SHARED MEMORY AND TCP STREAMS

Inter-process communication in Dora

Philipp Oppermann
os2edu
2023-11-27

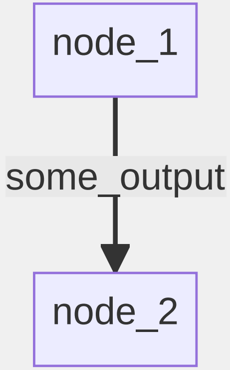
Agenda

- Background: Dora inputs/outputs and used IPC variants
- TCP Sockets
    - Basics
    - Usage in sync and async Rust
- Message passing using shared memory
    - General Design
    - Automatic cleanup
    - Optimizations
    - Cleanup with Arrow

Dora: Inputs and Outputs

- Dora dataflows consists of multiple nodes
  - Each node is a separate process → isolation, fairness, flexibility
- Nodes communicate through messages
  - Each node defines a set of inputs and outputs
  - Inputs are mapped to outputs of other nodes through `YAML` file:

```yaml
nodes:
- id: node_1
  custom:
    outputs:
      - some_output
- id: node_2
  custom:
    inputs:
      foo: node_1/some_output
```



Side Note

In addition to nodes, dora also allows defining **operators** that share an address space. This talk focuses on dora *nodes*.

Best way to pass messages?

- **TCP sockets**
  - ➕ cross-platform — works on Linux, Windows, etc.
  - ➕ local and remote — communication with remote machines is possible
  - ➖ relatively slow — overhead through ACKs, data copying, metadata
- **UNIX-specific IPC**
  - ➖ only on UNIX — does not work on Windows
  - ➖ local only — cannot communicate over network
  - ➕ faster than TCP — less overhead, but data is still copied
- **Shared memory**
  - ➕ cross-platform — works on Linux, Windows, etc.
  - ➖ local only — cannot communicate over network
  - ➕ fastest — zero-copy possible

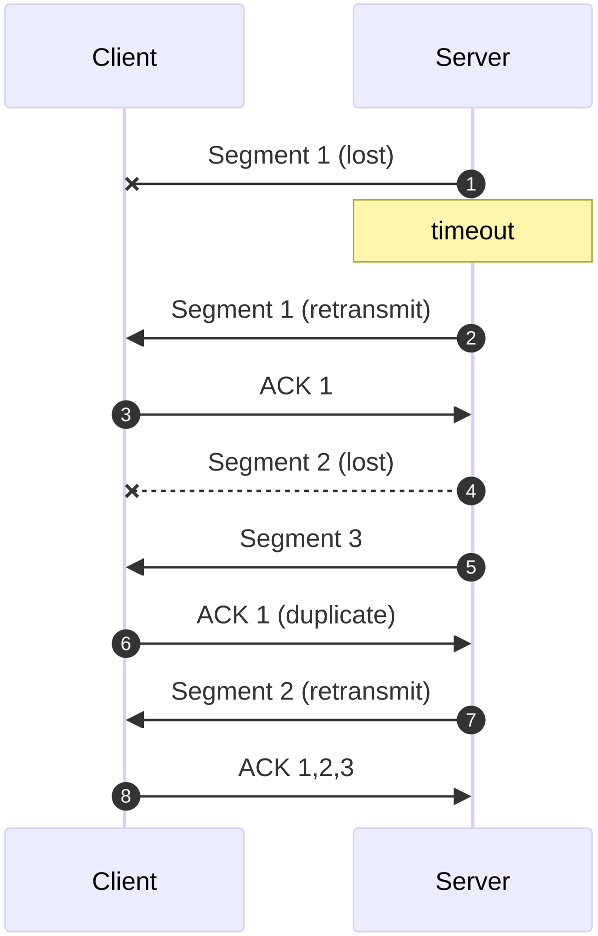
UNIX IPC Examples:

- domain sockets
- (named) pipes
- message queues (UNIX/POSIX)

→ in Dora, we use a combination of TCP sockets and shared memory

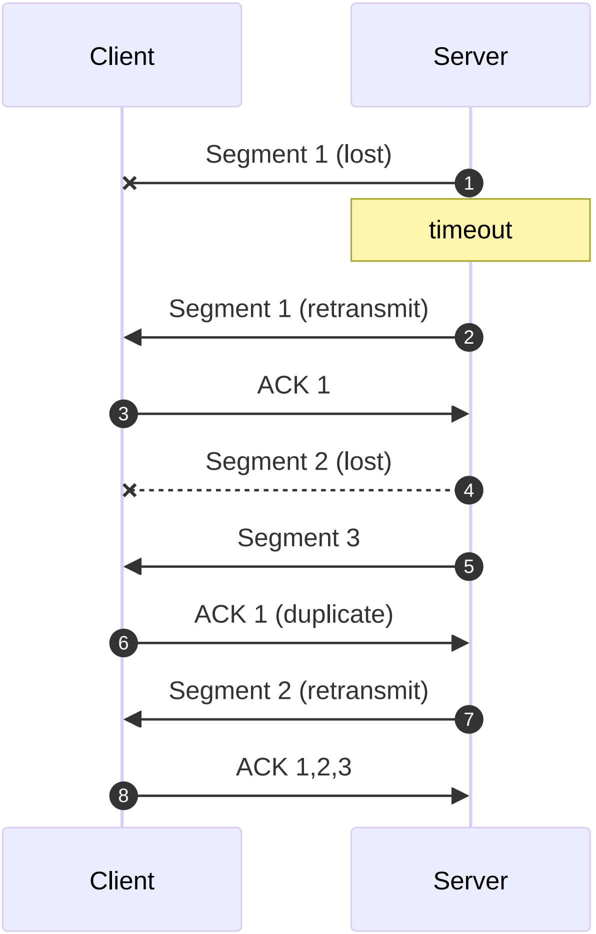
Transmission Control Protocol (TCP)

- Connection-oriented
  - server *listens* for incoming connections
  - client connects to server → new connection opened
- Reliable
  - *sequence number* allows restoring correct order of packets
  - received messages are acknowledged through `ACK` replies
  - retransmit segment when ACK is not received
    - on timeout (see step 2)
    - on duplicate ACK (see step 6)



Transmission Control Protocol (TCP)

- Connection-oriented
  - server *listens* for incoming connections
  - client connects to server → new connection opened
- Reliable
  - *sequence number* allows restoring correct order of packets
  - received messages are acknowledged through `ACK` replies
  - retransmit segment when ACK is not received
    - on timeout (see step 2)
    - on duplicate ACK (see step 6)
- Other TCP mechanisms
  - checksum for error detection
  - flow control for slowing down sender for slower receiver
  - congestion control to avoid overloading the network

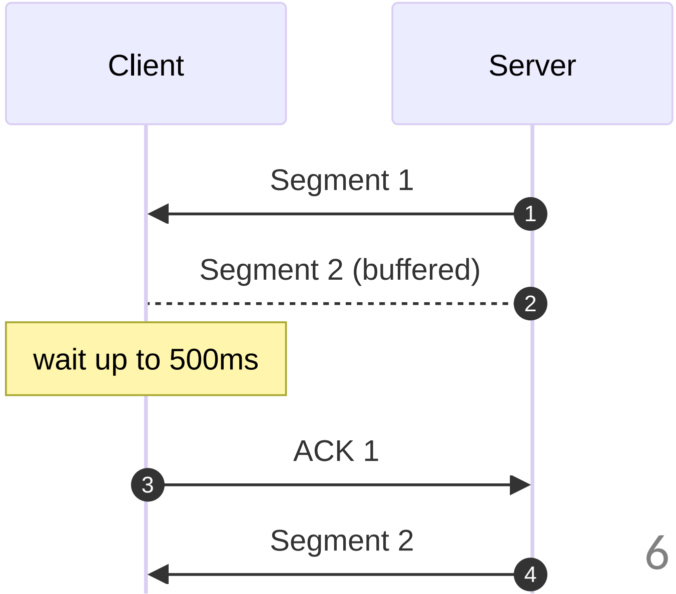


Avoiding TCP Overhead

- **Delayed ACKs**
  - ACK messages are very small → large protocol overhead
  - Approach: Wait until 500ms to combine multiple ACKs into single response
- **Nagle's Algorithm**
  - Goal: Avoid protocol overhead when *sending* small packets
  - Approach: Buffer small messages until previous packet is acknowledged
    - allows combining multiple messages into one large packet

Avoiding TCP Overhead

- **Delayed ACKs**
  - ACK messages are very small → large protocol overhead
  - Approach: Wait until 500ms to combine multiple ACKs into single response
- **Nagle's Algorithm**
  - Goal: Avoid protocol overhead when *sending* small packets
  - Approach: Buffer small messages until previous packet is acknowledged
    - allows combining multiple messages into one large packet

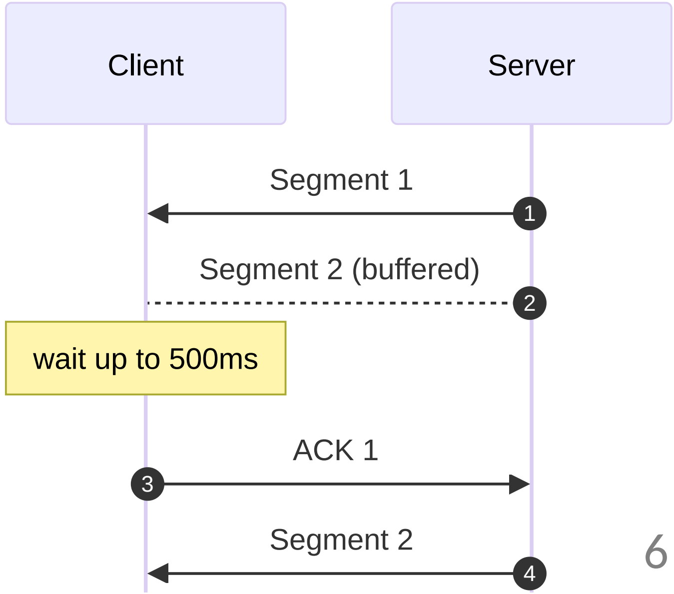


- **Problem:** Combining both algorithms can lead to significant delays
  - especially in low latency environments (e.g. local network)
  - most operating systems still enable both algorithms by default

Avoiding TCP Overhead

- **Delayed ACKs**
  - ACK messages are very small → large protocol overhead
  - Approach: Wait until 500ms to combine multiple ACKs into single response
- **Nagle's Algorithm**
  - Goal: Avoid protocol overhead when *sending* small packets
  - Approach: Buffer small messages until previous packet is acknowledged
    - allows combining multiple messages into one large packet
- **Problem:** Combining both algorithms can lead to significant delays
  - especially in low latency environments (e.g. local network)
  - most operating systems still enable both algorithms by default

→ Recommendation: disable Nagle's algorithm if latency is important



Example: Using TCP Sockets in Rust

Server:

```rust
let listener = std::net::TcpListener::bind("127.0.0.1:80")?;

for connection in listener.incoming() {
    handle_connection(connection?)?;
}
```

```rust
use std::net::TcpStream;

fn handle_connection(connection: TcpStream)
    -> std::io::Result<()>
{...}
```

Client:

```rust
let stream = std::net::TcpStream::connect("127.0.0.1:80")?;

// implements std::io::Read and std::io::Write traits
stream.write(&[42])?;
let mut data_buffer = [0; 128];
stream.read(&mut reply_buffer)?;
```

Example: Disabling Nagle's Algorithm

Server:

```
let listener = std::net::TcpListener::bind("127.0.0.1:80")?;

for connection in listener.incoming() {
    let connection = connection?;
    connection.set_nodelay(true)?;
    handle_connection(connection)?;
}
```

Client:

```
let stream = std::net::TcpStream::connect("127.0.0.1:80")?;
stream.set_nodelay(true)?;
```

Nagle's algorithm affects only the sending side → we need to disable it on both server and client

Message Boundaries

```rust
let mut buffer = [0; 1024];
let number_of_received_bytes = stream.read(&mut buffer)?;
let data = &buffer[..number_of_received_bytes];
```

- TCP is a stream-based protocol → no message boundaries
  - Does `data` contain a full message?
  - Does `data` contain multiple messages?

Message Boundaries

```
let mut buffer = [0; 1024];
let number_of_received_bytes = stream.read(&mut buffer)?;
let data = &buffer[..number_of_received_bytes];
```

- TCP is a stream-based protocol → no message boundaries
  - Does `data` contain a full message?
  - Does `data` contain multiple messages?
- We need a way to split the received bytes into messages again
  - Option 1: Add a **terminator** between messages → must not be used in serialized data
  - Option 2: Send the **message size** first

Example: Simple Message Protocol

```rust
fn send_message(connection: &mut TcpStream, message: &[u8]) -> std::io::Result<()> {
    // write message size first as little-endian u64
    let len_raw = (message.len() as u64).to_le_bytes();
    connection.write_all(&len_raw)?;
    // write the actual data
    connection.write_all(message)
}

fn receive_message(connection: &mut TcpStream) -> std::io::Result<Vec<u8>> {
    // read message length first as little-endian u64
    let data_len = {
        let mut raw = [0; 8];
        connection.read_exact(&mut raw)?;
        u64::from_le_bytes(raw) as usize
    };
    // read data_len bytes of data
    let mut data = vec![0; data_len];
    connection.read_exact(&mut data)?;
    Ok(data)
}
```

Example: Async TCP Sockets using tokio

- TCP streams work well with async Rust
  - async tasks have a very small overhead → spawning a task per connection is fine
  - easy to wait for multiple connections at once
- Example client using `tokio`:

```rust
use tokio::io::AsyncWriteExt;

#[tokio::main]
async fn main() -> Result<(), Box<dyn std::error::Error>> {
    let mut stream = tokio::net::TcpStream::connect("127.0.0.1:80").await?;

    // write some data
    stream.write_all(b"hello world!").await?;

    Ok(())
}
```

- `tokio::net::TcpStream` is based on `std::net::TcpStream` set to non-blocking mode
  - it is possible to convert `std::net::TcpStream` to an async `TcpStream`

Example: Async TCP Server using tokio

Spawn new task for each incoming connection:

```rust
let listener = tokio::net::TcpListener::bind("127.0.0.1:80").await?;

loop {
    let (socket, _) = listener.accept().await?;
    tokio::spawn(handle_connection(connection));
}
```

```rust
async fn handle_connection(socket: tokio::net::TcpStream) -> std::io::Result<()> {
    loop {
        match read_next_message(&mut socket).await? {
            Some(message_raw) => {
                let message = deserialize_message(message_raw)?;
                handle_message(message).await?;
            }
            None => break Ok(());
        }
    }
}
```

Waiting on Multiple Events

```rust
use tokio_stream::wrappers::{ReceiverStream, TcpListenerStream};
use futures_concurrency::stream::Merge;

let listener = tokio::net::TcpListener::bind("127.0.0.1:80").await?;
let new_connections = TcpListenerStream::new(listener).map(Event::NewConnection);

let (task_messages_tx, task_messages_rx) = tokio::sync::mpsc::channel(5);
let task_messages = ReceiverStream::new(task_messages_rx).map(Event::TaskMessage);

let mut events = (new_connections, task_messages).merge();
while let Some(event) = events.next().await {
    match event {
        Event::NewConnection(connection) => tokio::spawn(handle_connection(connection, task_messages_tx.clone())),
        Event::TaskMessage(message) => {...}
    }
}
```

```rust
enum Event {
    NewConnection(std::io::Result<tokio::net::TcpStream>),
    TaskMessage(TaskMessage),
}
```

Shared Memory

Shared Memory

Unix

- Allocation: create file descriptor through `shm_open("/some_id", flags, mode)`
- Mapping: map file descriptor into address space using `mmap`
- Deallocation: unmap memory from address space, then call `shm_unlink("/some_id")`

Windows

- Allocation: create temporary file with `dwShareMode` set
- Mapping: use `CreateFileMapping` or `OpenFileMapping`
- Deallocation: call `CloseHandle`

→ the **`shared_memory` crate** provides a cross-platform API

Shared Memory: Example

Process A:

```
use shared_memory::*;

let shmem = ShmemConf::new().size(4096).create()?;

// write some data
unsafe { *raw_ptr.as_ptr() = 42 };

let id = shmem.get_os_id().to_owned();
send_id_to_proc_b(id)?; // e.g. through a TCP message
```

Process B:

```
let id = receive_id_from_proc_a()?;
let shmem = ShmemConf::new().os_id(id).open()?;
let data = unsafe { *shmem.as_ptr() };
```

Pass Data using Shared Memory

1. Prepare message in sender
    - calculate required size (in bytes)
        - easy approach: serialize to `Vec<u8>`, then check length → drawback: copies the data
        - recursive approach:
            - use `size_of::<T>()` for self-containing types
            - for types containing pointers, calculate sum of all children
            - add padding to satisfy alignment requirements
    - allocate a large enough shared memory region

Pass Data using Shared Memory

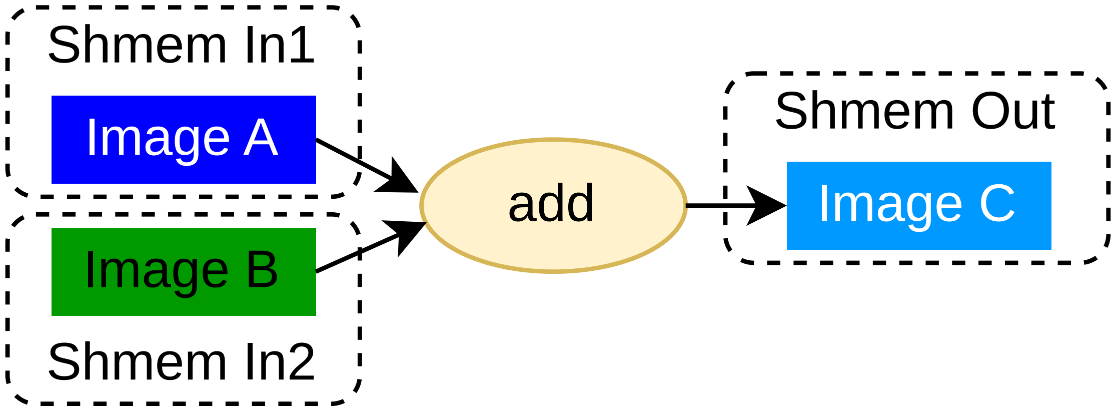
1. Prepare message in sender
    - calculate required size (in bytes)
        - easy approach: serialize to `Vec<u8>`, then check length → drawback: copies the data
        - recursive approach:
            - use `size_of::<T>()` for self-containing types
            - for types containing pointers, calculate sum of all children
            - add padding to satisfy alignment requirements
    - allocate a large enough shared memory region
    - copy the data into shared memory
        - avoiding this copy is difficult
        - idea: construct the data directly in shared memory, i.e. after the region has been allocated

Pass Data using Shared Memory

1. Prepare message in sender ✅
2. Send message to receivers
   - send ID of shared memory region to receiver
   - use different IPC channel, e.g. TCP socket
     - only a few bytes of data → throughput not that relevant
     - channel should be low-latency → disable Nagle's algorithm when using TCP
   - include some metadata, e.g.
     - source node ID
     - output ID
     - data type
   - multiple receivers are possible

Pass Data using Shared Memory

1. Prepare message in sender ✅
2. Send message to receivers ✅
3. Read out message in receiver
    - map shared memory region in receiver
        - read-only, as there might be multiple receivers
    - copy out data
    - or: perform only lazy operations on data
        - read directly from shared memory regions without copy
        - write result directly to an output shared memory region



Pass Data using Shared Memory

1. Prepare message in sender ✓
2. Send message to receivers ✓
3. Read out message in receiver ✓

Deallocation?

We need to deallocate all shared memory regions again.

- Where? In sender or receiver?
- When?
- How to deal with lost/dropped messages?

Shared Memory Cleanup

- Should happen in sender
  - there might be multiple (or zero) receivers
- We must not free shared memory while it's still in use
  - keep track of number of receivers
  - receivers report back once done with data
  - clean up once all receivers are done
- Dora needs to report dropped messages to sender
  - otherwise the sender will keep waiting for a confirmation from receiver
  - message drops happen when a sender is much faster than a receiver

Shared Memory Cleanup: Implementation

- Generate a unique token for each message in sender
- Dora daemon forwards message to receivers
  - Keeps track of token and pending receivers
- Receivers report to daemon when they're done with a message
  - identified by token
- Daemon notifies sender when all receivers dropped the message
- Sender cleans up shared memory region again
  - Cleanup is done in API crate → no manual operation is needed

Shared Memory Cleanup: Challenge

- Receivers might misbehave
  - large queue buildup
  - blocked or stuck
  - store received data too long (e.g. in some heap collection)
- We still want to free data at some point

Shared Memory Cleanup: Challenge

- Receivers might misbehave
  - large queue buildup
  - blocked or stuck
  - store received data too long (e.g. in some heap collection)
- We still want to free data at some point

- → Force clean-up after some timeout
  - Does not remove existing mappings from other processes
  - Creating new mappings will result in an error

Optimizations

- Reduce communication with daemon by bundling all information
  - For example, send tokens of dropped messages when requesting next input
- Cache freed shared memory regions in sender
  - Instead of deallocating them directly
  - If next sent message fits, reuse allocation
- Send small data directly over TCP
  - The overhead of allocating and mapping shared memory would be larger

Planned Optimizations

- Allocate larger shared memory region and partition it manually
  - Single allocation can be used for multiple messages
  - More opportunities for reuse → avoid extra allocations
  - Drawback: Manual memory management required for region (i.e. which parts are in use)
- Cache memory regions on receiver side as well
  - Goal: avoid syscall to map region when next message reuses previous region
- Use shared memory queue for sending metadata
  - Use native OS events for signalling new data
  - Avoids latency introduced by e.g. TCP stream

Using Shared Memory with Arrow

- We use Arrow to pass data to Python nodes/operators without copying
  - The Python runtime only owns a pointer to the data
  - To access the data, users need to use the FFI functions provided by the `pyarrow` library
- Approach:
  - Use official `arrow` crate to construct Arrow array backed by received shared memory region
    - first, create `arrow::Buffers` based on raw pointer and metadata
    - then combine the buffers into an `ArrayData` instance
  - Convert Arrow array to `PyObject` through `ToPyArrow` trait
    - converts the array to a FFI-compatible struct
    - invokes the `_import_from_c` function of the `pyarrow` Python library
  - Return the `PyObject` to the Python node
    - can be accessed using `pyarrow` library, or converted to `numpy` or `pandas` formats (no copy!)

Shared Memory Cleanup with Arrow

- Sender requires notification when shared memory can be dropped/reused
  → we need to know when Python code is done with the Arrow array
- Arrow format defines a *release callback*
  - **must** be called by consumers when dropping the data
  - the `pyarrow` library does this automatically when Python GC drops the array
- For proper cleanup, we need to set a *release callback* in the data
  - the `arrow` crate defines a callback that forwards to the standard Rust `Drop` trait
  - we only need to set a proper owner for the underlying buffer using `Buffer::from_custom_allocation`

```
pub unsafe fn from_custom_allocation(
    ptr: NonNull<u8>,
    len: usize,
    owner: Arc<dyn Allocation, Global>
) -> Buffer
```

Shared Memory Cleanup with Arrow

- Sender requires notification when shared memory can be dropped/reused
  → we need to know when Python code is done with the Arrow array
- Arrow format defines a *release callback*
  - **must** be called by consumers when dropping the data
  - the `pyarrow` library does this automatically when Python GC drops the array
- For proper cleanup, we need to set a *release callback* in the data
  - the `arrow` crate defines a callback that forwards to the standard Rust `Drop` trait
  - we only need to set a proper owner for the underlying buffer using `Buffer::from_custom_allocation`

```rust
pub unsafe fn from_custom_allocation(
    ptr: NonNull<u8>,
    len: usize,
    owner: Arc<dyn Allocation, Global>
) -> Buffer
```

- Open Question: How can we prevent users from keeping the data active for too long?
  - e.g. user might store it in a list and never drop it → shared memory is never freed
  - *Please let us know if you have a good solution!*

Summary

- TCP sockets
  - Nagle's algorithm can lead to latency issues
  - Simple message protocol based on sending message size first
  - Async TCP sockets with tokio → waiting on multiple events at once
- Shared memory for local, high-efficiency IPC
  - Shared memory message passing in Dora
  - Implemented and planned optimizations
  - Automatic memory cleanup with Arrow