Fast Random Access Log (FRAL)

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Overview

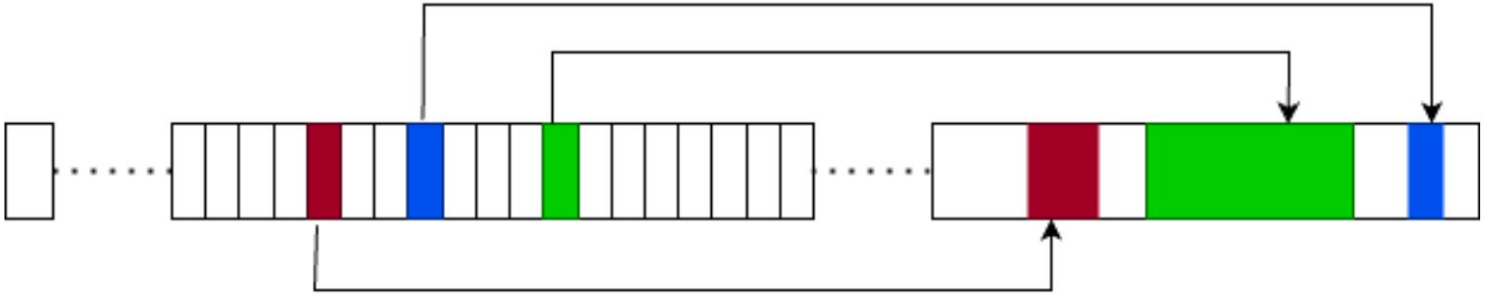
- Goal:
  - Allow multiple processes to read from and write to an array-indexed log as fast as possible
- A Random Access Log:
  - An array-indexed log over shared memory
  - Offers non-blocking writes
  - Reads are random access
- Implementation details:
  - Core engine implemented in C++
    - Python bindings are also provided and tested
- Standard Networking Tools:
  - Implemented and tested tool for syncing logs over network
- Some Use Cases:
  - High Frequency Trading
  - Log Aggregation

Core Architecture

- Three Main Functions:
    - **allocate:** allocates n contiguous bytes of the memory space (a blob) and returns a reference to the beginning of the allocation. This is similar to malloc in C.
    - **append:** appends a memory allocation (blob) to an indexed log, updates the size of the log and returns the index of the appended blob.
    - **load:** returns the memory allocation of a provided log-entry index

Core Architecture (Continued)

- Structuring shared memory:
  - Virtual memory = different addressing for different processes
    - Solution: Store offset from start of shared memory allocation in array
  - Array indexed allocations allows for random access of log entries
    - Array entries are random access
  - Atomic variables:
    - Next available address
    - Next available index (estimation)



Atomic Allocate

- Algorithm uses fetch-add primitive
  - Offset of next free memory address is an atomic variable
- Caveats:
  - Atomic offset variable is unbounded and can grow arbitrarily large
  - Process failure after fetch-add step (line 5) results in wasted space.

Algorithm 1 Atomic Allocate

```
1: s: allocation size (bytes)
2: S: size of memory space (bytes)
3: h: offset of next free memory address
4: function ALLOCATE(s)
5:     c = FetchAdd(h, s)
6:     if c + s > S then
7:         return null
8:     end if
9:     return c
10: end function
```

Atomic Append

- Motivation for approach:
  - What happens if a process fails in the middle of append?
    - Updates atomic index
    - Doesn't index blob
    - Stuck in infinite loop (never break through line 7)
- Want to write an append algorithm that:
  - prioritizes indexing blobs over updating the next-available index variable (atomic)
- Solution:
  - Estimate the next available index

Algorithm 2 Log Reader

```
1:  S: max size of log
2:  memspace: the shared memory data structure
3:  function READ(memspace)
4:      i ← 0
5:      for i < S do
6:          blob = load(memspace, i)
7:          if blob is not null then
8:              ProcessBlob(blob)
9:              i ← i + 1
10:         end if
11:     end for
12: end function
```

Atomic Append (Continued)

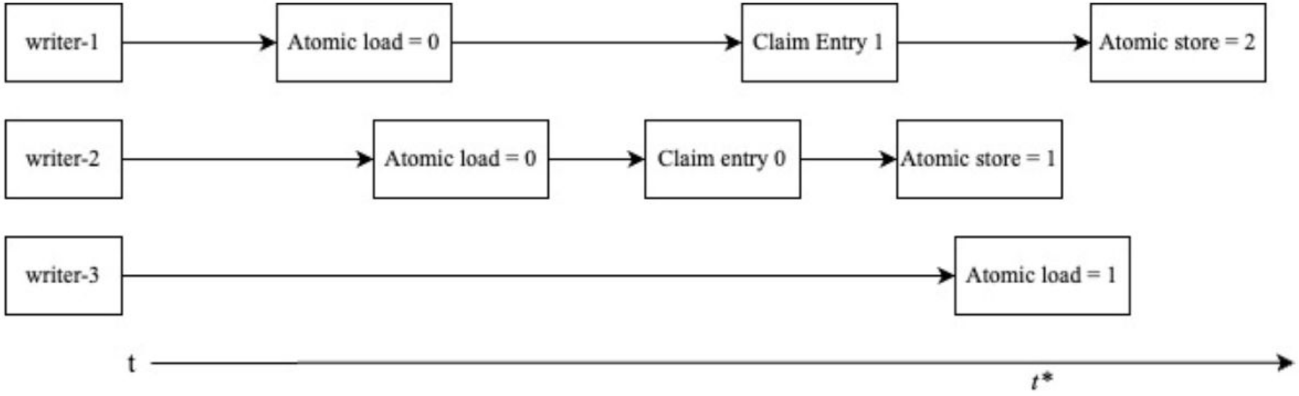
- Use compare-and-swap primitive:
  - Only store offset value if corresponding entry is entry
- A process can fail at any point during the append
  - Array entries are never wasted
  - Iterating over log will never yield infinite loop (previous slide)
- In the case of n writers in parallel:
  - A given writer has a worst case operation count of *O(n)*
  - The total operation count for

Algorithm 3 Atomic Append

```
blob: allocation to be appended
S: max size of log
k: the next available index
a: address of start of shared memory space
Arr: the log of offsets
function APPEND(blob)
    z ← BlobOffset(a, blob)
    i ← AtomicLoad(k)
    for i < S do
        if CompareAndSwap(Arr[i], 0, z) then
            AtomicStore(k, i + 1)
            return i
        end if
        i ← i + 1
    end for
    return -1
end function
```

Atomic Append (Continued)

- Problem: can't atomically update two variables at the same time
- The next available index is estimated (relaxed):
  - Example with 3 writers:
    - k = relaxed index of next available entry
    - writer-3 loads k = 1 at time *t**, but entry 1 has already been claimed by writer-1
    - writer-3 needs two compare-and-swap operations to claim next available index (k = 2)

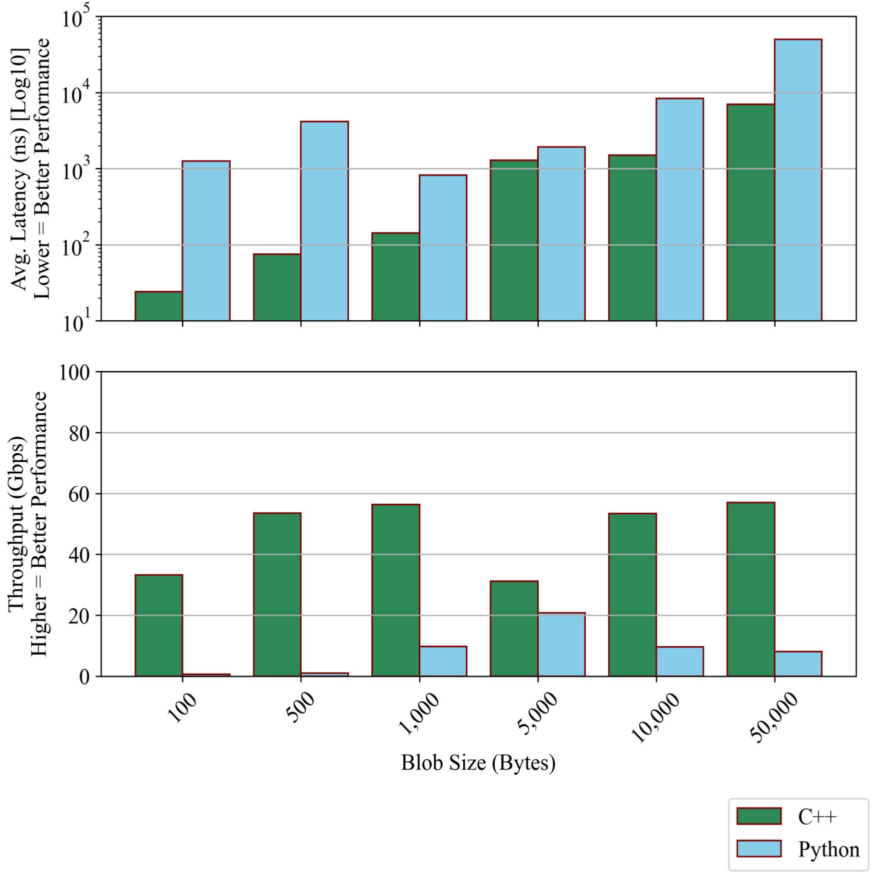


Performance Testing Results

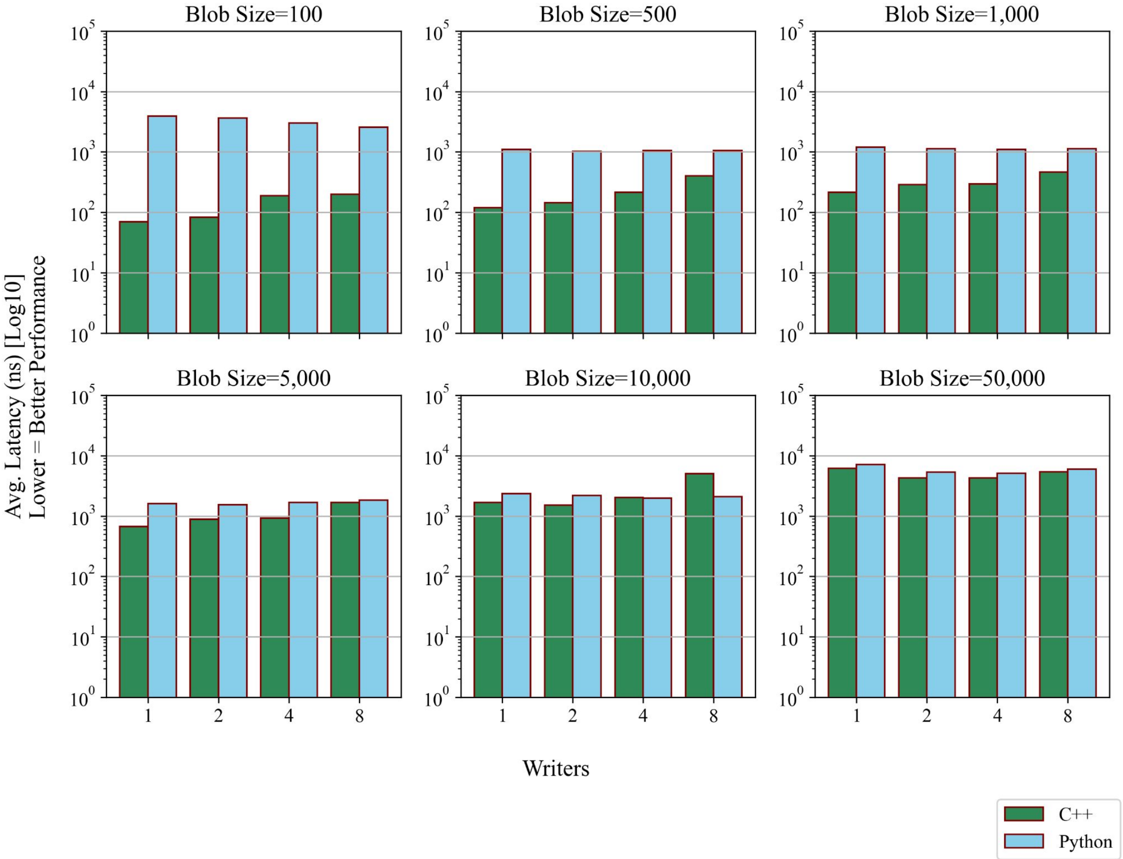
- ***Two tests of core architecture performance:***
  - Look to measure throughput and latency in various ways
  - *Write Test:*
    - Measures the speed and efficiency of writing *N* GB of data to the log in *n*-byte blobs
    - Assesses performance of high volume of write operations by one writer
    - The timer starts before the first write and ends after the last; latency is an average
  - *Producer-Consumer Test:*
    - Measures the speed and efficiency of simultaneously writing and reading *N* GB of data to the log in *n*-bytes blobs with *k* writers
    - Assesses performance of concurrent read and write operations from multiple sources
    - The timer starts before the first write and ends after the last read; latency, again, is an average

*Note that all testing was done with an 8-core Apple M2 machine with 8GB of unified RAM.

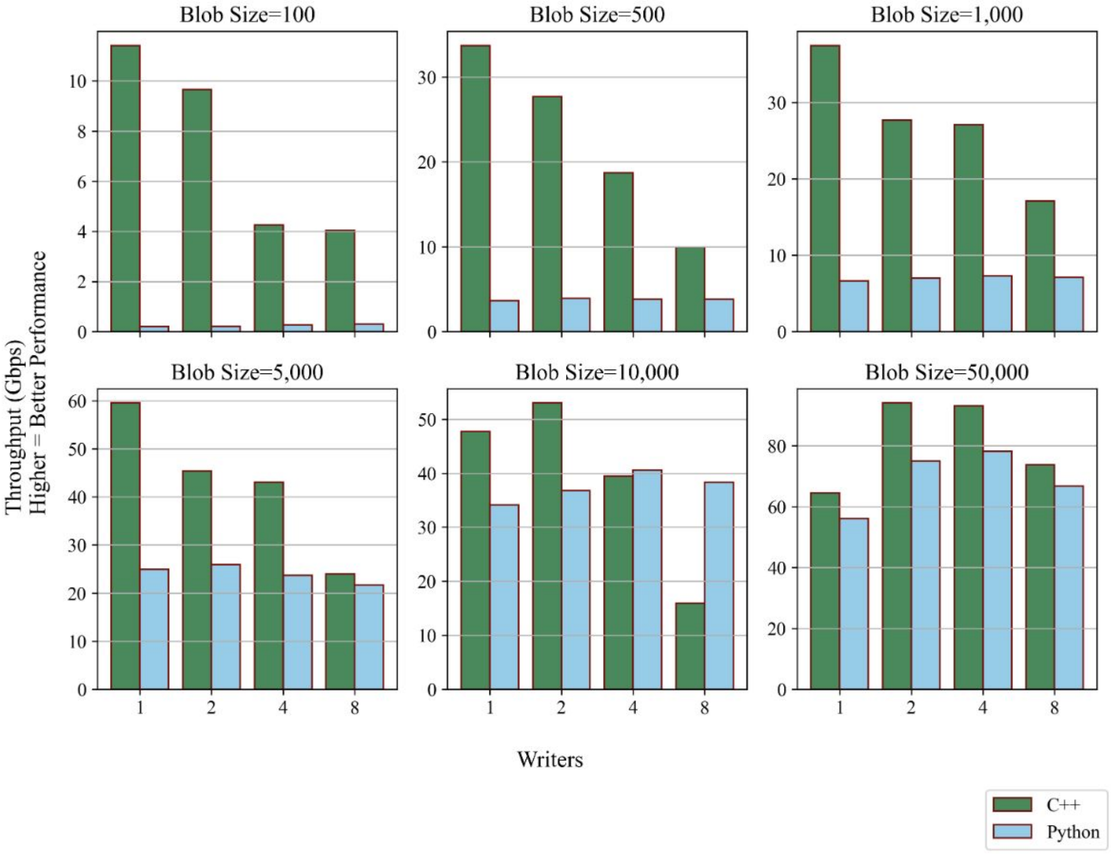
Write Test Results (Latency + Throughput)



Producer-Consumer Test Results (Latency)

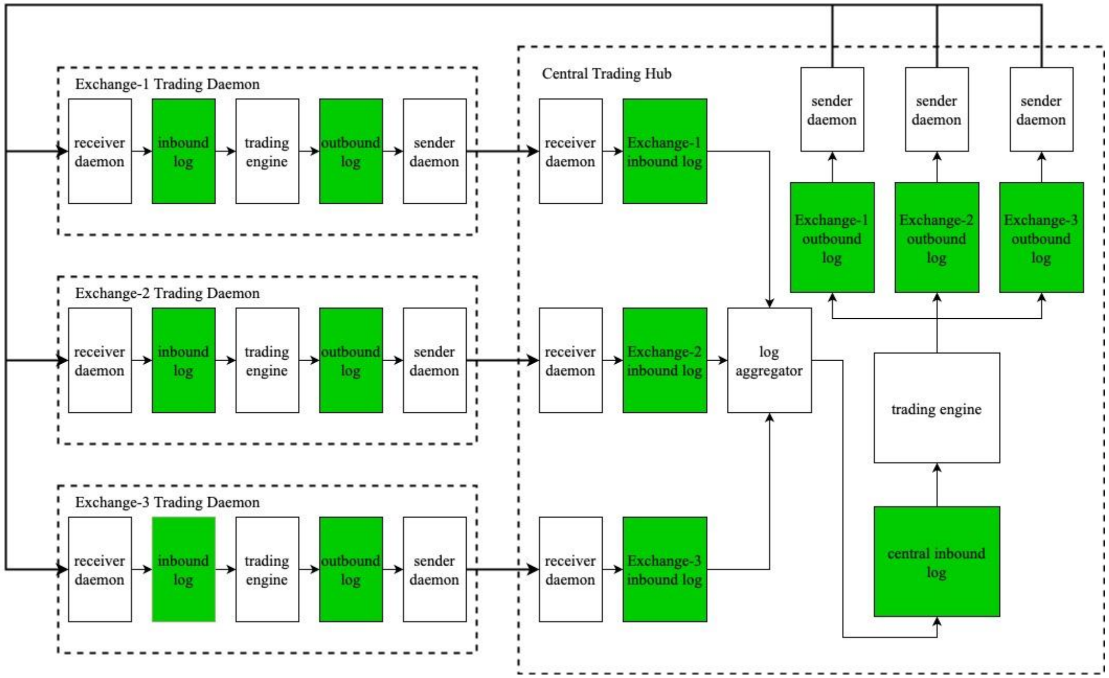


Producer-Consumer Test Results (Throughput)



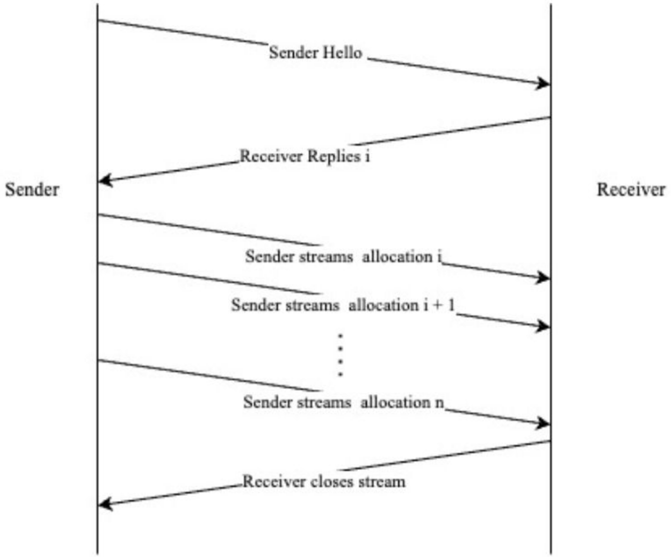
Syncing Over The Network

- A motivating use case:
  - *High Frequency Trading:* An entity trades on multiple exchanges in different geographic locations, while needing to keep track of net holdings in a central place

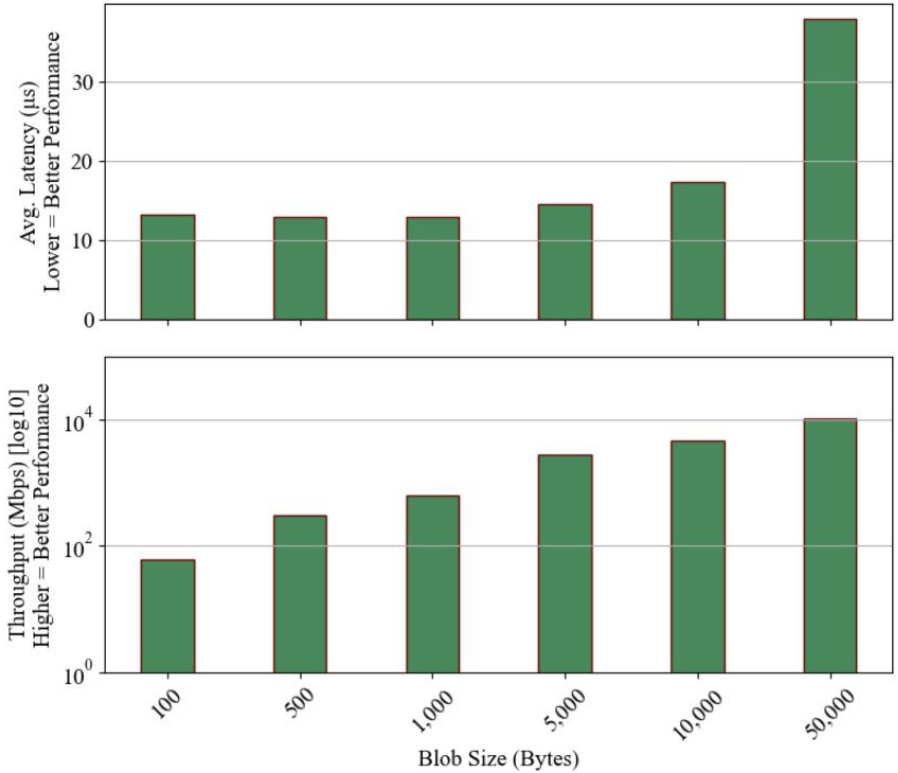


Syncing Over The Network (Continued)

- Intended Requirements:
  - Non-intrusive, i.e., don't need to alter the underlying log structure or add overhead
  - Order of entries is maintained over network
  - Robust to failure for both client and server; mirroring log is identical, through system failures
- Other details:
  - Initial design Implemented over gRPC and Protobuf
  - Future work: non-intrusive network sync tooling from multiple client logs to map to a single client log
- Network Test:
  - Similar to write test, but over the network:
    - Performance degrades (likely to client side buffering by gRPC)
    - Room for improvment



Syncing Over The Network (Network Test)



Simple Usage (C++)

```
//Process 1
auto ralA = fral::FRAL("test.bin");
const char *TEST_STR = "TEST";

auto blob = (char *) ralA.allocate(strlen(TEST_STR));
strcpy(blob, TEST_STR);
printf("%s\n", blob);

ralA.append(blob);
```

```
//Process 2
auto ralB = fral::FRAL("test.bin");

while(true){
    auto blob2 = (char *) ralB[0]; //load operation
    if(blob2){
        break;
    }
}

printf("%s\n", blob2);
blob2[0] = 'D';

auto blob3 = (char *) ralB[0]; //load operation
printf("%s\n", blob3);
```

```
TEST
TEST
DEST
```

Simple Usage (Python)

```python
# Process 1
ral_A = FRAL("test.bin", 1000, 100)
test_bytes = "TEST".encode()

test_blob = ral_A.allocate(len(test_bytes))
test_blob[:len(test_bytes)] = test_bytes

print(bytes(test_blob).decode())
ral_A.append(test_blob)
```

```python
# Process 2
ral_B = FRAL("test.bin")

while True:
    test_blob2 = ral_B[0]  # load operation
    if test_blob2:
        break

print(bytes(test_blob2).decode())
test_blob2[0:1] = 'D'.encode()

test_blob3 = ral_B[0]  # load operation
print(bytes(test_blob3).decode()))
```

```
TEST
TEST
DEST
```

Language-Agnostic Demo

- Language-Agnostic Framework
  - Shared memory opens door for language-agnostic data structures
  - Good for systems with microservices that vary in performance constraints
    - Use C++ for computationally-intensive tasks
    - Capitalize on rapid prototyping in development with Python
    - Example: HFT back-office tasks in Python, trading in C++
  - Demo (video):
    - Read integer from one language, increment by one and write
    - Python initiates process by writing and sending (appending 1)
    - Standard output for writing 5 entries:

```
Python sending 1 to C++!
C++ received 1 from Python, sending 2!
Python received 2 from C++, sending 3!
C++ received 3 from Python, sending 4!
Python received 4 from C++, sending 5!
C++ received 5 from Python, done!
```