functions such as addition and multiplication

Relies on the Python compiler for garbage collection (invoking deletion)

Everything gets turned into a message

Arkouda Example

Client

Server

- A = ak.randint(0,10,10)
- B = (A * A) + (A * A)
- C = ak.randint(0,10,10)
- print(C)
- Sends 8 messages and creates 5 arrays
  - 2 -> randint
  - 3 -> binopvv
  - 2 -> delete
  - 1 -> str

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- A = ak.randint(0,10,10)
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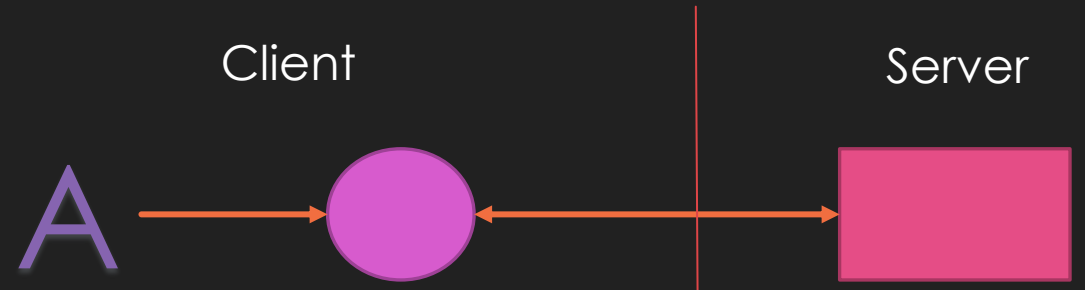

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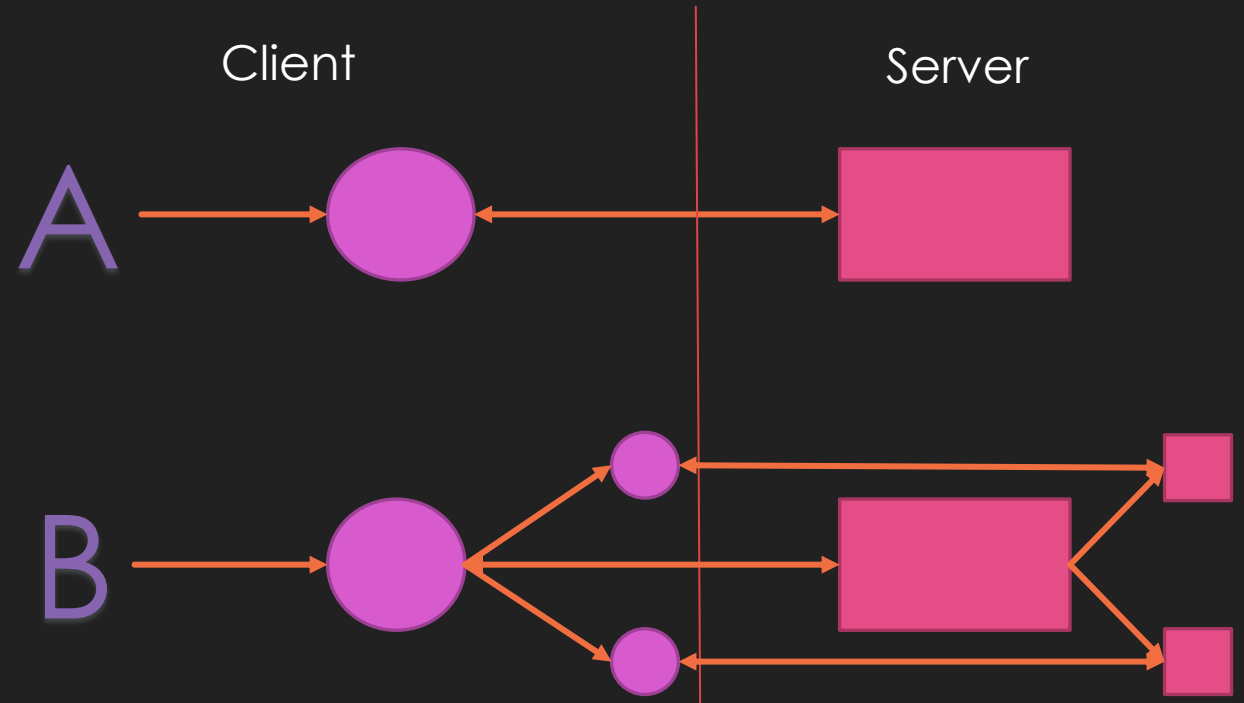

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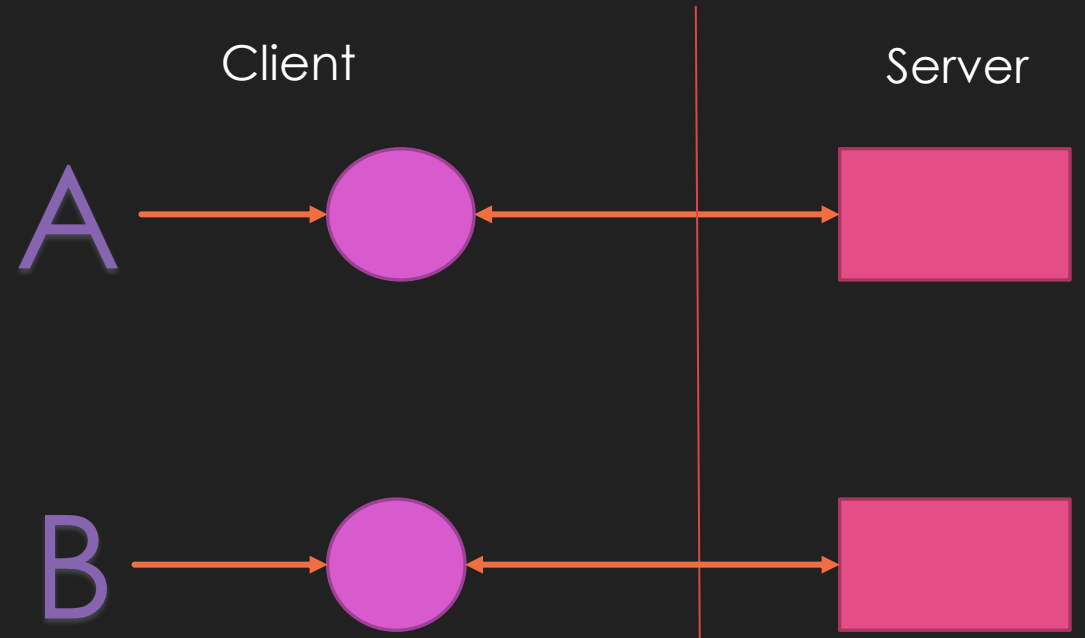

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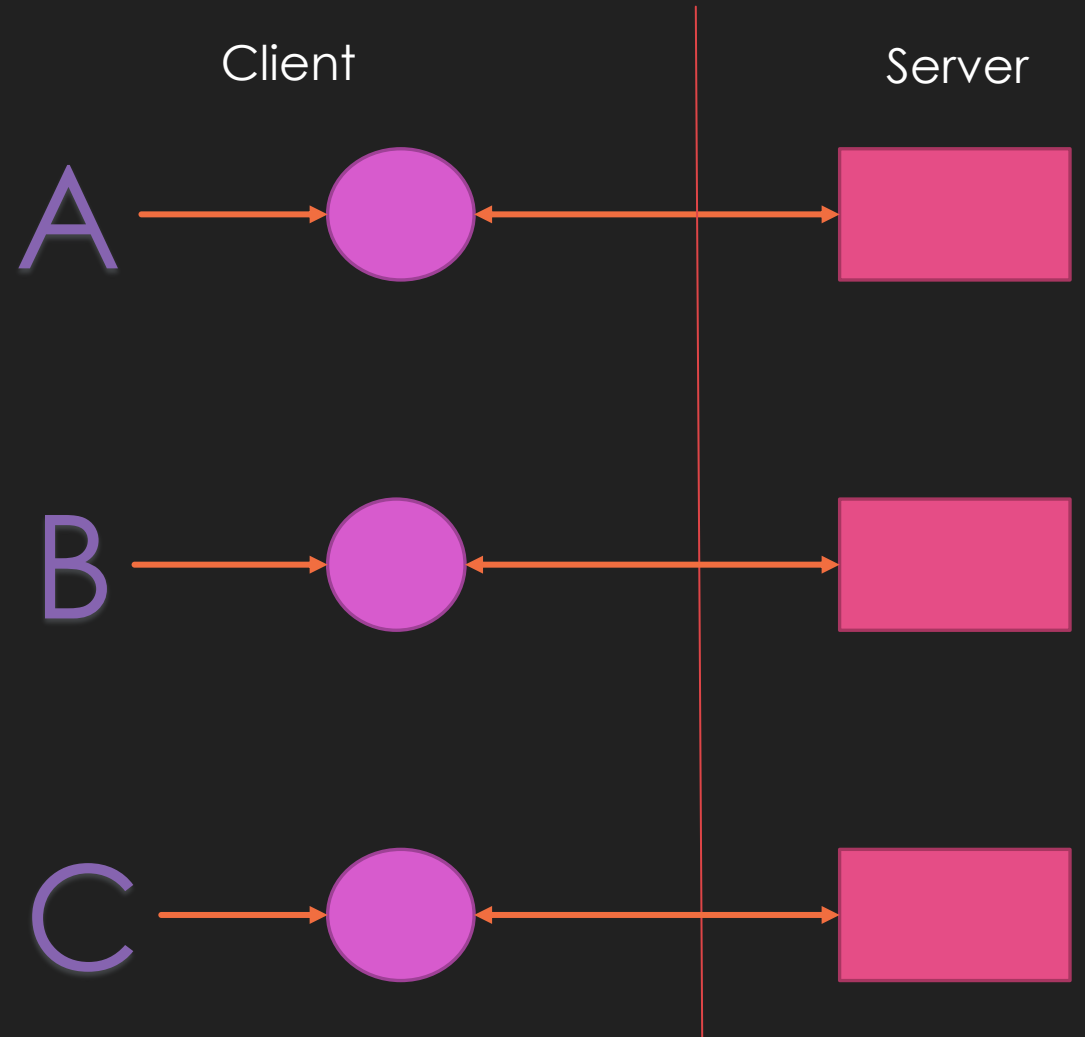

Section 2

Optimized Framework

Client-Side Optimization

Reduce	Reduce ZeroMQ messages between server and client using batching and code analysis
Optimize	Optimize programs using lazy evaluation and common subexpression elimination
Reuse	Reuse unused temporary arrays and improve server-side memory management

Room for Improvement

- A = ak.randint(0,10,10)
- B = (A * A) + (A * A)
- C = ak.randint(0,10,10)
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- Sends 2 messages and creates 1 array
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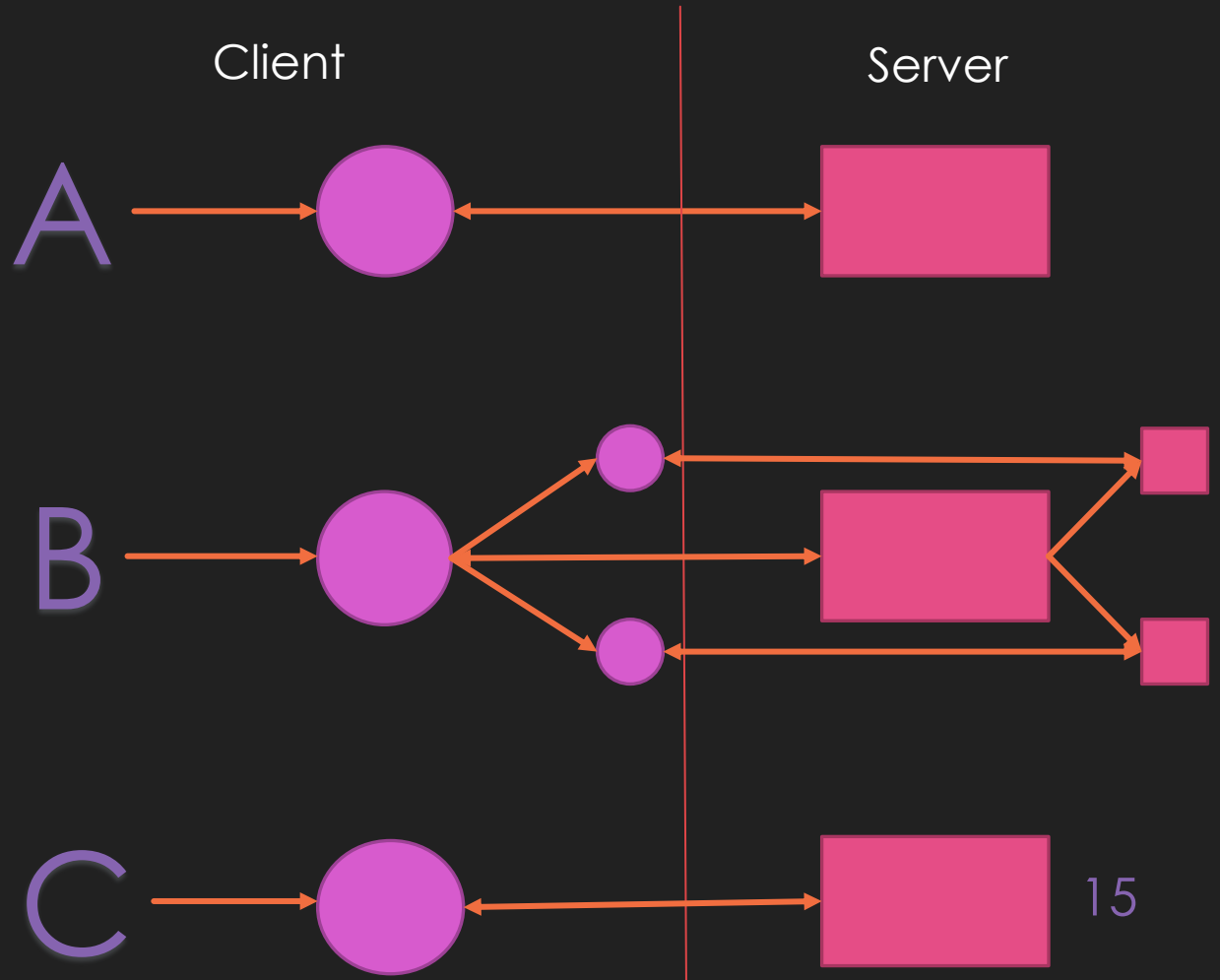

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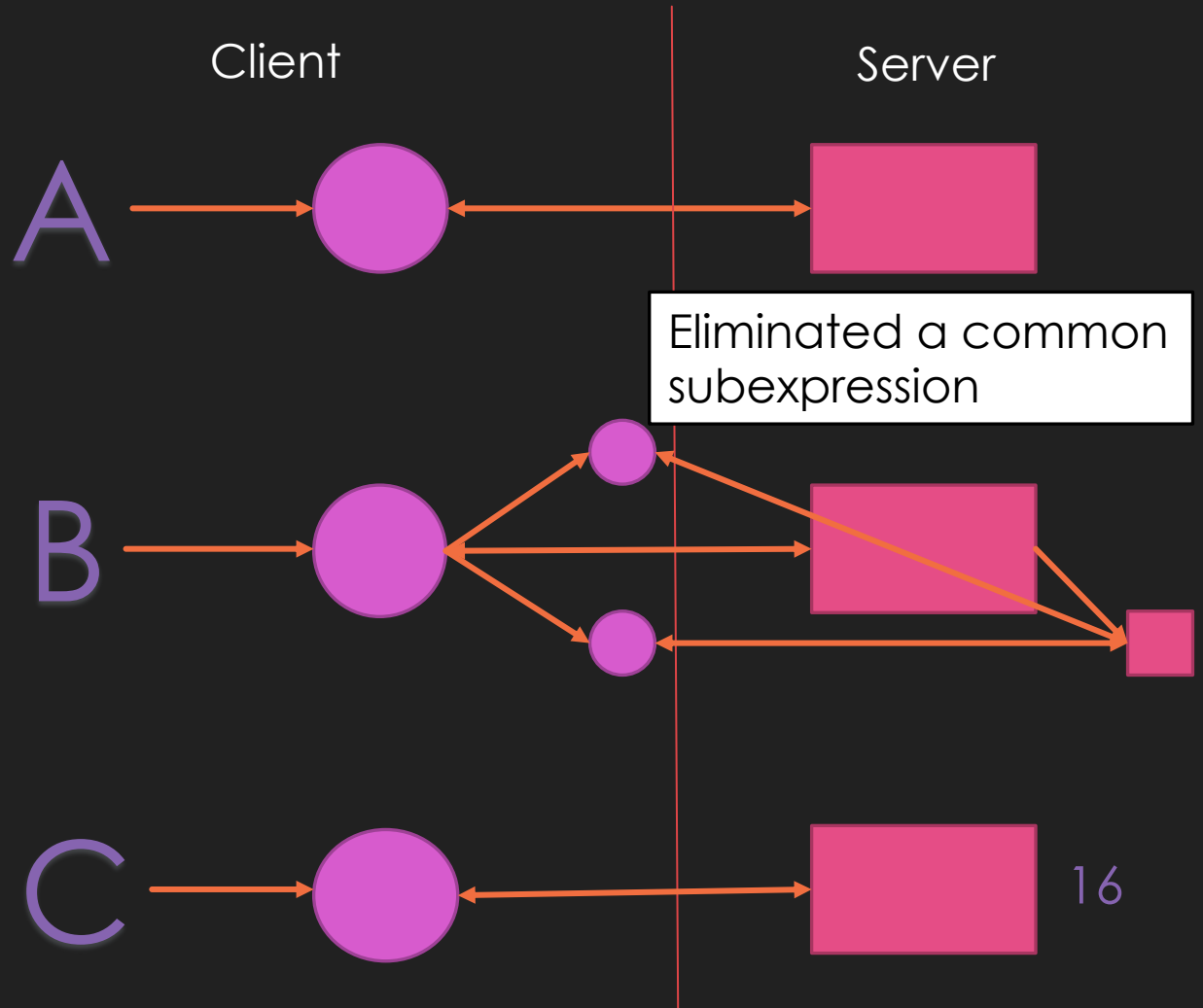

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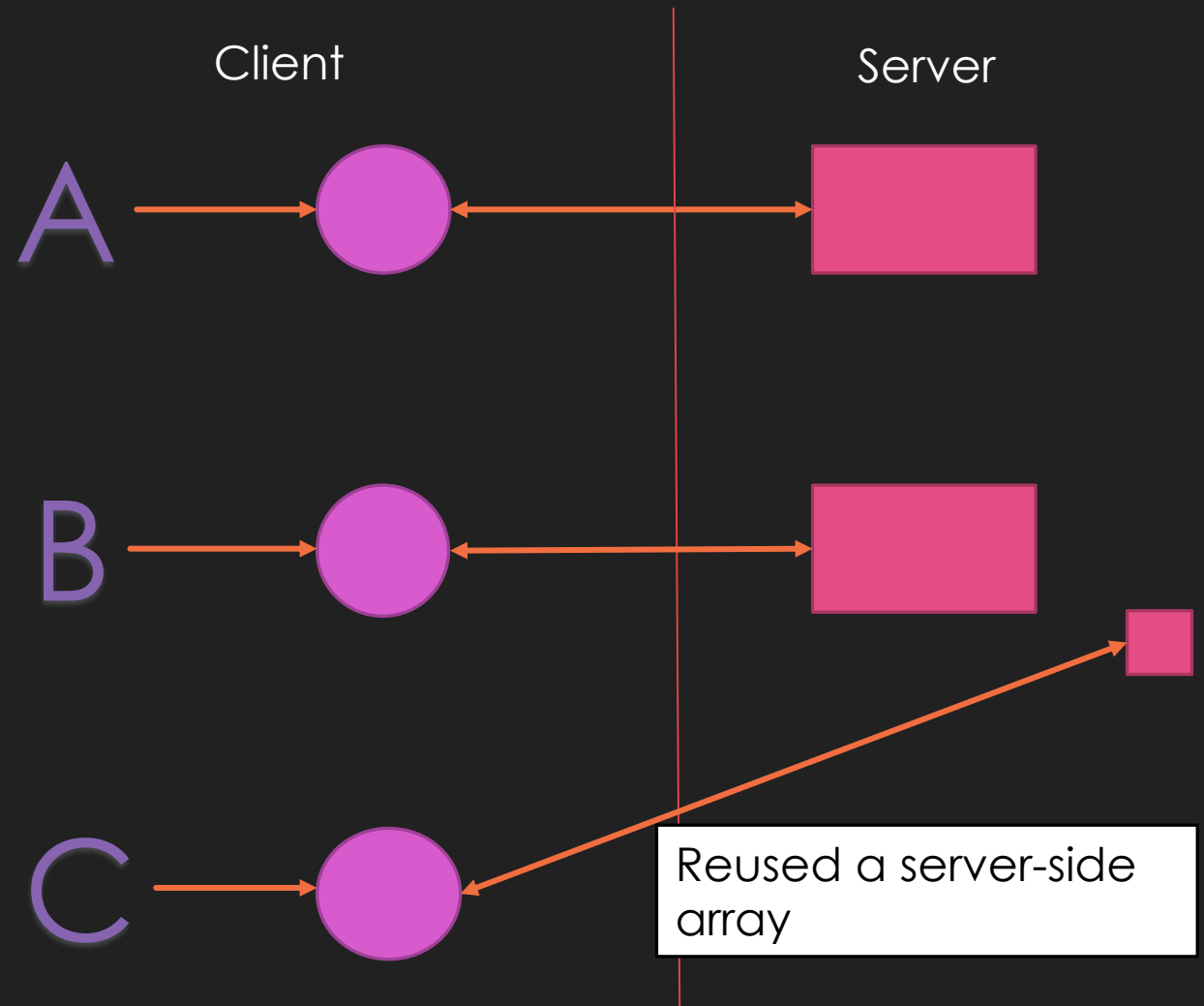

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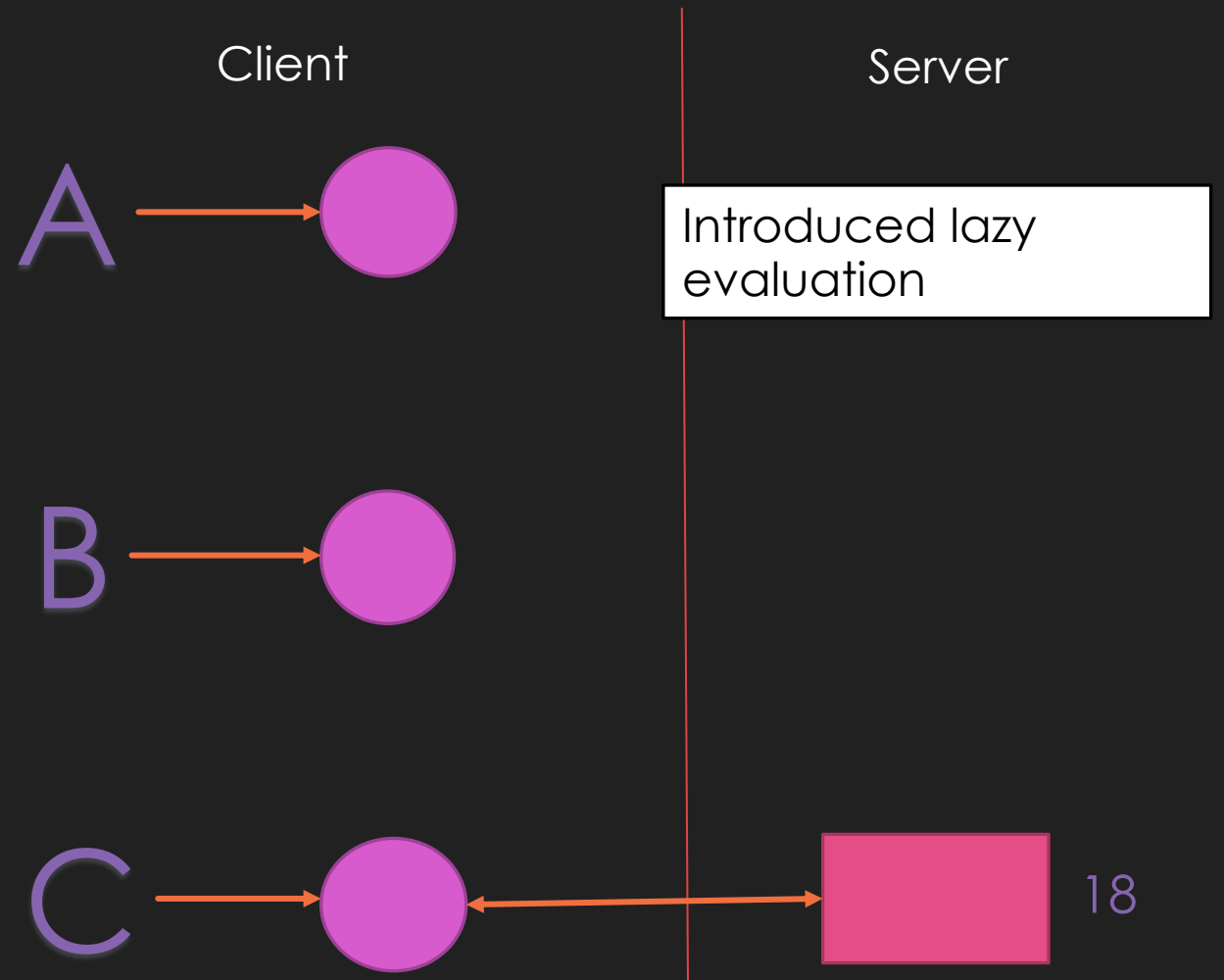

Architecture Components

Command Buffer

- Enables lazy evaluation and CSE which reduces sent messages and server-side arrays

Cache

- Allows reuse of server-side arrays which improves space efficiency

Store Functions

- Extends server API to overwrite arrays

Batch Command Buffer Data Structure

- FIFO queue of arkouda commands (BufItems)
- Hold a reference to a BufItem in each pdarray
- BufItem properties
  - Write id string
  - Comma separated read id string
  - Command string
  - Comma separated arg string
- Lazy evaluation on data access demand

BufItem("1", "", "randint", "0, 10, 10")

BufItem("2", "", "randint", "0, 10, 10")

BufItem("3", "1, 2", "binopvv", "+")

```
A = ak.randint(0,10,10)
B = ak.randint(0,10,10)
C = A+B
```

Caching: Optimize Server-Side Memory Management

Minimize messages that create/destroy server-side arrays

Keep track of server-side arrays and manage them on the client side

Map client array ids to server array ids

Reduce work done by server (creation/destruction of arrays)

```
for x in range(1000):
    A = ak.randint(0,10,10)
    B = ak.randint(0,10,10)
    C = A + B
    print(C)
```

Only use 3 arrays instead of 3000

Server API Extension: Store Functions

Specify where to store the result of arkouda operations

Allows us to use cached unused server arrays

Putting it all together

```
B = (A * A) + (A * A)
print(B)
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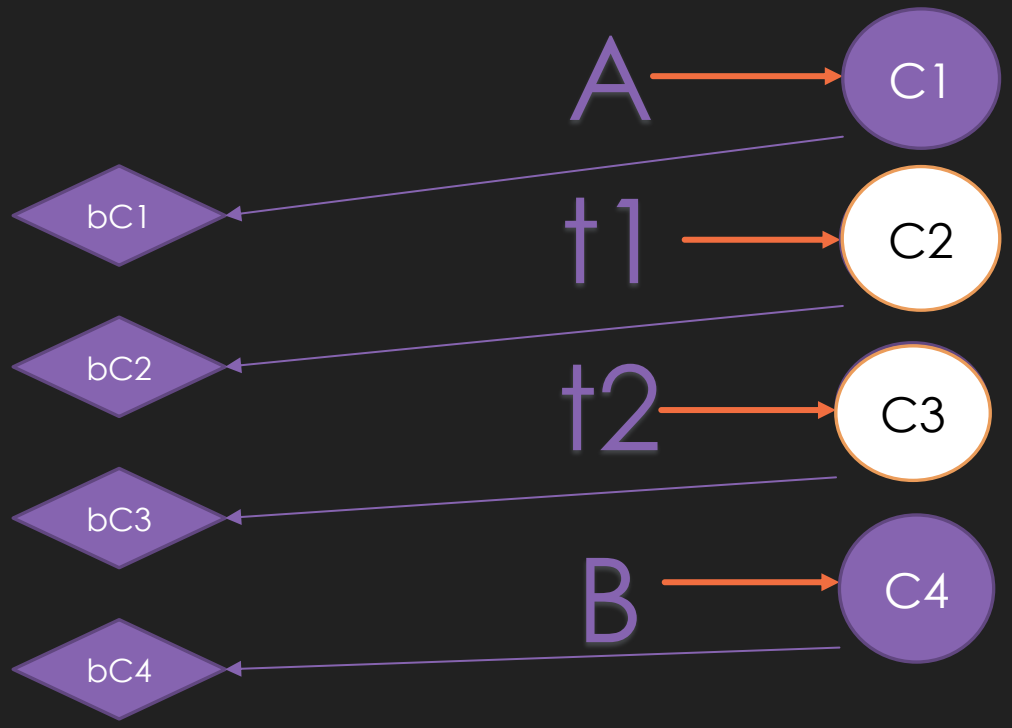

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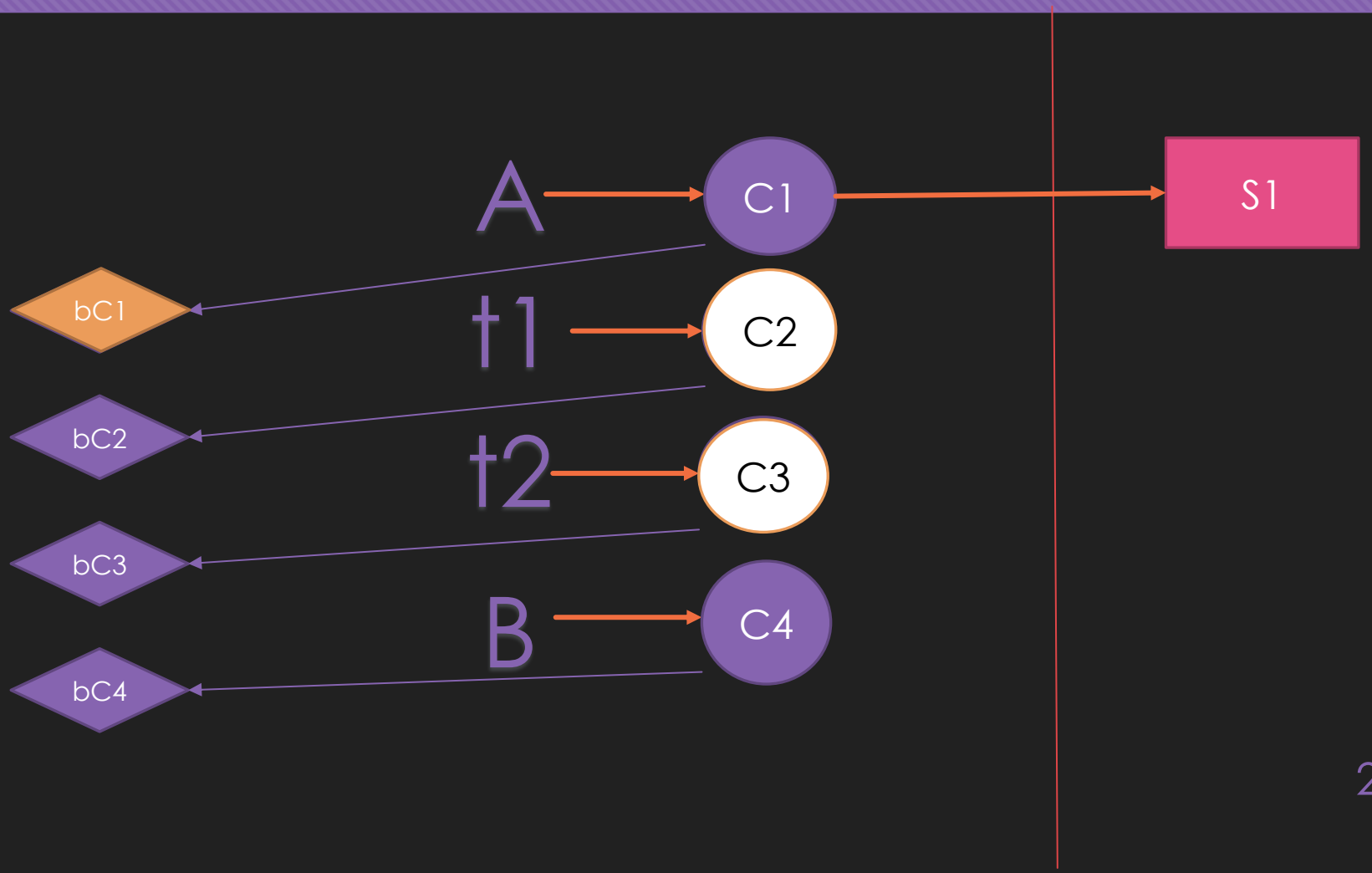

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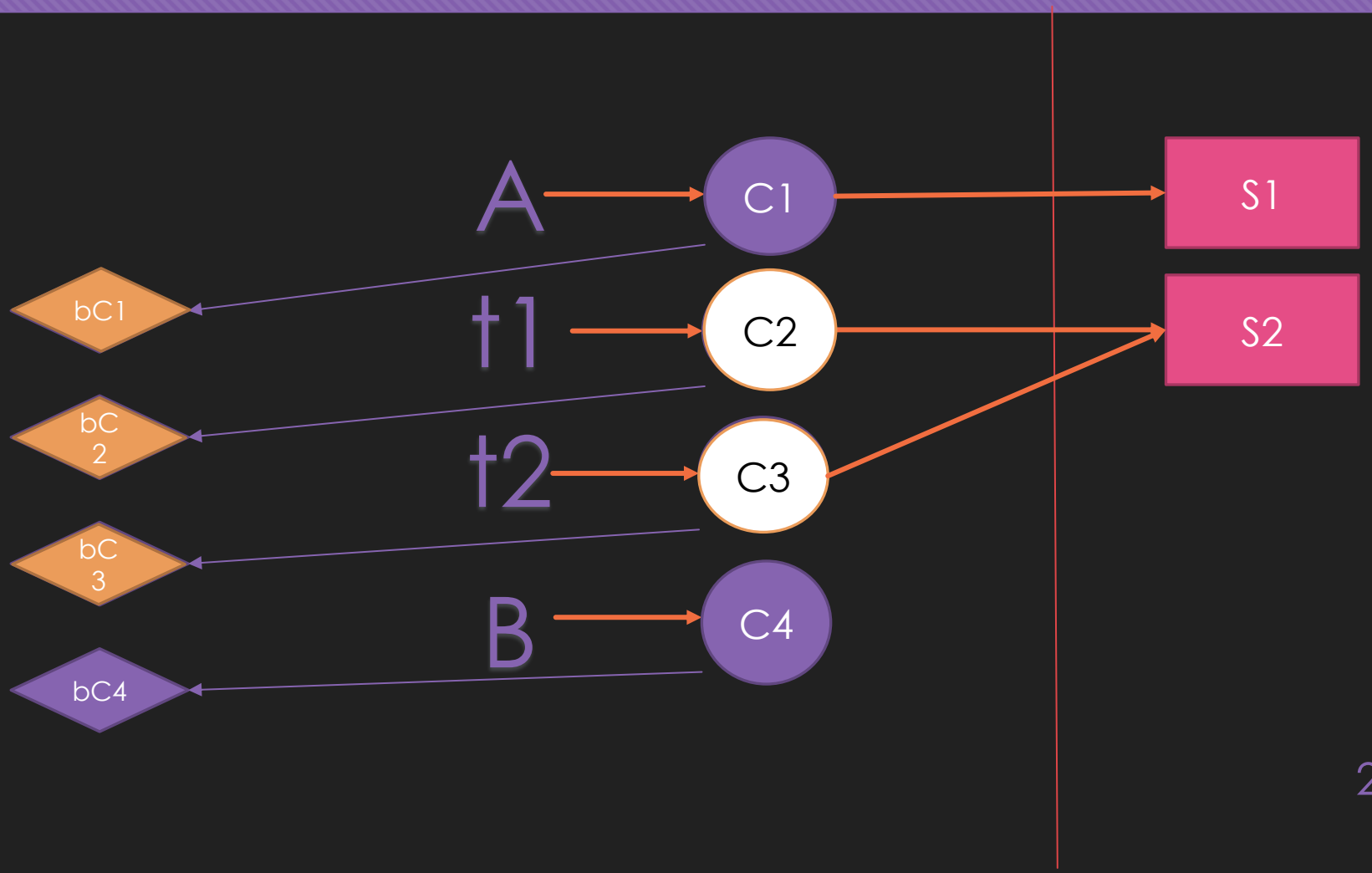

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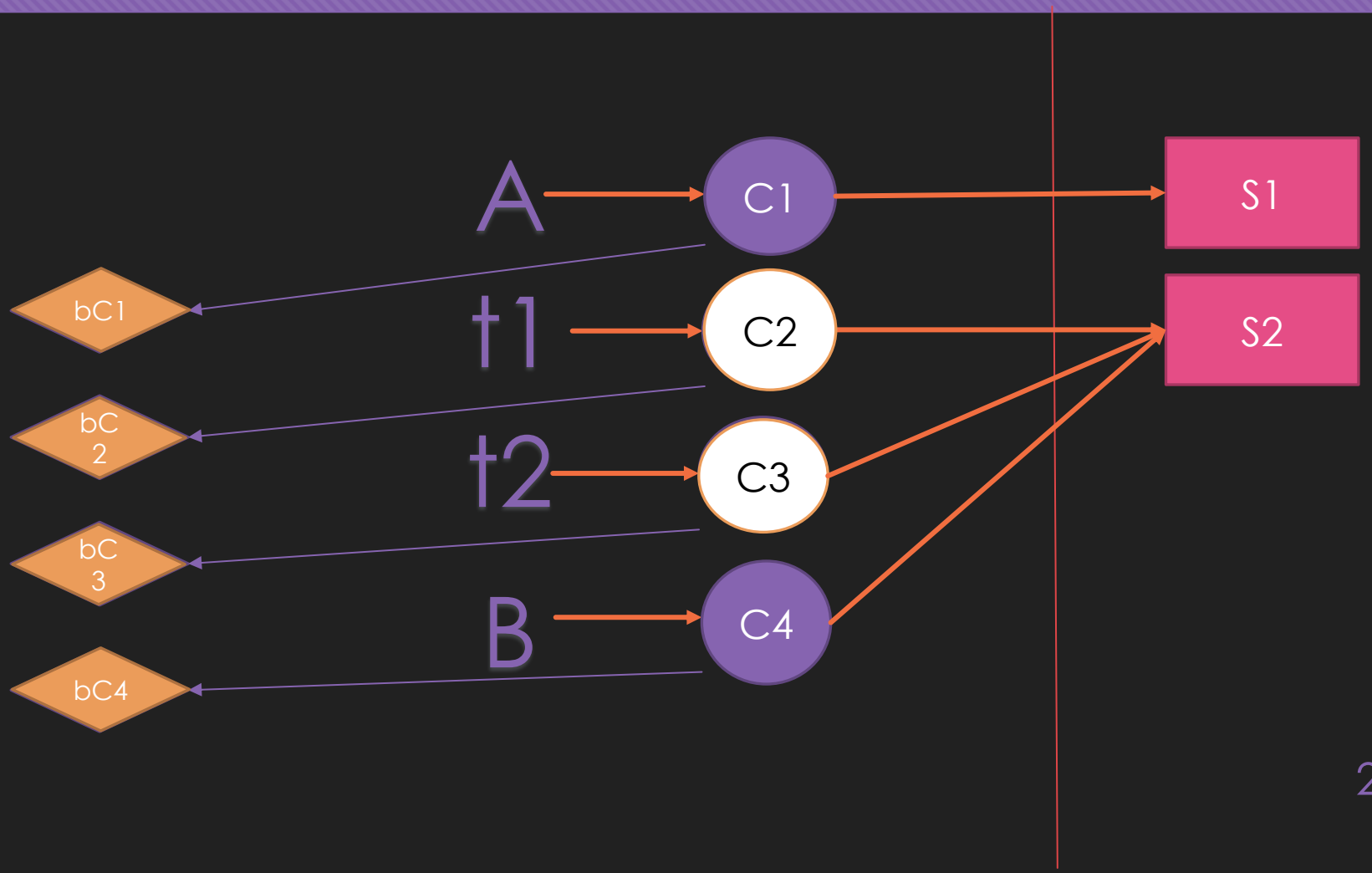


Section 3

Benchmarks & Results*

*All experiments were run on single shared memory node with a Xeon E3-1220 [7] processor

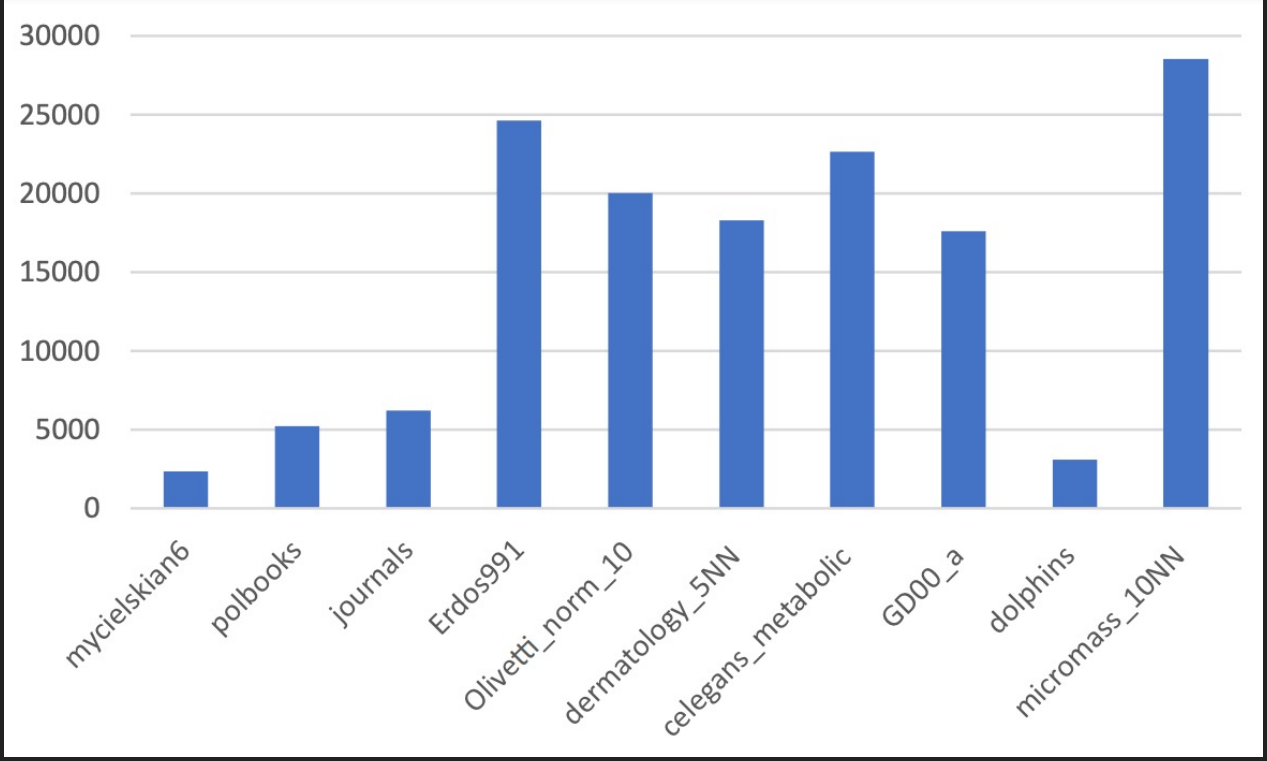
Example: Triangle Count for Dense Matrices

Simulates matrix – matrix multiplication and applies a mask sum((L * L) .*L)

```
maxi = 0
arr = np.zeros(len(A),np.int64)
for i in range(len(A)):
    for j in range(len(A)):
        k = ak.sum(A[i]*At[j])
        arr[j] = k
    pdarr = ak.array(arr)
    maxi += ak.sum(pdarr*A[i])
return maxi
```

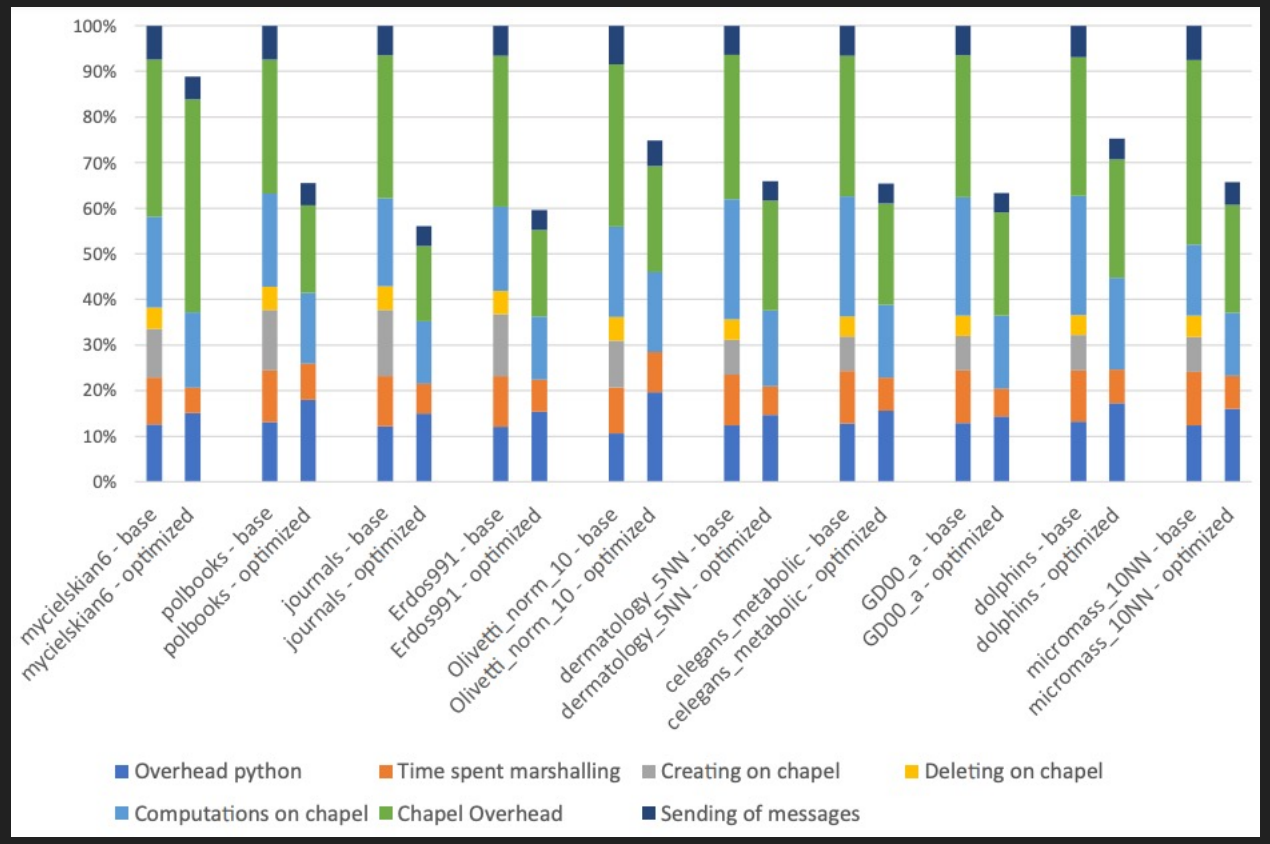
Opportunities to reuse arrays

Ratio of Created Arrays between Base/Optimized Arkouda (Dense)



- Fewer arrays used in optimized version across the board
- Scales based on size of matrix
- Nearly 30,000 times fewer created arrays on largest example

Profiling of Base/Optimized Arkouda (Dense)



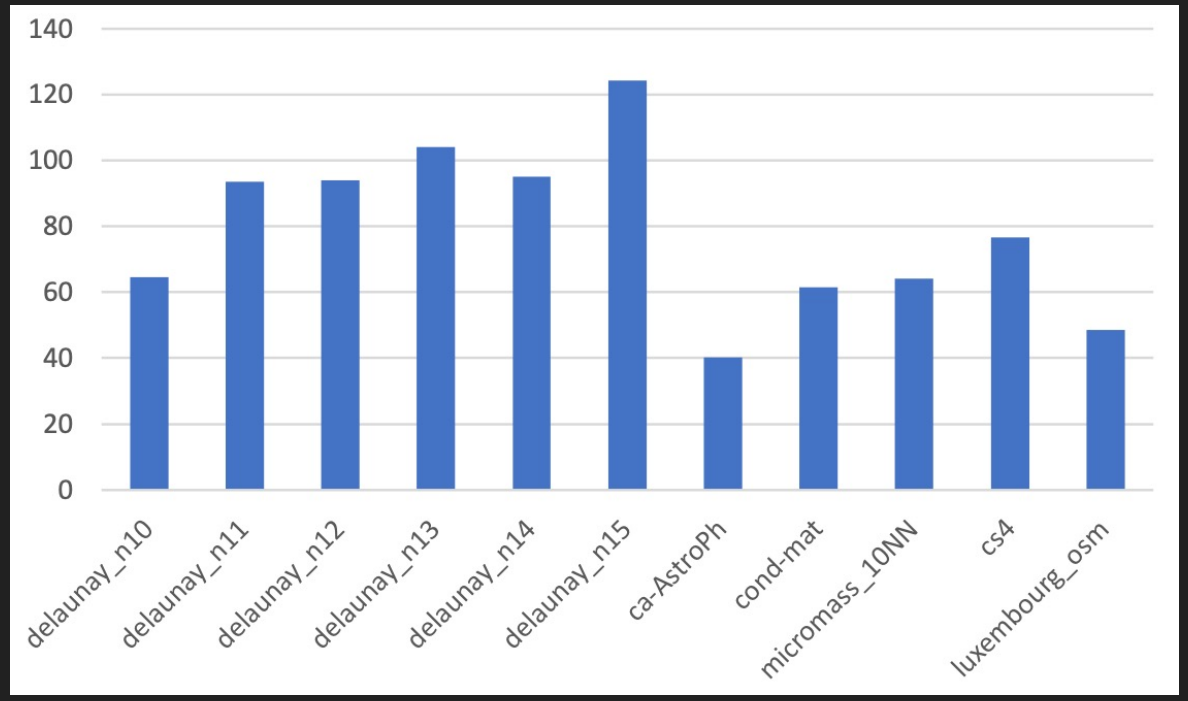
- Faster program execution across the board
- Significantly reduced time creating/deleting arrays on Chapel

Example: Triangle Count for Sparse Matrices

```
for i in range(len(pointers)-1):
   right = pointers[i+1]
   if (pointers[i] < right):
     for j in range(pointers[i],right) :
         s += ak.sortIntersect1d(find_splice(i, pointers, pd_indexes),
                                 find_splice(pd_indexes[j], pointers2, pd_indexes2)).size
```

- Uses CSR, CSE and Arkouda set operations
- Also room for array reuse

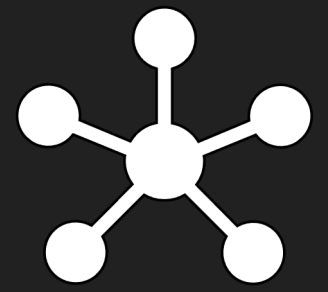
Performance Improvements as a Percentage (Sparse)



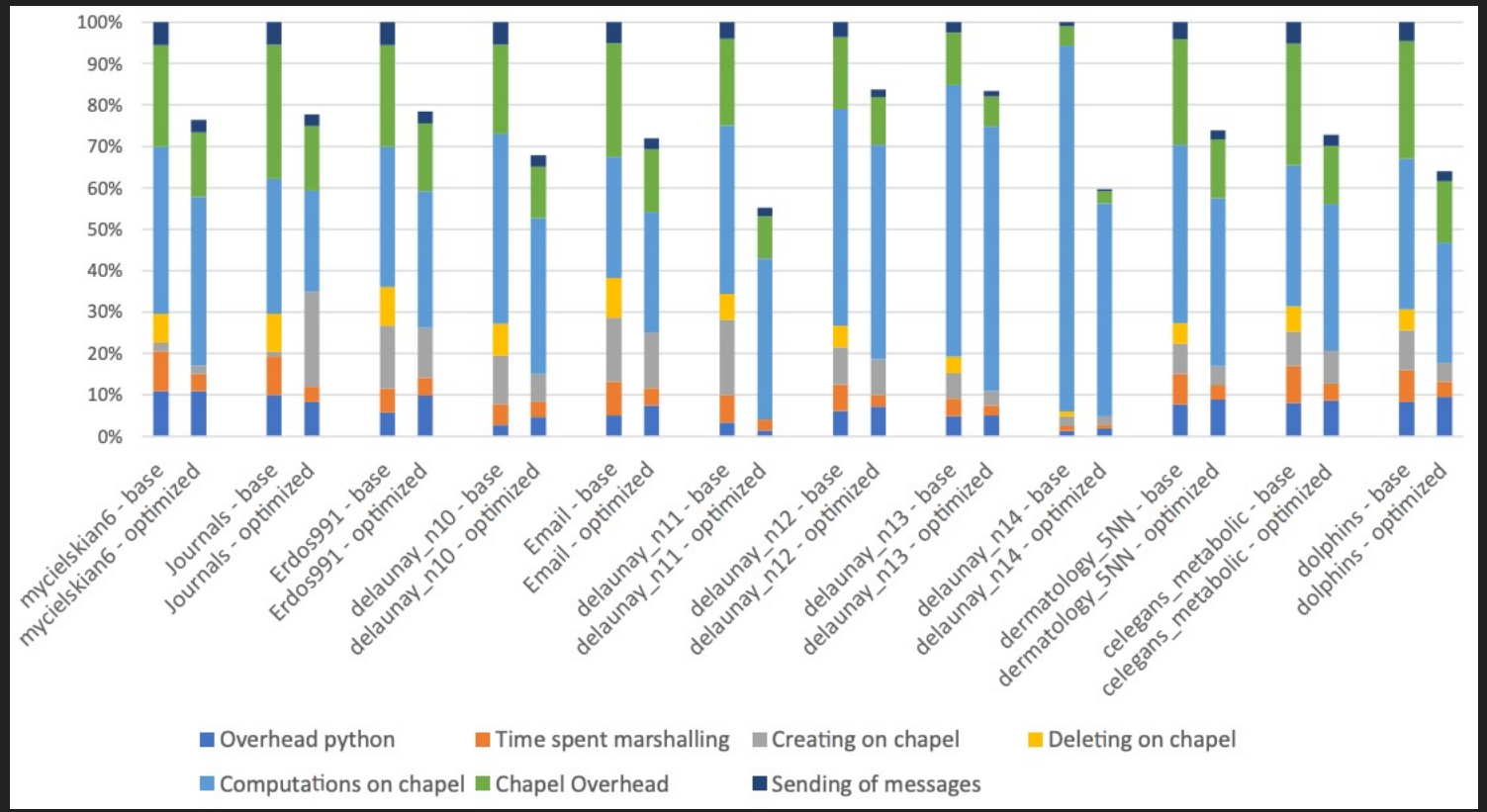
- Performance improvements across the board, especially for more sparse matrices
  - Less time spent on set operations
- Over 120% performance improvement for delaunay_n15

Example: Betweenness Centrality

- Measures the number of shortest paths that go through a node, divided by the number of shortest paths in the graph
- Mirrored off of a GraphBLAS implementation
- Two loops that each generate a series of temporaries
- O(n^2) rather than O(n^3) so easier to use larger matrices



Profiling of Betweenness Centrality



- Consistent performance improvements across the board
- Improvements not dependent on matrix size since Arkouda array size was consistent

Example: NYC Taxi Cab Example

- Real-world example based on database of NYC taxi trips in January 2020
- Series of unary operations applied to a single immutable Arkouda array
- Repetition of min() , max() , mean(), std()
  - Internal repetition of sum()
- Results
  - 35% performance increase (0.16s rather than 0.25s)
  - Sent 30 messages rather than 36 messages

Section 4

Current Work & Next Steps

Current Work: Message Aggregation in Loops

```
for i in range(len(array)):
    b = array[i]
    b = b - m
    b = b // e
    b = b % r
    b = math.floor(b)
    c = buckets[b]
    c = c + 1
    buckets[b] = c
```

- Example on left has 3 calls per loop iteration
  - (3 * number of iterations) message exchanges
- Can we generalize these loops on the server-side?
- Key idea: send entire loops from the client to the server using one message

Preliminary Results

3 Arkouda operations, 4 scalar operations

Iterations	Base (s)	Dependent (s)	Base-Dependent Ratio	Independent (s) using (iterations/100) tasks	Base-Independent Ratio
1k	3.7261	0.0769	48.4311	0.0760	49.0476
10k	40.3329	0.7139	56.4969	0.7046	57.2431
100k	379.6306	6.9259	54.8129	7.4018	51.2891
1M	3223.7308	67.1780	47.9879	82.4395	39.1042

* Server/client run on MacBookPro, single node, 2.4 GHz Quad-Core Intel Core i5, shared memory

Preliminary Results

13 Arkouda operations, 4 scalar operations

Iterations	Base (s)	Dependent (s)	Base-Dependent Ratio	Independent (s) using (iterations/100) tasks	Base-Independent Ratio
1k	15.6984	0.2271	69.1344	0.2401	65.3837
10k	164.7580	2.3256	70.8459	2.1745	75.7677

* Server/client run on MacBookPro, single node, 2.4 GHz Quad-Core Intel Core i5, shared memory

Looking Ahead

- Support larger subset of Arkouda operations
- Support more complex benchmarks
  - Nested loops and arrays as variables (dense triangle count), helper functions (sparse triangle count)
- Create easier-to-use client-side API
- Run server on distributed system to fine-tune number of tasks

Key Takeaways

Arkouda

- Powerful, interactive framework
- Room for improvement (memory footprint and messages)

Our architecture

- Implements lazy evaluation, caching, and CSE
- Performance increases across the board

Message aggregation

- Another powerful optimization tool
- Significantly reduce message exchanges

Current Milestones and Next Steps

Current Milestones

Revised architecture opens opportunities for CSE, lazy evaluation, and space efficiency

Next steps

Polish message aggregation optimization

Combine all optimizations

Move code into Arkouda repo