4. The Bounded Re-transmission Protocol

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Purpose of this Lecture

- The Bounded Re-transmission Protocol is a file transfer protocol

- This is a problem dealing with fault tolerance

- We suppose that the transfer channels are unreliable

- We present classical solutions to handle that problem: timers.

- We would like to see how we can formalize such timers

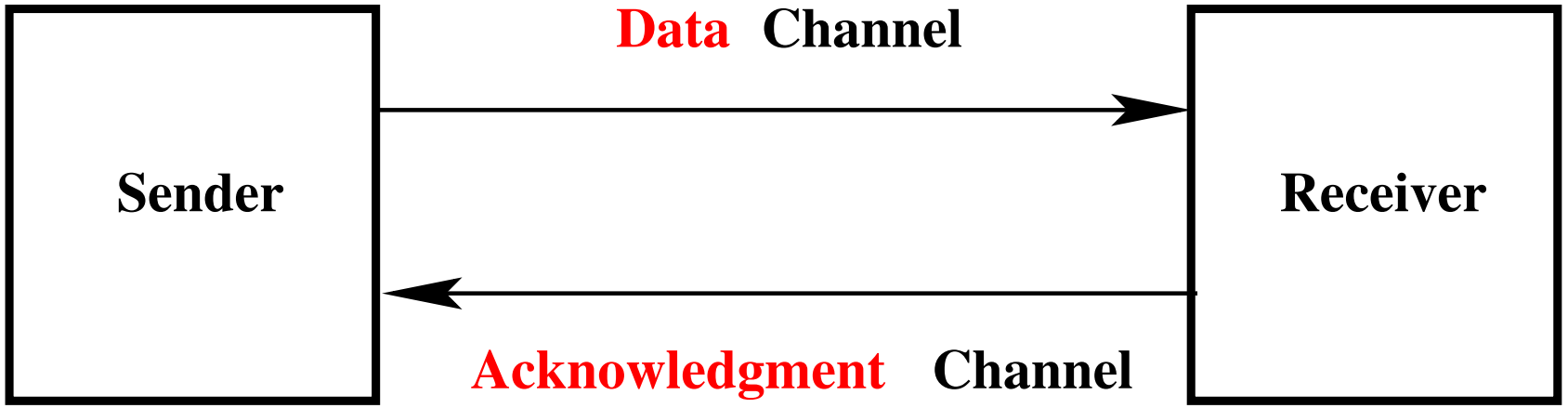
The Bounded Retransmission Protocol

- A sequential file is transmitted from a Sender to a Receiver

- The file is transmitted piece by piece through a Data Channel

- After receiving some data, the Receiver sends an acknowledgment

- After receiving it, the Sender sends the next piece of data, etc.



- Messages can be lost in the Data or Acknowledgment channels

Requirements (1)

The goal of the BRP is to totally or partially transfer a certain non-empty original sequential file from one site to another.	FUN_1
A total transfer means that the transmitted file is a copy of the original one.	FUN_2
A partial transfer means that the transmitted file is a genuine prefix of the original one.	FUN_3

Unreliability of the Communications (1)

- Messages can be lost in the Data or Acknowledgment channels

- The Sender starts a timer before sending a piece of data

- The timer wakes up the Sender after a delay dl

- This occurs if the Sender has not received an acknowledgment in the meantime

Unreliability of the Communications (2)

- dl is guaranteed to be greater than twice the transmission time

- When waken up, the Sender is then sure that the data or the acknowledgment has been lost

- When waken up, the Sender re-transmits the previous data

- The Sender sends an alternating bit together with a new data

- This ensures that the Receiver does not confuse (?) a new data with a retransmitted one.

Abortion of Protocol at the Sender Site

- The Sender can re-transmit the same data at most M times

- After this, the Sender decides to abort

- How does the Receiver know that the Sender aborted?

Abortion of Protocol at the Receiver Site

- Each time the Receiver receives a new piece of data, it starts a timer

- The timer wakes up the Receiver after a delay $(M + 1) \times d$

- This occurs if the Sender has not received a new data in the meantime.

- After this delay, the Receiver is certain that the Sender has aborted

- Then the Receiver aborts too.

Final Situation of the Protocol

- At the end of the protocol, we might be in one of the three situations:

(1) The file has been transmitted entirely and the Sender has received the last acknowledgment

(2) The file has been transmitted entirely but the Sender has not received the last acknowledgment

(3) The file has not been transmitted entirely

Requirements (2)

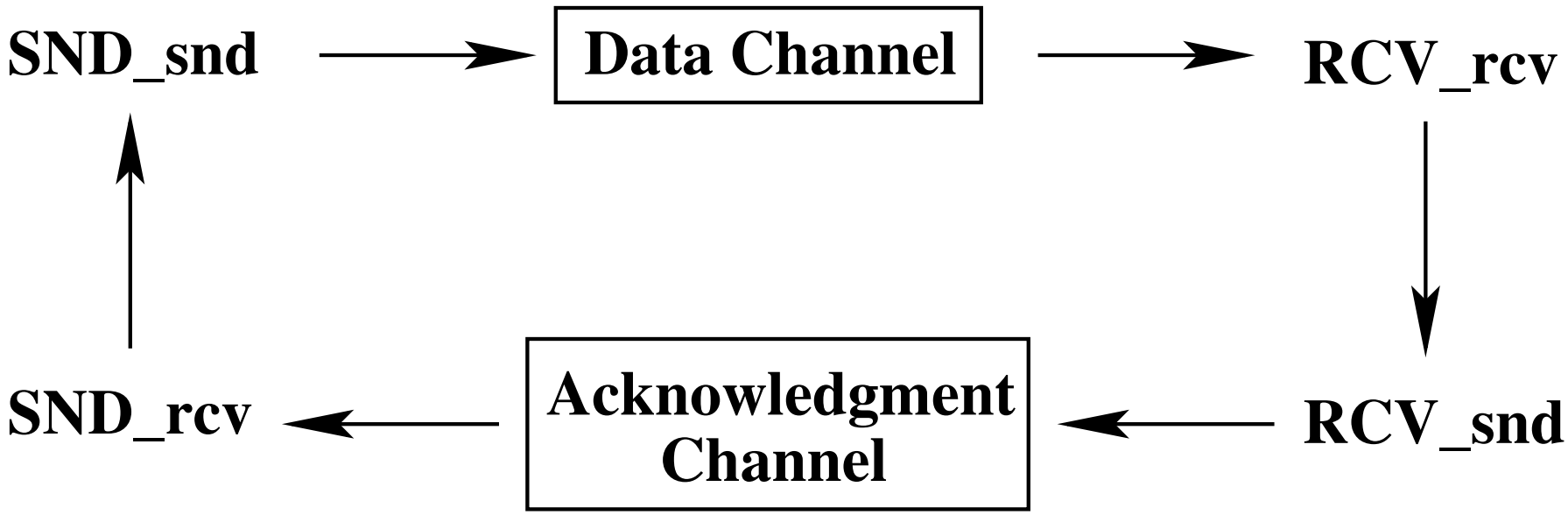
Each site may end up in any of the two situations: - either it believes that the protocol has terminated successfully, - or it believes that the protocol has aborted	FUN_4

When the Sender believes that the protocol has terminated successfully then the Receiver believes so too.	FUN_5

Requirements (3)

However, it is possible for the Sender to believe that the protocol has aborted while the Receiver believes that it has terminated successfully.	FUN_6
When the Receiver believes that the protocol has terminated successfully, this is because the original file has been entirely copied on the Receiver's site.	FUN_7
When the Receiver believes that the protocol has aborted, this is because the original file has not been copied entirely on the Receiver's site.	FUN_8

Pseudo-code for the Protocol



The Sender sends Data

SND_snd
  when
    SND_snd is waken up
  then
    Acquire data from Sender's file;
    Store acquired data on Data Channel;
    Store Sender's bit on Data Channel;
    Start Sender's timer;
    Activate Data Channel;
  end

The Receiver Receives Data

```
RCV_rcv
   when
      Data Channel interrupt occurs
   then
      Acquire Sender's bit from Data Channel;
      if  Sender's bit = Receiver's bit  then
         Acquire Data from Data Channel;
         Store data on Receiver's file;
         Modify Receiver's bit;
         if  data is not the last one  then
            Start Receiver's timer;
         end
      end
      Reset Data Channel Interrupt;
      Wake up RCV_snd;
   end
```

The Receiver sends Acknowledgment

RCV_snd
when
RCV_snd is waken up
then
Activate Acknowledgment Channel;
end

The Sender Receives Acknowledgment

```
SND_rcv
   when
      Acknowledgment Channel interrupt occurs
   then
      Remove Data from Sender's file;
      Reset retry counter;
      Modify Sender's bit;
      Wake up event SND_snd;
      Reset Acknowledgment Channel interrupt;
      if  Sender's file is not empty  then
         Wake up event SND_snd
      end
   end
```

Timer Interrupt occurs at Sender's Site


```
SND_timer
  when
    Sender's timer interrupt occurs
  then
    if  retry counter is equal to M+1  then
      Abort protocol on Sender's site;
    else
      Increment retry counter;
      Wake up event SND_snd;
    end
  end
```

Timer Interrupt occurs at Receiver's Site

RCV_timer
when
Receiver's timer interrupt occurs
then
Abort protocol on Receiver's site
end

About the Pseudo-code

- Quite often, protocol are "specified" by such pseudo-codes

- In fact, such a pseudo-code raises a number of questions:
    - Are we sure that this description is correct?
    - Are we sure that this protocol terminates?
    - What kinds of properties should this protocol maintain?

- Hence the formal development which is presented now

Refinement Strategy

(1) FUN_1, FUN_2, FUN_3: partial transmission of the file in one shot.

(2) FUN_4 to FUN_8: each participant has access to the other

(3) Introducing unreliable channels and timers.

(4) Optimize protocol

Reminder (1)

The goal of the BRP is to totally or partially transfer a certain non-empty original sequential file from one site to another.	FUN_1
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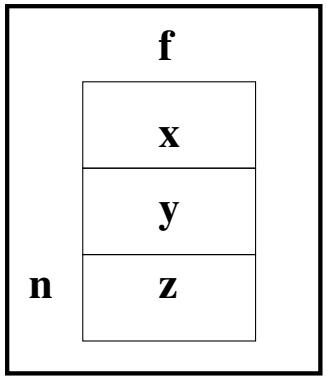
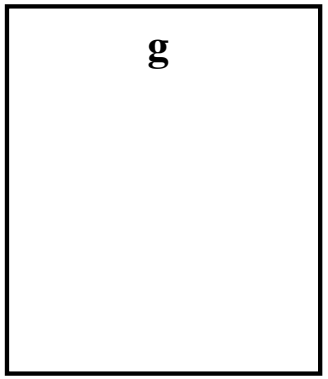
The Sender and the Receiver: a First View

INITIAL SITUATION

SENDER

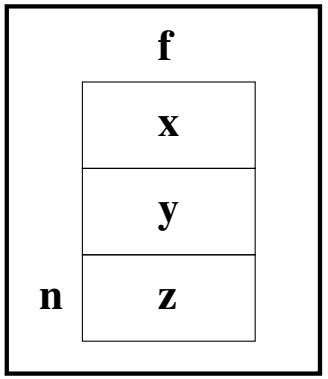


RECEIVER

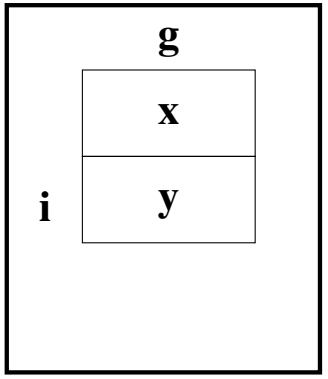


FINAL SITUATION

SENDER



RECEIVER



Initial Model: the Constants

- Set D denotes the objects in the files

- Constant n denotes the size of the non-empty file

- Constant f denotes the original file.

set: D

constants: n
f

axm0_1: $0 < n$

axm0_2: $f \in 1 \mathinner{..} n \rightarrow D$

Initial Model: the Variables

- Variable i denotes the size of file g

- Variable g denotes the transmitted file.

variables: i, g

inv0_1: $i \in 0 \mathinner{..} n$

inv0_2: $g \in 1 \mathinner{..} i \rightarrow D$

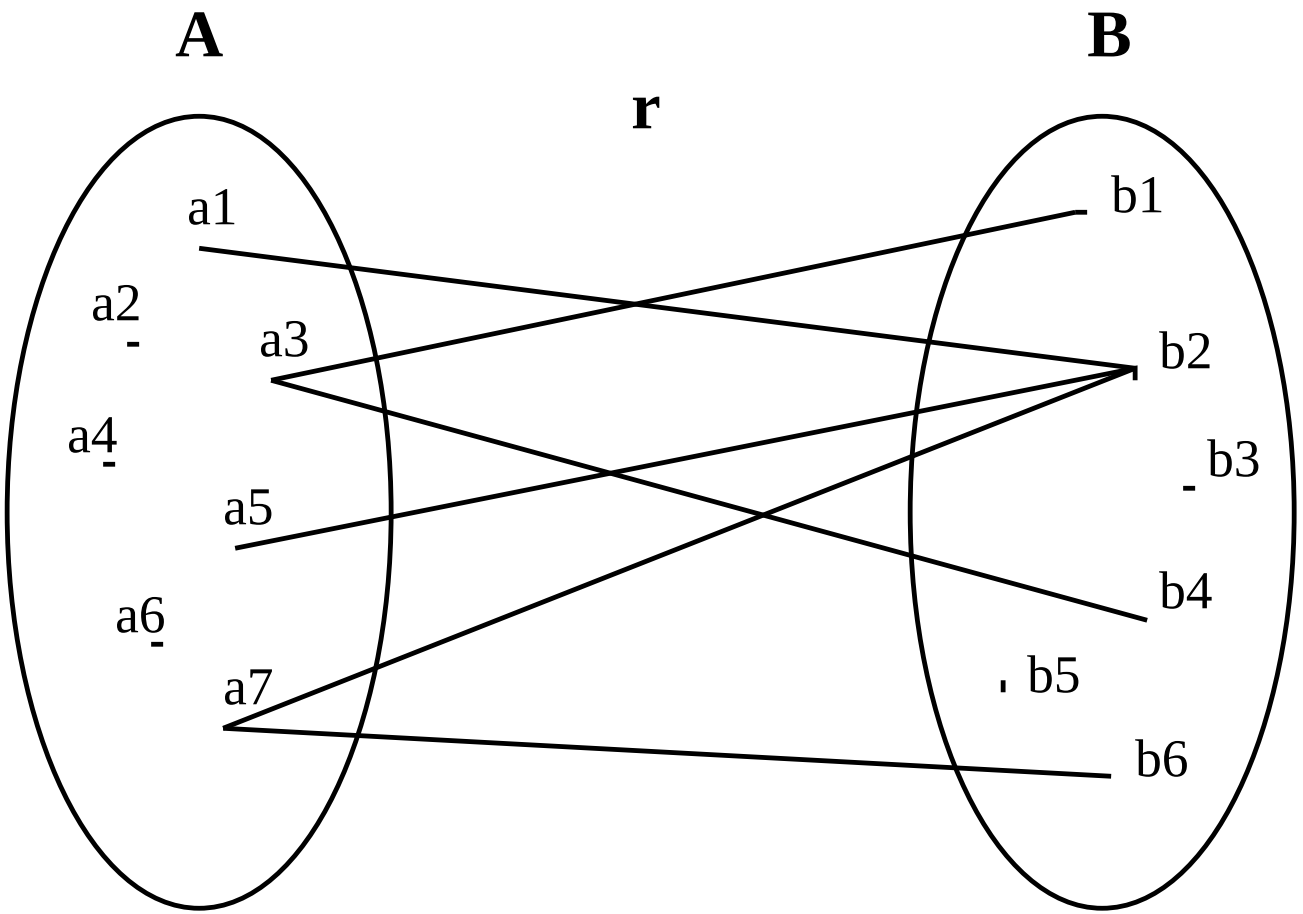
Reminder of Mathematical Conventions (1)

$x \in S$	set membership operator
$\mathbb{N}$	set of natural numbers: $\{0, 1, 2, 3, \ldots\}$
$a \,..\, b$	interval from a to b: $\{a, a+1, \ldots, b\}$ (empty when $b < a$)
$a \mapsto b$	pair constructing operator
$S \times T$	Cartesian product operator
$S \subseteq T$	set inclusion operator
$\mathbb{P}(S)$	power set operator

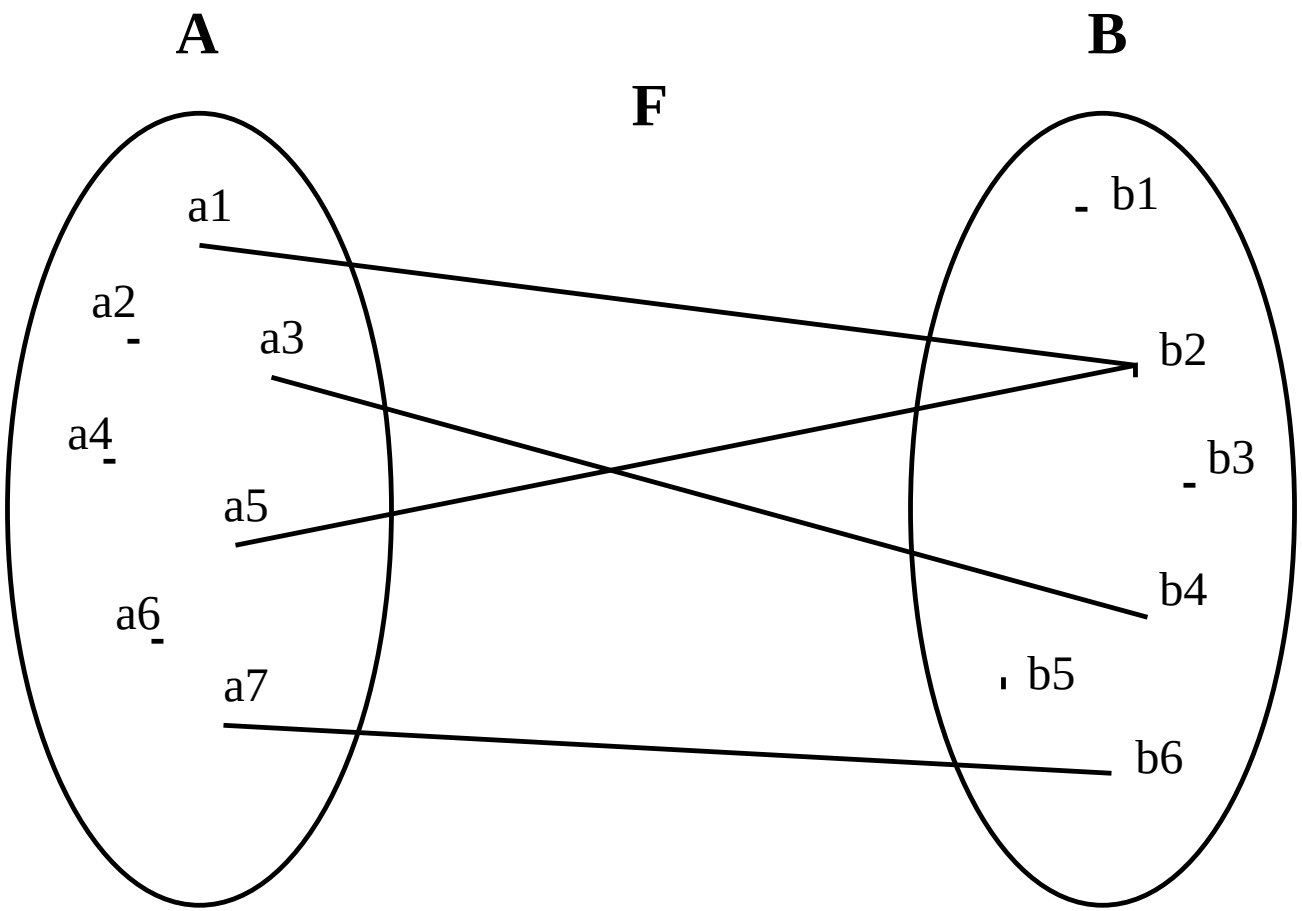
Reminder of Mathematical Conventions (2)

$S \leftrightarrow T$	set of binary relations from S to T
$S \rightarrow T$	set of total functions from S to T
$S \nrightarrow T$	set of partial functions from S to T
$\mathbf{dom}(r)$	domain of a relation r
$\mathbf{ran}(r)$	range of a relation r

A Binary Relation r from a Set A to a Set B



A Partial Function F from a Set A to a Set B

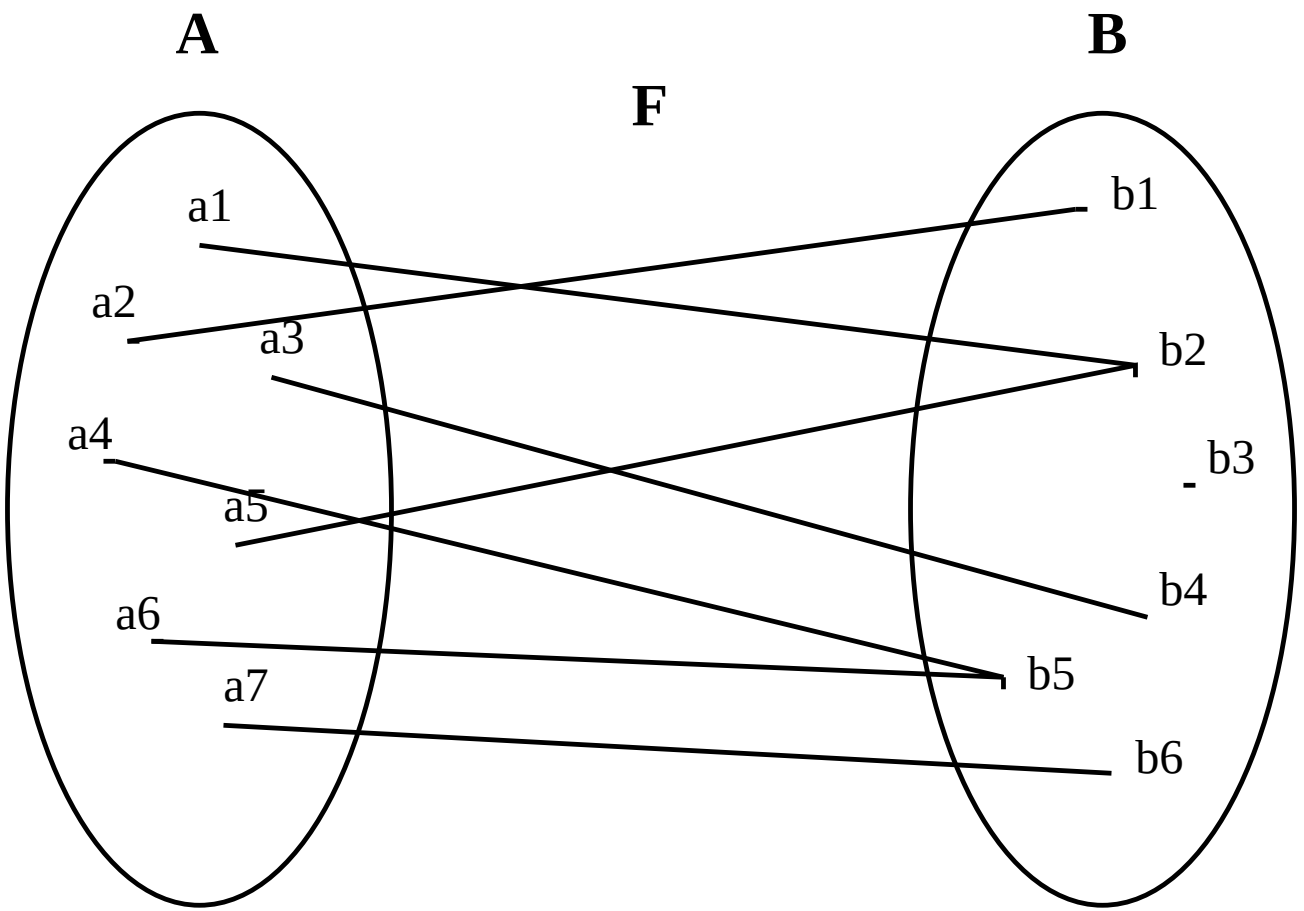


$$F = \{a1 \mapsto b2,\ \ a3 \mapsto b4,\ \ a5 \mapsto b2,\ \ a7 \mapsto b6\}$$

$$\mathsf{dom}\,(F) = \{a1,\ \ a3,\ \ a5,\ \ a7\}$$

$$\mathsf{ran}\,(F) = \{b2,\ \ b4,\ \ b6\}$$

A Total Function F from a Set A to a Set B



$$\mathrm{dom}\,(F) \;=\; A$$

Initial model: a Single Event (no Protocol)

- Event brp describes the situation at the end of the protocol

- It only says that the file might be partially transmitted

- It is made of a non-deterministic assignment

init
$$i := 0$$
$$g := \varnothing$$

brp
$$i, g \ :| \ i' \in 0 \,..\, n \ \wedge \ g' = (1 \,..\, i') \lhd f$$

- Operator :| is to be read: "become such that . . ."

Informal Meaning

brp

$$i, g :| \left(\begin{array}{l} i' \in 0 \mathinner{..} n \\ g' = (1 \mathinner{..} i') \lhd a \end{array} \right)$$

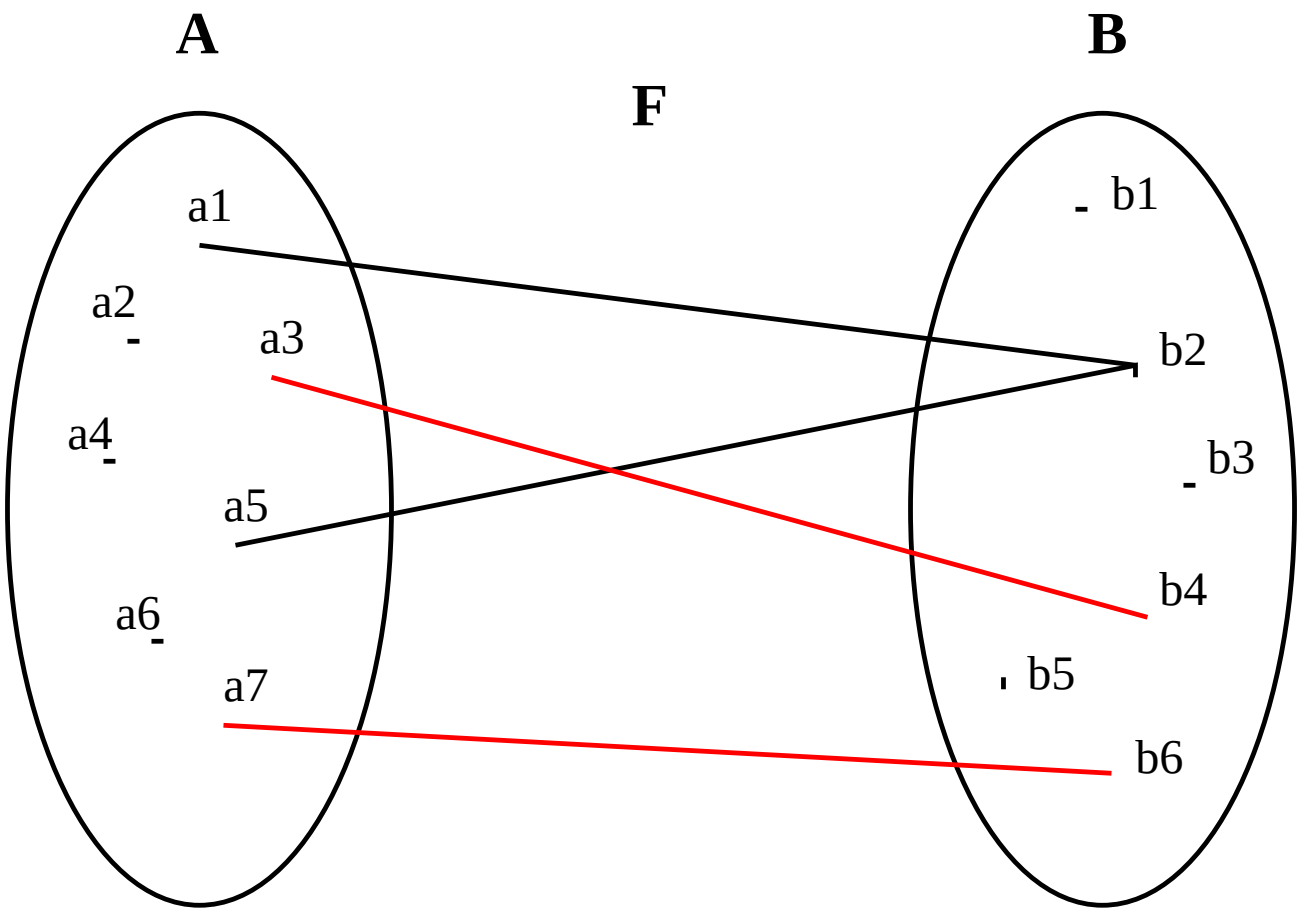
i and g are assigned any values i' and g' such that the following holds:

$$i' \in 0 \mathinner{..} n \ \land \ g' = (1 \mathinner{..} i') \lhd a$$

More Mathematical Conventions: Restrictions

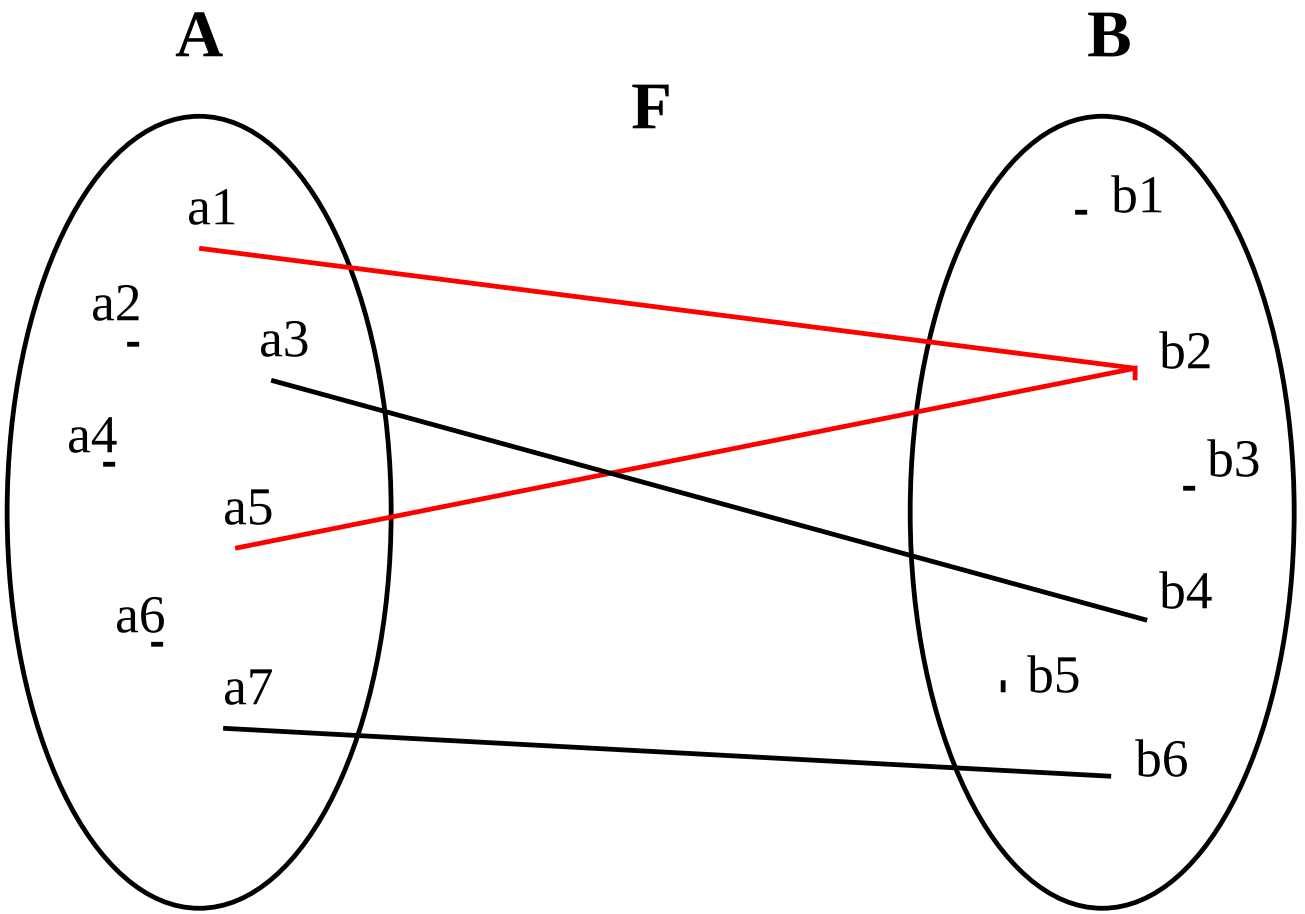
$s \lhd r$	domain restriction operator
$s \lhd\!\!\!\!- r$	domain subtraction operator
$r \rhd t$	range restriction operator
$r \rhd\!\!\!\!- t$	range subtraction operator

The Domain Restriction Operator



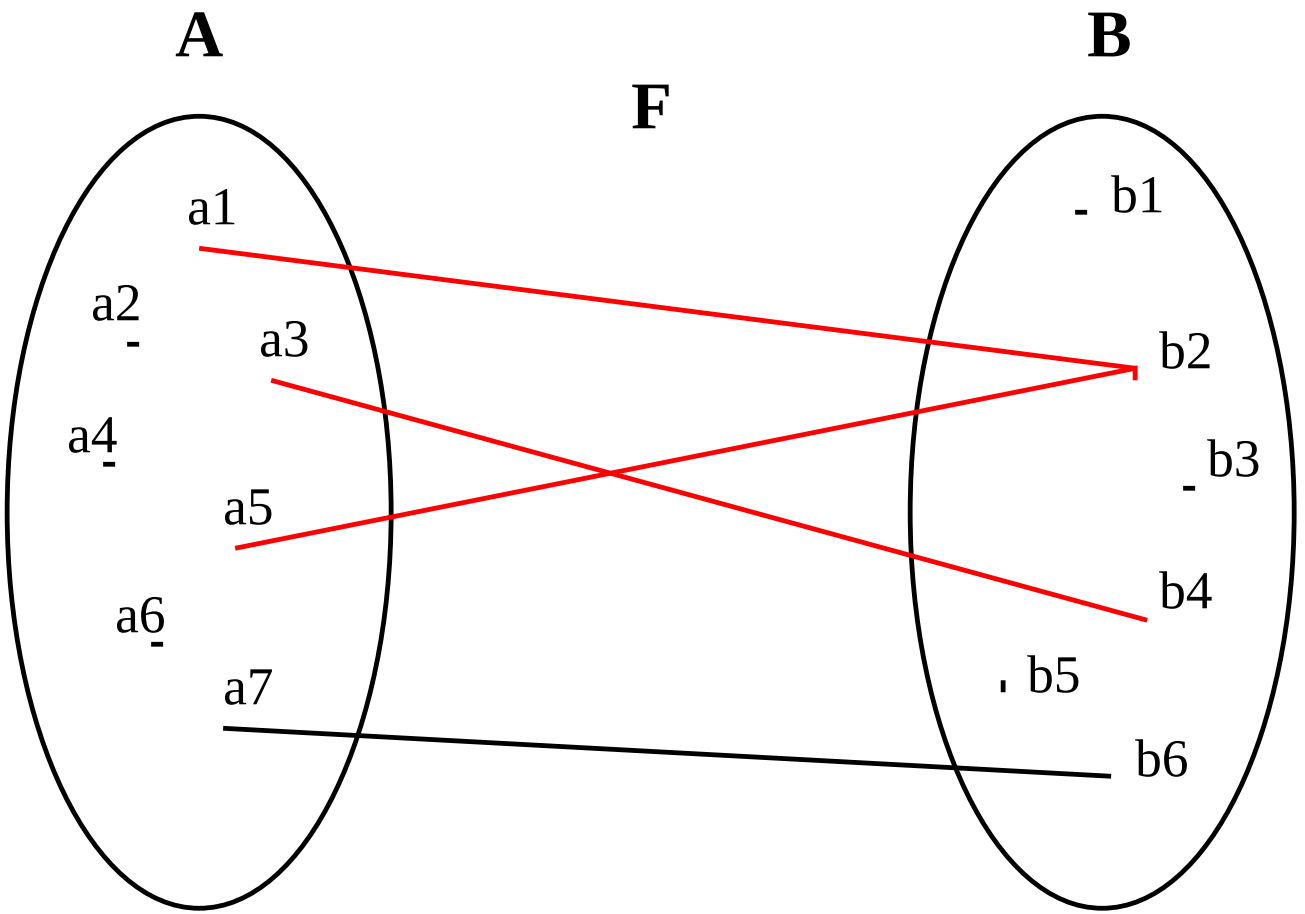
$$\{a3,\ a7\} \lhd F$$

The Domain Subtraction Operator



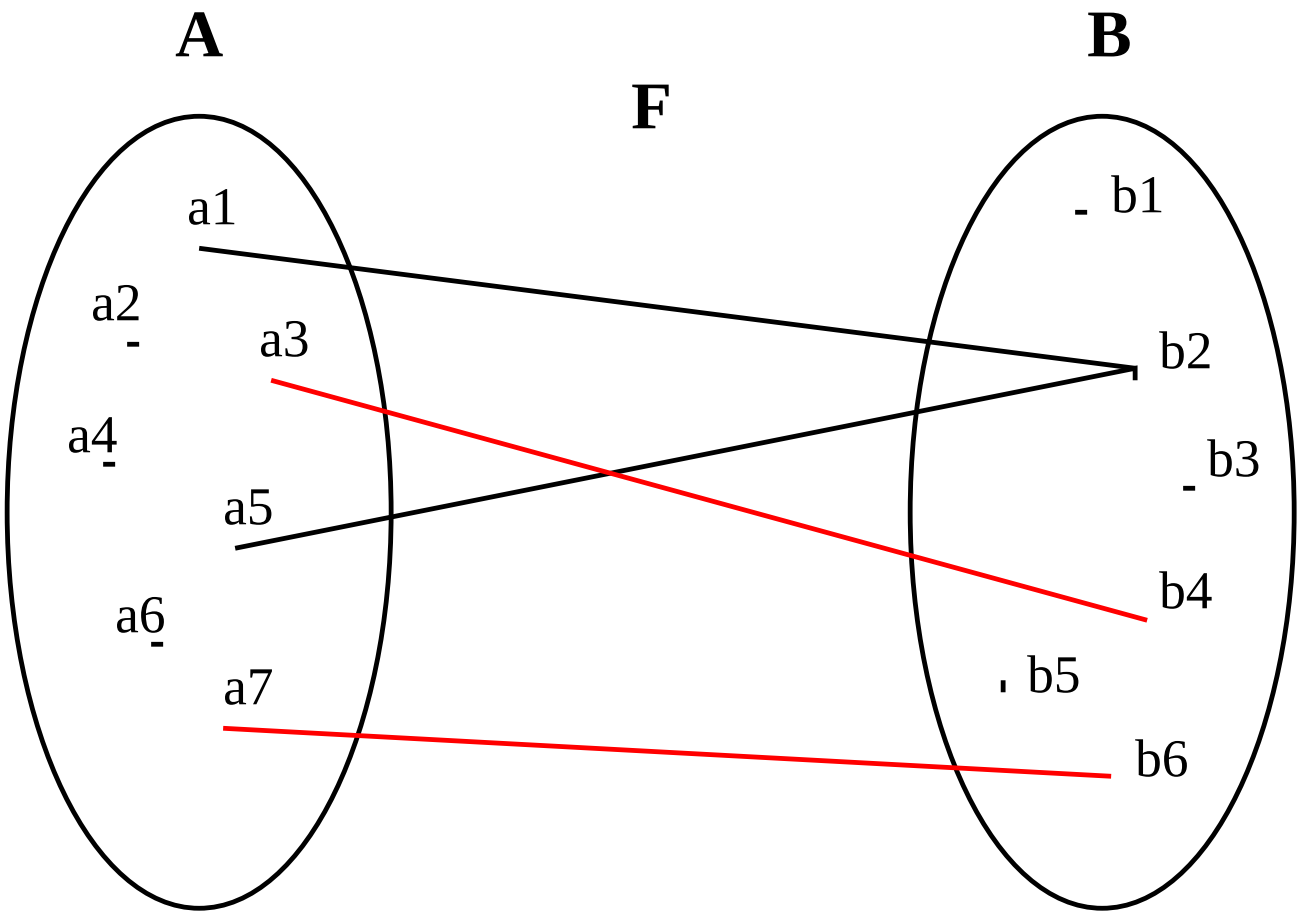
$$\{a3,\ a7\} \lhd F$$

The Range Restriction Operator



$$F \rhd \{b2, b4\}$$

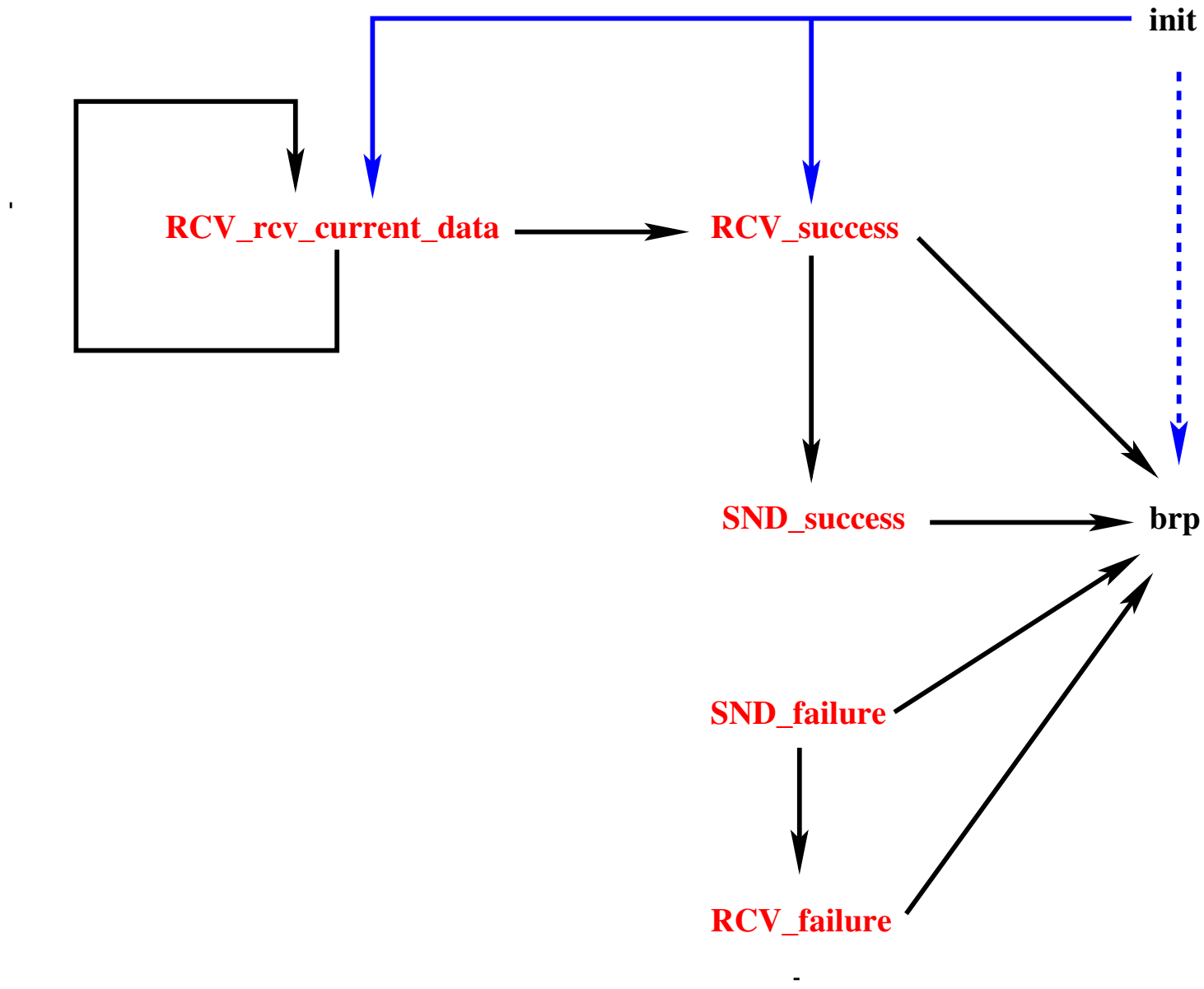
The Range Subtraction Operator



$$F \triangleright \{b2\}$$

The Abstract Situation

First Refinement: Introducing New Events



About new Events in a Refinement

- They allow to observe the (future) system with a finer time grain

- Analogies with a microscope or a parachute

- They refine the (implicit) event doing nothing (skip)

- They must not take control for ever (exhibiting a variant)

First Refinement: Defining more Constants

set: $STATUS$

constants: $\ldots$
$working$
$success$
$failure$

axm1_1: $STATUS = \{working, success, failure\}$

axm1_2: $working \neq success$

axm1_3: $working \neq failure$

axm1_4: $success \neq failure$

First Refinement: Variables

- Variables i and g are replaced by variables r and h

- Variable r denotes the size of the transmitted file

- Variable h denotes the transmitted file

- Variables s_st and r_st denote the status of the participants (Sender and Receiver respectively).

variables: r
h
s_st
r_st

First Refinement: Invariants (1)

- Variables h is a prefix of constant f (invariant **inv1_1** and **inv1_2**)

inv1_1: $r \in 0 \mathinner{..} n$

inv1_2: $h = (1 \mathinner{..} r) \lhd f$

First Refinement: Invariants (2)

- The typing of variables s_st and r_st is implicit (FUN_4)

- Requirements FUN_7 and FUN_8 (Receiver's belief is true) is taken care invariant **inv1_3**

- Requirements FUN_5 and FUN_6 (Sender's status) are taken care by invariant **inv_4**

inv1_3: $r\_st = success \Leftrightarrow r = n$

inv1_4: $s\_st = success \Rightarrow r\_st = success$

First Refinement: the Events (1)

- Initialisation

init
$r := 0$
$h := \varnothing$
$r\_st := working$
$s\_st := working$

First Refinement: the Events (2)

- Event (concrete_)brp now does nothing

- We give witnesses for the abstract after values i' and g'

(abstract_)brp

$$i, g :| \left(\begin{array}{lcl} i' & \in & 0 \,..\, n \\ g' & = & (1 \,..\, i') \lhd a \end{array} \right)$$

(concrete_)brp

when

$r \neq working$

$s \neq working$

with

$i' : \quad i' = r$

$g' : \quad g' = h$

then

skip

end

First Refinement: the Events (3)

RCV_rcv_current_data
when
$r\_st = working$
$r + 1 < n$
then
$r := r + 1$
$h := h \cup \{r + 1 \mapsto f(r + 1)\}$
end

- This event is "cheating" (accessing constant f)
- This new event maintains invariant **inv1_3** and it refines skip

inv1_3: $r = success \Leftrightarrow r = n$

First Refinement: the Events (4)

RCV_success
when
$r\_st = working$
$r + 1 = n$
then
$r\_st := success$
$r := r + 1$
$h := h \cup \{n \mapsto f(n)\}$
end

RCV_failure
when
$r\_st = working$
$s\_st = failure$
then
$r\_st := failure$
end

- These new events are cheating (accessing f and s_st)

- These new events maintain **inv1_3** and **inv1_4** and they refine skip

inv1_3: $r\_st = success \Leftrightarrow r = n$
inv1_4: $s\_st = success \Rightarrow r\_st = success$

First Refinement: the Events (5)

SND_success
when
$s\_st = working$
$r\_st = success$
then
$s\_st := success$
end

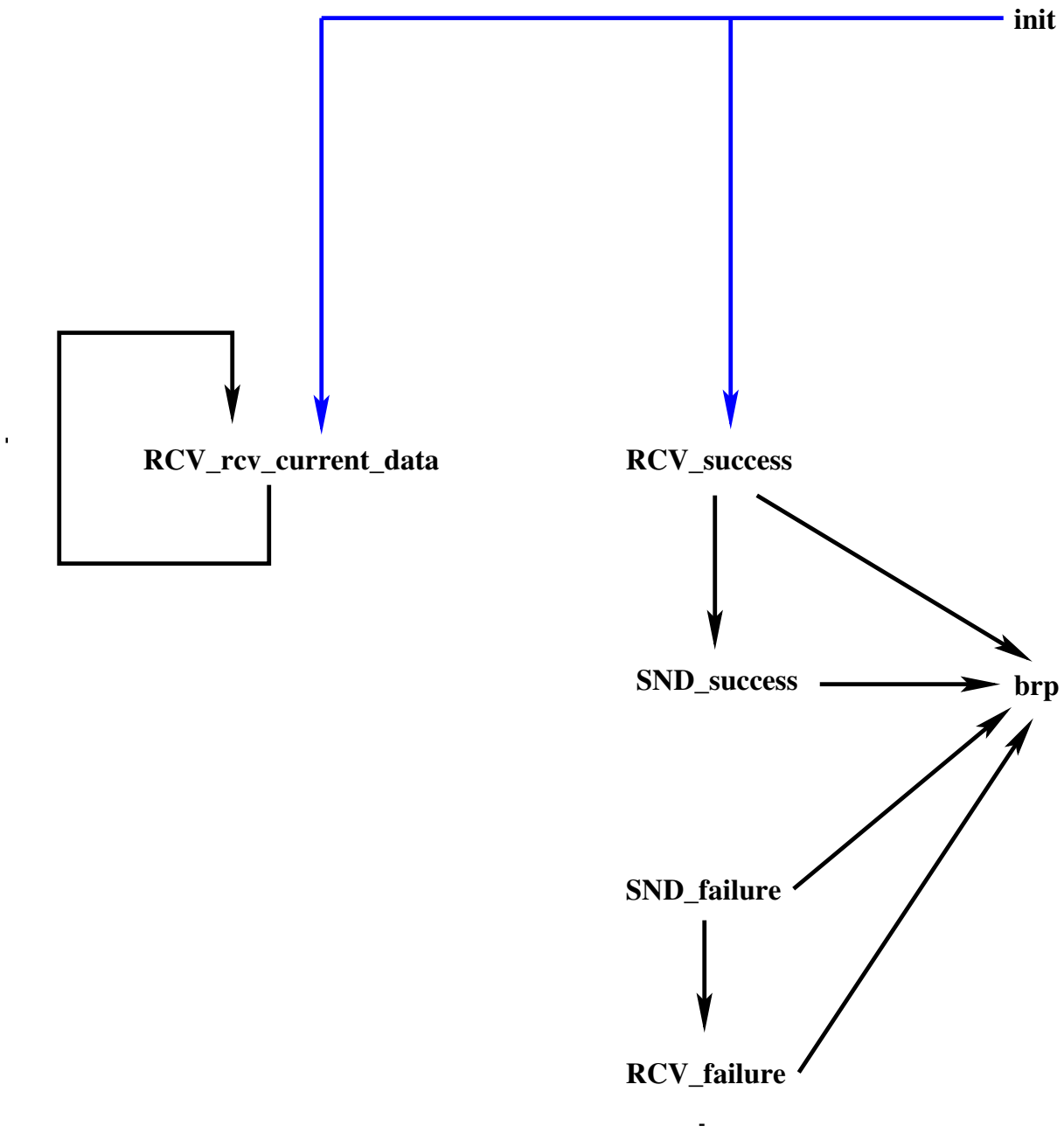
SND_failure
when
$s\_st = working$
then
$s\_st := failure$
end

- Event SND_success is cheating (accessing r_st)

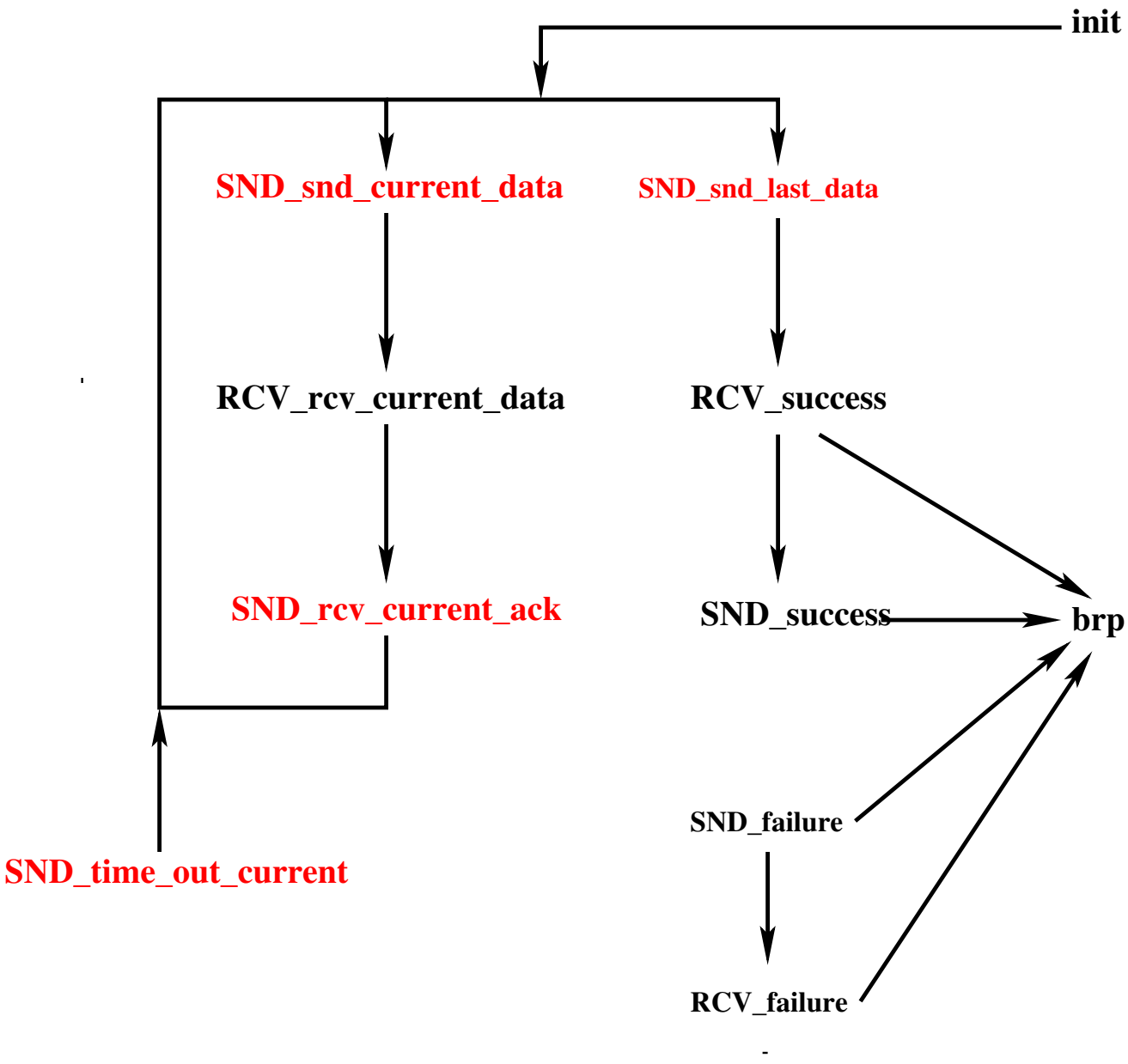
- Event SND_success maintains invariant **inv1_4**

inv1_4: $s\_st = success \Rightarrow r\_st = success$

Second Refinement: Introducing More Events



Second Refinement: Introducing More Events



Second Refinement: More Variables

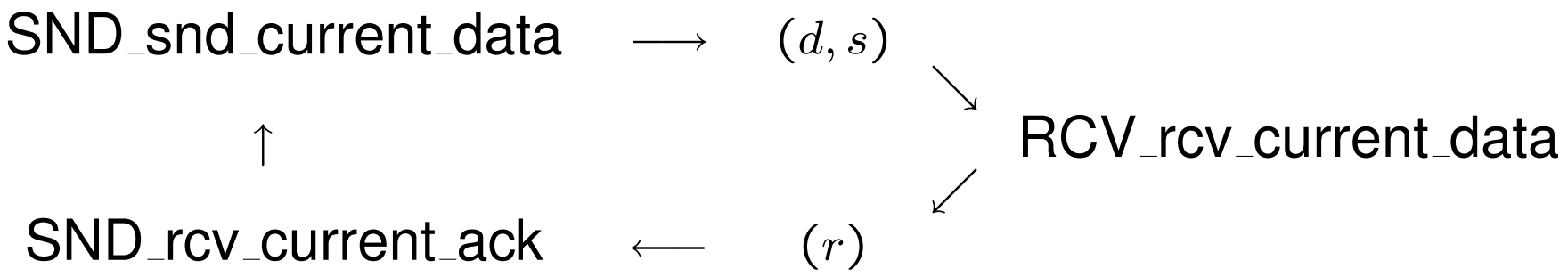
- Variable s is the Sender pointer sent to the Receiver
- Variable d is the data sent to the Receiver
- Variable w is the Sender activation bit
- When w is TRUE it means the Sender has just received the acknowledgement
- When w is FALSE it means the Sender has sent the information to the Receiver

variables: $\ldots$, w, s, d

inv2_1: $s \in 0 \,..\, n-1$

inv2_2: $r \in s \,..\, s+1$

inv2_3: $w = \mathrm{FALSE} \Rightarrow d = f(s+1)$


SND_snd_current_data
(d, s)
RCV_rcv_current_data
SND_rcv_current_ack
(r)

Second Refinement: the Events (1)

init

$r := 0$

$h := \varnothing$

$r\_st := working$

$s\_st := working$

$s := 0$

$d :\in D$

$w := \mathrm{TRUE}$

brp

when

$r\_st \neq working$

$s\_st \neq working$

then

skip

end

Second Refinement: the Events (2)

- New Events: the Sender prepares data d and pointer s to be sent

SND_snd_current_data
when
$s\_st = working$
$w = \mathrm{TRUE}$
$s + 1 < n$
then
$d := f(s+1)$
$w := \mathrm{FALSE}$
end

SND_snd_last_data
when
$s\_st = working$
$w = \mathrm{TRUE}$
$s + 1 = n$
then
$d := f(s+1)$
$w := \mathrm{FALSE}$
end

- These events clearly refine skip and maintain invariant **inv2_3**

inv2_3: $w = \mathrm{FALSE} \Rightarrow d = f(s+1)$

Second Refinement: the Events (3)

- The Receiver receives data d and pointer s. It sends pointer$r$.

RCV_rcv_current_data
when
$r\_st = working$
$w = \mathrm{FALSE}$
$r = s$
$r + 1 < n$
then
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
end

RCV_success
when
$r\_st = working$
$w = \mathrm{FALSE}$
$r = s$
$r + 1 = n$
then
$r\_st := success$
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
end

- The Receiver still cheats: it accesses constant n

Refinement of RCV_rcv_current_data

(abstract-)RCV_rcv_current_data
when
$r\_st = working$
$r + 1 < n$
then
$r := r + 1$
$h := h \cup \{r + 1 \mapsto f(r + 1)\}$
end

(concrete-)RCV_rcv_current_data
when
$r\_st = working$
$w = \mathrm{FALSE}$
$r = s$
$r + 1 < n$
then
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
end

- Observe guard strengthening

- This invariant helps proving event refinement

inv2_3: $w = \mathrm{FALSE} \Rightarrow d = f(s + 1)$

Refinement of RCV_success

(abstract-)RCV_success
when
$r\_st = working$
$r + 1 = n$
then
$r\_st := success$
$r := r + 1$
$h := h \cup \{n \mapsto f(n)\}$
end

(concrete-)RCV_success
when
$r\_st = working$
$w = \mathrm{FALSE}$
$r = s$
$r + 1 = n$
then
$r\_st := success$
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
end

- Observe guard strengthening

- This invariant helps proving event refinement

inv2_3: $w = \mathrm{FALSE} \Rightarrow d = f(s + 1)$

Second Refinement: the Events (4)

- The first event is new. It clearly refines skip

- The activation bit is set to $\mathbf{TRUE}$ (activating SND_snd_current_data)

- The Sender receives acknowledgment (pointer r)

SND_rcv_current_ack
when
$s\_st = working$
$w = \mathbf{FALSE}$
$s + 1 < n$
$r = s + 1$
then
$w := \mathbf{TRUE}$
$s := s + 1$
end

SND_success
when
$s\_st = working$
$w = \mathbf{FALSE}$
$s + 1 = n$
$r = s + 1$
then
$s\_st := success$
end

Refinement of SND_success

(abstract-)SND_success
when
$s\_st = working$
$r\_st = success$
then
$s\_st := success$
end

(concrete-)SND_success
when
$s\_st = working$
$w = \mathrm{FALSE}$
$s + 1 = n$
$r = s + 1$
then
$s\_st := success$
end

- The presence of **inv1_3** ensures that the guard is strengthen

inv1_3: $r\_st = success \Leftrightarrow r = n$

Second Refinement: the Events (5)

- This new events will receive a full explanation in the next refinement

SND_time_out_current
when
$s\_st = working$
$w = \mathrm{FALSE}$
then
$w := \mathrm{TRUE}$
end

Third Refinement: Introducing more Activation Bits

- At most one activation bit is TRUE at a time

variables: $\ldots$, db, ab, v

inv3_1: $w = \mathrm{TRUE} \Rightarrow db = \mathrm{FALSE}$

inv3_2: $w = \mathrm{TRUE} \Rightarrow ab = \mathrm{FALSE}$

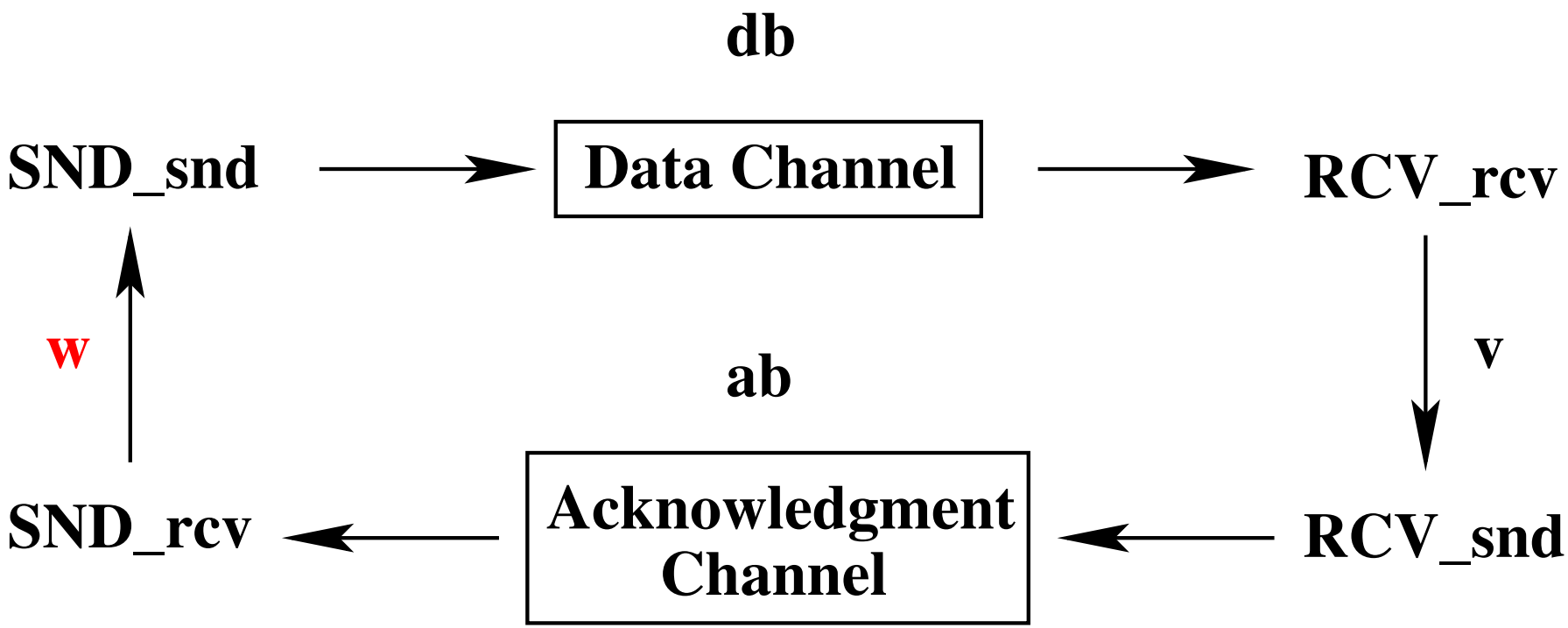
inv3_3: $w = \mathrm{TRUE} \Rightarrow v = \mathrm{FALSE}$

inv3_4: $db = \mathrm{TRUE} \Rightarrow ab = \mathrm{FALSE}$

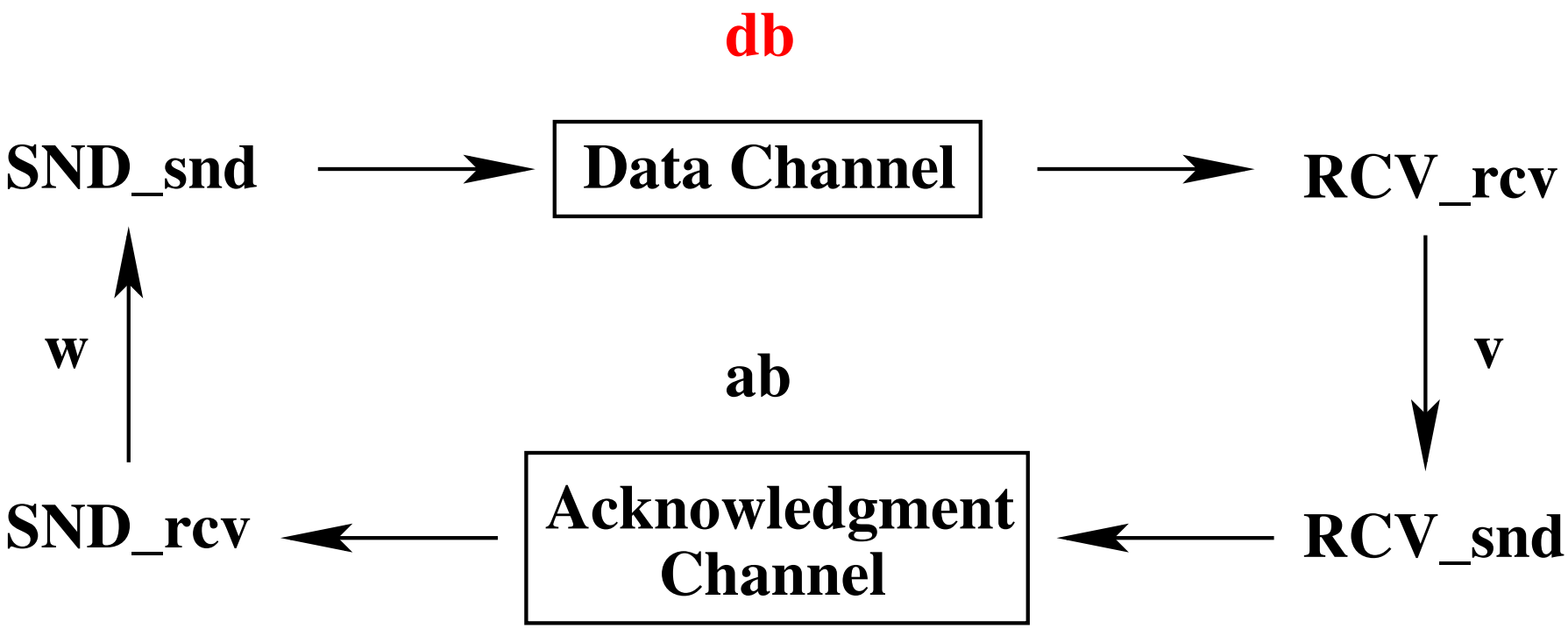
inv3_5: $db = \mathrm{TRUE} \Rightarrow v = \mathrm{FALSE}$

inv3_6: $ab = \mathrm{TRUE} \Rightarrow v = \mathrm{FALSE}$

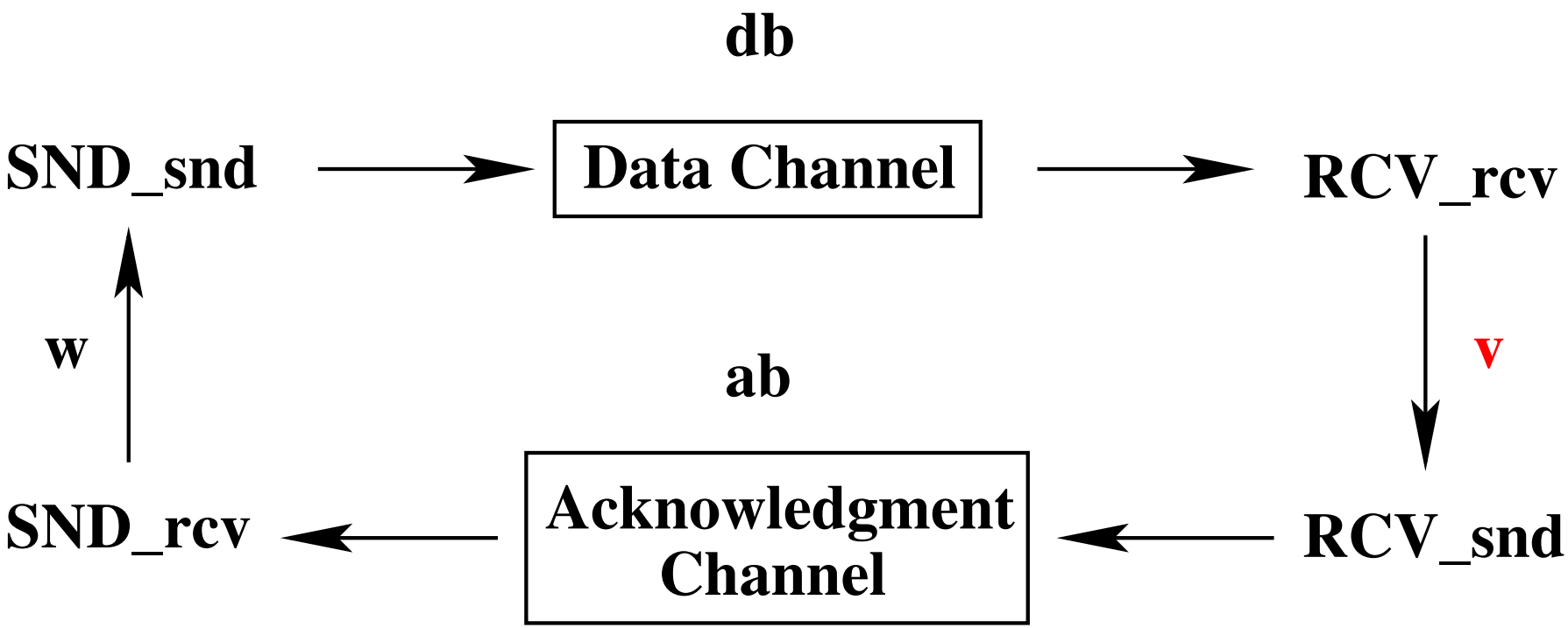
Activation bits at work



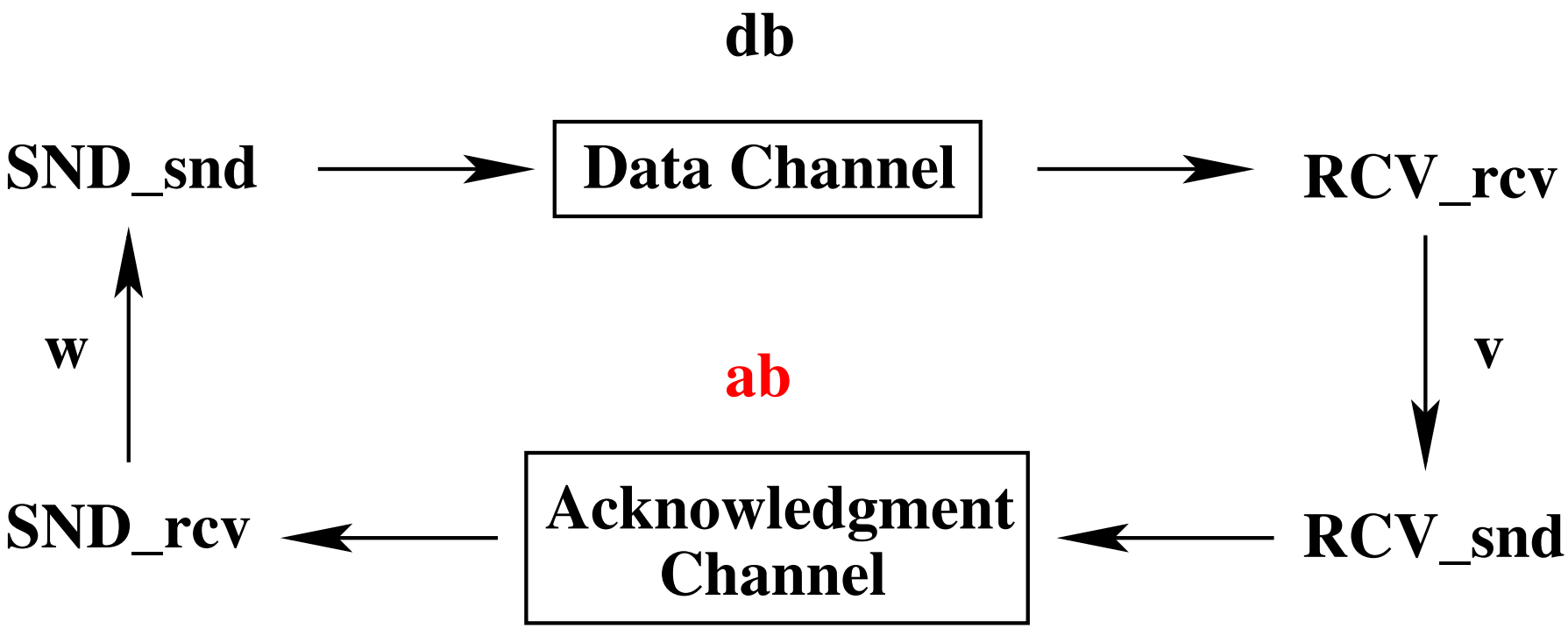
Activation bits at work



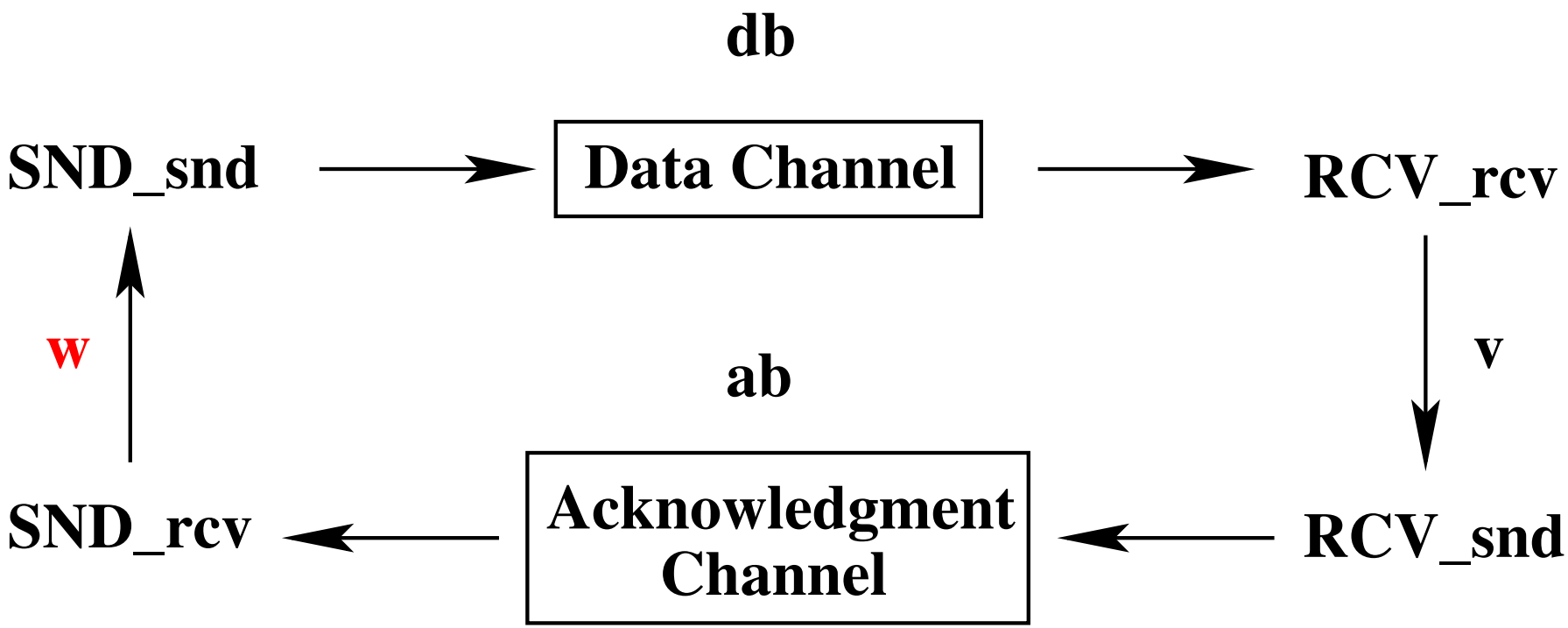
Activation bits at work



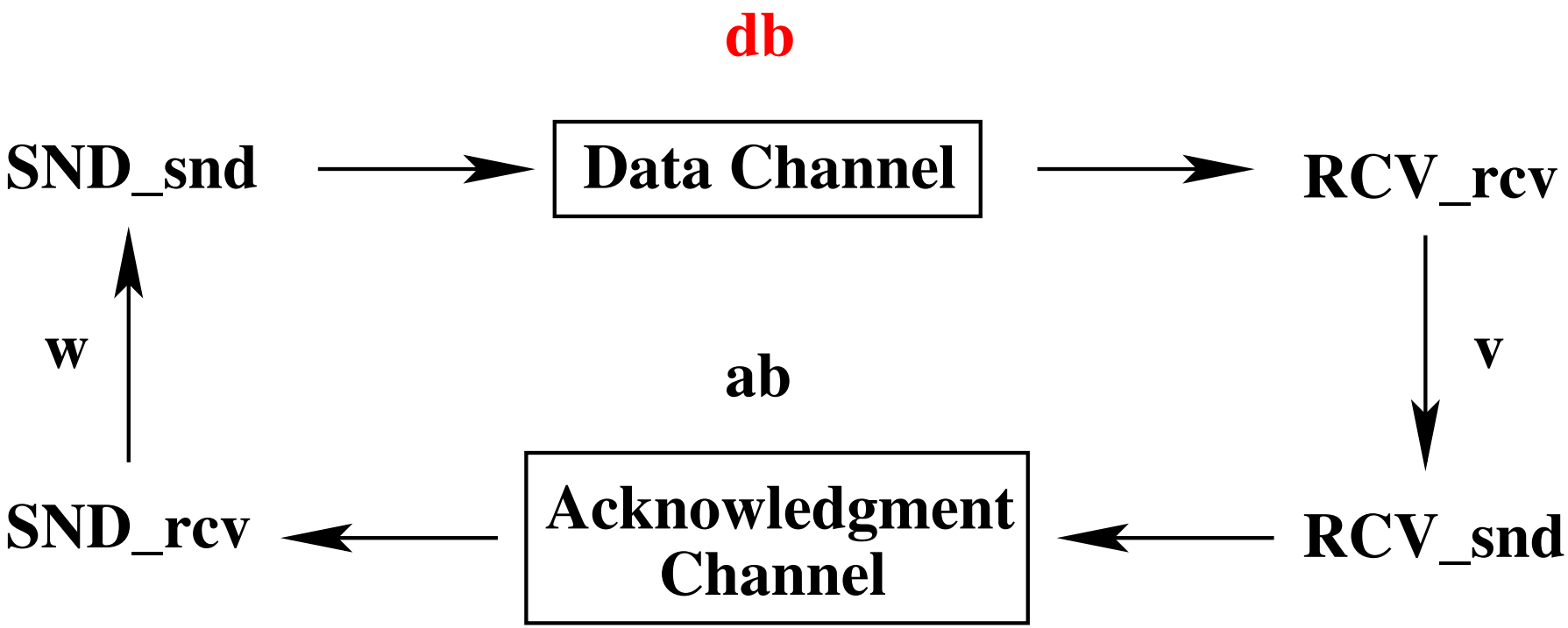
Activation bits at work



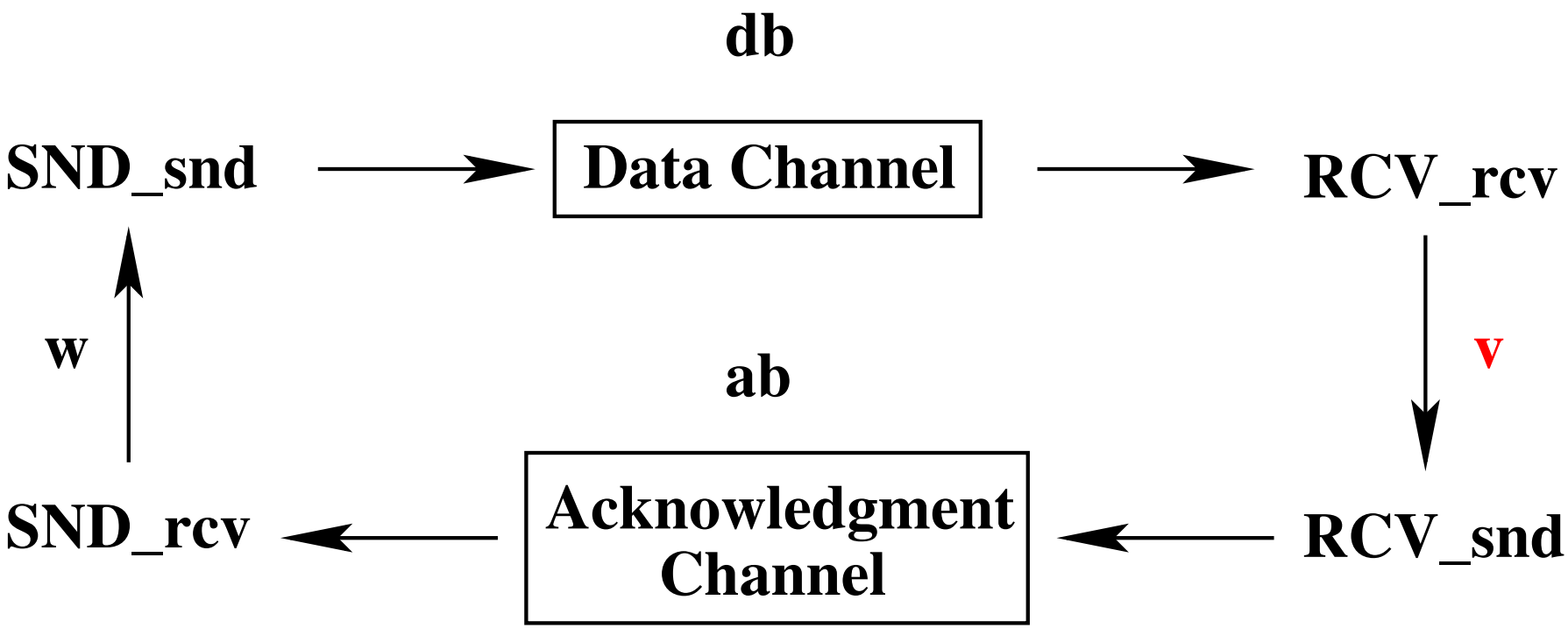
Activation bits at work



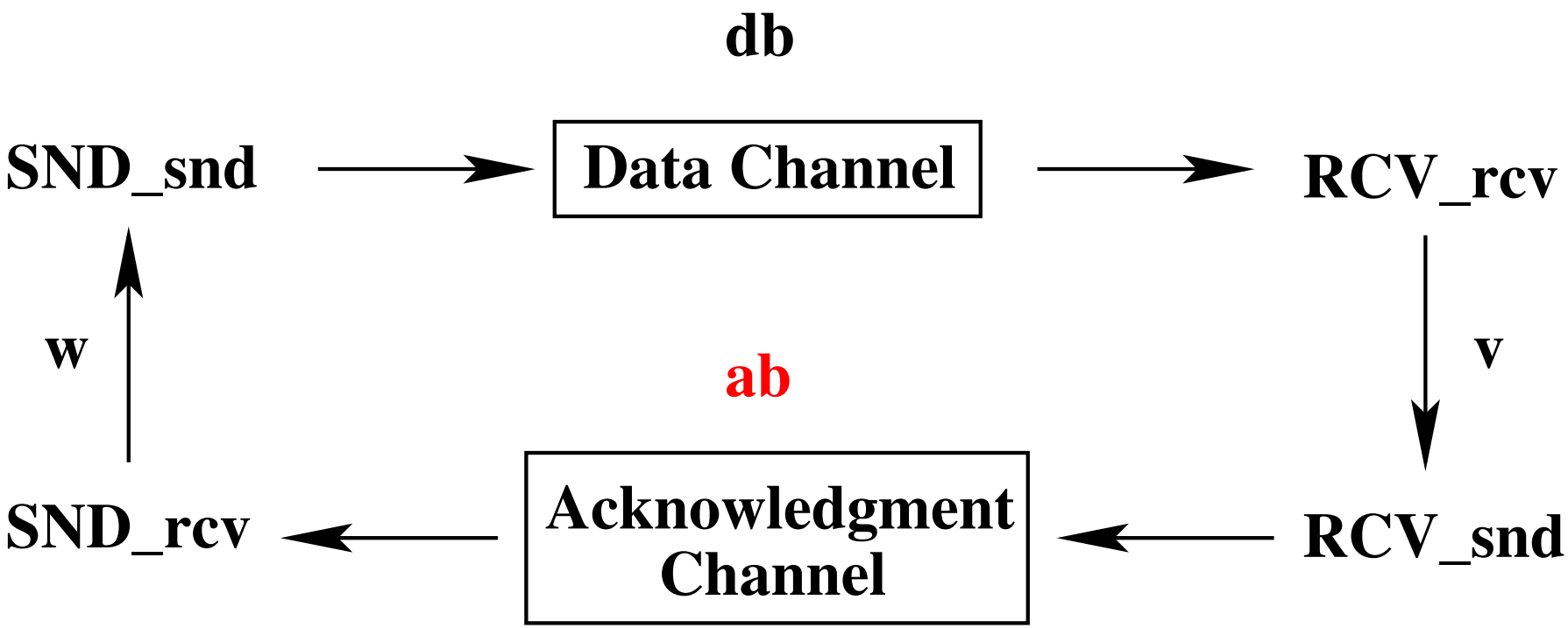
Activation bits at work



Activation bits at work



Activation bits at work



Third Refinement: Introducing the Last Item Indicator

- These invariants define the last data indicator

variables: $\ldots$, l

inv3_7: $db = \mathrm{TRUE} \ \wedge \ r = s \ \wedge \ l = \mathrm{FALSE} \ \Rightarrow \ r + 1 < n$

inv3_8: $db = \mathrm{TRUE} \ \wedge \ r = s \ \wedge \ l = \mathrm{TRUE} \ \Rightarrow \ r + 1 = n$

- This bit is sent by the Sender to the Receiver

- When equal to TRUE, this bit indicates that the sent item is the last one

Third Refinement: Introducing the Retry Counter c

- Constant MAX denotes the maximum number of retries

- The sender fails iff the retry counter c exceeds MAX (**inv3_10**)

constants: $\ldots$
MAX

axm3_1: $MAX \in \mathbb{N}$

variables: $\ldots$
c

inv3_9: $c \in 0 \mathinner{..} MAX + 1$

inv3_10: $c = MAX + 1 \Leftrightarrow s\_st = failure$

Third Refinement: the Events (1)

init
$r := 0$
$h := \varnothing$
$r\_st := working$
$s\_st := working$
$s := 0$
$d :\in D$
$w := \mathrm{TRUE}$
$db := \mathrm{FALSE}$
$ab := \mathrm{FALSE}$
$v := \mathrm{FALSE}$
$l := \mathrm{FALSE}$
$c := 0$

brp
when
$r \neq working$
$s \neq working$
then
skip
end

Third Refinement: the Events (2)

SND_snd_current_data
when
$s\_st = working$
$w = \mathrm{TRUE}$
$s + 1 < n$
then
$d := f(s + 1)$
$w := \mathrm{FALSE}$
$db := \mathrm{TRUE}$
$l := \mathrm{FALSE}$
end

SND_snd_last_data
when
$s\_st = working$
$w = \mathrm{TRUE}$
$s + 1 = n$
then
$d := f(s + 1)$
$w := \mathrm{FALSE}$
$db := \mathrm{TRUE}$
$l := \mathrm{TRUE}$
end

Third Refinement: New Events

- Daemons are breaking the channels

DMN_data_channel
when
$db = \mathbf{TRUE}$
then
$db = \mathbf{FALSE}$
end

DMN_ack_channel
when
$ab = \mathbf{TRUE}$
then
$ab = \mathbf{FALSE}$
end

- A failure is characterized by all activation bits being $\mathbf{FALSE}$

Third Refinement: the Events (3)

SND_time_out_current
when
$s\_st = working$
$w = \mathbf{FALSE}$
$ab = \mathbf{FALSE}$
$db = \mathbf{FALSE}$
$v = \mathbf{FALSE}$
$c < MAX$
then
$w := \mathbf{TRUE}$
$c := c + 1$
end

SND_failure
when
$s\_st = working$
$w = \mathbf{FALSE}$
$ab = \mathbf{FALSE}$
$db = \mathbf{FALSE}$
$v = \mathbf{FALSE}$
$c = MAX$
then
$s\_st := failure$
$c := c + 1$
end

- Sender aborts after MAX tries

Third Refinement: the Events (4)

RCV_rcv_current_data
when
$r\_st = working$
$db = \text{TRUE}$
$r = s$
$l = \text{FALSE}$
then
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
$db := \text{FALSE}$
$v := \text{TRUE}$
end

RCV_success
when
$r\_st = working$
$db = \text{TRUE}$
$r = s$
$l = \text{TRUE}$
then
$r\_st := success$
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
$db := \text{FALSE}$
$v := \text{TRUE}$
end

Reminder: l is the last data indicator

Third Refinement: Guard Srengthening (1)

(abstract-)RCV_rcv_current_data
when
$r\_st = working$
$w = \text{FALSE}$
$r = s$
$r + 1 < n$
then
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
end

(concrete-)RCV_rcv_current_data
when
$r\_st = working$
$db = \text{TRUE}$
$r = s$
$l = \text{FALSE}$
then
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
$db := \text{FALSE}$
$v := \text{TRUE}$
end

inv3_1': $db = \text{TRUE} \Rightarrow w = \text{FALSE}$

inv3_7: $db = \text{TRUE} \wedge r = s \wedge l = \text{FALSE} \Rightarrow r + 1 < n$

Third Refinement: Guard Srengthening (2)

(abstract-)RCV_success
when
$r\_st = working$
$w = \text{FALSE}$
$r = s$
$r + 1 = n$
then
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
end

(concrete-)RCV_success
when
$r\_st = working$
$db = \text{TRUE}$
$r = s$
$l = \text{TRUE}$
then
$r\_st := success$
$r := r + 1$
$h := h \cup \{r + 1 \mapsto d\}$
$db := \text{FALSE}$
$v := \text{TRUE}$
end

inv3_1': $db = \text{TRUE} \Rightarrow w = \text{FALSE}$

inv3_8: $db = \text{TRUE} \wedge r = s \wedge l = \text{TRUE} \Rightarrow r + 1 = n$

Third Refinement: the Events (5)

RCV_rcv_retry
when
$db = \mathrm{TRUE}$
$r \neq s$
then
$db := \mathrm{FALSE}$
$v := \mathrm{TRUE}$
end

RCV_snd_ack
when
$v = \mathrm{TRUE}$
then
$v := \mathrm{FALSE}$
$ab := \mathrm{TRUE}$
end

RCV_failure
when
$r\_st = working$
$c = MAX + 1$
then
$r\_st := failure$
end

Third Refinement: the Events (6)

SND_rcv_current_ack

when

$s\_st = working$

$ab = \mathrm{TRUE}$

$s + 1 < n$

then

$w := \mathrm{TRUE}$

$s := s + 1$

$c := 0$

$ab := \mathrm{FALSE}$

end

SND_success

when

$s\_st = working$

$ab = \mathrm{TRUE}$

$s + 1 = n$

then

$s\_st := success$

$c := 0$

$ab := \mathrm{FALSE}$

end

Third Refinement: Guard Strengthening (1)

(abstract-)SND_rcv_current_ack
when
$s\_st = working$
$w = \text{FALSE}$
$s + 1 < n$
$r = s + 1$
then
$w := \text{TRUE}$
$s := s + 1$
end

(concrete-)SND_rcv_current_ack
when
$s\_st = working$
$ab = \text{TRUE}$
$s + 1 < n$
then
$w := \text{TRUE}$
$s := s + 1$
$c := 0$
$ab := \text{FALSE}$
end

inv3_2': $ab = \text{TRUE} \Rightarrow w = \text{FALSE}$

- In order to prove guard strengthening we need invariant **inv3_11**

inv3_11: $ab = \text{TRUE} \Rightarrow r = s + 1$

inv3_12: $v = \text{TRUE} \Rightarrow r = s + 1$

- Invariant **inv3_12** is needed to prove **inv3_11**

Third Refinement: Guard Strengthening (2)

(abstract-)SND_success
when
$s\_st = working$
$w = \text{FALSE}$
$s + 1 = n$
$r = s + 1$
then
$s\_st := success$
end

(concrete-)SND_success
when
$s\_st = working$
$ab = \text{TRUE}$
$s + 1 = n$
then
$s\_st := success$
$c := 0$
$ab := \text{FALSE}$
end

inv3_2': $ab = \text{TRUE} \Rightarrow w = \text{FALSE}$

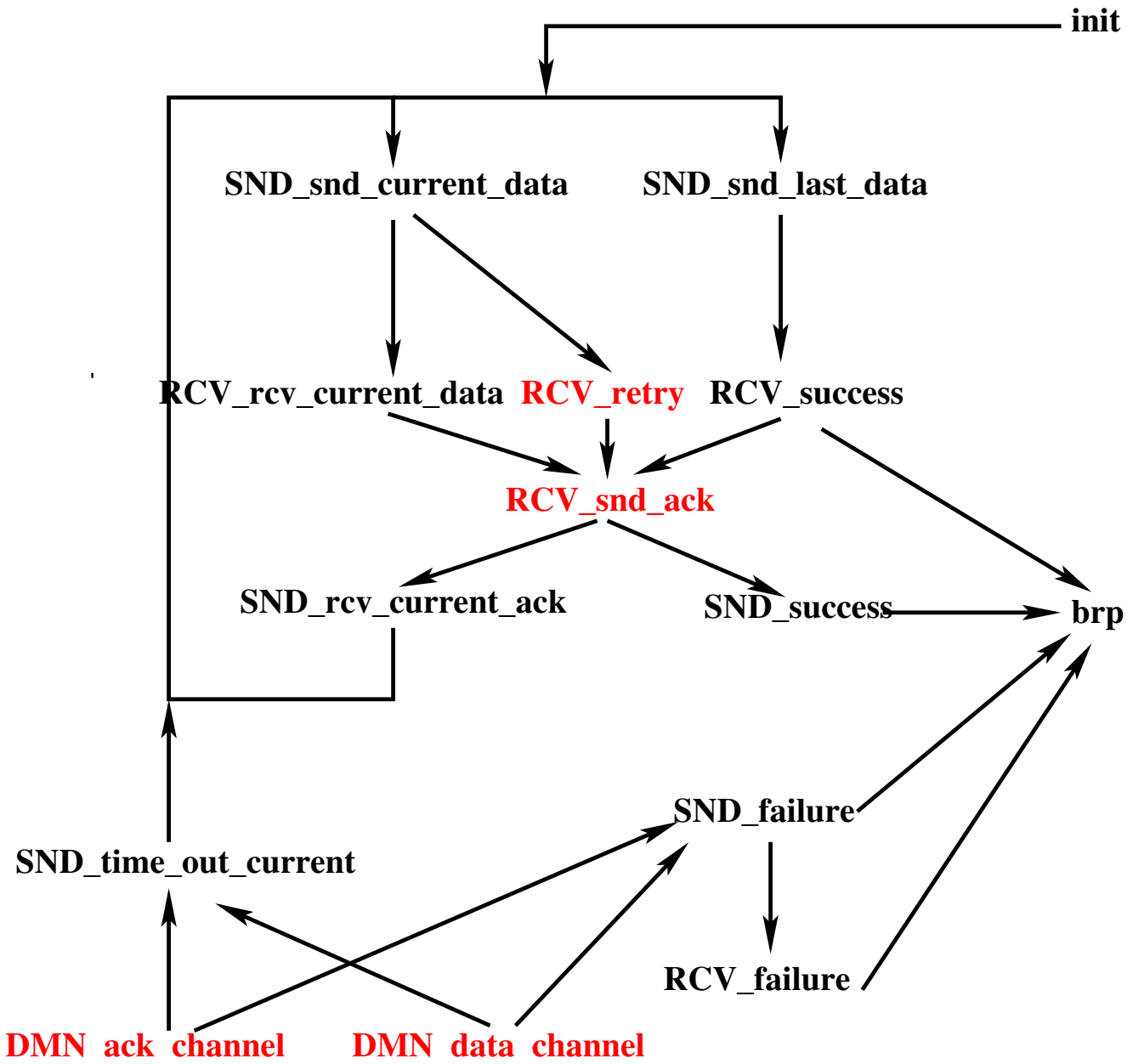
- In order to prove guard strengthening we need invariant **inv3_11**

inv3_11: $ab = \text{TRUE} \Rightarrow r = s + 1$

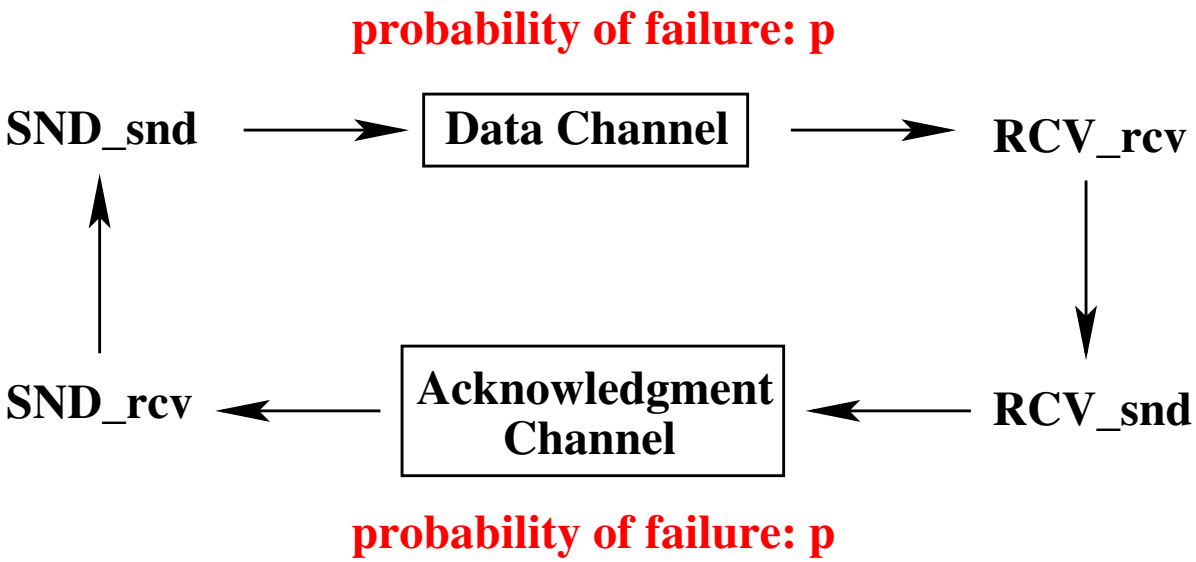
inv3_12: $v = \text{TRUE} \Rightarrow r = s + 1$

- Invariant **inv3_12** is needed to prove **inv3_11**

Final Synchronization of the Events



Computing Probabilities



- We would like to compute the probability of success
- It is a function of:
  - p: probability of failure for one channel
  - n: size of the file
  - $MAX + 1$: number of re-tries

Failure on one channel p

Failure on one channel	p
Success on one channel	$1 - p$

Computing Probabilities

Failure on one channel	p
Success on one channel	$1 - p$
Success on both channels	$(1 - p)^2$

Computing Probabilities

Failure on one channel	p
Success on one channel	$1 - p$
Success on both channels	$(1 - p)^2$
Failure on one try	$1 - (1 - p)^2$

Computing Probabilities

Failure on one channel	p
Success on one channel	$1 - p$
Success on both channels	$(1 - p)^2$
Failure on one try	$1 - (1 - p)^2$
Failure on MAX tries	$(1 - (1 - p)^2)^{MAX+1}$

Computing Probabilities

Failure on one channel	p
Success on one channel	$1 - p$
Success on both channels	$(1 - p)^2$
Failure on one try	$1 - (1 - p)^2$
Failure on MAX tries	$(1 - (1 - p)^2)^{MAX+1}$
Success on MAX tries	$1 - (1 - (1 - p)^2)^{MAX+1}$

Computing Probabilities

Failure on one channel	p
Success on one channel	$1-p$
Success on both channels	$(1-p)^2$
Failure on one try	$1-(1-p)^2$
Failure on MAX tries	$(1-(1-p)^2)^{MAX+1}$
Success on MAX tries	$1-(1-(1-p)^2)^{MAX+1}$
Success for n data	$(1-(1-(1-p)^2)^{MAX+1})^n$

Computing Probabilities

Failure on one channel	p
Success on one channel	$1-p$
Success on both channels	$(1-p)^2$
Failure on one try	$1-(1-p)^2$
Failure on MAX tries	$(1-(1-p)^2)^{MAX+1}$
Success on MAX tries	$1-(1-(1-p)^2)^{MAX+1}$
Success for n data	$(1-(1-(1-p)^2)^{MAX+1})^n$

$p = .1$
$MAX = 5$
$n = 100$ $\quad .995$