Abstract Model Checking and CEGAR

Abstraction

- Abstraction of states → abstract states
- A mapping $\alpha : S \rightarrow A$
- Usually, *A* is much simpler than *S*
  - Typically, *A* is a finite set while *S* is infinite
- Example: alternating bit protocol
  - State is a tuple of
    - Sender's state
    - Receiver's state
    - Channels' states --- infinite ← apply abstraction

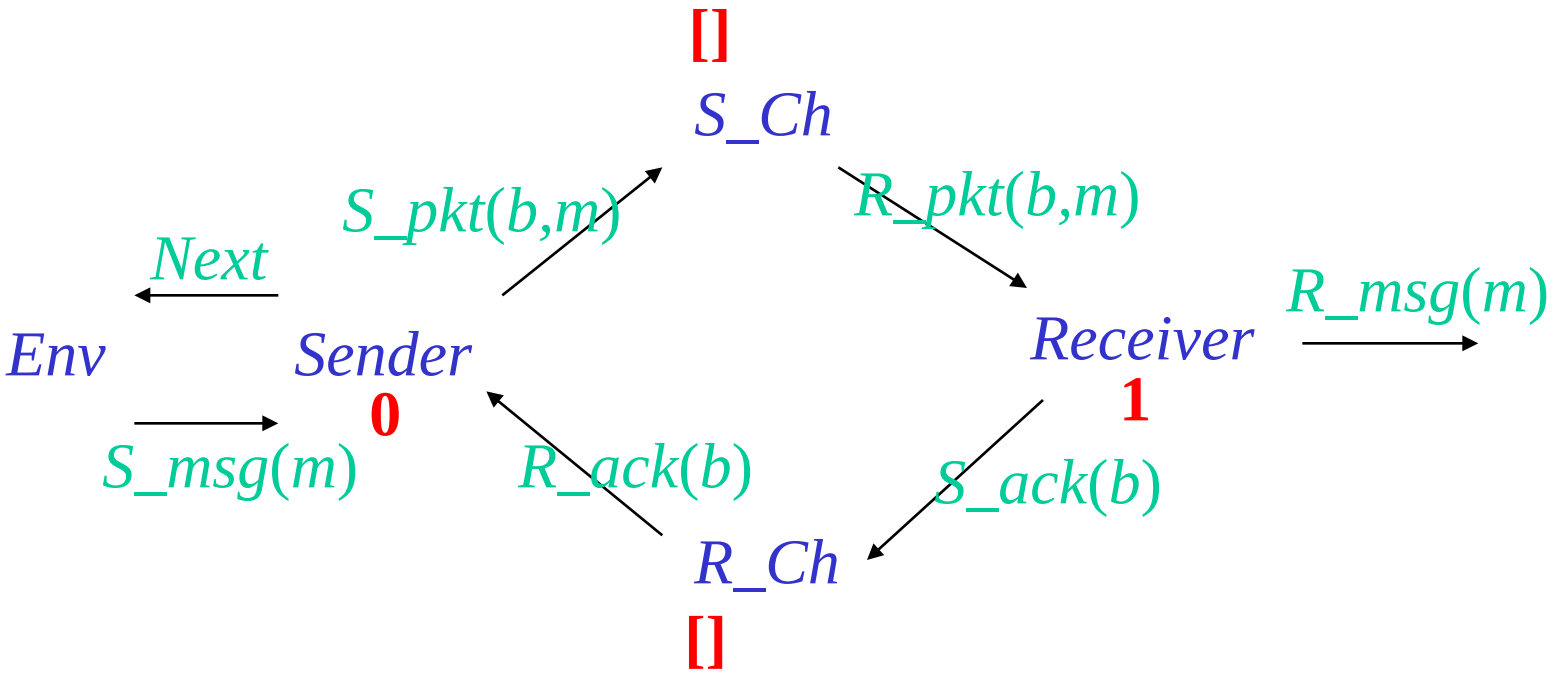
Various Kinds of Abstraction

- Abstraction of data (abstract interpretation)
  - Sign abstraction
    - Numbers → "**-**", **0**, "**+**"
    - "**+**"+"**+**" = "**+**", "**+**"+**0**="**+**", "**+**"+"**-**"=**T** (unknown)
  - Abstraction of lists/multisets → sets
    - [a,b,c,a,b,a,a,c] → {a,b,c}
  - Boolean abstraction (cf. SLAM)
  - Constant abstraction
- Abstraction of processes
  - Processes with identical state are mapped to one
    - A kind of multisets→sets

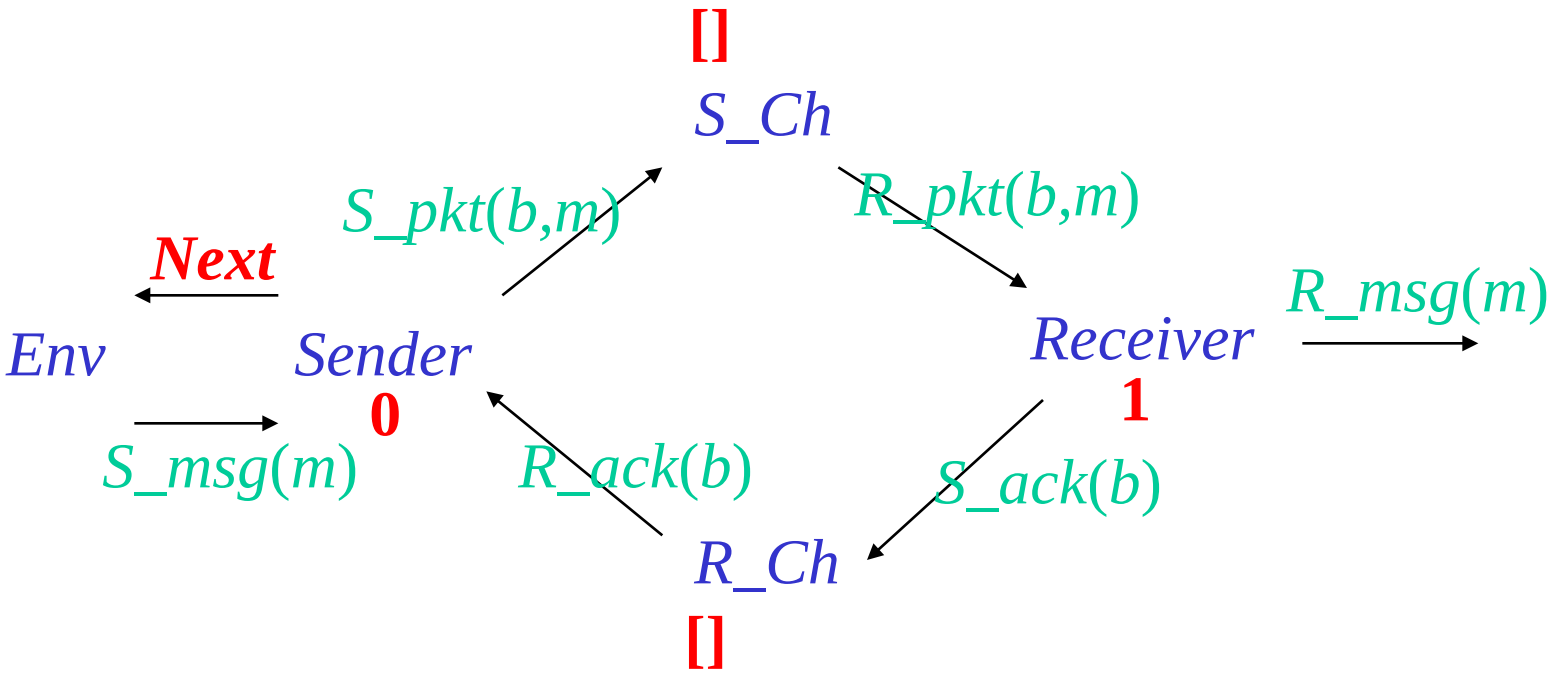
Alternating Bit Protocol

- *Sender*
- *Receiver*
- *S_Ch*: channel of message packets
  - Each packet is a pair of a message and a header
  - Modeled as a queue of packets
  - Messages may be duplicated or lost
- *R_Ch*: channel of acknowledgements
  - Ditto

Alternating Bit Protocol



Alternating Bit Protocol



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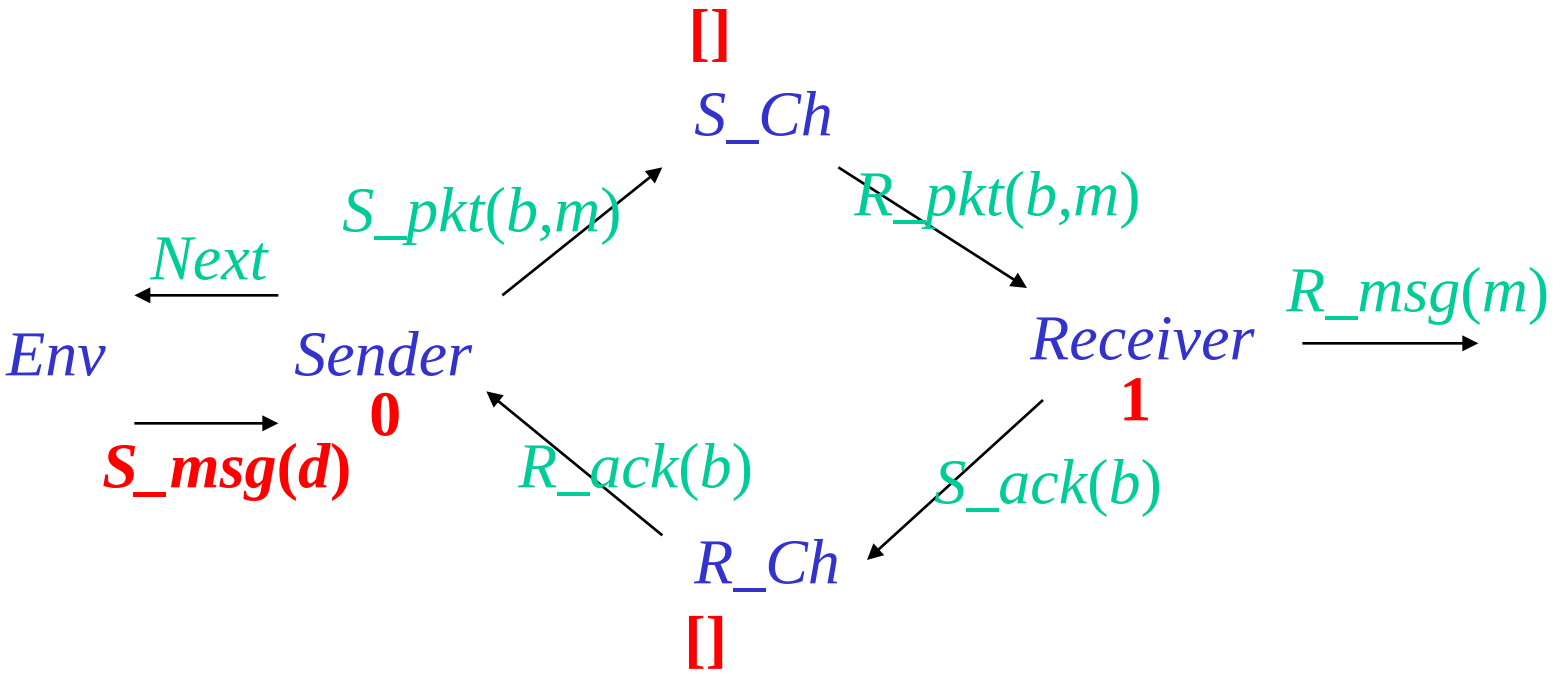

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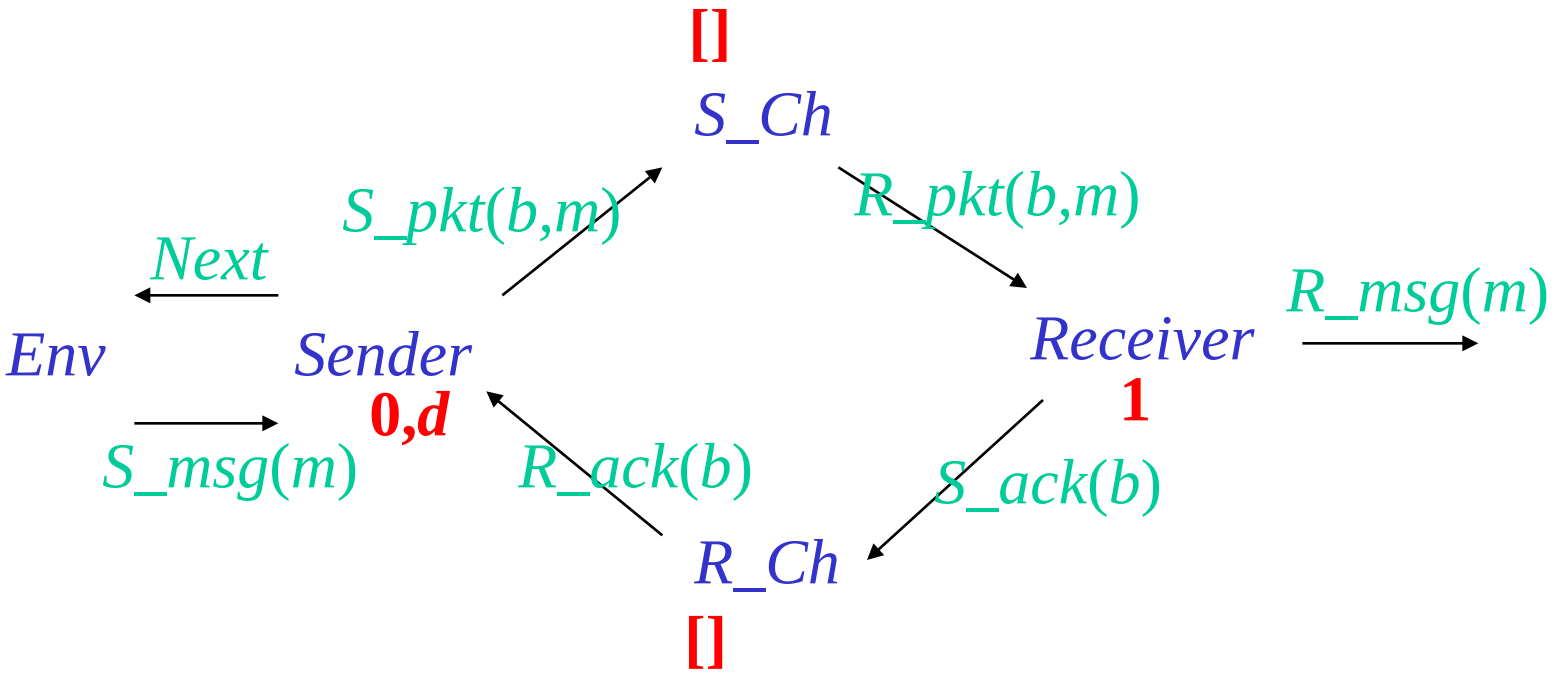
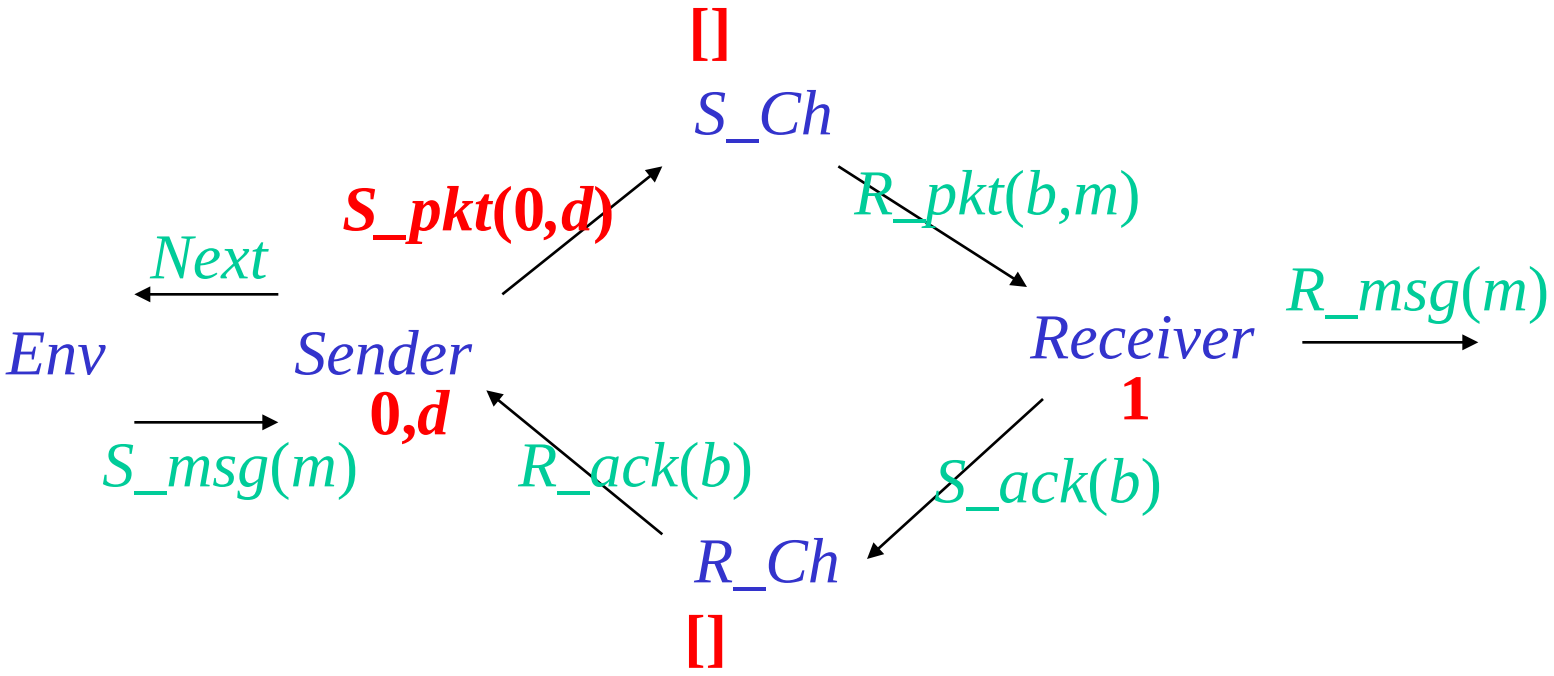
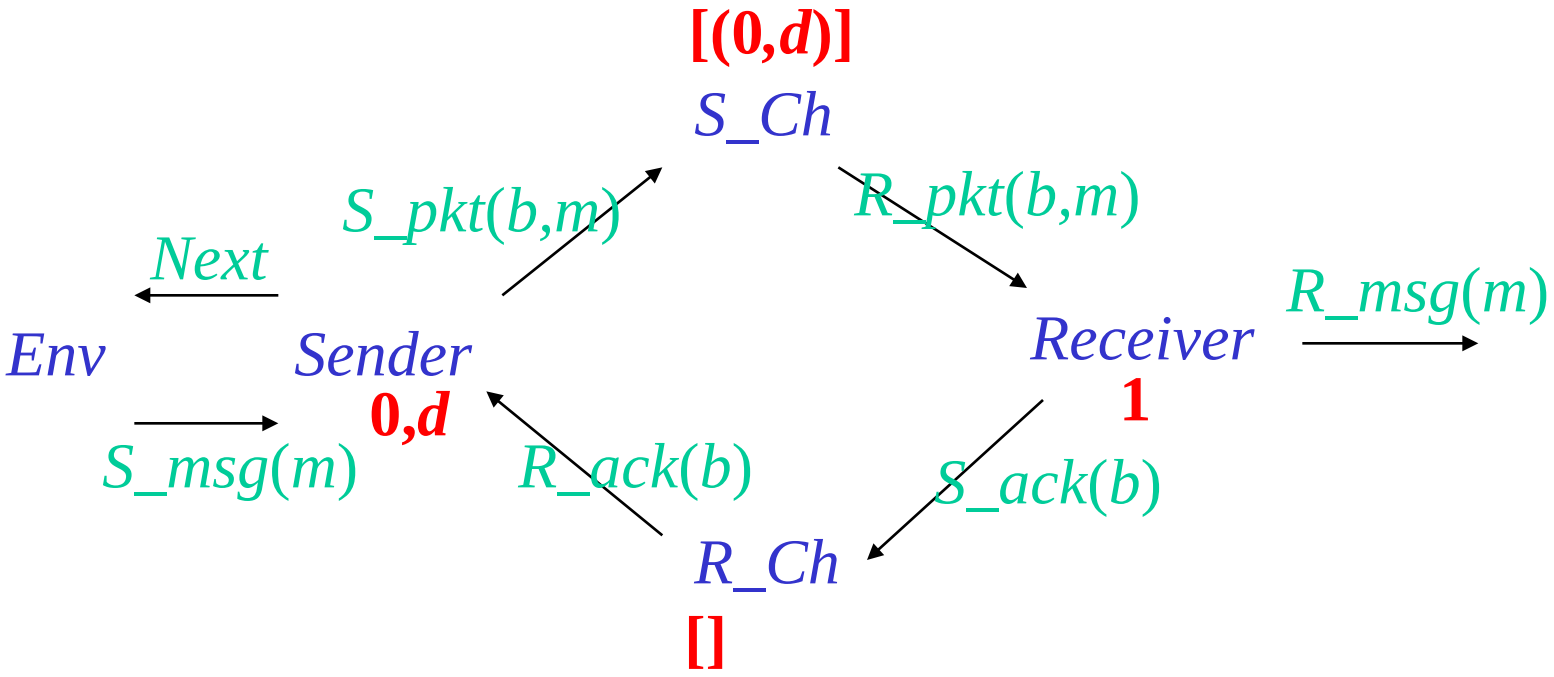


Alternating Bit Protocol



Alternating Bit Protocol



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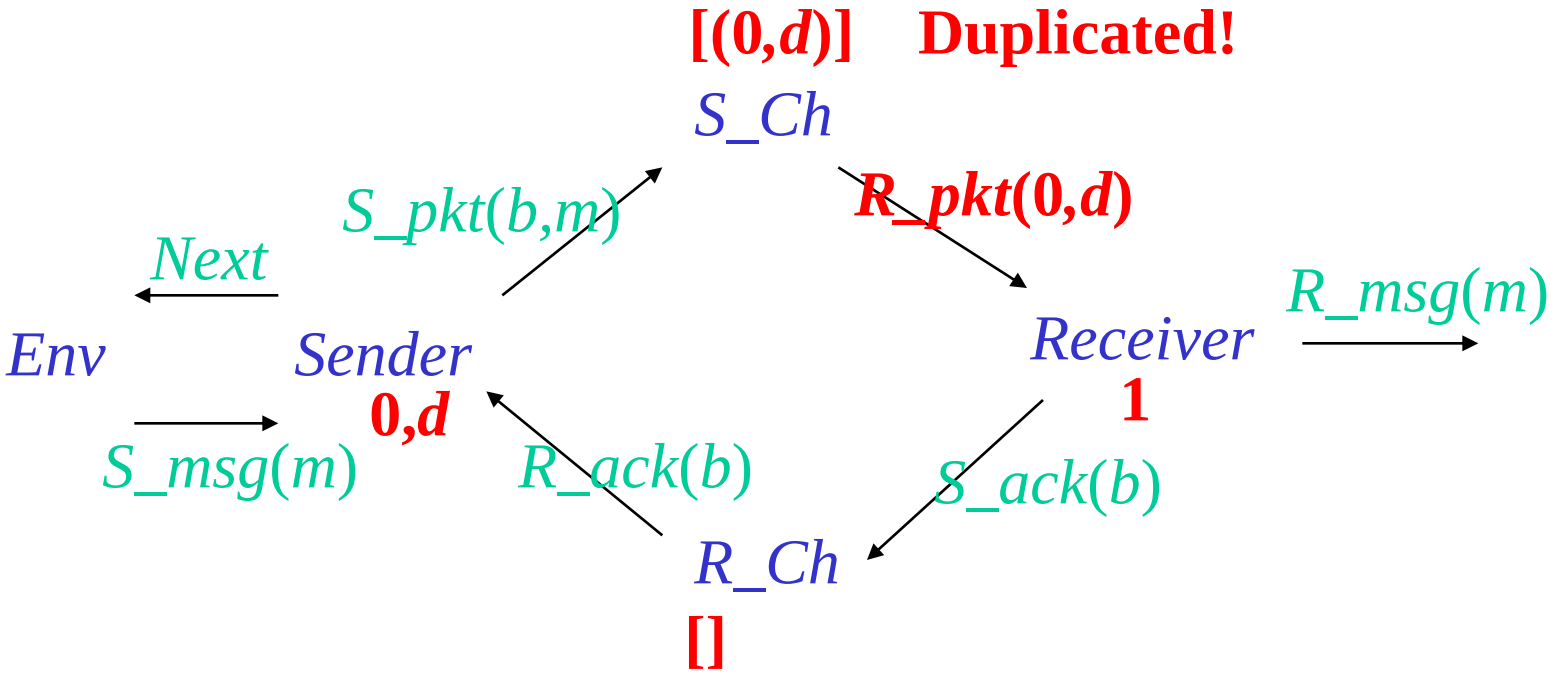

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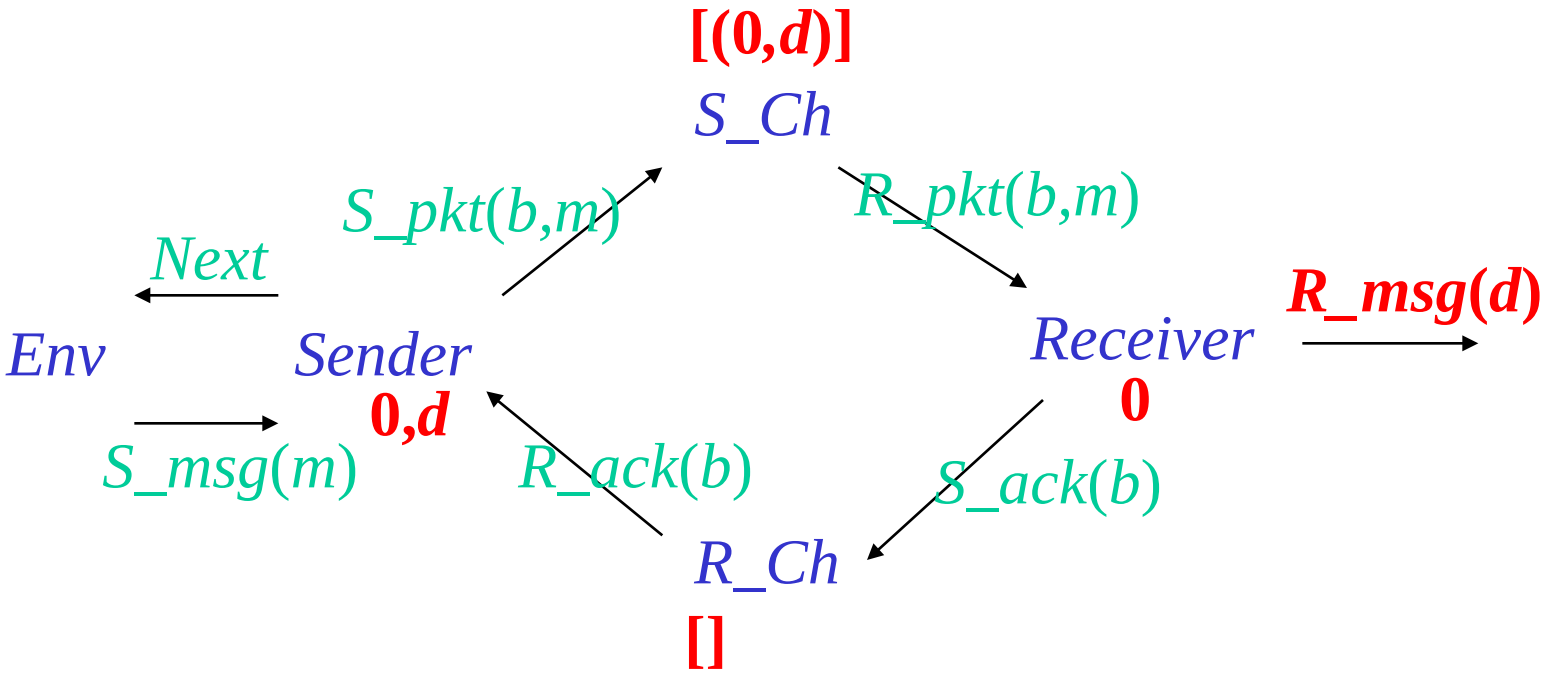

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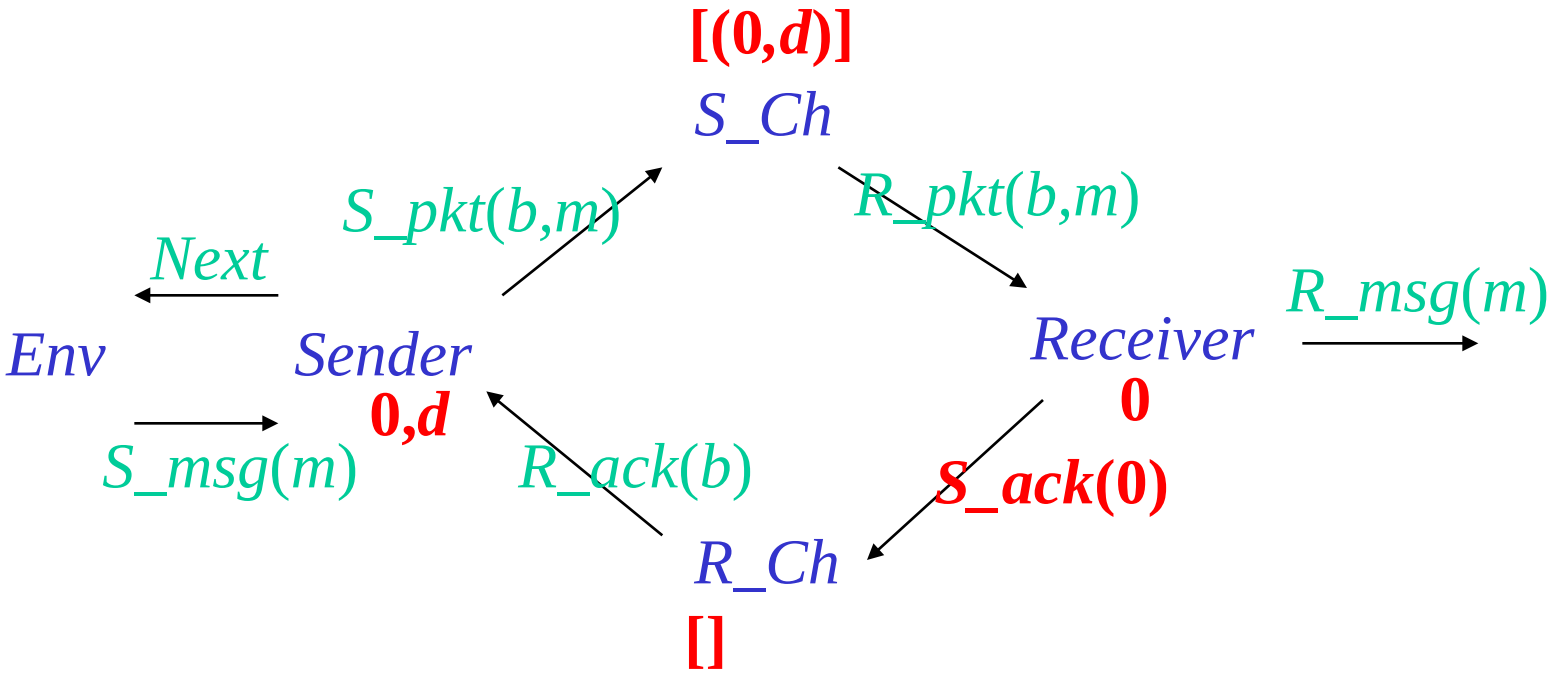

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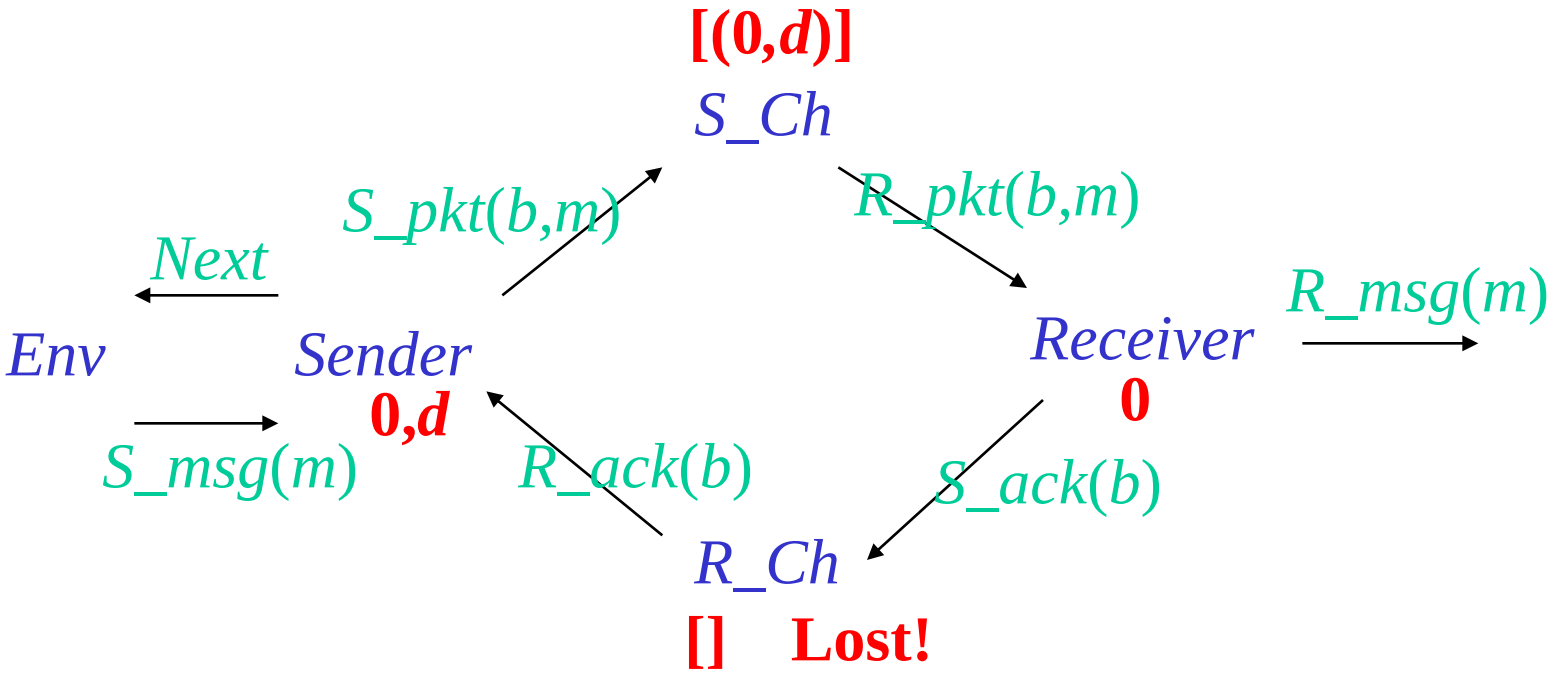

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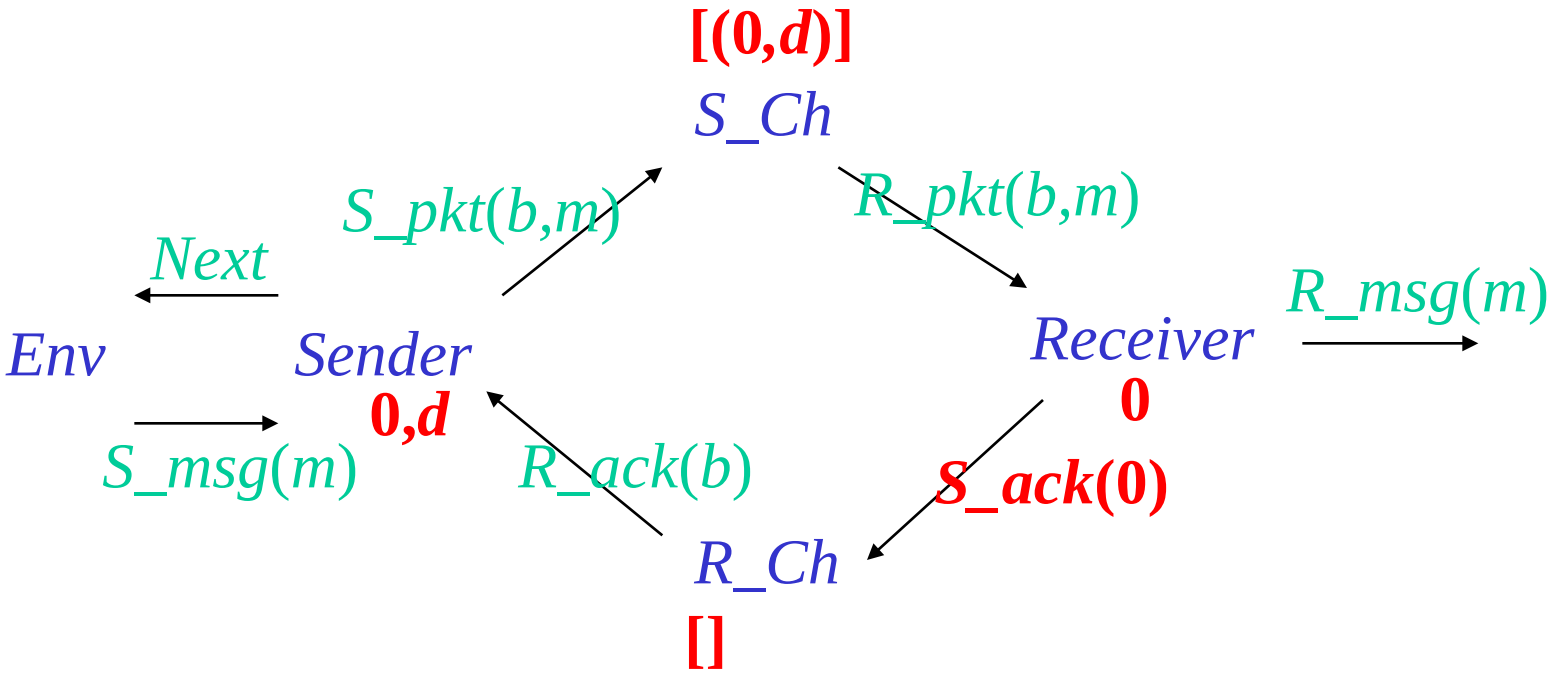

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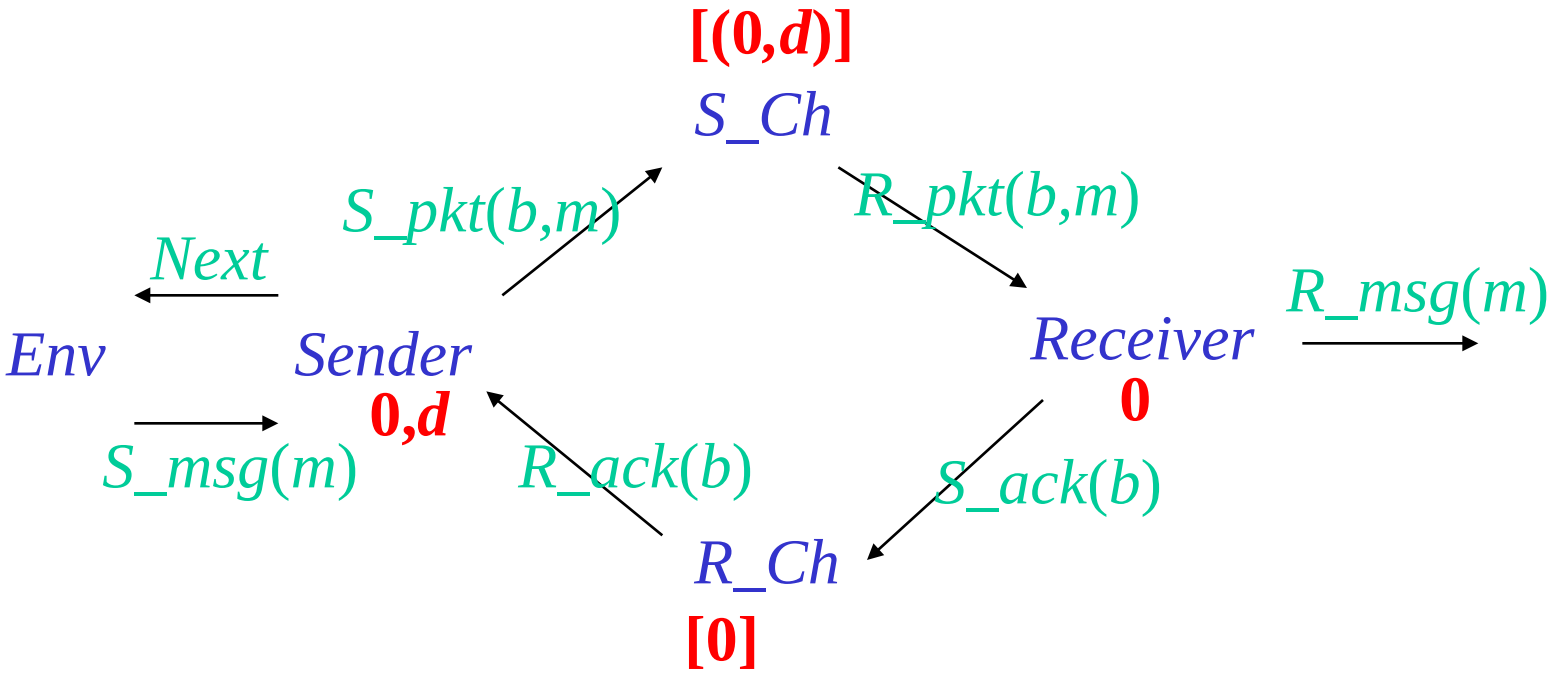
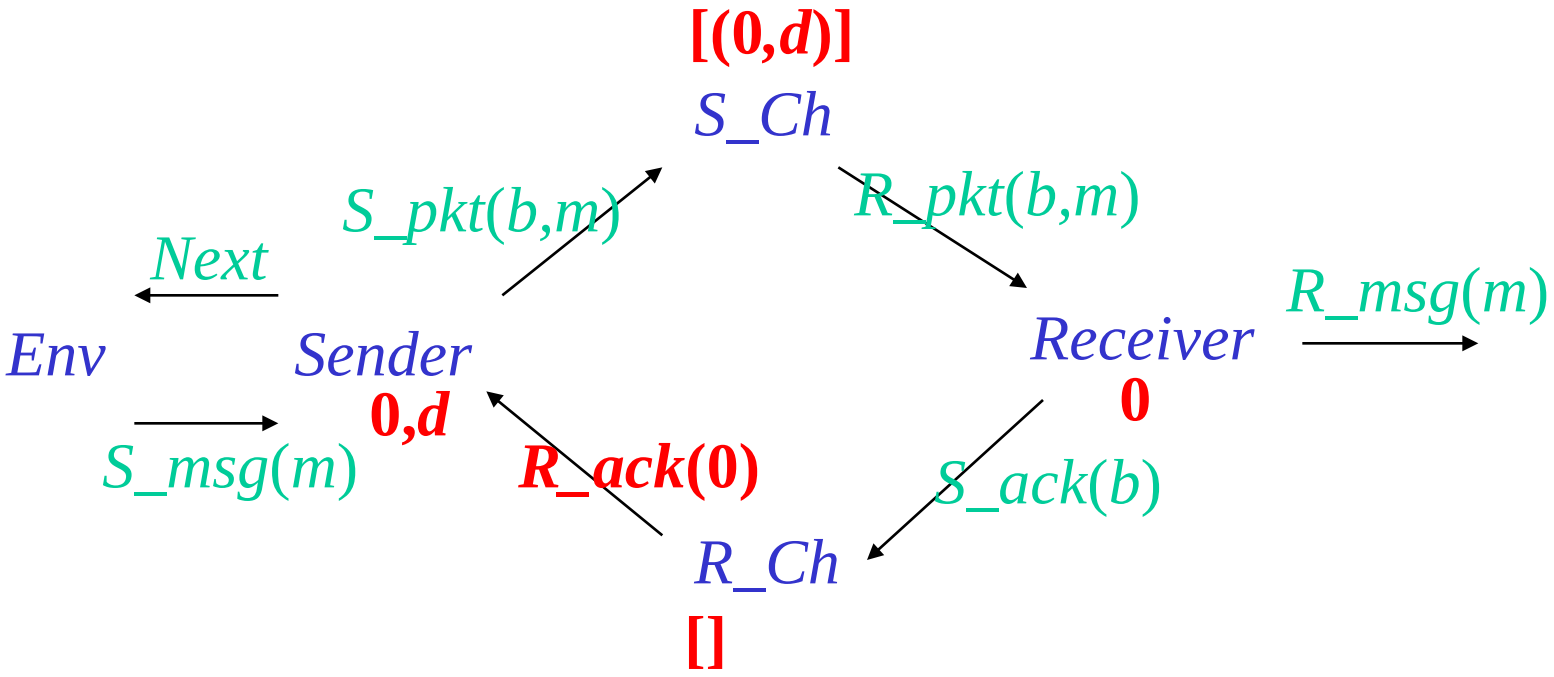
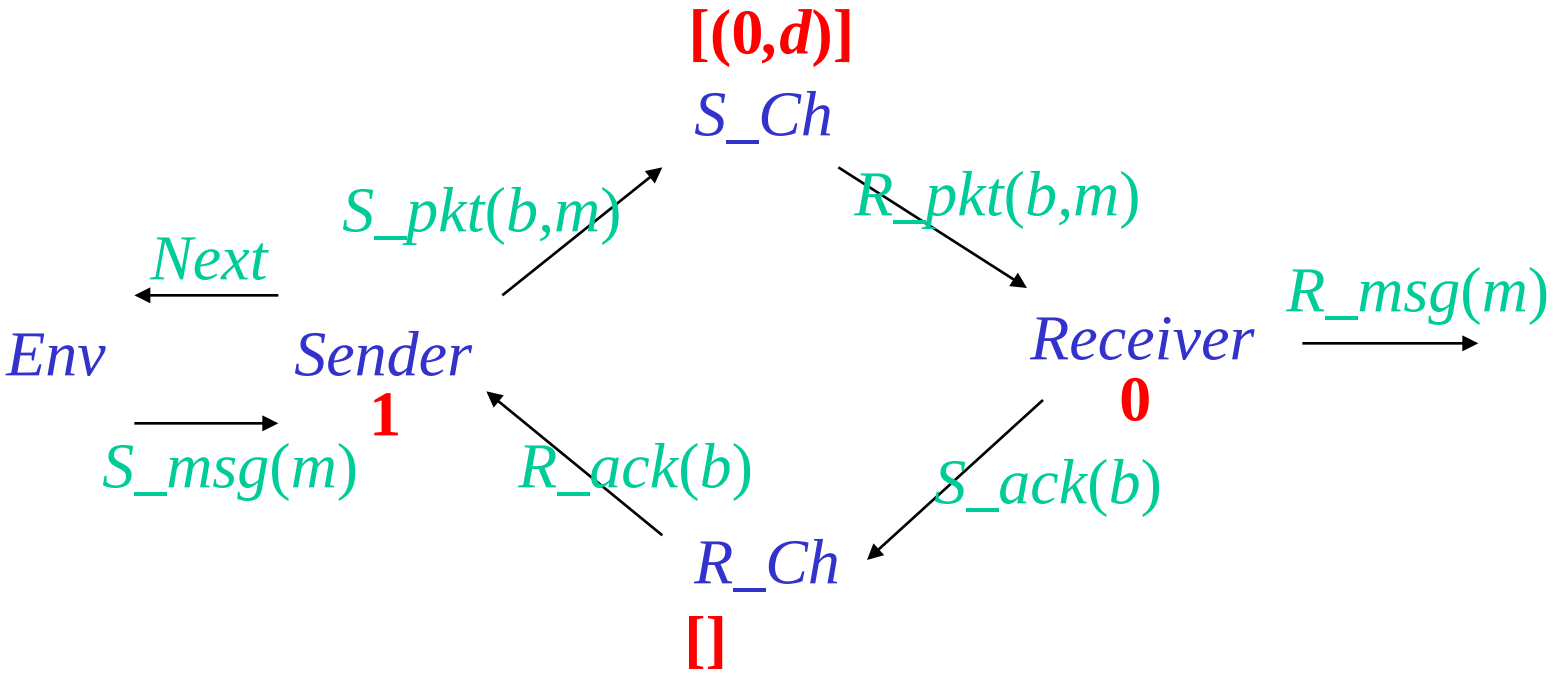


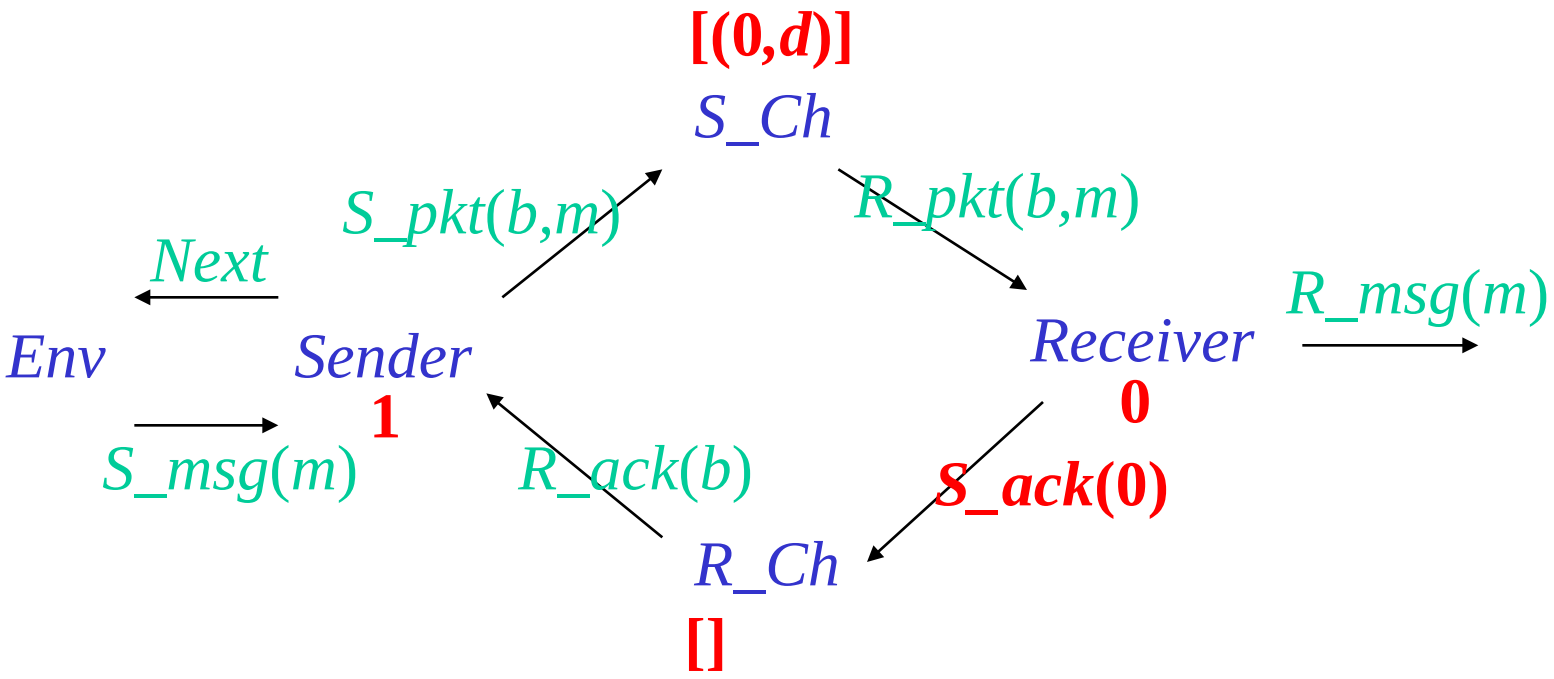
Alternating Bit Protocol



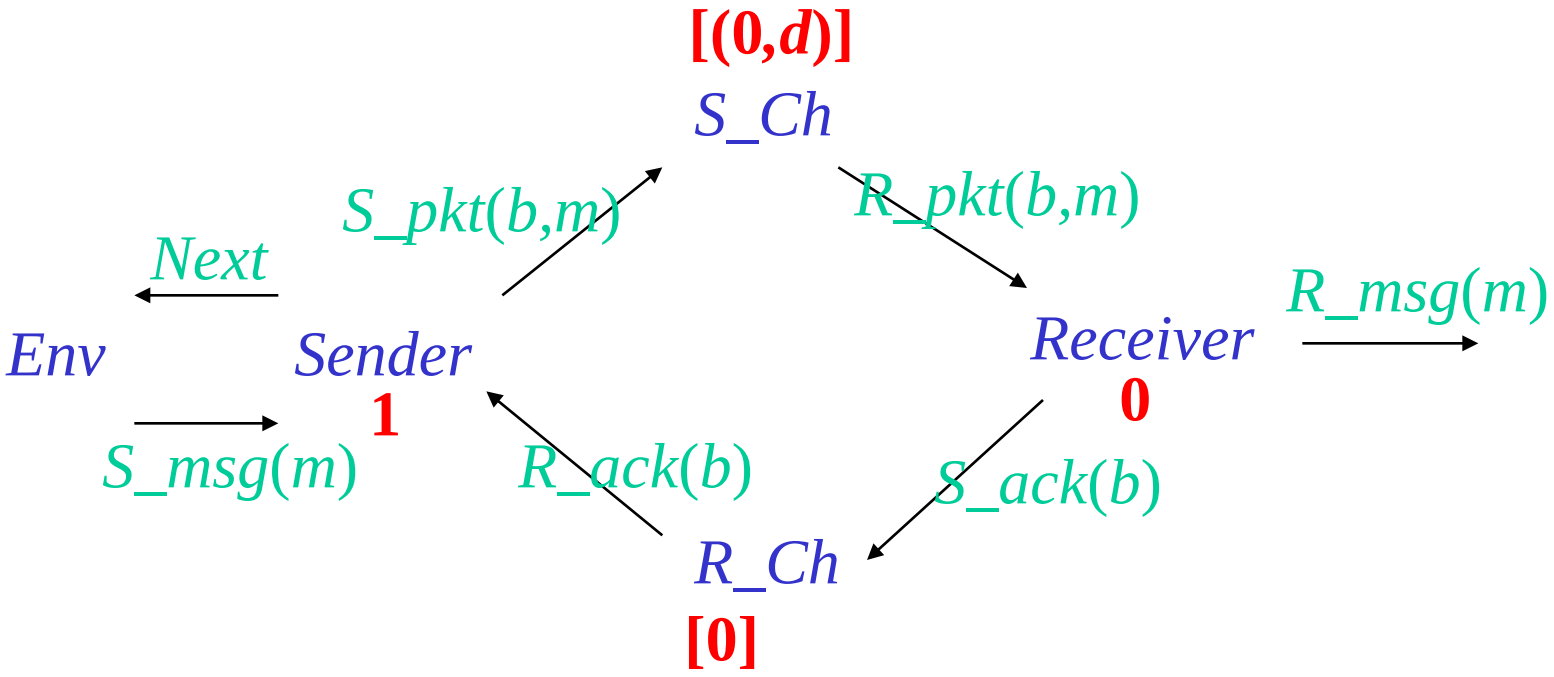
Alternating Bit Protocol



Alternating Bit Protocol



Alternating Bit Protocol



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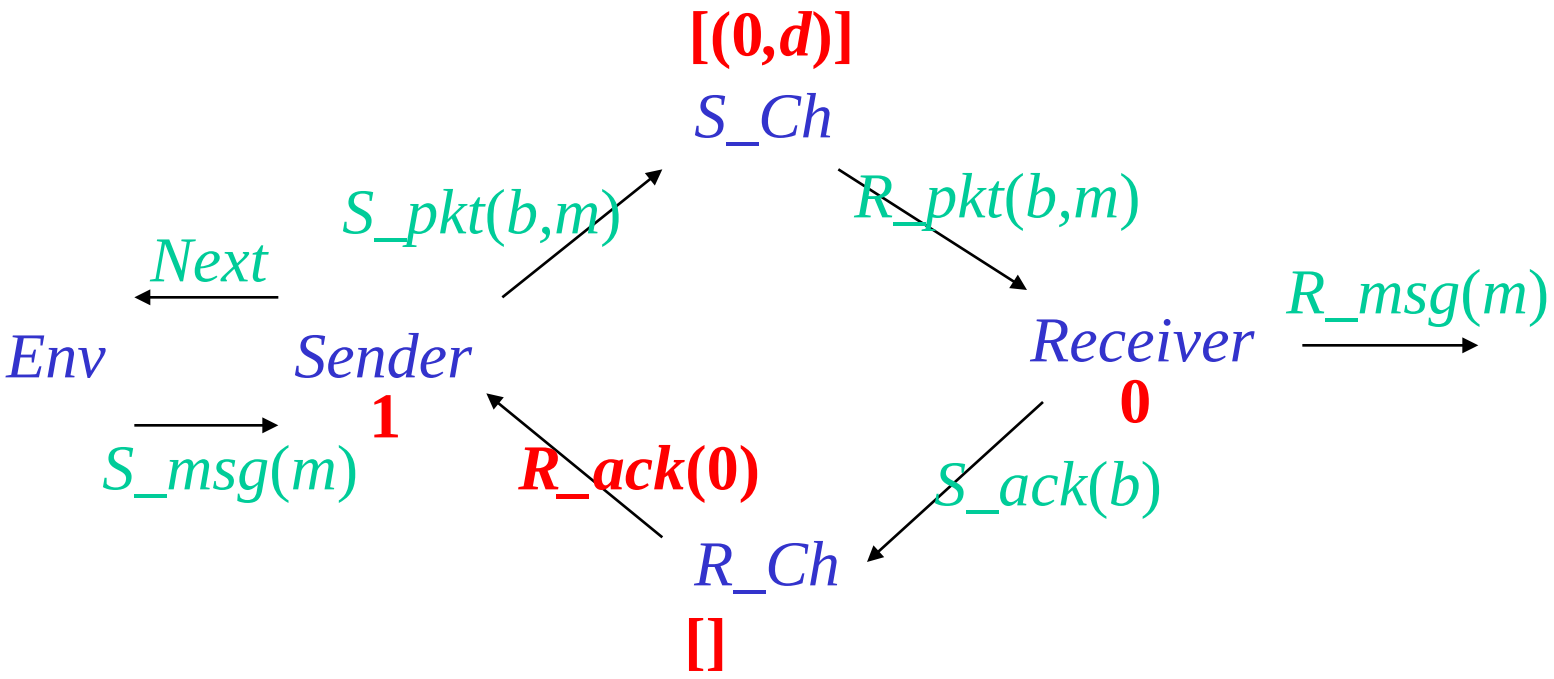

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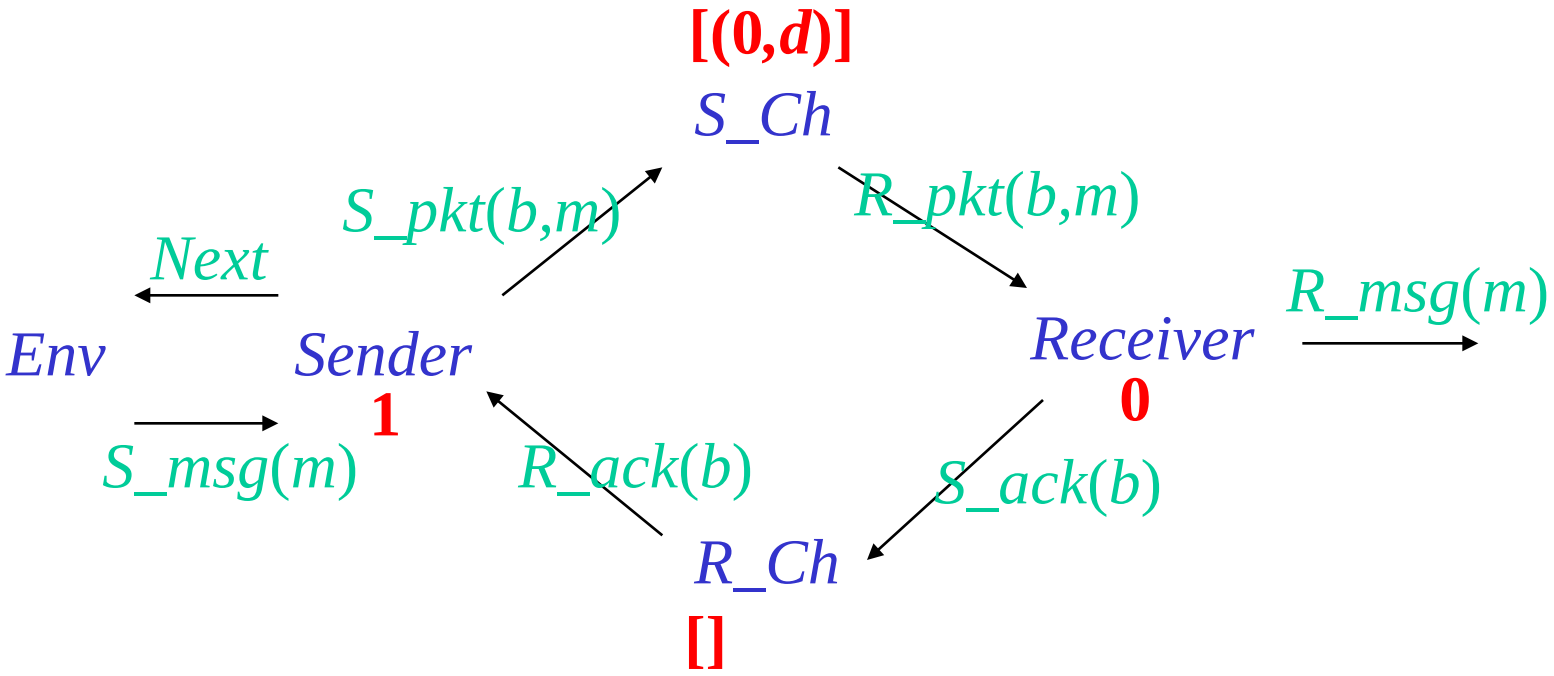

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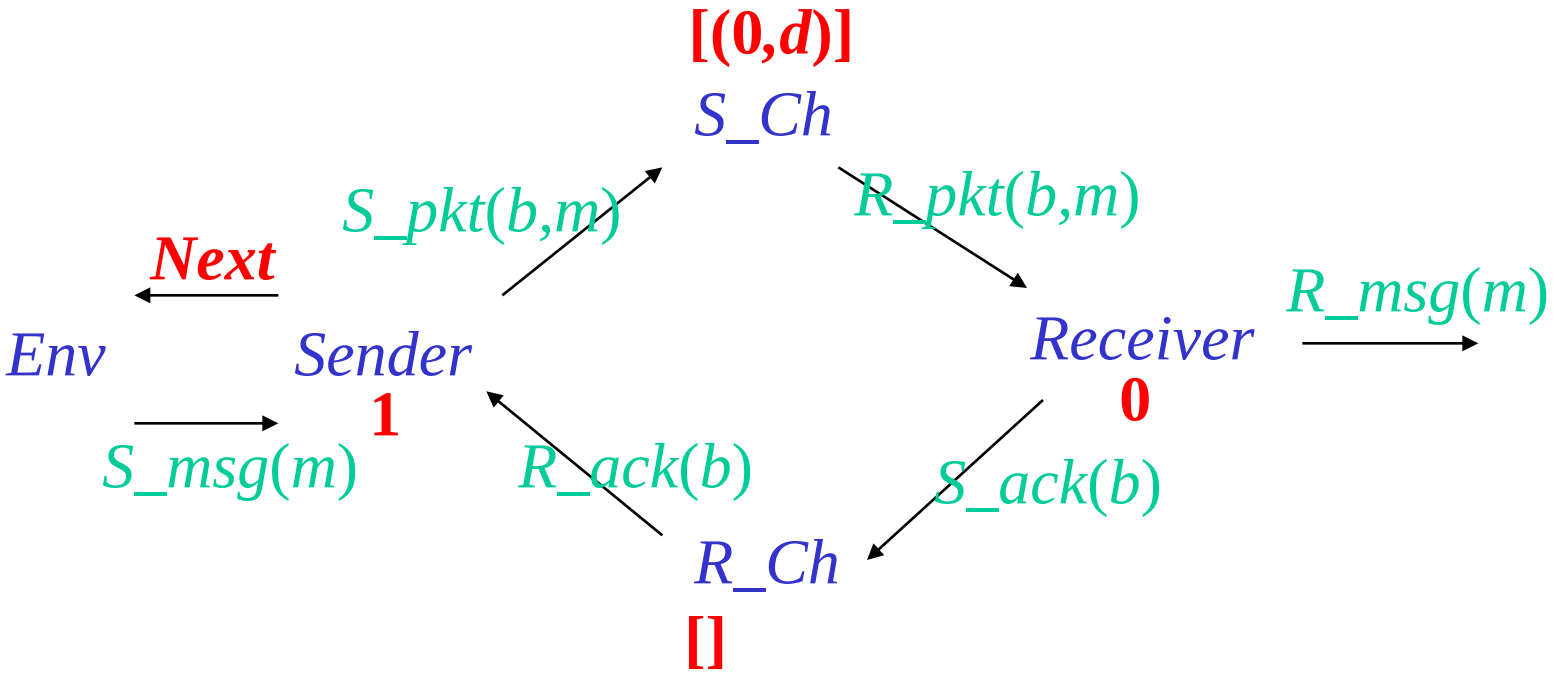

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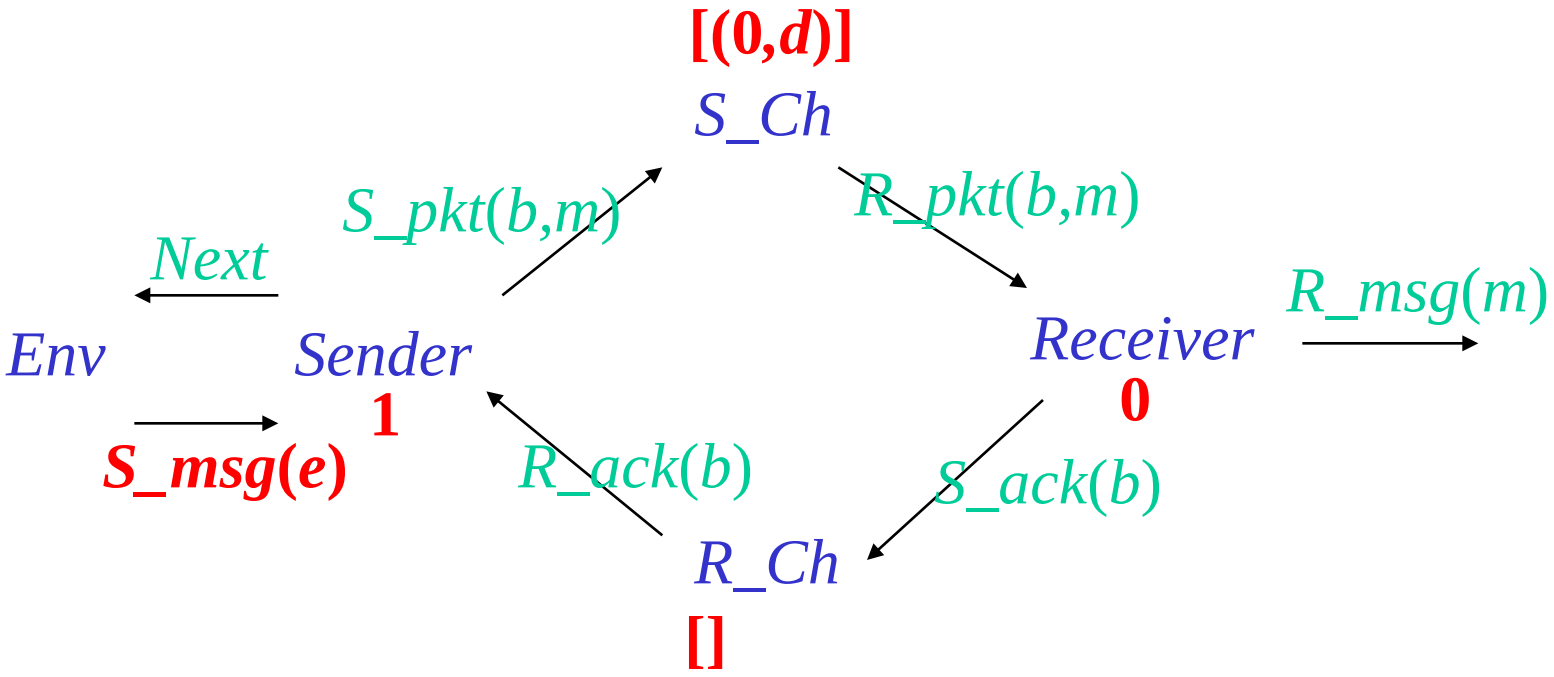

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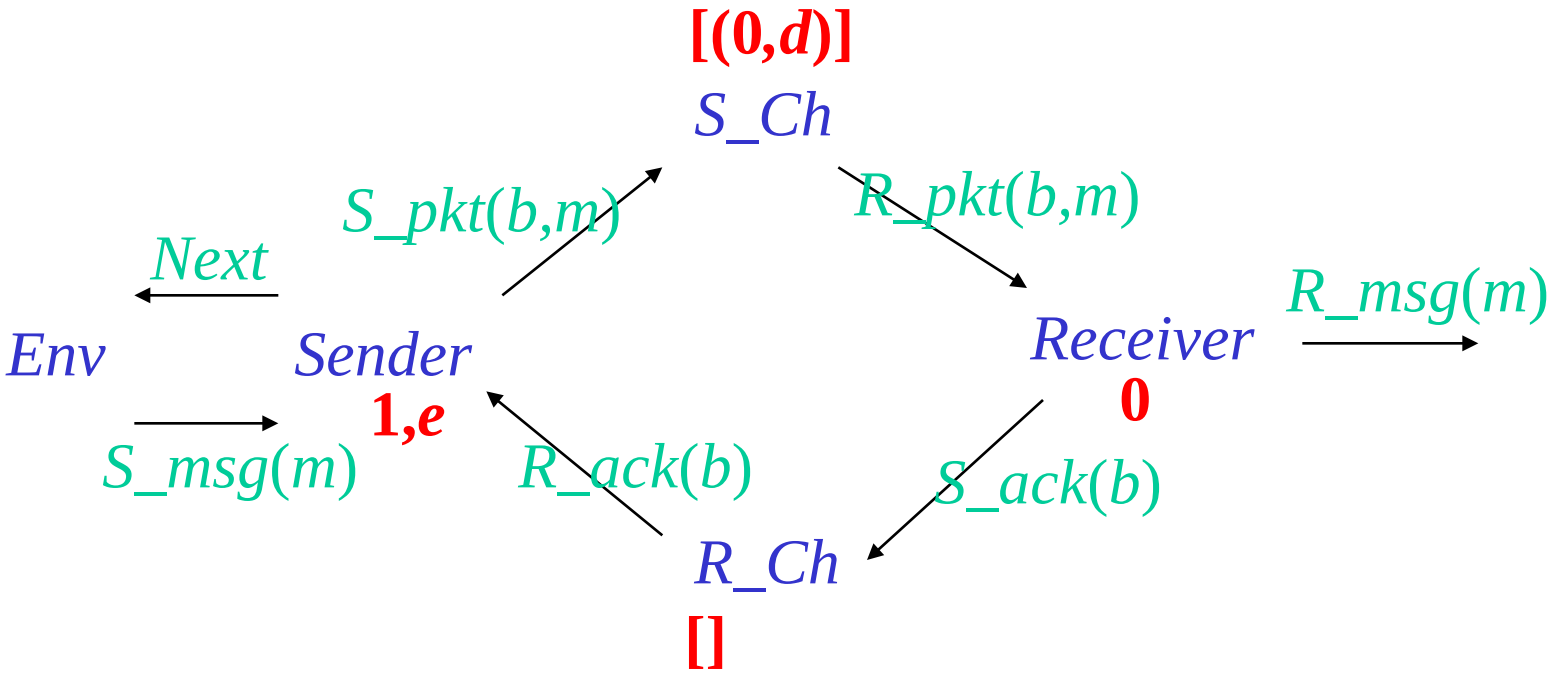

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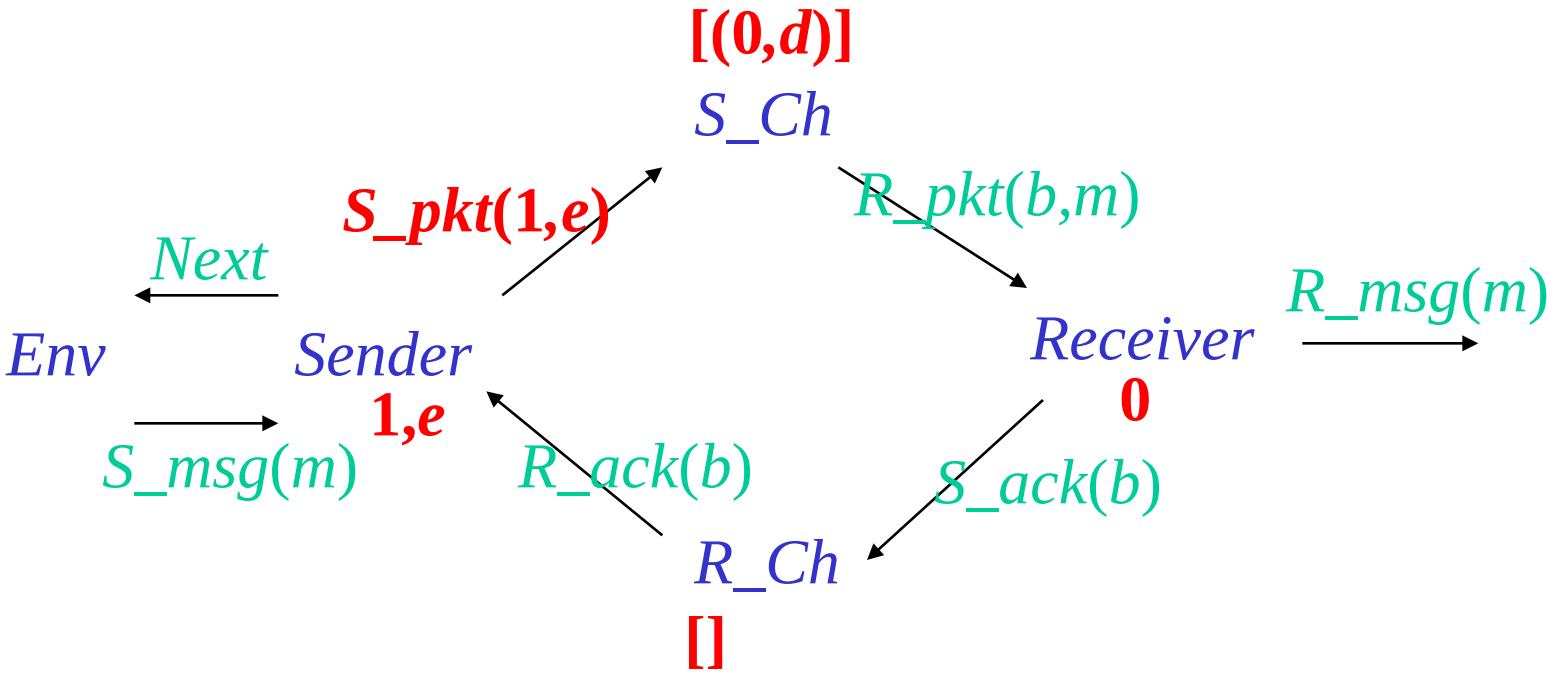

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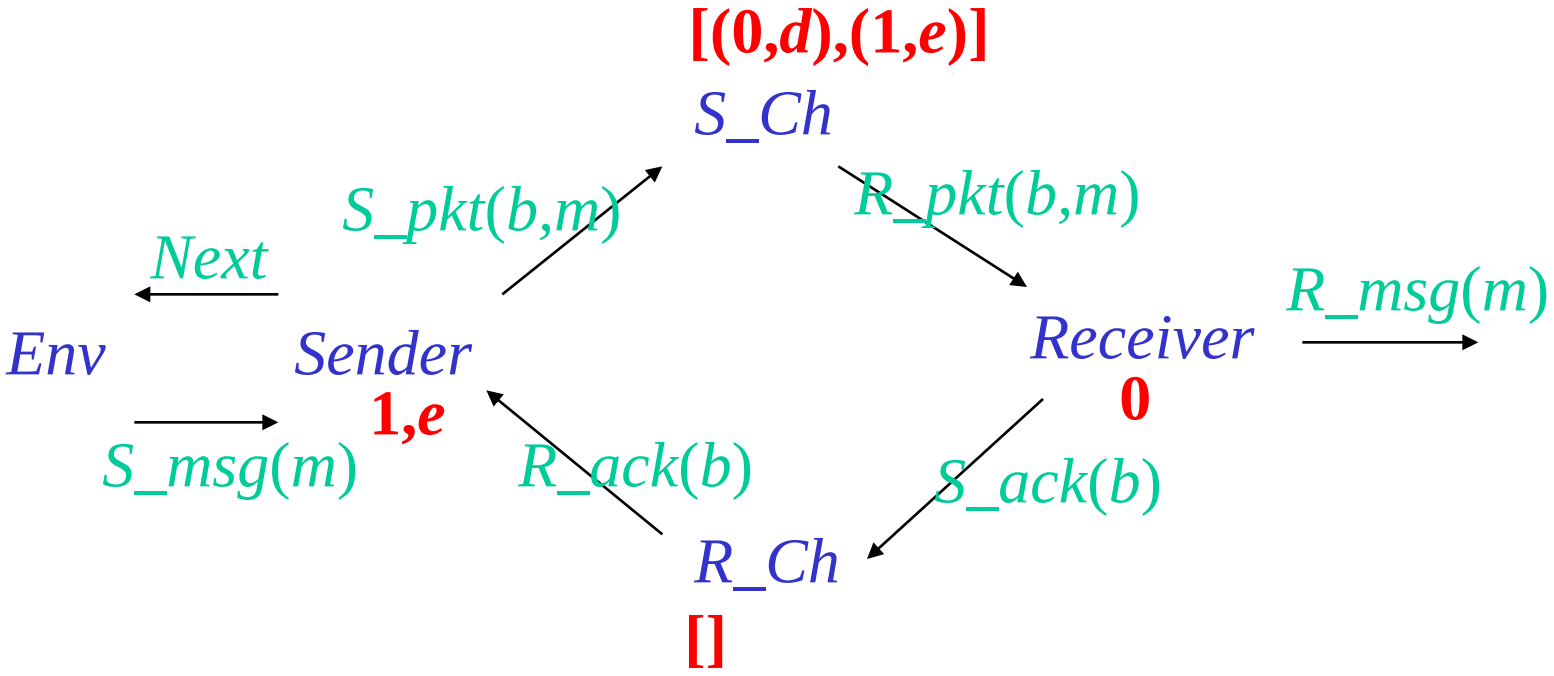

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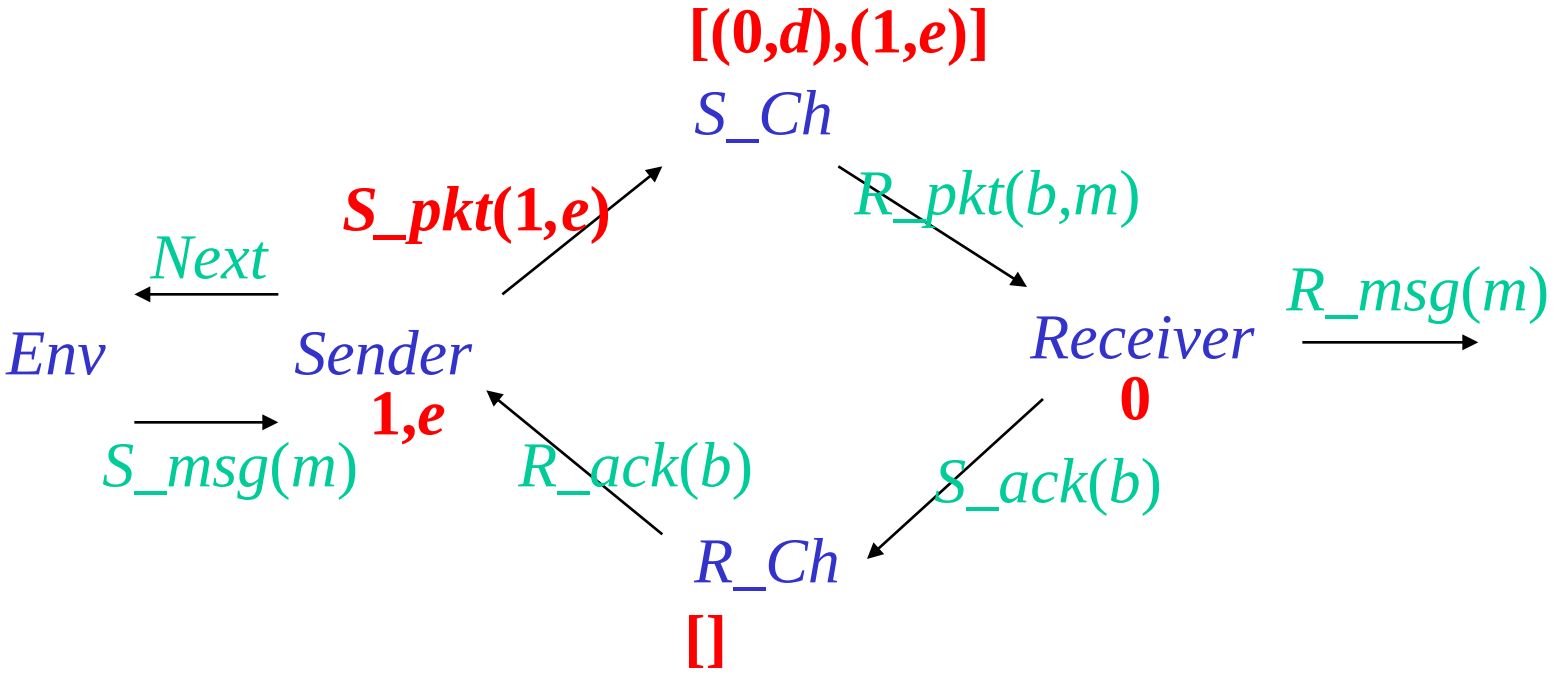

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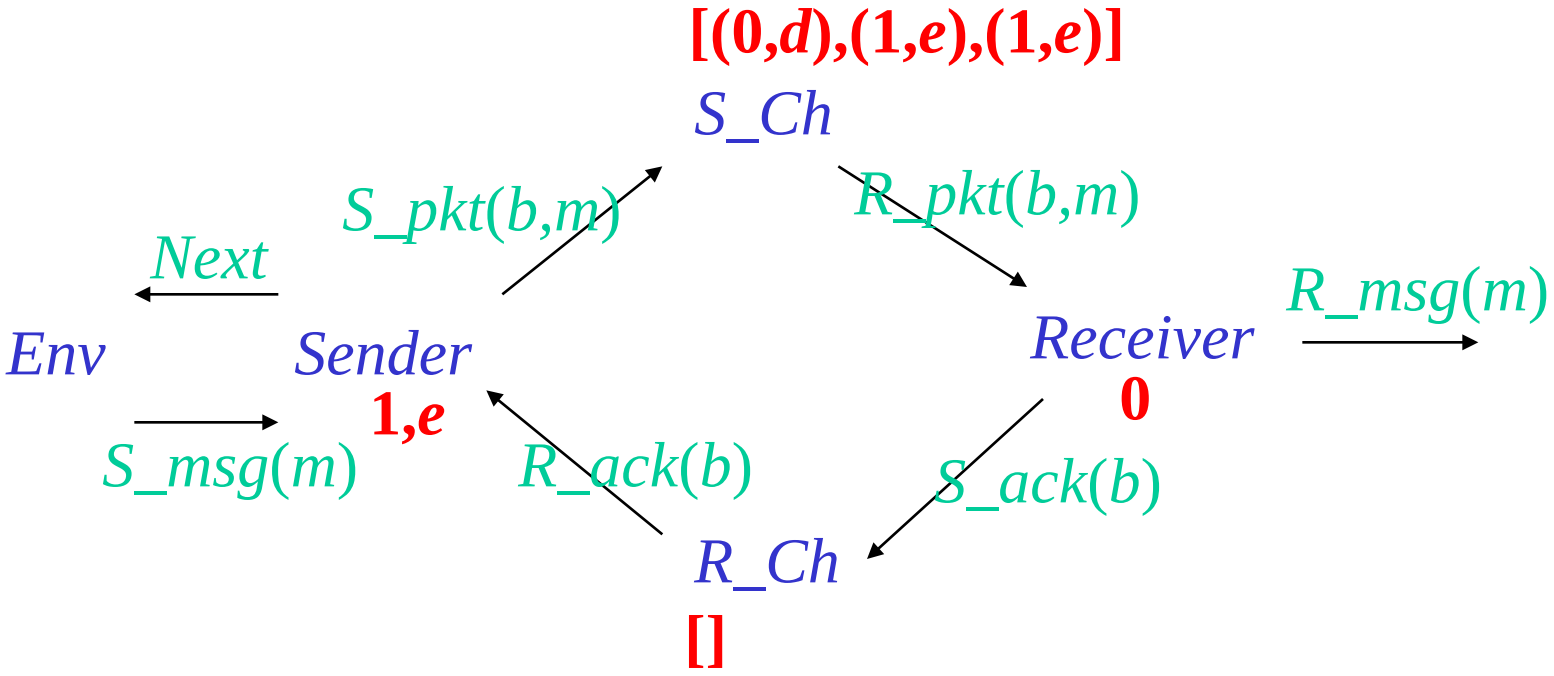

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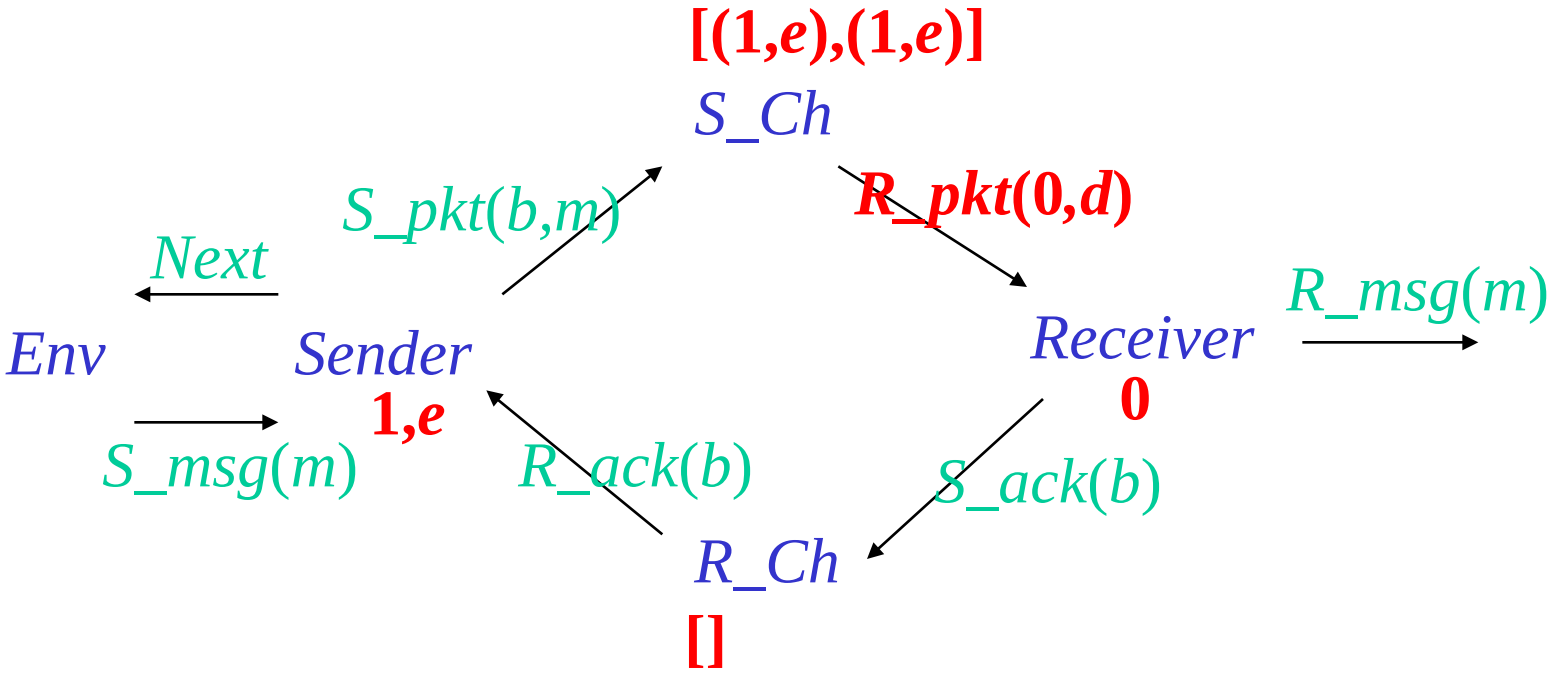

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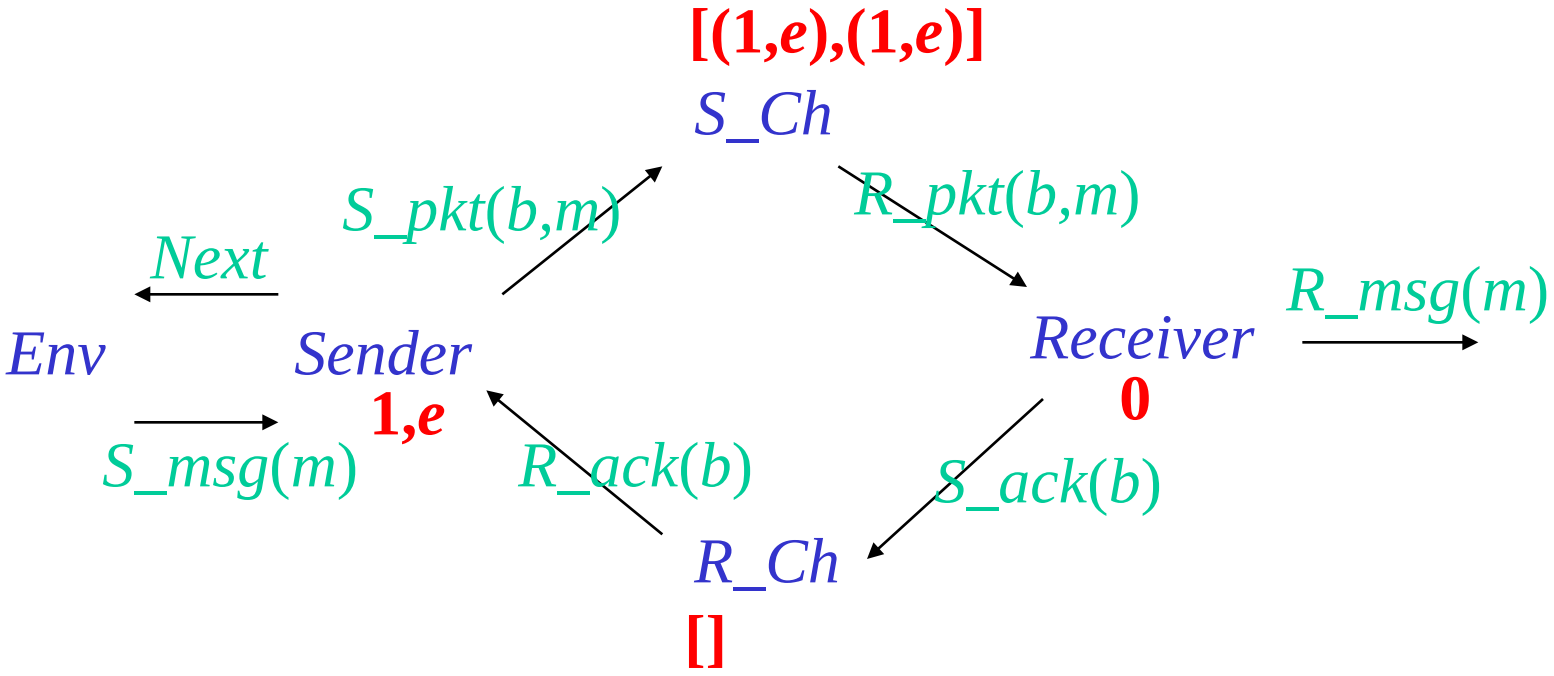

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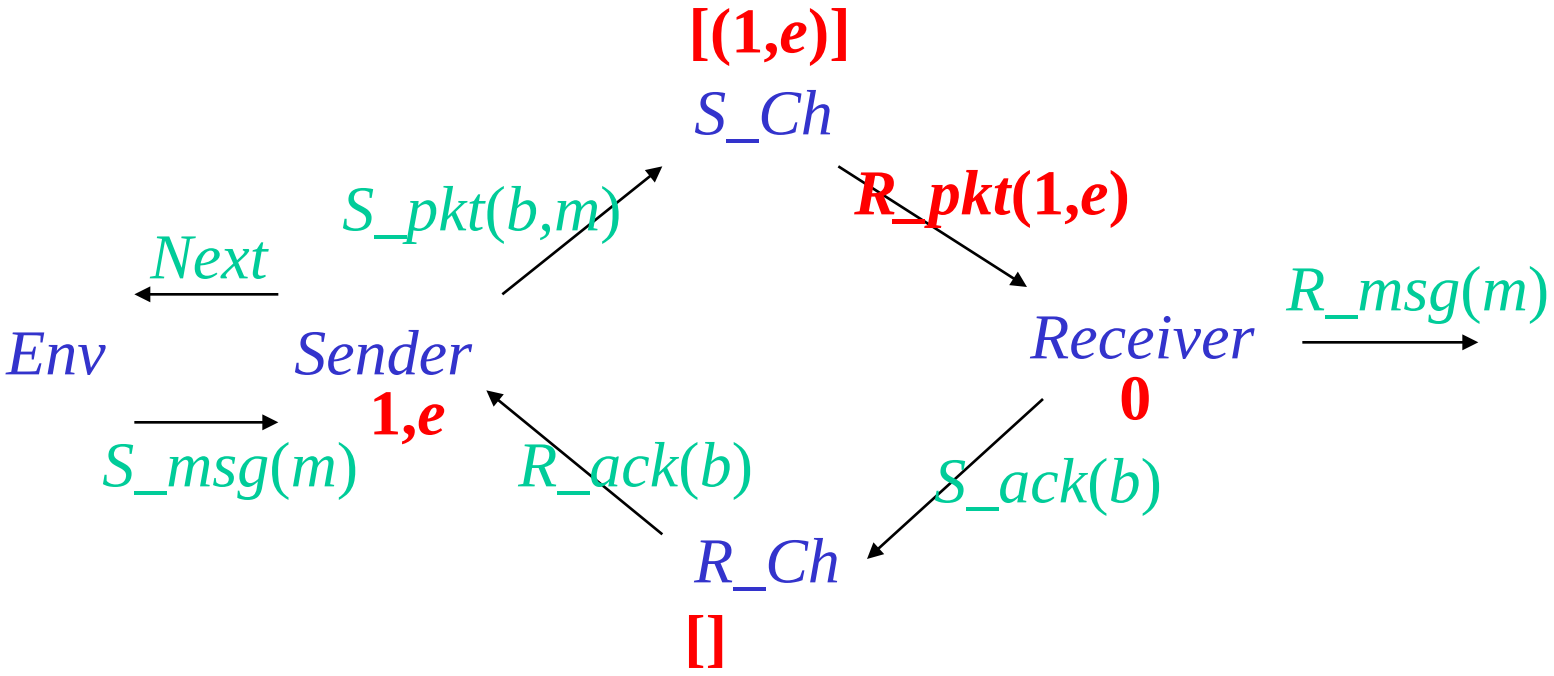

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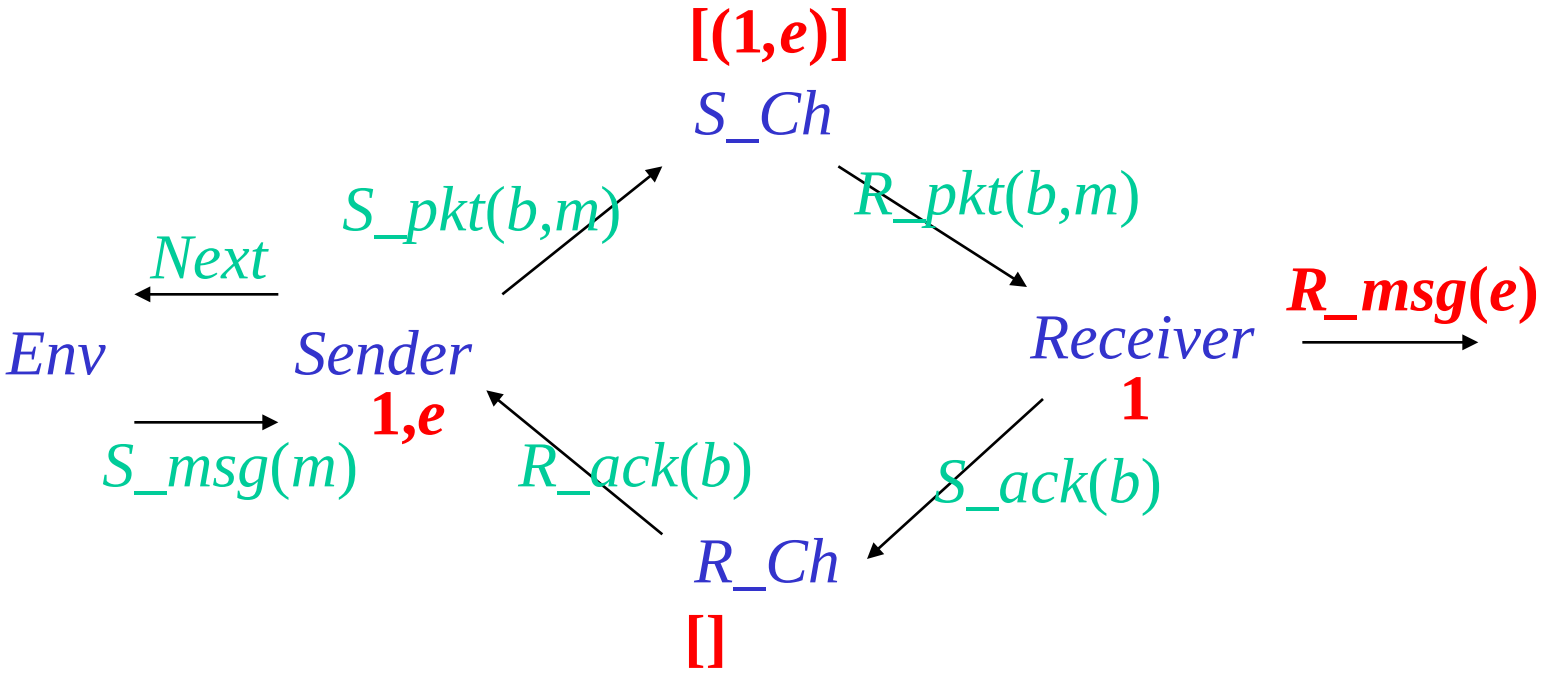

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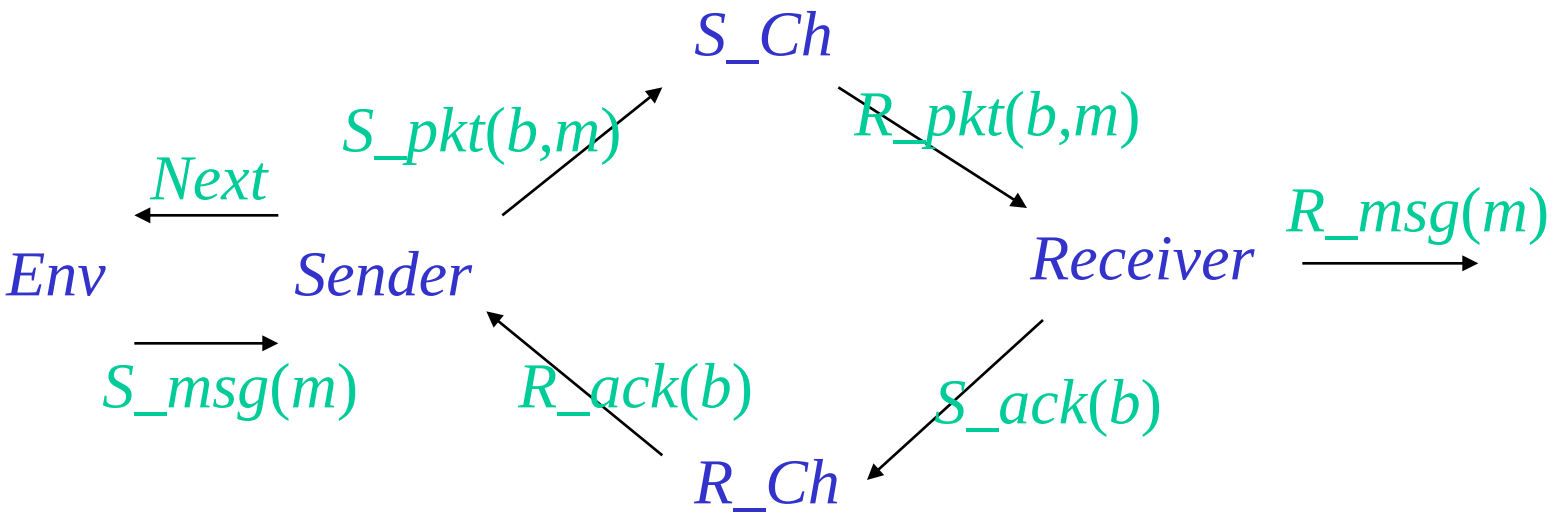
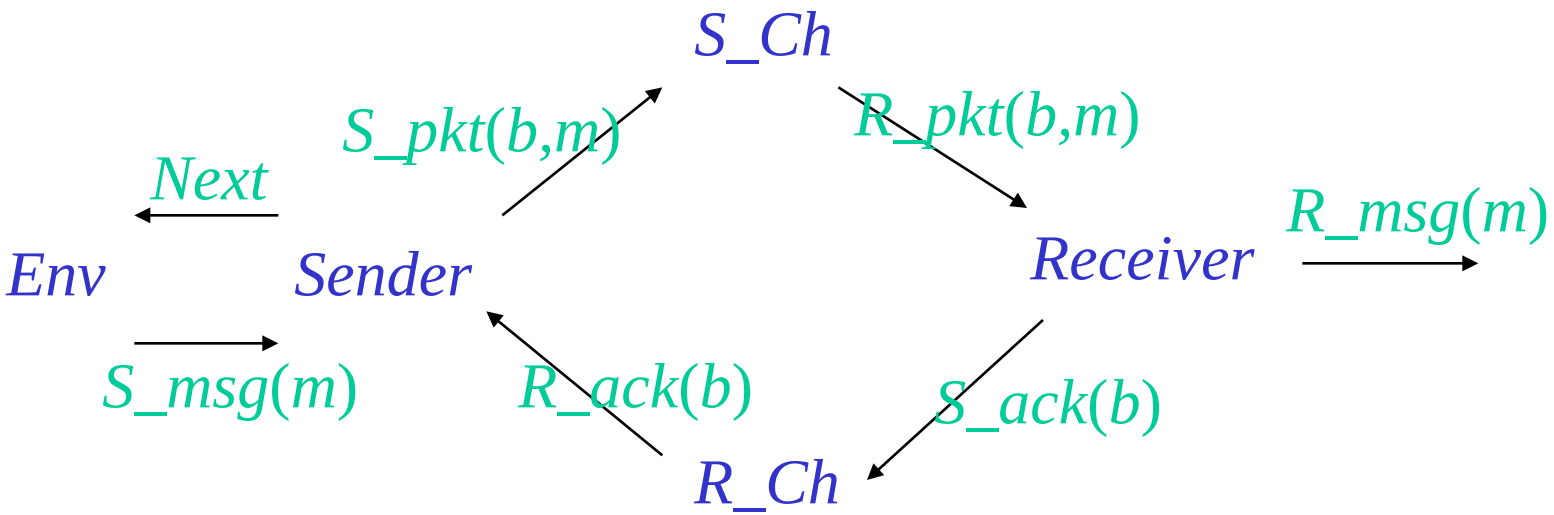


Sender state: *message* : *None* or *Some*(*m*)

header : 0 or 1

trans.:
- if *message*=*None* then
  send *Next* ; get *S_msg*(*m*) ; *message* := *Some*(*m*)
- if *message*=*Some*(*m*) then send *S_pkt*(*header*,*m*)
- when *R_ack*(*b*) is received
  if *b*=*header* then flip *header* ; *message* := *None*

Alternating Bit Protocol

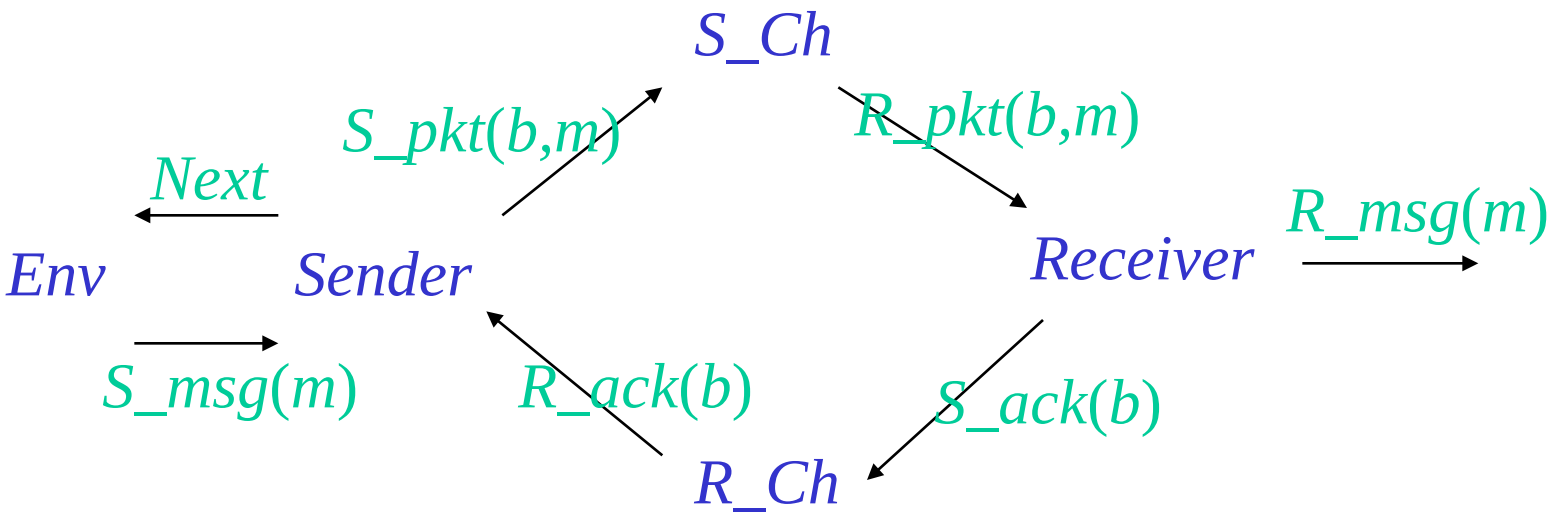


Receiver

state: *header* : 0 or 1

trans.: • when *R_pkt*(*b*,*m*) is received
if *b*≠*header* then
send *R_msg*(*m*) ; flip *header*
• send *S_ack*(*header*)

Alternating Bit Protocol



S_Ch state: queue of packets

trans.:
- when *bm*(=*S_pkt*(*b*,*m*)) is received
  enqueue *bm* or ignore *bm* (*bm* is lost)
- if the queue is not empty
  let *bm*(=…) be the first packet ; send *R_pkt*(*b*,*m*)
  dequeue *bm* or do not dequeue *bm*
  (*bm* is duplicated)

Concrete States

- Queues may grow unlimitedly
  - An element of a queue may be duplicated indefinitely
- The concrete state space is obviously infinite

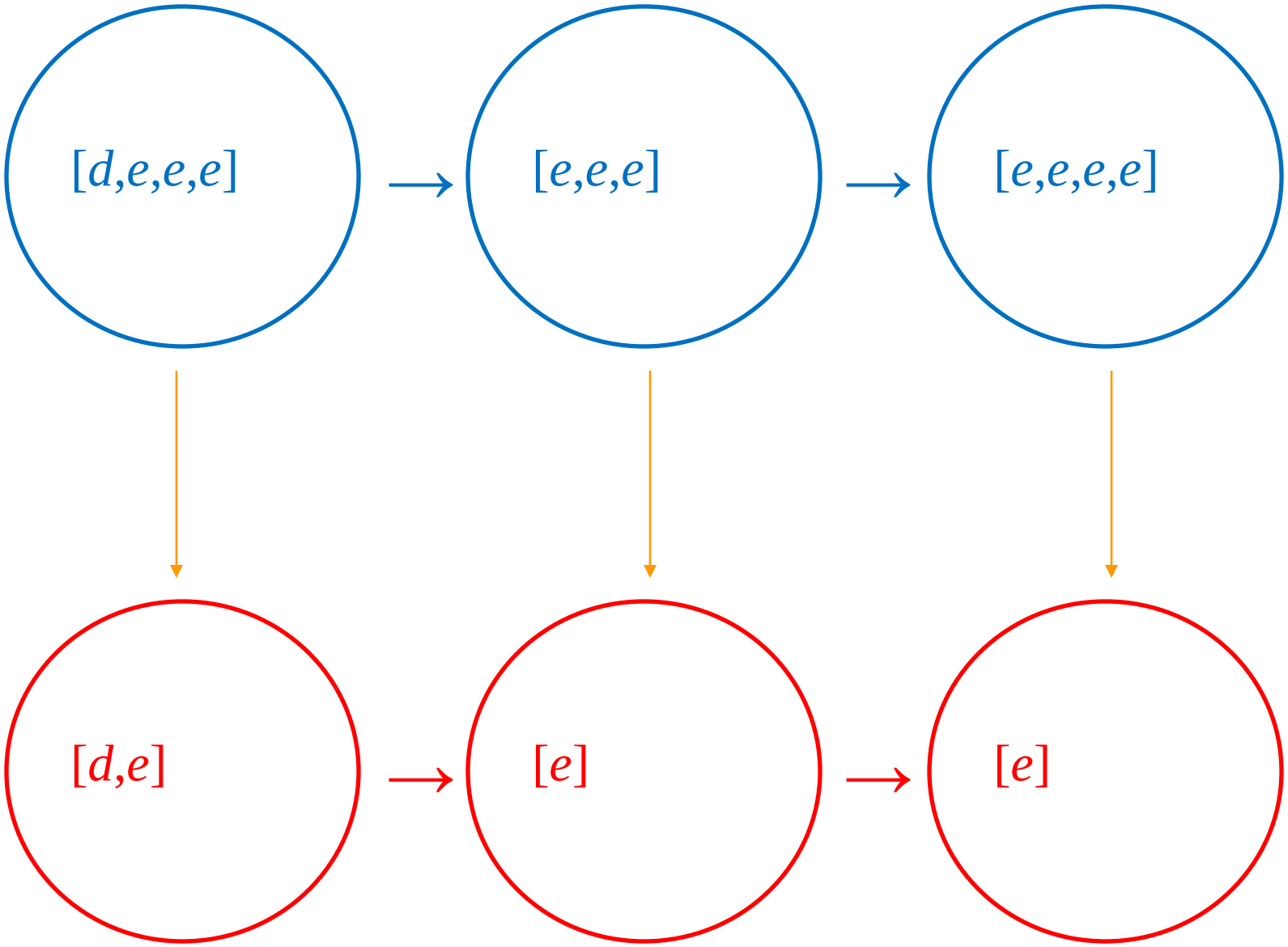
Abstraction of Channels

- Reducing queues by removing duplicated elements in a queue
  - For example, [*d*,*d*,*d*,*d*,*e*,*e*,*e*,*f*] is reduced to [*d*,*e*,*f*]
- Accordingly, transitions of channels are abstracted

Abstract S_Ch

state: reduced queue of packets

trans.:
- when *bm*(=*S_pkt*(*b*,*m*)) is received
  enqueue *bm* ; reduce or ignore *bm* (*bm* is lost)
- if the queue is not empty
  let *bm*(=…) be the first packet ; send *R_pkt*(*b*,*m*)
  dequeue *bm* or do not dequeue *bm*
  (*bm* is duplicated)


[d,e,e,e]
[e,e,e]
[e,e,e,e]
[d,e]
[e]
[e]

Abstract States

- Queues in channels are reduced
- Even though the abstract state space is still infinite in this example,
- Only a finite number of abstract states are reachable from an initial state
  - The length of a reduced queue in a channel is at most 2

Simulation

- If t is an abstraction of s and $s \rightarrow s'$ then there exists an abstraction t' of s' such that $t \rightarrow t'$ (if $s \rightarrow s'$ then $\alpha(s) \rightarrow \alpha(s')$)

Concrete path

$$s_0 \rightarrow s_1 \rightarrow s_2 \rightarrow \ldots \rightarrow s_n$$

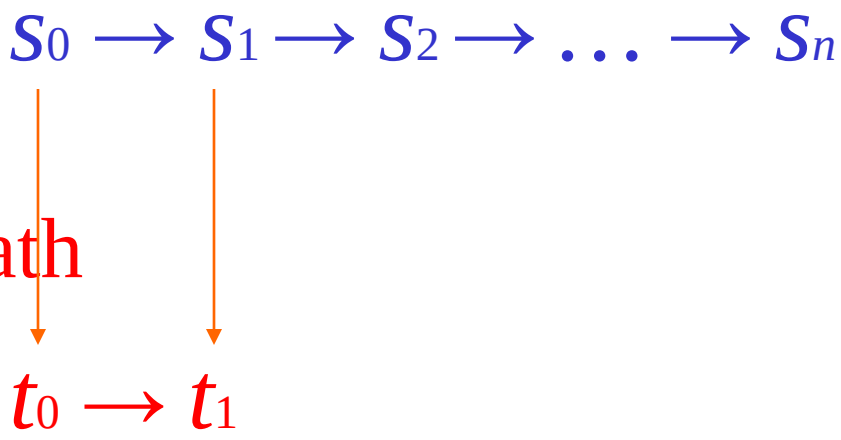
Abstract path

t_0

Simulation

- If t is an abstraction of s and $s \rightarrow s'$ then there exists an abstraction t' of s' such that $t \rightarrow t'$ (if $s \rightarrow s'$ then $\alpha(s) \rightarrow \alpha(s')$)

Concrete path



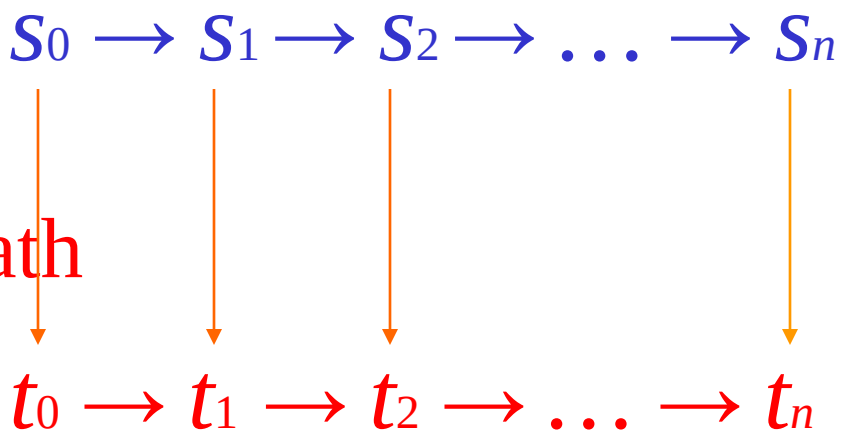
Abstract path

Simulation

- If t is an abstraction of s and $s \rightarrow s'$ then there exists an abstraction t' of s' such that $t \rightarrow t'$ (if $s \rightarrow s'$ then $\alpha(s) \rightarrow \alpha(s')$)

Concrete path

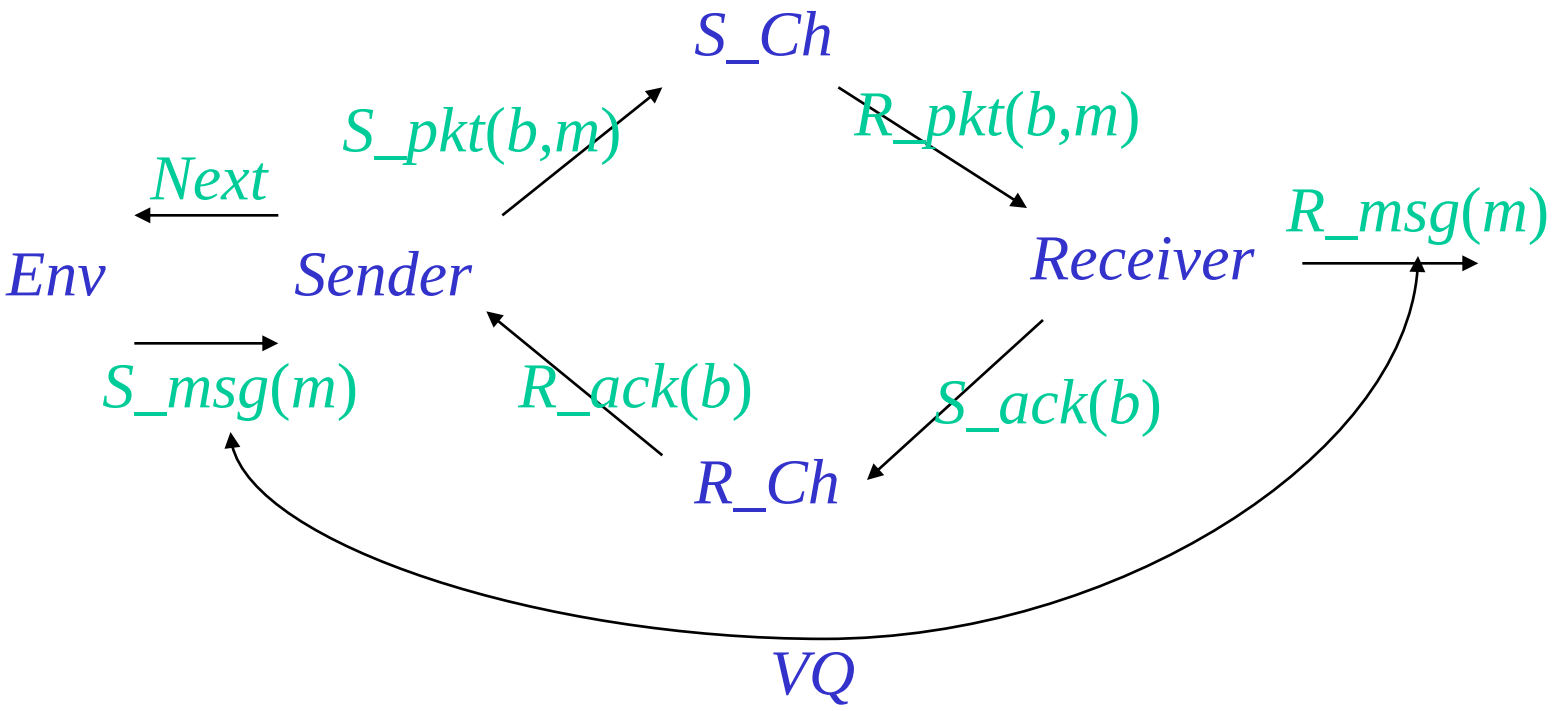
Abstract path



Abstract Model Checking

- If a property holds in any abstract path, then the corresponding property holds in any concrete path
- Example
  - After a transition by $S\_msg(m)$, if there exists a transition by $R\_msg(m')$, then $m=m'$

Alternating Bit Protocol



After a transition by *S_msg*(*m*), if there exists a transition by *R_msg*(*m′*), then *m*=*m′*

(This property is expressed by a virtual queue (*VQ*) that stores *S_msg*(*m*) and compares it with *R_msg*(*m′*))

Microsoft Static Driver Verifier (SDV)

- Hostile model of the driver's execution environment
  - *Harness code* simulates the operating system initializing and invoking the device driver
  - *Stub code* provides the semantics for the kernel APIs
- SLAM Tookit
  - CEGAR
- API usage rules (properties)
  - About 60, described in SLIC

SLAM Toolkit

- Safety verification of system software
  - Target: Device drivers for Windows with well defined interface
- Three phases
  - C2BP: tool for translating (abstracting) C programs to Boolean programs, using predicates in specifications (API usage rules)
  - BEBOP: model checker for Boolean programs
  - NEWTON: tool that analyzes error paths produced by the model checker, and discovers predicates for refining Boolean programs

CEGAR

- Counter
- Example-
- Guided
- Abstraction
- Refinement

```
state {
   enum { Unlocked=0, Locked=1 }
     state = Unlocked;
}


KeAcquireSpinLock.return {
  if (state == Locked)
    abort;
  else
    state = Locked;
}

KeReleaseSpinLock.return {
  if (state == Unlocked)
    abort;
  else
    state = Unlocked;
}
```

SLIC spec. Specification Language for Interface Checking

```
enum { Unlocked=0, Locked=1 }
  state = Unlocked;

void slic_abort() {
  SLIC_ERROR: ;
}

void KeAcquireSpinLock_return {
  if (state == Locked)
    slic_abort();
  else
    state = Locked;
}

void KeReleaseSpinLock_return {
  if (state == Unlocked)
    slic_abort();
  else
    state = Unlocked;
}
```

C program obtained by compiling SLIC spec.

```
void example() {
 do {
  KeAcquireSpinLock();

  nPacketsOld = nPackets;
  req = devExt->WLHV;
  if(req && req->status) {
    devExt->WLHV = req->Next;
    KeReleaseSpinLock();

    irp = req->irp;
    if(req->status > 0){
      irp->IoS.Status = SUCCESS;
      irp->IoS.Info = req->Status;
    } else {
      irp->IoS.Status = FAIL;
      irp->IoS.Info = req->Status;
    }
    SmartDevFreeBlock(req);
    IoCompleteRequest(irp);
    nPackets++;
  }
 } while(nPackets!=nPacketsOld);
 KeReleaseSpinLock();

}
```

Code for a device driver

```
void example() {
 do {
  KeAcquireSpinLock();
A:KeAcquireSpinLock_return();
  nPacketsOld = nPackets;
  req = devExt->WLHV;
  if(req && req->status) {
    devExt->WLHV = req->Next;
    KeReleaseSpinLock();
B:  KeReleaseSpinLock_return();
    irp = req->irp;
    if(req->status > 0){
      irp->IoS.Status = SUCCESS;
      irp->IoS.Info = req->Status;
    } else {
      irp->IoS.Status = FAIL;
      irp->IoS.Info = req->Status;
    }
    SmartDevFreeBlock(req);
    IoCompleteRequest(irp);
    nPackets++;
  }
 } while(nPackets!=nPacketsOld);
 KeReleaseSpinLock();
C:KeReleaseSpinLock_return();
}
```

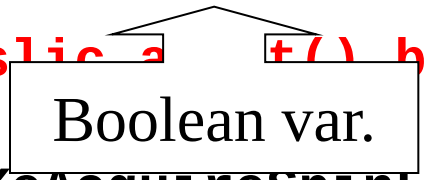
Device driver code with inserted checks for specification

```
decl {state==Locked}, {state==Unlocked};

void slic_a    t() begin SLIC    OR: skip; end

void KeAcquireSpinLock_return
begin
  if ({state==Locked})
    slic_abort();
  else
    {state==Locked},{state==Unlocked} := T,F;
begin

void KeReleaseSpinLock_return
begin
  if ({state==Unlocked})
    slic_abort();
  else
    {state==Locked},{state==Unlocked} := F,T;
end
```



Boolean program obtained from SLIC spec.

```
decl bL, bU;

void slic_abort() begin SLIC_ERROR: skip; end

void KeAcquireSpinLock_return
begin
  if (bL)
    slic_abort();
  else
    bL,bU := T,F;
begin

void KeReleaseSpinLock_return
begin
  if (bU)
    slic_abort();
  else
    bL,bU := F,T;
end
```

Boolean program obtained from SLIC spec.

```
void example() begin
 do {
  skip();
A:KeAcquireSpinLock_return();
  skip;
  skip;
  if(*) then
    skip;
    skip();
B:  KeReleaseSpinLock_return();
    skip;
    if(*) then
      skip;
      skip;
    else
      skip;
      skip;
    fi
    skip;
    skip;
    skip;
  }
 } while(*);
 skip();
C:KeReleaseSpinLock_return();
end
```

Boolean program obtained from device driver code

***** : undetermined

Model Checking

- Find a path that reaches "**SLIC_ERROR**"
- In this case, an error path

  A, **A**, **SLIC_ERROR**

  is found
- Verify if the error path is valid with respect to the original C program
  - Verification condition generation（VCGen）
- In this case, it is not valid because the predicate

  nPackets==nPacketsOld

  is both true and false in the path

Re-abstraction

- Use the predicate **`nPackets==nPacketsOld`**
- The statement **`nPacketsOld = nPackets`** makes the predicate true
- The statement **`nPackets++`** makes the predicate false if it is now true (detected by the theorem prover)

```
bool choose(pos, neg)
begin
     if (pos) then return T; elsif (neg) then return F;
  elsif (*)   then return T; else             return F; fi
end
```

```
void example() begin
 do {
  skip();
A:KeAcquireSpinLock_return();
  b := T;
  skip;
  if(*) then
    skip;
    skip();
B:  KeReleaseSpinLock_return();
    skip;
    if(*) then
      skip;
      skip;
    else
      skip;
      skip;
    fi
    skip;
    skip;
    b := choose(F,b);
  }
 } while(!b);
 skip();
C:KeReleaseSpinLock_return();
end
```

Boolean program obtained by re-abstraction (refinement)

b:

nPackets==nPacketsOld

Model Checking Again

- In this case, there is no error path that reaches "**`SLIC_ERROR`**"
- Loop invariant :

$$(\text{state} = \text{Locked} \wedge \text{nPackets} = \text{nPacketsOld})$$

$$\vee\ (\text{state} = \text{Unlocked} \wedge \text{nPackets} \neq \text{nPacketsOld})$$

References

– T. Ball, and S. K. Rajamani. Automatically Validating Temporal Safety Properties of Interfaces, *SPIN*, LNCS2057, 2001.

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– T. Ball, E. Bounimova, R. Kumar, V. Levin. SLAM2: Static Driver Verification with Under 4% False Alarms, *FMCAD*, 2010.

SLAM

- SLAM2
- The Static Driver Verifier Research Platform
- http://research.microsoft.com/en-us/projects/slam/
- Related project
  - http://mtc.epfl.ch/software-tools/blast/index-epfl.php
    - Lazy abstraction