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

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This deck of slides are heavily based on CPSC 433/533 at Yale University, by courtesy of Dr. Y. Richard Yang.

Outline

- Admin and recap
- Transport overview

Admin

- Lab assignment 3 due on Nov. 14
- Midterm exam on Nov. 11
  - 15 subjective questions over 100 minutes
  - Don't forget to bring your 1-page cheat sheet

- Lab assignment 5 to be posted later this week

Recap

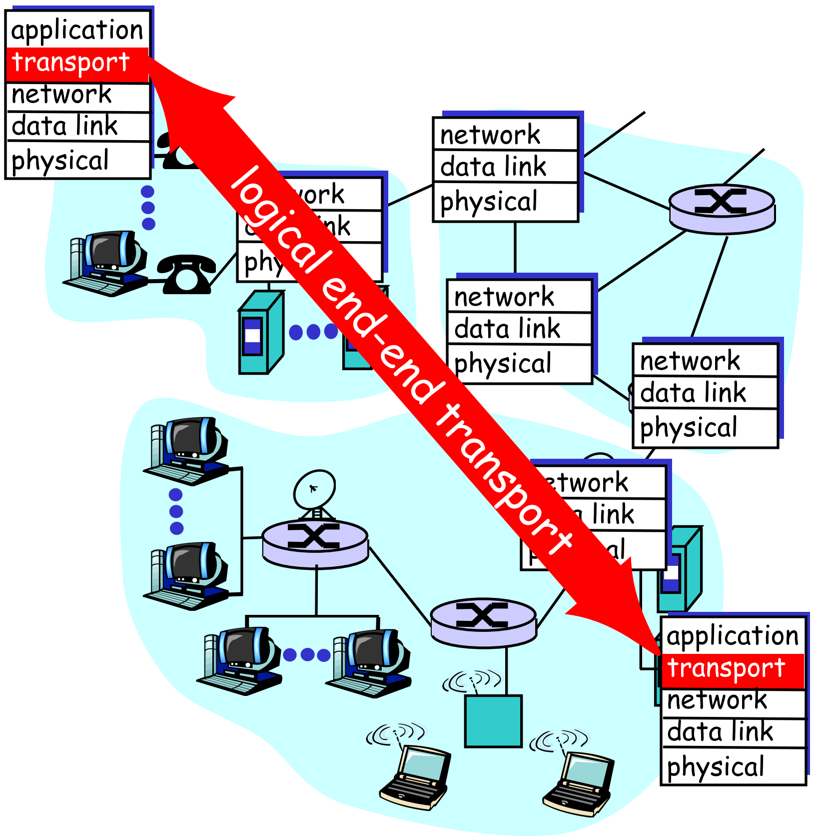
- Applications
  - Client-server applications
    - Single server
    - Multiple servers load balancing
  - Application overlays (distributed network applications) to
    - scale bandwidth/resource (BitTorrent)
    - distribute content lookup (Freenet, DHT, Chord) [optional]
    - distribute content verification (Block chain) [optional]
    - achieve anonymity (Tor) [optional]

Outline

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

Overview

- 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

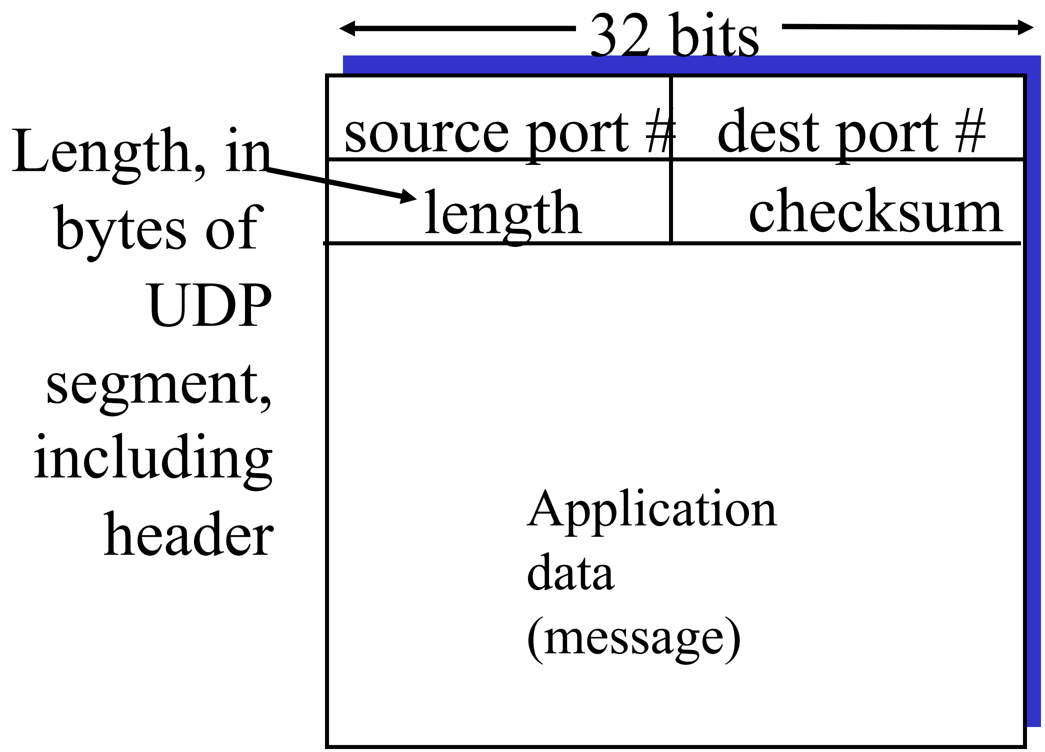
- Class 1 (today):
  - transport layer services
  - connectionless transport: UDP
  - reliable data transfer using stop-and-wait/alternating-bit protocol
- Class 2 (Nov. 11; ready for lab assignment 5/part 1):
  - sliding window reliability
  - TCP reliability
    - overview of TCP
    - TCP RTT measurement
    - TCP connection management
- Class 3 (Nov. 16; ready for lab assignment 5/part 2):
  - principles of congestion control
  - TCP congestion control; AIMD; TCP Reno
- Class 4 (Nov. 18):
  - TCP Vegas, performance modeling; Nash Bargaining solution
- Class 5 (Nov. 23):
  - primal-dual as a resource allocation and analysis framework
- ...

Outline

- Admin and recap
- Overview of transport layer
- *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 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: ?`
    - `11111111: ?`
  - addition: conventional binary addition except adding any resulting carry back into the resulting sum
    - Example: -1 + 2

UDP Checksum: Algorithm

- Example checksum:

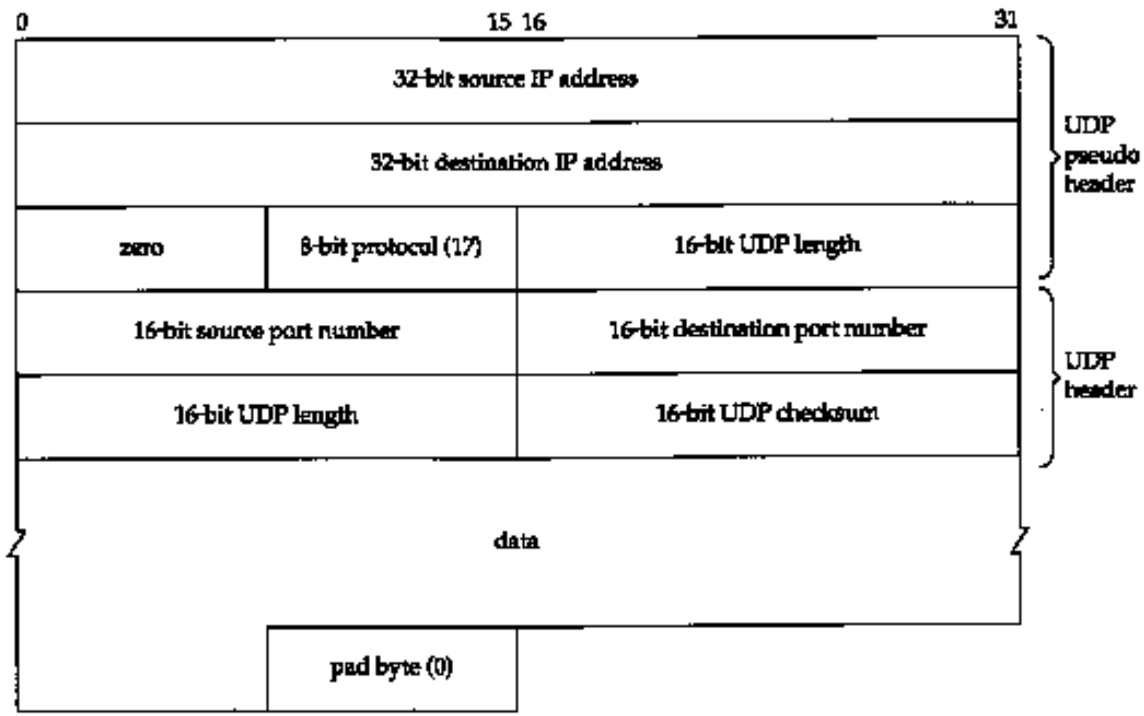
		1	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0
		1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
wraparound	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1
sum		1	0	1	1	1	0	1	1	1	0	1	1	1	1	0	0
checksum		0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	1

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

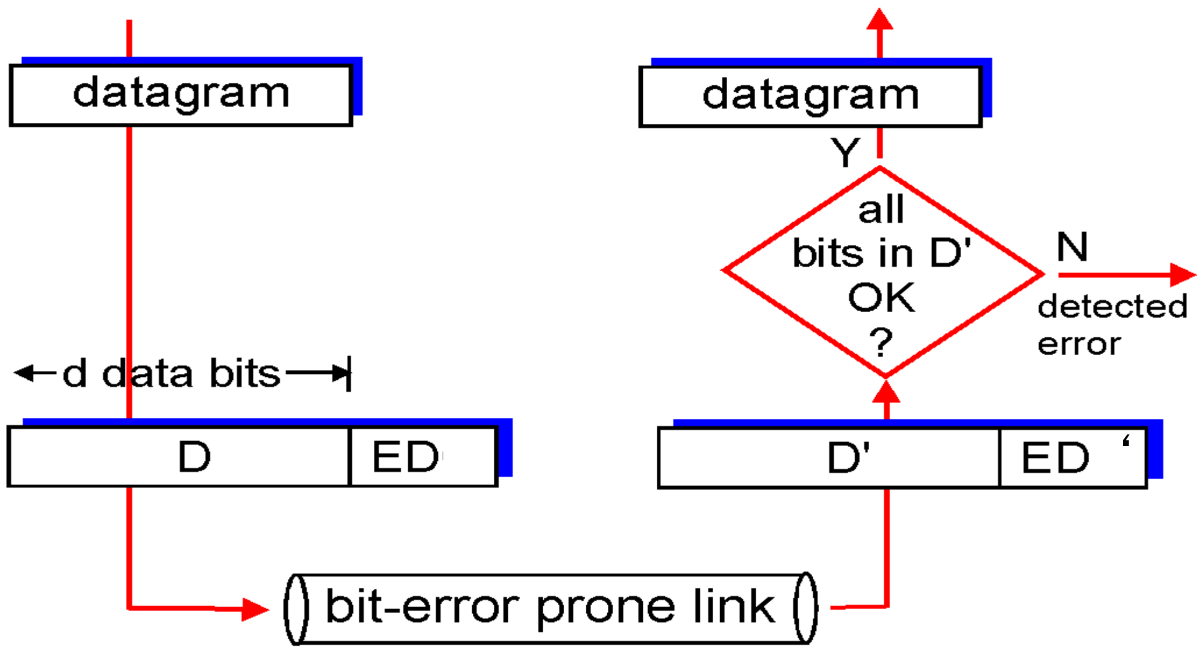
UDP Checksum: Coverage

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)

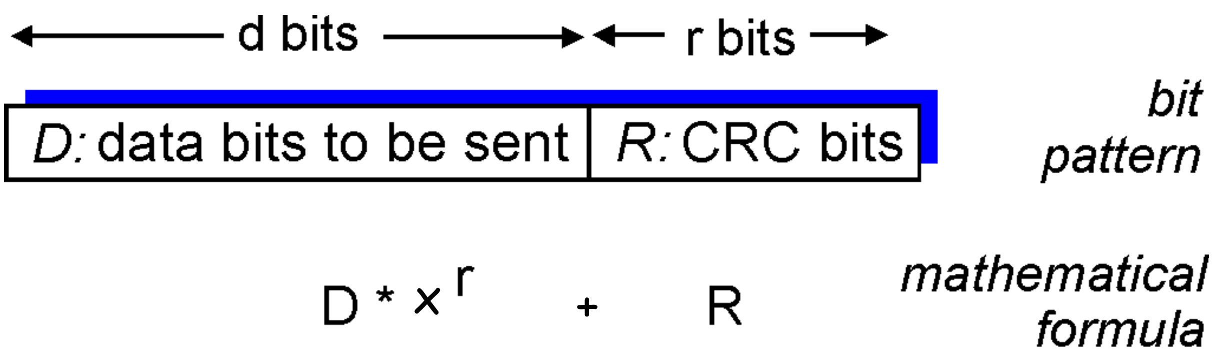
- Error detection not 100% reliable!
  - a good error detector may miss some errors, but rarely
  - larger ED field generally yields better detection

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 $G(x)$

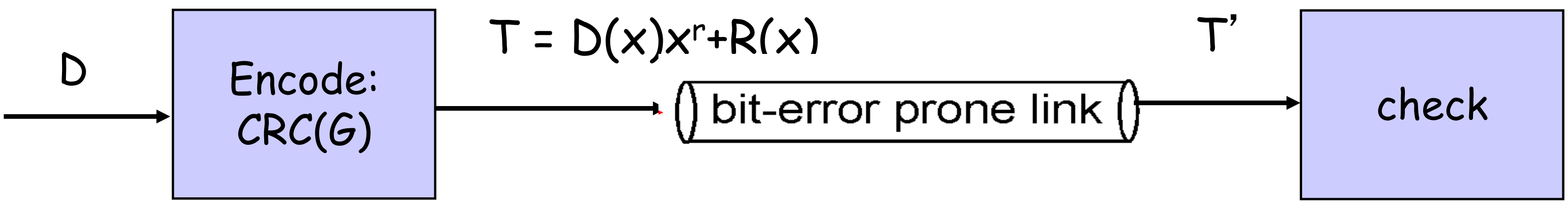
Cyclic Redundancy Check: Encode

- Given data 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

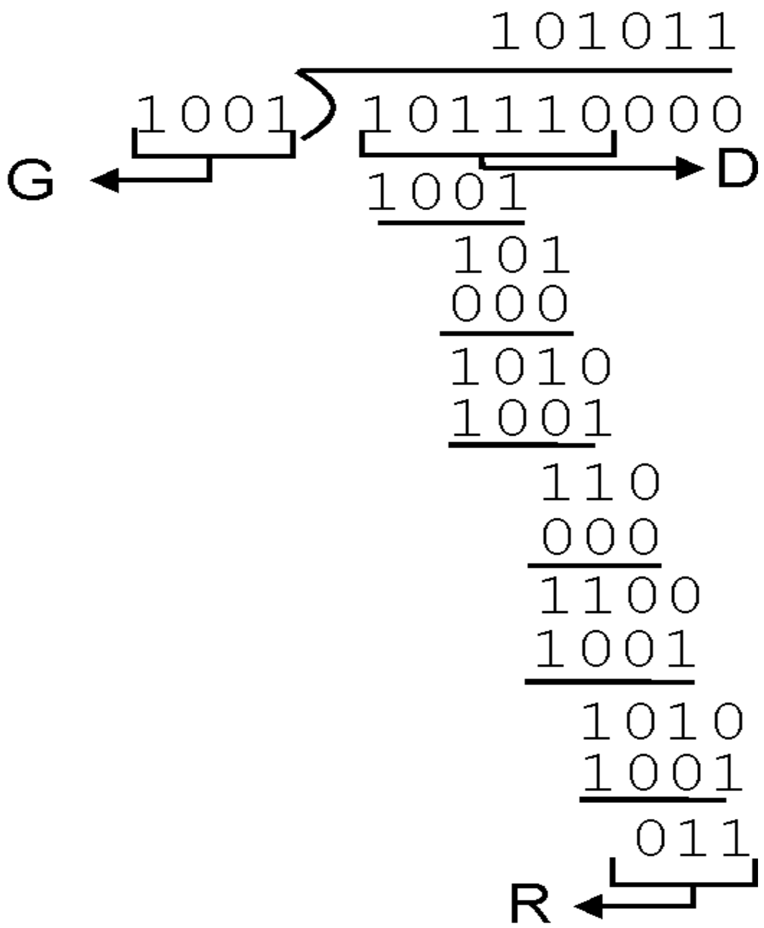
CRC: Steps and an Example

Suppose the degree of G(x) is r

Append r zero to D(x), i.e. consider $D(x)x^r$

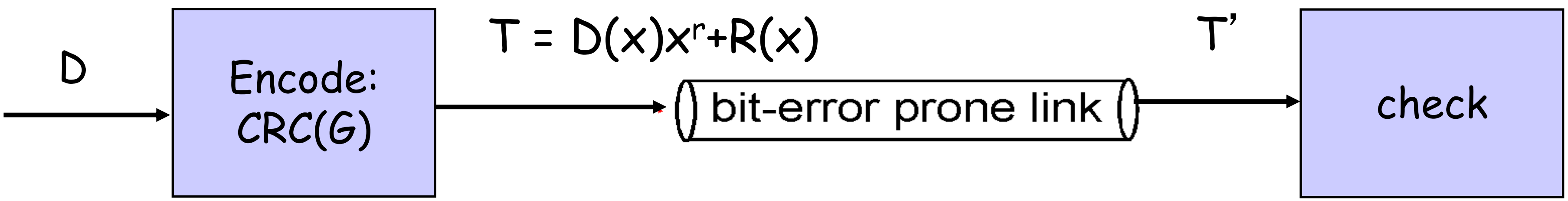
Divide $D(x)x^r$ by G(x). Let R(x) denote the reminder

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

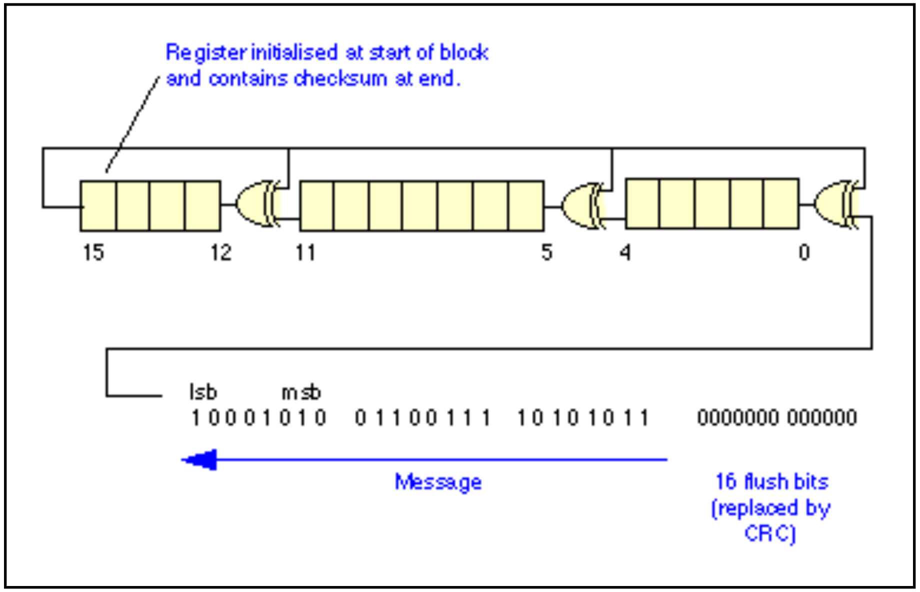
- Detect a single-bit error: $E(x) = x^i$
  - if $G(x)$ contains two or more terms, $E(x)$ is not divisible by $G(x)$

- 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

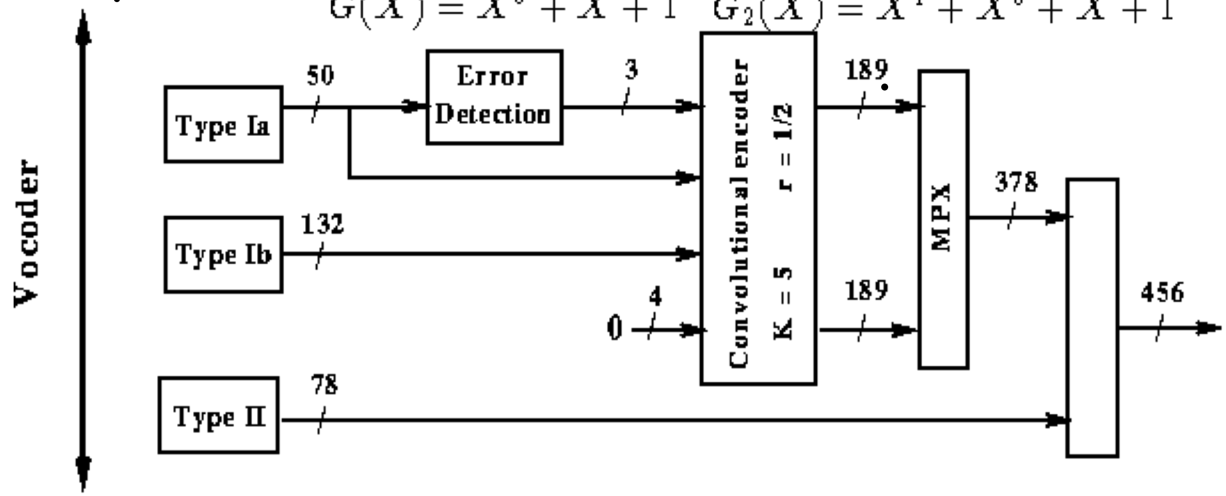
http://en.wikipedia.org/wiki/CRC-32#Implementation

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

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

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



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

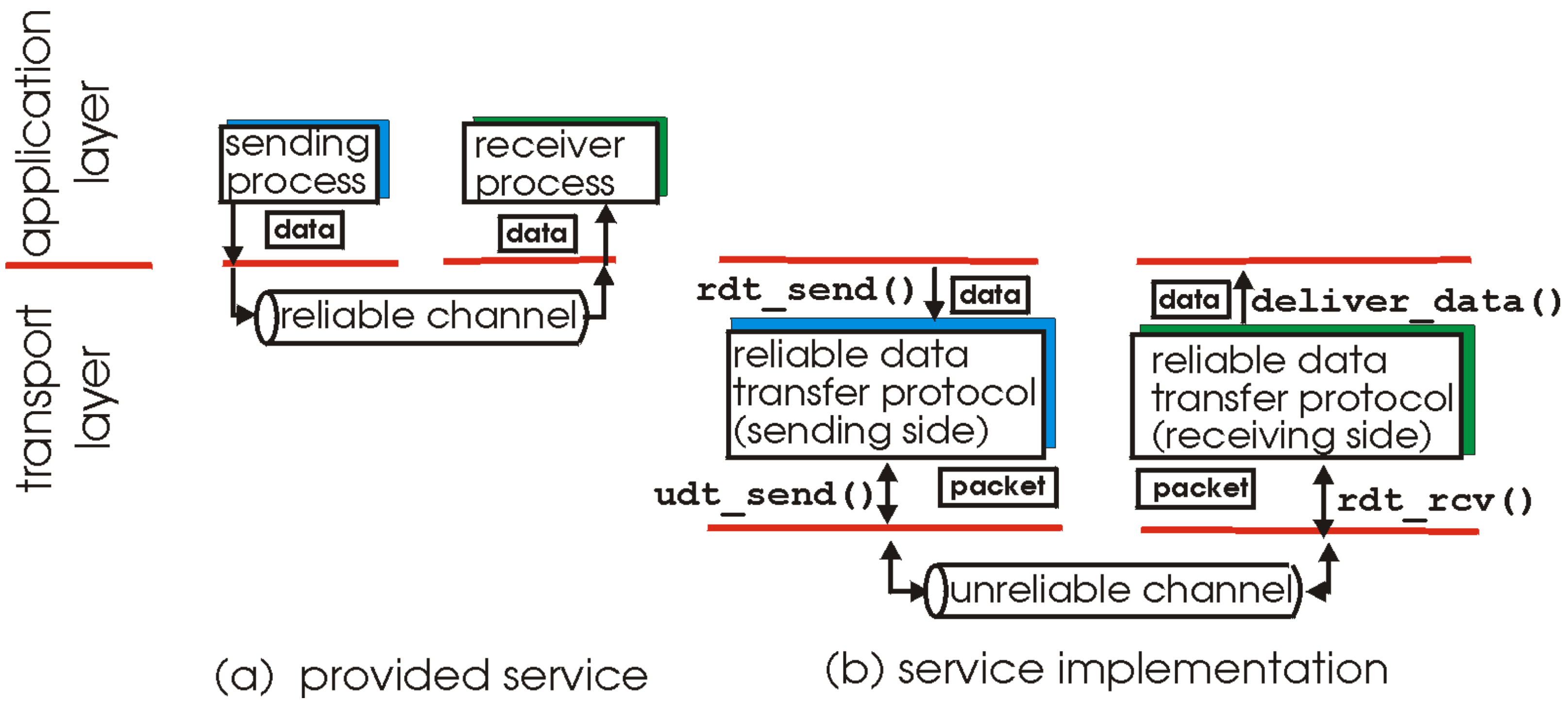
Outline

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

Principles of Reliable Data Transfer (RDT)

- Important in app., transport, link layers
- Foundation to other protocols
- We use the development of RDT to also better appreciate understanding distributed protocols

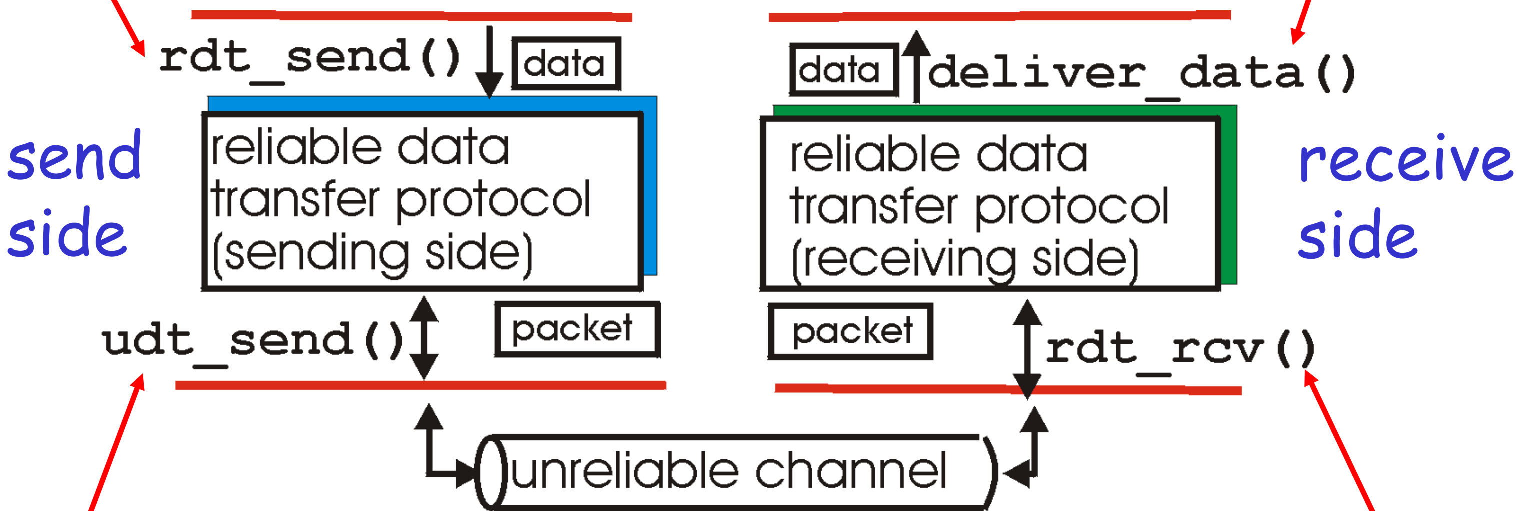
Reliable Data Transfer



Reliable Data Transfer: Getting Started

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

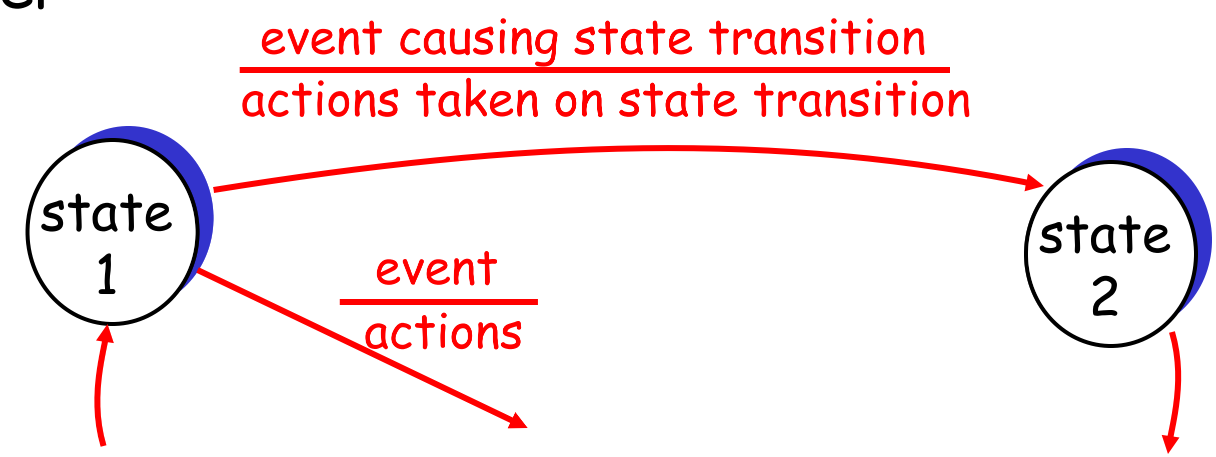
rdt_rcv(): called from below; when packet arrives on rcv-side of channel

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

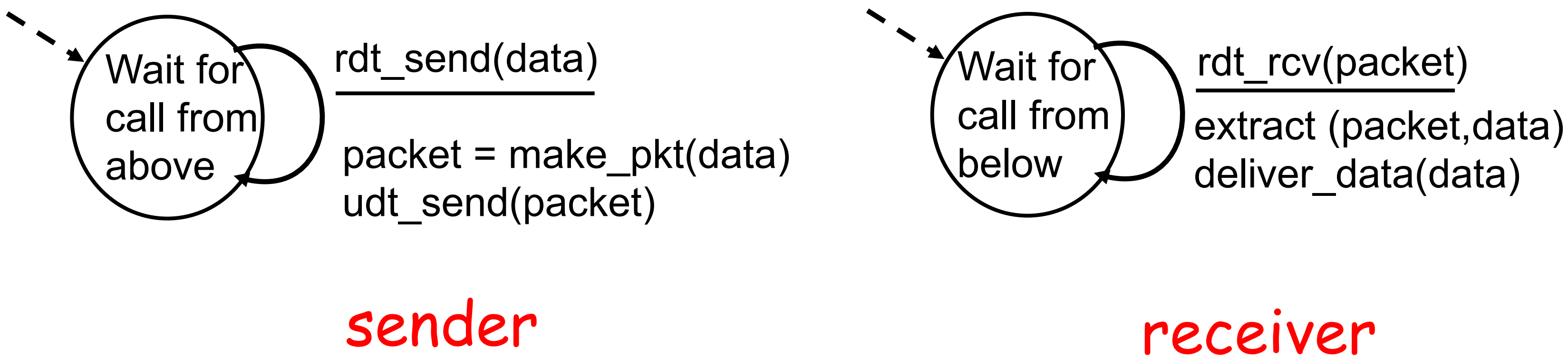


Outline

- 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



Exercise: Prove correctness of Rdt1.0.

Potential Channel Errors

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

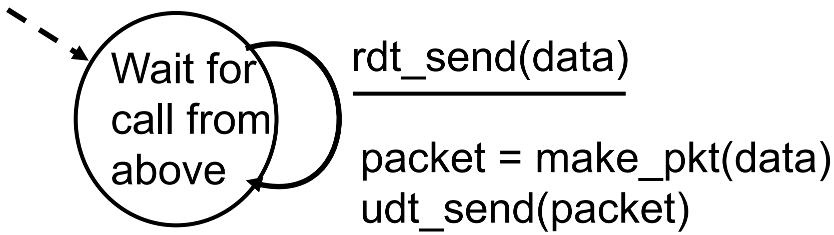
Characteristics of unreliable channel will determine complexity of reliable data transfer protocol (rdt).

Outline

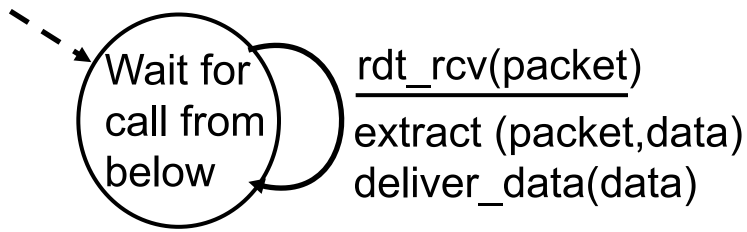
- Admin and recap
- Overview of transport layer
- UDP and error checking
- Reliable data transfer
  - perfect channel
  - *channel with bit errors*

rdt2.0: Channel With Bit Errors

- Assume: Underlying channel may only flip bits in packet



sender



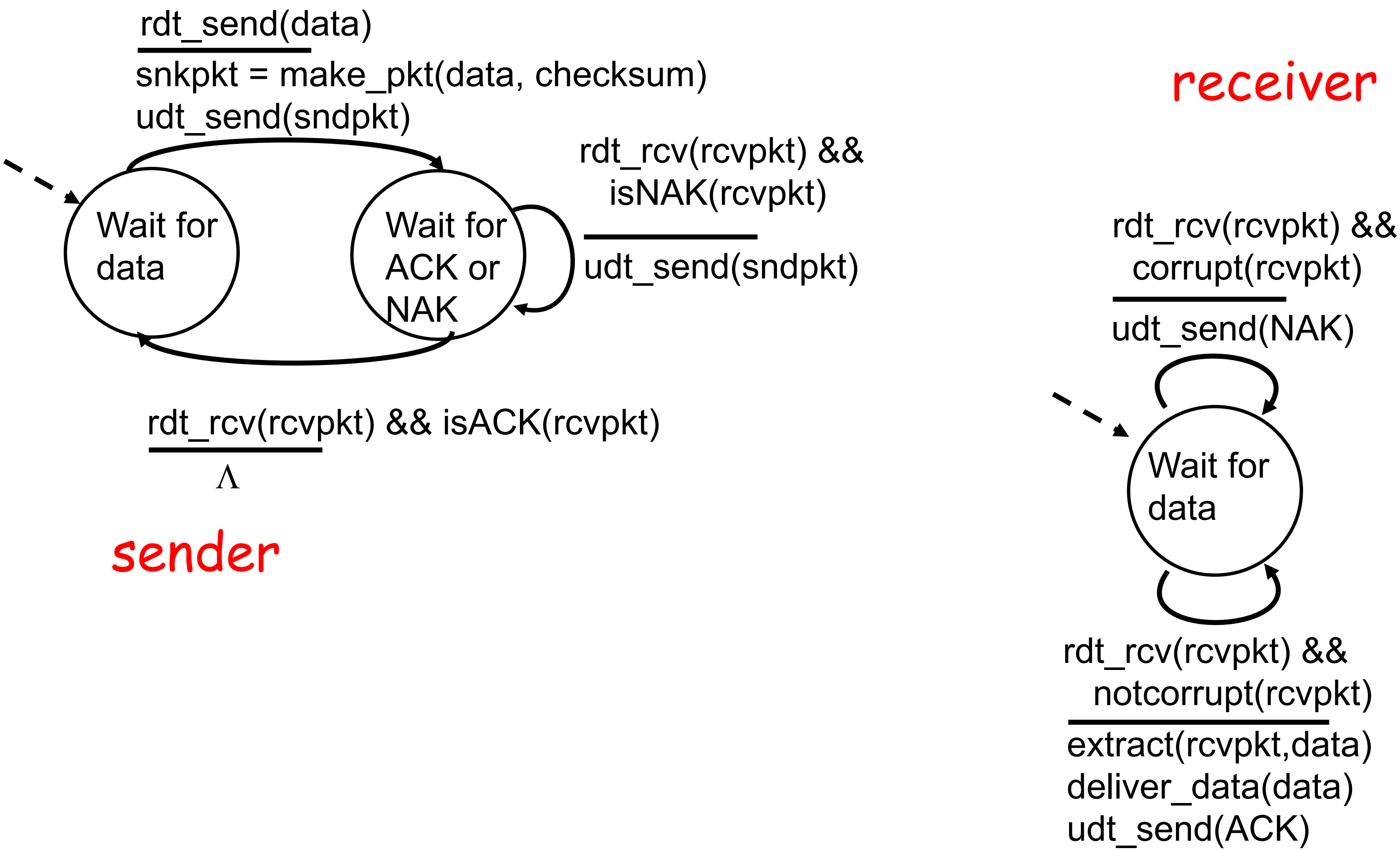
receiver

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

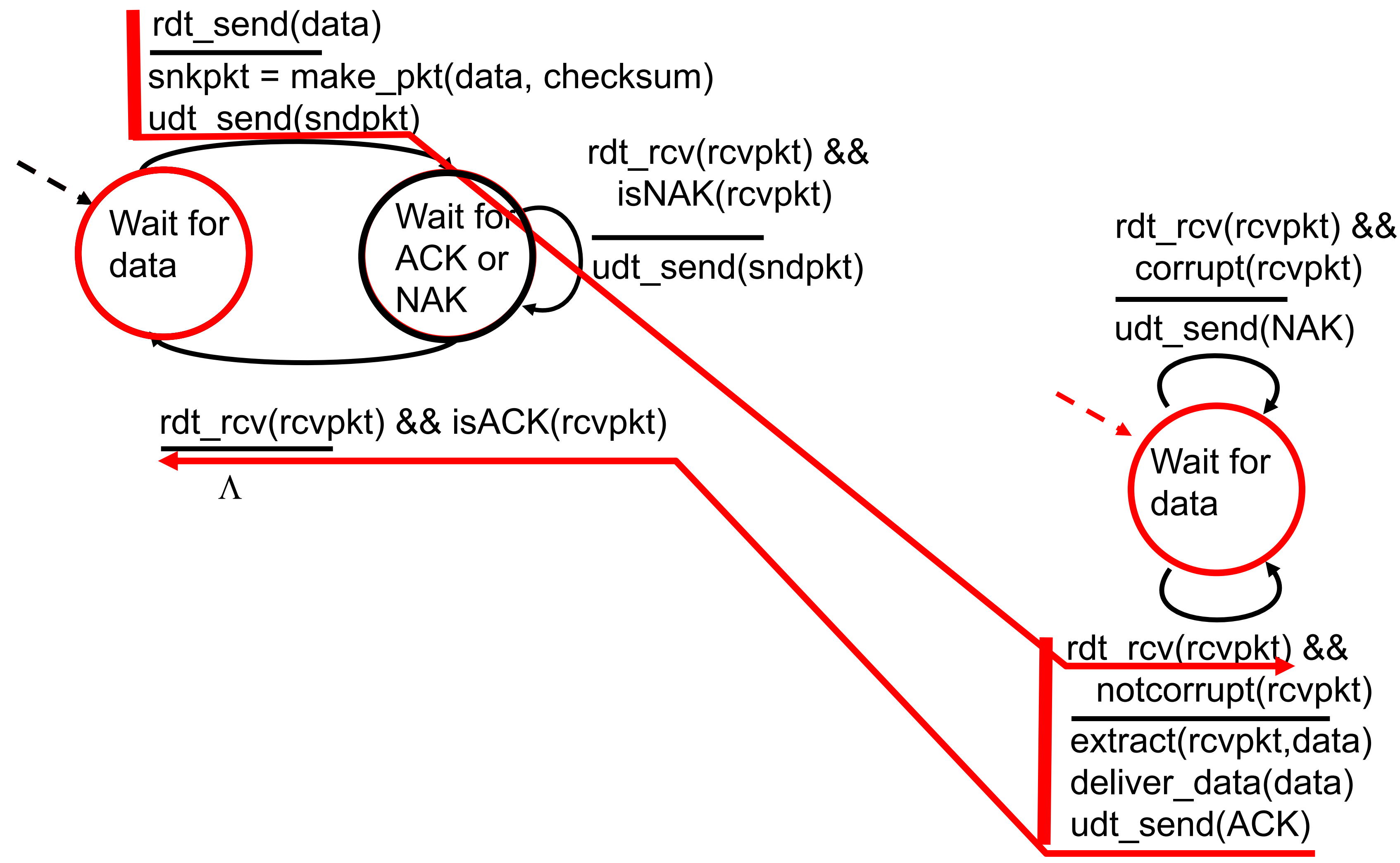
rdt2.0: Channel With Bit Errors

- 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

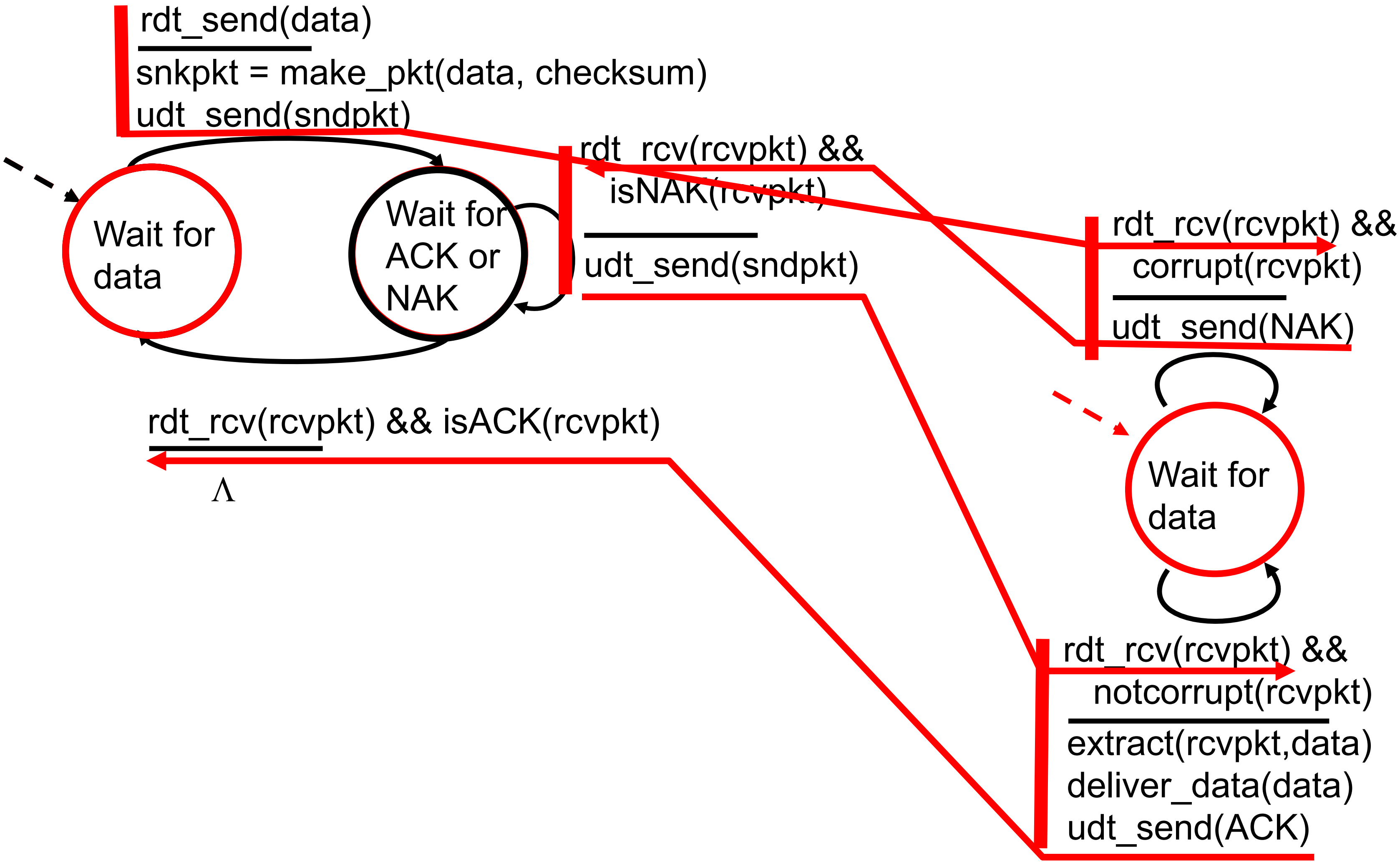
rdt2.0: FSM Specification



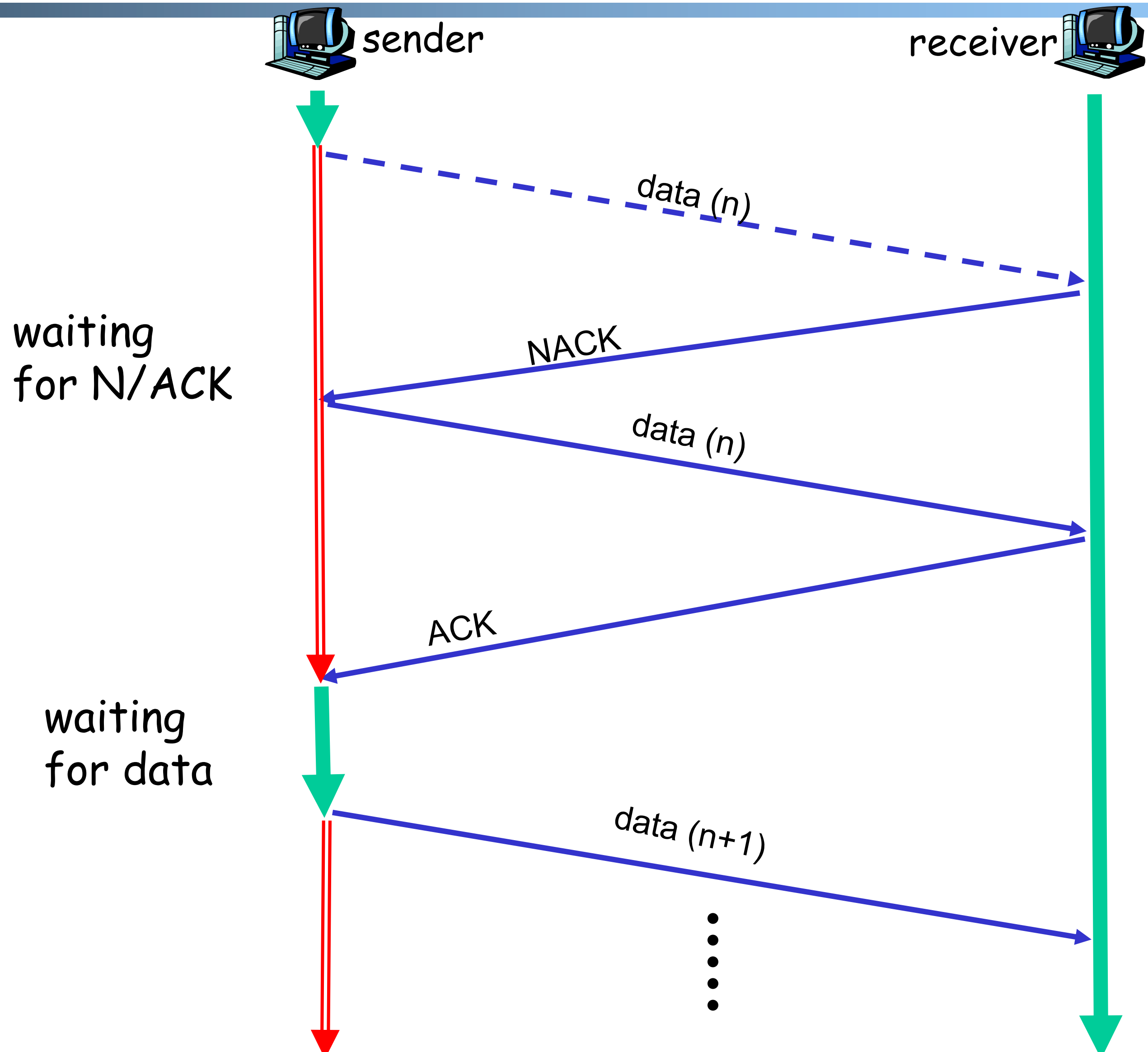
rdt2.0: Operation with No Errors



rdt2.0: Error Scenario



Rdt2.0 Analysis



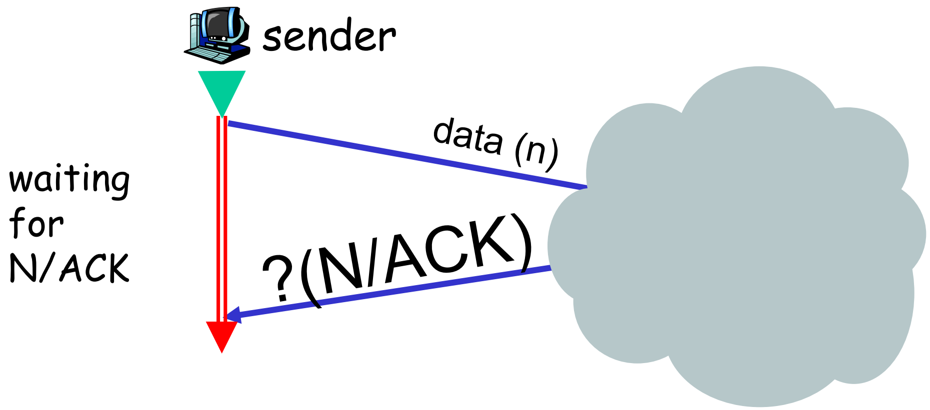
Execution traces
of rdt2.0:
{data^ NACK}*
data deliver
ACK

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

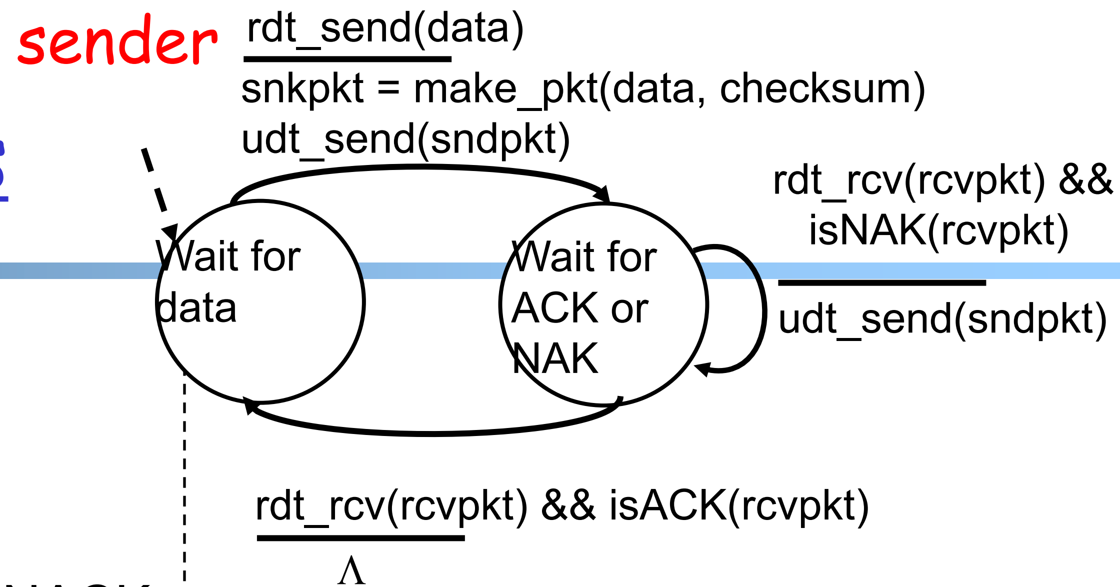
rdt2.0 is Incomplete!

What happens if ACK/NAK corrupted?

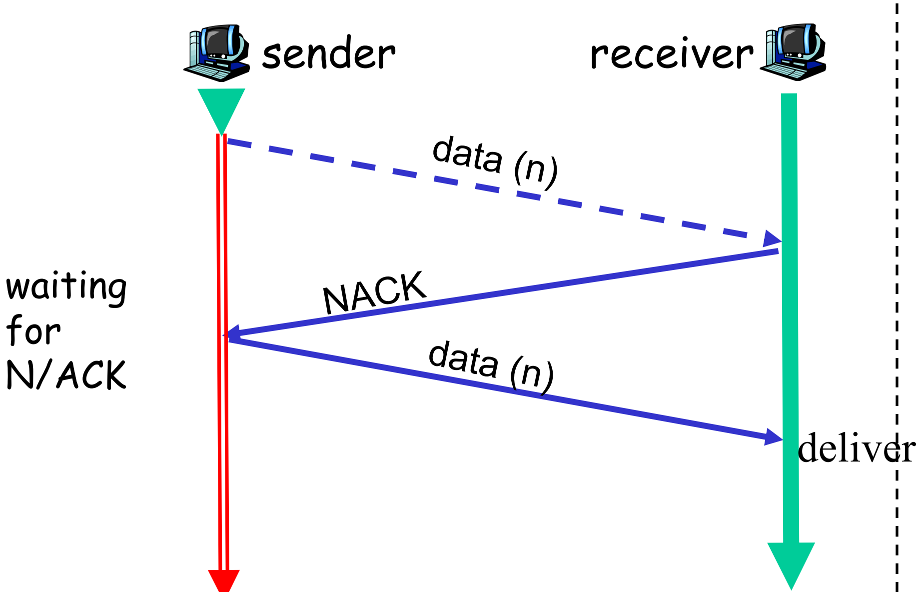
- Although sender receives feedback, but doesn't know what happened at receiver!



Two Possibilities

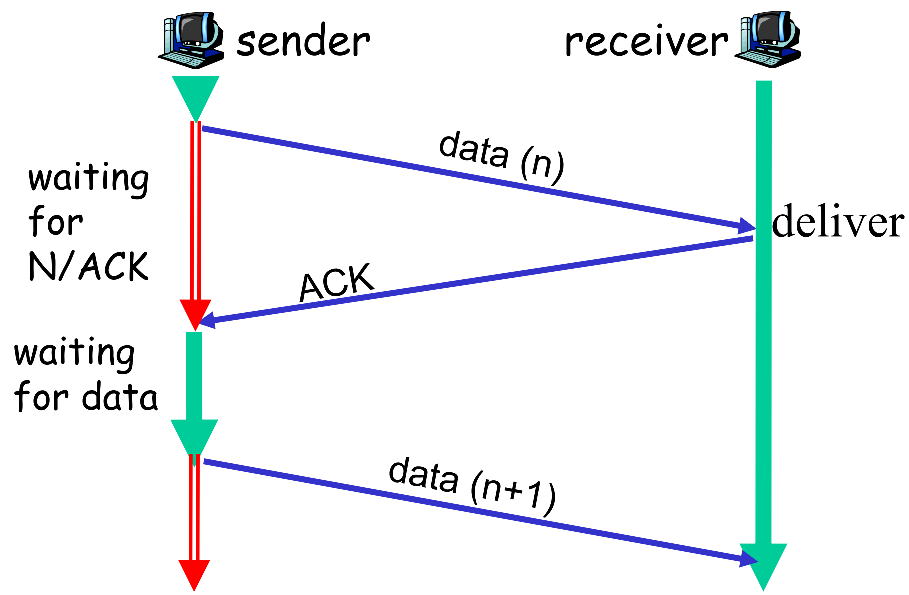


sender can't just guess NACK:
if wrong, duplicate



Fix miss guess NACK:
provide info for receiver to distinguish

sender can't just guess ACK:
if wrong, missing pkt



Home exercise: fix miss guess ACK

Handle Control Message Corruption

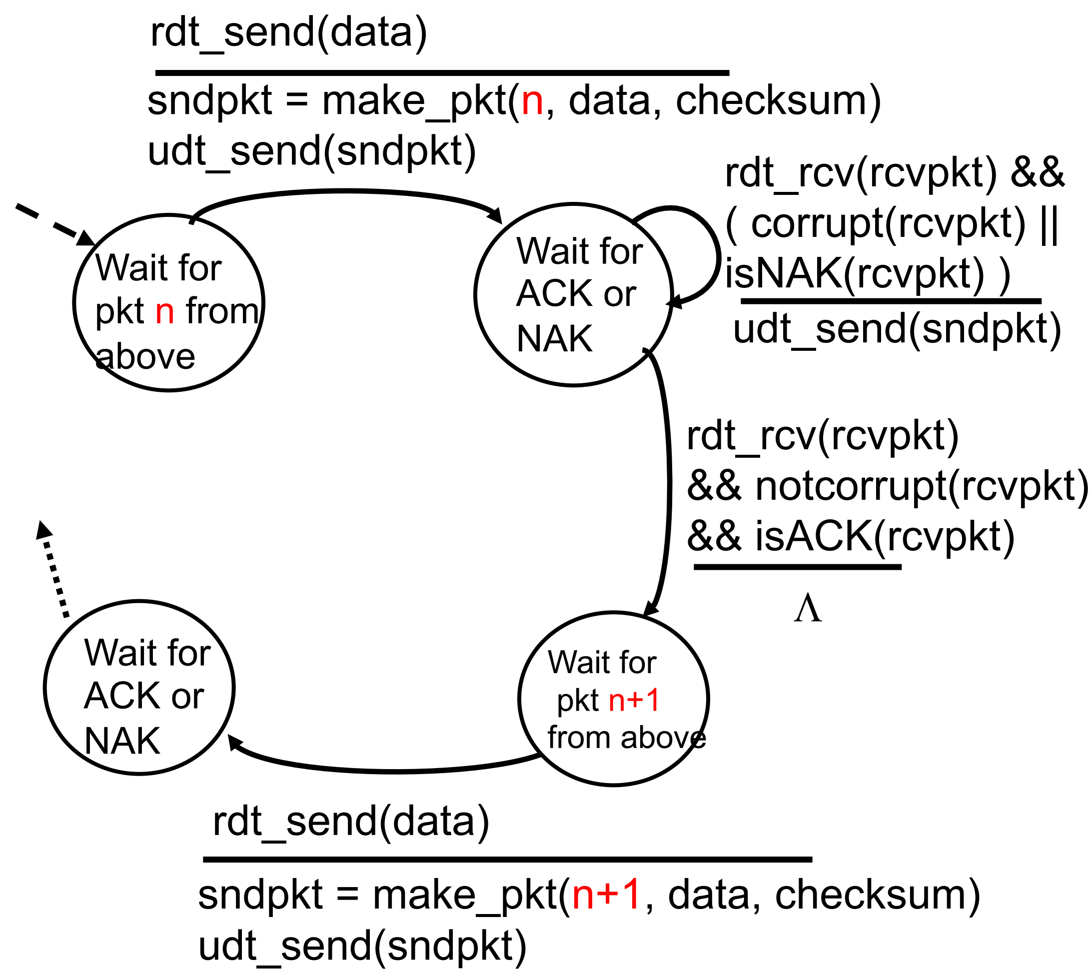
Handling ambiguity:

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

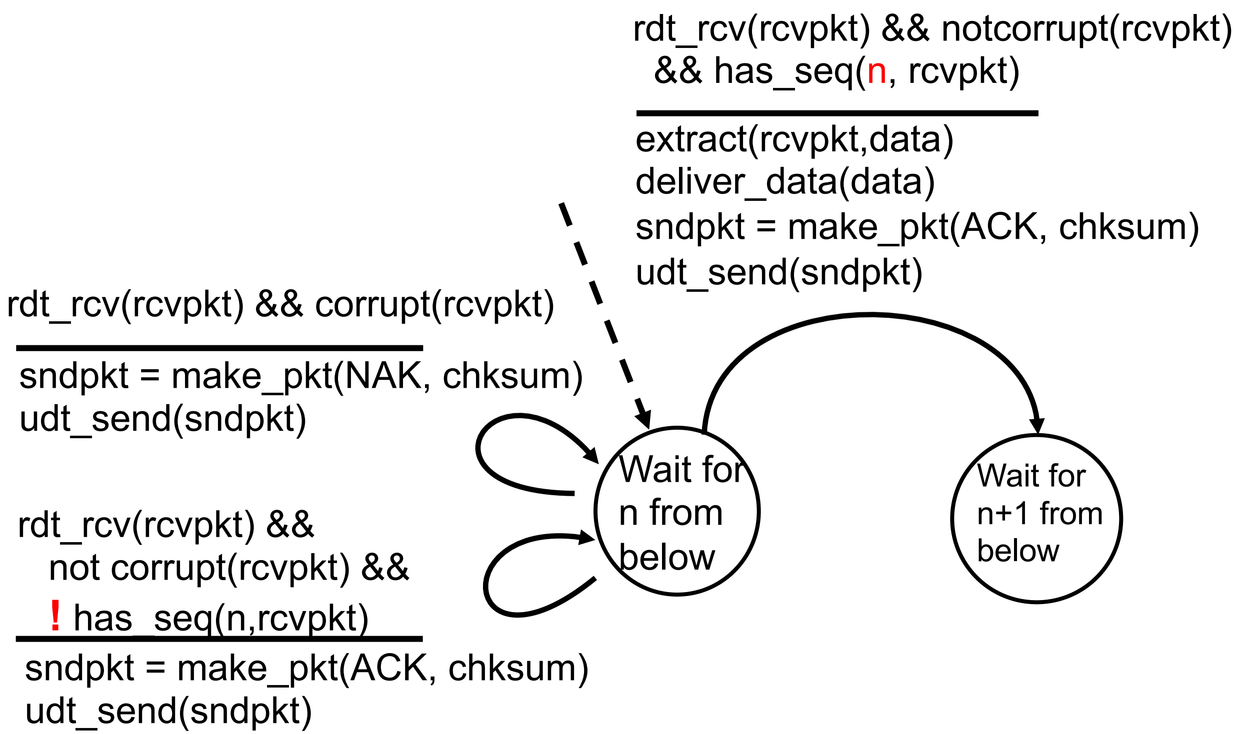
stop and wait
sender sends one packet, then waits for receiver response

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

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



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



rdt2.1b: Summary

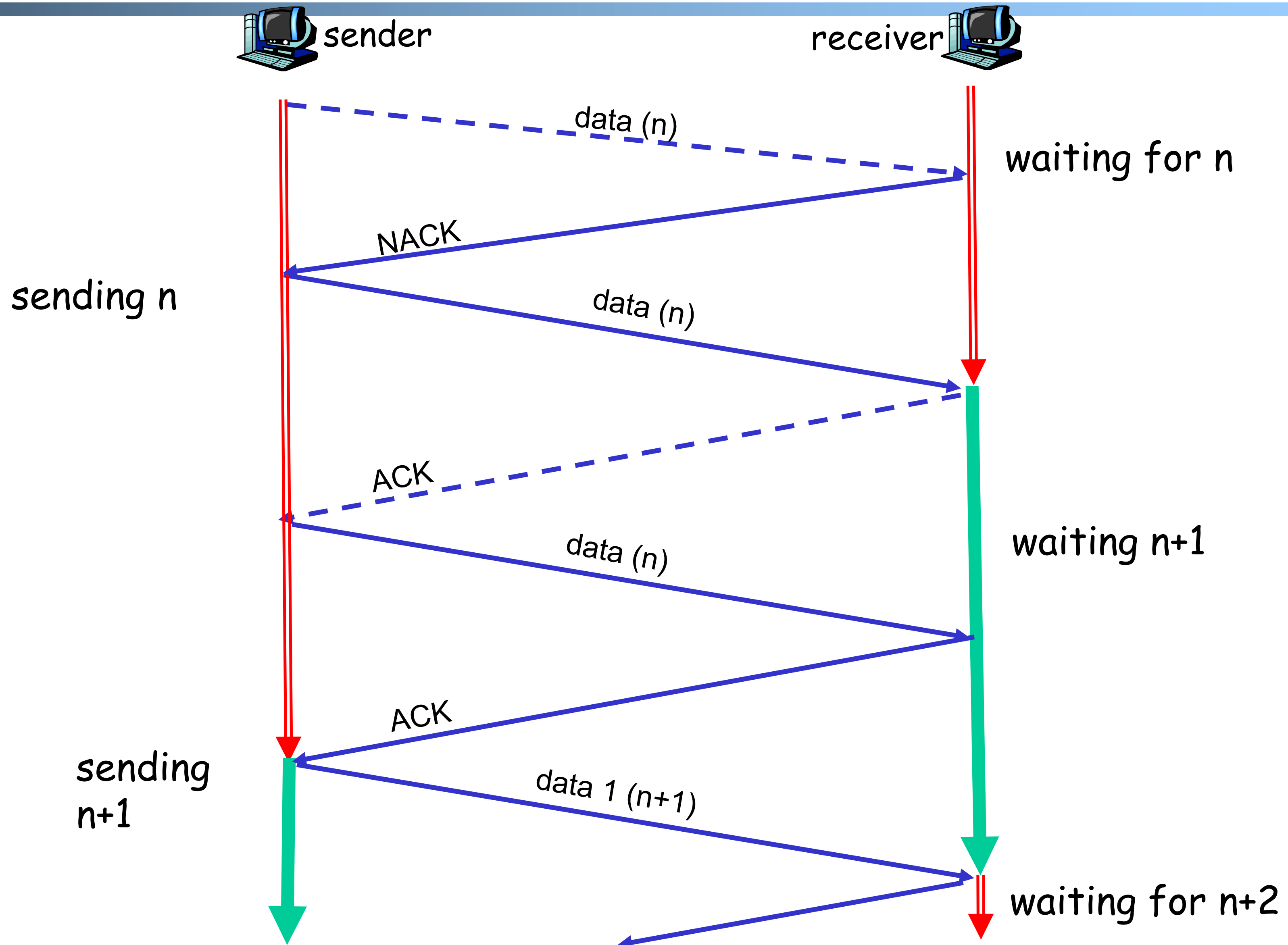
Sender:

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

Receiver:

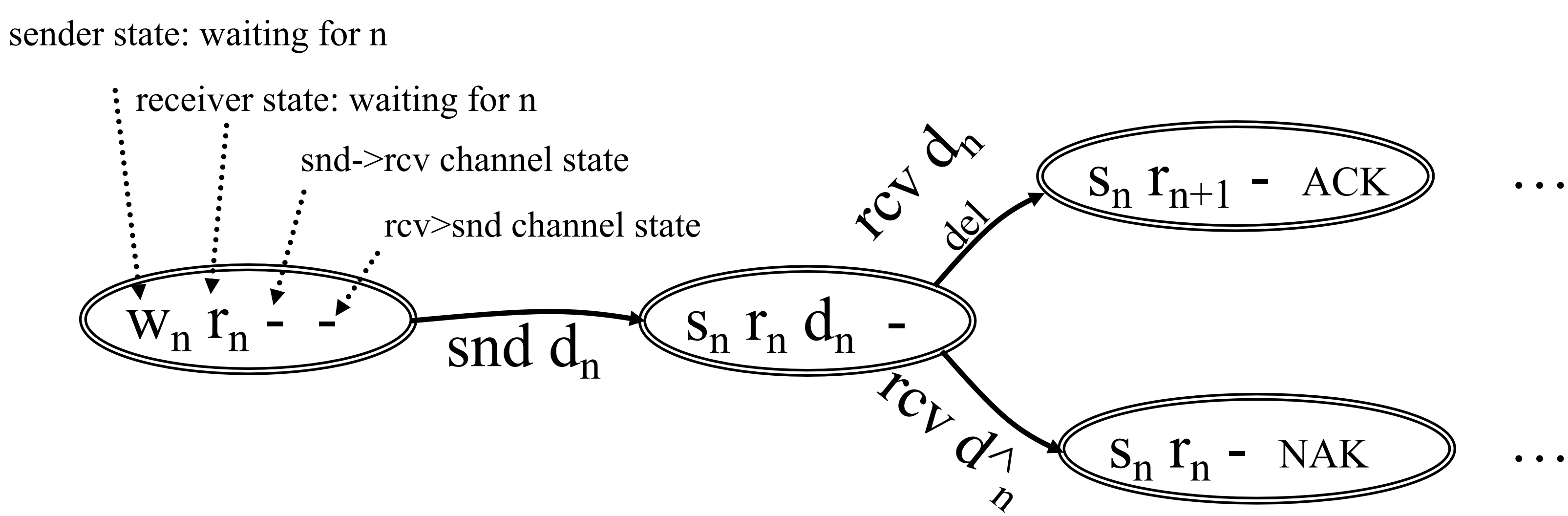
- must check if received packet is duplicate
  - by checking if the packet has the expected pkt seq #

rdt2.1b Analysis: Execution Traces?

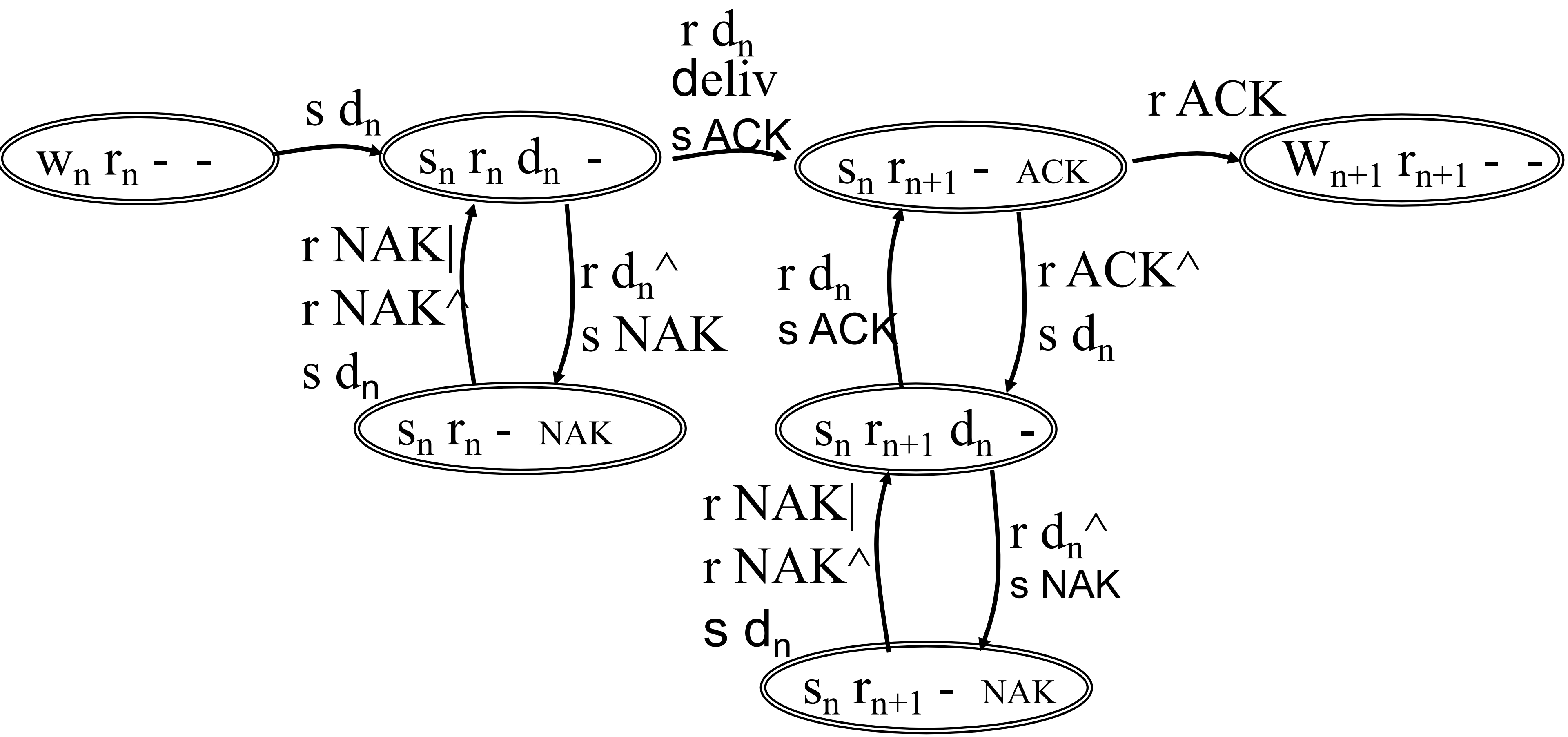


Protocol Analysis using (Generic) Execution Traces Technique

- 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



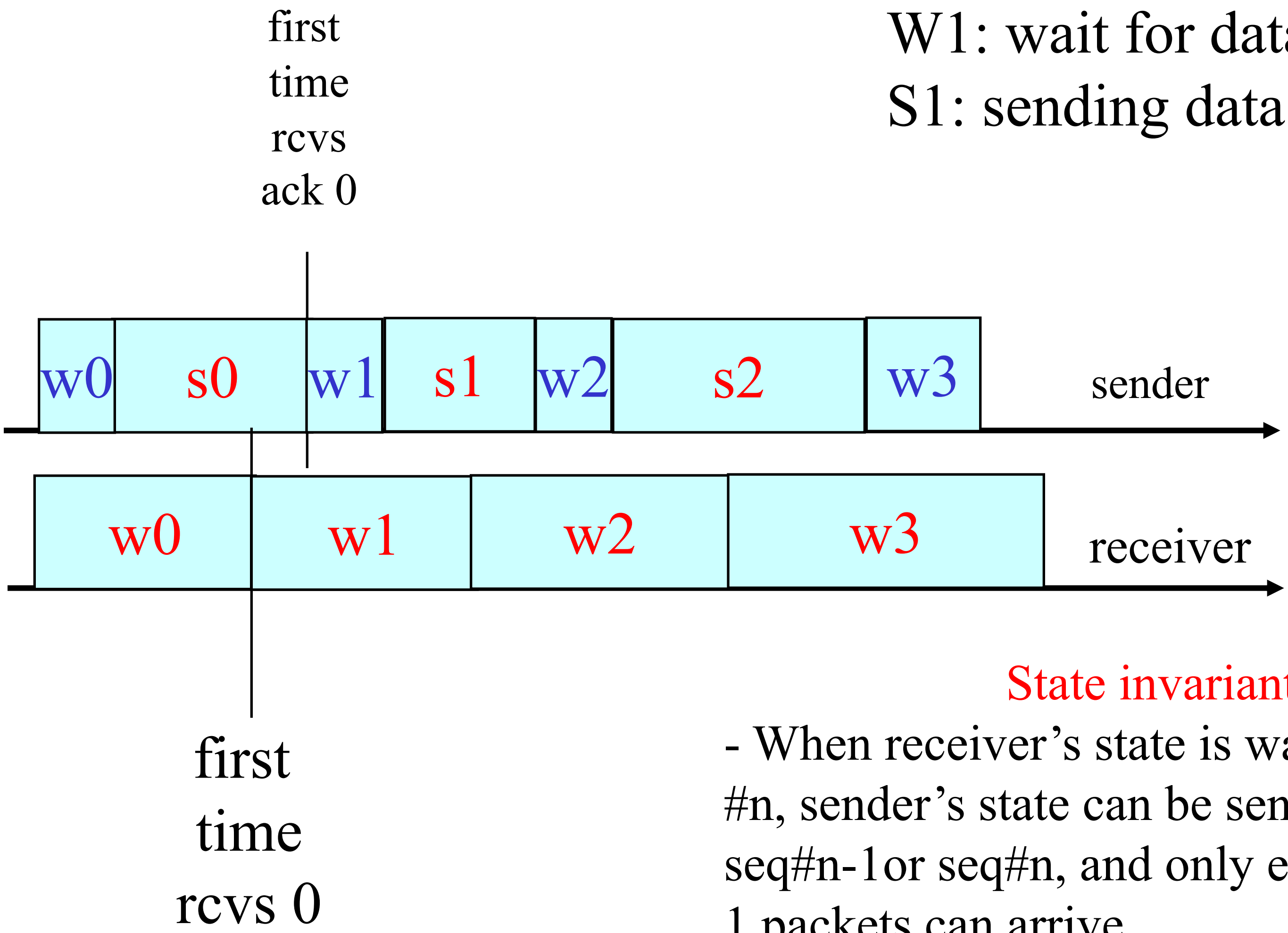
Recap: Protocol Analysis using (Generic) Execution Traces Technique



Execution traces of rdt2.1b are all that can be generated by the finite state machine above.

rdt2.1b Analysis: State Invariants

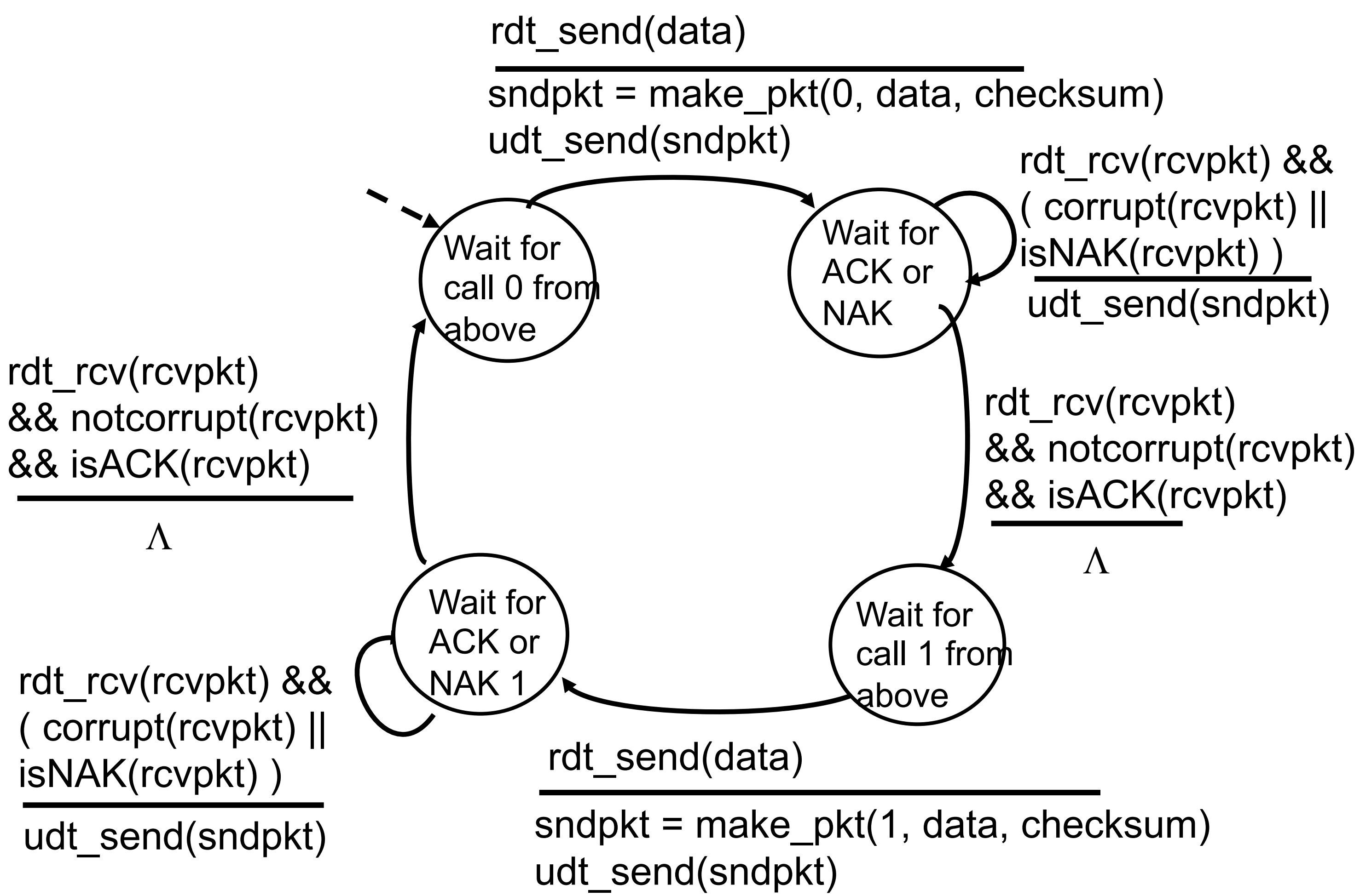
W1: wait for data with seq. 1
S1: sending data with seq. 1



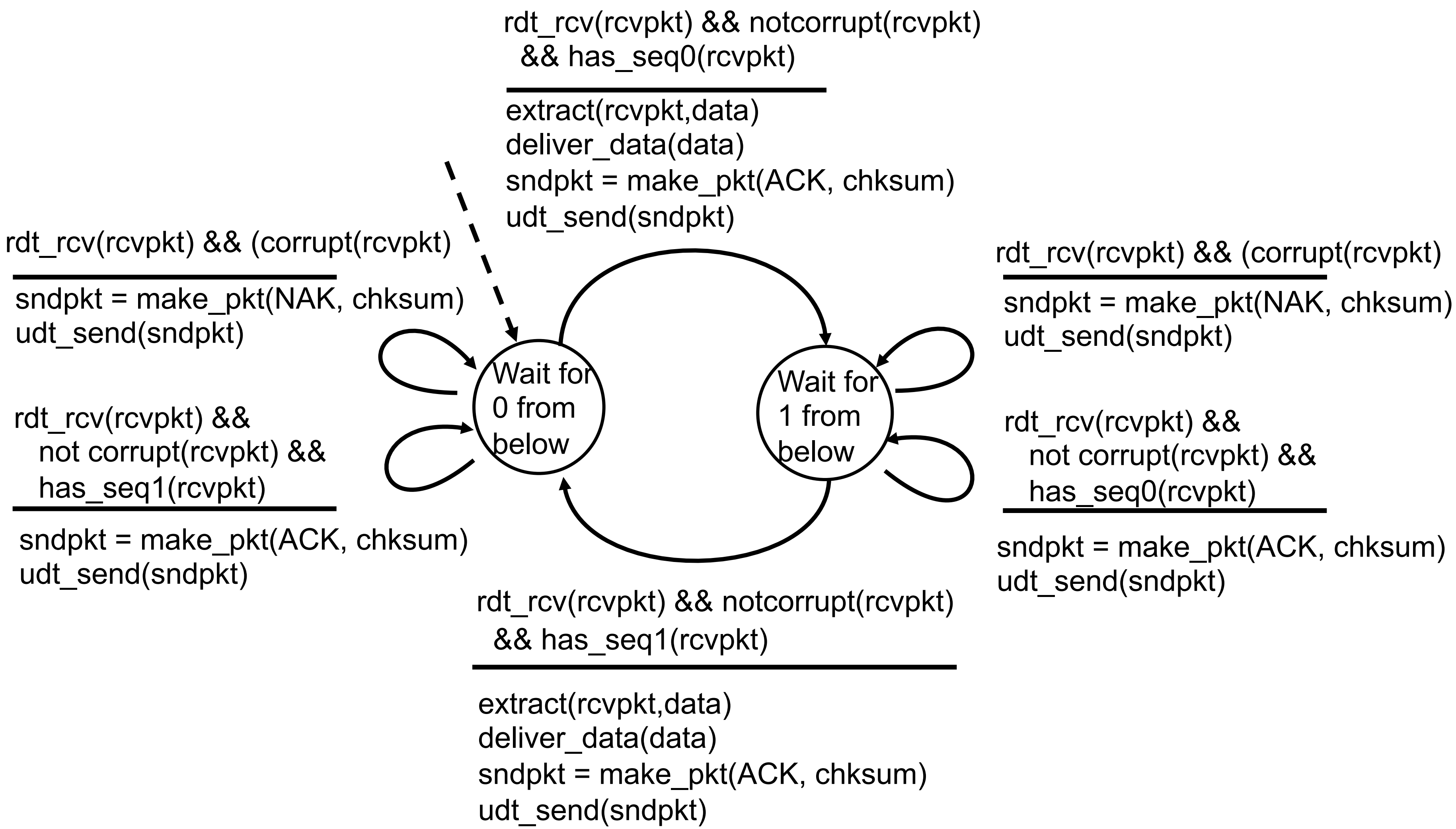
State invariant:

- 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 #