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High-Level and Target-Agnostic Transport Programs

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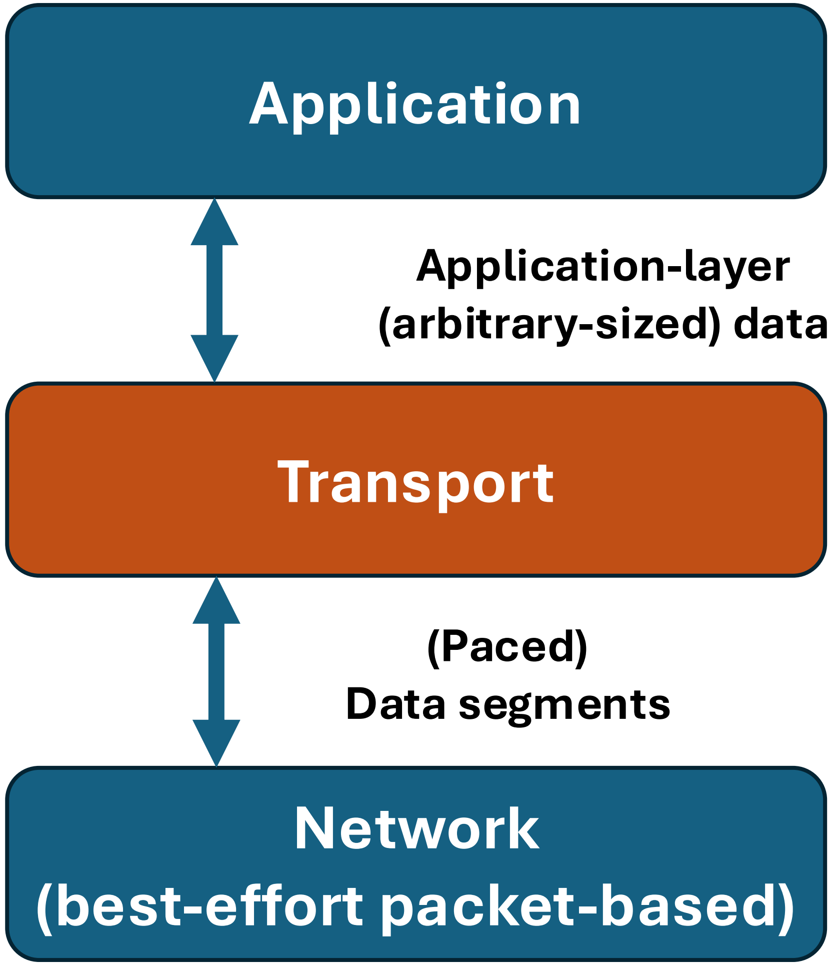
No “one-size-fits-all” transport protocol

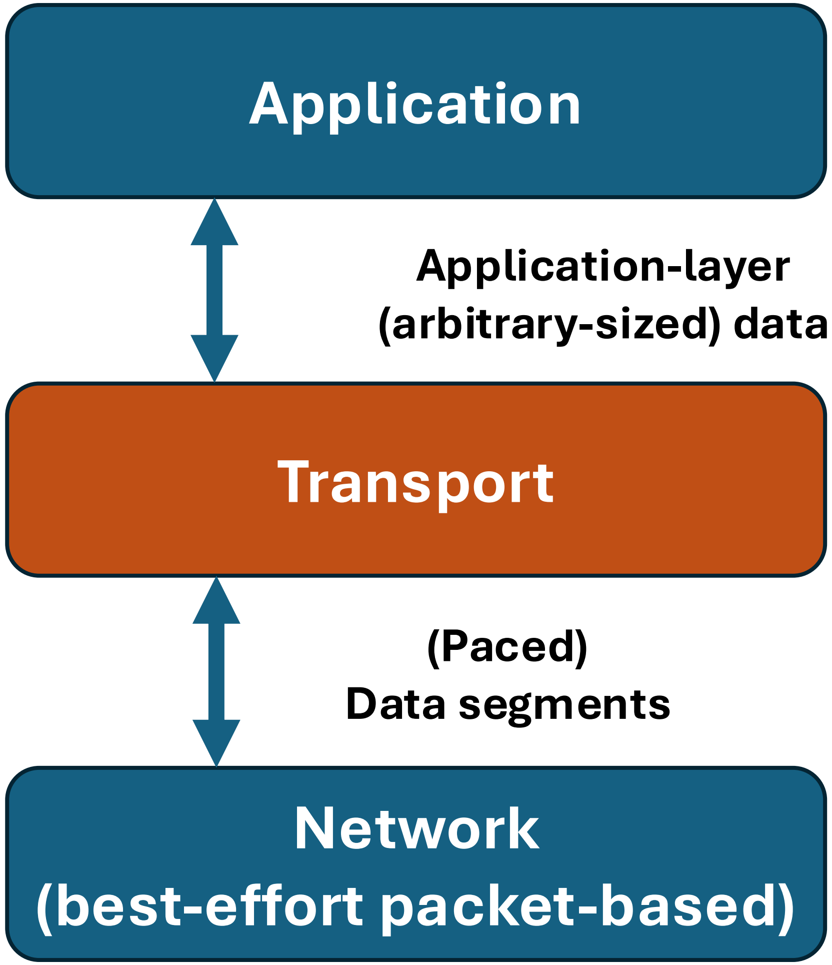


which data segment to send and when

such that

- Data is reliably delivered to the receiver
- as fast as possible
- w/o overwhelming the network and receiver

No “one-size-fits-all” transport protocol



which data segment to send and when

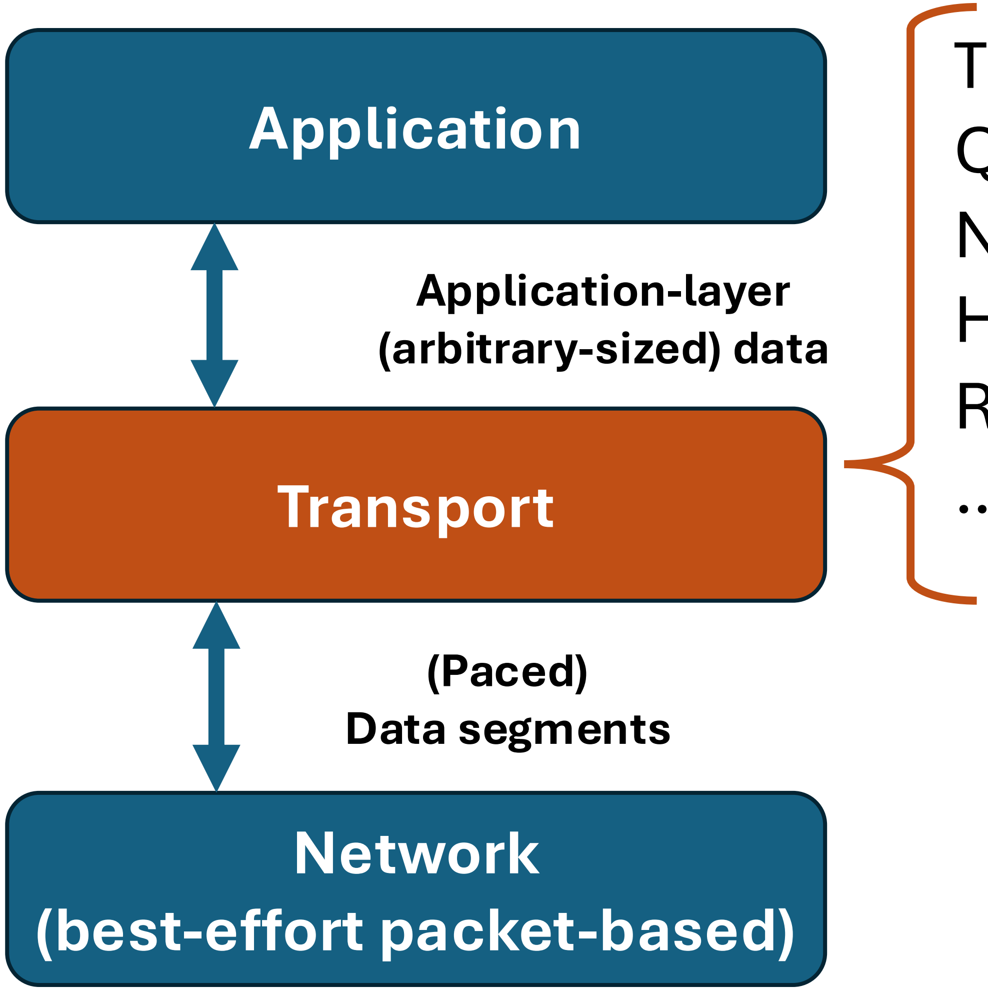
such that

- Data is reliably delivered to the receiver

Depends on

- Network characteristics
  - Wide area? Data center?
- Applications
  - Traffic patterns: small flows? Bursty?
  - Requirements: low latency? High throughput?

No “one-size-fits-all” transport protocol



Application

Application-layer (arbitrary-sized) data

Transport

(Paced) Data segments

Network (best-effort packet-based)

TCP and its many many variants

QUIC

NDP

Homa

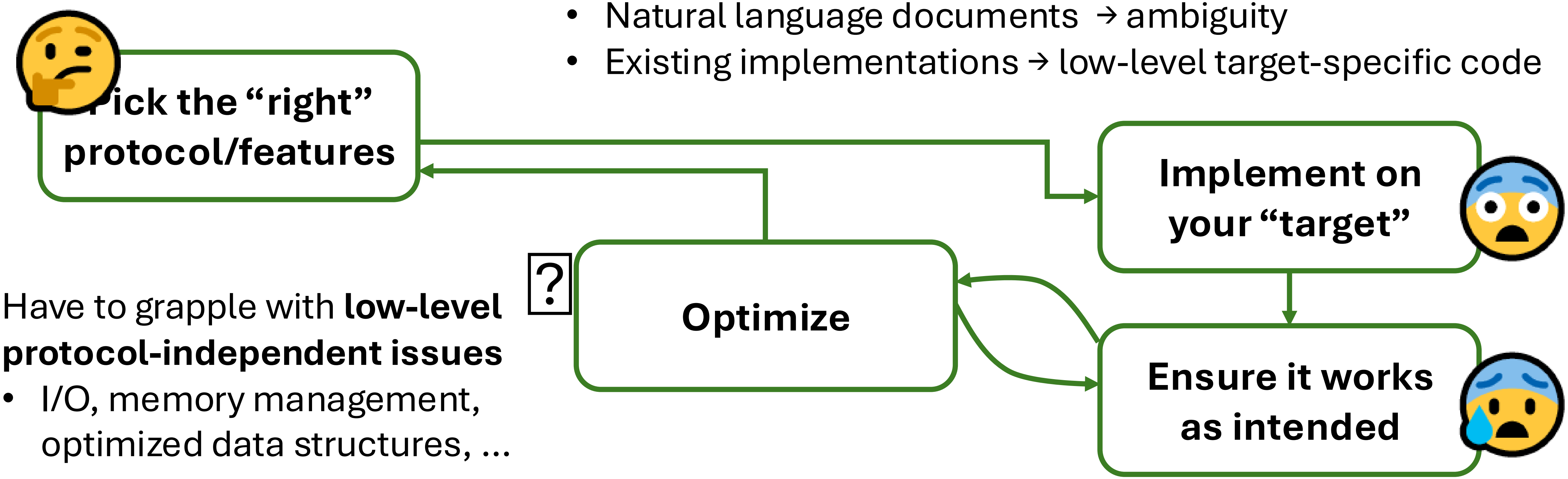
RoCEv2

…

The transport protocol development cycle today

No high-level specification with well-defined semantics

- Natural language documents → ambiguity
- Existing implementations → low-level target-specific code


Pick the "right" protocol/features
Implement on your "target"
Optimize
Ensure it works as intended

Have to grapple with **low-level protocol-independent issues**

- I/O, memory management, optimized data structures, …

No high-level specification with well-defined semantics

- Intended behavior is not always clear
- Pick and choose scenarios to test
- No automated high-coverage analysis and testing

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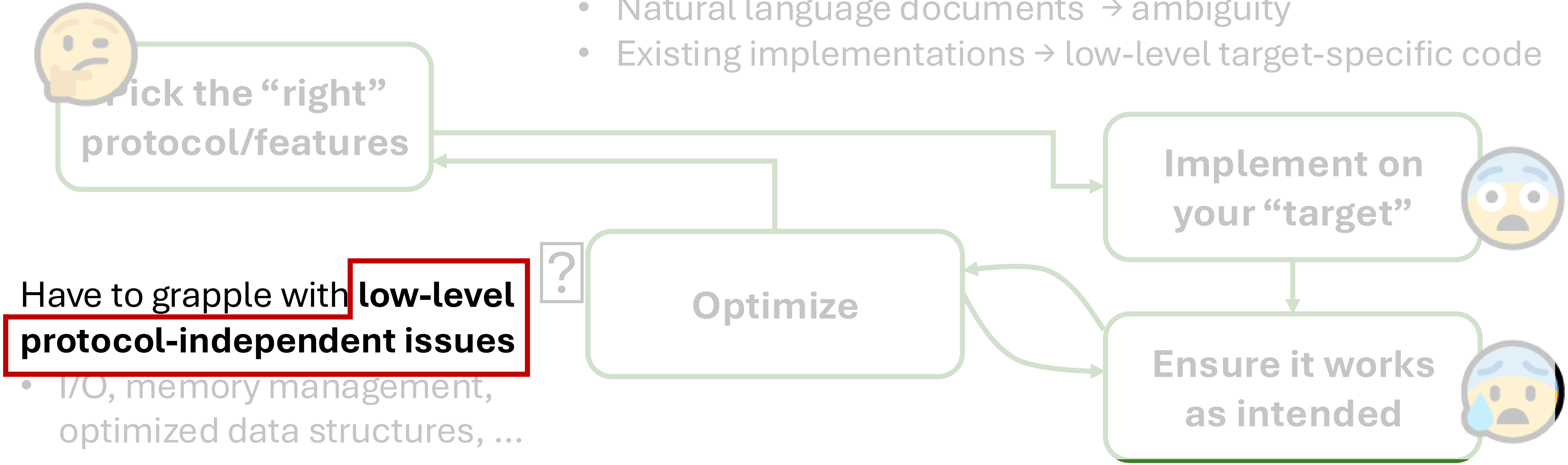
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The transport protocol development cycle today

No high-level specification with well-defined semantics

- Natural language documents → ambiguity
- Existing implementations → low-level target-specific code

Pick the "right" protocol/features

We need a *high-level target-agnostic protocol-independent* programming interface for transport

Have to grapple with **low-level protocol-independent issues**

- I/O, memory management, optimized data structures, ...

as intended

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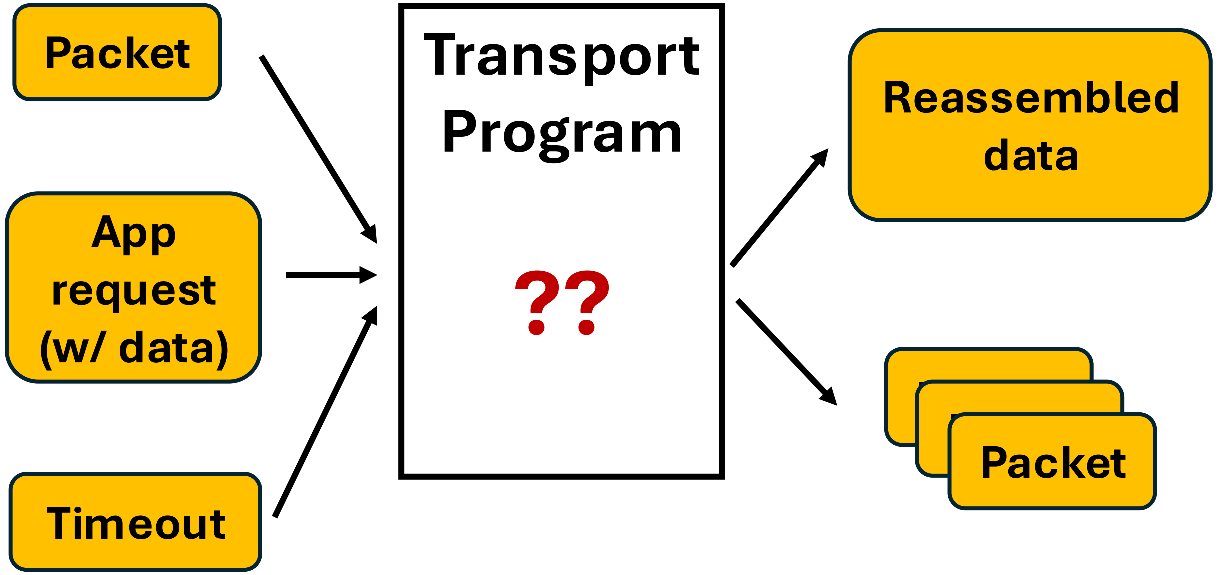
What should a transport program look like?



Packet

App request (w/ data)

Timeout

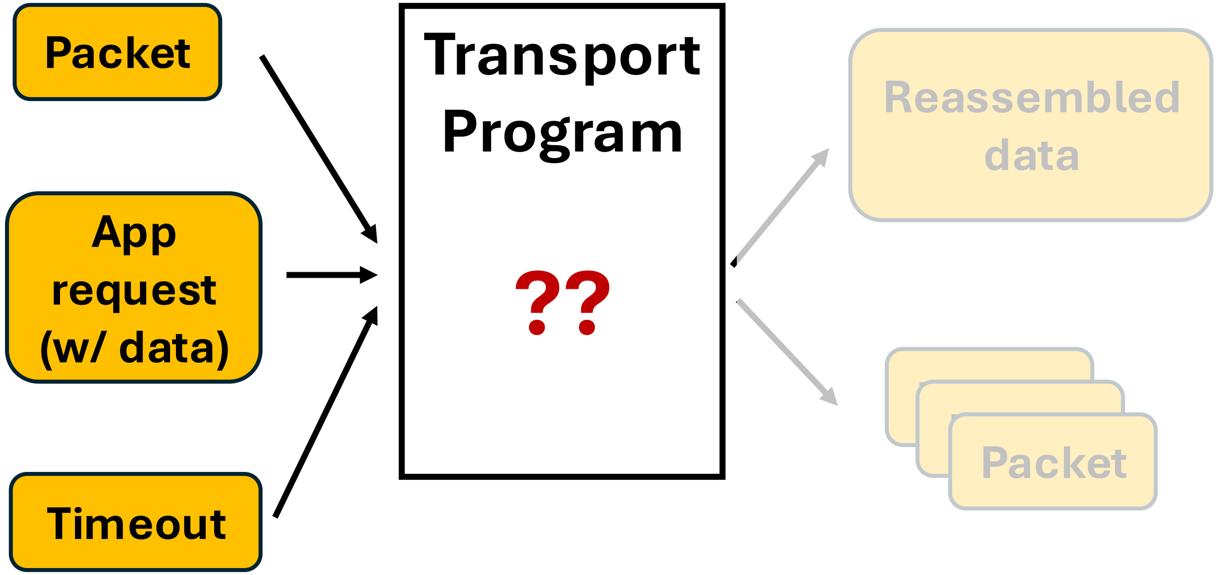
Transport Program

??

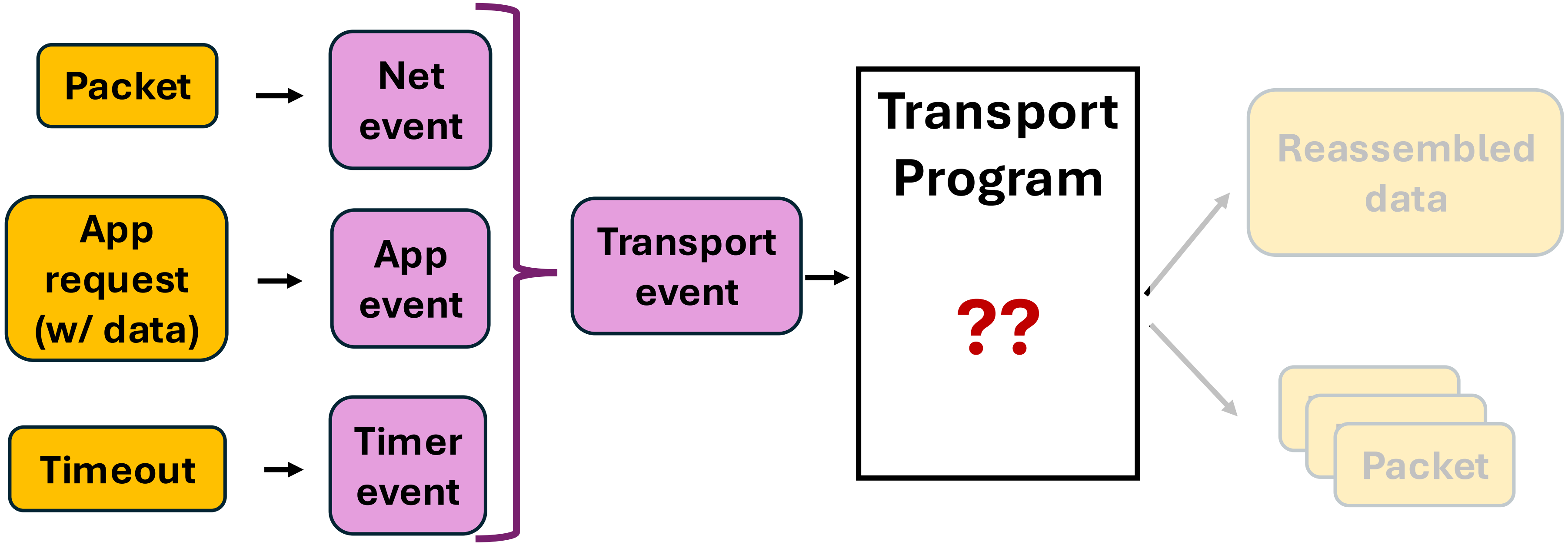
Reassembled data

Packet

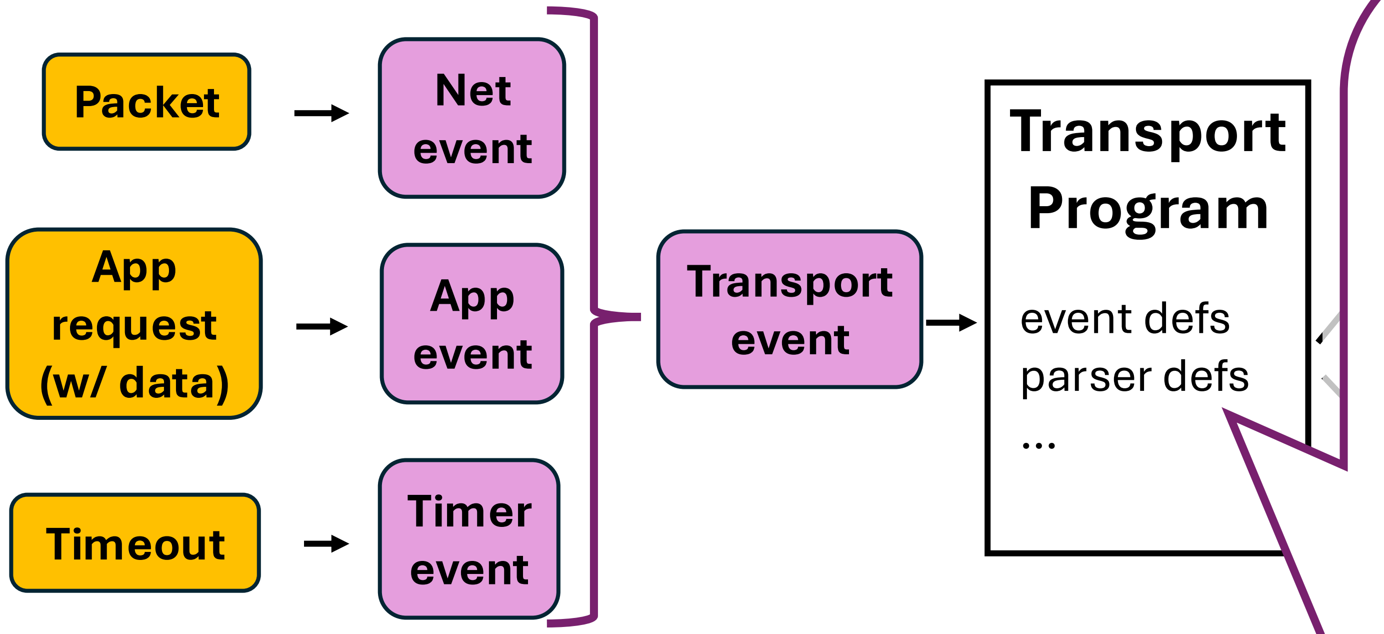
What should a transport program look like?



Transport events



Transport events



Packet

App request (w/ data)

Timeout

Net event

App event

Timer event

Transport event

Transport Program

event defs

parser defs

…

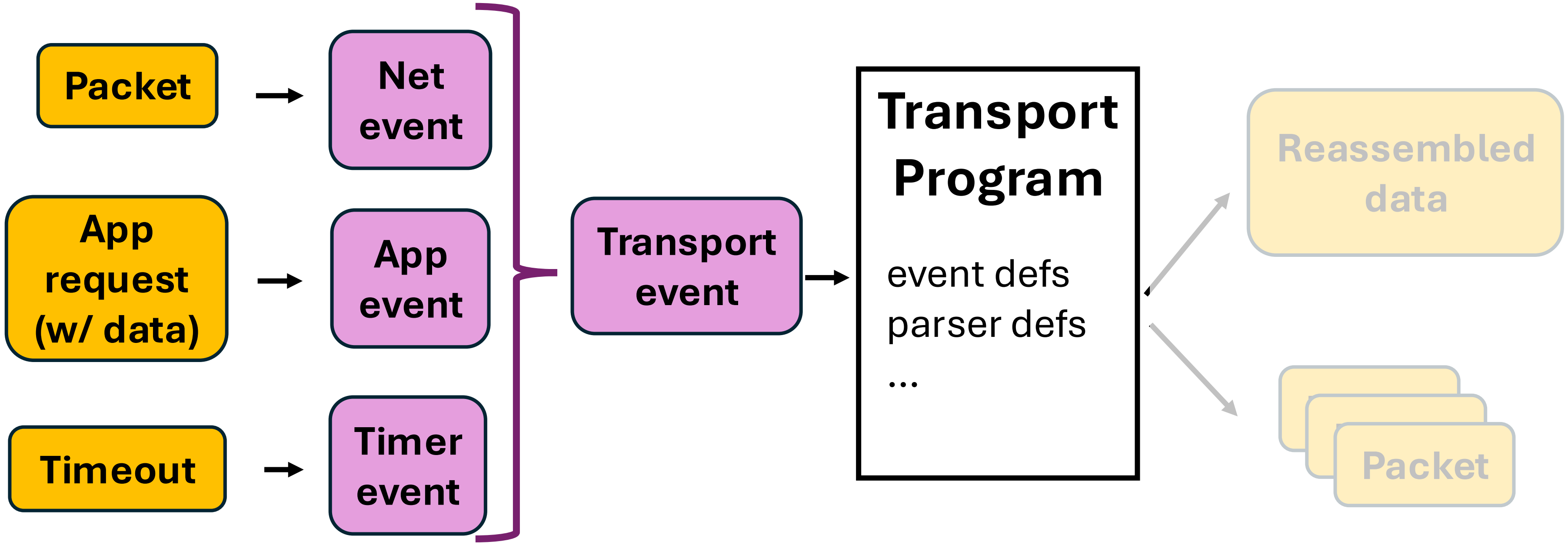
- Specifies what events it expects:

```
event tcp_snd : APP {
  uint32 data_size;
  addr_t user_buff_addr;
  ...}

event tcp_data_pkt : NET {
  uint32 seq_num;
  uint32 payload_size;
  addr_t payload_addr;
  ...}
```

- Specifies how to create events from packets and app requests
- Syntax similar to other network languages

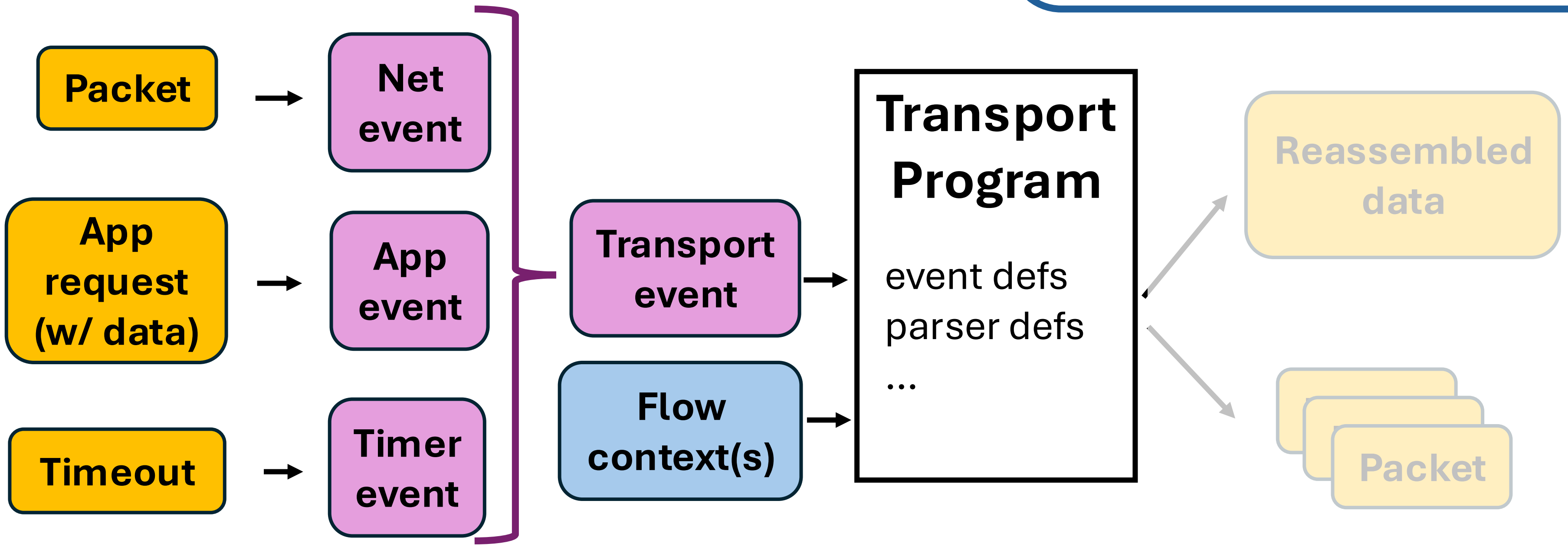
Transport events



Flow contexts

Each flow has some **state (or context)** that is

- used in event processing
- **maintained across events**
- E.g., sliding window start and end in TCP



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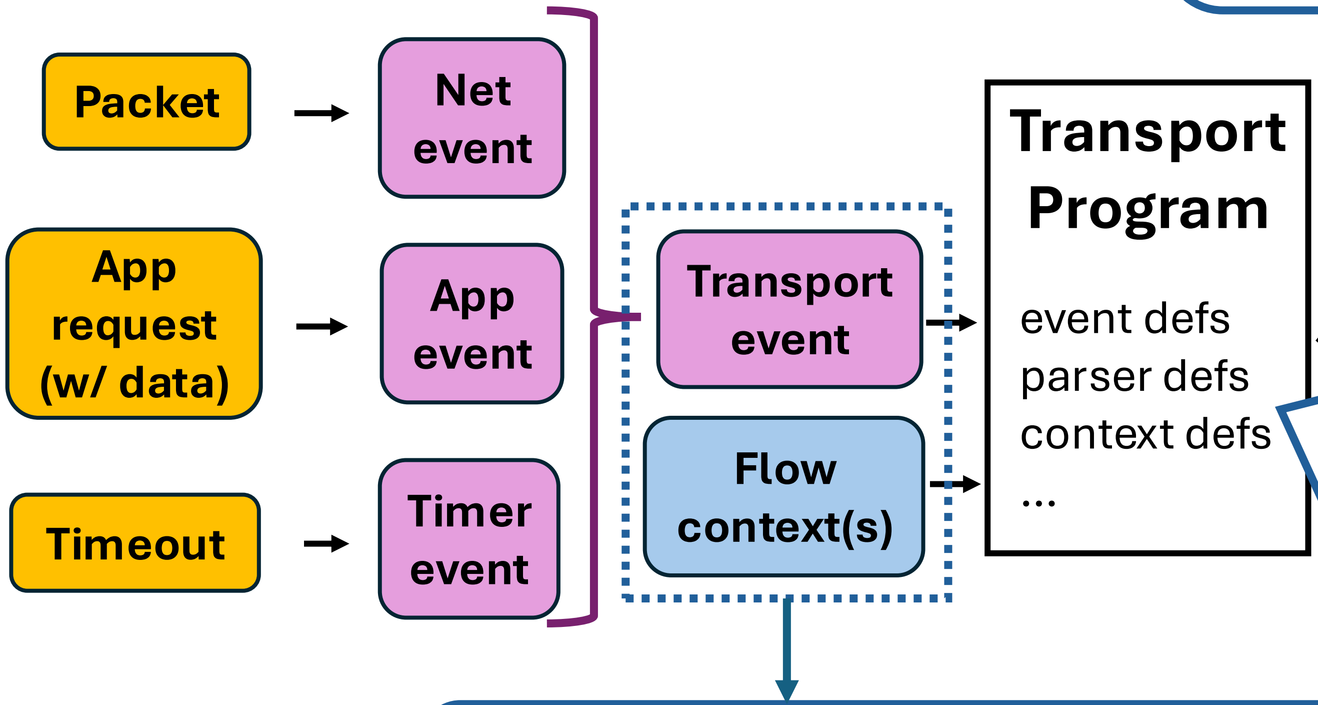
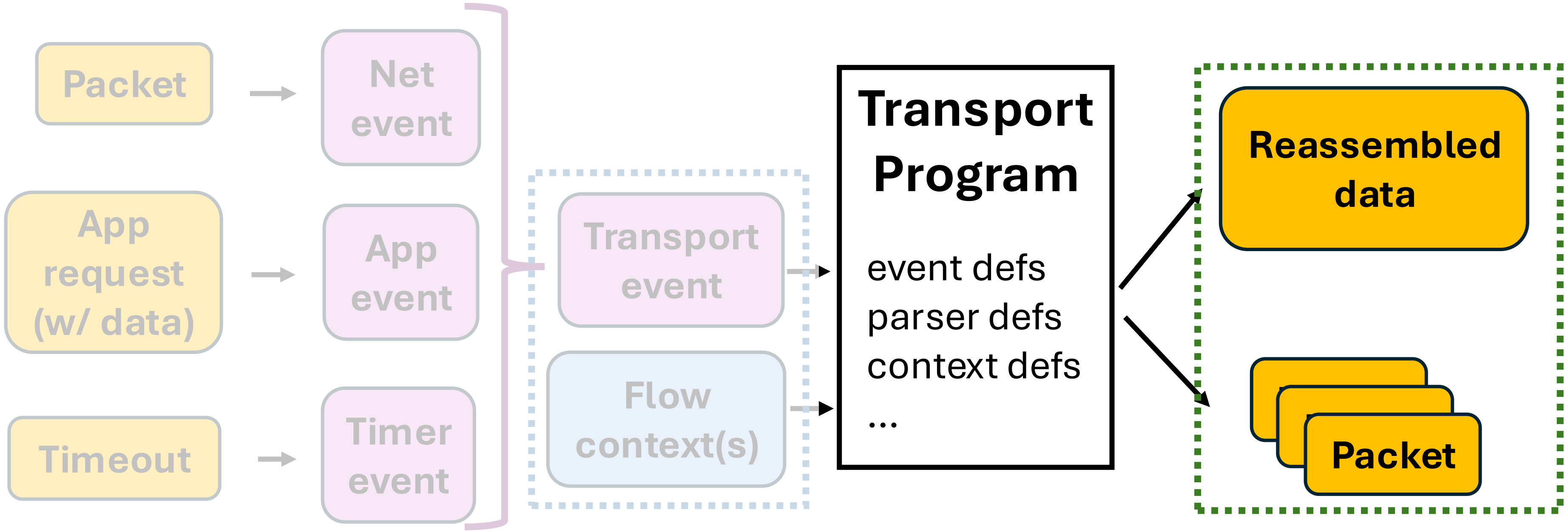


- Specifies what information to keep in the context.

```
context tcp_context {
  uint32 send_una;
  uint32 send_nxt;
  uint32 cwnd_size;
  …
}
```

- Each event is associated with a specific flow
- Programs attach look-up keys to events during parsing

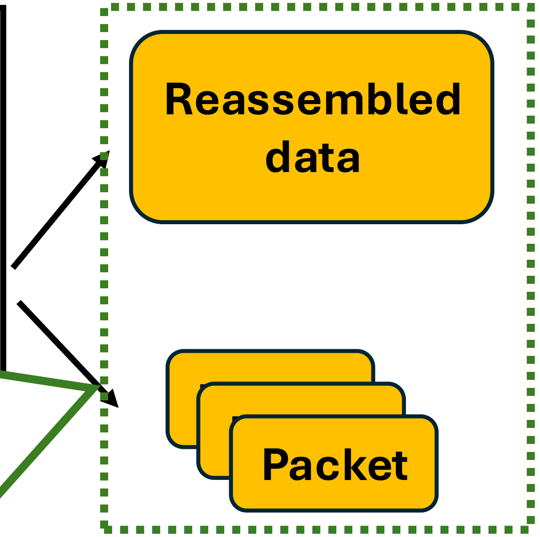
Output: ??


Packet
App request (w/ data)
Timeout
Net event
App event
Timer event
Transport event
Flow context(s)
Transport Program
event defs
parser defs
context defs
…
Reassembled data
Packet

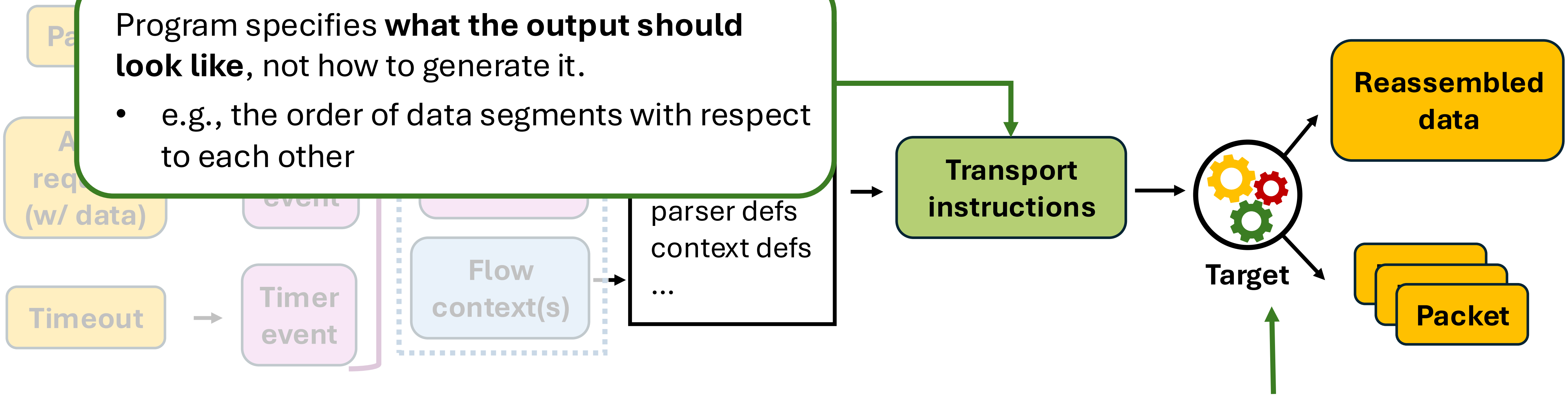
Output: ??

How do we **decouple protocol logic** for reassembly and packet generation from target-specific **implementation details**?

- Involves performance-sensitive operations:
  - Data movement
  - Buffer management
  - Packet pacing
  - …
- The most "optimal" implementation is **target-dependent**



Transport instructions



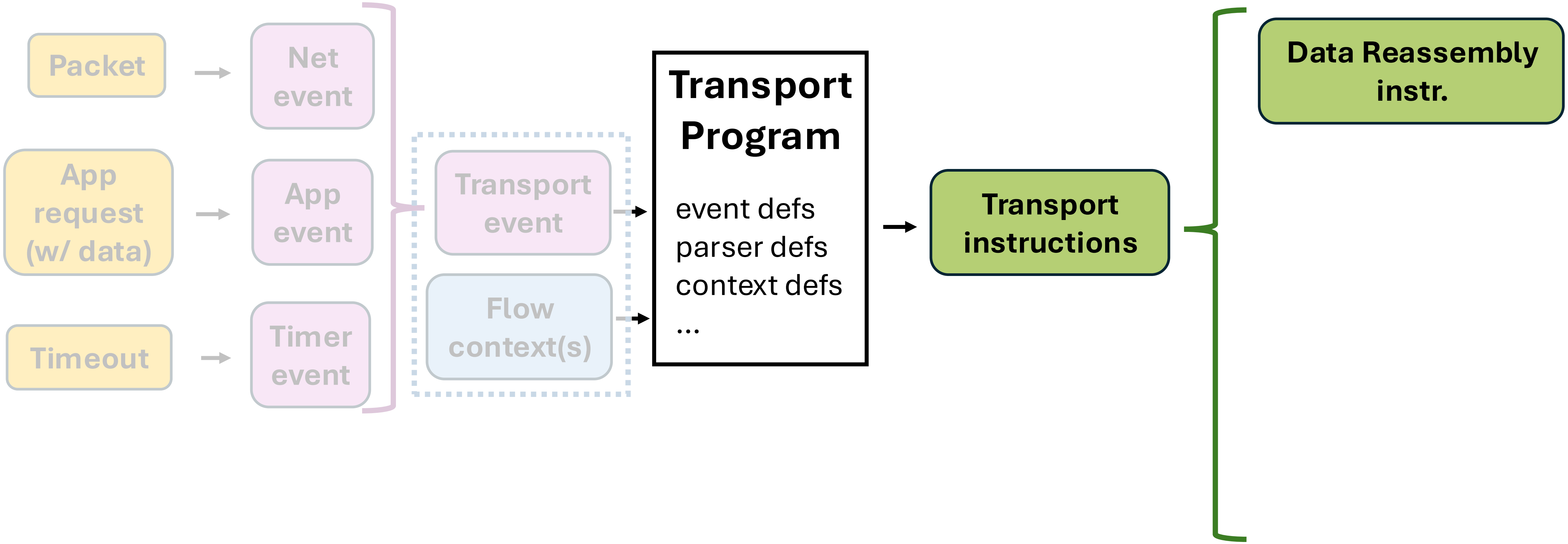
Program specifies **what the output should look like**, not how to generate it.

- e.g., the order of data segments with respect to each other

The target follows the instruction to generate the output, in the most efficient way for that target.

- e.g., copies packet payloads to a buffer and maintains them in the specified order.

Transport instructions



Transport instructions – Data Reassembly

Transport instructions issued by the program

new_rx_ordered_data(uid, size[, addr])

- I expect to receive *size* bytes of consecutive data
  - *size* can be *INF* for byte streams
- The identifier for this "unit" is *uid*
- The data should eventually be available at *addr*

What the target should do

- Allocate memory accordingly
  - Dynamic allocation?
  - Pool of buffers?
  - Zero copy *(addr)?*
  - …
- Maintain a mapping between *uid* and the allocated space

Transport instructions – Data Reassembly

Transport instructions issued by the program

```
add_rx_data_seg(addr, len, uid, offset)
```

- I want *len* bytes starting from *addr* to be at index *offset* of the consecutive data unit *uid*
  - *addr* → where incoming packet's payload is stored

What the target should do

- Find the right "destination" memory locations based on *offset* and *uid*
- Copy data from *addr*

Transport instructions – Data Reassembly

Transport instructions issued by the program

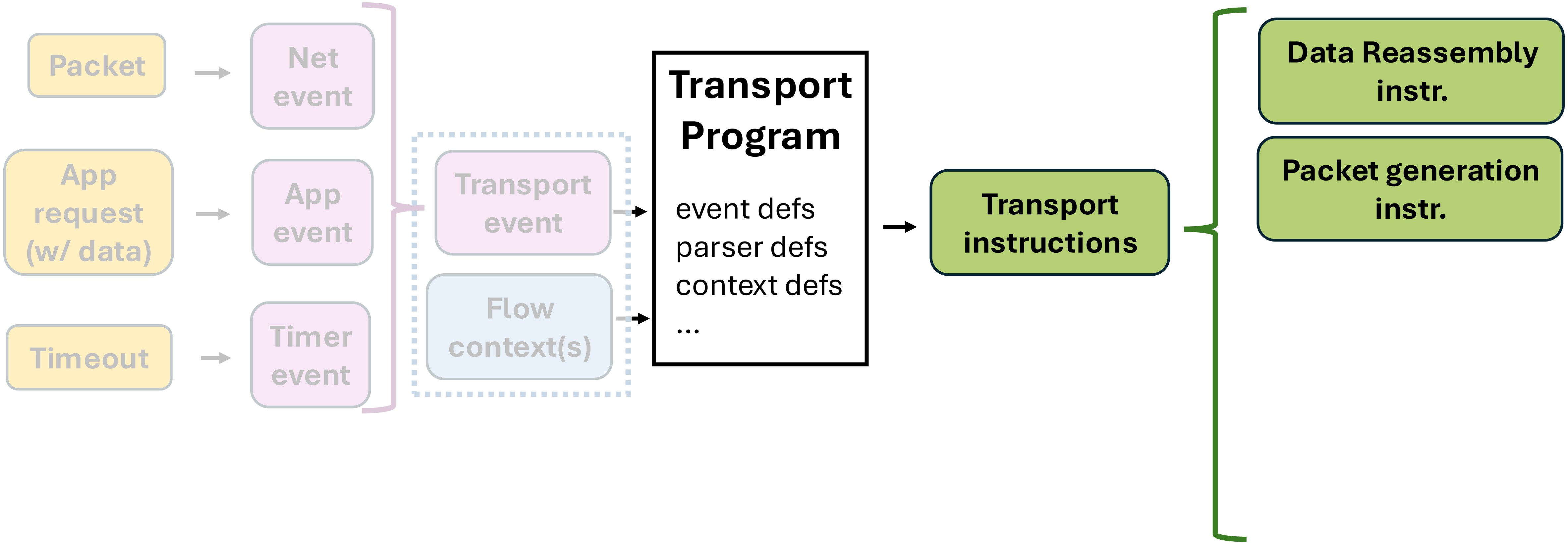
rx_flush_and_notify(uid, len, addr)

- I want *len* more bytes from *uid* to be made available to the application at *addr*
  - *addr* → user's buffer address

What the target should do

- Keep track of how far into *uid* has been "flushed" to the app
- Find the right "source" memory locations accordingly
- Move data to *addr*

Transport instructions



Transport instructions – Packet Generation

Transport instructions issued by the program

```
new_tx_ordered_data(uid, size[, addr])
add_tx_data_seg(addr, len, uid)
tx_flush_and_notify(uid, len)
```

- Similar to the “rx” counter-parts
- Abstracts operations on send buffers

What the target should do

- Allocate memory for *uid*
- Append app data to *uid*
- Remove data from *uid*
- …

Transport instructions – Packet Generation

Transport instructions issued by the program

```
pkt_gen(pkt_bp[, seg_rule_id, ...])
```

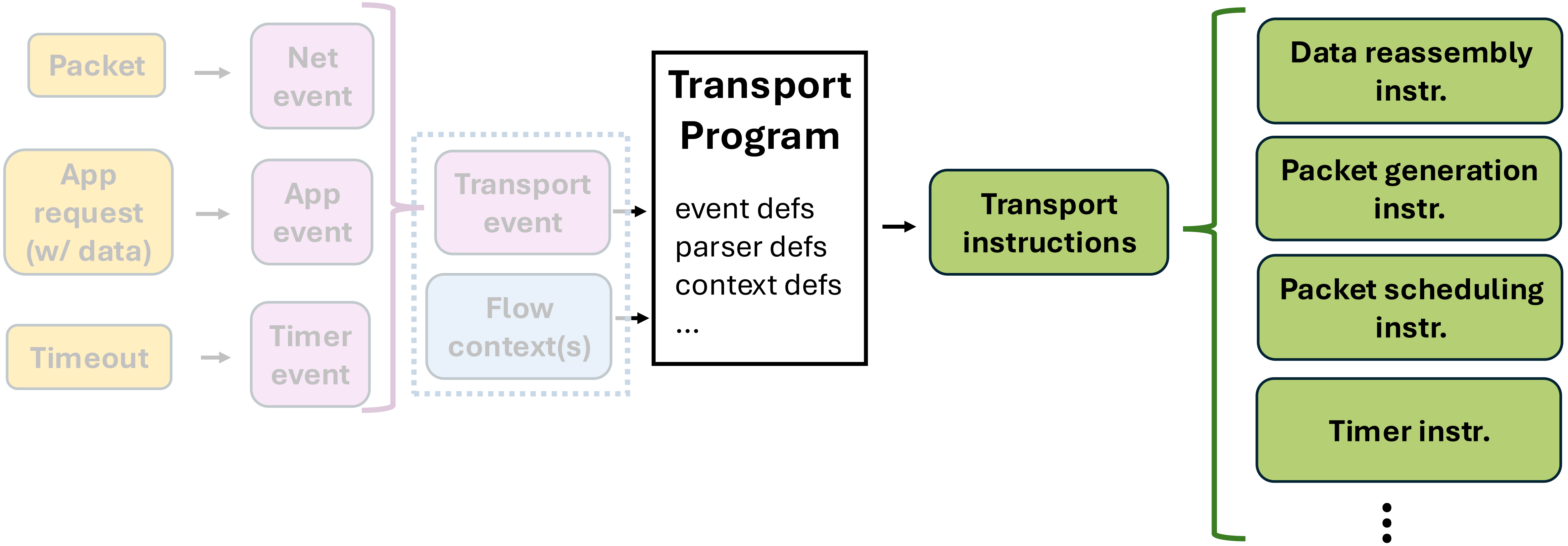
- I want packets looking like this *blueprint*
- blueprint:
  - header
  - data address and size for payload
- If data does not fit in one packet, segment it:
  - Update headers based on *seg_rule_id*

What the target should do

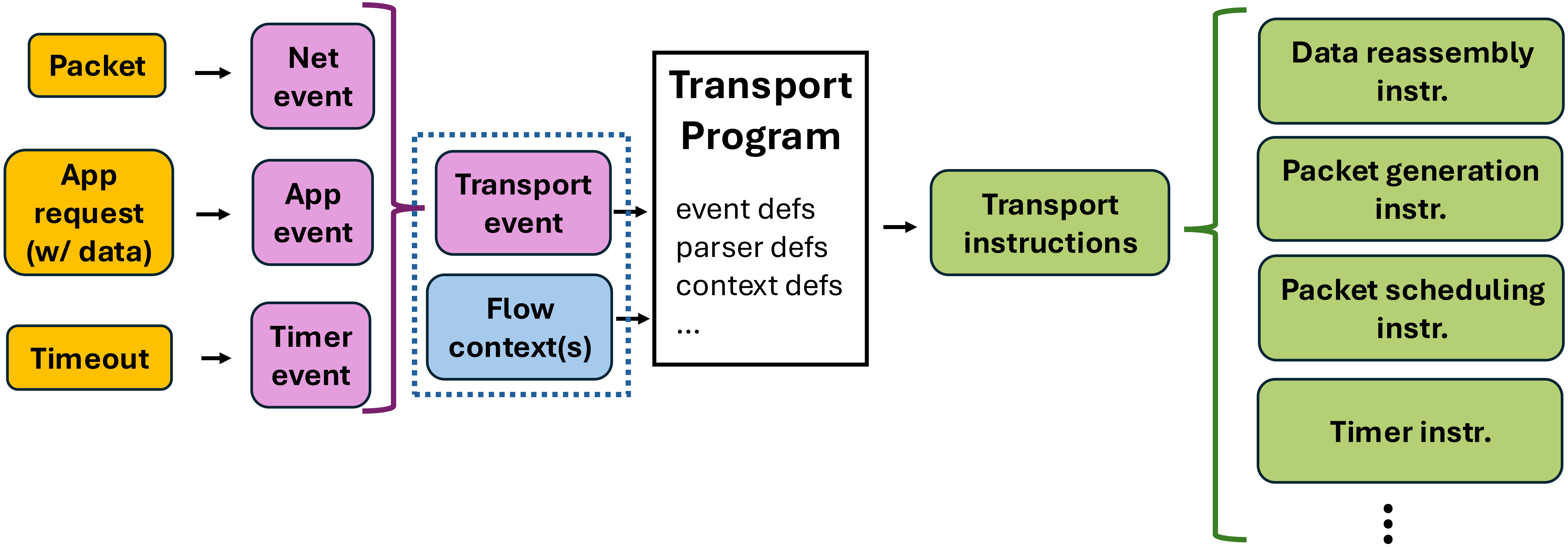
Generate the actual packets:

- Allocate packet memory
- Fill out headers
- Move data for payload
- ...

Transport instructions



From inputs to outputs



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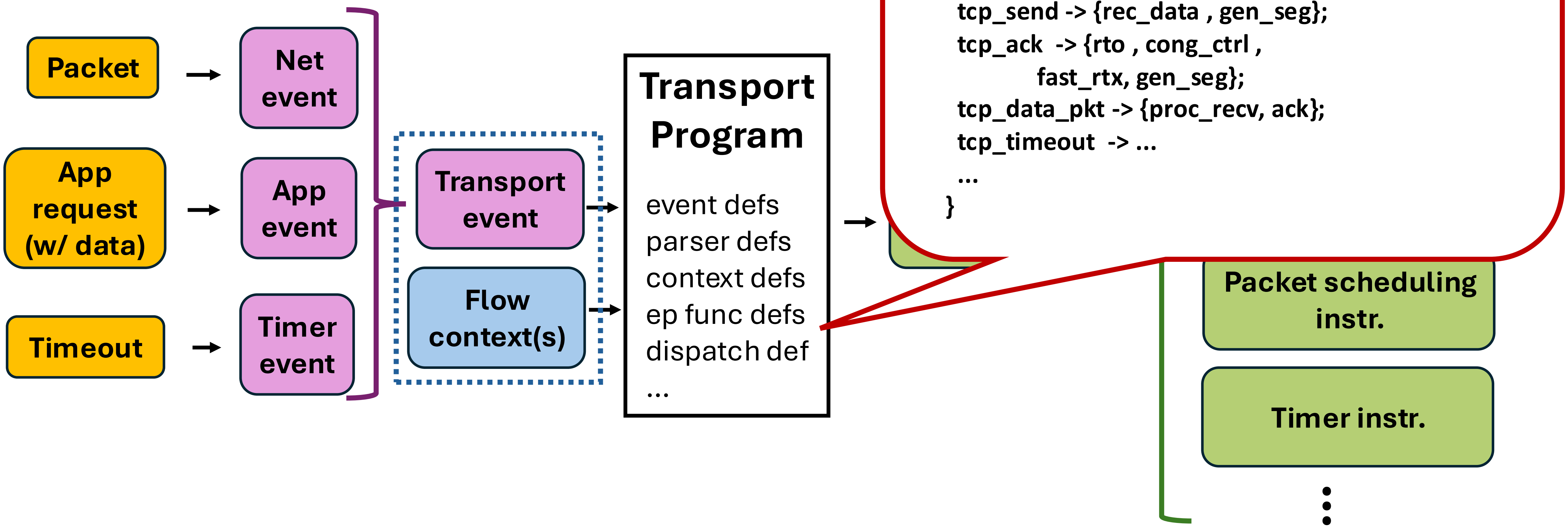
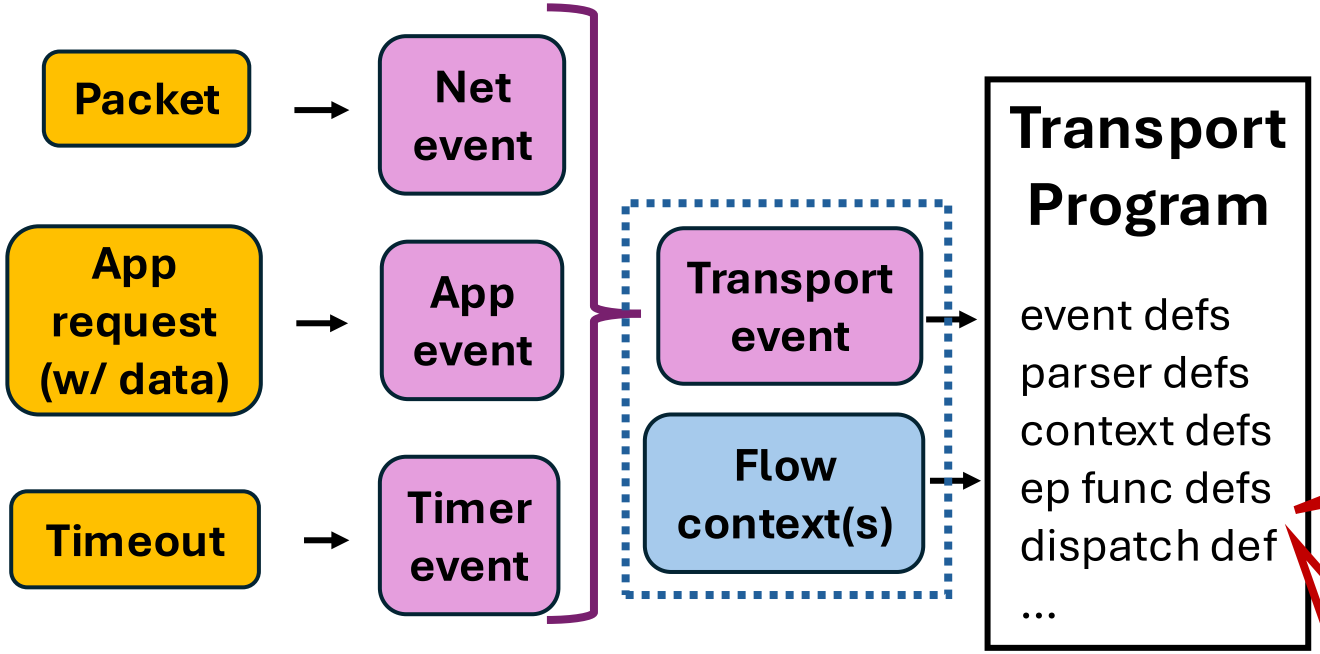


Mapping events to **chain of event processing functions**

```
dispatch tcp_dispatch {
 tcp_send -> {rec_data , gen_seg};
 tcp_ack  -> {rto , cong_ctrl ,
          fast_rtx, gen_seg};
 tcp_data_pkt -> {proc_recv, ack};
 tcp_timeout  -> ...
 ...
}
```

From inputs to outputs



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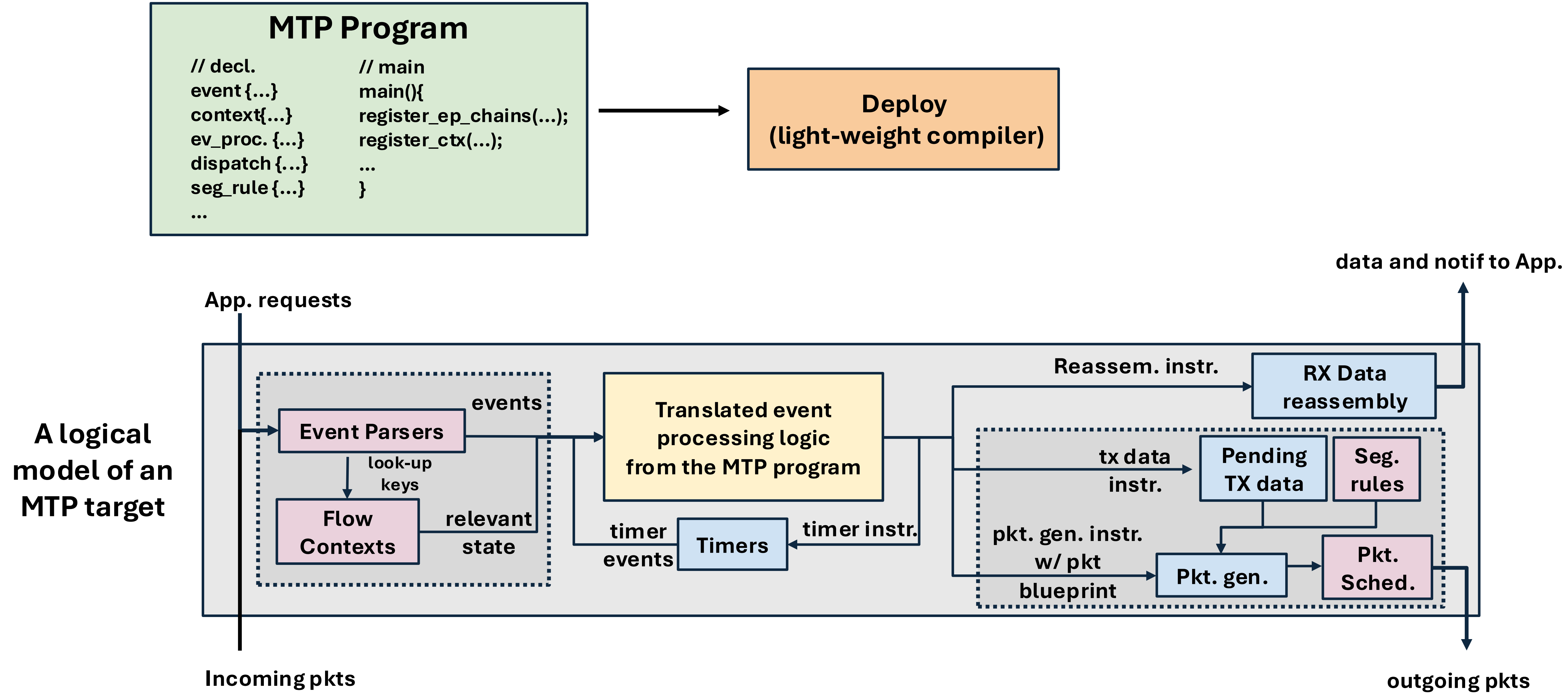
Event processing functions:

- Simple & C-like:
  - Bounded loops
  - No pointers
- Update context
- Issue instructions

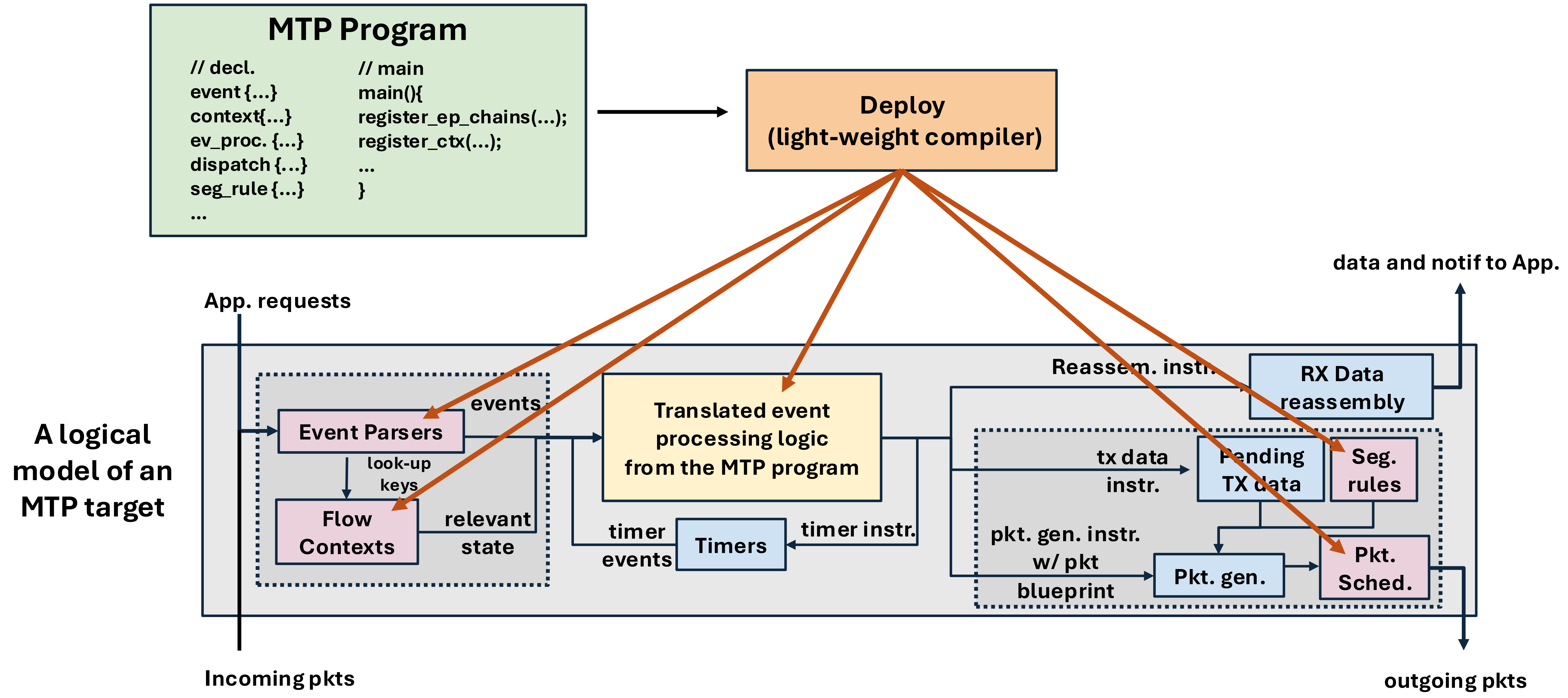
Modular Transport Programming (MTP)



MTP Program

```
// decl.            // main
event {…}           main(){
context{…}          register_ep_chains(…);
ev_proc. {…}        register_ctx(…);
dispatch {…}        …
seg_rule {…}        }
…
```

Modular Transport Programming (MTP)



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```

Expressiveness

✓ TCP
✓ QUIC-Lite

- Stream-based
  - Applications append data to byte streams to be sent
  - TCP: one per connection
  - QUIC-Lite: multiple parallel ones per connection
- Sender-side congestion control

✓ Homa
✓ NDP

- Message-based
  - Application message size is known (e.g., RPC)
- Receiver-driven

✓ RoCEv2

- Message-based
- Queue pairs as “connections”
- Designed for hardware

What about performance?

Observation:

Existing protocol implementations already know how to do transport tasks *efficiently* in a specific execution environment

- e.g., buffer management, packet I/O, per-flow state tracking, …

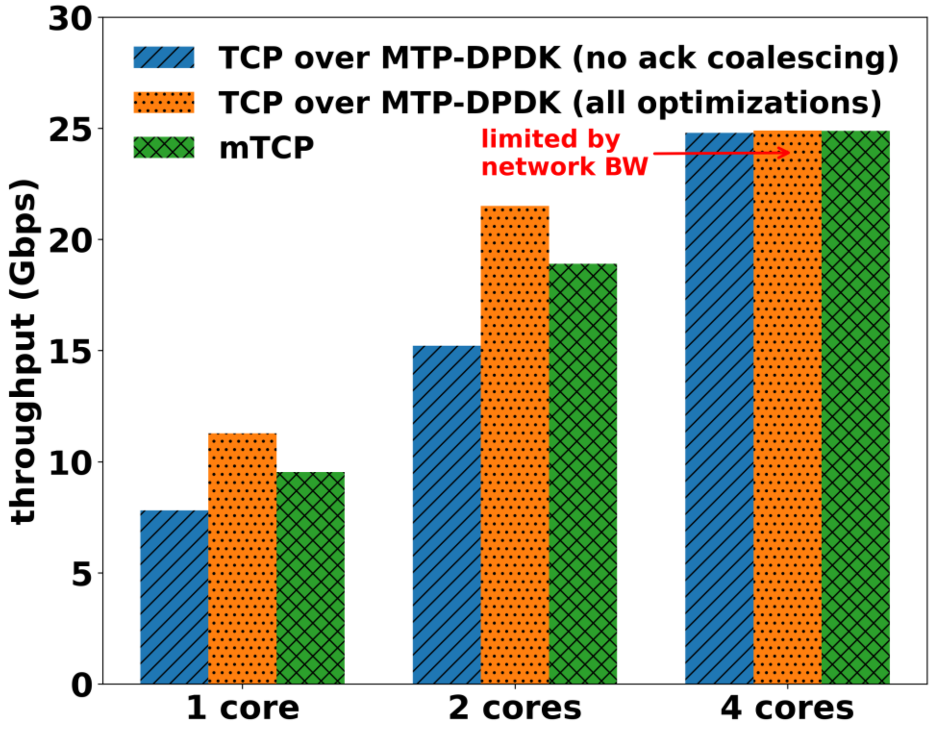
We can “refactor” them to expose these tasks via MTP’s high-level unifying interface.

Target #1: MTP-DPDK

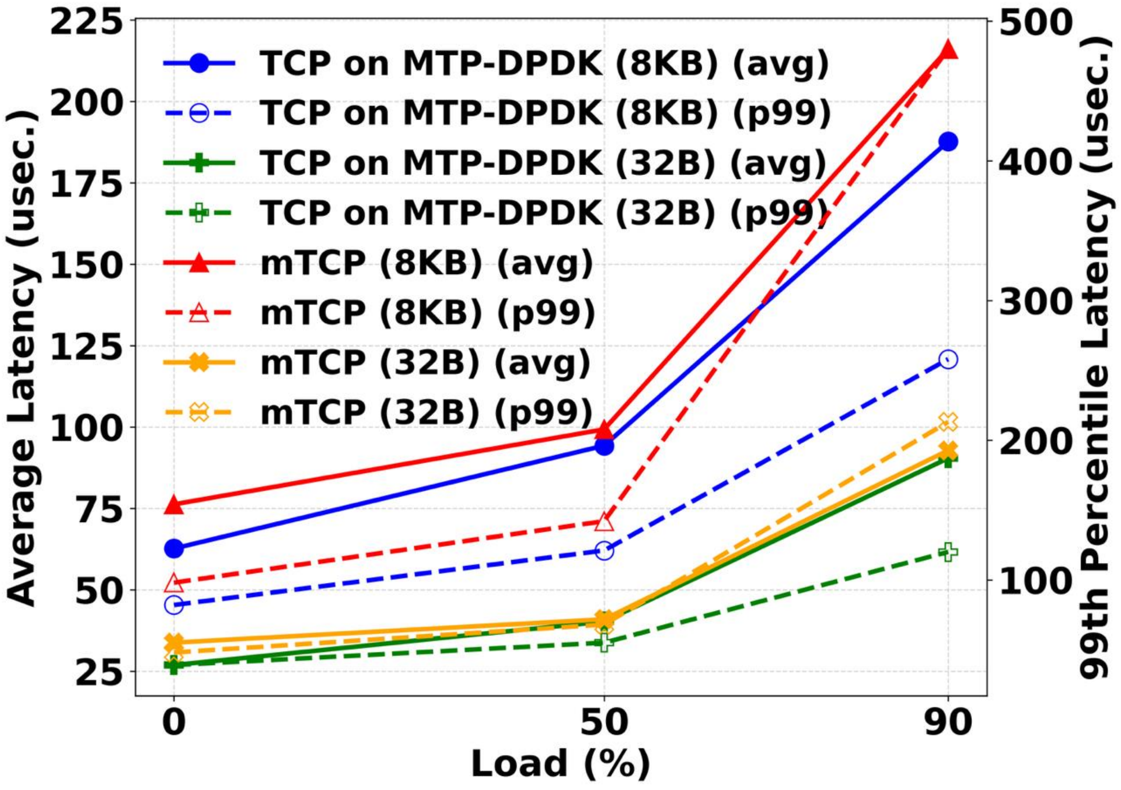
- DPDK: kernel-bypass networking
  - A user-space process can directly send/receive packets from the NIC
  - Specialized, user-space network stacks
- mTCP (NSDI’14)
  - TCP implemented over DPDK
- MTP-DPDK
  - mTCP refactored to implement MTP’s API (Details in the paper!)
- Experiments:
  - Cloudlab, xl170 nodes, 25Gbps network

TCP over MTP-DPDK

- Clients sending HTTP requests of varying size in a closed loop.



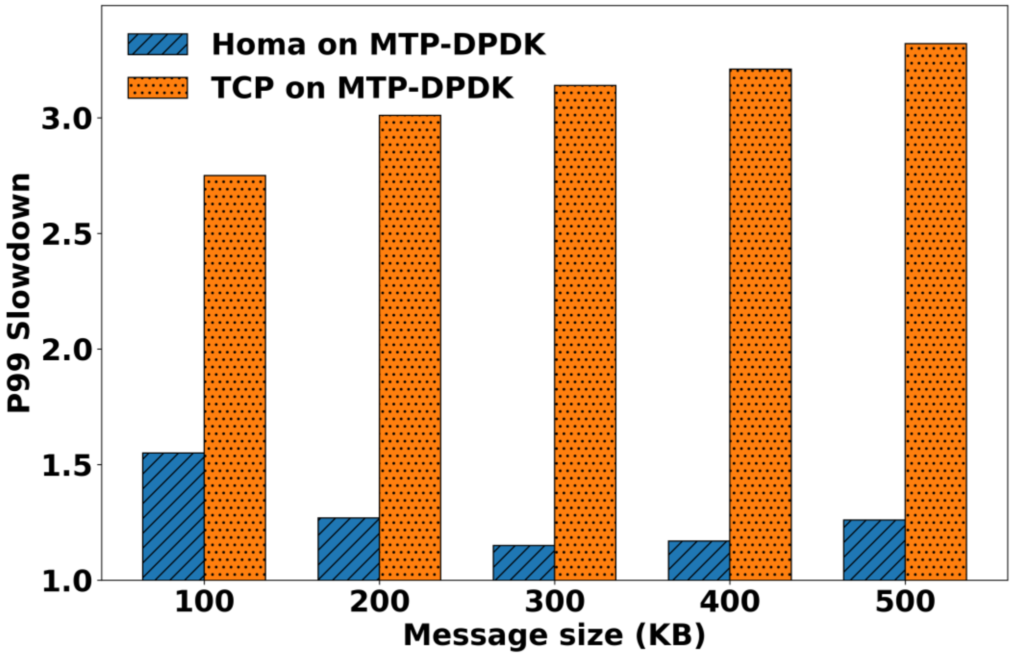
Server throughput for 1MB files



Message response latency, single server thread

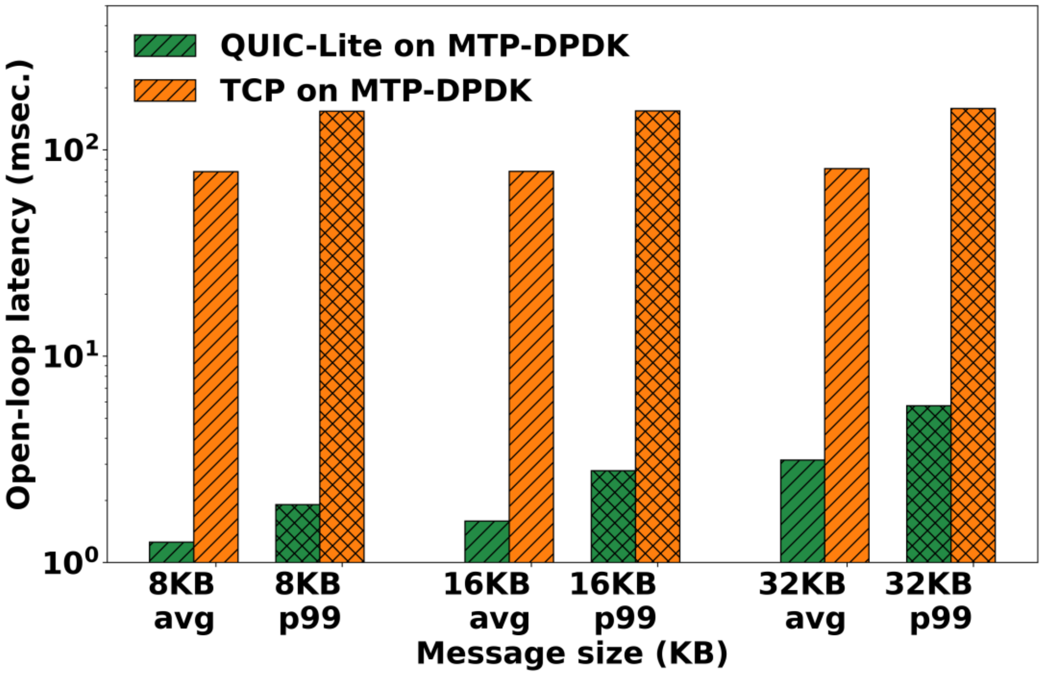
Multiple protocols over MTP-DPDK

Homa



Message response slow-down
TCP vs. Homa on the same target
50% load from 1MB messages

QUIC-Lite



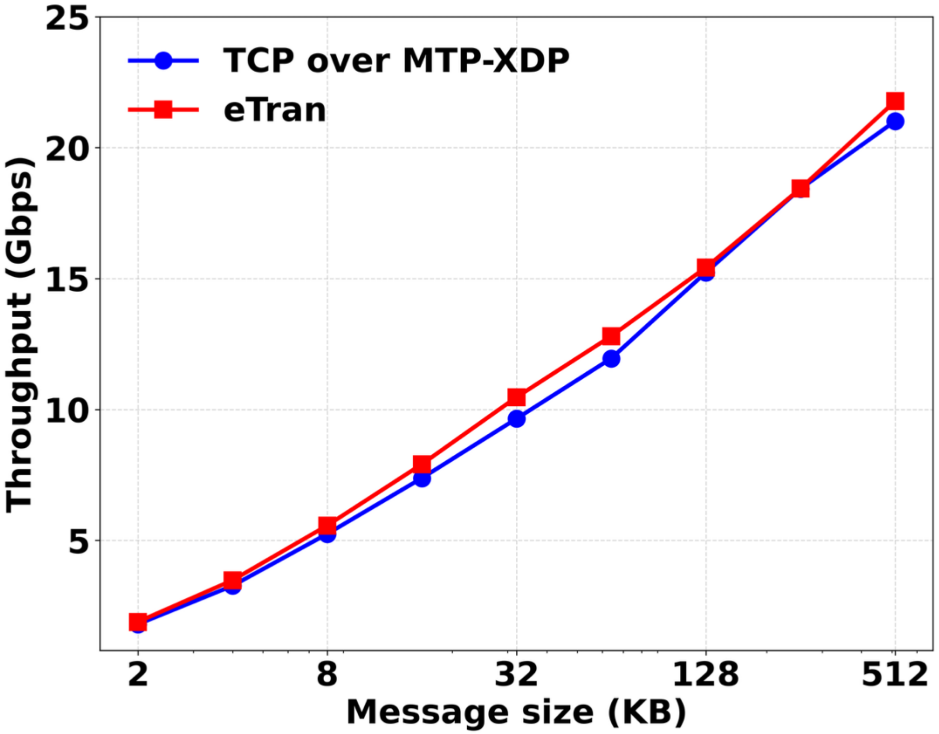
Message response latency
TCP vs QUIC-Lite on the same target
Small message competing with 1MB ones
Over the same connection

Target #2: MTP-XDP

- eBPF: can insert programs into various ”hooks” across the kernel
- XDP “hook”: executes in the NIC driver
- eTran (NSDI’25)
  - TCP and Homa implemented in some XDP hooks + user space
- MTP-XDP
  - eTran refactored to implement MTP’s API (Details in the paper!)
- Experiments:
  - Cloudlab, xl170 nodes, 25Gbps network

Multiple protocols over MTP-XDP

TCP



Server throughput (1 thread)

Homa (one server thread)

Metric	Homa (MTP-XDP)	Homa (eTran)
32B message avg. latency	8.45us	8.29 us
1MB message throughput	19.75 Gbps	20.52 Gbps

QUIC-Lite (one server thread, open loop)

32KB message	QUIC-Lite	TCP
avg. latency	3.4ms	20.1ms
tail latency	5.8ms	28.8ms

Takeaways

- MTP’s API is at the right level of abstraction
    - abstracts away enough details to be target-agnostic
    - implementable with already existing efficient mechanisms
- Different targets’ impl. of transport tasks vary in non-trivial ways
    - Confirmed our decision to abstract them as instructions
- The heavy lifting is in implementing the instructions
    - Abstract away most of the complexity
- Translating the event chains can be done with a light-weight compiler

Reduction in development effort

MTP Programs
Target-independent
Written once

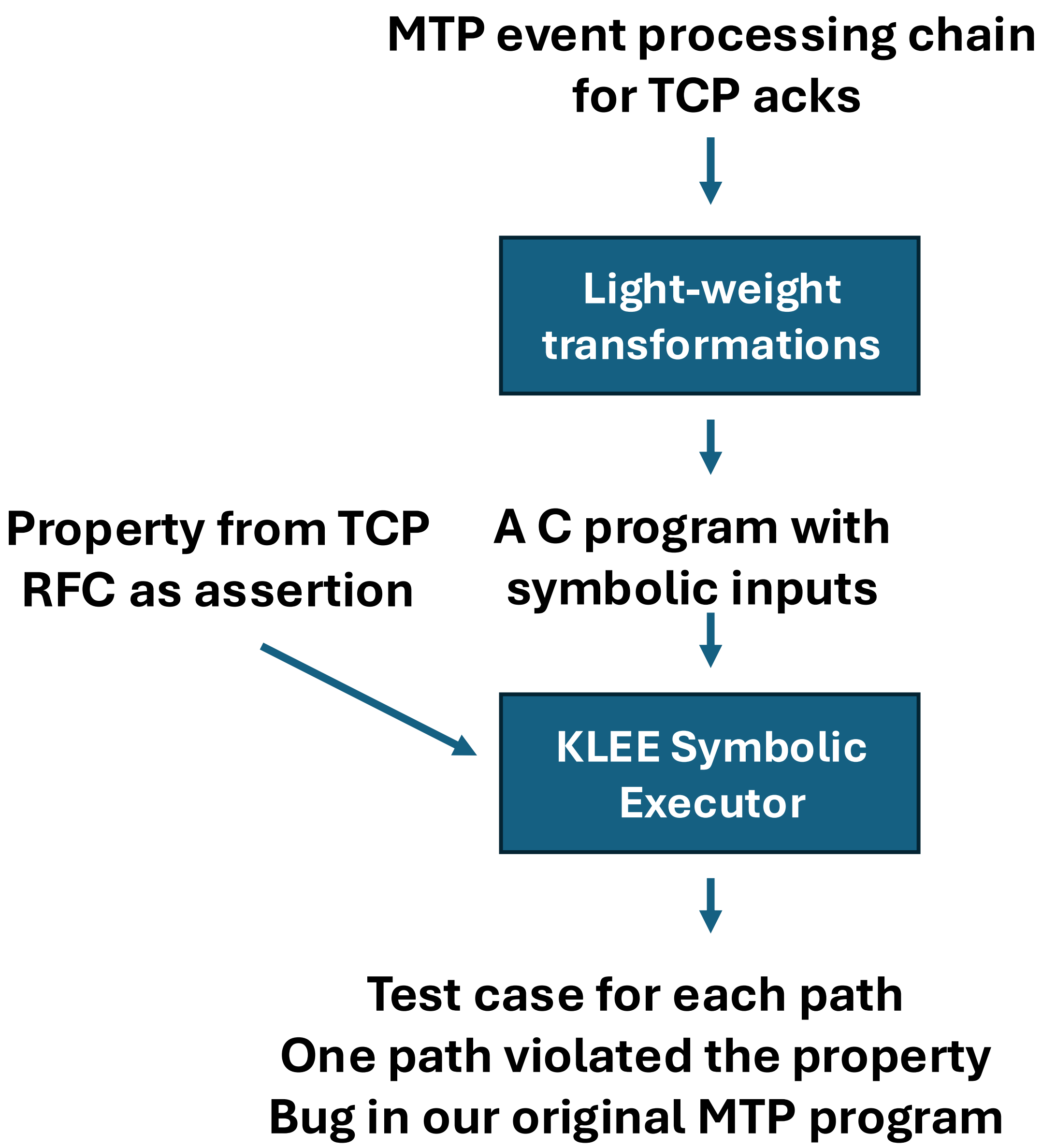
TCP	753 LoC
Homa	1205 LoC
QUIC-Lite	920 LoC

MTP-Compliant Targets
Protocol-independent
Developed once per target

MTP-DPDK	15,593 LoC
MTP-XDP	14,837 LoC

Automated analysis

- MTP programs are amenable to automated analysis
  - Constrained C-like language
    - no pointers
    - Bounded loops
    - Constrained data structures
  - target-agnostic instructions hiding low-level details


MTP event processing chain for TCP acks
Light-weight transformations
A C program with symbolic inputs
Property from TCP RFC as assertion
KLEE Symbolic Executor
Test case for each path
One path violated the property
Bug in our original MTP program

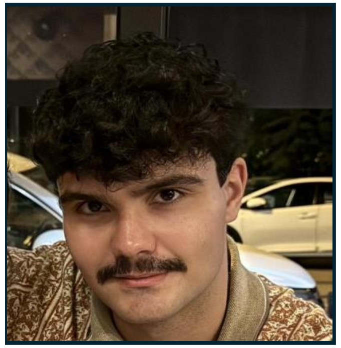
A shout-out to the team!

Pedro Mizuno
UWaterloo

Kimiya Mohammadtaheri
UWaterloo

Linfan Qian
UWaterloo

Joshua Johnson
UWaterloo



Danny Akbarzadeh
UWaterloo

Chris Neely
AMD

Mario Baldi
NVIDIA

Nachiket Kapre
UWaterloo

Mina Tahmasbi Arashloo
UWaterloo

Summary and looking forward

- Transport protocols will continue to evolve
- Their execution environments will continue to evolve
  - Software: Kernel, Kernel-bypass, eBPF
  - Hardware accelerators
- This diversity calls for a language abstraction that is *high-level, target-agnostic, and protocol-independent* …
  - MTP takes a significant step in this direction.
- … that can unlock a myriad of benefits:
  - Seamlessly swapping in new protocols and add features on a target
  - Automated functional and performance verification
  - Automated testing
  - Write-once run-anywhere
  - ….