Network Transport Layer: Overview; UDP; Stop-and-Wait ARQ

Y. Richard Yang

http://zoo.cs.yale.edu/classes/cs433/

11/1/2018

Outline

- Admin and recap
- Transport overview

Admin

- Exam 1 to be returned on Tuesday next week
- Assignment three benchmarking by next week
- Assignment four to be posted

Recap

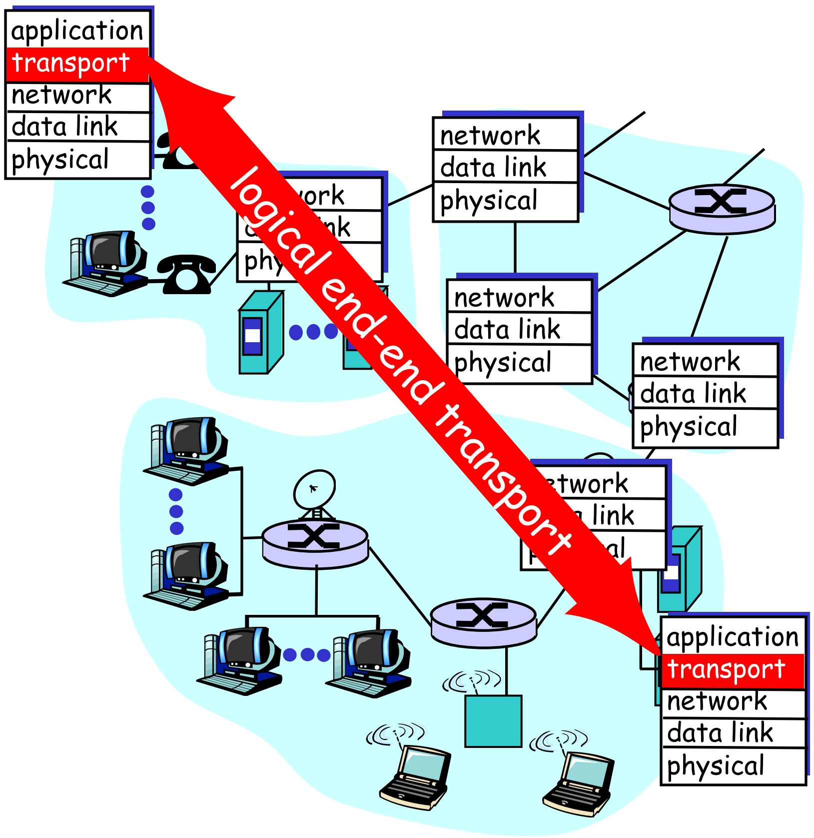
- Applications
  - Client-server applications
    - Single server
    - Multiple servers load balancing
  - distributed servers
    - Distributed content distribution
      - upper bound analysis
      - BitTorrent design
      - distributed content distribution with anonymity (Tor)
      - distributed content verification (Block chain)
      - distributed content distribution using Freenet [optional]

Outline

- Admin and recap
- Overview of transport layer
- UDP
- Reliable data transfer, the stop-and-go protocols

Overview: Transport Layer

- Provide *logical communication* between app' processes
- Transport protocols run in end systems
  - send side: breaks app messages into segments, passes to network layer
  - rcv side: reassembles segments into messages, passes to app layer
- Transport vs. network layer services:
  - *Network layer:* data transfer between end systems
  - *Transport layer:* data transfer between processes
    - relies on, enhances network layer services



Transport Layer Services and Protocols

- Reliable, in-order delivery (TCP)
  - multiplexing
  - reliability and connection setup
  - congestion control
  - flow control
- Unreliable, unordered delivery: UDP
  - multiplexing
- Services not available:
  - delay guarantees
  - bandwidth guarantees

Transport Layer: Road Ahead

- Class 1 (today):
  - transport layer services
  - connectionless transport: UDP
  - reliable data transfer using stop-and-wait/alternating-bit protocol
- Class 2 (Nov. 6; ready for PS4/part 1):
  - sliding window reliability (ready for PS4/part 1 initial part) [revised]
  - TCP reliability
    - overview of TCP
    - TCP RTT measurement
    - TCP connection management
- Class 3 (Nov. 8; ready for PS4/part 2):
  - principles of congestion control
  - TCP congestion control; AIMD; TCP Reno, QUIC
- Class 4 (Nov. 13):
  - TCP Vegas, performance modeling; Nash Bargaining solution
- Class 5 (Nov. 15):
  - primal-dual as a resource allocation and analysis framework

Outline

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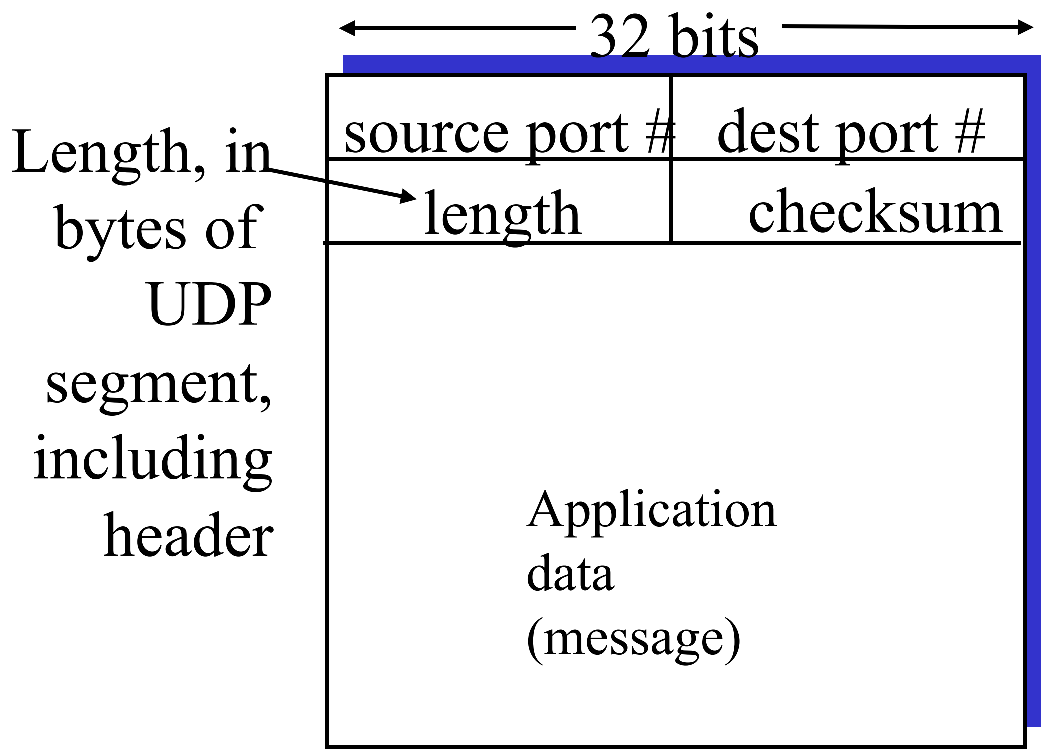
- UDP and error checking
- Reliable data transfer, the stop-and-go protocols

UDP: User Datagram Protocol [RFC 768]

- Often used for streaming multimedia apps
  - loss tolerant
  - rate sensitive
- Other UDP uses
  - DNS
  - SNMP



UDP segment format

UDP Checksum

Goal: end-to-end detection of "errors" (e.g., flipped bits) in transmitted segment

Sender:

- treat segment contents as sequence of 16-bit integers
- checksum: addition of segment contents to be zero
- sender puts checksum value into UDP checksum field

Receiver:

- compute checksum of received segment
- compute sum of segment and checksum; check if sum zero
  - NO - error detected
  - YES - no error detected. *But maybe errors nonetheless?*

One's Complement Arithmetic

- UDP checksum is based on one's complement arithmetic
  - one's complement was a common representation of signed numbers in early computers
- One's complement representation
  - bit-wise NOT for negative numbers
  - example: assume 8 bits
    - `00000000: 0`
    - `00000001: 1`
    - `01111111: 127`
    - `10000000: ?`
    - `11111110: ?`
    - `11111111: ?`
  - addition: conventional binary addition except adding any resulting carry back into the resulting sum (try -1 + 2)

UDP Checksum: Algorithm

- Example checksum:

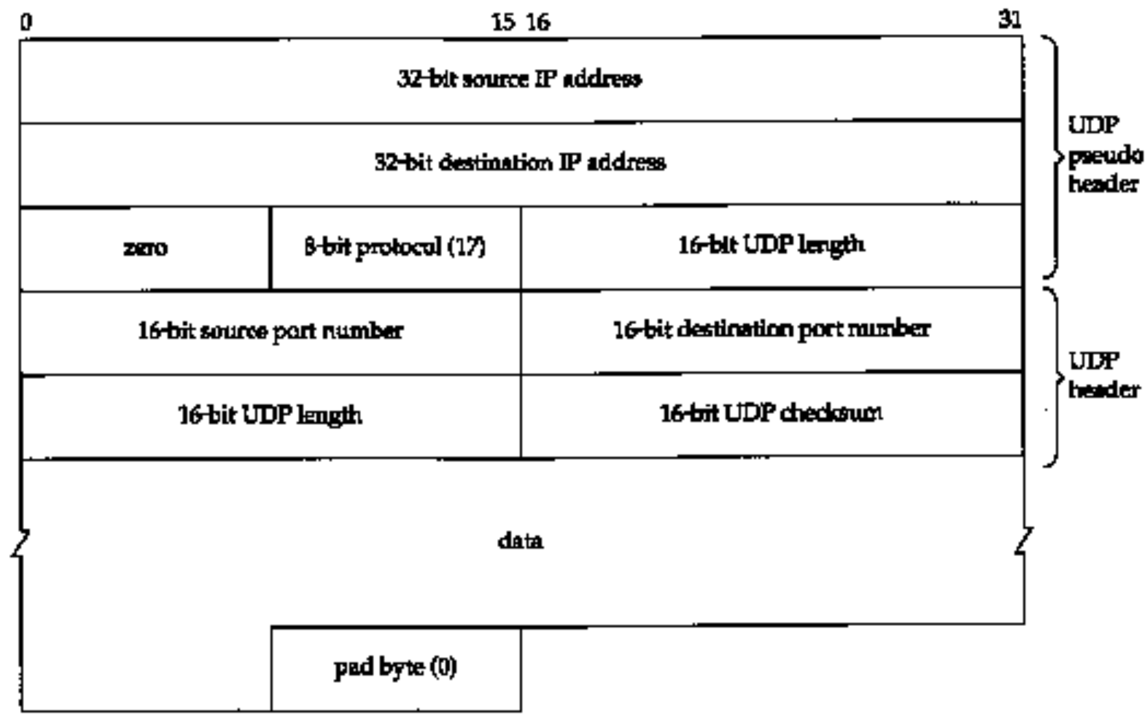
		1	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0
		1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
wraparound	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1
sum		1	0	1	1	1	0	1	1	1	0	1	1	1	1	0	0
checksum		0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	1

- For fast implementation of computing UDP checksum, see http://www.faqs.org/rfcs/rfc1071.html

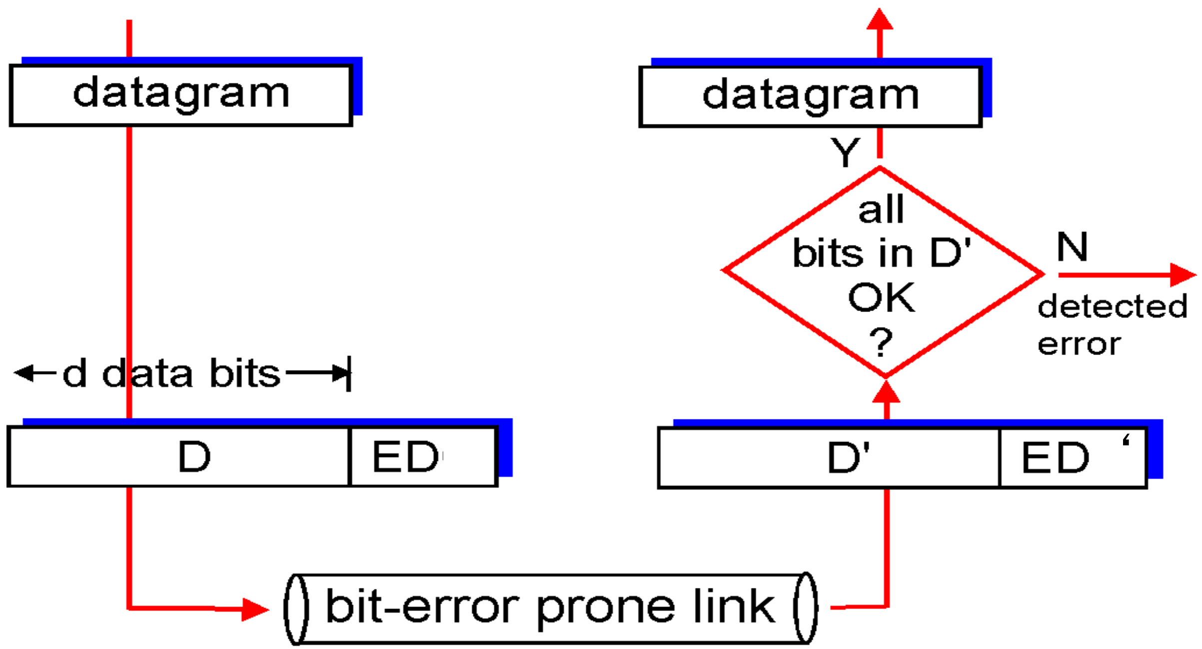
UDP Checksum: Coverage

Calculated over:

- A pseudo-header
  - IP Source Address (4 bytes)
  - IP Destination Address (4 bytes)
  - Protocol (2 bytes)
  - UDP Length (2 bytes)
- UDP header
- UDP data



General Error Detection (Checksum)



D = Data protected by error checking, may include header fields
ED = Error Detection bits (redundancy)

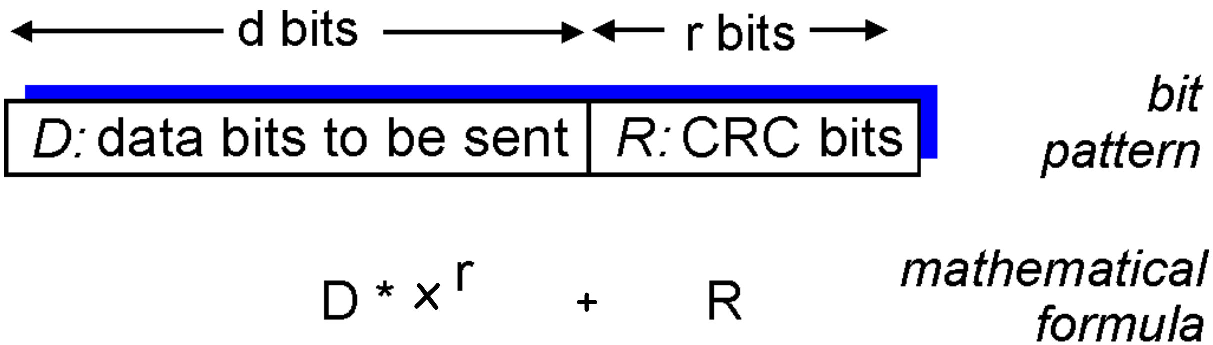
- Error detection not 100% reliable!
    - a good error detector may miss some errors, but rarely
    - larger ED field generally yields better detection

Cyclic Redundancy Check: Background

- Widely used in practice, e.g.,
  - Ethernet, DOCSIS (Cable Modem), FDDI, PKZIP, WinZip, PNG
- For a given data D, consider it as a polynomial D(x)
  - consider the string of 0 and 1 as the coefficients of a polynomial
    - e.g. consider string 10011 as x^4+x+1
  - addition and subtraction are modular 2, thus the same as xor
- Choose generator polynomial G(x) with r+1 bits, where r is called the degree of G(x)

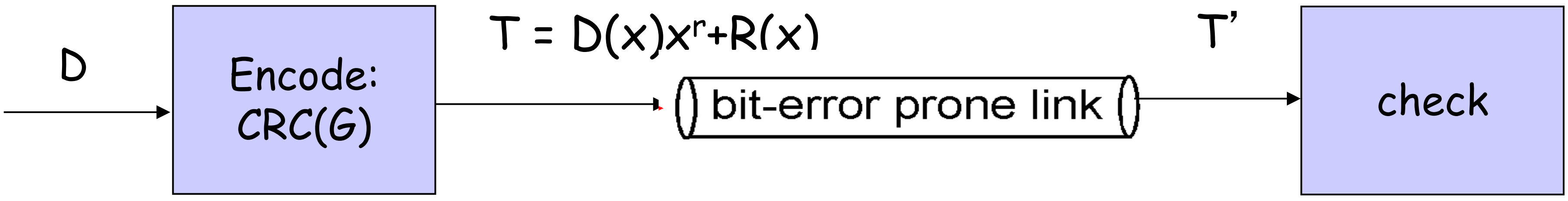
Cyclic Redundancy Check: Encode

- Given G(x) and D(x), choose R(x) with r bits, such that
  - $D(x)x^r+R(x)$ is exactly divisible by G(x)



- The bits correspond to $D(x)x^r+R(x)$ are sent to the receiver

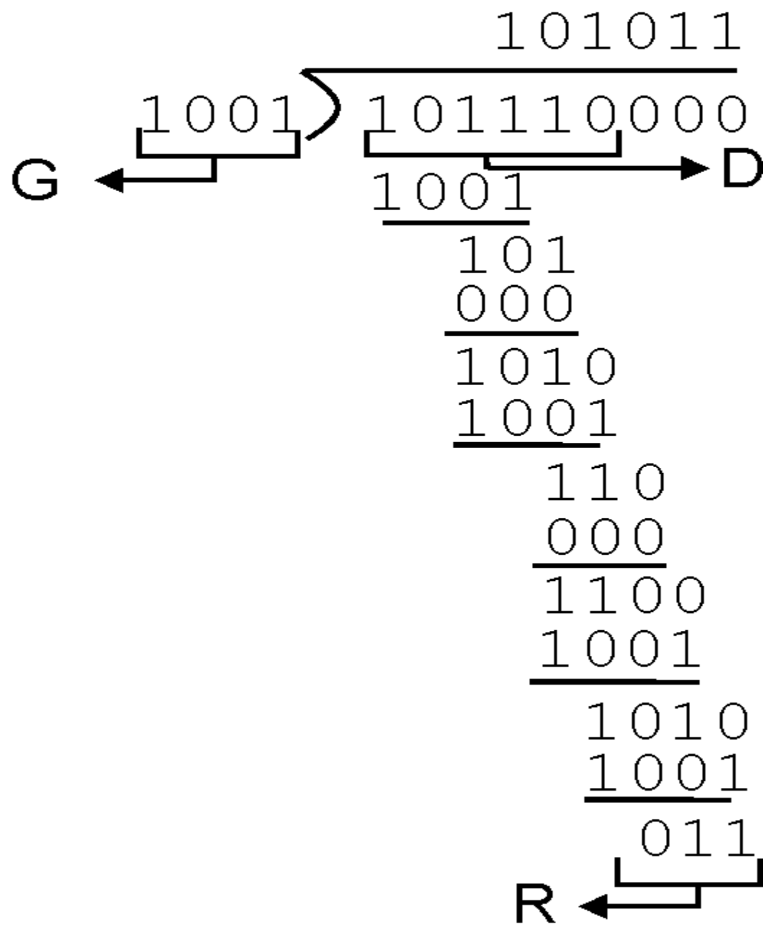
Cyclic Redundancy Check: Decode



- Since G(x) is global, when the receiver receives the transmission T' (x), it divides T' (x) by G(x)
  - if non-zero remainder: error detected!
  - if zero remainder, assumes no error

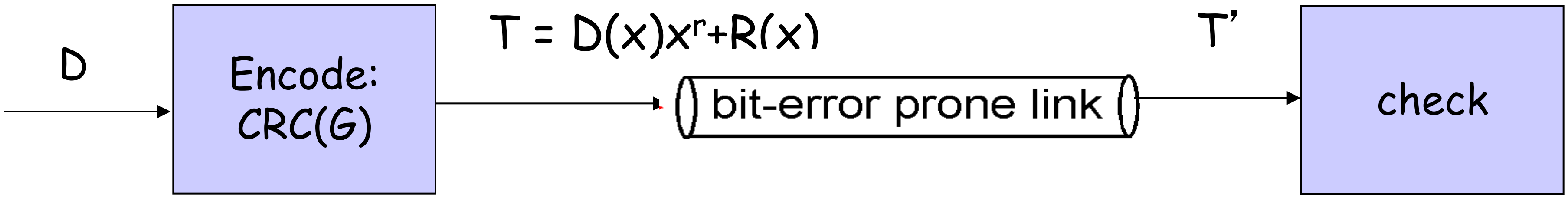
CRC: Steps and an Example

- Suppose the degree of $G(x)$ is r
- Append r zero to $D(x)$, i.e. consider $D(x)x^r$
- Divide $D(x)x^r$ by $G(x)$. Let $R(x)$ denote the reminder
- Send <D, R> to the receiver



The Power of CRC

- Let T(x) denote $D(x)x^r+R(x)$, and E(x) the polynomial of the error bits
  - the received signal is T' (x) = T(x)+E(x)



- Since T(x) is divisible by G(x), we only need to consider if E(x) is divisible by G(x)

The Power of CRC

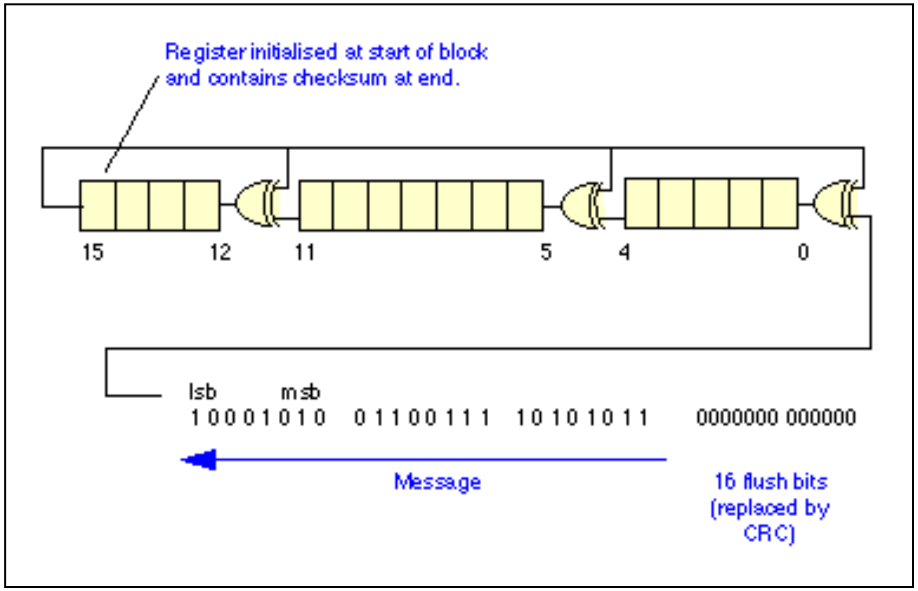
- Detect a single-bit error: $E(x) = x^i$
  - if G(x) contains two or more terms, E(x) is not divisible by G(x)

- Detect an odd number of errors: E(x) has an odd number of terms:
  - lemma: if E(x) has an odd number of terms, E(x) cannot be divisible by (x+1)
    - suppose E(x) = (x+1)F(x), let x=1, the left hand will be 1, while the right hand will be 0
  - thus if G(x) contains x+1 as a factor, E(x) will not be divided by G(x)

- Many more errors can be detected by designing the right G(x)

Example G(x)

- 16 bits CRC:
  - CRC-16: $x^{16}+x^{15}+x^2+1$,
    CRC-CCITT: $x^{16}+x^{12}+x^5+1$
  - both can catch
    - all single or double bit errors
    - all odd number of bit errors
    - all burst errors of length 16 or less
    - >99.99% of the 17 or 18 bits burst errors



CRC-16 hardware implementation
Using shift and XOR registers

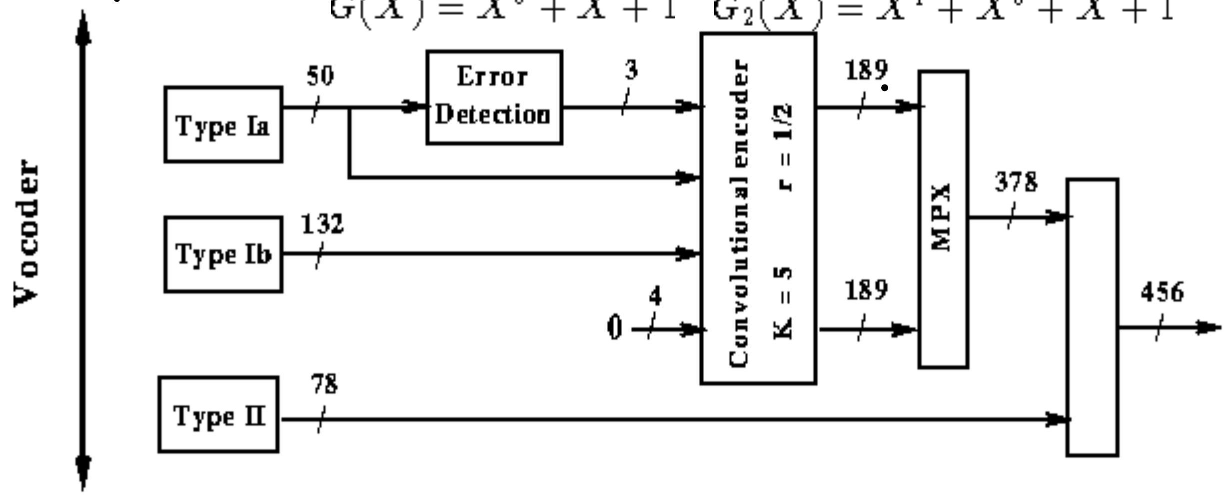
http://en.wikipedia.org/wiki/CRC-32#Implementation

Example G(x)

- 32 bits CRC:
  - *CRC32:* $x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^{8} + x^{7} + x^{5} + x^{4} + x^{2} + x + 1$
  - used by Ethernet, FDDI, PKZIP, WinZip, and PNG
- GSM phones

$$G_1(X) = X^4 + X^3 + 1$$

$$G(X) = X^3 + X + 1 \qquad G_2(X) = X^4 + X^3 + X + 1$$



- For more details see the link below and further links it contains:
  - http://en.wikipedia.org/wiki/Cyclic_redundancy_check

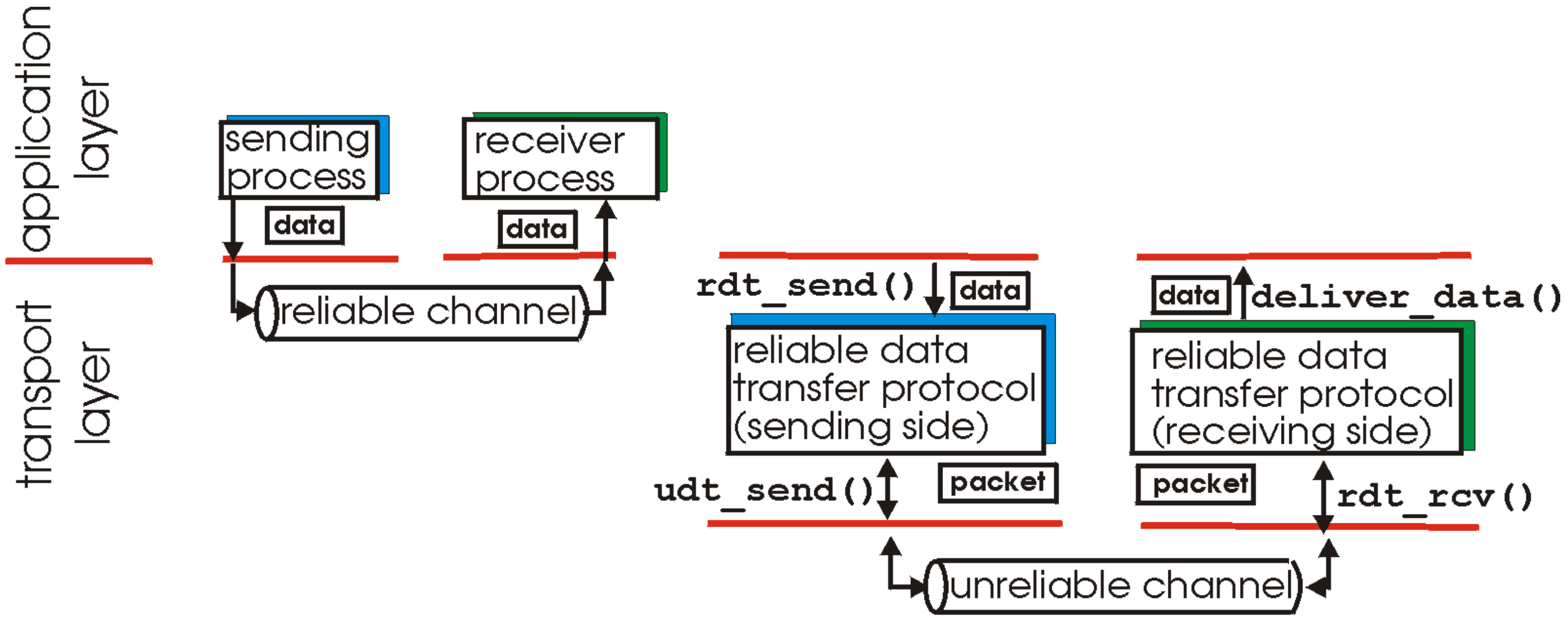
Outline

- Admin and recap
- Overview of transport layer
- UDP and error checking
- Reliable data transfer

Principles of Reliable Data Transfer (RDT)

- Important in application, transport, link layers
- Foundation to other protocols
- A good example on the design and analysis of low-level distributed protocols
  - Driven by more complex protocol finite-state machines than typical application layer protocol finite-state machines

Reliable Data Transfer: Abstraction



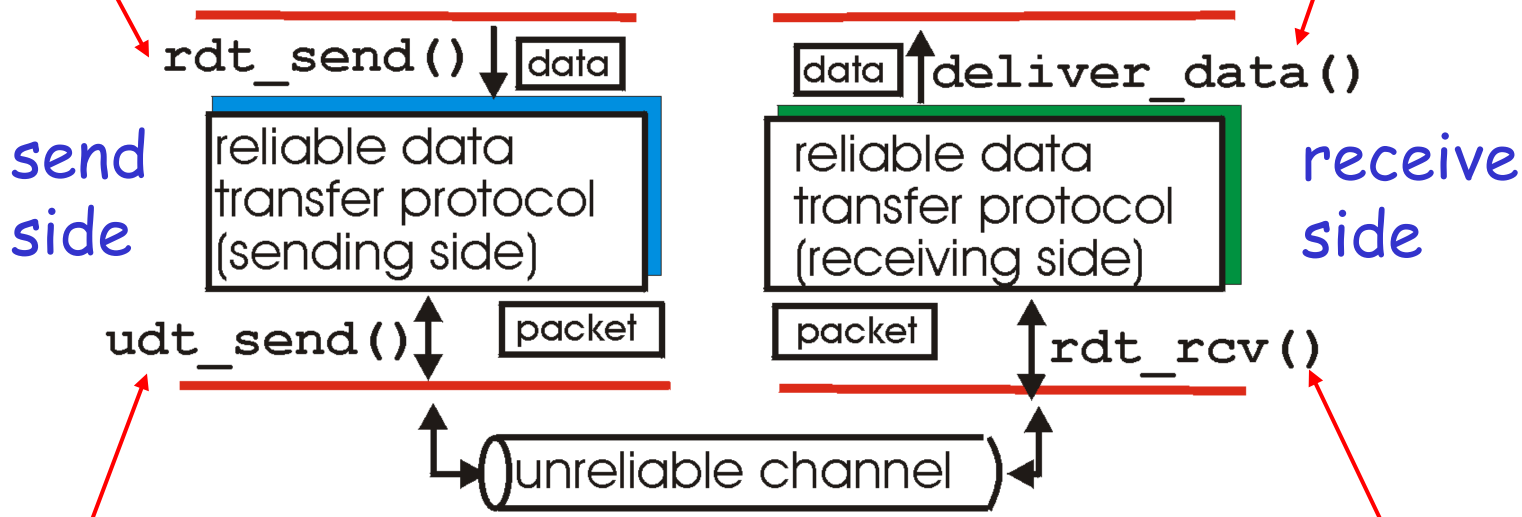
(a) provided service

(b) service implementation

Reliable Data Transfer: Context

rdt_send(): called from above, (e.g., by app.)

deliver_data(): called by **rdt** to deliver data to upper



udt_send(): called by rdt, to transfer packet over unreliable channel to receiver

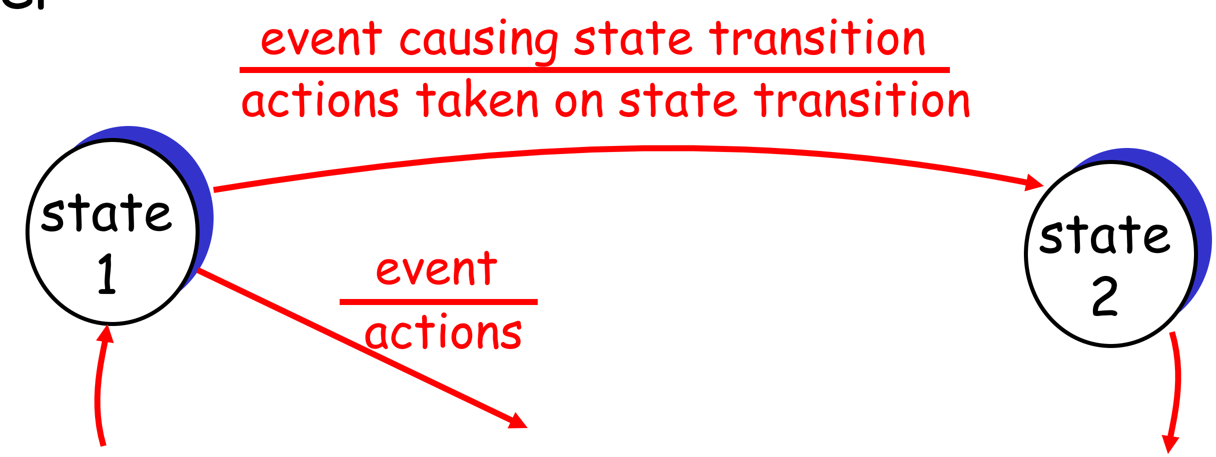
rdt_rcv(): called from below; when packet arrives on rcv-side of channel

Reliable Data Transfer: Getting Started

We'll:

- incrementally develop sender, receiver sides of reliable data transfer protocol (rdt)
- consider only unidirectional data transfer
  - but control info will flow on both directions !
- use finite state machines (FSM) to specify sender, receiver

state: when in this "state" next state uniquely determined by next event

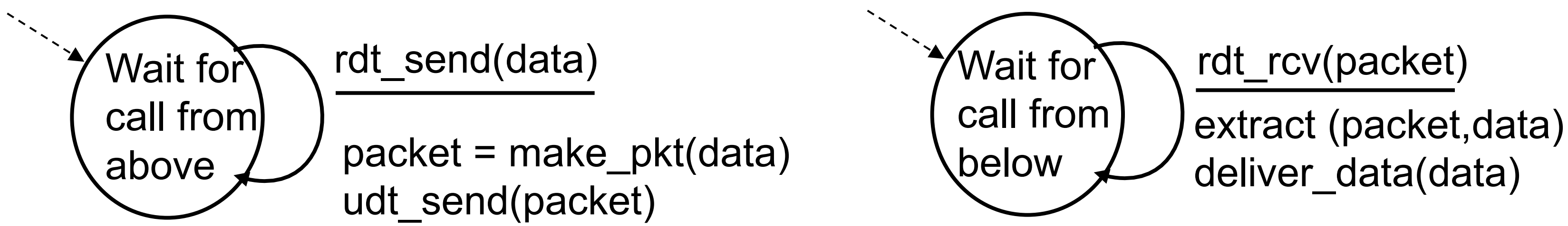


Outline

- Admin and review
- Overview of transport layer
- UDP and error checking
- Reliable data transfer
  - perfect channel

Rdt1.0: reliable transfer over a reliable channel

- separate FSMs for sender, receiver:
  - sender sends data into underlying channel
  - receiver reads data from underlying channel



sender

receiver

Discussion: Correctness requirements of Rdt1.0.

Execution Traces as a Technique to Understand Protocols

- Execution traces: all possible executions, including both sender and receiver side events

- Rdt1.0 trace
  - <S data1> <R data1>
    <S data2> <R data2>
    ....

Potential Channel Errors

- bit errors
- loss (drop) of packets
- reordering or duplication

Characteristics of unreliable channel will determine complexity of reliable data transfer protocol (rdt).

Outline

- Admin and recap
- Overview of transport layer
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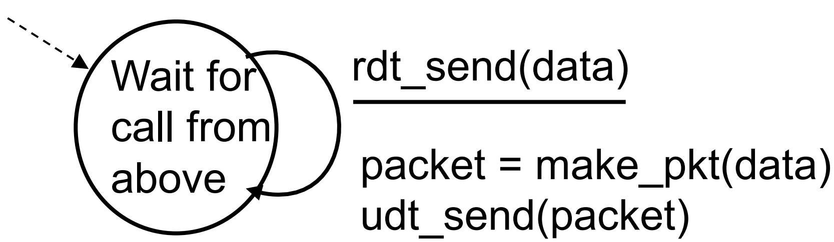
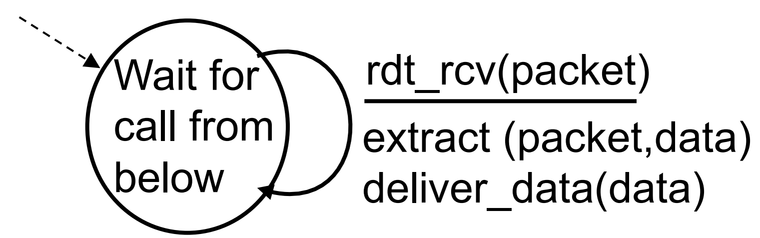
- Reliable data transfer
  - perfect channel
  - channel with bit errors

rdt2.0: Channel With Bit Errors

- Assume: Underlying channel may only flip bits in packet



sender



receiver

Exercise: What correctness requirement(s) rdt1.0 cannot provide?

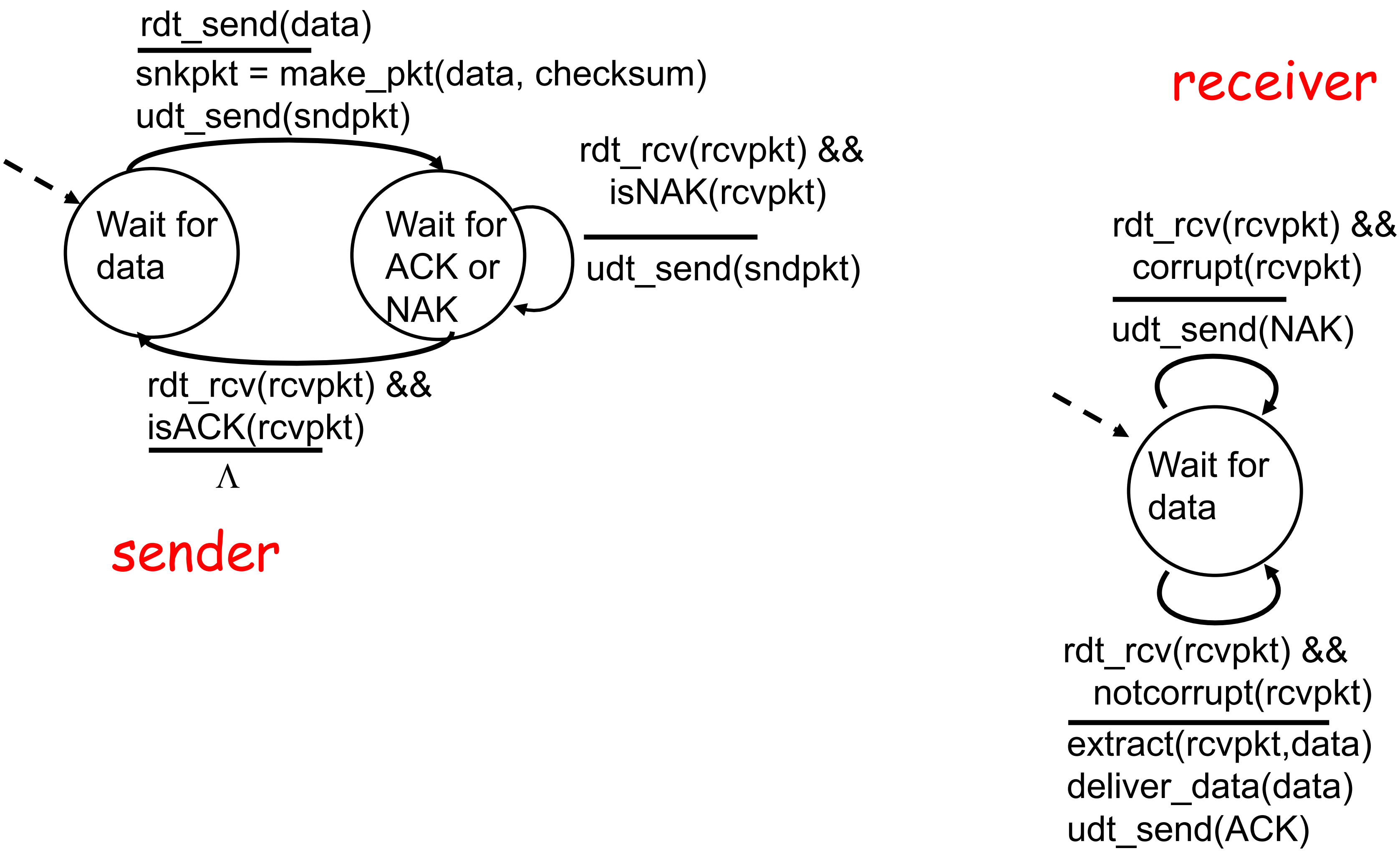
Rdt1.0 Execution Traces with Bit Errors

- <S data1> <R data1>|<R data1^>
  <S data2> <R data2>|<R data2^>
  ....

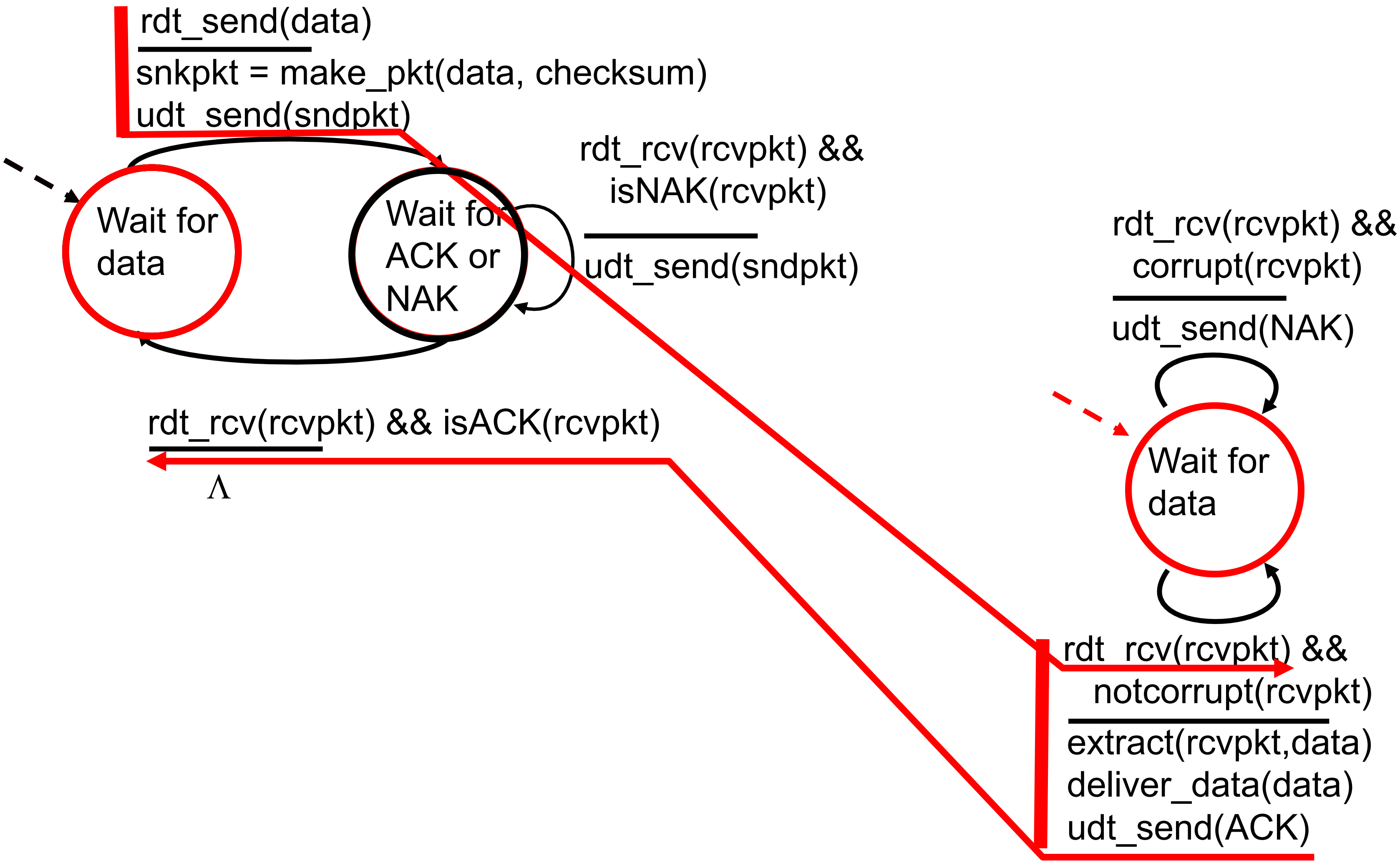
rdt2.0: Channel With Bit Errors

- New mechanisms in **`rdt2.0`** (beyond **`rdt1.0`**):
  - receiver error detection: recall: UDP checksum/Ethernet CRC detects bit errors
  - receiver feedback: control msgs (ACK,NAK) rcvr->sender
    - *acknowledgements (ACKs):* receiver explicitly tells sender that pkt received OK
    - *negative acknowledgements (NAKs):* receiver explicitly tells sender that pkt had errors
  - sender retransmission
    - sender retransmits pkt on receipt of NAK

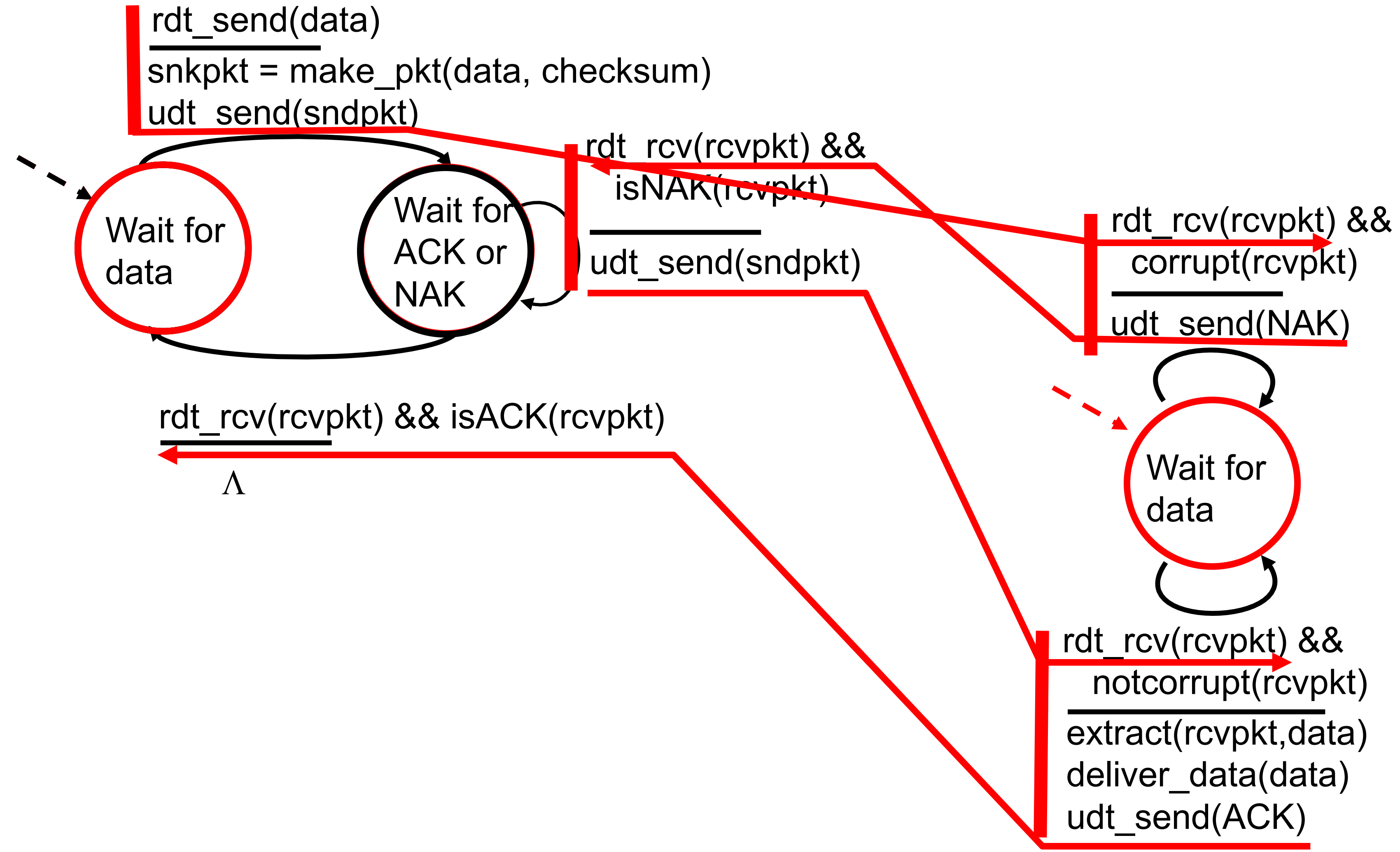
rdt2.0: FSM Specification



rdt2.0: Operation with No Errors

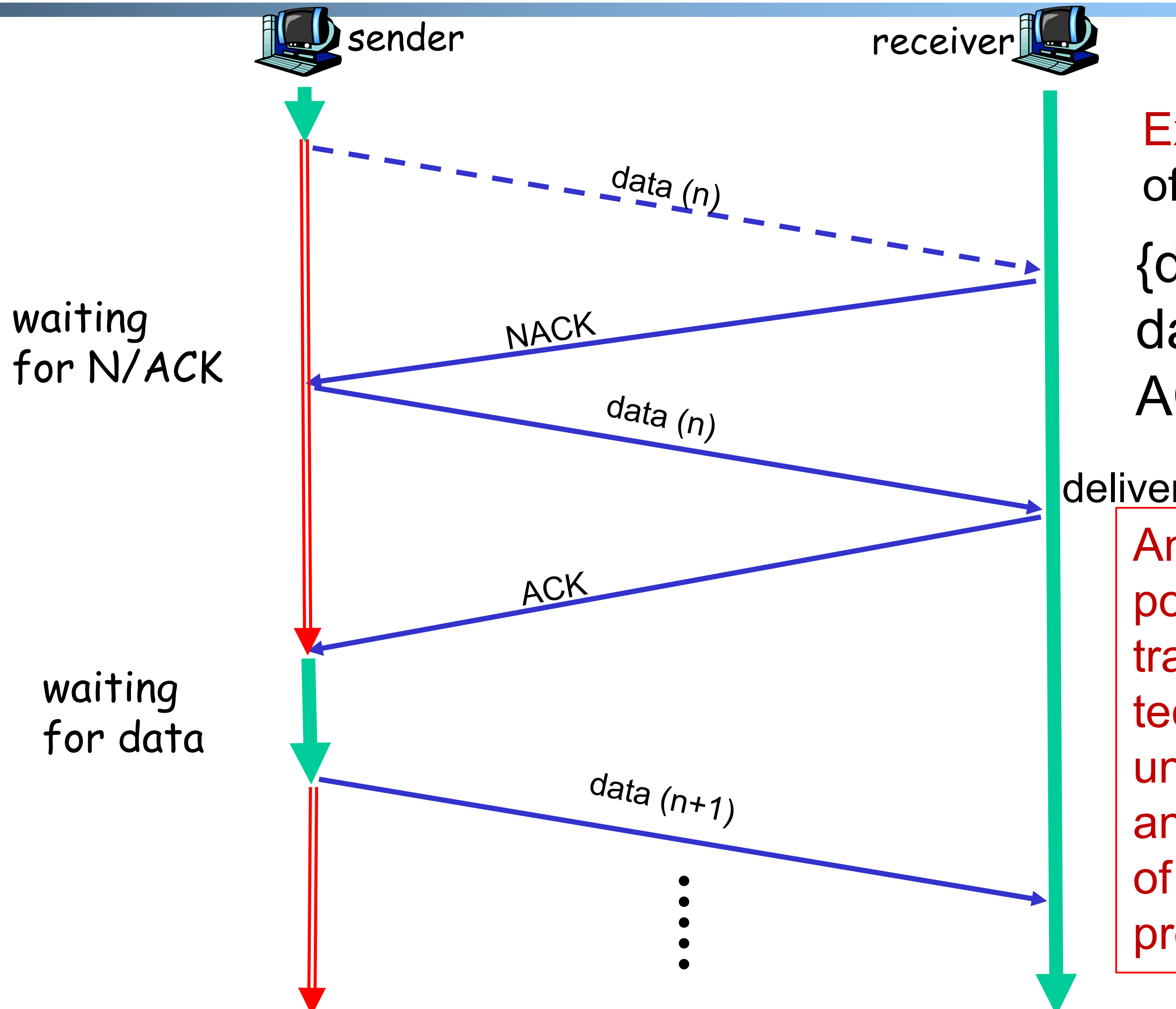


rdt2.0: Error Scenario



Rdt2.0 Analysis

data^: <S data> <R data’>
data: <S data> <R data>



Execution traces of rdt2.0:

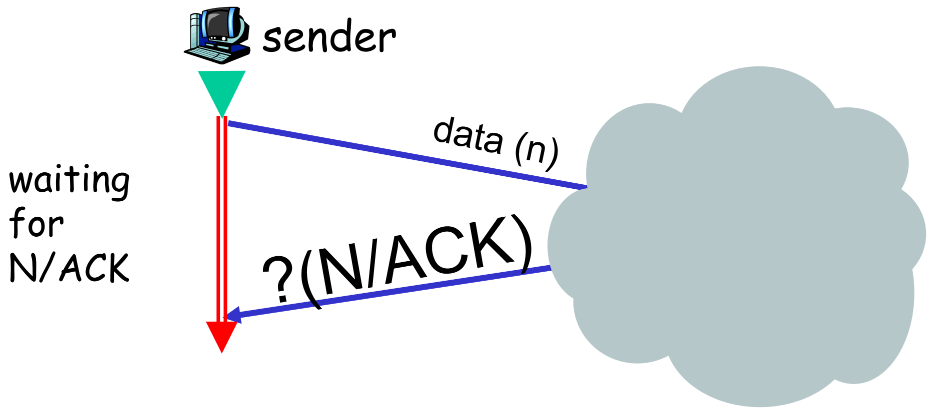
{data^ NACK}*
data deliver
ACK

Analyzing set of all possible execution traces is a common technique to understand and analyze many types of distributed protocols.

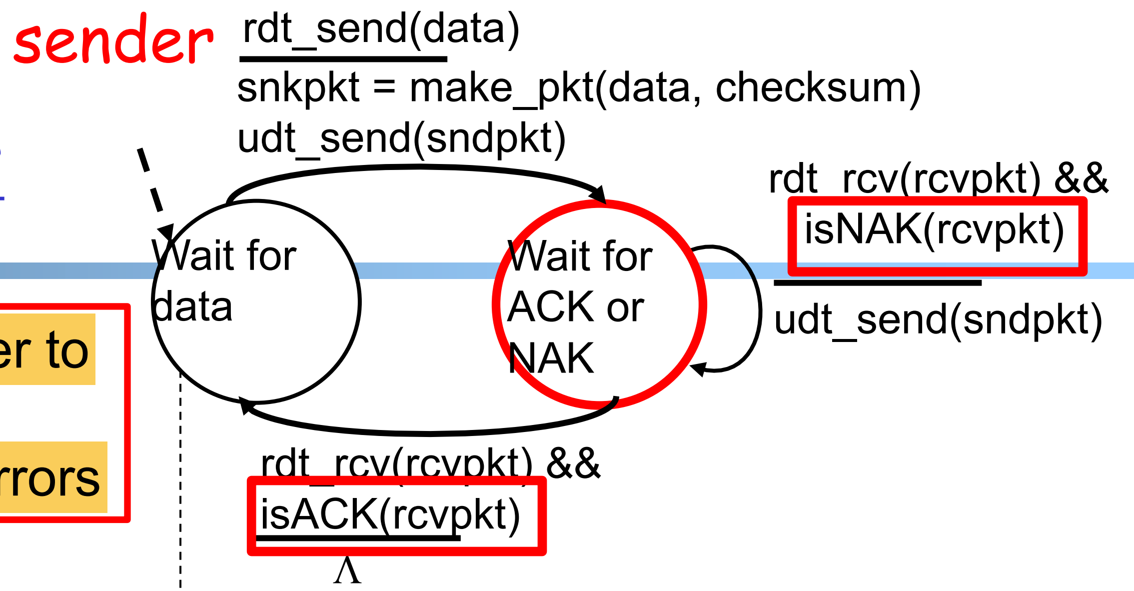
rdt2.0 is Incomplete!

What happens if ACK/NAK corrupted?

- Although sender receives feedback, but doesn't know what happened at receiver!



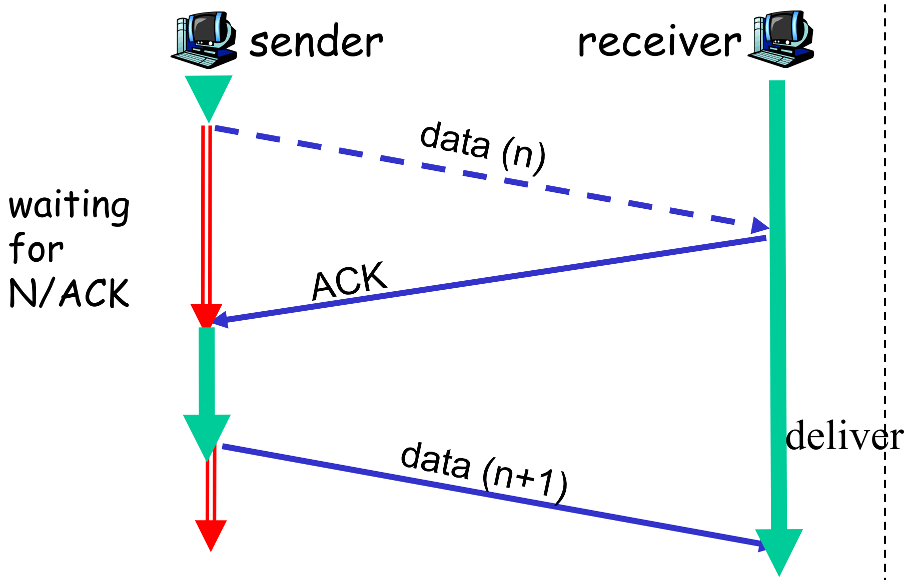
Two Possibilities



Comment: It is always harder to deal with control message errors than data message errors

sender guess ACK:

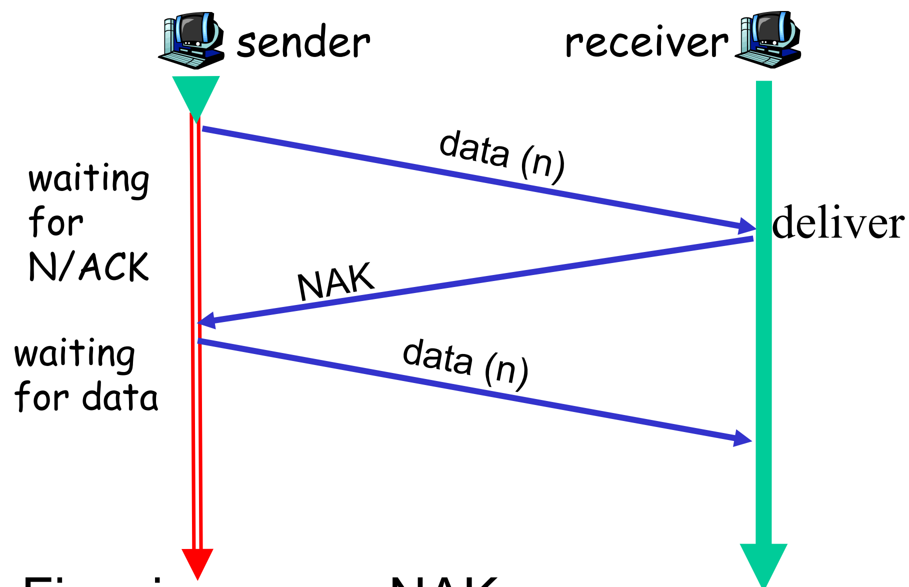
if wrong, missing pkt



Home exercise: fix miss guess ACK

sender guess NAK:

if wrong, duplicate pkt



Fix miss guess NAK:

provide info for receiver to distinguish

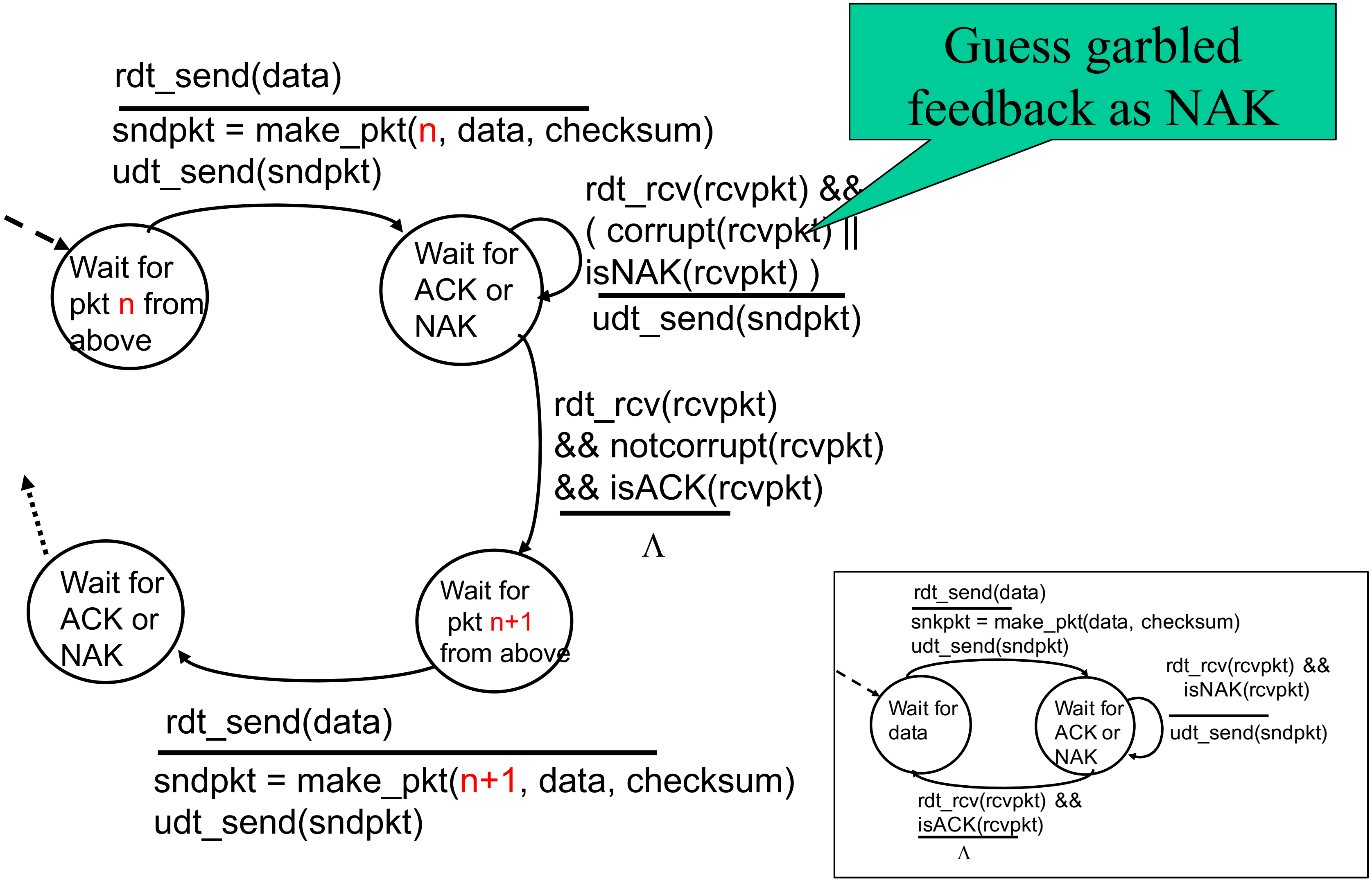
Handle Control Message Corruption

Handling ambiguity:

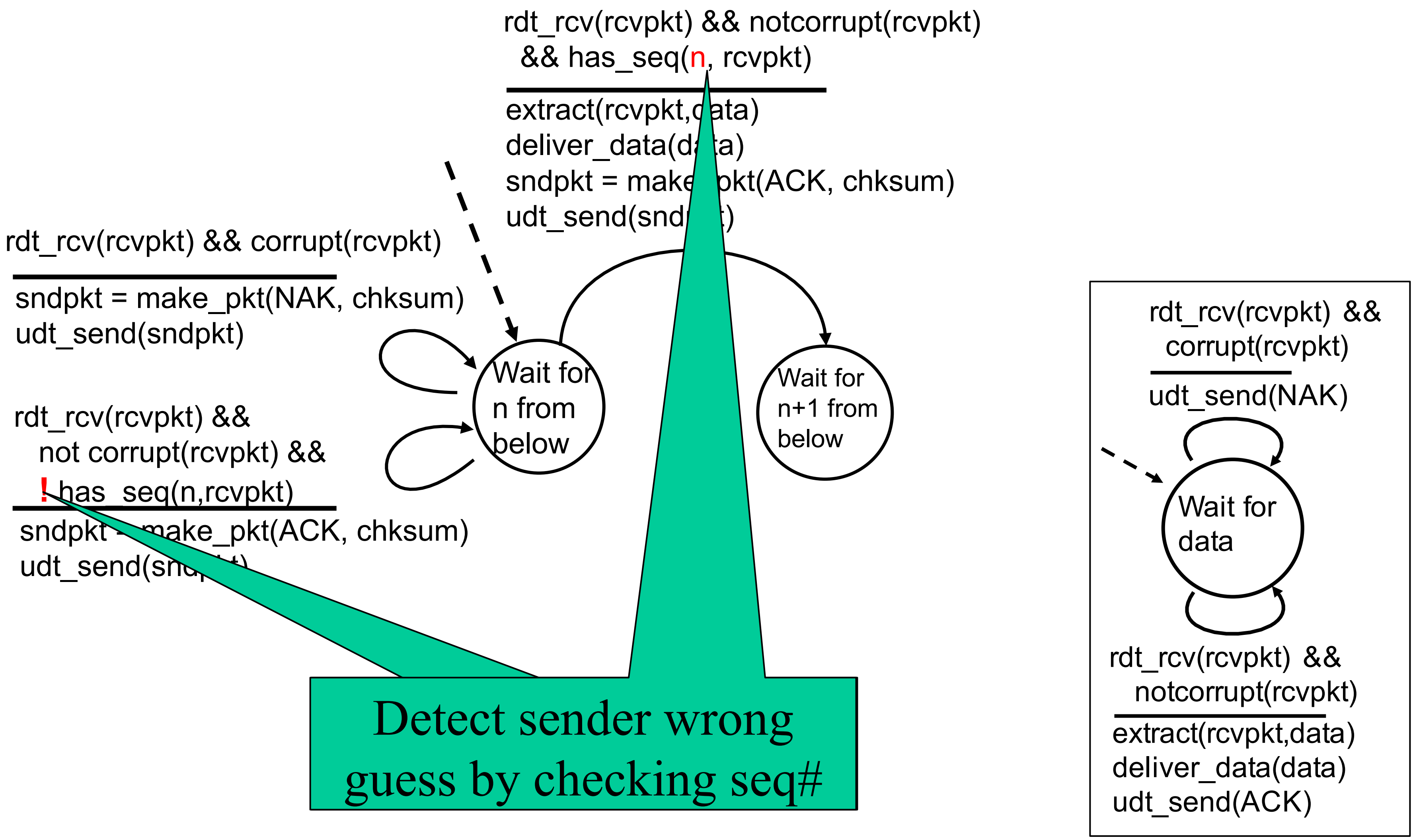
- sender retransmits current pkt if ACK/NAK garbled
  - Assume NAK
- sender adds *sequence number* to each pkt
- receiver discards (doesn't deliver up) duplicate pkt
  - fix effect of wrong guess

stop and wait
sender sends one packet, then waits for receiver response

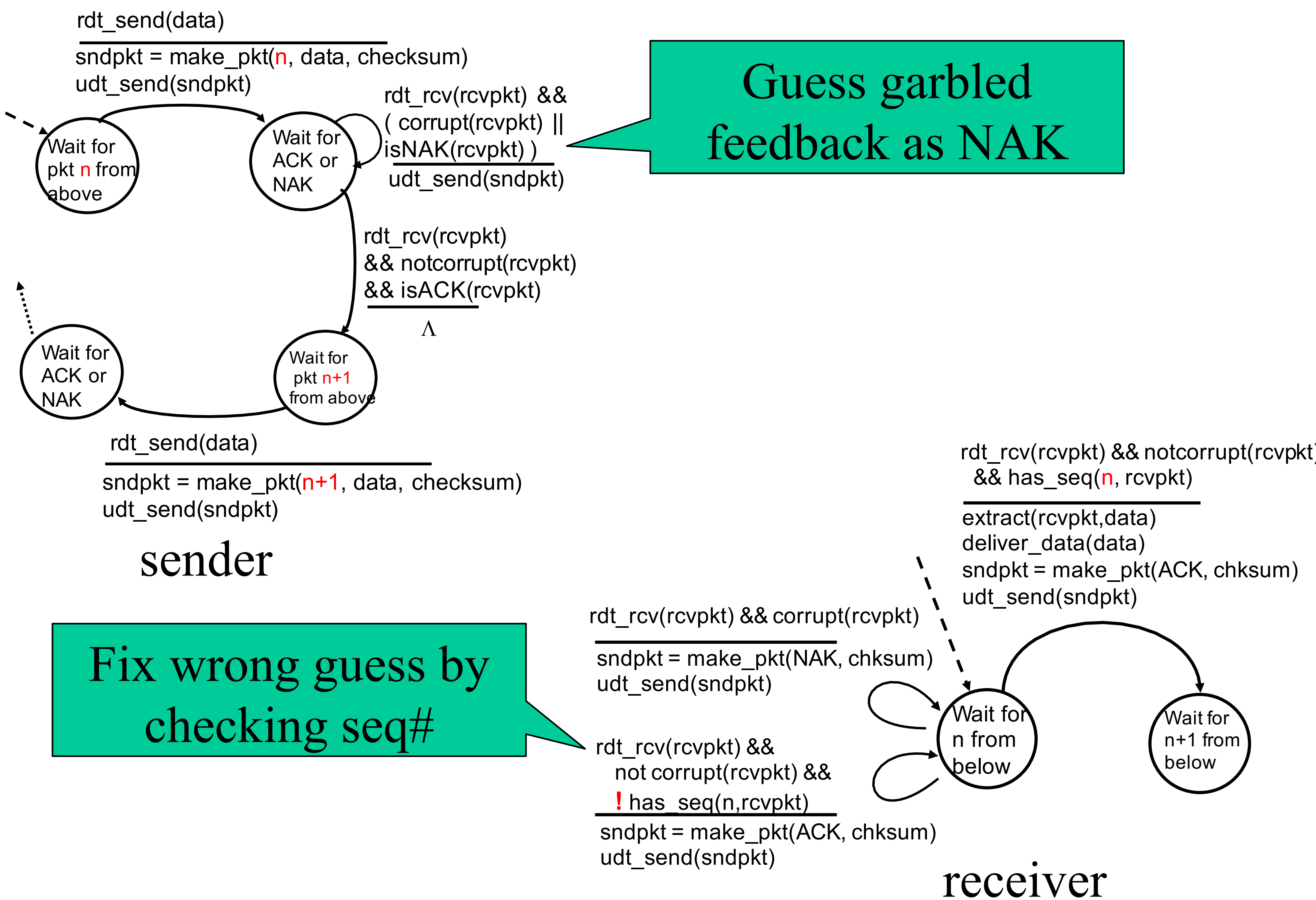
rdt2.1b: Sender, Handles Garbled ACK/NAKs



rdt2.1b: Receiver, Handles Garbled ACK/NAKs



Summary: rdt2.1b: Reliability allowing Data/Control Msg Corruption



Guess garbled feedback as NAK

Fix wrong guess by checking seq#

rdt2.1b: Summary

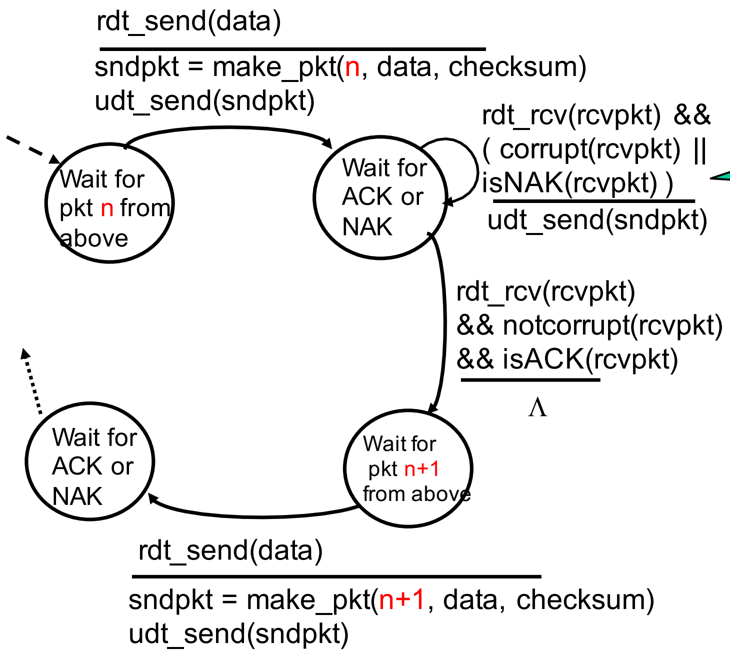
Sender:

- seq # added to pkt
- must check if received ACK/NAK corrupted

Receiver:

- must check if received packet is duplicate
  - by checking if the packet has the expected pkt seq #

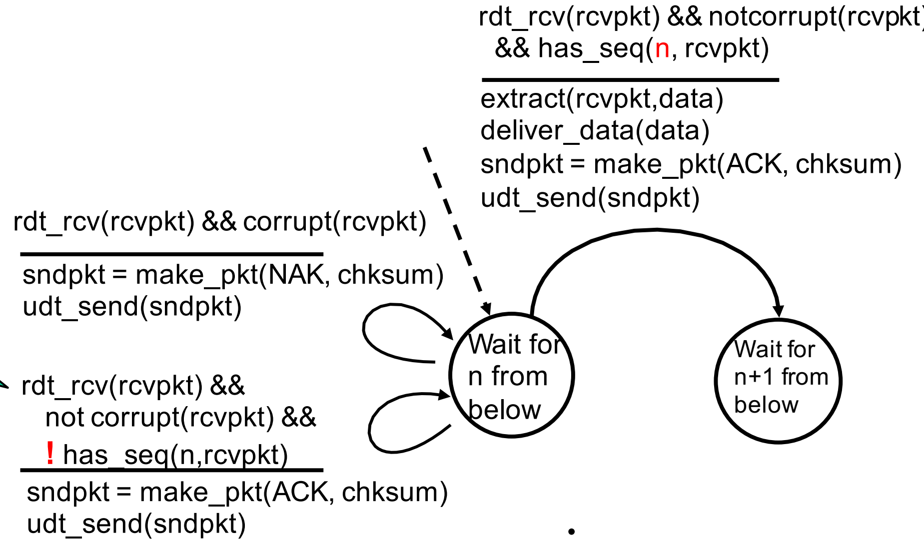
rdt2.1b Analysis: Execution Traces?



sender

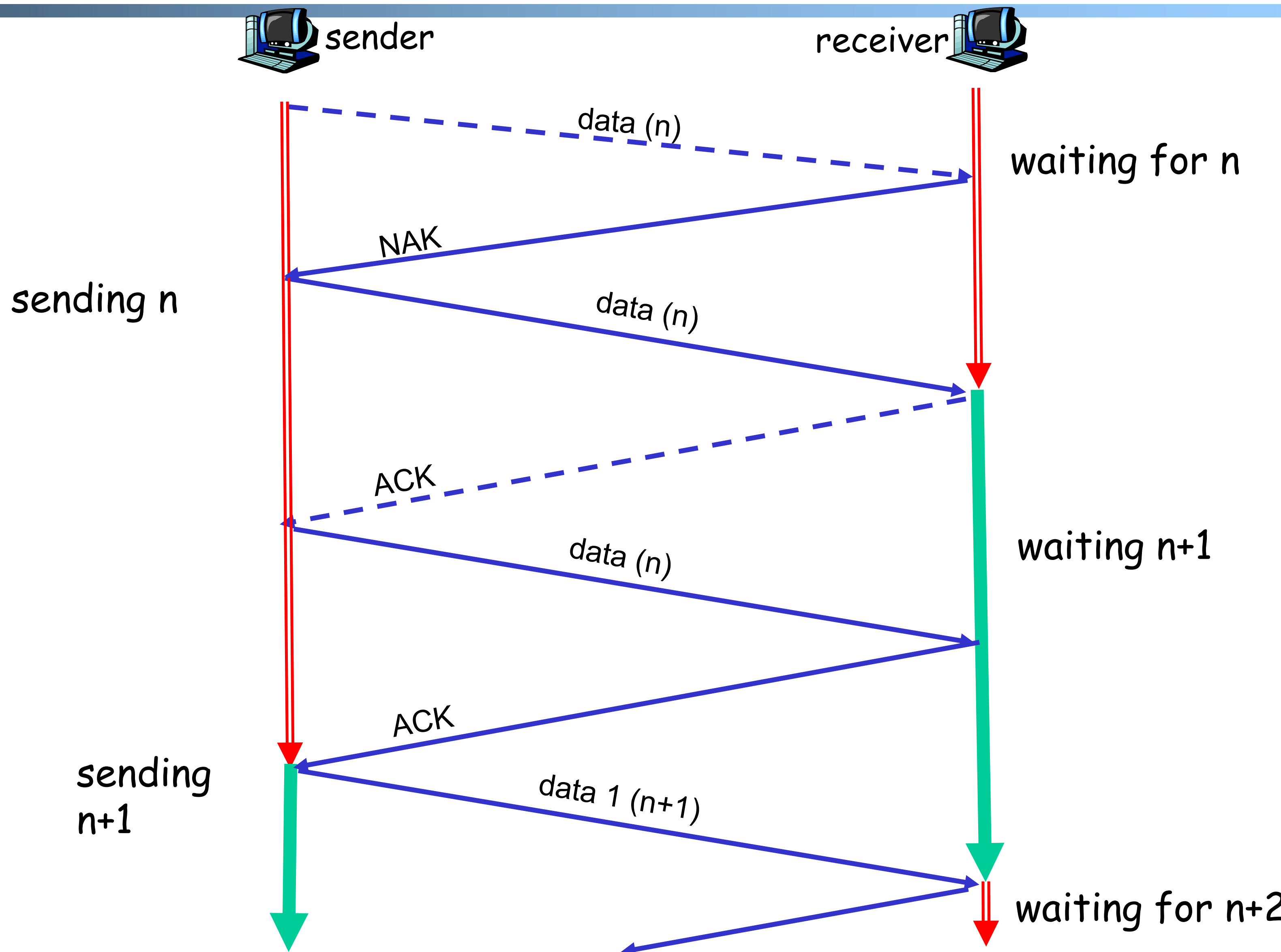
Guess garbled feedback as NAK

Fix wrong guess by checking seq#



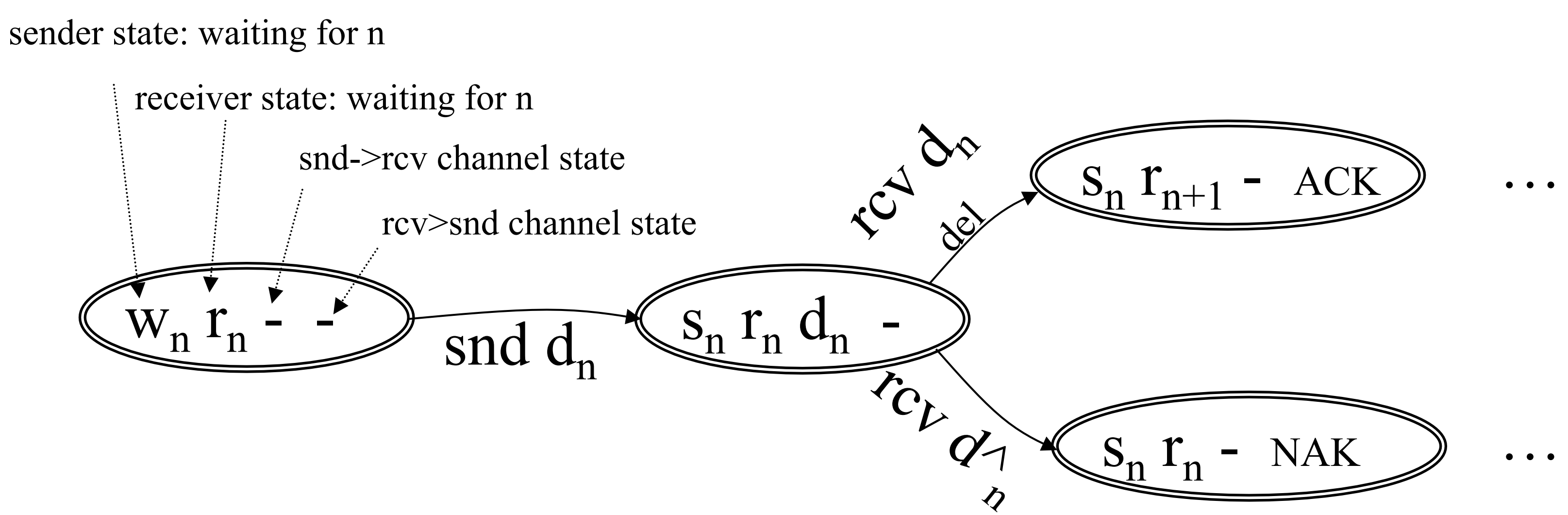
receiver

rdt2.1b Analysis: Execution Traces?

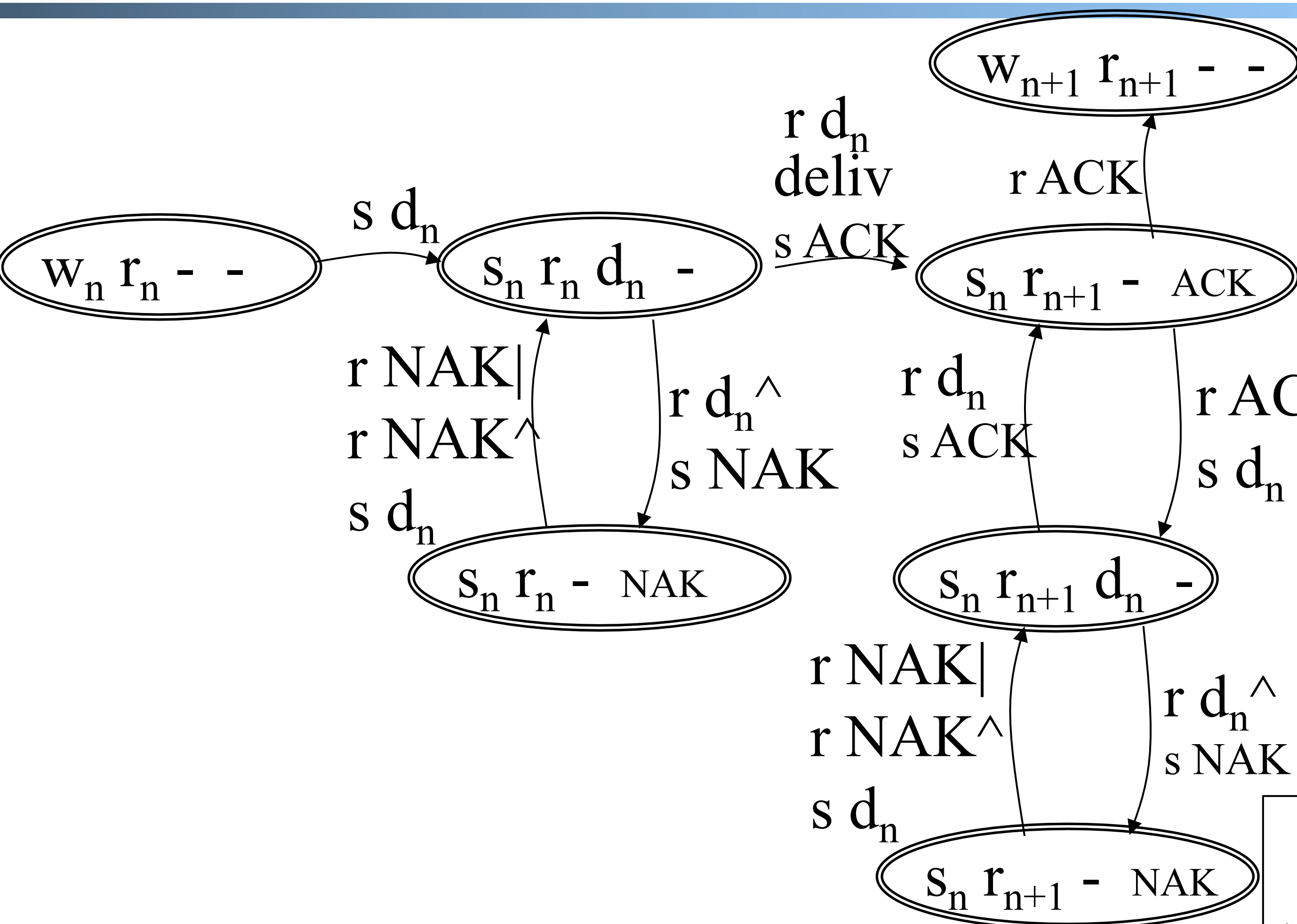


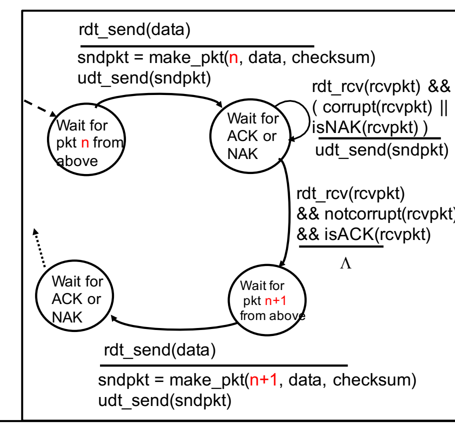
Protocol Analysis using (Generic) Execution Traces Technique

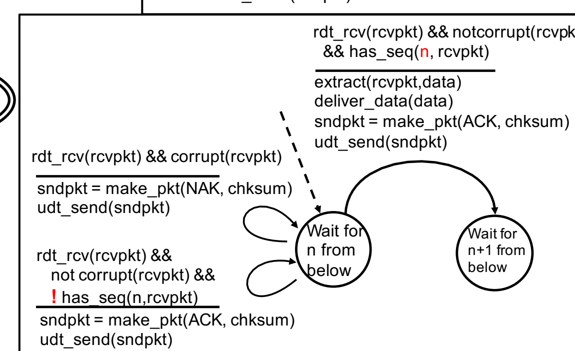
- Issue: how to systematically enumerate all potential execution traces to understand and verify correctness
- A systematic approach to enumerating exec. traces is to compute joint sender/receiver/channels state machine



Protocol Analysis using (Generic) Execution Traces Technique



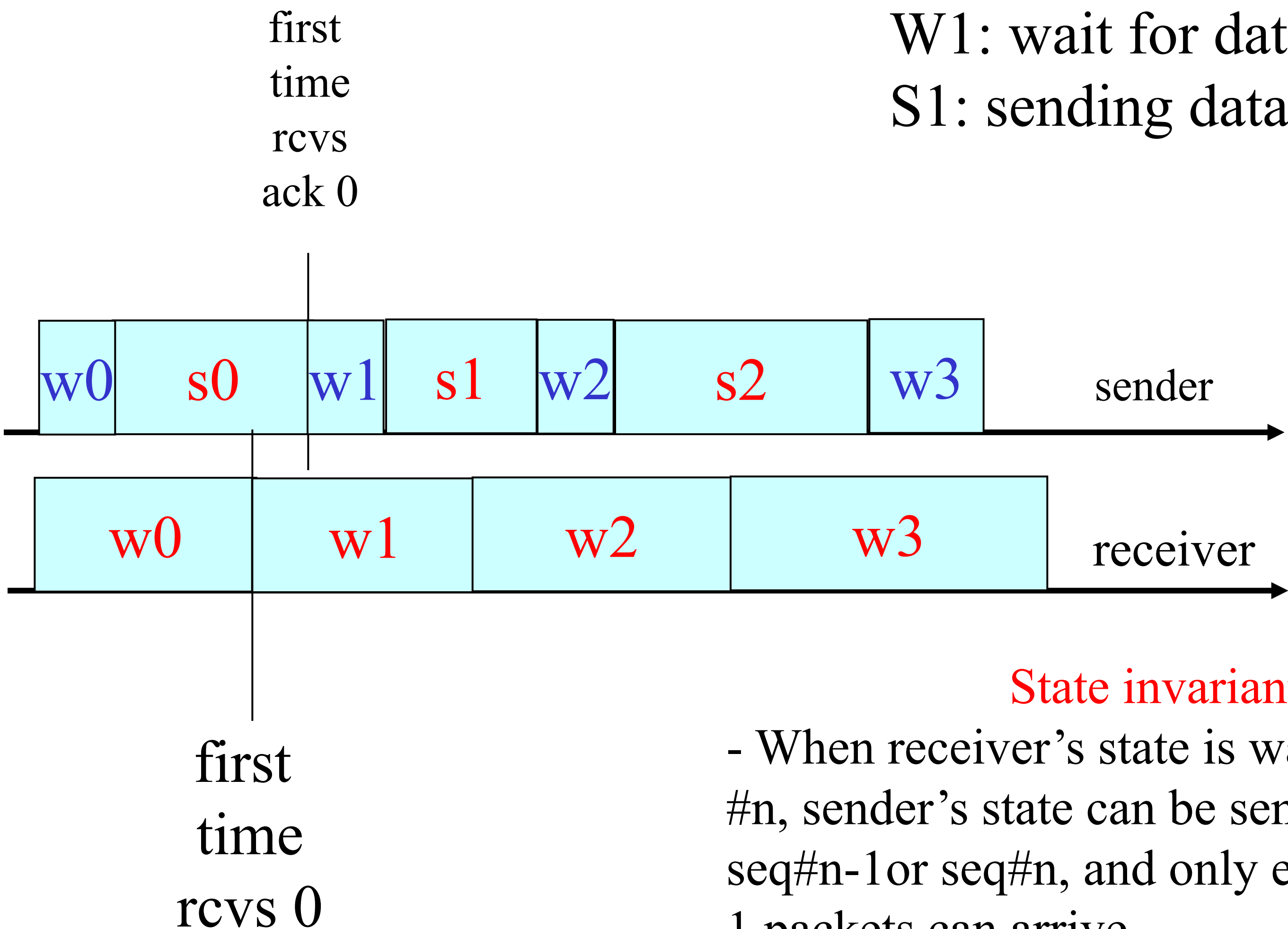




Exercise: Write down all execution traces.

rdt2.1b Analysis: State Invariants

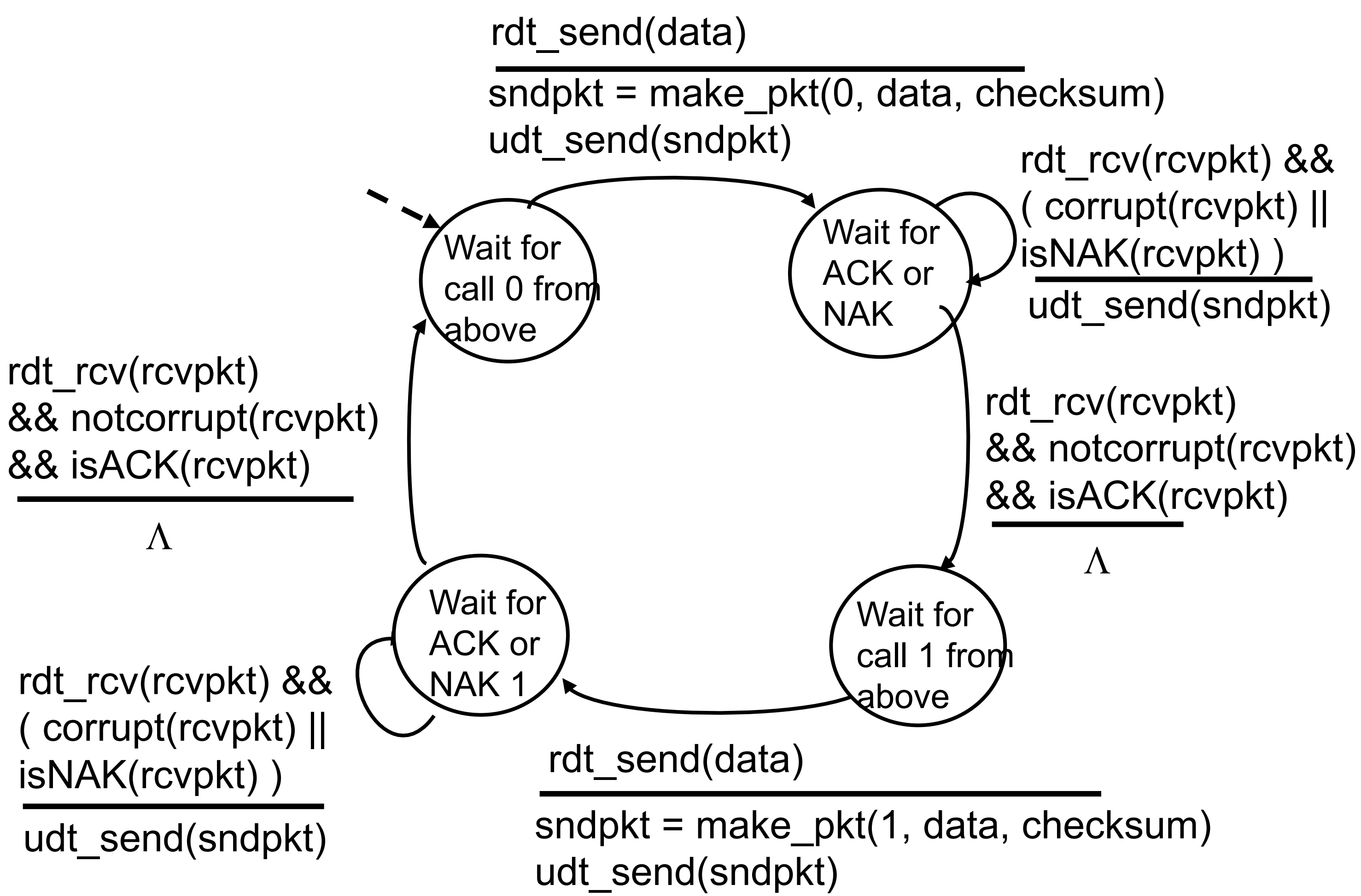
W1: wait for data with seq. 1
S1: sending data with seq. 1



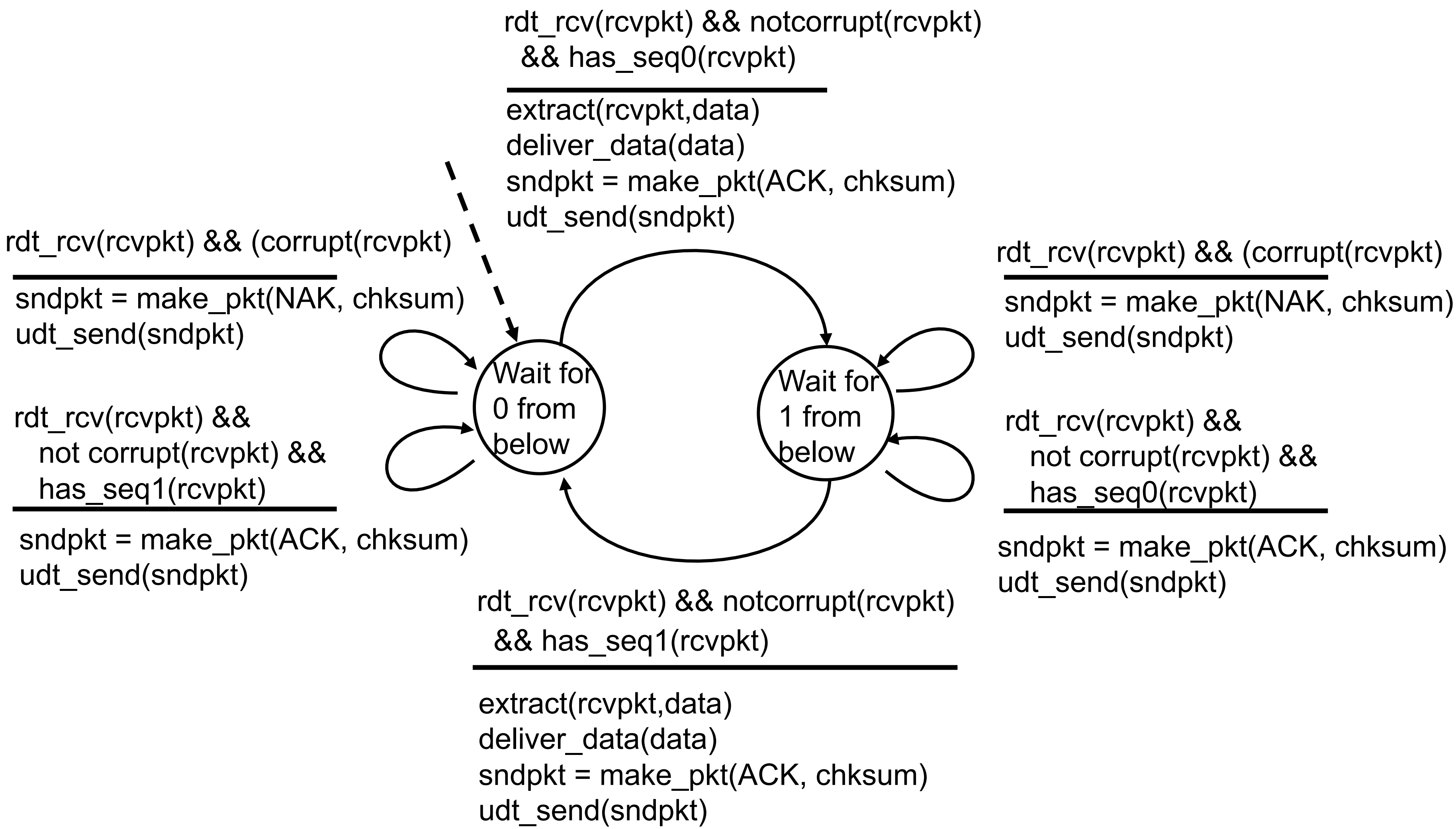
State invariant:

- When receiver's state is waiting for seq #n, sender's state can be sending either seq#n-1or seq#n, and only either #n or #n-1 packets can arrive

rdt2.1c: Sender, Handles Garbled ACK/NAKs: Using 1 bit (Alternating-Bit Protocol)



rdt2.1c: Receiver, Handles Garbled ACK/NAKs: Using 1 bit



rdt2.1c: Summary

Sender:

- state must "remember" whether "current" pkt has 0 or 1 seq. #

Receiver:

- must check if received packet is duplicate
  - state indicates whether 0 or 1 is expected pkt seq #