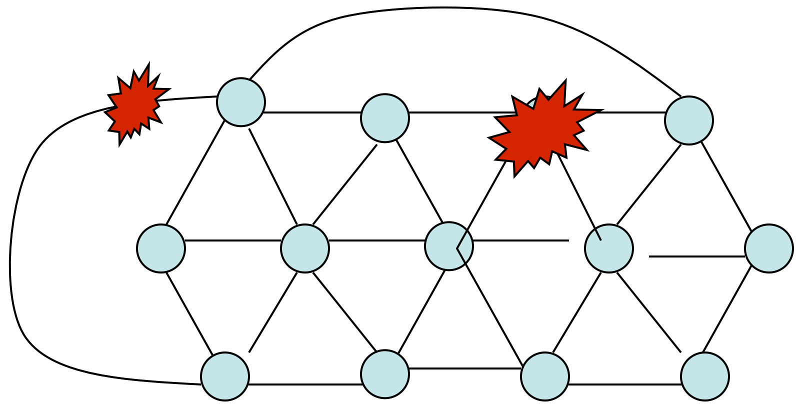
Faults and fault-tolerance



One of the selling points of a distributed system is that *the system will continue to perform (at some level) even if some components / processes / links fail.*

Cause and effect

- Study examples of **what causes what**.
- We view the effect of failures at **our level of abstraction**, and then try to mask it, or recover from it.
- Reliability and availability
- **MTBF** (Mean Time Between Failures) and **MTTR** (Mean Time To Repair) are two commonly used metrics in the engineering world

A classification of failures

- Crash failure
- Omission failure
- Transient failure
- Software failure
- Security failure
- Byzantine failure
- Temporal failure
- Environmental perturbations

Crash failures

Crash failure = the process halts. It is *irreversible*.

Crash failure is a form of "nice" failure. In a synchronous system, it can be detected using timeout, but in a asynchronous system, crash detection becomes tricky.

Some failures may be complex and nasty. Fail-stop failure is a *simple abstraction* that *mimics* crash failure when process behavior becomes arbitrary. *Implementations* of fail-stop behavior help detect which processor has failed.

If a system cannot tolerate fail-stop failure, then it cannot tolerate crash.

Omission failures

Message lost in transit. May happen due to various causes, like

- Transmitter malfunction
- Buffer overflow
- Collisions at the MAC layer
- Receiver out of range

Transient failure

(Hardware) Arbitrary perturbation of the global state. May be induced by power surge, weak batteries, lightning, radio-frequency interferences, cosmic rays etc.

Not *Heisenberg*

(Software) Heisenbugs are a class of temporary internal faults and are intermittent. They are essentially permanent faults whose conditions of activation occur rarely or are not easily reproducible, so they are harder to detect during the testing phase.

Over 99% of bugs in IBM DB2 production code are non-deterministic and transient (Jim Gray)

Software failures

Coding error or human error

On September 23, 1999, NASA lost the $125 million Mars orbiter spacecraft because one engineering team used metric units while another used English units leading to a navigation fiasco, causing it to burn in the atmosphere.

Design flaws or inaccurate modeling

Mars pathfinder mission landed flawlessly on the Martial surface on July 4, 1997. However, later its communication failed due to a design flaw in the real-time embedded software kernel VxWorks. The problem was later diagnosed to be caused due to *priority inversion*, when a medium priority task could preempt a high priority one.

Software failures (continued)

Memory leak

Operating systems may crash when processes fail to entirely free up the physical memory that has been allocated to them. This effectively reduces the size of the available physical memory over time. When this becomes smaller than the minimum memory needed to support an application, it crashes.

Incomplete specification (example Y2K)

Year = 09 (1909 or 2009 or 2109)?

Many failures (like crash, omission etc) can be caused by software bugs too.

Temporal failures

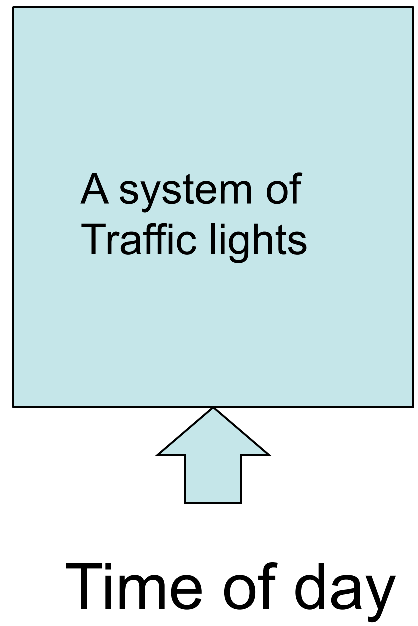
Inability to meet deadlines – correct results are generated, but too late to be useful. Very important in real-time systems.

May be caused by poor algorithms, poor design strategy or loss of synchronization among the processor clocks.

Environmental perturbations

Consider open systems or dynamic systems. Correctness is related to the environment. If the environment changes, then a correct system becomes incorrect.

Example of environmental parameters: time of day, network topology, user demand etc. Essentially, distributed systems are expected to adapt to the environment



Security problems

Security loopholes can lead to failure. Code or data may be corrupted by security attacks. In wireless networks, rogue nodes with powerful radios can sometimes impersonate for good nodes and induce faulty actions.

Byzantine failure

Anything goes! Includes every conceivable form of erroneous behavior. It is the weakest type of failure.

Numerous possible causes. Includes malicious behaviors (like a process executing a different program instead of the specified one) too.

Most difficult kind of failure to deal with.

Specification of faulty behavior

(Most faulty behaviors can be **modeled as** a fault action F superimposed on the normal action S. This is for specification purposes only)

program example1;
define x : **boolean** (**initially** x = true);
{**a, b are messages);**
do {S}: x → send **a** {specified action}
[] {F}: true → send **b** {faulty action}
od

a a a a b a a a b b a a a a a a a …

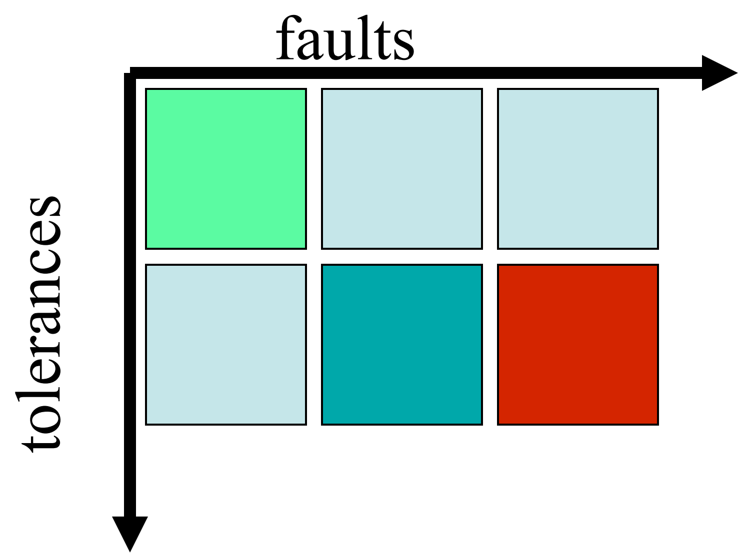
Fault-tolerance

F-intolerant vs F-tolerant systems

A system that
tolerates failure
of type F

Four types of tolerance:

- Masking
- Non-masking
- Fail-safe
- Graceful degradation

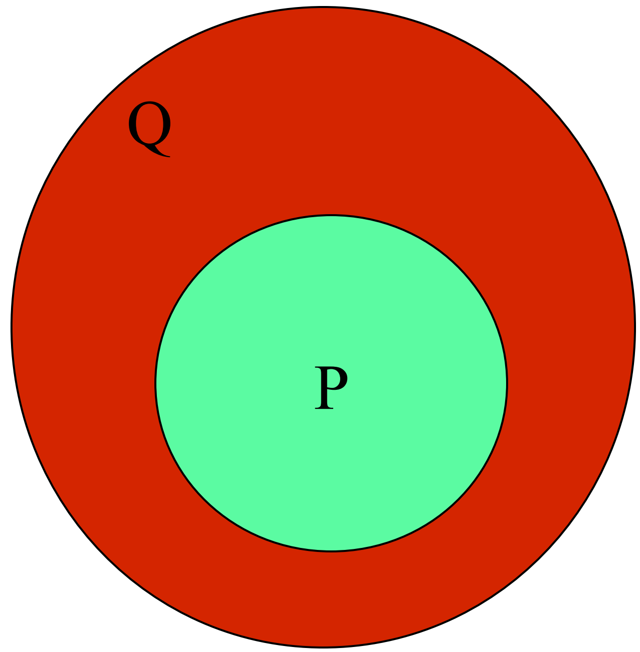


Fault-tolerance

P is the invariant of the original fault-free system

Q represents the worst possible behavior of the system when failures occur. It is called the fault span.

Q is closed under S or F.



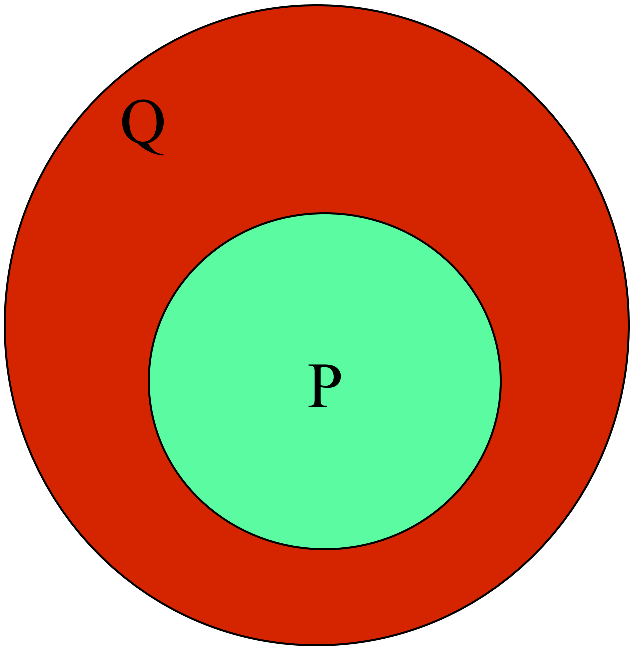
Fault-tolerance

Masking tolerance: P = Q

(neither safety nor liveness is violated)

Non-masking tolerance: **$P \subset Q$**

(safety property may be ***temporarily*** violated, but not liveness). Eventually safety property is restored.



Classifying fault-tolerance

Masking tolerance.
Application runs as it is. The failure does not have a visible impact.
All properties (both liveness & safety) continue to hold.

Non-masking tolerance.
Safety property is *temporarily affected*, but not liveness.

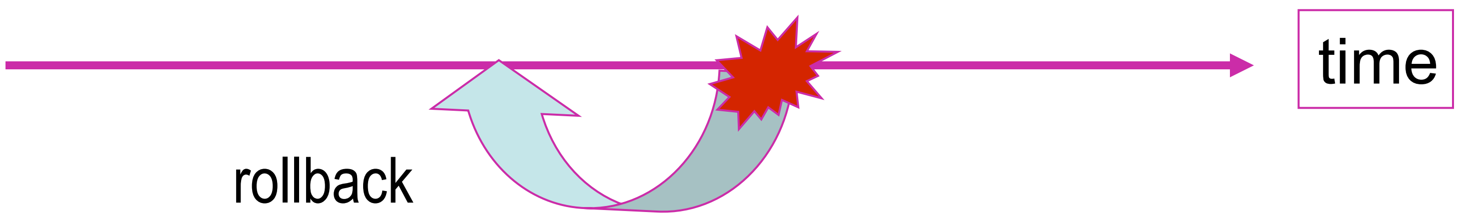
Example 1. Clocks lose synchronization, but recover soon thereafter.
Example 2. Multiple processes temporarily enter their critical sections, but thereafter, the normal behavior is restored.
Example 3. A transaction crashes, but eventually recovers

Backward vs. forward error recovery

These are two forms of non-masking tolerance:

Backward error recovery

When safety property is violated, the computation **rolls back** and resumes from a previous correct state.



Forward error recovery

Computation does not care about getting the history right, but moves on, as long as eventually the safety property is restored. True for self-stabilizing systems.

Classifying fault-tolerance

Fail-safe tolerance

Given safety predicate is preserved, but liveness may be affected

Example. Due to failure, no process can enter its critical section for an indefinite period. In a traffic crossing, failure changes the traffic in both directions to red.

Graceful degradation

Application continues, but in a “degraded” mode. Much depends on what kind of degradation is acceptable.

Example. Consider message-based mutual exclusion. Processes will enter their critical sections, but not in timestamp order.

Failure detection

The design of fault-tolerant systems will be easier if failures can be detected. Depends on the

1. System model, and
2. The type of failures.

Asynchronous models are more tricky. We first focus on synchronous systems only

Detection of crash failures

Failure can be detected using heartbeat messages (periodic "I am alive" broadcast) and timeout

- if processors speed has a known lower bound
- channel delays have a known upper bound.

True for synchronous models only. We will address failure detectors for asynchronous systems later.

Detection of omission failures

For FIFO channels: Use sequence numbers with messages.

(1, 2, 3, 5, 6 …) $\Rightarrow$ message 5 was received but not message 4 $\Rightarrow$ message must be is missing

Non-FIFO bounded delay channels delay - use timeout

(Message 4 should have arrived by now, but it did not)

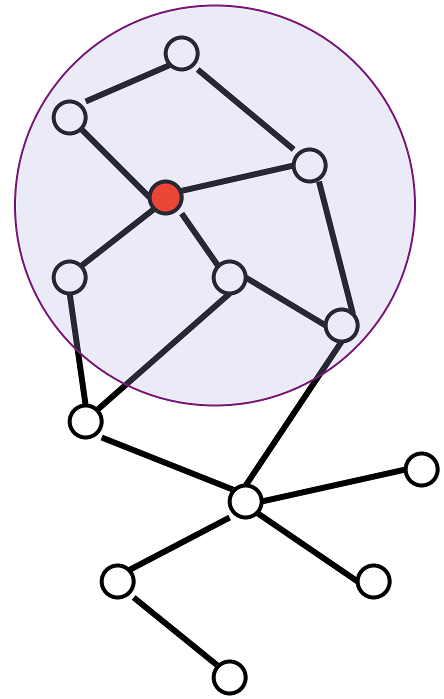
What about non-FIFO channels for which the upper bound of the delay is not known?

-- Use *sequence numbers* and acknowledgments. But acknowledgments may also be lost.

We will soon look at a real protocol dealing with omission failure ….

Detection of transient failures

The detection of an abrupt change of state from S to S' requires the periodic computation of local or global snapshots of the distributed system. The failure is *locally detectable* when a snapshot of the distance-1 neighbors reveals the violation of some invariant.



Example: Consider graph coloring

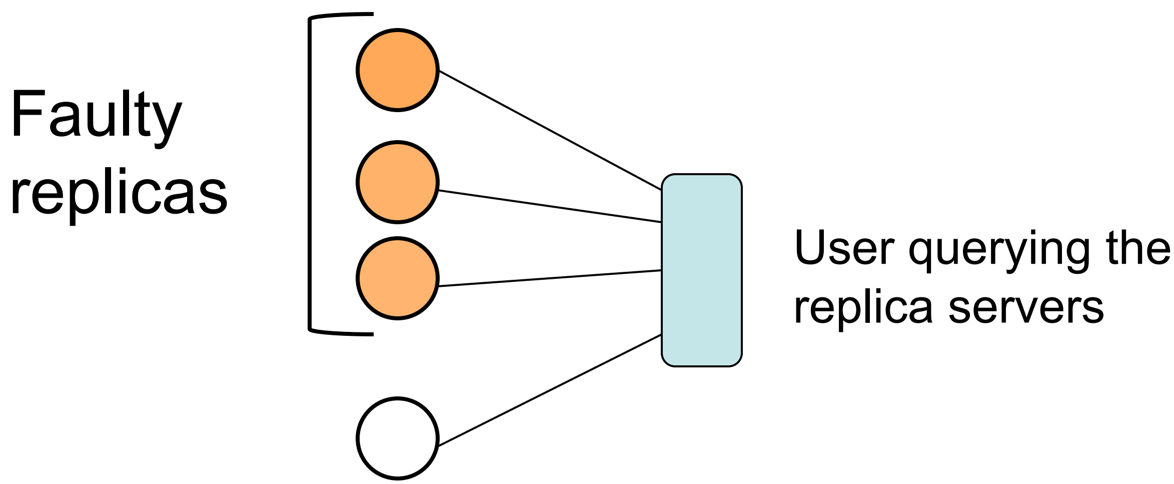
Detection of Byzantine failures

A system with 3f+1 processes is considered adequate for (sometimes) detecting (and definitely masking) up to f byzantine faults.

More on Byzantine faults later.

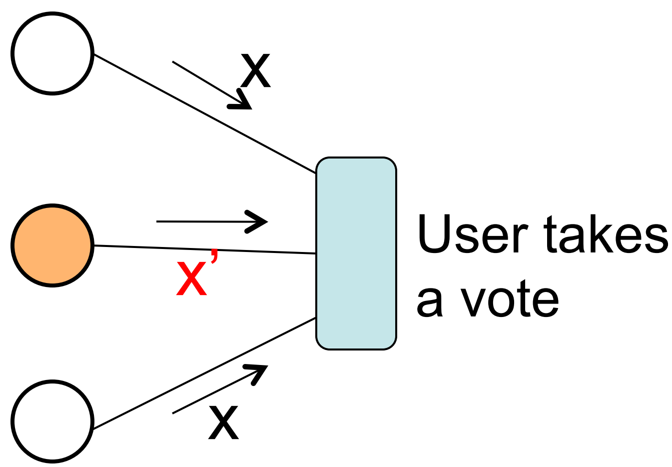
Tolerating crash failures

It is possible to tolerate f crash failures using (f+1) servers. So for tolerating a single crash failure, Double Modular Redundancy (DMR) is adequate



Triple Modular Redundancy

Triple modular redundancy (TMR) for masking any single failure.

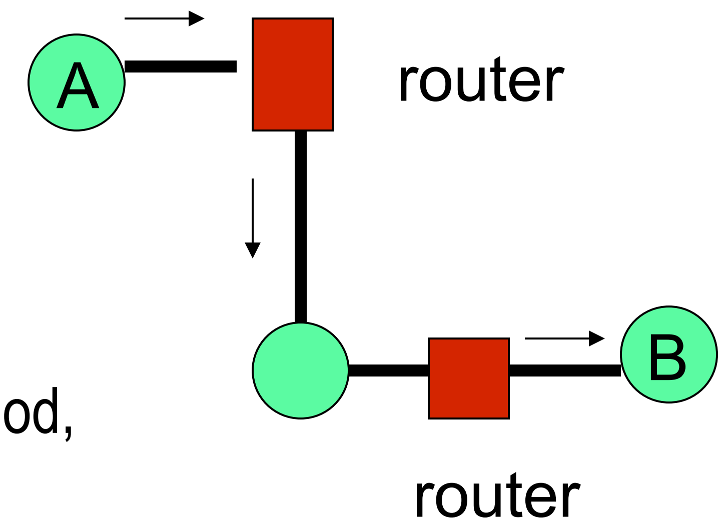


N-modular redundancy masks up to m failures, when $N = 2m + 1$

Tolerating omission failures

A central issue in networking

Routers may drop messages, but reliable end-to-end transmission is an important requirement. If the sender does not receive an ack within a time period, it retransmits (it may so happen that the was not lost, so a duplicate is generated). This implies, the communication must tolerate **Loss, Duplication, and Re-ordering** of messages



Stenning's protocol

{program for process S}

define ok : **boolean**; next : **integer**;

initially next = 0, ok = true, both channels are empty;

do ok $\rightarrow$ send (m[next], next); ok:= false

[] (ack, next) is received $\rightarrow$ ok:= true; next := next + 1

[] timeout (R,S) $\rightarrow$ send (m[next], next)

od

{program for process R}

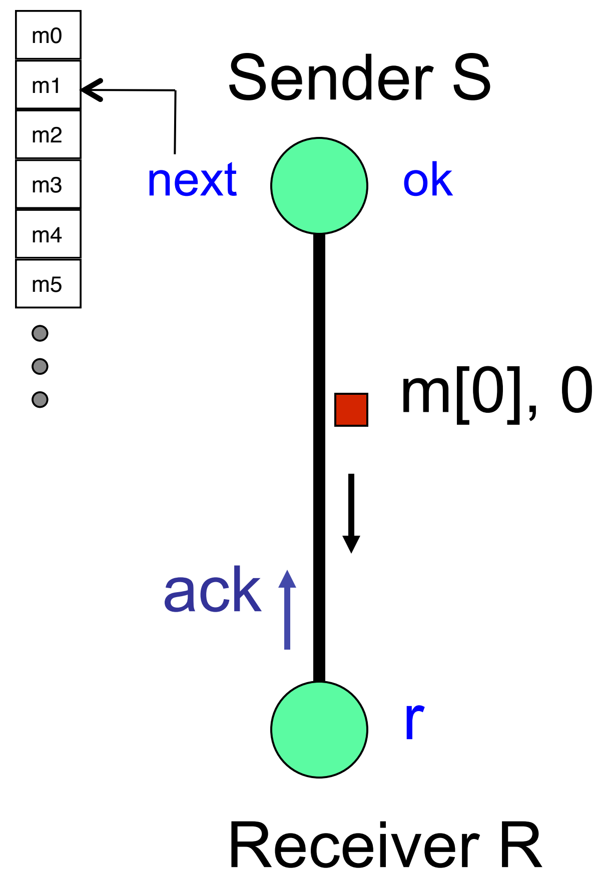
define r : **integer**;

initially r = 0;

do (m[ ], s) is received $\wedge$ s = r $\rightarrow$ accept the message;
send (ack, r);
r:= r+1

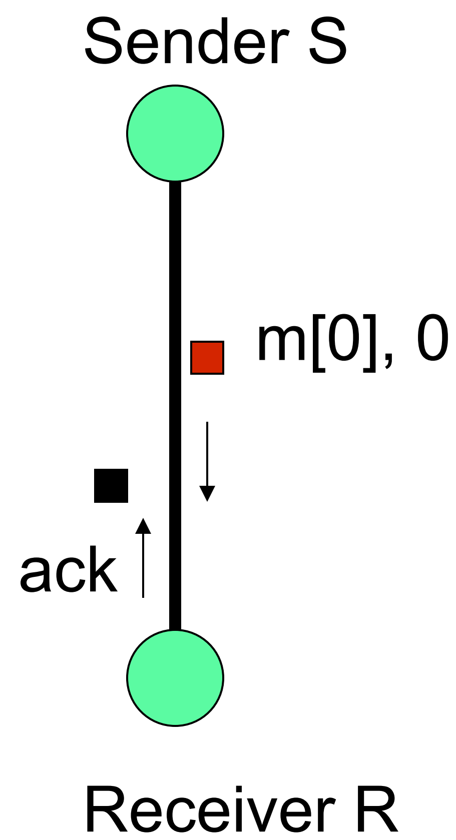
[] (m[ ], s) is received $\wedge$ s $\neq$ r $\rightarrow$ send (ack, r-1)

od



Observations on Stenning's protocol

Both messages and acks may be lost



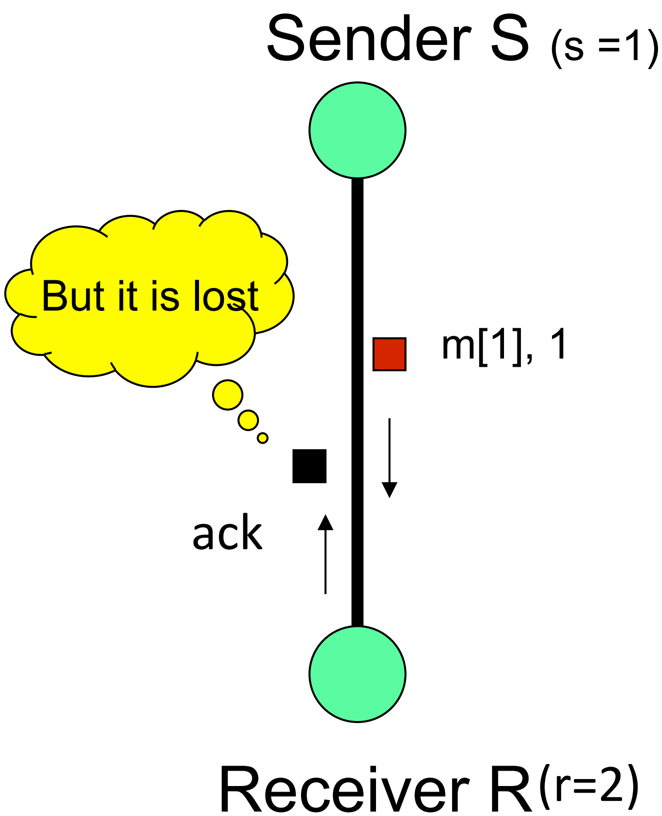
Q. Why is the last ack reinforced by R when s≠r?

A. Needed to guarantee progress.

Progress is guaranteed, but the protocol

is inefficient due to low throughput.

Observations on Stenning's protocol

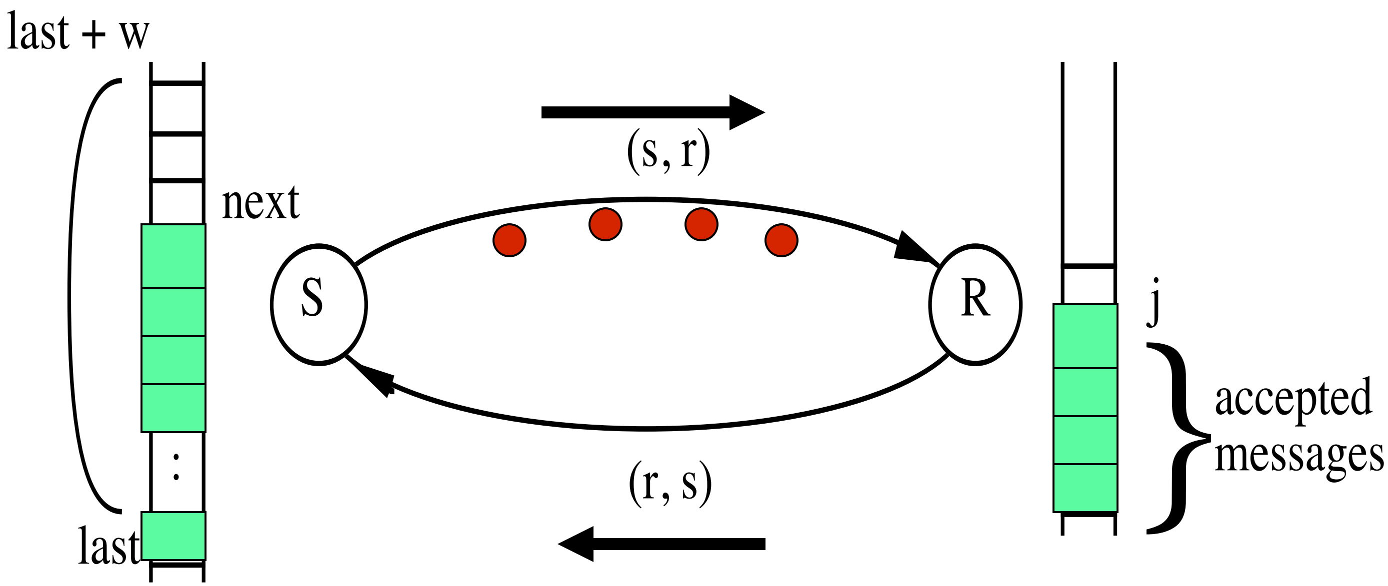


If the last ack is not reinforced
by the receiver when s≠r, then
the following scenario is possible

-- The ack of m[1] is lost.
-- After timeout, S sends m[1] again.
-- But R was expecting m[2], so does not send ack.

And S keeps sending m[1] repeatedly.
This affects progress.

Sliding window protocol



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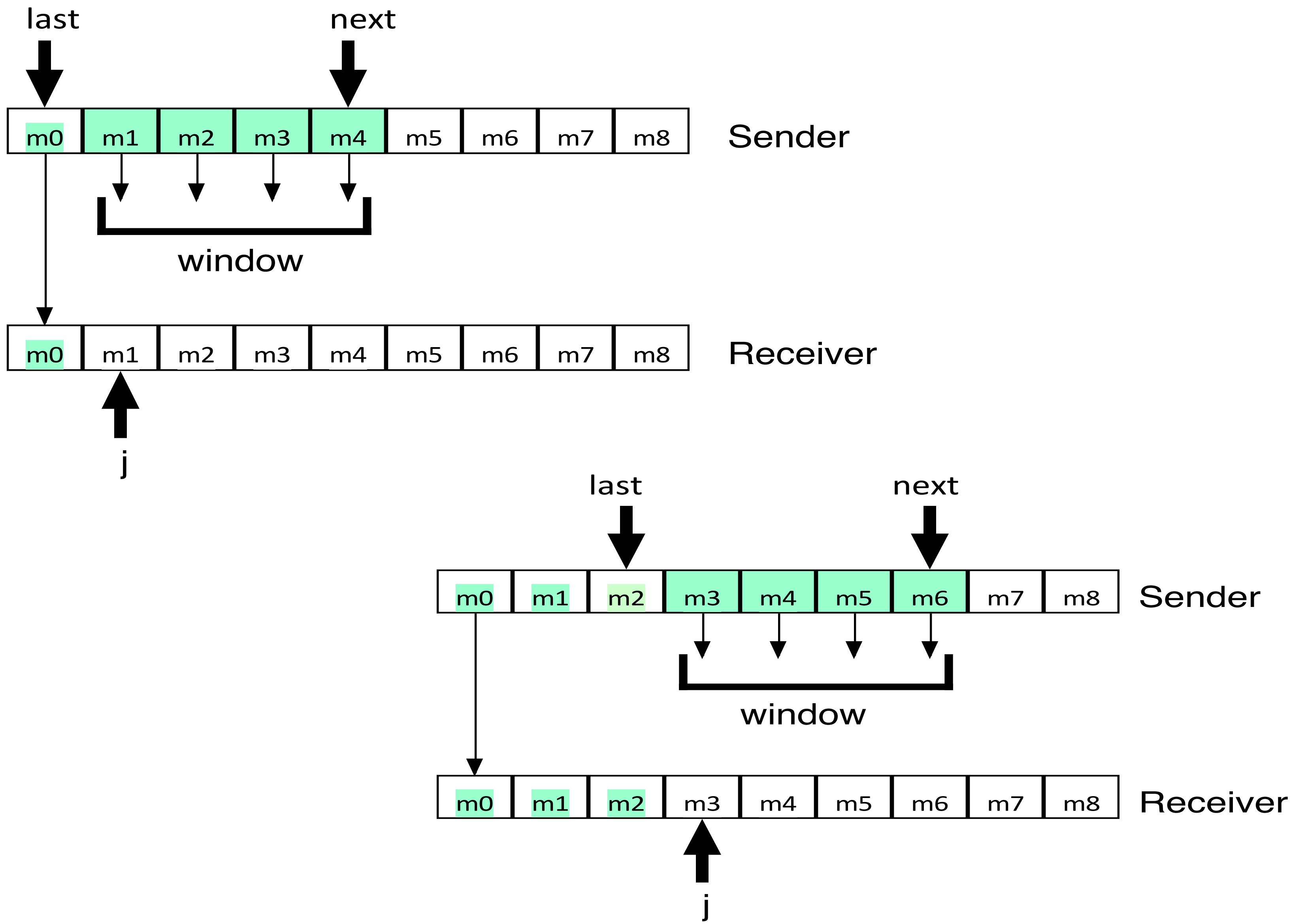
The sender continues the send action
without receiving the acknowledgements of *at most*
w messages (**w > 0), w** is called the **window size**.

Sliding window protocol

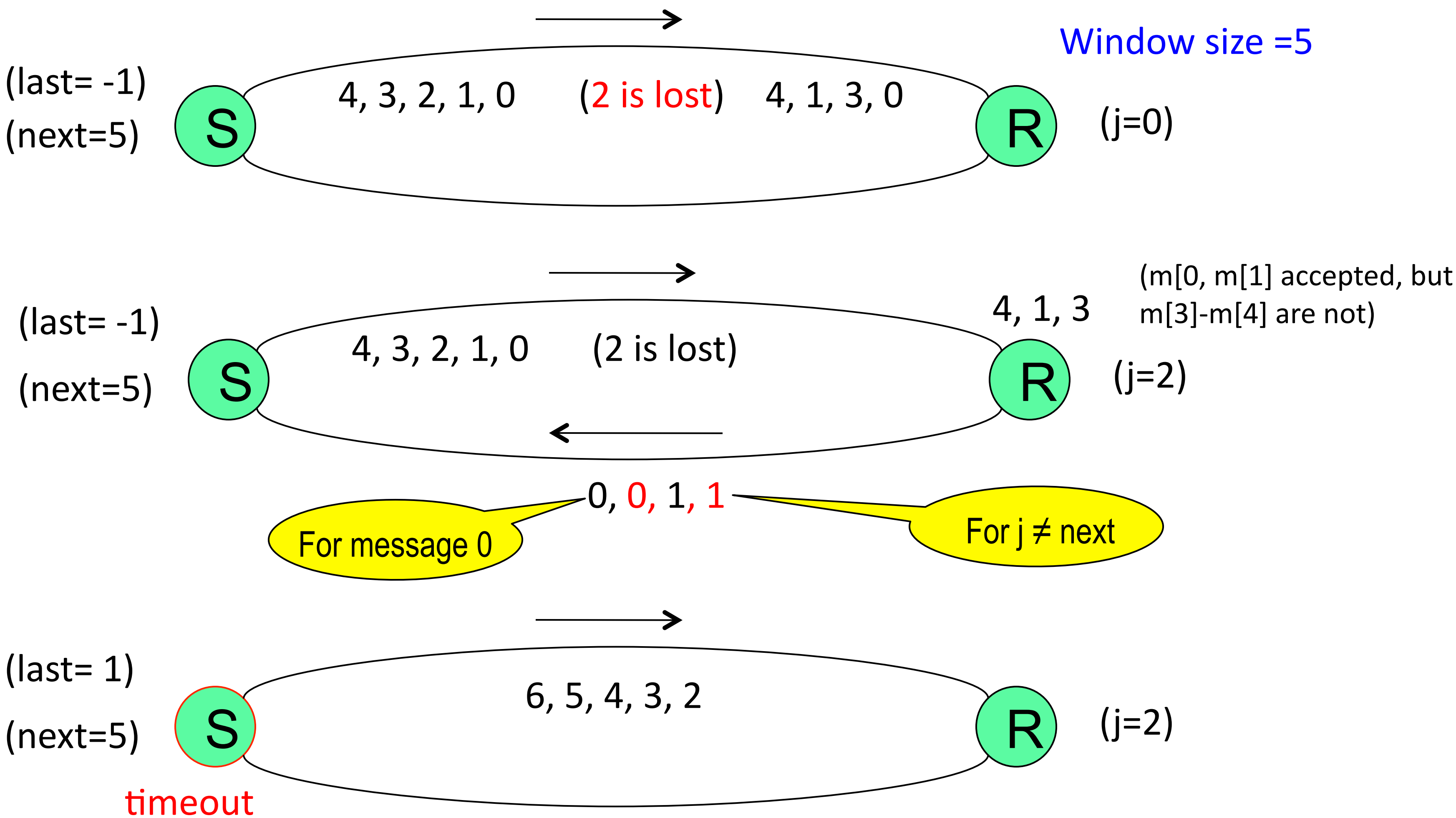


Sliding window protocol

```
{program for process S}
define    next,  last, w : integer;
initially  next = 0, last = -1, w > 0

do   last+1 ≤ next ≤ last + w →
  send  (m[next], next);  next := next + 1
[]   (ack, j) is received        →
             if      j > last →    last := j
             []      j ≤ last  →    skip
             fi
[]   timeout (R,S) → next := last+1
             {retransmission begins}
od
```

```
{program for process R}
define  j  :    integer;
initially  j = 0;

do (m[next], next) is received →

    if j = next  →   accept message;
                     send (ack, j);
                     j:= j+1
    []  j ≠ next   →   send (ack, j-1)
     fi;
od
```

Example



Window size =5
(last= -1)
(next=5)
S
4, 3, 2, 1, 0
(2 is lost)
4, 1, 3, 0
R
(j=0)
(m[0, m[1] accepted, but
m[3]-m[4] are not)
4, 1, 3
(last= -1)
(next=5)
S
4, 3, 2, 1, 0
(2 is lost)
R
(j=2)
0, 0, 1, 1
For message 0
For j ≠ next
(last= 1)
(next=5)
S
6, 5, 4, 3, 2
R
(j=2)
timeout

Observations

Lemma. Every message is accepted exactly once.

(Note the difference between reception and acceptance)

Lemma. Message m[k] is always accepted before m[k+1].

(Argue that these are true. Consider various scenarios of omission failure)

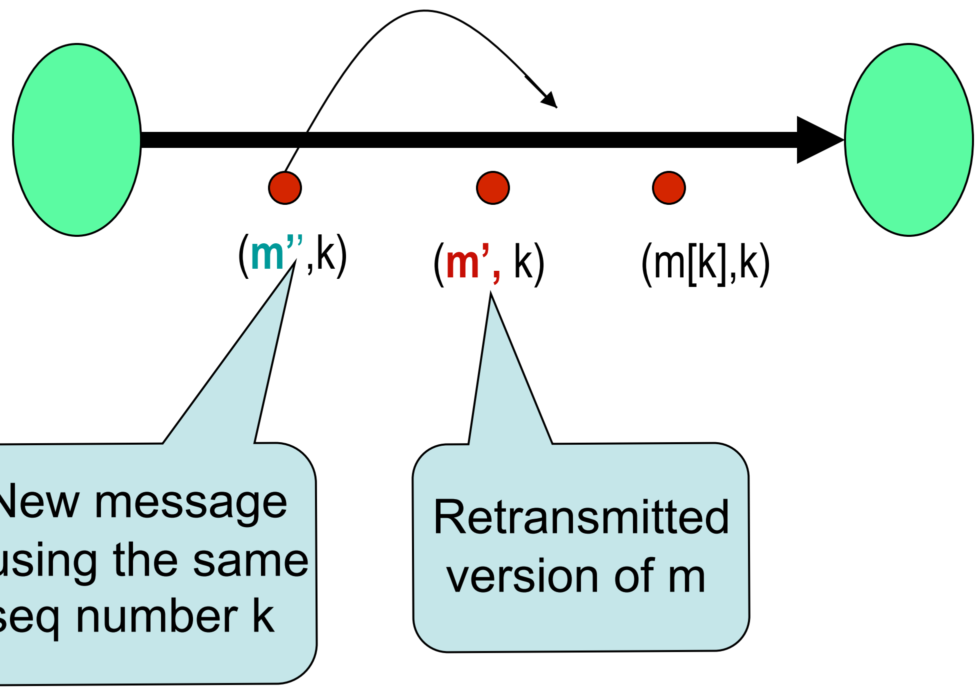
Uses unbounded sequence number.

This is bad. Can we avoid it?

Theorem

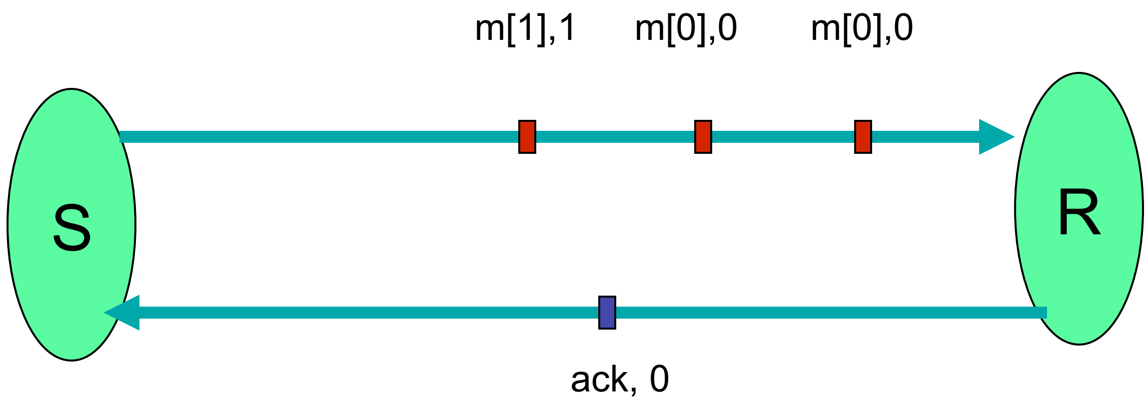
If the communication channels are non-FIFO, and the message propagation delays are arbitrarily large, then using bounded sequence numbers, it is impossible to design a window protocol that can withstand the (1) loss, (2) duplication, and (3) reordering of messages.

Why unbounded sequence no?



We want to accept m" but reject m'. How is that possible?

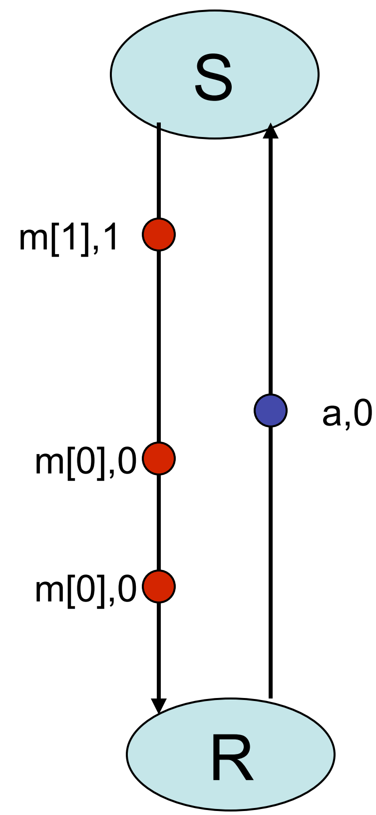
Alternating Bit Protocol



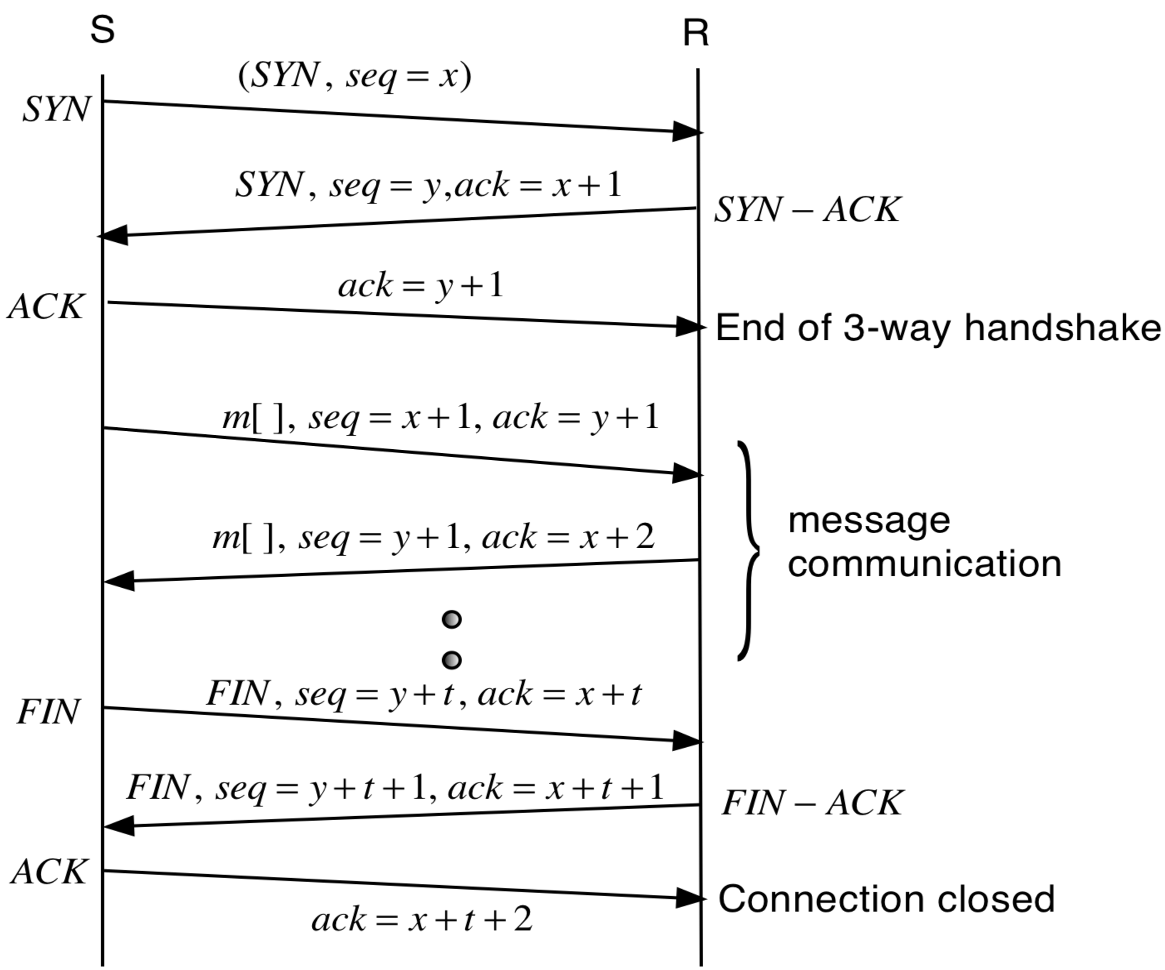
ABP is a ***link layer protocol***. Works on **FIFO channels only**. Guarantees reliable message delivery with a **1-bit sequence number** (this is the **t**raditional version with window size = 1). Study how this works.

Alternating Bit Protocol

```
program ABP;
{program for process S}
define  sent, b  :  0 or 1; next :  integer;
initially  next = 0, sent = 1, b = 0, and channels are empty;
do sent ≠ b   →        send  (m[next], b);
                        next := next+1; sent := b
[] (ack, j) is received  →  if  j = b → b := 1- b
                            [] j ≠ b → skip
                            fi
[] timeout (R,S)  →  send  (m[next-1], b)
od
{program for process R}
define j  :   0 or 1; {initially  j = 0};
do          (m[ ], b) is received →
            if   j = b → accept  the message;
                         send (ack, j); j:= 1 - j
             [] j ≠ b → send (ack, 1-j)
            fi
od
```



How TCP works



Three-way handshake. *Sequence numbers* are unique w.h.p.

TCP sequence numbers

Supports **end-to-end logical connection** **between any two computers on the Internet**. Basic idea is the same as those of sliding window protocols. But TCP uses bounded sequence numbers (32 or 64 bits)!

The primary issue here is to *prevent another connection from reusing an existing sequence number,* such re-use may **open the door for an attack**. By correctly guessing (or acquiring) an existing sequence number, the attacker may inject arbitrary messages that will be accepted by the receiver as valid messages from the sender. The use of a *random initial sequence numbers* by the sender and the receiver prevents it.

TCP sequence numbers

There is the potential of old packets with sequence numbers belonging to an acceptable window appearing into the system. These are prevented by automatically killing old packets (using TTL) after a **time = 2d**, where **d** is the round trip delay.

How TCP works: Various Issues

•Why is the knowledge of roundtrip delay important?

--Timeout can be correctly chosen

• What if the timeout period is too small / too large?

--

• What if the window is too small / too large?

--

• *Adaptive retransmission*: receiver can throttle sender

and control the window size to save its buffer space.