

Communication Detection and Data Transfer Event Synchronization from Dual Trace

by

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ABSTRACT

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I believe I know the only cure, which is to make one's centre of life inside of one's self, not selfishly or excludingly, but with a kind of unassailable serenity-to decorate one's inner house so richly that one is content there, glad to welcome any one who wants to come and stay, but happy all the same in the hours when one is inevitably alone.

Edith Wharton

DEDICATION

Just hoping this is useful!

Chapter 1

Modeling

The goal of this modelling section is to 1) define the communication between two running programs. 2) design the communication identification strategy. 3) discuss the implementation of the communication methods in Windows 4) understand the dual-trace of two programs in the perspective of communication and how to retrieve the event information of the communications from the dual-trace

With this model, it is able to decide how communications being identified from the dual-trace and how to present them to the user.

1.1 Communication of Two Programs

This section describe my understanding of communications happen between two running programs in the real world. The communication in this work is data transfer activities between two running programs through a specific channel. Some collaborative activities between the programs such as remote procedure call is out of the scope of this research. Communication among multiple programs (more than two) is not discussed in this work. The channel can be reopened again to start new communications after being closed. However, the reopened channel will be treated as a new communication. The way that I define the communication is leading to the communication identification in the dual-trace. So the definition is not about how the communication works but what it looks like. The definition of the communication consist of terminology and definition.

1.1.1 Terminology

Endpoint:

An instance in a program at which a stream of data are sent or received (or both). It usually is identified by the handle of a specific communication method in the program. Such as a socket handle of TCP or UDP or a file handle of the named piped channel.

Channel:

A conduit connected two endpoints through which data can be sent and received

Channel open event:

Operation to create and connect an endpoint to a specific channel

Channel close event:

Operation to disconnect and delete the endpoint from the channel.

Send event:

Operation to send a trunk of data from one endpoint to the other through the channel.

Receive event:

Operation to receive a trunk of data at one endpoint from the other through the channel.

Channel open stream:

A set of all channel open events regarding to a specific endpoint.

Channel close stream:

A set of all channel close events regarding to a specific endpoint.

Send stream:

A set of all send events regarding to a specific endpoint.

Receive stream:

A set of all receive events regarding to a specific endpoint.

Stream:

A stream consist of a channel open stream, a channel close stream, a send stream and a receive stream. All of these streams regard to the same endpoint.

1.1.2 Definition

With the defined terminologies, a communication consist of two endpoints to a channel, each endpoint is corresponding to a stream. A stream contains one or more channel open events, one or zero send stream, one or zero receive stream and one or more channel close events. A visualized definition can be found in Figure1.1. The event numbers in this figure do not representing the exact number of a real communication but only an example. There are many communication methods for

the data transfer communications, but all of them are compatible to this communication definition.

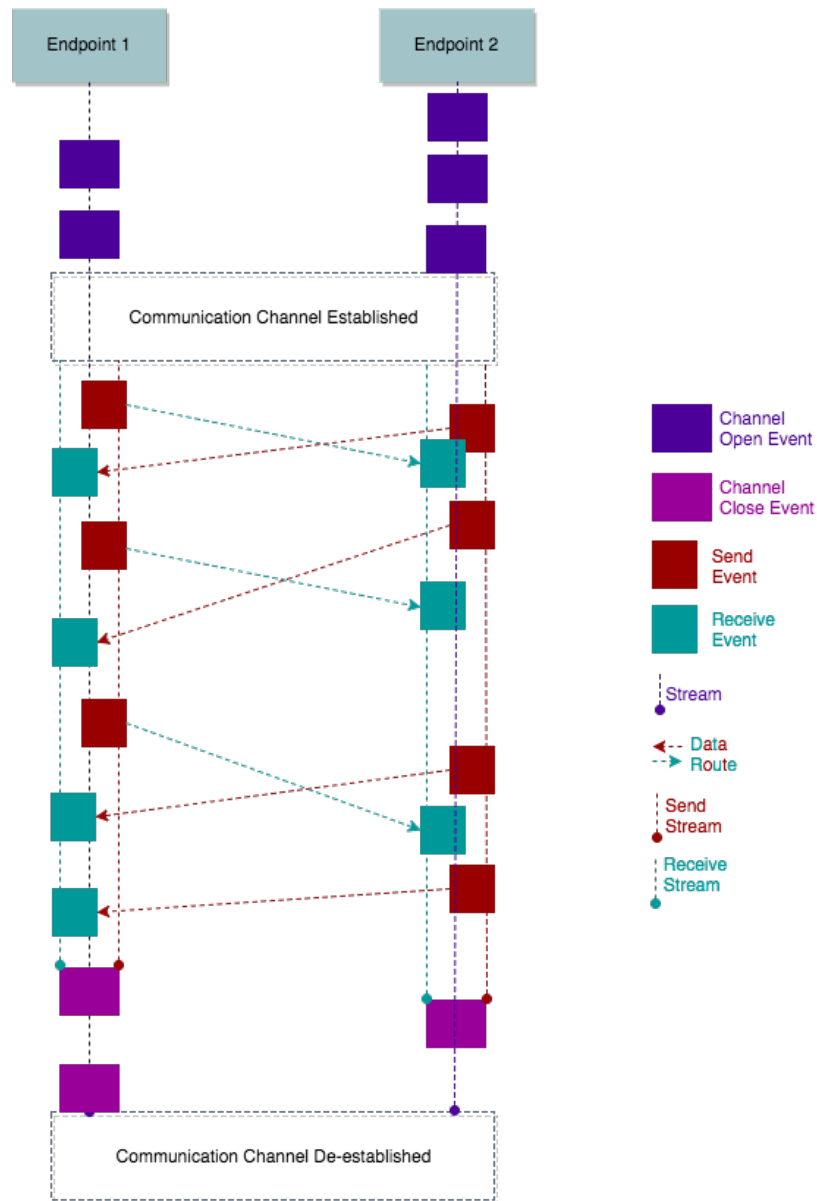


Figure 1.1: General Communication Model

1.2 Communication Categorization and Communication Methods⁴

This model divides all communication methods in two groups: reliable and unreliable communications. The reason to divide the communication methods into these two categories is that the send and receive streams or send and receive events matching strategies are respective for these two categories. In the first following two subsections, I summarize the characteristics of these two communication categories. The communication methods list in Table 1.1 will be discussed further to provide more concrete comprehension. Not all communication methods in the real world are being leveraged in this thesis. However, this model is supposed to be applicable to other communication methods.

Table 1.1: Communication Methods Discussed in This Work

Reliable Communication	Unreliable Communication
Named Pipes TCP	Message Queue UDP

1.2.1 Reliable Communication

A reliable communication guarantees the data being sent by one endpoint of the channel always received lossless and in order to the other endpoint. With this property, the send data union in the send stream of one endpoint should equal to the receive data union in the receive stream of the other endpoint. The send data union is the conjunction of the data trunks in all send events in the send stream by the event time ordering. The receive data union is the conjunction of the data trunks in all receive events in the receive stream by the event time ordering. Therefore, the send and receive data verification should be in send and receive stream level by comparing the send data union of one endpoint to the receive data union of another. For some communication methods, a channel can be closed without waiting the completion of all data transmission. In this case, the receive data union can be a sub string of the send data union.

1.2.2 Unreliable Communication

An unreliable communication does not guarantee the data being send always arrive the receiver. Moreover, the data packets can arrive to the receiver in any order. However, the bright side of unreliable communication is that the packets being sent are always arrived as the origin packet, no

data re-segmentation would happen. Accordingly, the send and receive data verification should be done by matching the data packets in a send event to a receive event on the other side.

1.2.3 Communication Methods

In this section, I describe the mechanism and the basic data transfer characteristics of each communication method in Table 1.1 briefly. Moreover, data transfer scenarios are represented correspondingly in diagrams for each communication method.

Named Pipe

In computing, a named pipe provides FIFO communication mechanism for inter-process communication. It allows two programs send and receive message through the named pipe.

The basic data transfer characteristics of Named Pipe are:

- Bytes received in order
- Bytes sent as a whole trunk can be received in segments
- No data duplication
- Only the last trunk can be lost

Based on these characteristics, the data transfer scenarios of Named pipe can be summarized in Figure 1.2.

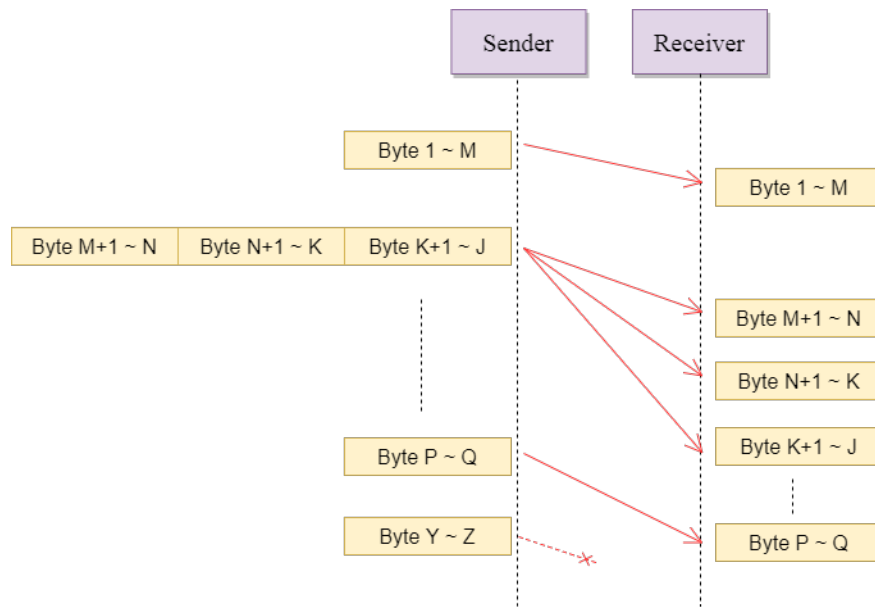


Figure 1.2: Data Transfer Scenarios for Named Pipe

Message Queue

Message Queuing (MSMQ) is a communication method to allow applications which are running at different times across heterogeneous networks and systems that may be temporarily offline can still communicate with each other. Messages are sent to and read from queues by applications. Multiple sending applications can send messages to and multiple receiving applications can read messages from one queue.[8] The applications are the endpoints of the communication. In this work, only one sending application versus one receiving application case is considered. Multiple senders to multiple receivers scenario can always be divided into multiple sender and receiver situation. Both endpoints of a communication can send to and receive from the channel.

The basic data transfer characteristics of Message Queue are:

- Bytes sent in packet and received in packet, no bytes re-segmented
- Packets can lost
- Packets received in order
- No data duplication

Based on these characteristics, the data transfer scenarios of Message Queue can be summarized in Figure1.3.

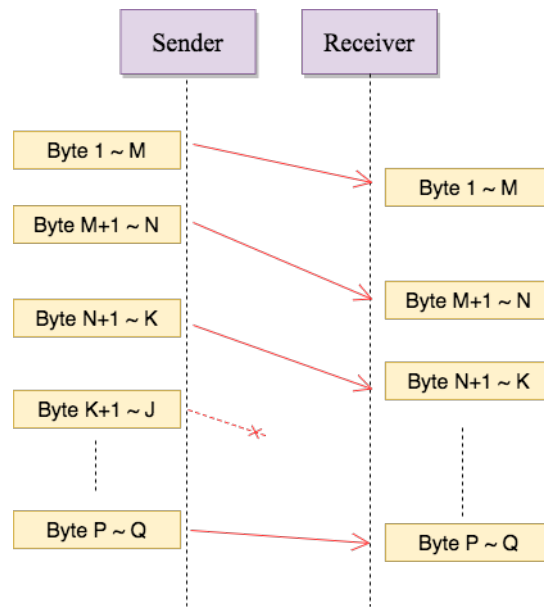


Figure 1.3: Data Transfer Scenarios for Message Queue

TCP

TCP is the most fundamental reliable transport method in computer networking. TCP provides reliable, ordered, and error-checked delivery of a stream of octets between applications running on hosts in an IP network. The TCP header contains the sequence number of the sending octets and the acknowledge sequence this endpoint is expecting from the other endpoint(if ACK is set). The retransmission mechanism is based on the ACK.

The basic data transfer characteristics of TCP are:

- Bytes received in order
- No data lost (lost data will be retransmitted)
- No data duplication
- Sender window size is different from receiver's window size, so packets can be re-segmented

Based on these characteristics, the data transfer scenarios of TCP can be summarized in Figure 1.4.

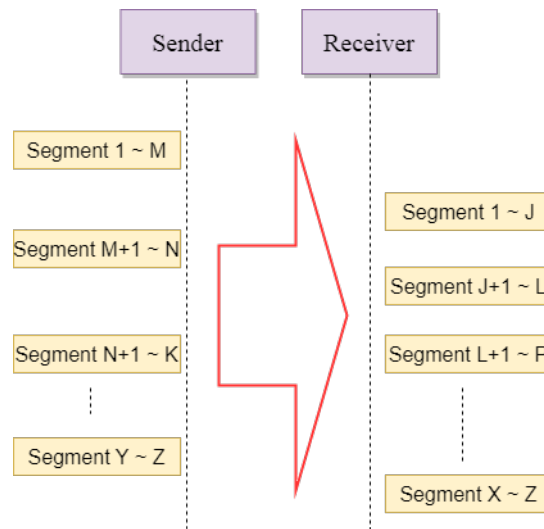


Figure 1.4: Data Transfer Scenarios for TCP

UDP

UDP is a widely used unreliable transmission method in computer networking. It is a simple protocol mechanism, which has no guarantee of delivery, ordering, or duplicate protection. This transmission method is suitable for many real time systems.

The basic data transfer characteristics of UDP are:

- Bytes sent in packet and received in packet, no re-segmentation
- Packets can lost
- Packets can be duplicated
- Packets can arrive receiver out of order

Based on these characteristics, the data transfer scenarios of UDP can be summarized in Figure1.5.

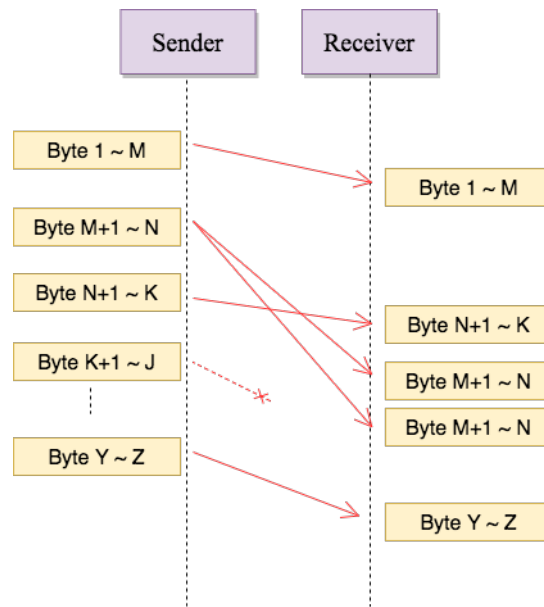


Figure 1.5: Data Transfer Scenarios for UDP

1.3 Communication Identification Strategy

In the first section of this chapter, I define what is a communication. The identification of the communications from a dual-trace should be able to identify the concerned communications as well as all the components defined in it. The section section in this chapter investigate the characteristics of the communication methods which is the key factor affecting the verification of the transferred data of a communication. From the trace analysis point of view, channel open events are essential to identify an endpoint while all other events are optional in the identification.

The identification contains seven major steps:

- Locate all events
- Identify the endpoints from the channel open events
- Group the related events into streams, send streams and receive streams, then bind them to the corresponding endpoint
- Match the endpoints to the communications
- For reliable communication, verify if the send data union in the stream of one endpoint match the receive data union in the stream of the other endpoint; For unreliable communication, try to match the send and receive events of both endpoints

- Construct and organize all the retrieved data of the communication
- Present the identified communications to the user

1.4 Communication Methods' Implementation in Windows

In this section, the implementations of the four communication methods in Windows system are investigated. The goal of this investigation is to determine the system functions for the events in the communication definition and summarize the necessary parameters of all the communication events to further identify a communication. Each function call will be considered as an event. The channel opening mechanism is essential for identifying the endpoints and further the communication. Hence the channel opening mechanisms of each method are described in detail and represented in diagrams.

I reviewed the Windows APIs of the communication methods and their example code. For each communication method, a system function list is provided for reference. These lists contain function names, essential parameters. These functions are supported in most Windows operating systems, such as Windows 8, Window 7.

Windows API set is very sophisticated and multiple solutions are provided to fulfil a communication method. It is impossible to enumerate all solutions for each communication method. I only give the most basic usage provided in Windows documentation. Therefore, the provided system function lists for the events should not be considered as the only combination or solution for each communication method. With the understanding of the model, it should be fairly easy to draw out lists for other solutions or other communication methods.

Moreover, the instances of this model only demonstrate Windows C++ APIs. This model may be generalizable to other operating systems with the effort of understanding the APIs of those operating systems.

1.4.1 Windows Calling Convention

The Windows calling convention is important to know in this research. The communication identification relies not only on the system function names but also the key parameter values. In the assembly level execution traces, the parameter values is captured in the memory changes of the instructions. The memory changes are recognized by the register names or the memory address. The calling convention helps us to understand where the parameters are stored so that we can find them in the memory change map in the trace.

Calling Convention is different for operating systems and the programming language. Based on the need of this work, we only list the Microsoft* x64 calling convention for interfacing with C/C++ style functions:

1. RCX, RDX, R8, R9 are used for integer and pointer arguments in that order left to right.
2. XMM0, 1, 2, and 3 are used for floating point arguments.
3. Additional arguments are pushed on the stack left to right. ...
4. Parameters less than 64 bits long are not zero extended; the high bits contain garbage.
5. Integer return values (similar to x86) are returned in RAX if 64 bits or less.
6. Floating point return values are returned in XMM0.
7. Larger return values (structs) have space allocated on the stack by the caller, and RCX then contains a pointer to the return space when the callee is called. Register usage for integer parameters is then pushed one to the right. RAX returns this address to the caller.

1.4.2 Named Pipes

In Windows, a named pipe is a communication method for the pipe server and one or more pipe clients. The pipe has a name, can be one-way or duplex. Both the server and clients can read or write into the pipe.[7] In this work, I only consider one server versus one client communication. One server to multiple clients scenario can always be divided into multiple server and client communications thanks to the characteristic that each client and server communication has a separate conduit. The server and client are endpoints in the communication. We call the server “server endpoint” while the client “client endpoint”. The server endpoint and client endpoint of a named pipe share the same pipe name, but each endpoint has its own buffers and handles.

There are two modes for data transfer in the named pipe communication method, synchronous and asynchronous. Modes affect the functions used to complete the send and receive operation. I list the related functions for both synchronous mode and asynchronous mode. The create channel functions for both modes are the same but with different input parameter value. The functions for send and receive message are also the same for both cases. However, the operation of the send and receive functions are different for different modes. In addition, an extra function *GetOverlappedResult* is being called to check if the sending or receiving operation finish, the output message will be stored in the overlap structure whose memory address saved in the function’s output parameter

Overlap Structure Address. Table 1.2 lists the functions for synchronous mode while Table 1.3 lists the functions for the asynchronous mode for a Named pipe communication.

Table 1.2: Function List for Synchronous Named Pipe

Event	Server Endpoint		Client Endpoint	
	Function	Parameters	Function	Parameters
Channel Open	CreateNamedPipe	RAX: File Handler	CreateFile	RAX: File Handler
		RCX: File Name		RCX: File Name
Send	WriteFile	RCX: File Handle	WriteFile	RCX: File Handle
		RDX: Buffer Address		RDX: Buffer Address
		R9: Message Length		R9: Message Length
Receive	ReadFile	RCX: File Handle	ReadFile	RCX: File Handle
		RDX: Buffer Address		RDX: Buffer Address
		R9: Message Length		R9: Message Length
Channel Close	CloseHandle	RCX: File Handler	CloseHandle	RCX: File Handler

Table 1.3: Function List for Asynchronous Named Pipe

Event	Server Endpoint		Client Endpoint	
	Function	Parameters	Function	Parameters
Channel Open	CreateNamedPipe	RAX: File Handler	CreateFile	RAX: File Handle
		RCX: File Name		RCX: File Name
Send	WriteFile	RCX: File Handle	WriteFile	RCX: File Handle
		RDX: Buffer Address		RDX: Buffer Address
		R9: Message Length		R9: Message Length
Receive	ReadFile	RAX: File Handle	ReadFile	RCX: File Handle
		RDX: Buffer Address		RDX: Buffer Address
		R9: Message Length		R9: Message Length
Receive	GetOverlapped-Result	RCX: File Handler	GetOverlapped-Result	RCX: File Handler
		RDX: Overlap Structure address		RDX: Overlap Structure Address
Channel Close	CloseHandle	RCX: File Handler	CloseHandle	RCX: File Handler

A named pipe server is responsible for the creation of the pipe, while clients can connect to the pipe after it was created. The creation and connection of a named pipe returns the handle ID

of that pipe. These handler Ids will be used later when data is being sent or received to a specified pipe. Figure 1.6 shows the channel set up process for a Named Pipe communication.

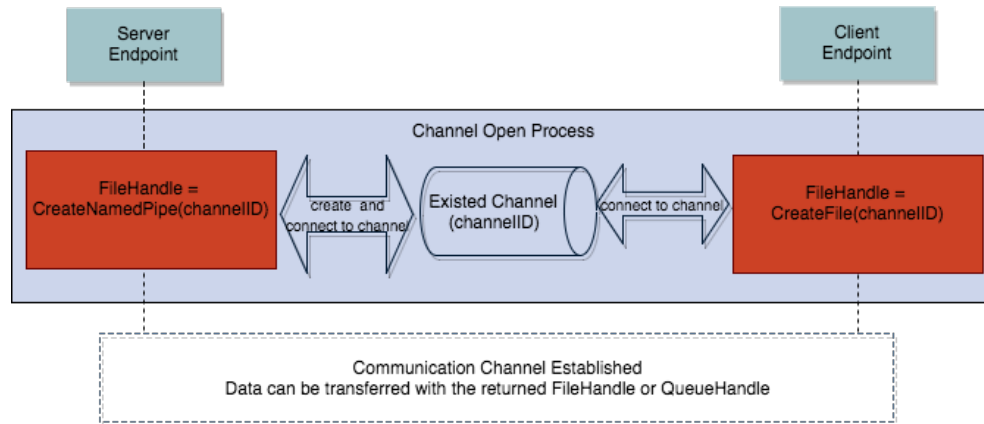


Figure 1.6: Channel Open Process for a Named Pipe

1.4.3 Message Queue

Similar to Named Pipe, Message Queue's implementation in Windows also has two modes, synchronous and asynchronous. Moreover, the asynchronous mode further divides into two operations, one with callback function while the other without. With the callback function, the callback function would be called when the send or receive operations finish. Without callback function, the general function *MQGetOverlappedResult* should be called by the endpoints to check if the message sending or receiving operation finish, the output message will be stored in the overlap structure whose memory address saved in the function's output parameter Overlap Structure Address. Table 1.4 lists the functions for synchronous mode while Table 1.5 and Table 1.6 list the functions for the asynchronous mode with and without callback.

Table 1.4: Function List for Synchronous MSMQ

Event	Function	Parameters
Channel Open	MQOpenQueue	RAX: Queue Handler
		RCX: Queue Format Name
Send	MQSendMessage	RCX: Queue Handle
		RDX: Message description structure Address
Receive	MQReceiveMessage	RCX: Queue Handle
		R9: Message description structure Address
Channel Close	MQCloseQueue	RCX: Queue Handler

Table 1.5: Function List for Asynchronous MSMQ with Callback

Event	Function	Parameters
Channel Open	MQOpenQueue	RAX: Queue Handler
		RCX: Queue Format Name
Send	MQSendMessage	RCX: Queue Handle
		RDX: Message description structure Address
Receive	MQReceiveMessage	RCX: Queue Handle
		R9: Message description structure Address
Receive	CallbackFuncName	Parameters for the callback function.
Channel Close	MQCloseQueue	RCX: Queue Handler

Table 1.6: Function List for Asynchronous MSMQ without Callback

Event	Function	Parameters
Channel Open	MQOpenQueue	RAX: Queue Handler
		RCX: Queue Format Name
Send	MQSendMessage	RCX: Queue Handle
		RDX: Message description structure Address
Receive	MQReceiveMessage	RCX: Queue Handle
		R9: Message description structure Address
Receive	MQGetOverlappedResult	RCX: Overlap Structure address
Channel Close	MQCloseQueue	RCX: Queue Handler

The endpoints of the communication can create the queue or use the existing one. However, both of them have to open the queue before they access it. The handle ID returned by the open queue function will be used later on when messages are being sent or received to identify the queue. Figure1.7 shows the channel set up process for a Message Queue communication.

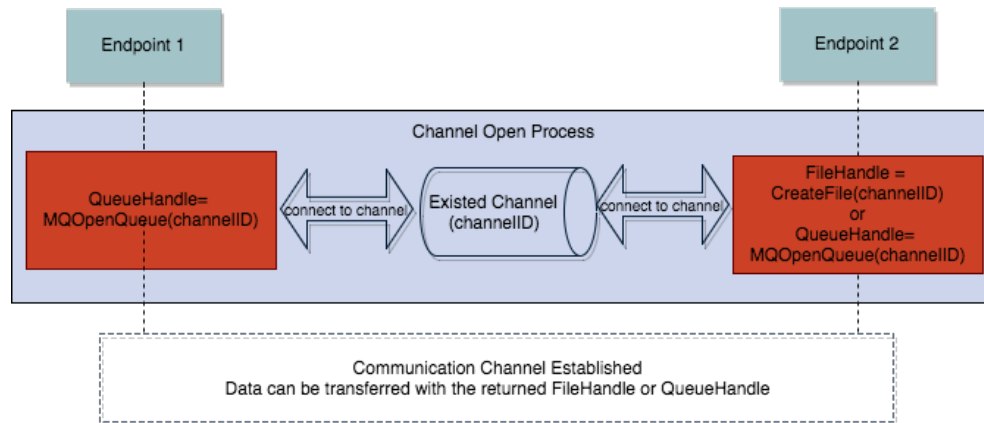


Figure 1.7: Channel Open Process for a Message Queue

1.4.4 TCP and UDP

In Windows programming, these two methods shared the same set of APIs regardless the input parameter values and operation behaviour are different. In Windows socket solution, one of the two endpoints is the server while the other one is the client. Table 1.7 lists the functions of a UDP or TCP communication.

Table 1.7: Function APIs for TCP and UDP

Event	Server Endpoint		Client Endpoint	
	Function	Parameters	Function	Parameters
Channel Open	socket	RAX: Socket Handle	socket	RAX: Socket Handle
Channel Open	bind	RCX: Socket Handle	connect	RCX: Socket Handle
		RDX: Server Address & Port		RDX: Server Address & Port
Channel Open	accept	RAX: New Socket Handle		
		RCX: Socket Handle		
		RDX: Client Address & Port		
Send	send	RCX: New Socket Handle	send	RCX: Socket Handle
		RDX: Buffer Address		RDX: Buffer Address
Receive	recv	RCX: New Socket Handle	recv	RCX: Socket Handle
		RDX: Buffer Address		RDX: Buffer Address
Channel Close	closesocket	RCX: New Socket Handle	closesocket	RCX: Socket Handle

The communication channel is set up by both of the endpoints. The function *socket* should be called to create their own socket on both endpoints. After the sockets are created, the server

endpoint binds the socket to its service address and port by calling the function *bind*. Then the server endpoint calls the function *accept* to accept the client connection. The client will call the function *connect* to connect to the server. When the function *accept* return successfully, a new socket handle will be generated and returned for further data transfer between the server endpoint and the connected client endpoint. After all these operations are performed successfully, the channel is established and the data transfer can start. During the channel open stage, server endpoint has two socket handles, the first one is used to listen to the connection from the client, while the second one is created for real data transfer. Figure 1.8 shows the channel open process for TCP and UDP.

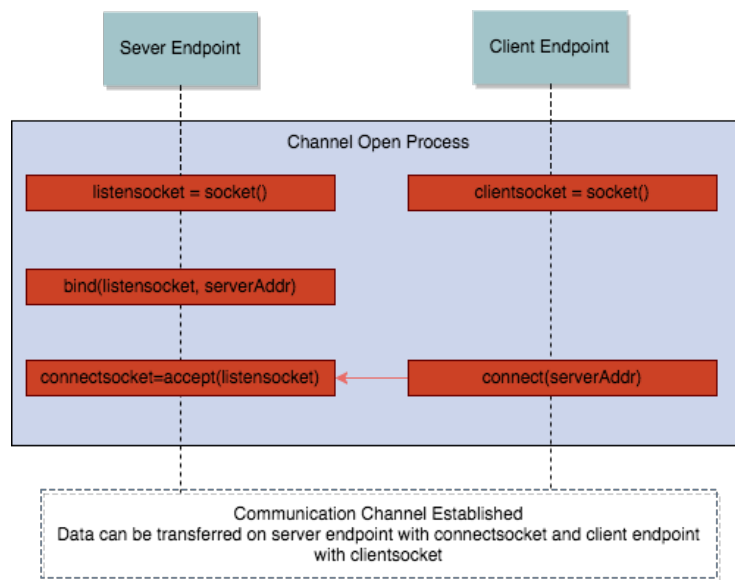


Figure 1.8: Channel Open Model for TCP and UDP

1.5 Communication Event Locating in Assembly Execution Traces

The goal of this research is to identify the communications from the dual-trace and present them to the user. The identification of all events of the communications from the execution trace would be the first step. Last section concludes communication events including system function names, parameters and the function calls relationship. This section will 1) discuss the basis of the execution traces. and 2) conclude how to retrieve the event information from the execution traces.

1.5.1 Assembly Execution Trace

The dual-trace being analysed are in assembly level. One dual-trace contains two execution traces. There is no timing information of these two traces which means we don't know the timestamps of the events of these two traces and can not match the events from both sides by time sequence. However the captured instructions in the trace are ordered in execution sequence. The execution traces contain all executed instructions as well as the corresponding changed memory by each instruction. Additionally, system calls are also captured by instruction id, which means if .dll or .exe files are provided, the system function calls can be identified with function names. Memory states can be reconstructed from the recorded memory changes to get the data information of the communication.

1.5.2 Event Information Retrieval

For simplification, each function call is treated as an event. A function call in the trace starts from the function call instruction to the function return instruction. The input parameters' value and input buffer content should be retrieved from the memory state of the the function call instruction line while the return value, output parameters' value and output buffer content should be retrieved from the memory state of the function return instruction line. Tables in section 1.4 indicate all the functions of the communication methods as well as the concerned parameters. Following the windows calling convention, the concerned parameter value or buffer address can be found in the corresponding register or stack positions. The buffer content can be found in the memory address in the reconstructed memory state.

Chapter 2

Communication Identification Algorithms

In the Modeling Chapter, I elaborate the definition of the communications and the strategy of the communication identification. There are several major step in the identification strategy and some of them are not strange forward. In this chapter, I list developed the algorithms for the key steps in the identification strategy.

2.1 Event Locating Algorithm

The concerned event types in a communication consist of channel open, channel close, send and receive events. Each of these event type would contain one or more functions. The functions list for a communication method is needed as a input of this algorithm. Tables in Section1.4 give the examples of event type list of communication methods. The algorithm is designed for locating events of one communications method. If more than one communication methods are being investigated, this algorithm should be run multiple times, each for a method. Events in the output event list is sorted by time of occurrence, since the search of event is line by line of the assembly instructions.

Algorithm 1: Event Locating Algorithm

Input: dual-trace, function list for concerned events

Output: two event lists for two separate traces in the dual-trace

```

1 eventLists  $\leftarrow$  Map(String, List(Event));
2 for trace  $\in$  dual-trace do
3   eventList  $\leftarrow$  List(Event);
4   while not at end of trace do
5     for  $f \in$  functionList do
6       if Is function call of  $f$  then
7         find function return instruction line;
8         event.inputs  $\leftarrow$  get input parameters from this instruction line;
9         event.outputs  $\leftarrow$  get output parameters and return value from the return
          instruction line;
10        event.type  $\leftarrow$   $f.eventType$ ;
11        eventList.add (event);
12  eventLists.add (eventList);
13 return eventLists;

```

2.2 Endpoint and Corresponding Streams Identification Algorithm

The events located in the traces may correspond to different endpoints, the next step is to group them for each endpoints and furthermore group them into streams of the endpoints. The input of this algorithm is one of the event list from the Event Locating Algorithm. So this algorithm should be run separately for both trace in the dual-trace. Since the input event list is sorted by time of occurrence and the channel open events should always happen before other events, it is reasonable to assume the new endpoint can be identified by its first channel open function call. The output of this algorithm is the endpoint list. Each endpoint in this list contains the stream which consist of the sub streams. The concepts of the stream and sub streams are defined in Section 1.1.1.

Algorithm 2: Endpoint Identification Algorithm

Input: event list of a trace

Output: endpoint list

```

1 endpoints ← Map⟨String, List⟨EndPoint⟩⟩;
2 for event ∈ eventList do
3   if event is a channel open event then
4     handle ← get the handle identifier from the function parameter list;
5     endpoint ← endpoints.get(handle);
6     if event is an accept(event) function call for TCP or UDP then
7       newHandle ← get the second socket handle identifier which is the return
          value from the function parameter list;
8       endpoints.remove(handle);
9       endpoints.add(newHandle, endpoint);
10    if endpoint is null then
11      endpoint = New EndPoint();
12      endpoints.add(hanele, endpoint);
13    endpoint.openStream.add(event);
14    if event is a channel send event then
15      handle ← get the handle from the function parameter list;
16      endpoint ← endpoints.get(handle);
17      if endpoint is not null and endpoint.complete is False then
18        endpoint.sendStream.add(event);
19    if event is a channel receive event then
20      handle ← get the handle from the function parameter list;
21      endpoint ← endpoints.get(handle);
22      if endpoint is not null and endpoint.complete is False then
23        endpoint.receiveStream.add(event);
24    if event is a channel close event then
25      handle ← get the handle from the function parameter list;
26      endpoint ← endpoints.get(handle);
27      if endpoint is not null then
28        endpoint.closeStream.add(event);
29        endpoint ← True;
30 return endpoints;

```

2.3 Communication Identification Algorithm

The Communication Identification Algorithm aims at identify all the concerned communication channels from the dual-trace. The input of this algorithm is the two endpoint lists for both traces in the dual-trace from the ‘Endpoint and Corresponding Streams Identification Algorithm’. The output of this algorithm is the channel list. Each channel recognized from the dual-trace contains two endpoints.

In the communication identification algorithm, it first try to match the endpoint identifiers. In this level, the matching only depends on the channel opening events and their parameters which are different from communication method to communication method. For TCP and UDP the matching can be considered as local address and port of server endpoint matching with remote address and port of client endpoint. It uses the file name for Named pipe while the queue name for MSMQ as the identifier for matching of two endpoints.

The first level matching can not guarantee the exact endpoint matching and channel identification. For Named pipd and Message Queue, there are two situations which false positive error might emerge. The first one is multiple(more than two) interacting programs shared the same file or queue as the channel. For example, the Named pipe server is connected by two clients with the file as the channel. In the server trace, there are two endpoints found. In each client trace, there is one endpoint found. In the channel identification algorithm for the dual-trace of server and client1, there will be two possible identified channels, one is the real used one for server and client1 while the other is the false positive one actually is for server and client2. The endpoint in client1’s trace will be matched by two endpoints in the server’s trace. The second situation is the same channel is reused by endpoints of only two interacting programs. For example, the Named pipe server and client finished the first communication and then closed the channel. After a while they both open the same file again for another communication. Since the first level matching is only base on the identifier and the first and the second communications have the same identifier since they used the same file. Similar situations can also happen in MSMQ, TCP and UDP communication methods.

To reduce the false positive error, the second level matching should be apply, which is also being named as transmitted data verification algorithm. On top of the endpoint identifiers matching, further data verification should be applied to make sure the matching is reliable. This verification crossly compare the sent and received data of both endpoint in the matching. If comparison is considered to be identical. The matching is confirm, otherwise it was a false positive error. However, we still can not exclude all the false positive error, due to the data transmitted in two communication can be identical. Figure2.1 indication the ineffective second level matching scenario and the effective one.

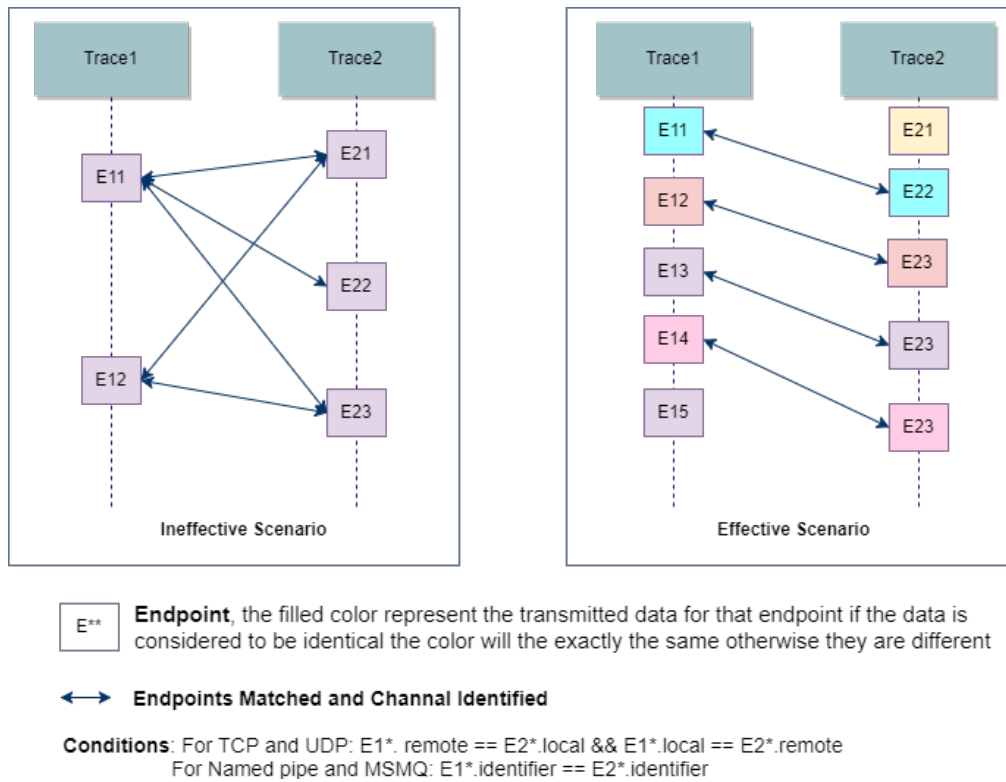


Figure 2.1: Second Level Matching Scenarios

The following subsections of this one discuss the algorithms for these two level matching. In Section 1.4, I elaborate the channel open process and the data transfer categories for the concerned communication methods. Based on the different channel process, two algorithms are developed for first level matching, one is for Named Pipe and Message Queue, while the other is for TCP and UDP. The input of the first level algorithm is the two endpoint lists of the two traces of the analyzing dual-trace while the output is the identified channels. Each channel contains the matched endpoints from both side of the traces. The data transfer characteristics divided the communication methods into reliable and unreliable transmissions. Named pipe and TCP fall in the reliable category while MSMQ and UDP fall in the unreliable one. The second level matching algorithms are distinct for these two categories. The corresponding second level data matching algorithms are being used in the first level algorithms. The input of the second level algorithms is the streams of both endpoint while the output a boolean to indicate if the transmitted data of this two endpoint streams are matched.

2.3.1 Communication Identification Algorithm for Named pipe and Message Queue

For the Named pipe and MSMQ only one channel open function is being call for each endpoint. So in the below algorithm, when it try to get the channel open event from the *endpoint.openStream* list, only one event should be found and return. The channel identifier parameters can be found in the *event.inputs* of the channel open event. The identifier for Named pipe is the file name of the pipe while for MSMQ is the format queue name of the queue.

This algorithm will find out all the possible channels regardless some of them might be false positive. The called data verification algorithm should be “Matching by Data Streams Algorithm” for Named pipe and “Matching by Data Events Algorithm” for MSMQ.

Algorithm 3: Communication Identification Algorithm for Named pipe and Message Queue

Input: two endpoint lists of the dual-trace

Output: communication list

```

1 communications  $\leftarrow$  Map(String, List(Communication));
2 for endpoint1  $\in$  endpointList1 do
3   openEvent1  $\leftarrow$  get the event from endpoint1.openStream, which should only
     contain one event;
4   channelId1  $\leftarrow$  get the channel identifier from openEvent1.inputs;
5   for endpoint2  $\in$  endpointList2 do
6     openEvent2  $\leftarrow$  get the event from endpoint2.openStream, which should only
       contain one event;
7     channelId2  $\leftarrow$  get the channel identifier from openEvent2.inputs;
8     if channelId1 == channelId2 then
9       DataVerified  $\leftarrow$  Call the corresponding data verification algorithm. if
         DataVerified == True then
10        communication = New Communication();
11        communication.endpoint1 = endpoint1;
12        communication.endpoint2 = endpoint2;
13        communication.dataMatch  $\leftarrow$  The output from data verification
          algorithm;
14        communications.add (communication);
15 return channels;

```

2.3.2 Communication Identification Algorithm for TCP and UDP

For TCP and UDP multiple functions are collaborating to create the final communication channel. Local address and port of the server endpoint and Remote address and port of the client endpoint are used to identify the channel. This algorithm first try to get the Local address and port of the server endpoint and remote address and port from client endpoint. Then it try to match two endpoints by comparing the local and remote address and port.

Algorithm 4: Communication Identification Algorithm for TCP and UDP

Input: two endpoint lists of the dual-trace

Output: channel list

```

1 communications  $\leftarrow$  Map(String, List(Communication));
2 for endpoint1  $\in$  endpointList1 do
3   bindEvent1  $\leftarrow$  get the bind () function call related event from
     endpoint1.openStream;
4   connectEvent1  $\leftarrow$  get the connect () function call related event from
     endpoint1.openStream;
5   for endpoint2  $\in$  endpointList2 do
6     bindEvent2  $\leftarrow$  get the bind () function call related event from
       endpoint2.openStream;
7     connectEvent2  $\leftarrow$  get the connect () function call related event from
       endpoint2.openStream;
8     if socketEvent1! = null AND socketEvent2! = null then
9       if bindEvent1! = null AND connectEvent2 == null then
10        localServerAddr  $\leftarrow$  get the serverAddr parameter value from
          bindEvent1.inputs;
11        else if bindEvent2 == null AND connectEvent1! = null then
12          remoteServerAddr  $\leftarrow$  get the serverAddr parameter value from
            connectEvent1.inputs;
13        else
14          Break the inner For loop;
15        if localServerAddr == remoteServerAddr then
16          DataVerified  $\leftarrow$  Call the corresponding data verification algorithm.
            communication = New Communication();
17          communication.endpoint1 = endpoint1;
18          communication.endpoint2 = endpoint2;
19          communication.dataMatch  $\leftarrow$  The output from data verification
            algorithm;
20          communications.add (communication);
21 return channels;

```

2.3.3 Transmitted Data Verification for Named pipe and TCP by Data Union

As describe in Section1.2.1 the data being receive by one endpoint should always equal to or at least is sub string of the data being sent fro the other endpoint in a communication for the reliable transmission methods, such as Named pipe and TCP. So the transmitted data verification algorithm is in data union level. The send data union is retrieved by the conjunction of the input buffer content of the send events in the send stream of an endpoint. The receive data union is retrieved by the conjunction of the output buffer content of the receive events in the receive stream of an endpoint. The input of this algorithm is the two endpoints from two traces which are being matched.

Algorithm 5: Transmitted Verification by Data Union

Input: two endpoint from each trace of the dual-trace

Output: send data union and receive data union of two endpoints

```

1 return Indicator of if transmitted data union are considered to be identical send1 ←
   empty string;
2 send2 ← empty string;
3 recv1 ← empty string;
4 recv2 ← empty string;
5 for sendEvent ∈ endpoint1.sendStream do
6   | sendmessage ← get the input buffer content from the sendEvent.inputs;
7   | send1.append(sendmessage);
8 for sendEvent ∈ endpoint2.sendStream do
9   | sendmessage ← get the input buffer content from the sendEvent.inputs;
10  | send2.append(sendmessage);
11 for recvEvent ∈ endpoint1.receiveStream do
12  | recvmessage ← get the output buffer content from the recvEvent.outputs;
13  | recv1.append(recvmessage);
14 for recvEvent ∈ endpoint2.receiveStream do
15  | recvmessage ← get the output buffer content from the recvEvent.outputs;
16  | recv2.append(recvmessage);
17 if recv1 is substring of send2 AND recv2 is substring of send1 then
18  | return True;
19 else
20  | return False;

```

2.3.4 Transmitted Data Verification for MSMQ and UDP by Data of Events

For the unreliable communication methods, the data packets being transmitted are not delivery and ordering guaranteed. So it is impossible to verify the transmitted data as a whole chunk. Fortunately, the packets arrived to the receivers are always as the original one from the sender. Therefore, we perform the transmitted data verification by single events instead of the whole stream. This algorithm basically goes through the send event list from one endpoint trying to find the matched receive event from the receive event list from the other endpoint. And then calculate the fail packet arrival rate. The fail packet arrival rate should be comparable to the packet lost rate. So we set the packet lost rate as the threshold to determine if the transmitted data can be considered to be identical in both directions. The packet lost rate can be various from network to network or even from time to time for the same network. The inputs of this algorithm are the copies of two endpoints from two traces which are being matched, the packet lost rate as the threshold. The threshold should be an integer. For example if the lost rate is 5%, the threshold should be set as 5. I use copies instead of original endpoints is that for efficiency I modify the input list directly in the algorithm.

Algorithm 6: Transmitted Verification by Data of Events

Input: two endpoint lists of the dual-trace, threshold

Output: matched event list of two endpoints

```

1 return Indicator of if transmitted data union are considered to be identical
    $sendPktNum1 \leftarrow endpoint1.sendStream.length;$ 
2  $sendPktNum2 \leftarrow endpoint2.sendStream.length;$ 
3  $recvPktNum1 \leftarrow 0;$ 
4  $recvPktNum2 \leftarrow 0;$ 
5  $eventMatches \leftarrow List\langle EventMatch \rangle;$ 
6 for  $sendEvent \in endpoint1.sendStream$  do
7    $sendmessage \leftarrow$  get the input buffer content from the  $sendEvent.inputs;$ 
8   for  $recvEvent \in endpoint2.receiveStream$  do
9      $recvmessage \leftarrow$  get the output buffer content from the  $recvEvent.outputs;$ 
10    if  $sendmessage == recvmessage$  then
11       $recvPktNum1 ++;$ 
12       $endpoint2.receiveStream.remove(recvEvent);$ 
13       $eventMatch = NeweventMatch();$ 
14       $eventMatches.add(eventMatch);$ 
15 if  $(sendPktNum1 - recvPktNum1) * 100 / sendPktNum1 > threshold$  then
16   return False;
17 for  $sendEvent \in endpoint2.sendStream$  do
18    $sendmessage \leftarrow$  get the input buffer content from the  $sendEvent.inputs;$ 
19   for  $recvEvent \in endpoint1.receiveStream$  do
20      $recvmessage \leftarrow$  get the output buffer content from the  $recvEvent.outputs;$ 
21     if  $sendmessage == recvmessage$  then
22        $recvPktNum2 ++;$ 
23        $endpoint1.receiveStream.remove(recvEvent);$ 
24 if  $(sendPktNum2 - recvPktNum2) * 100 / sendPktNum2 > threshold$  then
25   return False;
26 return True;

```

2.4 Data Structures for Identified Communications

In the previous sections, I elaborate all the essential algorithms to identify the communications. The information of identified communications should be organized properly for the further presentation or visualization to the user. In this section, I define the output data structures to fulfill this requirement. There are totally two major data structure. The first one is clustered as communications align the definition at Section 1.1. The second one is clustered by endpoints in the traces. The reason to provide the second data structure is due to the false positive errors of the channel identification. The endpoint lists in the traces provides more original data information. So with other assistant information and the access of the relatively original information from the dual-trace, the user has more flexibility to analysis the dual-trace. This data structures have been used in the algorithms implicitly.

Algorithm 7: Data Structure for Identified Communications

```

1 communications  $\leftarrow$  Map(String, List(Communication));           // communication
   clustering
2 traceEndpoints  $\leftarrow$  Map(String, List(Endpoint));           // endpoint clustering
3 struct {
4   | Endpoint endpoint1           // endpoint1 is from trace1 of the dual-trace
5   | Endpoint endpoint2           // endpoint2 is from trace2 of the dual-trace
6   | DataMatch dataMatch
7 } Communication
8 struct {
9   | Int    handle
10  | Stream stream
11 } Endpoint
12 union {
13  | DataUnionMatch unionMatch           // For data union verification
14  | List  $\langle$  EventMatch  $\rangle$  eventMatches           // For data event verification
15 } DataMatch
16 struct {
17  | String sData1           // send data union of endpoint1
18  | String rData1           // receive data union of endpoint1, substring of sData2
19  | String sData2           // send data union of endpoint2
20  | String rData2           // receive data union of endpoint2, substring of sData1
21 } DataUnionMatch
22 struct {
23  | Event    event1           // event1 is from endpoint1
24  | Event    event2           // event2 is from endpoint2
25 } EventMatch
26 struct {
27  | List  $\langle$  Event  $\rangle$  openStream
28  | List  $\langle$  Event  $\rangle$  closeStream
29  | List  $\langle$  Event  $\rangle$  sendStream
30  | List  $\langle$  Event  $\rangle$  receiveStream
31 } Stream
32 struct {
33  | Int    lineNum
34  | Map  $\langle$  String, String  $\rangle$  inputs
35  | Map  $\langle$  String, String  $\rangle$  outputs
36 } Event

```

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