6.1800 Spring 2024

Lecture #24: Tor

what to do when secure channels aren't enough

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6.1800 in the news

Maximum-severity GitLab flaw allowing account hijacking under active exploitation

The threat is potentially grave because it could be used in supply-chain attacks.

DAN GOODIN - 5/2/2024, 3:02 PM

A maximum severity vulnerability that allows hackers to hijack GitLab accounts with no user interaction required is now under active exploitation, federal government officials warned as data showed that thousands of users had yet to install a patch released in January.

A change GitLab implemented in May 2023 made it possible for users to initiate password changes through links sent to secondary email addresses. The move was designed to permit resets when users didn't have access to the email address used to establish the account. In January, GitLab disclosed that the feature allowed attackers to send reset emails to accounts they controlled and from there click on the embedded link and take over the account.

6.1800 in the news

Maximum-severity GitLab flaw allowing account hijacking under active exploitation

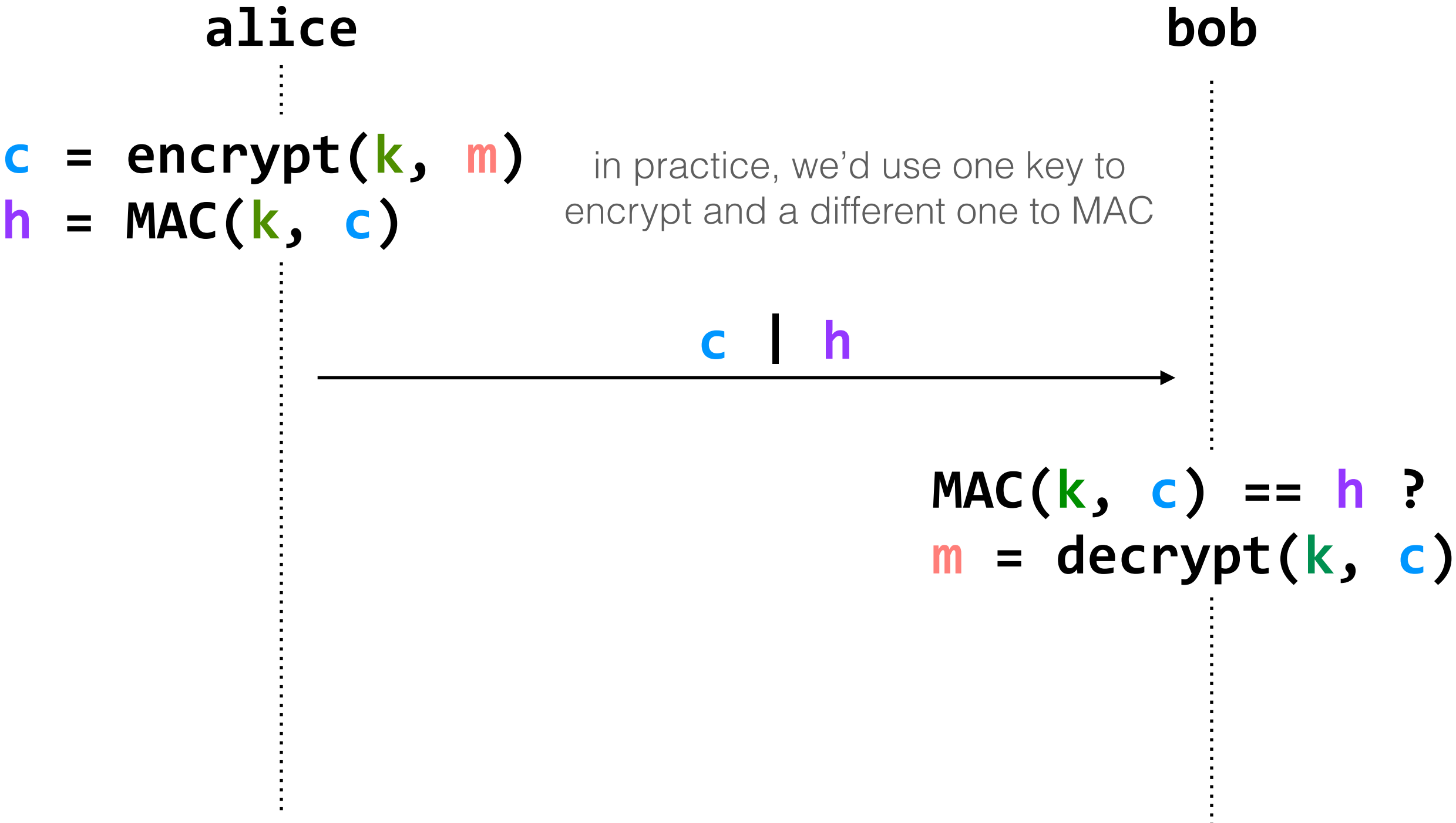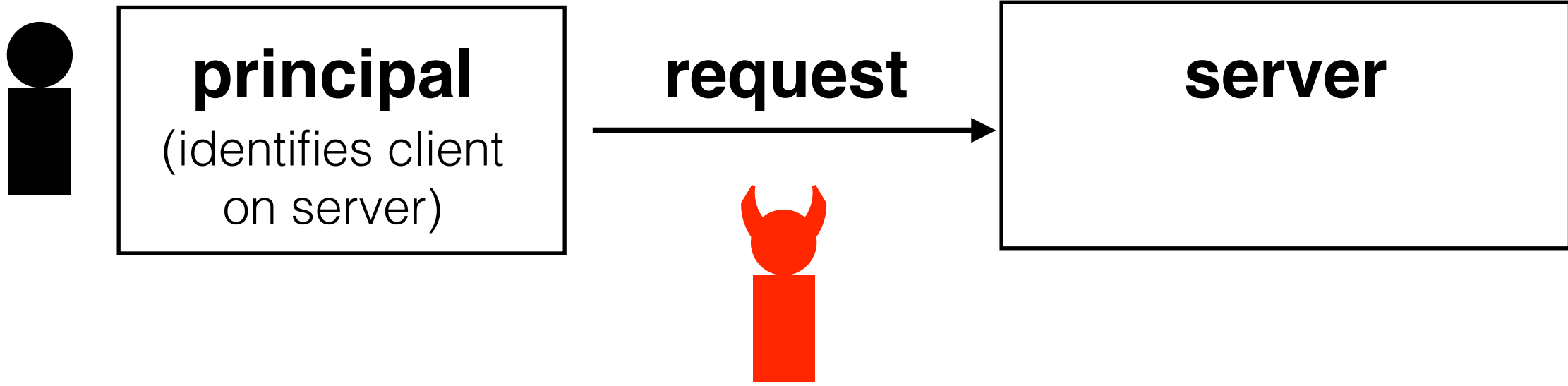The threat is potentially grave because it could be used in supply-chain attacks.

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note that the attack does **not** exploit how passwords are stored, but instead how the system allows them to be reset

today, we're still considering adversaries that are observing data on the network

principal
(identifies client on server)

request

server

alice   bob

```
c = encrypt(k, m)        in practice, we'd use one key to
h = MAC(k, c)            encrypt and a different one to MAC
```

c | h

```
MAC(k, c) == h ?
m = decrypt(k, c)
```

public-key cryptography: a message to **x** is encrypted with **x**'s public key; only **x**'s secret key can decrypt the message

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$$\text{encrypt}(\text{PK}_x,\ m) = c$$

$$\text{decrypt}(\text{SK}_x,\ c) = m$$

public-key cryptography: a message to **x** is encrypted with **x**'s public key; only **x**'s secret key can decrypt the message

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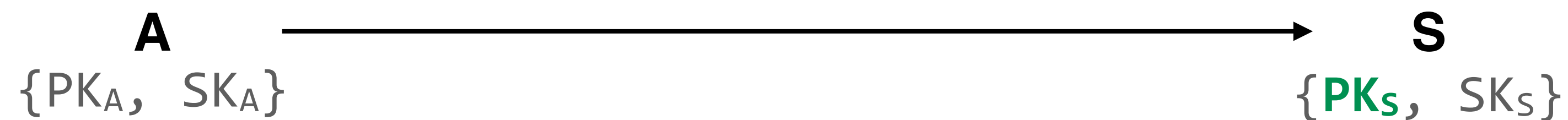$$\text{decrypt}(SK_x, c) = m$$

this is different from how you saw public-key cryptography used for signatures, and different from how you saw symmetric keys used for encryption

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this is different from how you saw public-key cryptography used for signatures, and different from how you saw symmetric keys used for encryption

A
$\{PK_A, SK_A\}$

S
$\{PK_S, SK_S\}$

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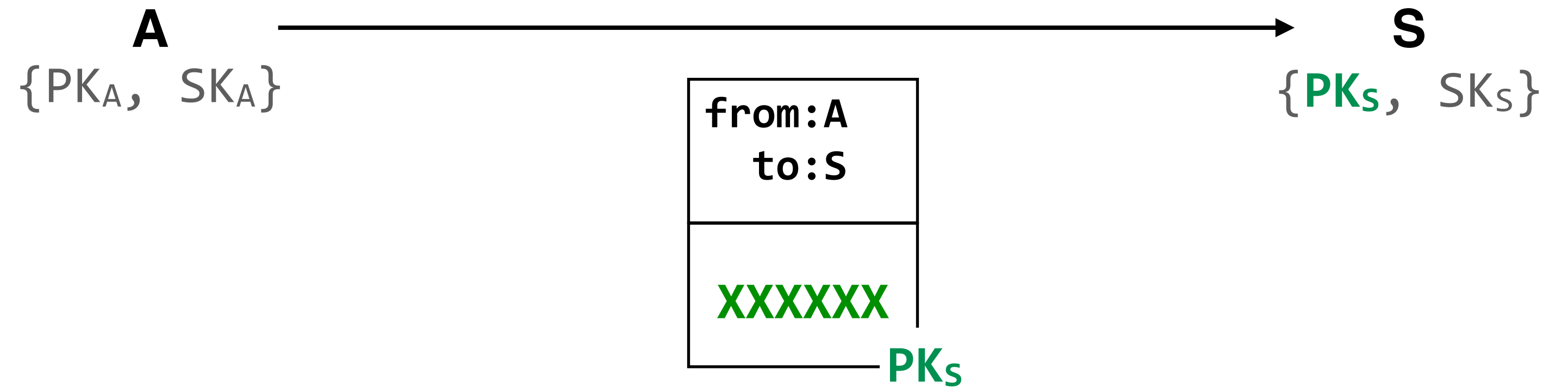
A
$\{PK_A, SK_A\}$

S
$\{PK_S, SK_S\}$

```
from:A
  to:S
```

XXXXXX
— PK_S

alice is encrypting data **to** S using its public key

public-key cryptography: a message to **x** is encrypted with **x**'s public key; only **x**'s secret key can decrypt the message

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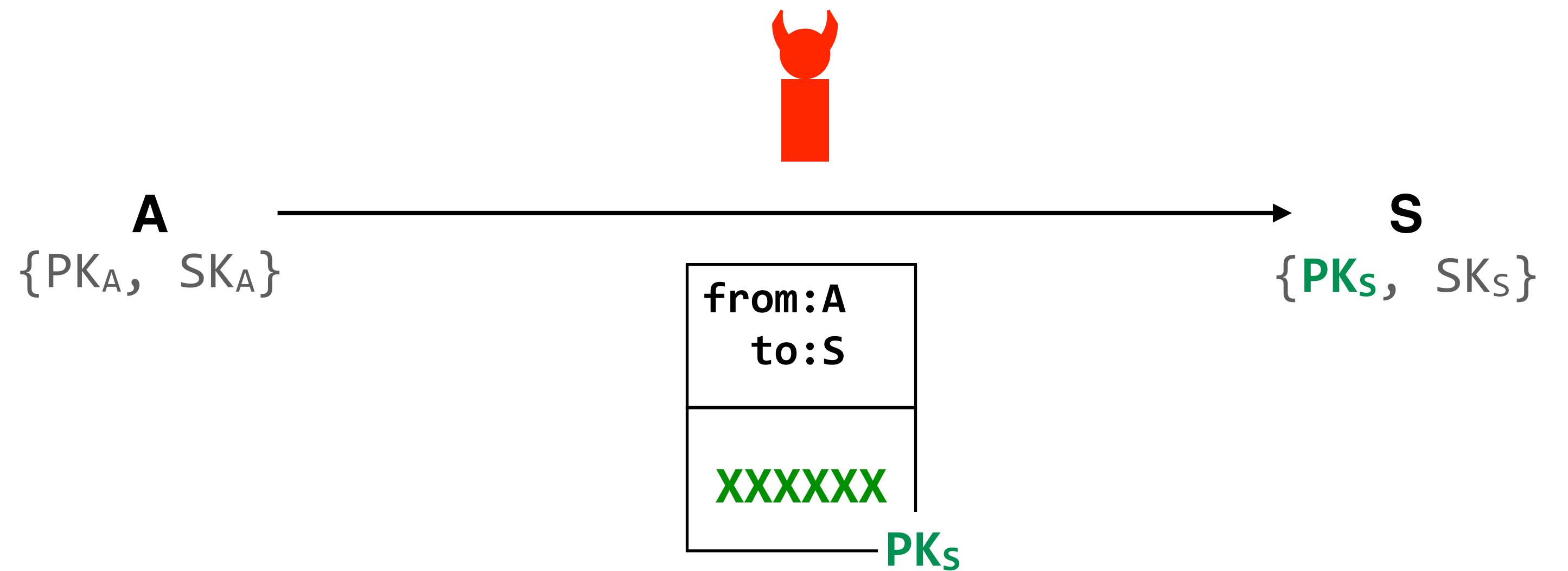
A
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S
$\{PK_S, SK_S\}$

```
from:A
to:S
```

XXXXXX

PK_S

alice is encrypting data **to** S using its public key

threat model: adversary is on the path between the client and the server

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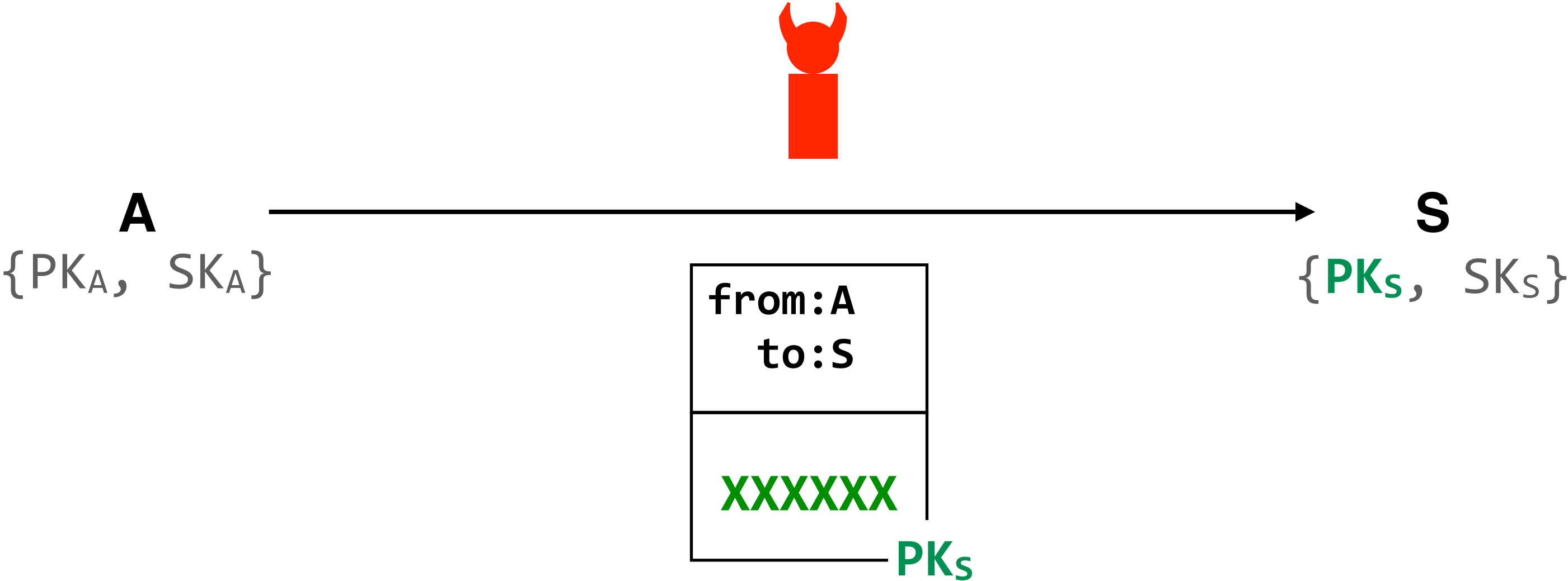
A
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S
$\{PK_S, SK_S\}$

from:A
to:S

XXXXXX

PK_S

alice is encrypting data **to** S using its public key

policy: provide **anonymity** (only the client should know that they're communicating with the server)

threat model: adversary is on the path between the client and the server

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A
$\{PK_A, SK_A\}$

```
from:A
  to:S

XXXXXX
```
PK$_S$

S
$\{PK_S, SK_S\}$

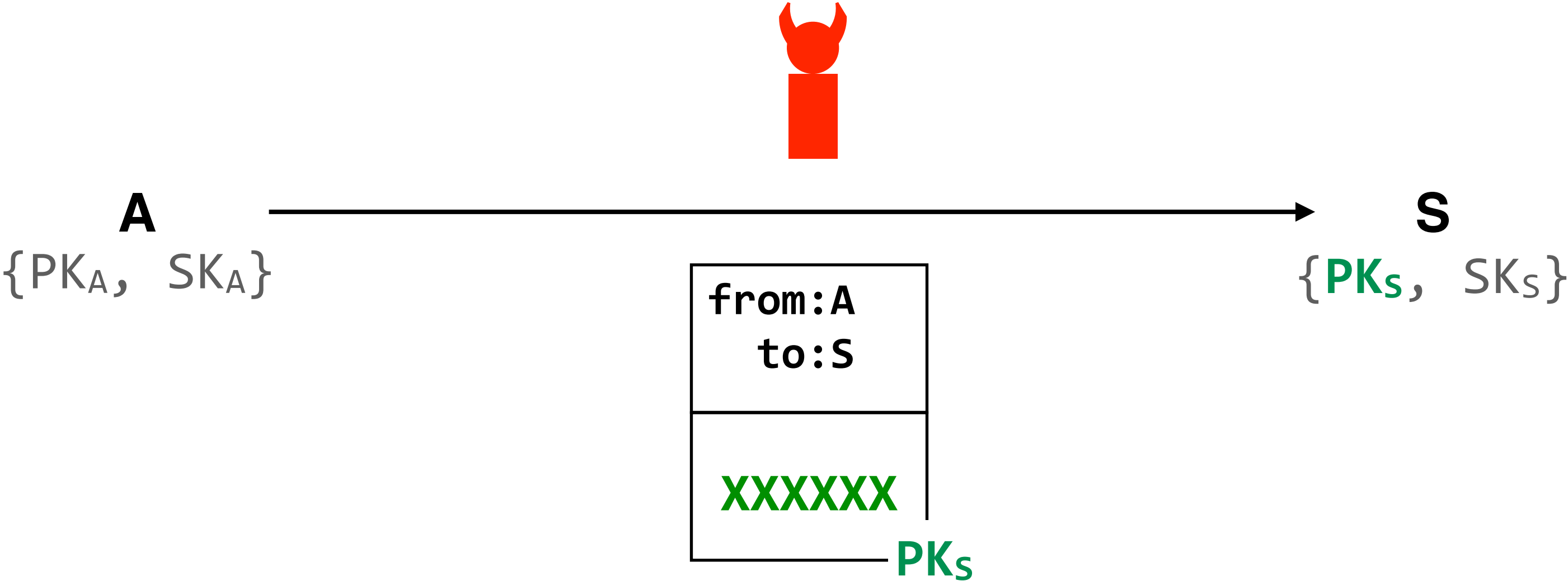alice is encrypting data **to** S using its public key

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XXXXXX
PK_S

alice is encrypting data **to** S using its public key

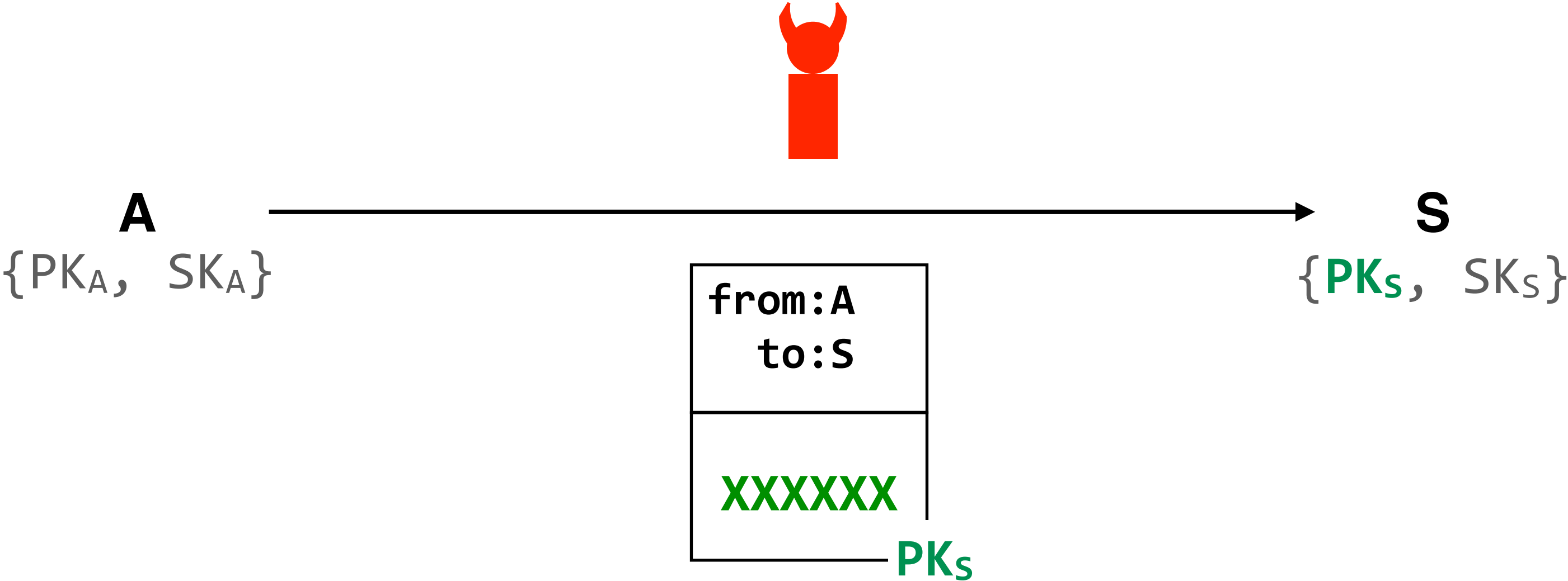**problem:** packet header exposes to the adversary that **A** is communicating with **S**

policy: provide **anonymity** (only the client should know that they're communicating with the server)

threat model: adversary is on the path between the client and the server

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PK_S

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things to avoid

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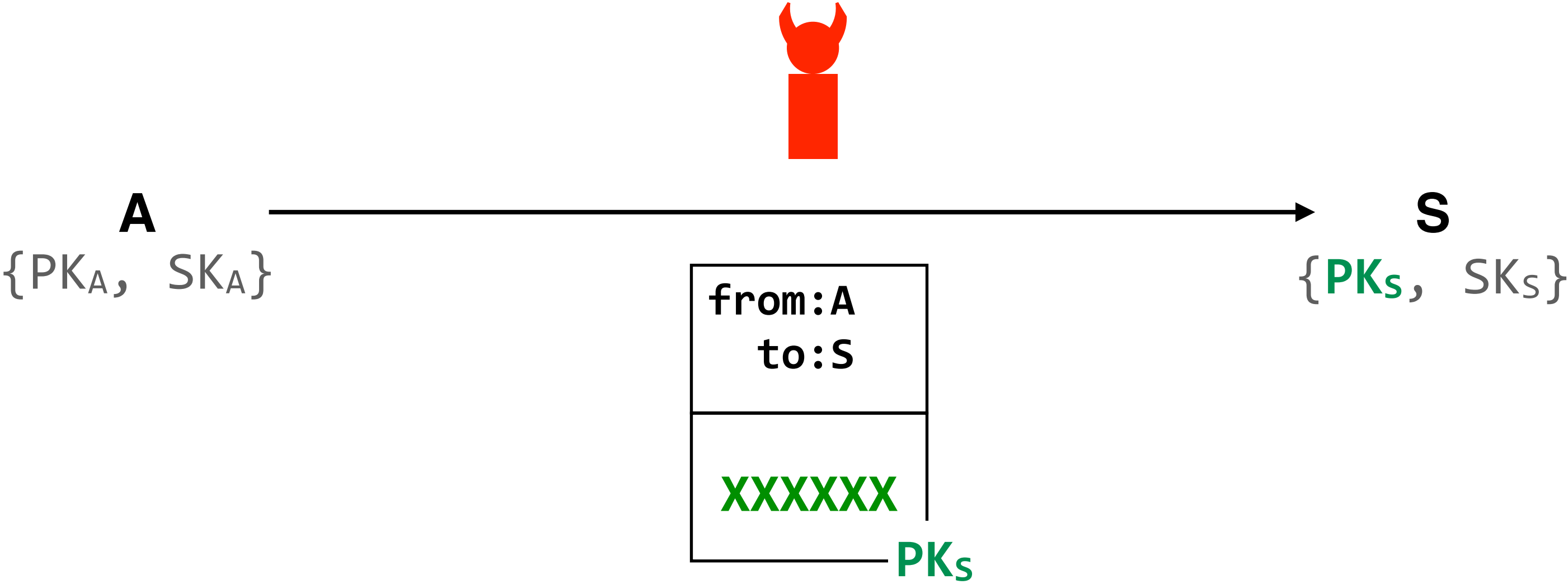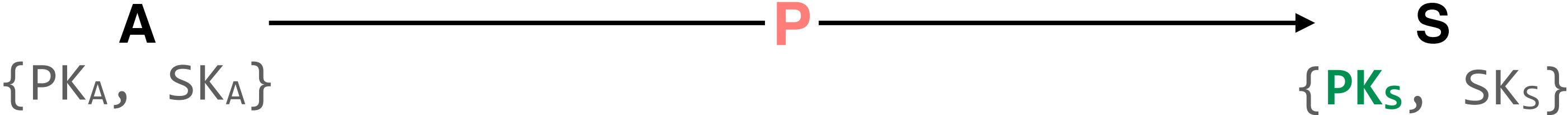
threat model: adversary is on the path between the client and the server

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$$\texttt{encrypt(PK}_x\texttt{, m) = c}$$

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A
$\{PK_A, \ SK_A\}$

P

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things to avoid

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$$A \rightarrow S$$

A
$\{PK_A, SK_A\}$

P

S
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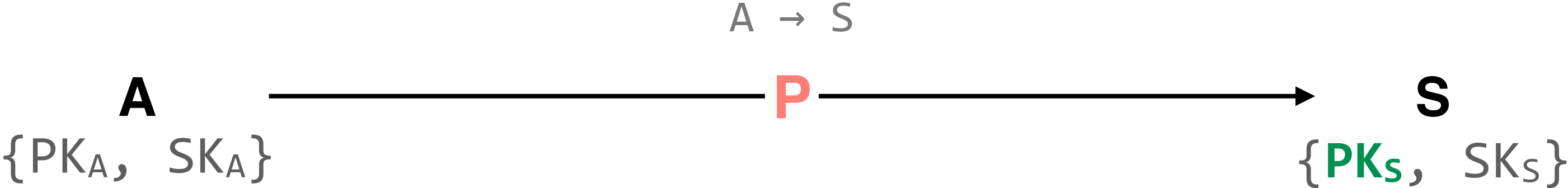
things to avoid

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things to avoid

no packet should say "from: A; to: S"

A → S

A
{PK$_A$, SK$_A$}

P

S
{PK$_S$, SK$_S$}

```
from:A
  to:P
```

XXXXXX
PK$_S$

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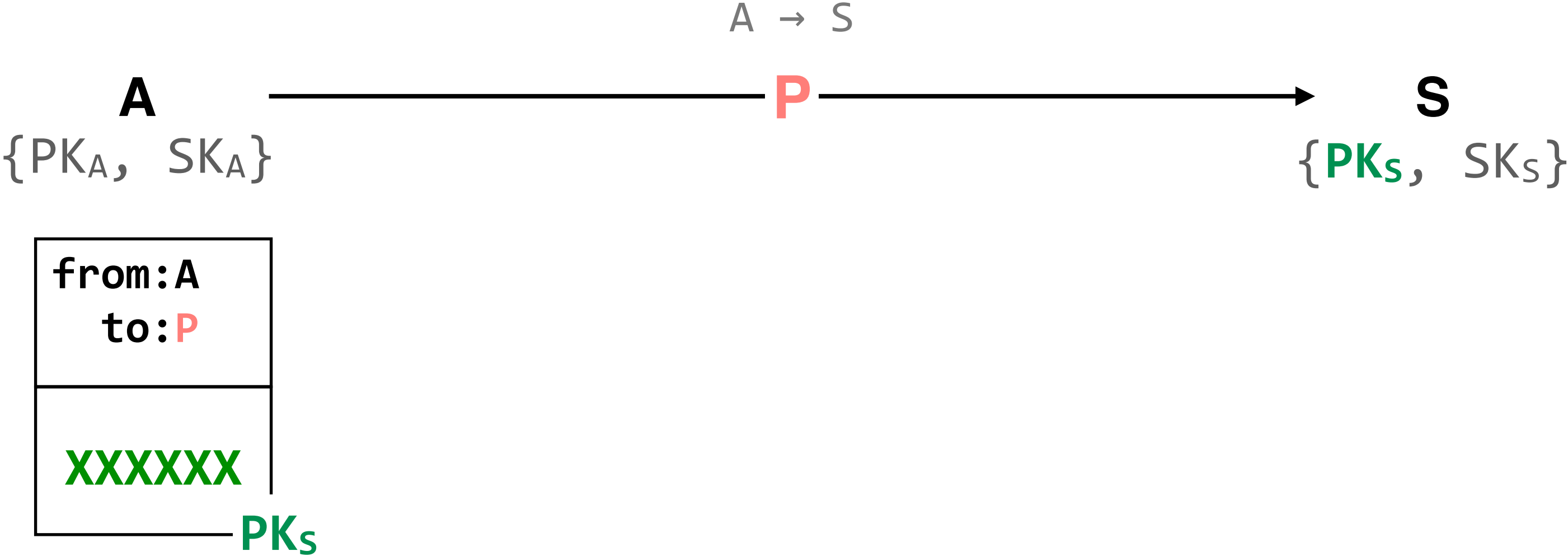
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XXXXXX

PK_S

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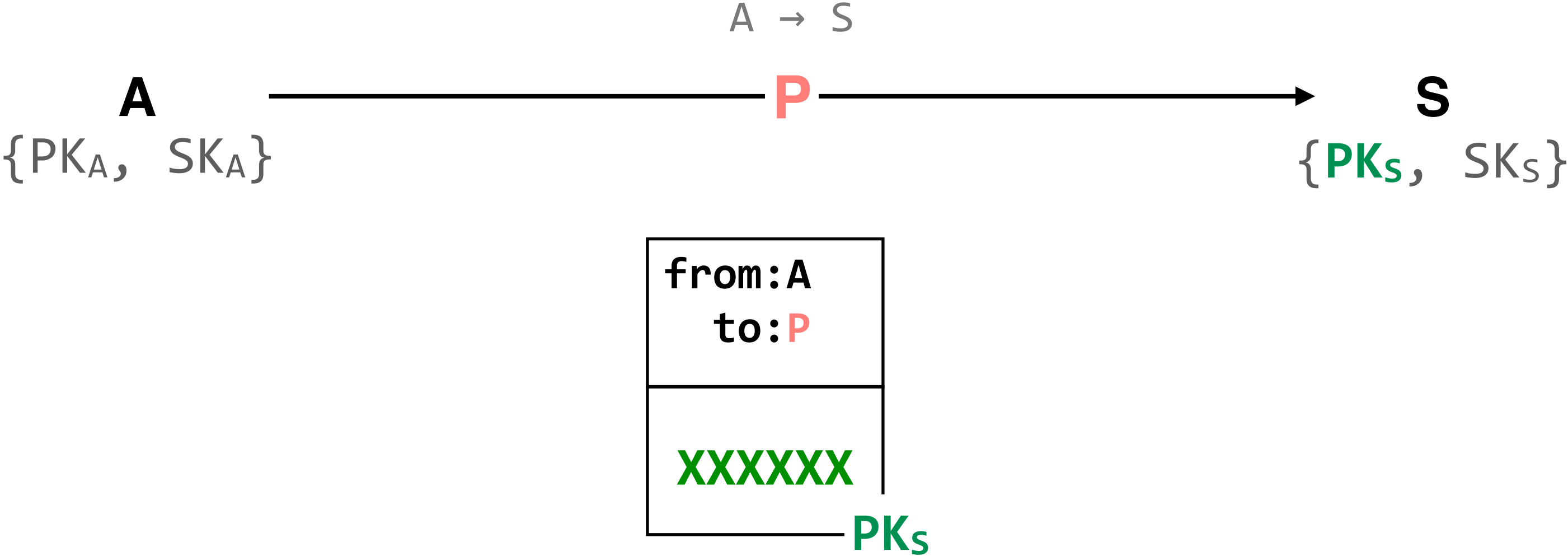
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A → S

A
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P

S
{PK$_S$, SK$_S$}

```
from:P
  to:S
```

XXXXXX

PK$_S$

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from:P
to:S

XXXXXX
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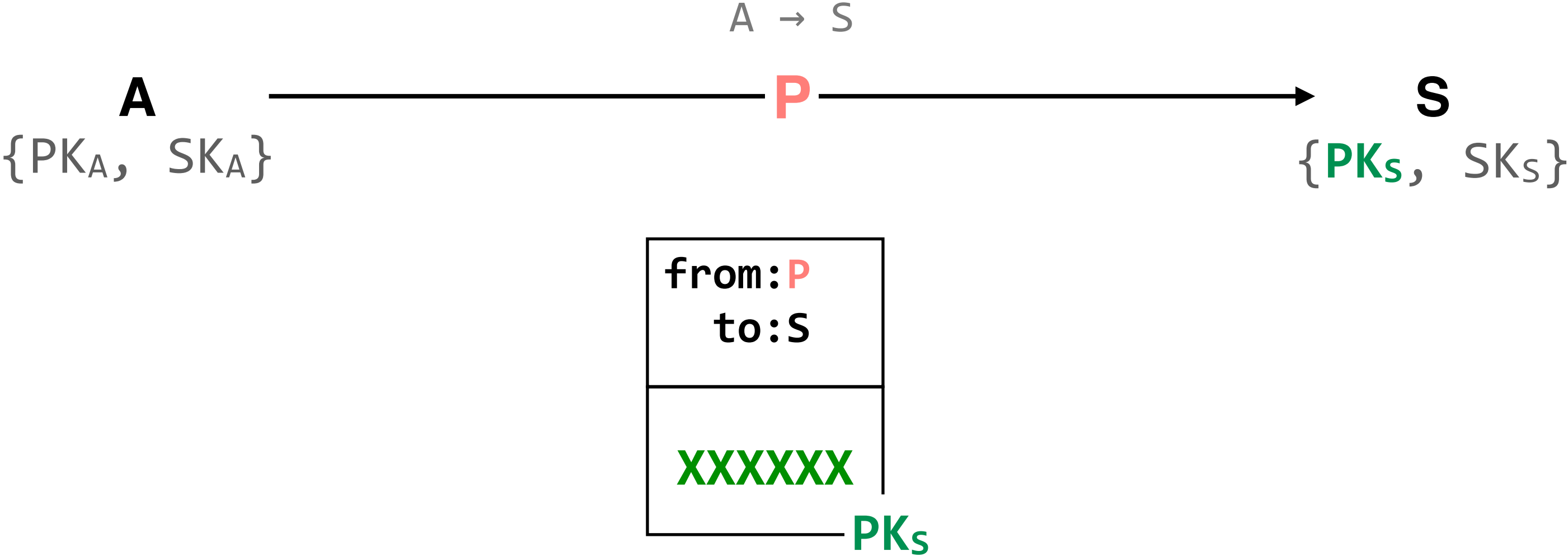
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```

XXXXXX

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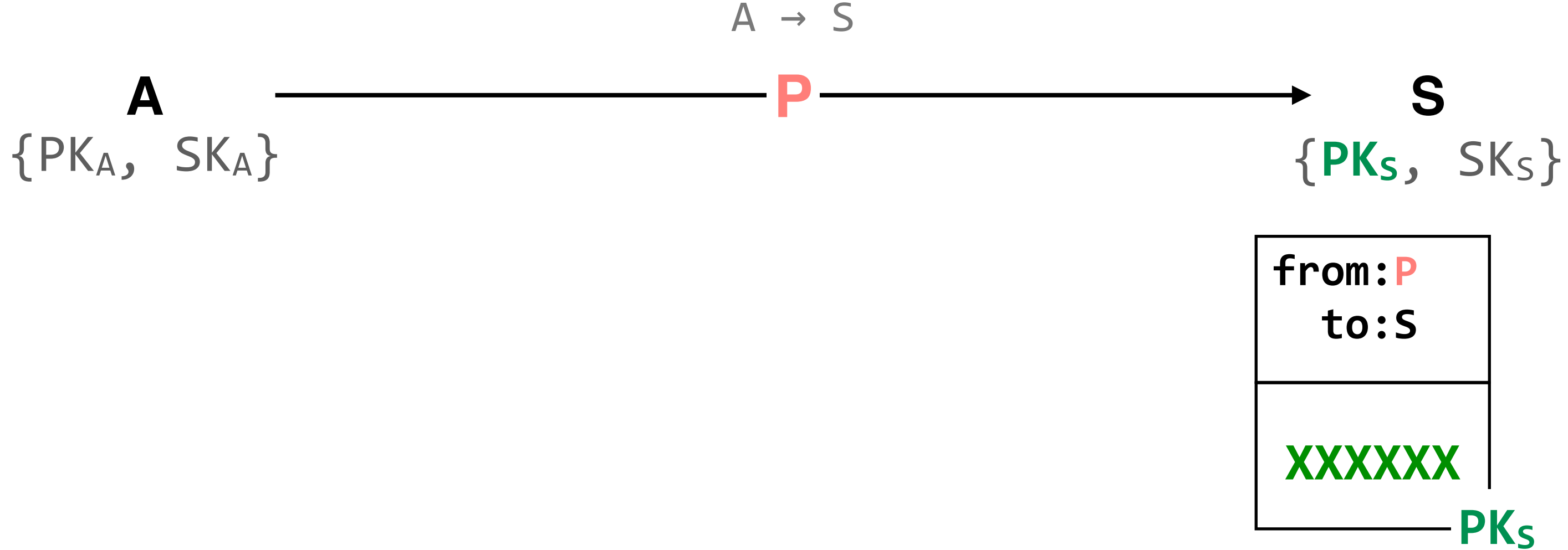
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A → S

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{PK$_A$, SK$_A$}

P

S
{PK$_S$, SK$_S$}

from:P
  to:S

XXXXXX
————PK$_S$

problem: P knows that **A** is communicating with **S**

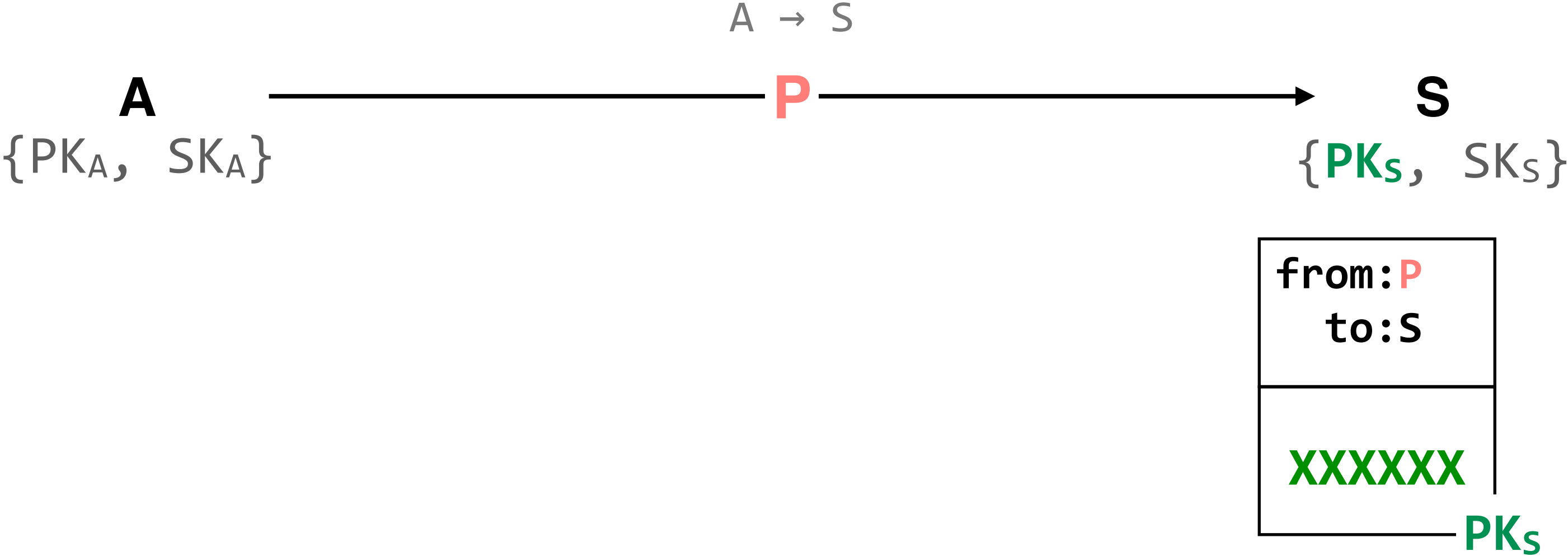**policy:** provide **anonymity** (only the client should know that they're communicating with the server)

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things to avoid

👍 no packet should say "from: A; to: S"

no entity in the network should receive a packet from A and send it directly to S

A → S

A
{PK_A, SK_A}

P

S
{PK_S, SK_S}

from:P
to:S

XXXXXX
PK_S

problem: P knows that **A** is communicating with **S**

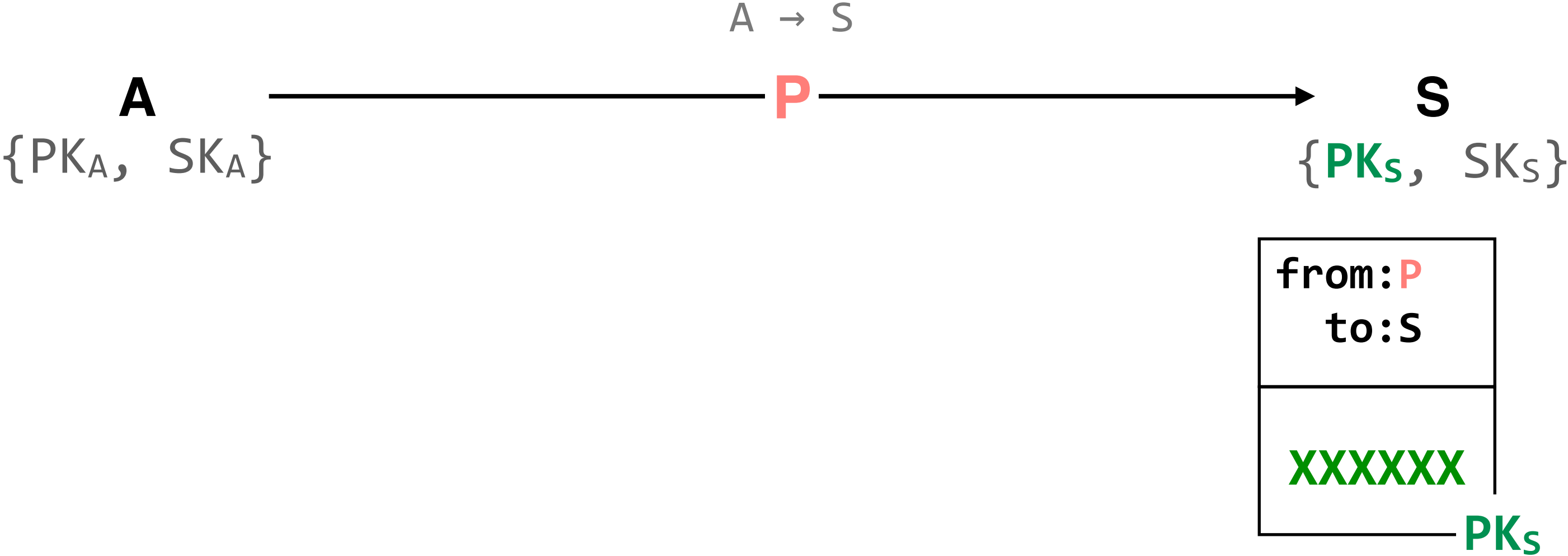**policy:** provide **anonymity** (only the client should know that they're communicating with the server)

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things to avoid

👍 no packet should say "from: A; to: S"

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no entity in the network should keep *state* that links A to S

A → S

A
{PK$_A$, SK$_A$}

P

S
{PK$_S$, SK$_S$}

from:P
to:S

XXXXXX
PK$_S$

problem: P knows that **A** is communicating with **S**

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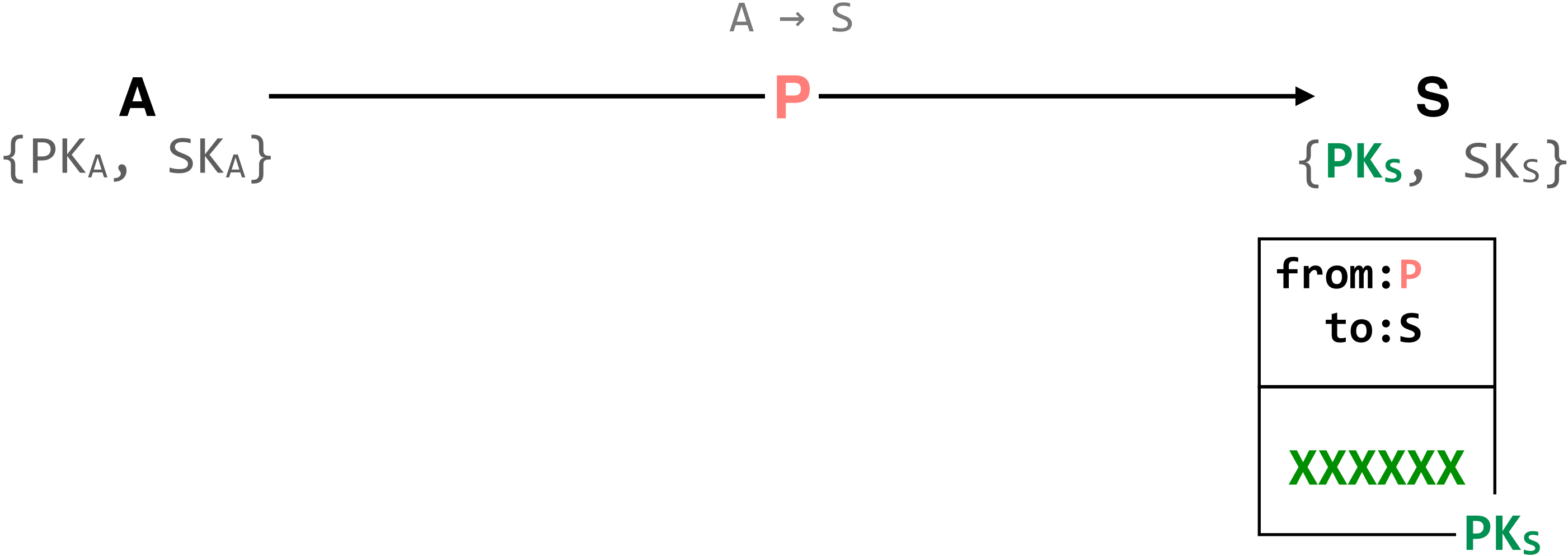
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$$\texttt{encrypt(PK}_\texttt{x}\texttt{, m) = c}$$

$$\texttt{decrypt(SK}_\texttt{x}\texttt{, c) = m}$$

A → S

A
{PK$_A$, SK$_A$}

P

S
{PK$_S$, SK$_S$}

```
from:P
  to:S

XXXXXX
```
PK$_S$

things to avoid

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no entity in the network should receive a packet from A and send it directly to S

no entity in the network should keep *state* that links A to S

problem: P knows that **A** is communicating with **S**

a single proxy alone *can* be useful for other things; we'll return to this later in the lecture.

policy: provide **anonymity** (only the client should know that they're communicating with the server)

threat model: adversary is on the path between the client and the server

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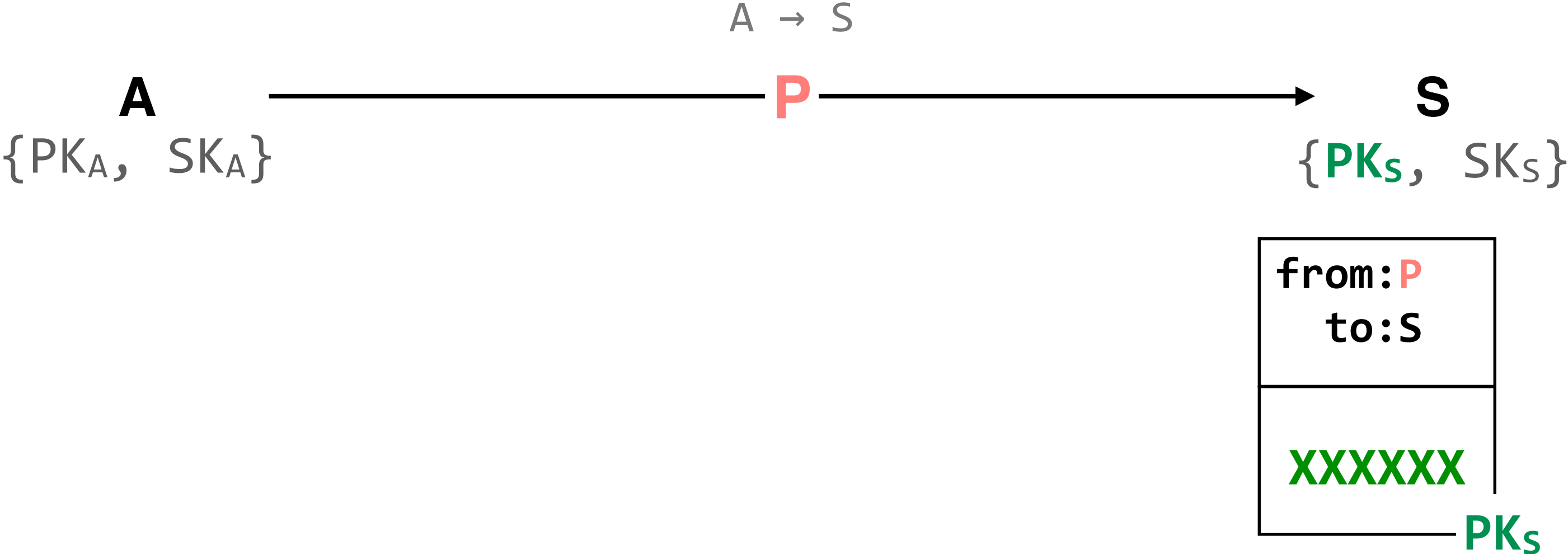
$$\text{encrypt}(PK_x, m) = c$$

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A — P₁ —— P₂ —— P₃ → S

A $\{PK_A, SK_A\}$

S $\{PK_S, SK_S\}$

things to avoid

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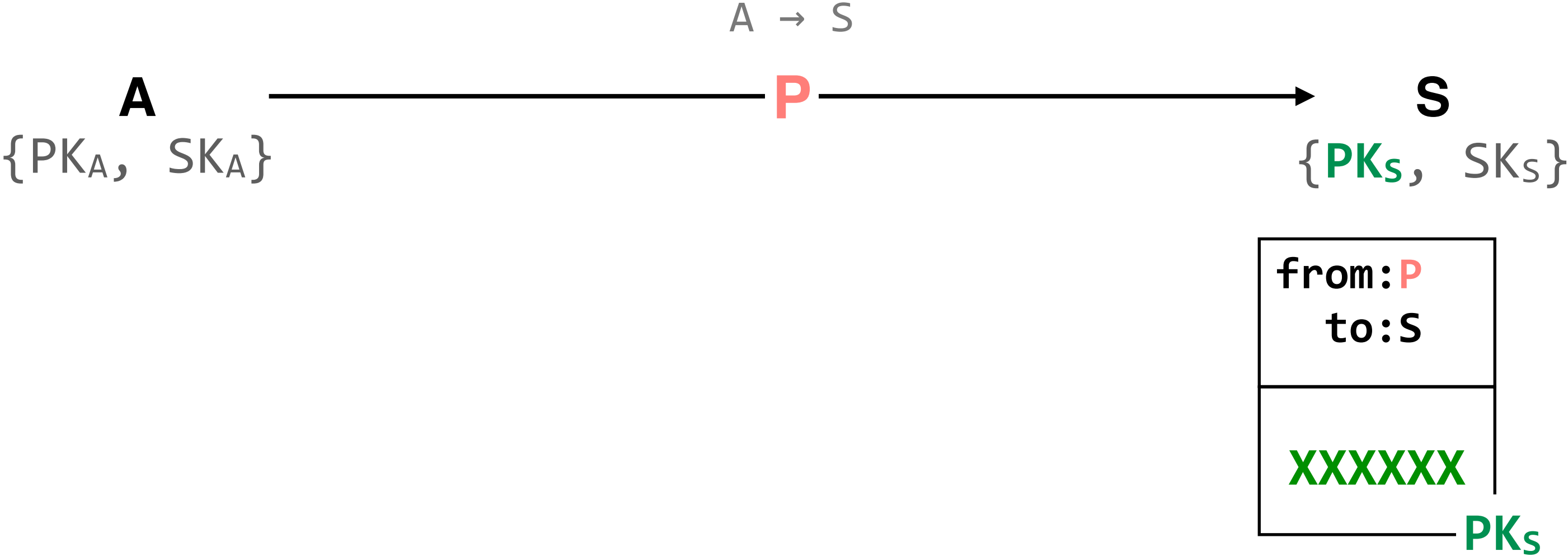
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$$\texttt{encrypt(PK}_x\texttt{, m) = c}$$

$$\texttt{decrypt(SK}_x\texttt{, c) = m}$$

$$P_1 \qquad\qquad A \rightarrow P_2 \qquad\qquad P_1 \rightarrow P_3 \qquad\qquad P_2 \rightarrow S$$

$$\textbf{A} \longrightarrow \textbf{P}_1 \longrightarrow \textbf{P}_2 \longrightarrow \textbf{P}_3 \longrightarrow \textbf{S}$$

$$\{PK_A,\ SK_A\} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \{PK_S,\ SK_S\}$$

things to avoid

no packet should say "from: A; to: S"

no entity in the network should receive a packet from A and send it directly to S

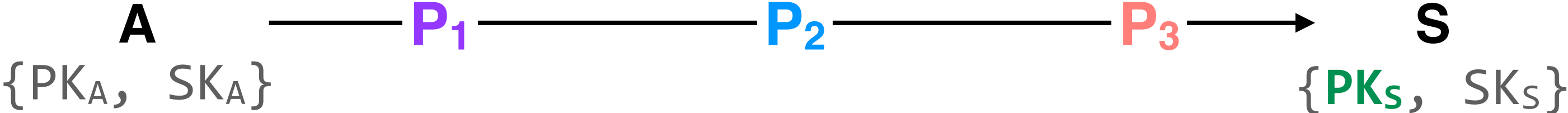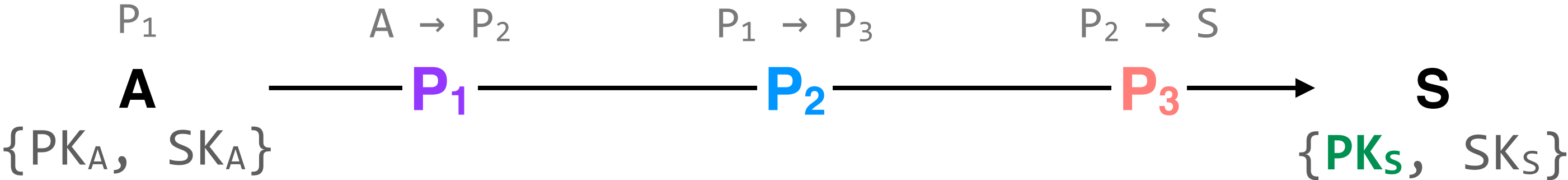no entity in the network should keep *state* that links A to S

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things to avoid

no packet should say "from: A; to: S"

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P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A ————**P₁**————————**P₂**————————**P₃**———→ **S**
{PK$_A$, SK$_A$}   {PK$_S$, SK$_S$}

```
from:A
   to:P₁

XXXXXX
```
————PK$_S$

policy: provide **anonymity** (only the client should know that they're communicating with the server)
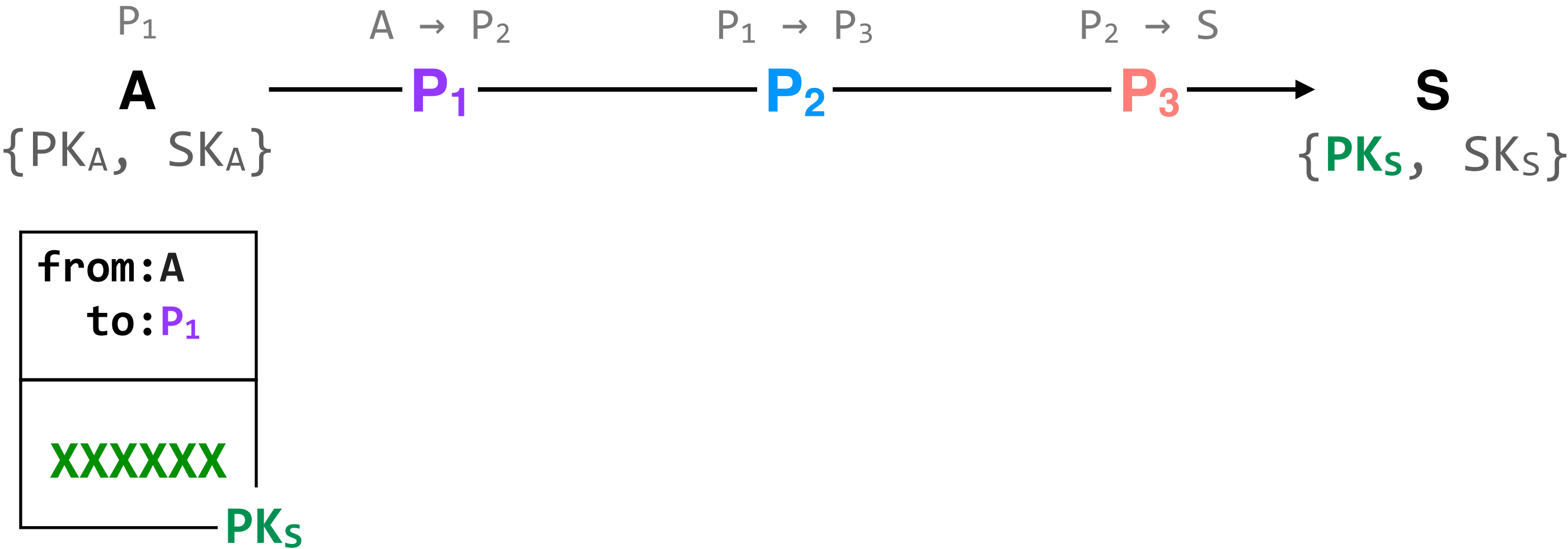
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```
encrypt(PKx, m) = c

decrypt(SKx, c) = m
```

things to avoid

no packet should say "from: A; to: S"

no entity in the network should receive a packet from A and send it directly to S

no entity in the network should keep *state* that links A to S

P₁   A → P₂   P₁ → P₃   P₂ → S

A —— **P₁** ———— **P₂** ———— **P₃** → **S**

{PKₐ, SKₐ}   {PKₛ, SKₛ}

```
from:A
   to:P₁

XXXXXX
```
—— PKₛ

policy: provide **anonymity** (only the client should know that they're communicating with the server)

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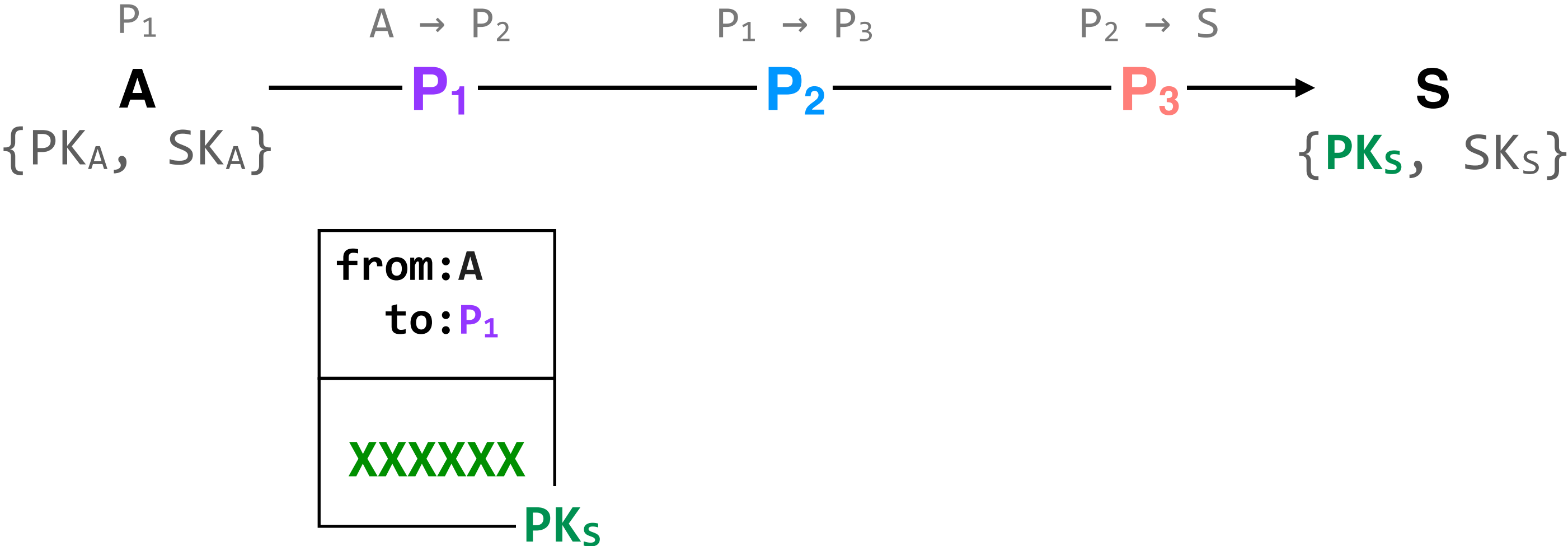$$\texttt{encrypt(}PK_x\texttt{, m) = c}$$

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things to avoid

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P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A —— **P_1** —————— **P_2** —————— **P_3** ——→ **S**

$\{PK_A,\ SK_A\}$ $\{PK_S,\ SK_S\}$

```
from:P₁
  to:P₂

XXXXXX
```
——PKs

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```
encrypt(PKₓ, m) = c
decrypt(SKₓ, c) = m
```

P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A   **P₁**   **P₂**   **P₃**   →   **S**

{PK_A, SK_A}   {PK_S, SK_S}

```
from:P₁
  to:P₂
```

XXXXXX
PK_S

things to avoid

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policy: provide **anonymity** (only the client should know that they're communicating with the server)
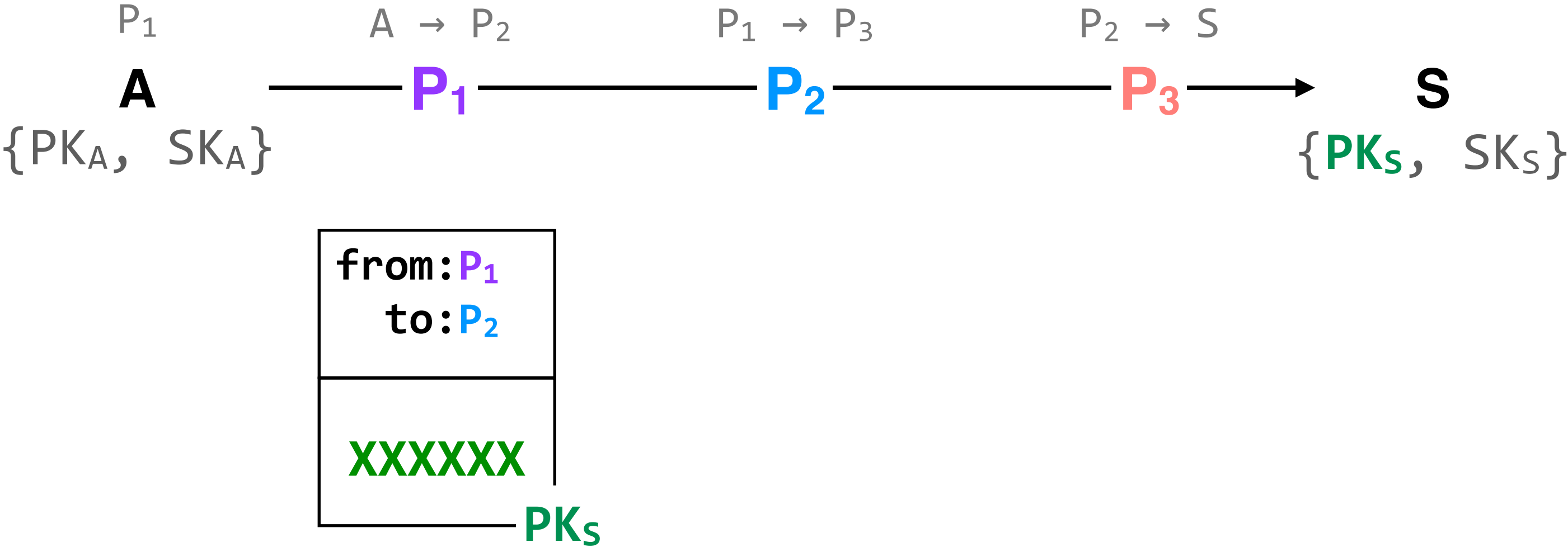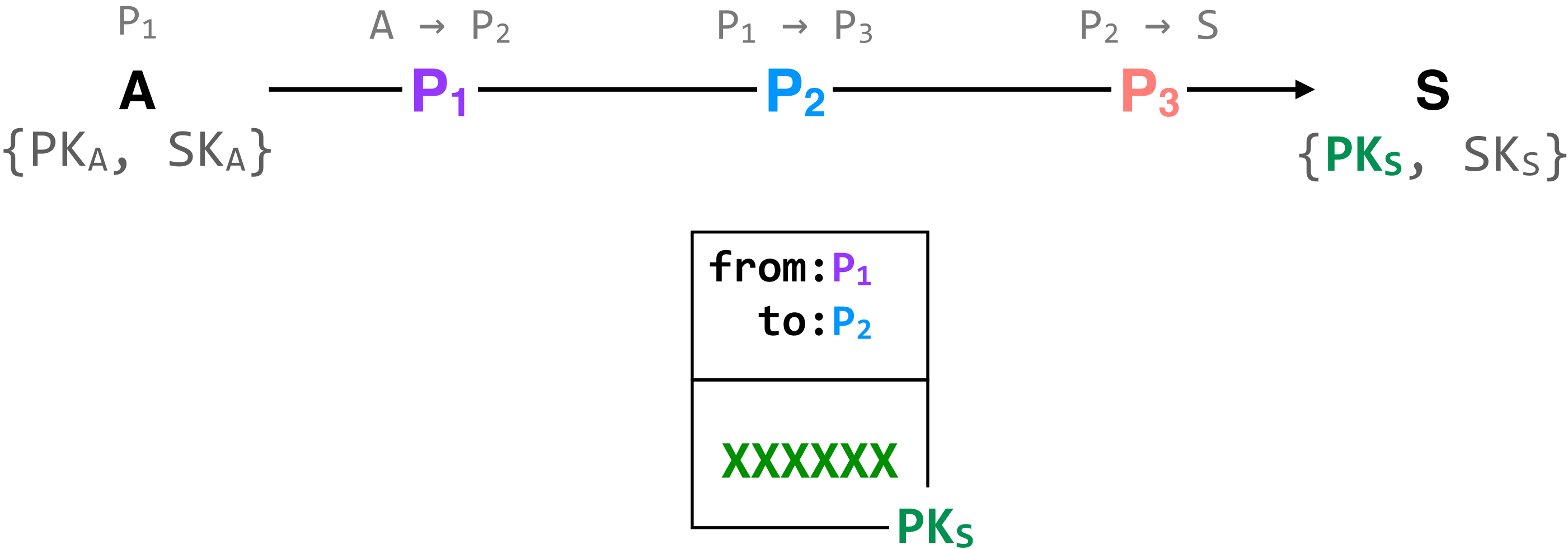
threat model: adversary is on the path between the client and the server

public-key cryptography: a message to **x** is encrypted with **x**'s public key; only **x**'s secret key can decrypt the message

```
encrypt(PKx, m) = c
decrypt(SKx, c) = m
```

P₁   A → P₂   P₁ → P₃   P₂ → S

A ———— **P₁** ———————— **P₂** ———————— **P₃** ——→ **S**

{PK_A, SK_A}   {PK_S, SK_S}

```
from:P₂
  to:P₃
────────
XXXXXX
```
———PK_S

things to avoid

no packet should say "from: A; to: S"

no entity in the network should receive a packet from A and send it directly to S

no entity in the network should keep *state* that links A to S

policy: provide **anonymity** (only the client should know that they're communicating with the server)

threat model: adversary is on the path between the client and the server

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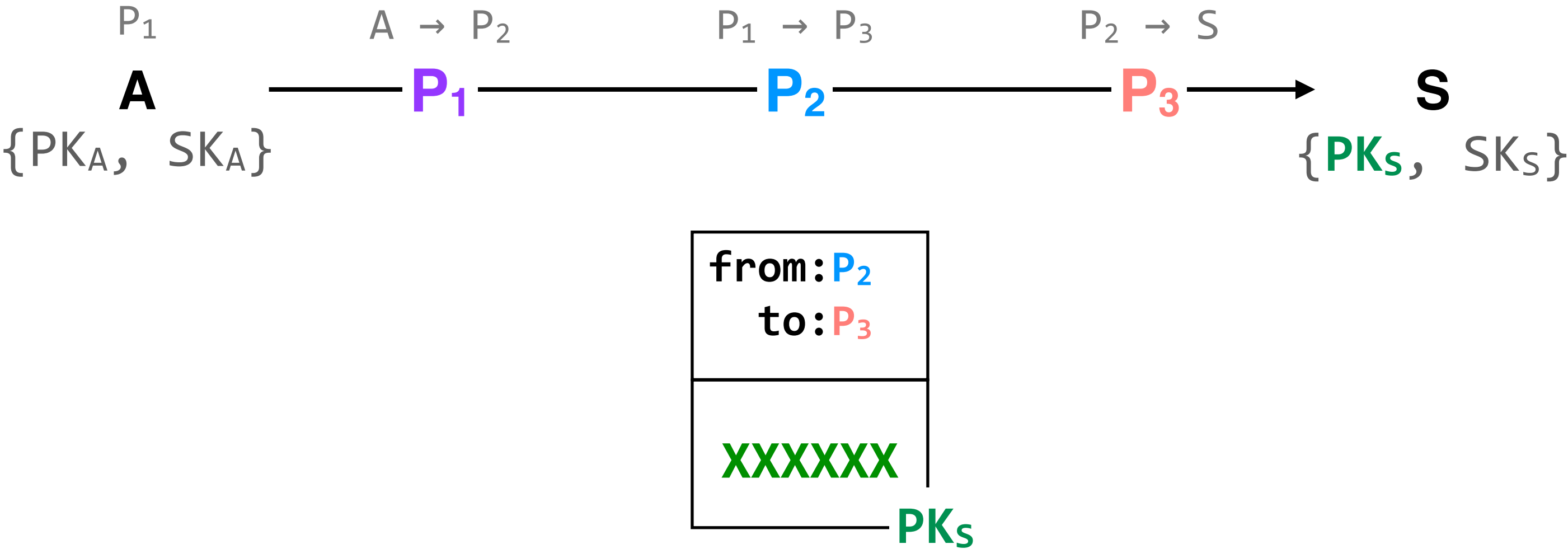
$$encrypt(PK_x, m) = c$$

$$decrypt(SK_x, c) = m$$

things to avoid

no packet should say "from: A; to: S"

no entity in the network should receive a packet from A and send it directly to S

no entity in the network should keep *state* that links A to S

P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A ——— **P₁** ——————— **P₂** ——————— **P₃** ⟶ **S**

$\{PK_A, SK_A\}$ $\{PK_S, SK_S\}$

```
from:P₂
  to:P₃

XXXXXX
```
PK_S

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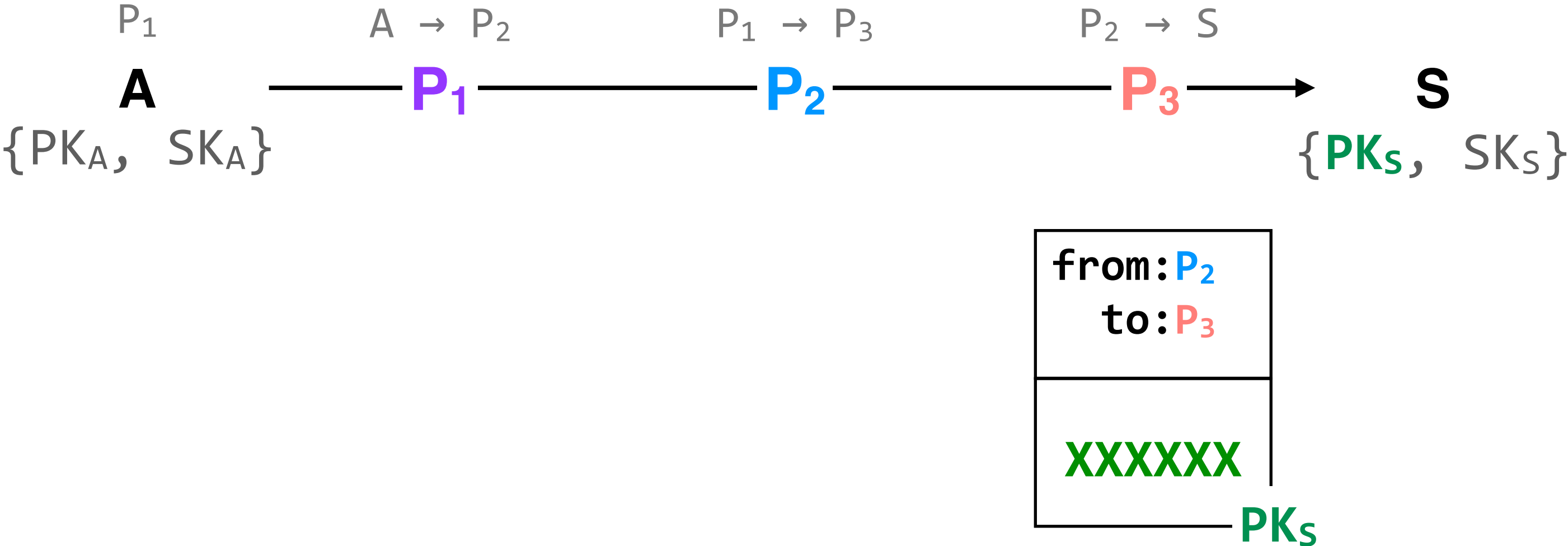
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things to avoid

no packet should say "from: A; to: S"

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P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A ——— **P$_1$** ——————— **P$_2$** ——————— **P$_3$** $\longrightarrow$ **S**

{PK$_A$, SK$_A$}   {PK$_S$, SK$_S$}

```
from:P₃
  to:S
```

XXXXXX

PK$_S$

policy: provide **anonymity** (only the client should know that they're communicating with the server)

threat model: adversary is on the path between the client and the server

public-key cryptography: a message to **x** is encrypted with **x**'s public key; only **x**'s secret key can decrypt the message
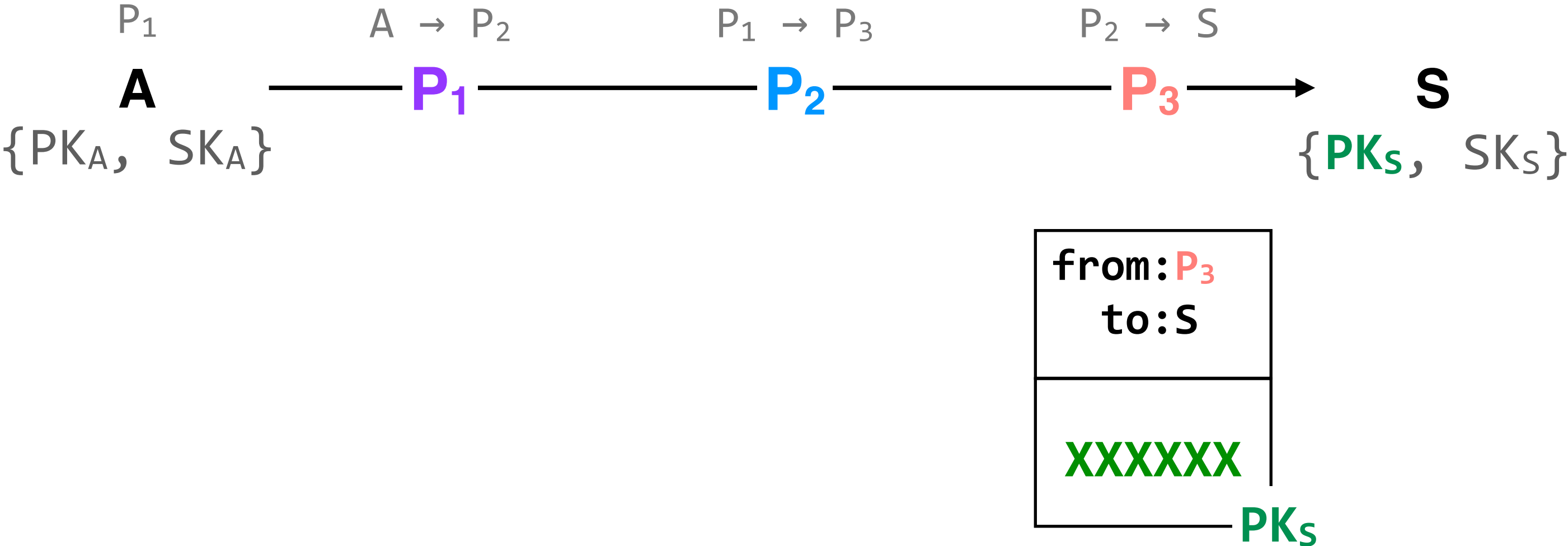
$$\texttt{encrypt(PK}_\texttt{x}\texttt{, m) = c}$$

$$\texttt{decrypt(SK}_\texttt{x}\texttt{, c) = m}$$

P₁   A → P₂   P₁ → P₃   P₂ → S

$$A \quad\quad P_1 \quad\quad P_2 \quad\quad P_3 \longrightarrow S$$

$\{PK_A, \ SK_A\}$ $\{PK_S, \ SK_S\}$

```
from:P₃
  to:S
```

XXXXXX

PK_S

things to avoid

no packet should say "from: A; to: S"

no entity in the network should receive a packet from A and send it directly to S

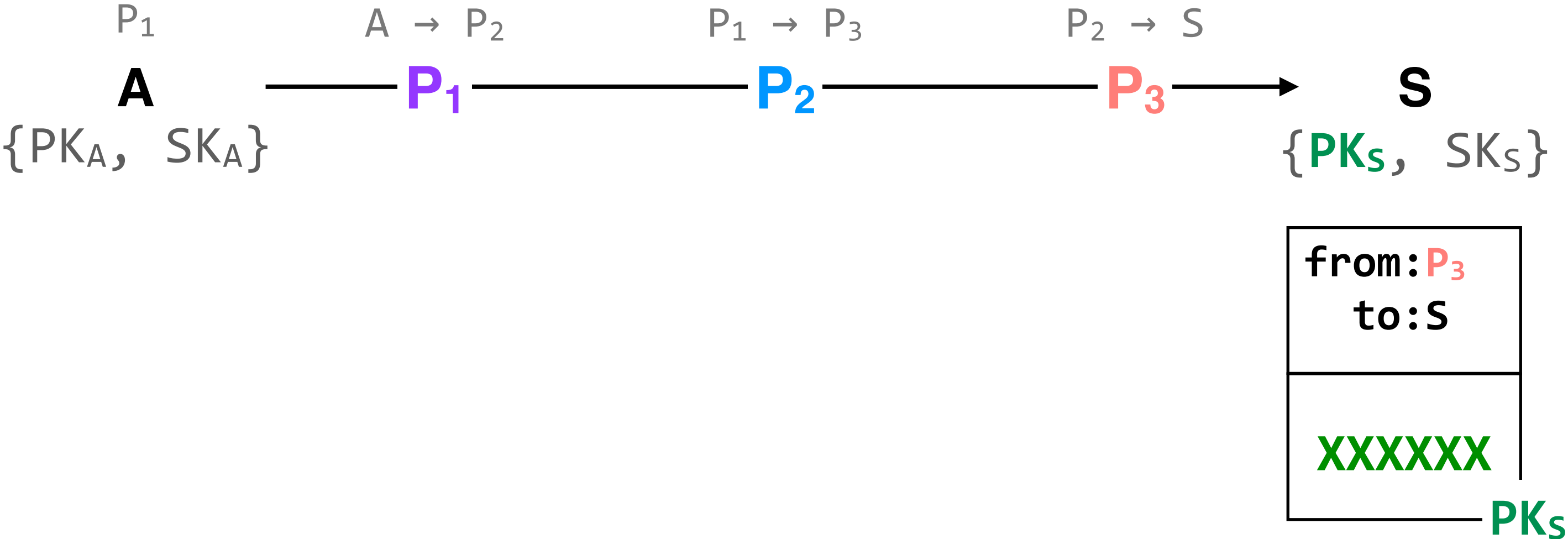no entity in the network should keep *state* that links A to S

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P₁   A → P₂   P₁ → P₃   P₂ → S

A —— **P₁** ———— **P₂** ———— **P₃** ⟶ **S**

{PK_A, SK_A}   {PK_S, SK_S}

```
from:P₃
   to:S

XXXXXX
```
PK_S

things to avoid

👍 no packet should say "from: A; to: S"

no entity in the network should receive a packet from A and send it directly to S
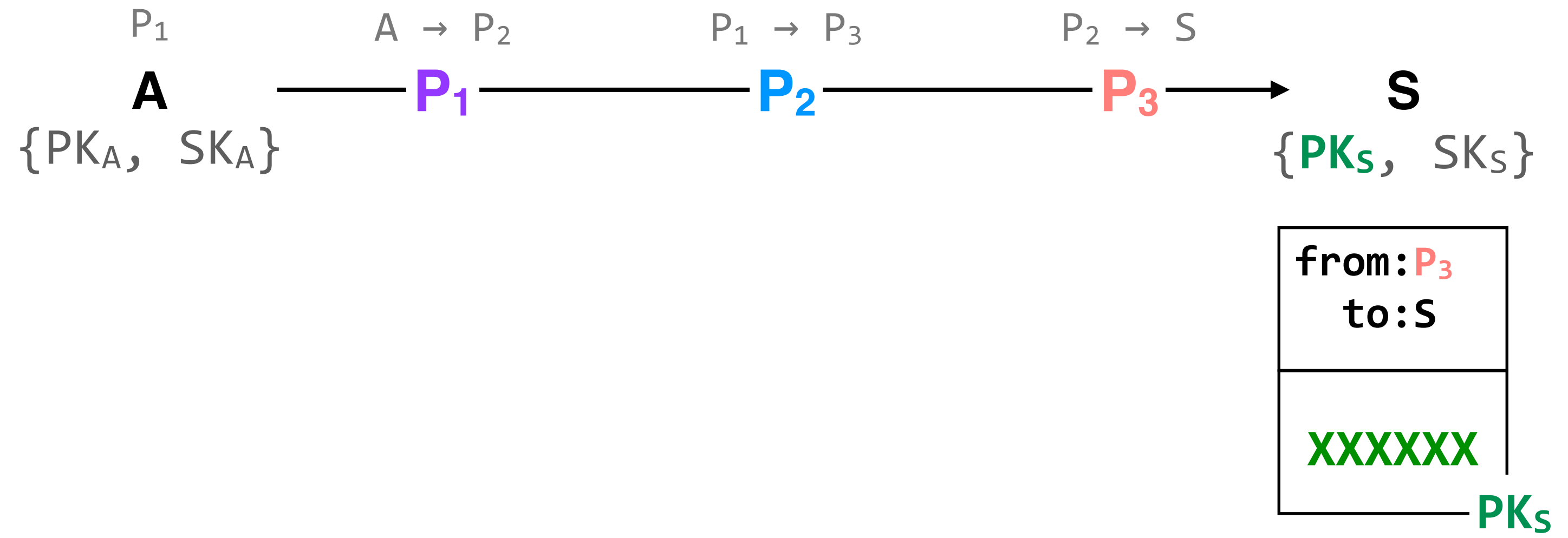
no entity in the network should keep *state* that links A to S

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$$\texttt{encrypt(PK}_x\texttt{, m) = c}$$

$$\texttt{decrypt(SK}_x\texttt{, c) = m}$$

P₁   A → P₂   P₁ → P₃   P₂ → S

A —————**P₁**—————————**P₂**————————————**P₃**——→ **S**
{PK_A, SK_A}   {PK_S, SK_S}

```
from:P₃
  to:S

XXXXXX
```
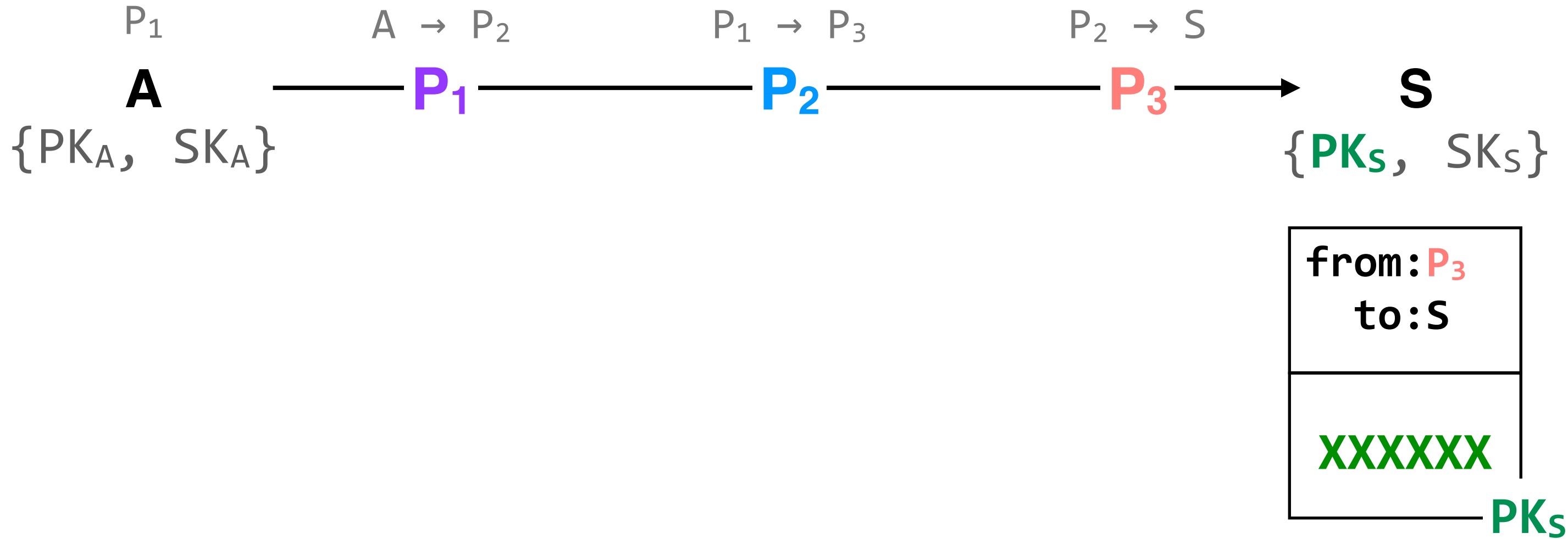————PK_S

things to avoid

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P₁   A → P₂   P₁ → P₃   P₂ → S

A ——— **P₁** ——————— **P₂** ——————— **P₃** ——→ **S**

{PK_A, SK_A}   {PK_S, SK_S}
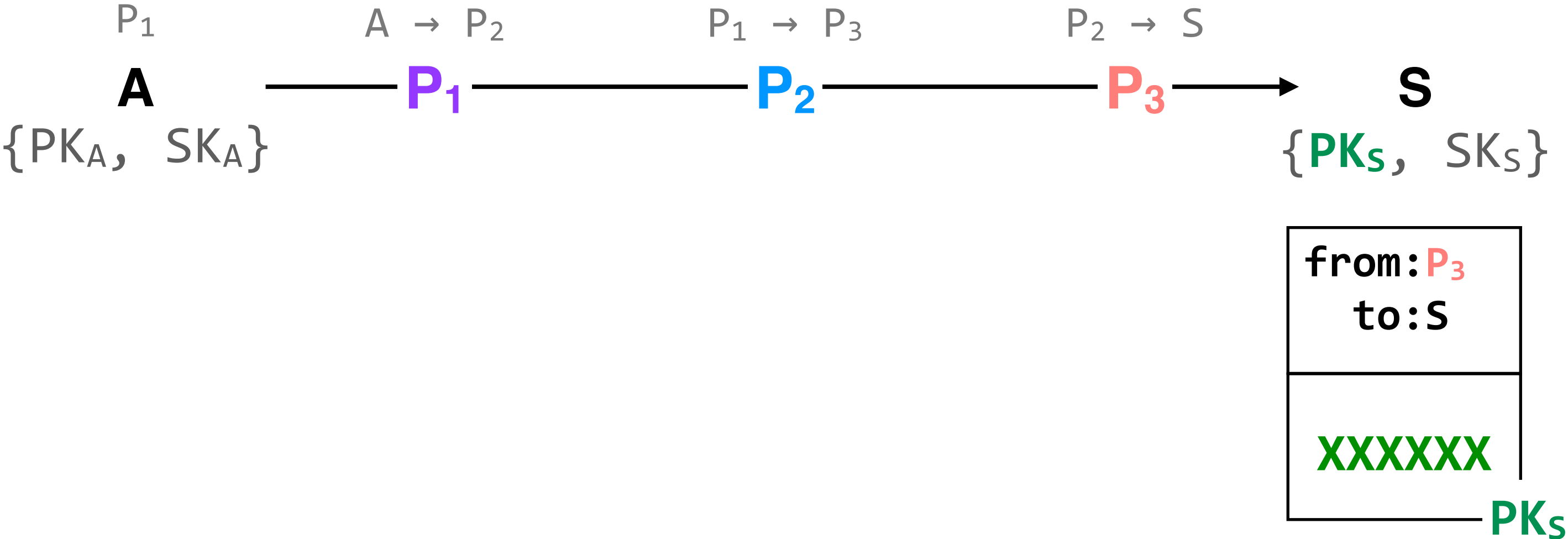
```
from:P₃
   to:S

XXXXXX
```
PK_S

things to avoid

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P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A   **P₁**   **P₂**   **P₃**   **S**

$\{PK_A, SK_A\}$ $\{PK_S, SK_S\}$

from:P_3
to:S

XXXXXX

PK_S

things to avoid
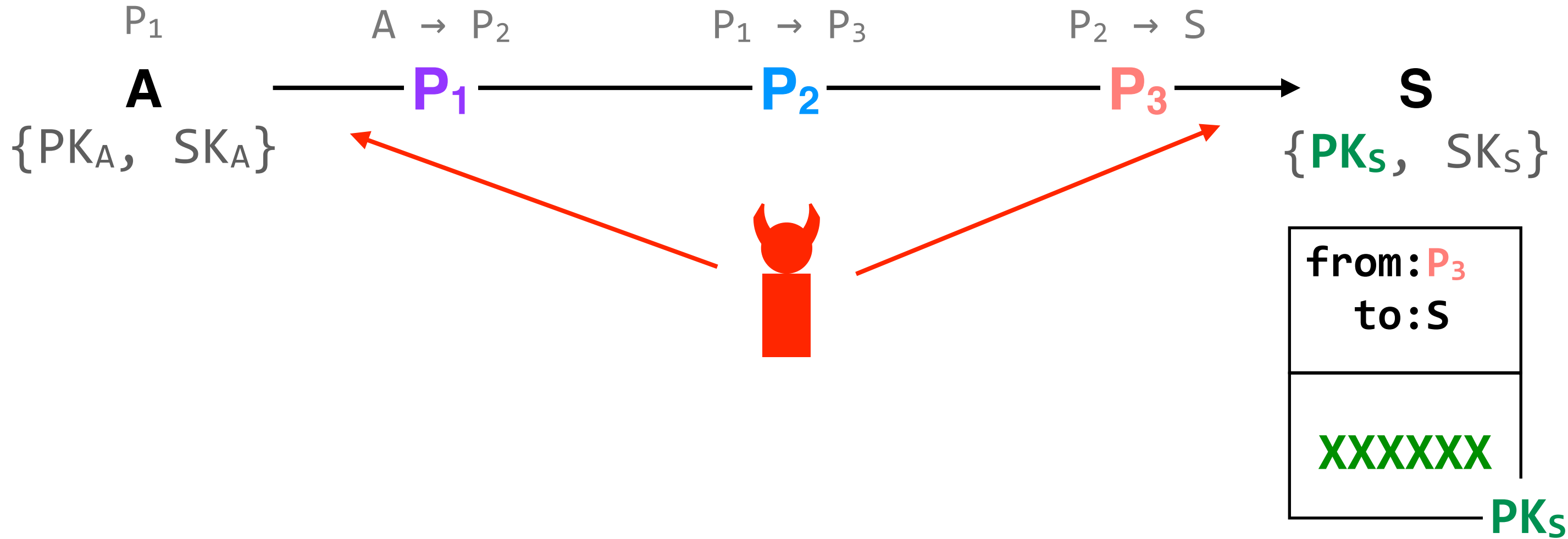
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things to avoid
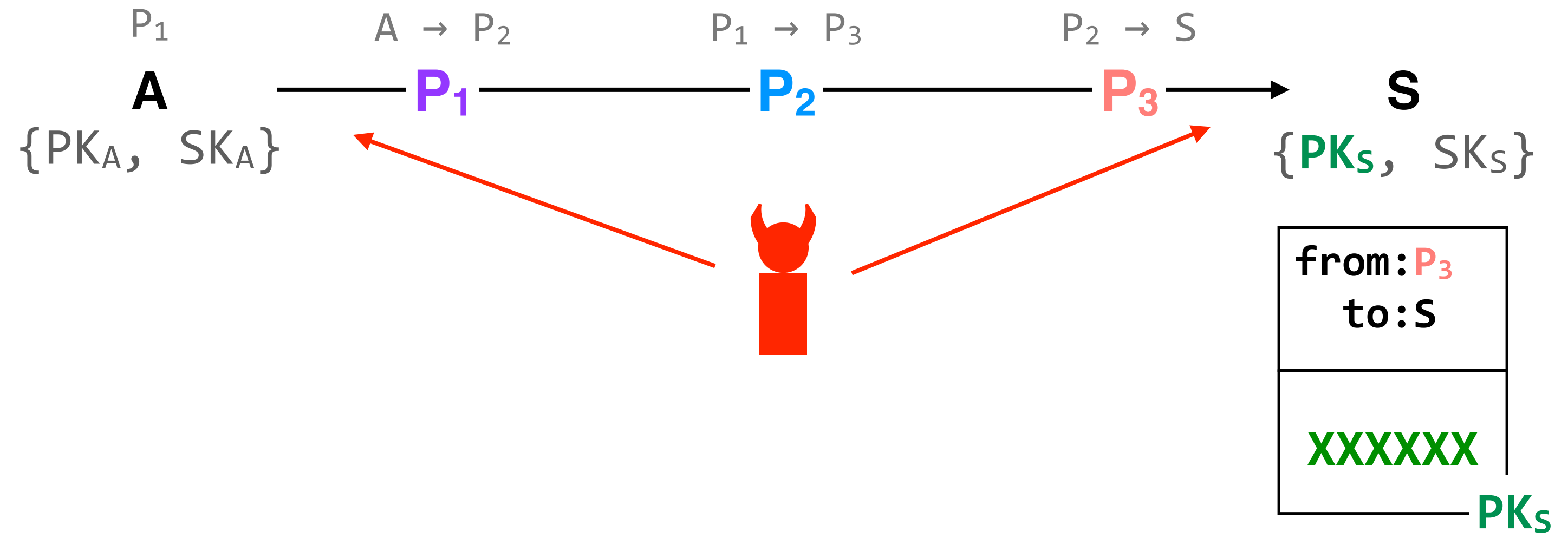
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P₁   A → P₂   P₁ → P₃   P₂ → S

A ——— **P₁** ————— **P₂** ————— **P₃** ——→ **S**

{PK_A, SK_A}   {PK_S, SK_S}

from:P₃
  to:S

XXXXXX
——— PK_S

problem: an adversary with multiple vantage points can observe the same data traveling from **A** to **S**

policy: provide **anonymity** (only the client should know that they're communicating with the server)

threat model: adversary is on the path between the client and the server

public-key cryptography: a message to **x** is encrypted with **x**'s public key; only **x**'s secret key can decrypt the message

$$\texttt{encrypt(PK}_x\texttt{, m) = c}$$

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$$P_1 \qquad A \rightarrow P_2 \qquad P_1 \rightarrow P_3 \qquad P_2 \rightarrow S$$

A ——— **P₁** ——————— **P₂** ——————— **P₃** ⟶ **S**

$\{PK_A, SK_A\}$ $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $\{PK_S, SK_S\}$

from:P_3
to:S

XXXXXX

PK_S

things to avoid

👍 no packet should say "from: A; to: S"

👍 no entity in the network should receive a packet from A and send it directly to S

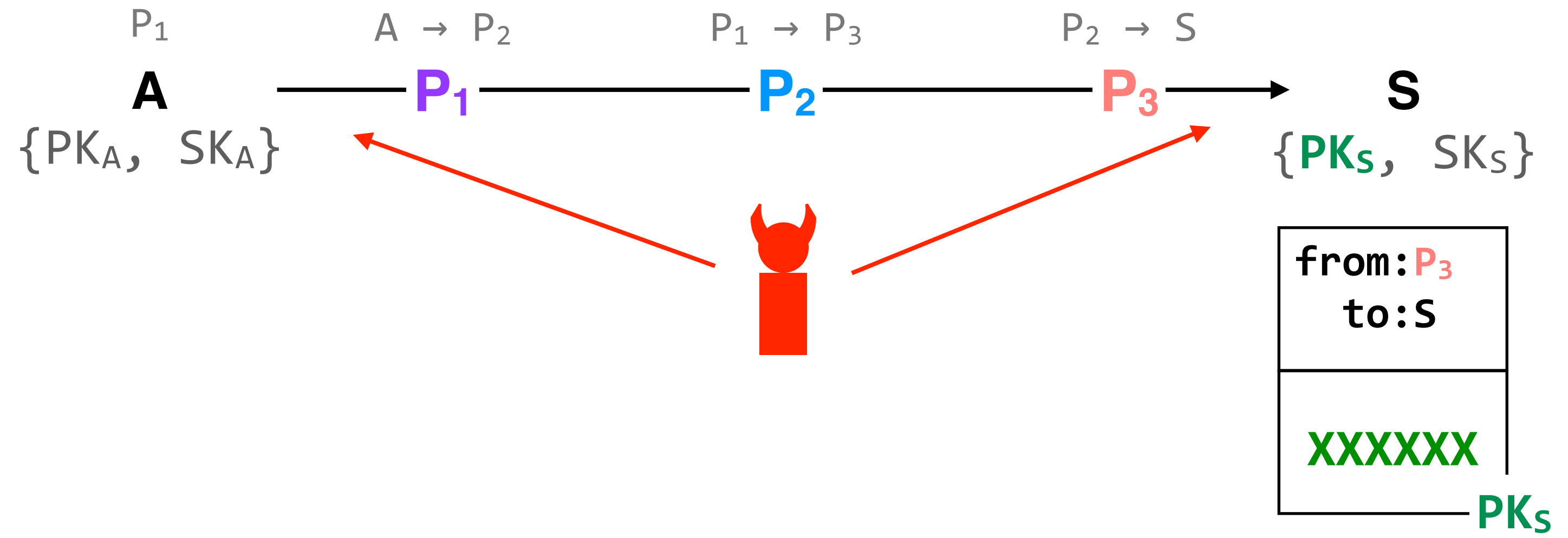👍 no entity in the network should keep *state* that links A to S
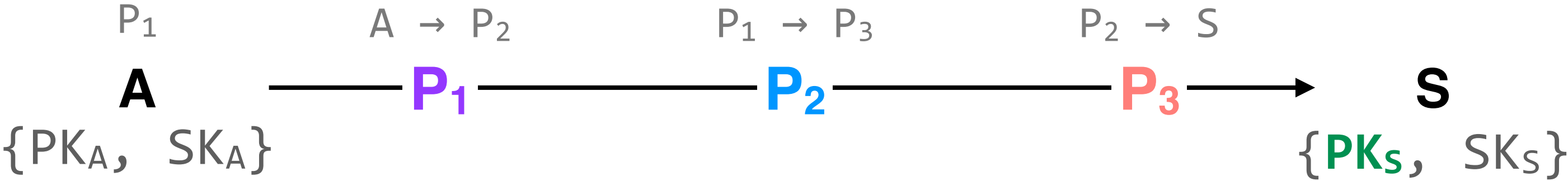
data should not appear the same across packets

problem: an adversary with multiple vantage points can observe the same data traveling from **A** to **S**

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P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A ——— **P$_1$** ——————— **P$_2$** ——————— **P$_3$** ⟶ **S**

$\{PK_A, \ SK_A\}$ $\{PK_S, \ SK_S\}$

things to avoid

no packet should say "from: A; to: S"

no entity in the network should receive a packet from A and send it directly to S

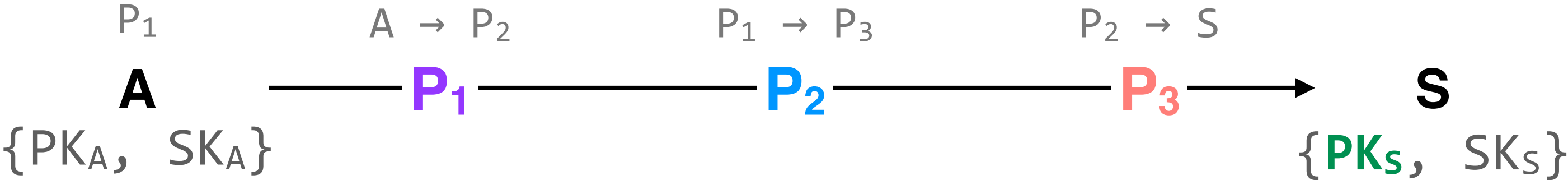no entity in the network should keep *state* that links A to S

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P₁   A → P₂   P₁ → P₃   P₂ → S

A ———— **P₁** ———————— **P₂** ———————————— **P₃** ——→ **S**

{PK_A, SK_A}   {PK_S, SK_S}

things to avoid

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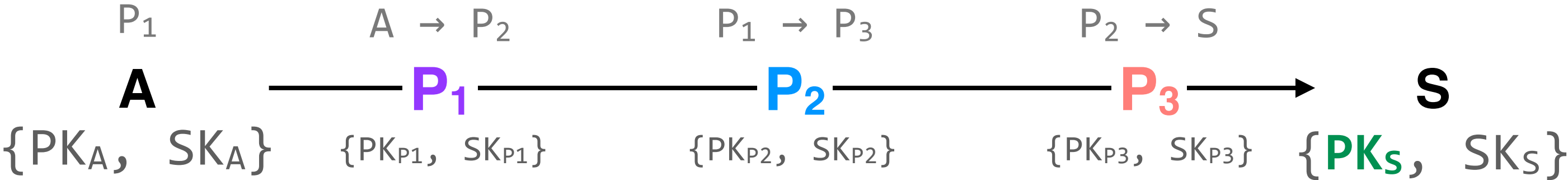data should not appear the same across packets

onion routing adds layers of encryption that nodes on the path can strip off as the packet traverses the network

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P$_1$ A → P$_2$ P$_1$ → P$_3$ P$_2$ → S

A ——— **P$_1$** ——— **P$_2$** ——— **P$_3$** ——→ **S**

{PK$_A$, SK$_A$}   {PK$_{P1}$, SK$_{P1}$}   {PK$_{P2}$, SK$_{P2}$}   {PK$_{P3}$, SK$_{P3}$}   {**PK$_S$**, SK$_S$}

things to avoid

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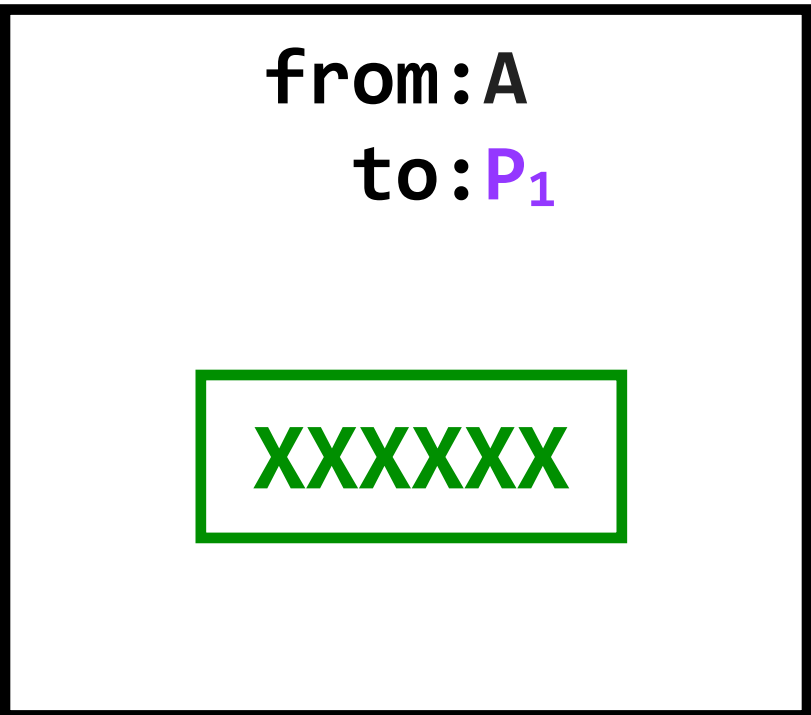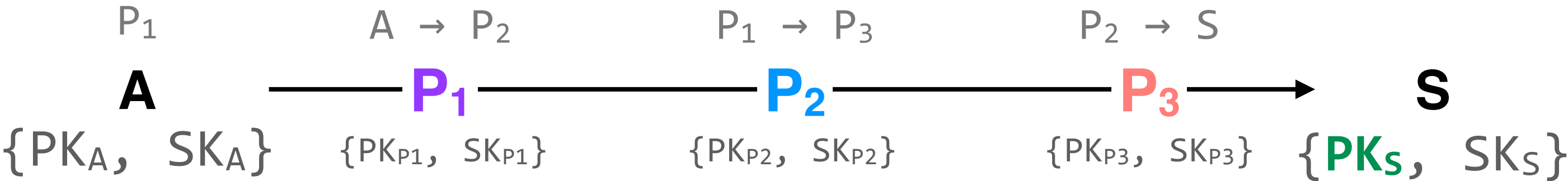**policy:** provide **anonymity** (only the client should know that they're communicating with the server)

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data should not appear the same across packets

P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A ——— **P₁** ——————— **P₂** ——————— **P₃** ⟶ **S**

$\{PK_A, SK_A\}$ $\{PK_{P1}, SK_{P1}\}$ $\{PK_{P2}, SK_{P2}\}$ $\{PK_{P3}, SK_{P3}\}$ $\{PK_S, SK_S\}$

```
from:A
  to:P₁


XXXXXX
```

onion routing adds layers of encryption that nodes on the path can strip off as the packet traverses the network

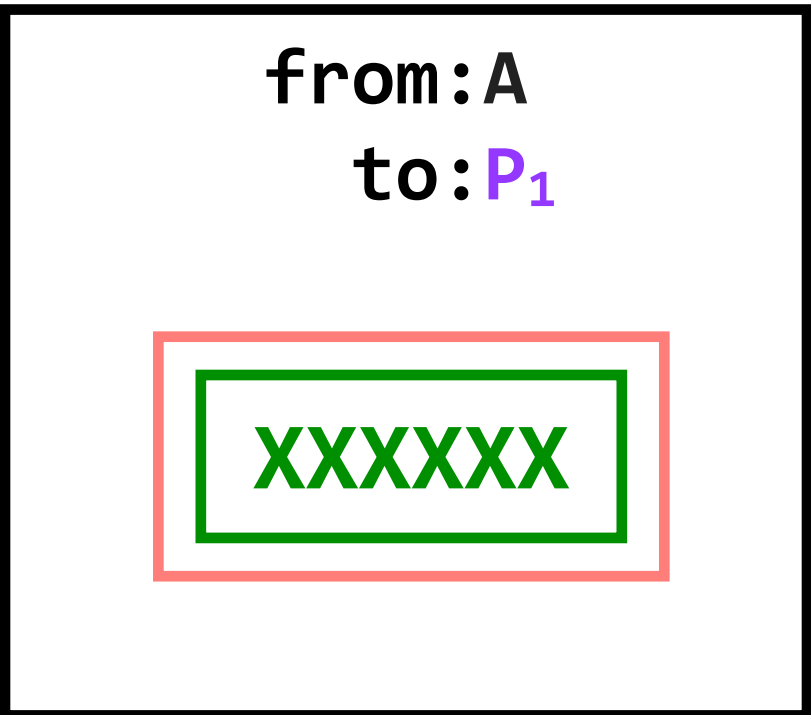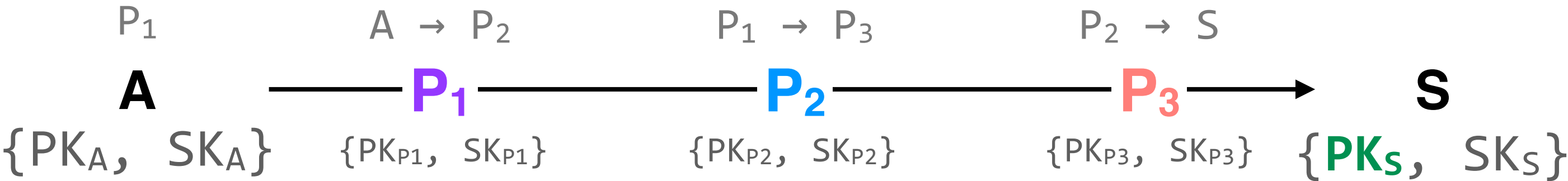**policy:** provide **anonymity** (only the client should know that they're communicating with the server)

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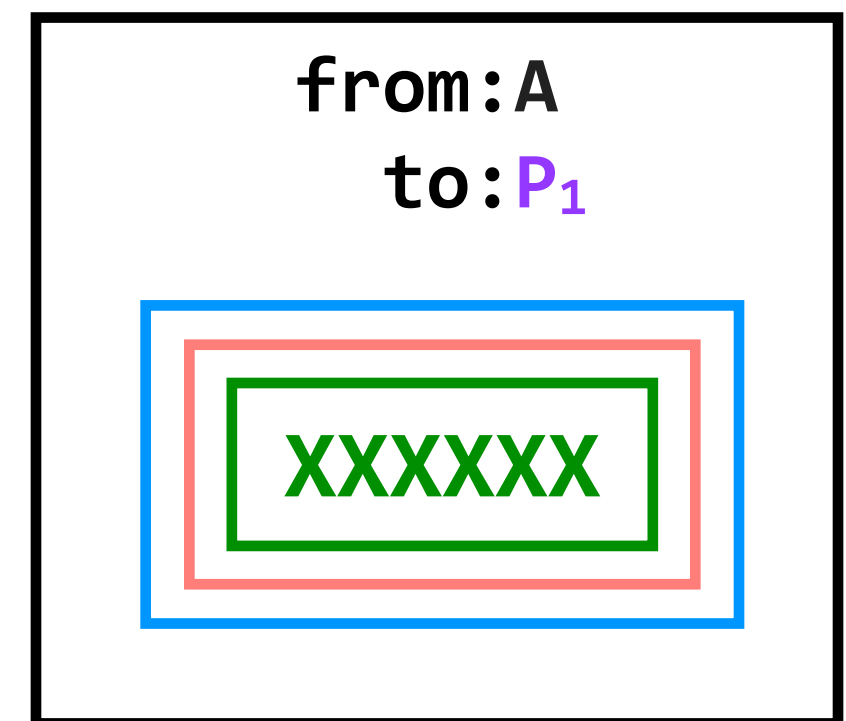
data should not appear the same across packets

P_1	$A \rightarrow P_2$	$P_1 \rightarrow P_3$	$P_2 \rightarrow S$

A —— **P₁** ——— **P₂** ———— **P₃** → **S**

$\{PK_A, SK_A\}$ $\{PK_{P1}, SK_{P1}\}$ $\{PK_{P2}, SK_{P2}\}$ $\{PK_{P3}, SK_{P3}\}$ $\{PK_S, SK_S\}$

```
from:A
  to:P₁

┌──────────┐
│  XXXXXX  │
└──────────┘
```

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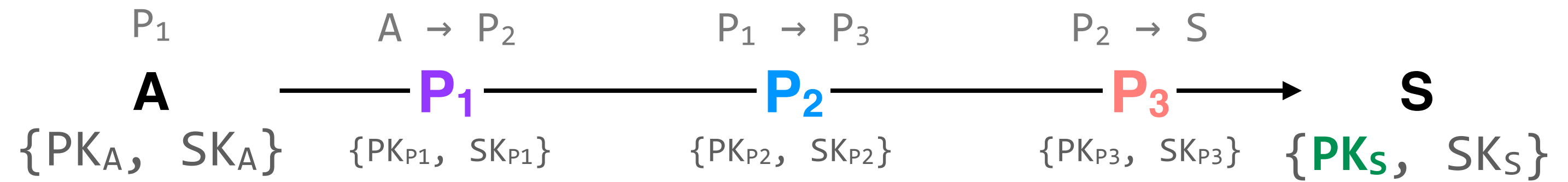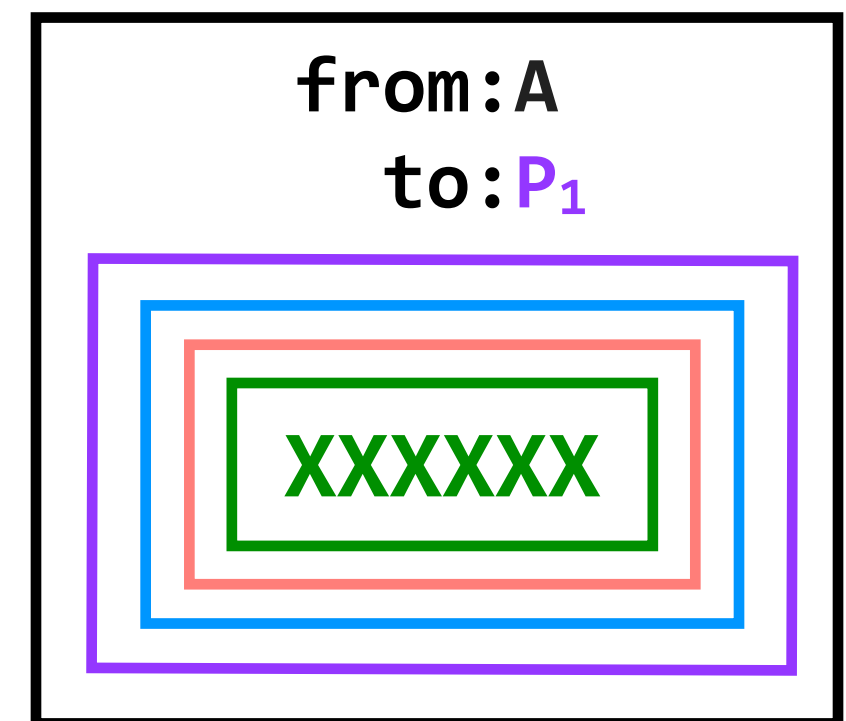
data should not appear the same across packets

P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A ——— **P₁** ——————— **P₂** ——————— **P₃** ——→ **S**

$\{PK_A, SK_A\}$ $\{PK_{P1}, SK_{P1}\}$ $\{PK_{P2}, SK_{P2}\}$ $\{PK_{P3}, SK_{P3}\}$ $\{PK_S, SK_S\}$

```
from:A
to:P₁

XXXXXX
```

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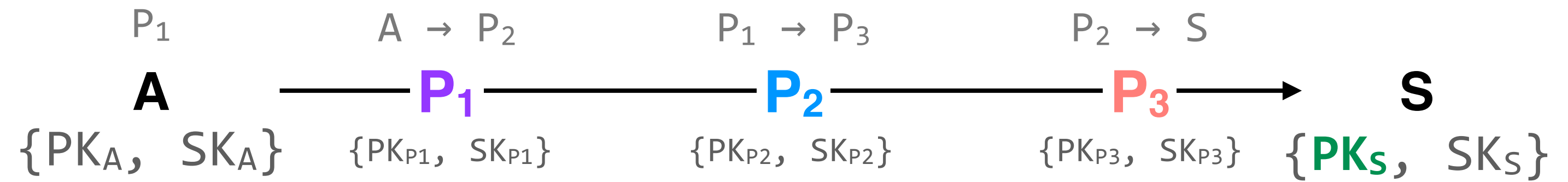data should not appear the same across packets

P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

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```
from:A
  to:P₁


  XXXXXX
```

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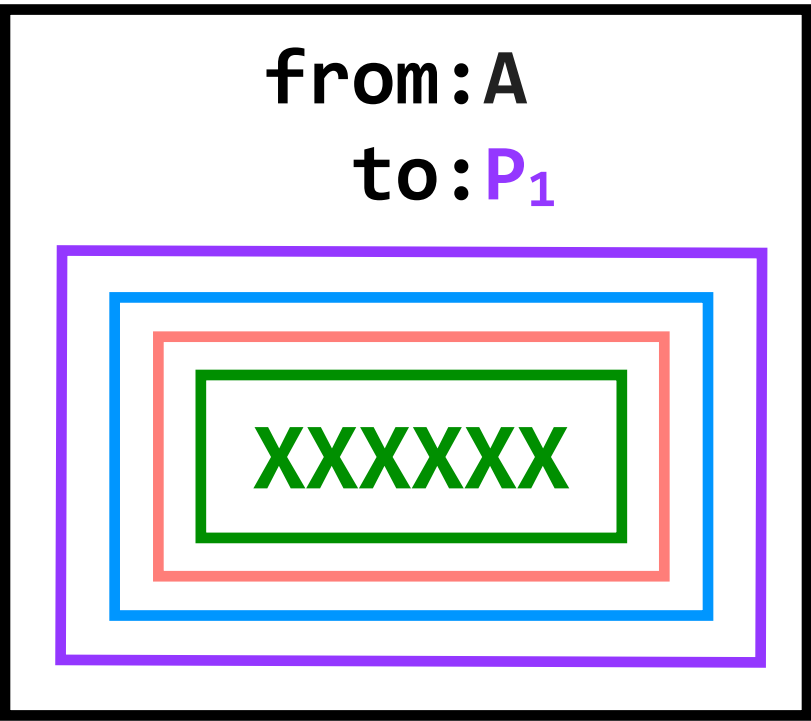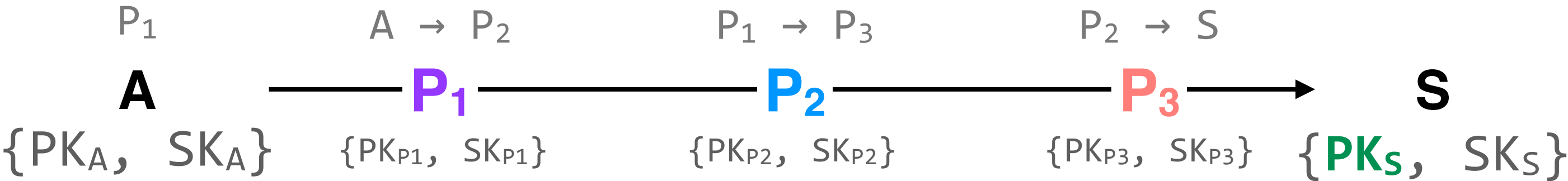**policy:** provide **anonymity** (only the client should know that they're communicating with the server)

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data should not appear the same across packets

P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A —— **P₁** —— **P₂** —— **P₃** ⟶ **S**

$\{PK_A, SK_A\}$ $\{PK_{P1}, SK_{P1}\}$ $\{PK_{P2}, SK_{P2}\}$ $\{PK_{P3}, SK_{P3}\}$ $\{PK_S, SK_S\}$

```
from:A
to:P₁
```

XXXXXX

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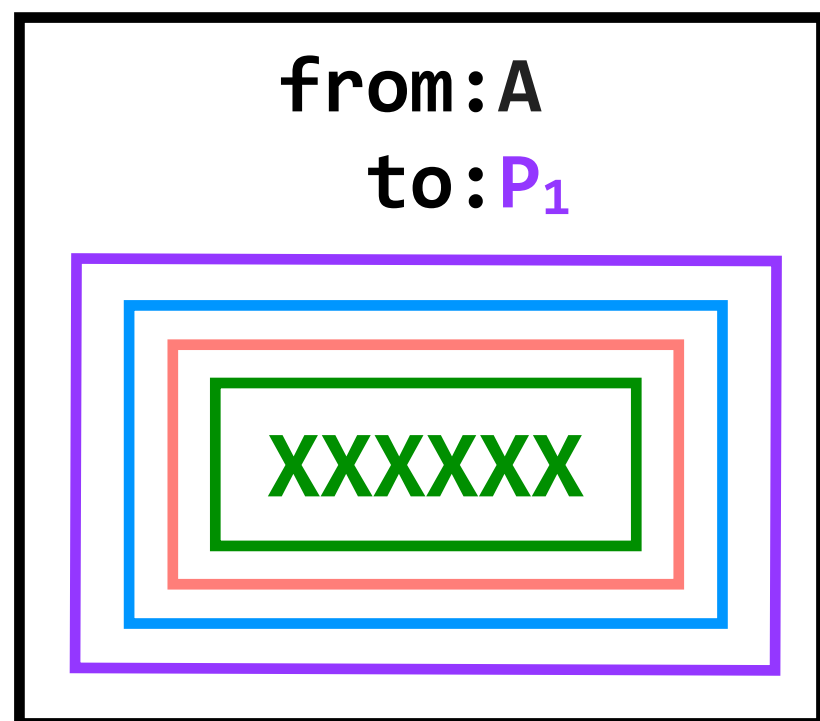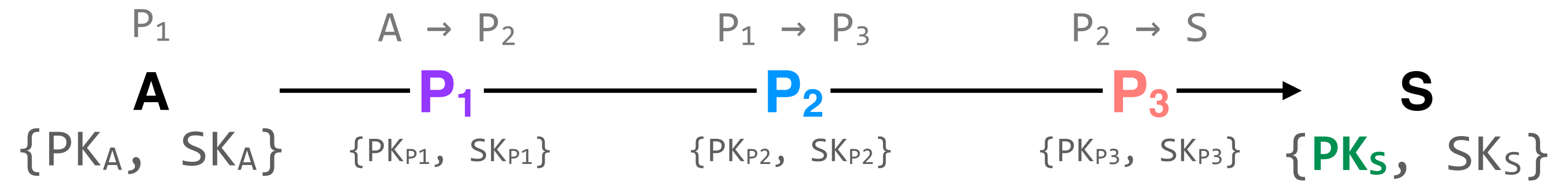
data should not appear the same across packets

$P_1 \qquad A \to P_2 \qquad P_1 \to P_3 \qquad P_2 \to S$

A ———— **P₁** ———— **P₂** ———— **P₃** ⟶ **S**

$\{PK_A,\ SK_A\} \quad \{PK_{P1},\ SK_{P1}\} \quad \{PK_{P2},\ SK_{P2}\} \quad \{PK_{P3},\ SK_{P3}\} \quad \{PK_S,\ SK_S\}$

```
from:A
to:P₁
```

```
XXXXXX
```

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$$\text{encrypt}(PK_x, m) = c$$

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things to avoid

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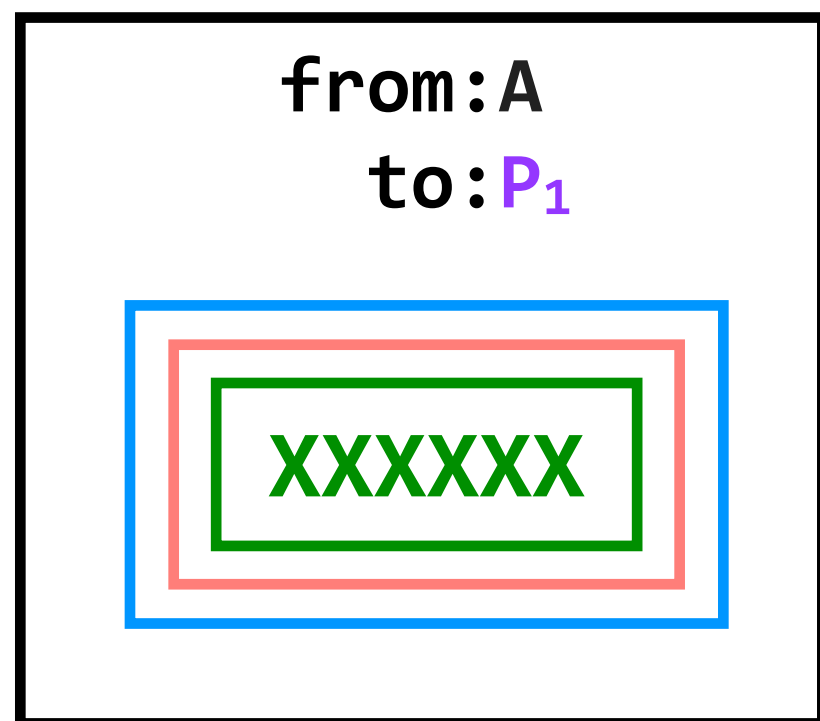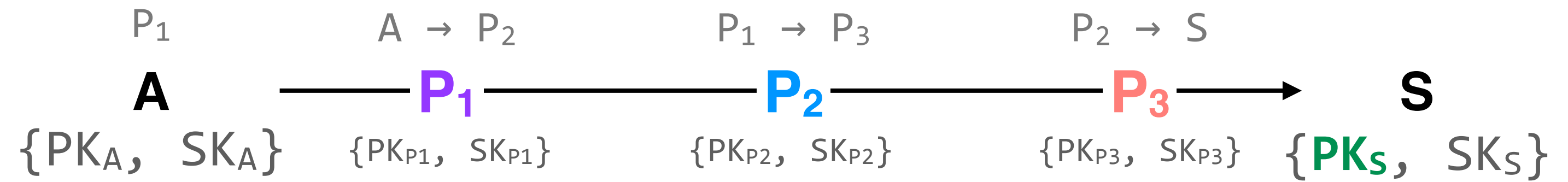
data should not appear the same across packets

P_1 $\quad$ $A \rightarrow P_2$ $\quad$ $P_1 \rightarrow P_3$ $\quad$ $P_2 \rightarrow S$

A —— **P₁** —— **P₂** —— **P₃** → **S**

$\{PK_A, SK_A\}$ $\{PK_{P1}, SK_{P1}\}$ $\{PK_{P2}, SK_{P2}\}$ $\{PK_{P3}, SK_{P3}\}$ $\{PK_S, SK_S\}$

```
from:A
  to:P₁

  XXXXXX
```

onion routing adds layers of encryption that nodes on the path can strip off as the packet traverses the network

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```
from:P₁
  to:P₂

  XXXXXX
```

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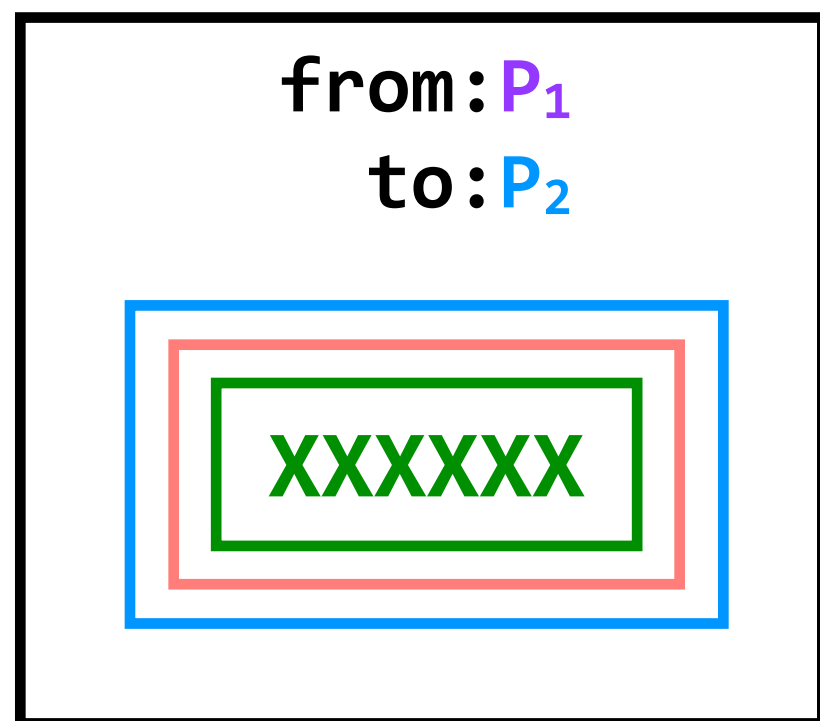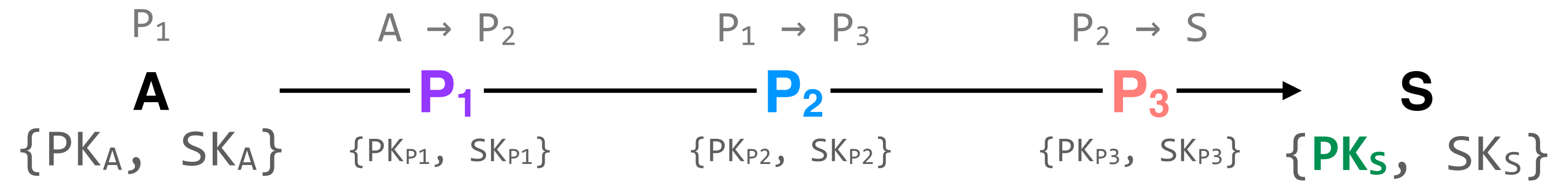
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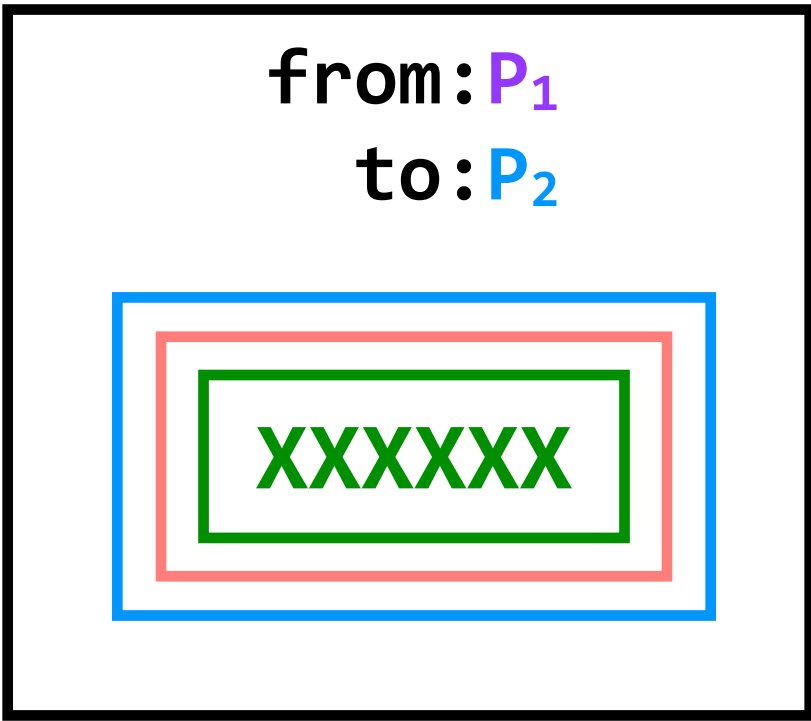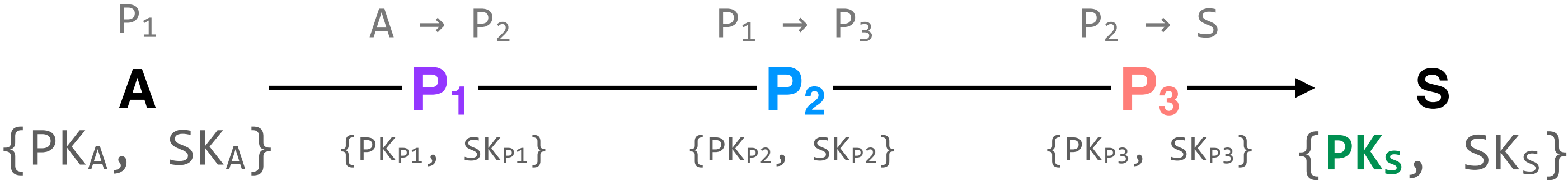data should not appear the same across packets

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from: P_1
to: P_2

XXXXXX

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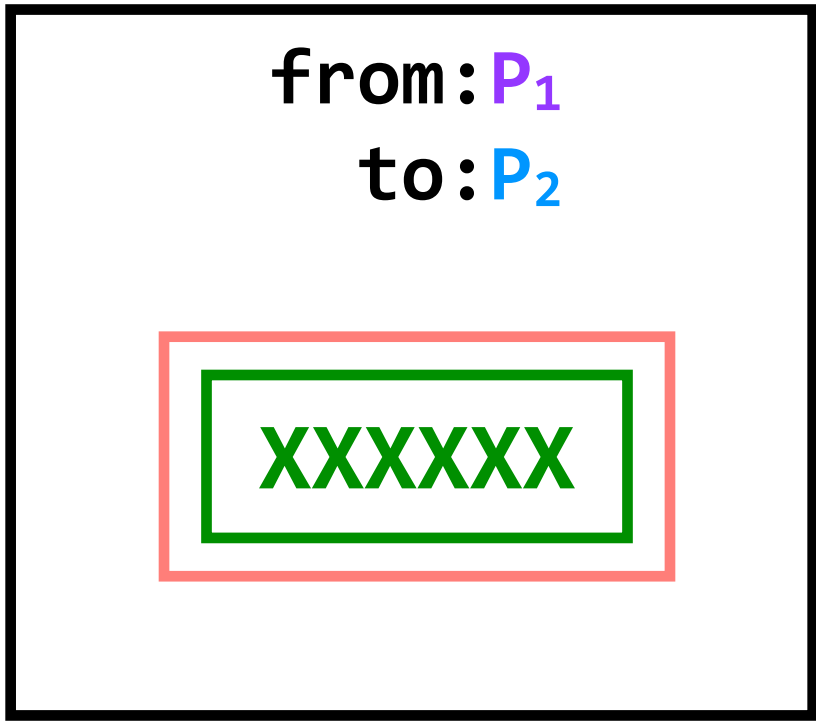**policy:** provide **anonymity** (only the client should know that they're communicating with the server)

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from:P_1
to:P_2

XXXXXX

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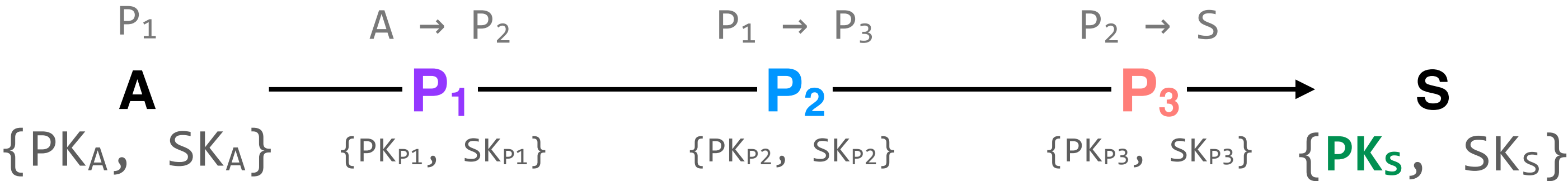
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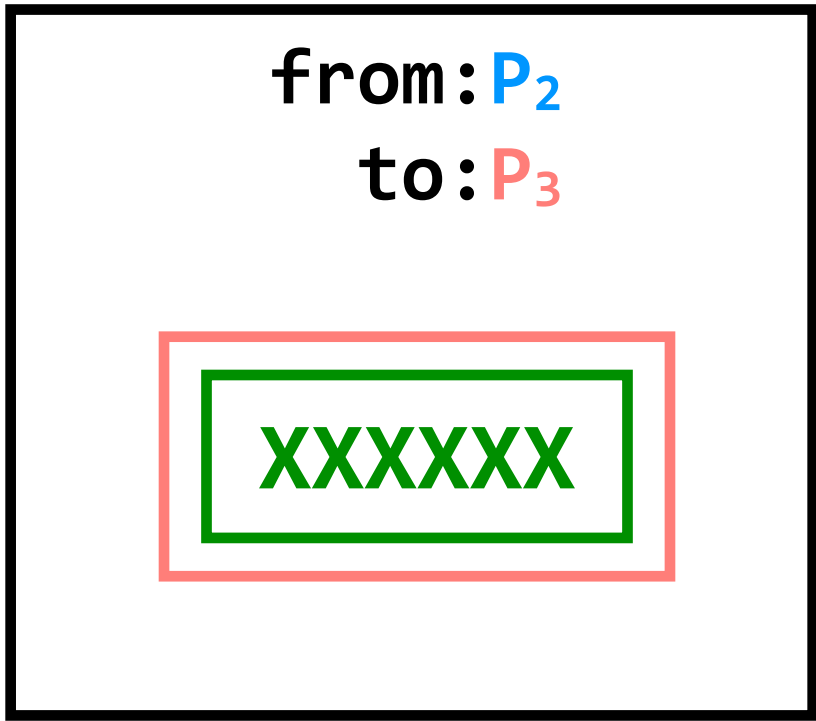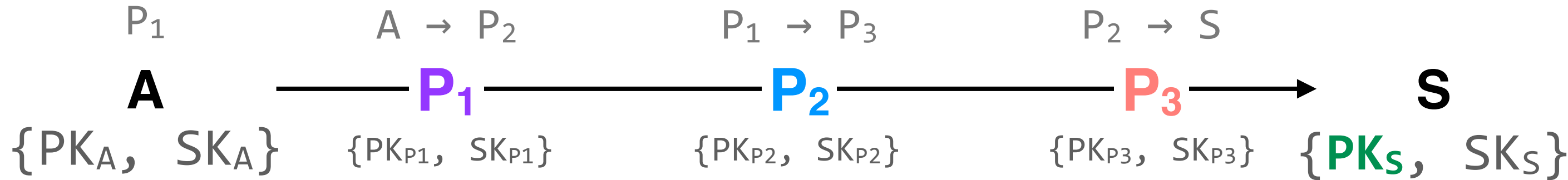
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P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A —— **P₁** ———— **P₂** ———— **P₃** ⟶ **S**

$\{PK_A,\ SK_A\}$ $\{PK_{P1},\ SK_{P1}\}$ $\{PK_{P2},\ SK_{P2}\}$ $\{PK_{P3},\ SK_{P3}\}$ $\{PK_S,\ SK_S\}$

from:P_2
to:P_3

XXXXXX

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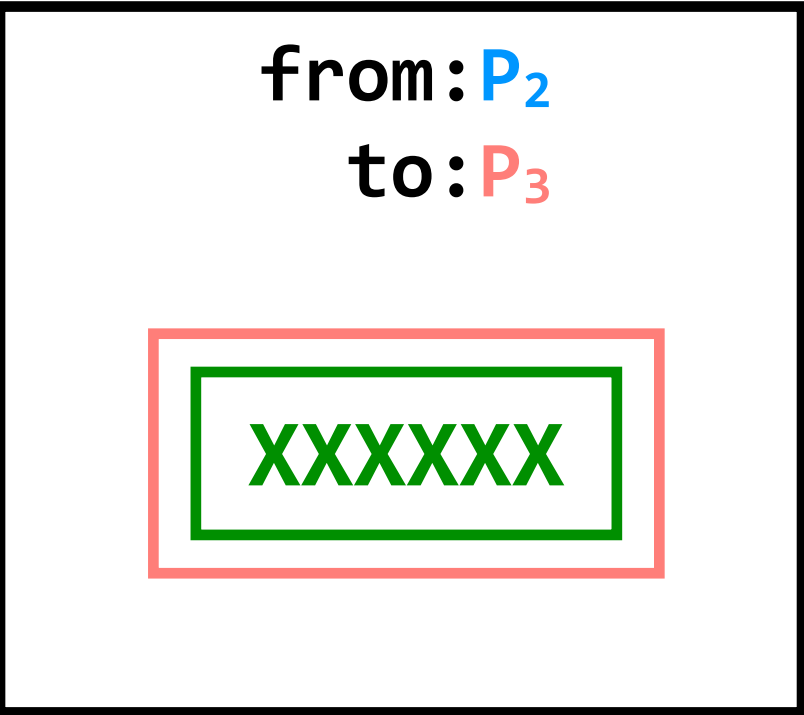
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data should not appear the same across packets

P₁   A → P₂   P₁ → P₃   P₂ → S

A ——— **P₁** ——————— **P₂** ——————— **P₃** ——→ **S**

{PK_A, SK_A}   {PK_P1, SK_P1}   {PK_P2, SK_P2}   {PK_P3, SK_P3} {PK_S, SK_S}

```
from:P₂
  to:P₃


XXXXXX
```

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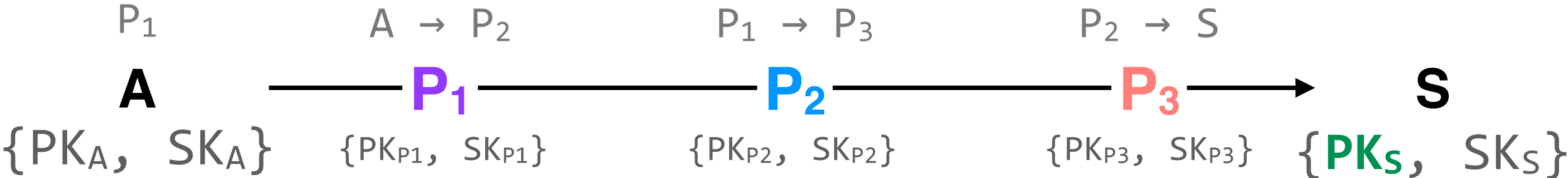**policy:** provide **anonymity** (only the client should know that they're communicating with the server)

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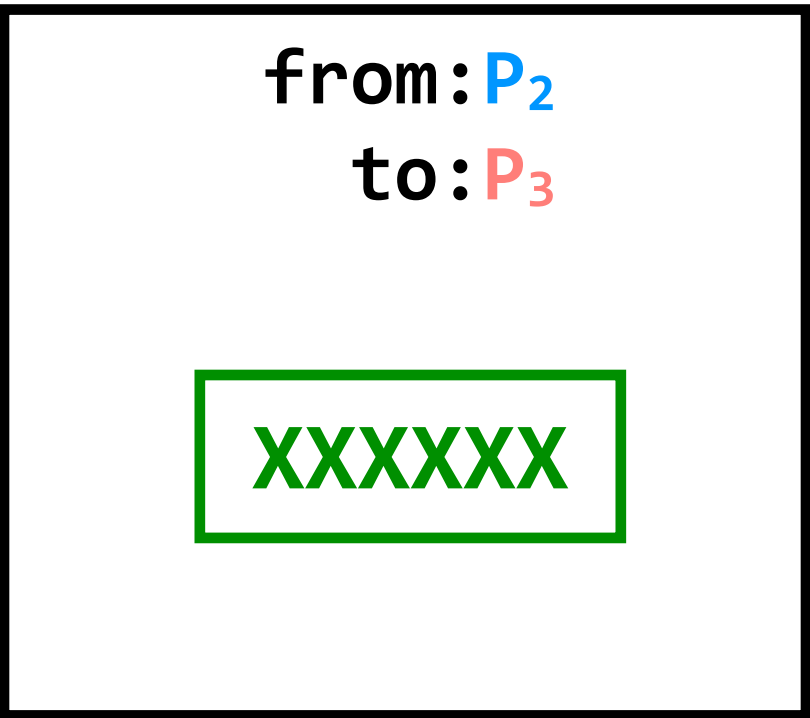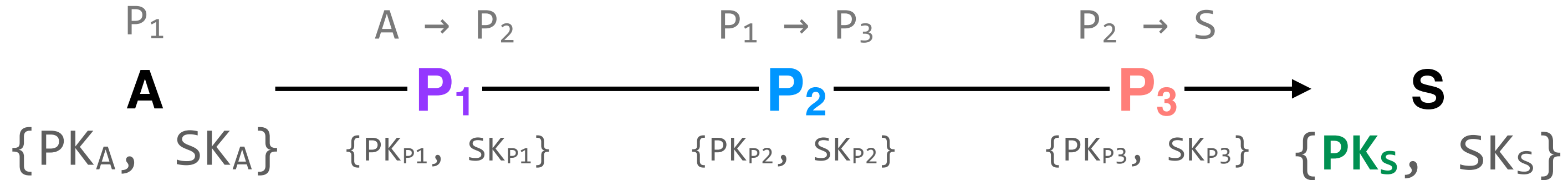
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```
from:P₂
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 XXXXXX
```

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$$\texttt{encrypt(PK}_x\texttt{, m) = c}$$

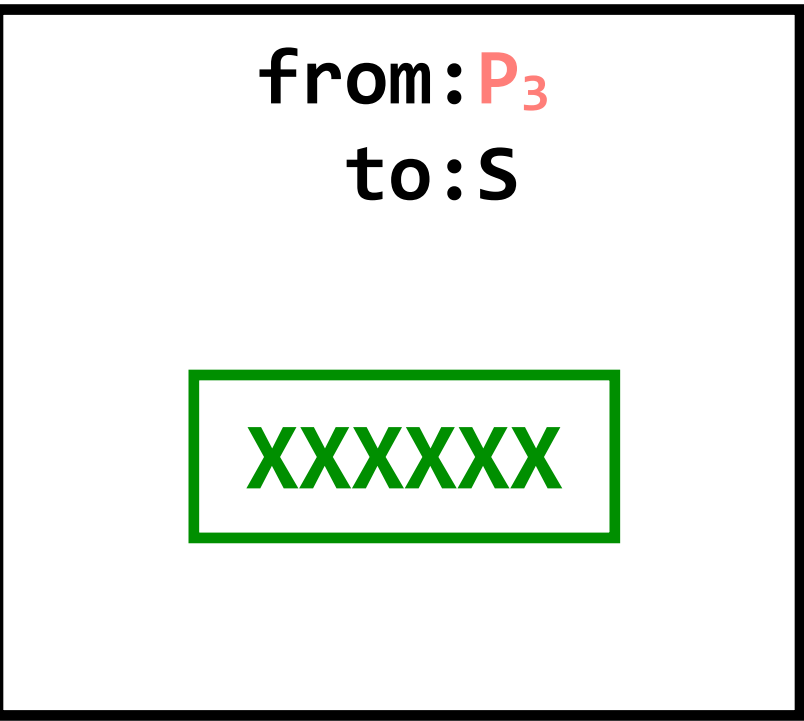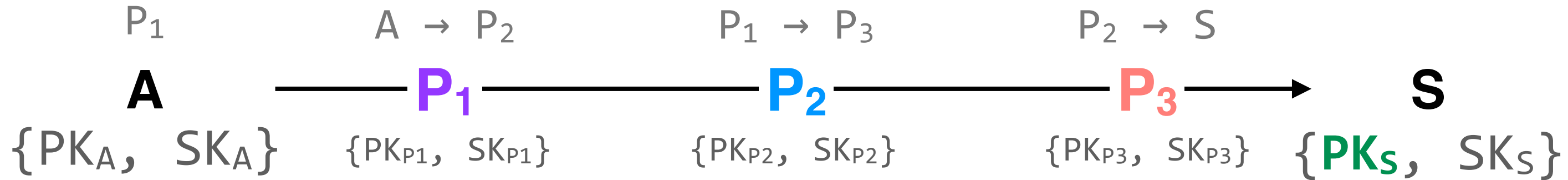$$\texttt{decrypt(SK}_x\texttt{, c) = m}$$

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```
from:P₃
   to:S


 XXXXXX
```

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A ——— **P$_1$** ——————— **P$_2$** ——————— **P$_3$**——→ **S**

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```
from: P₃
  to: S
```

XXXXXX

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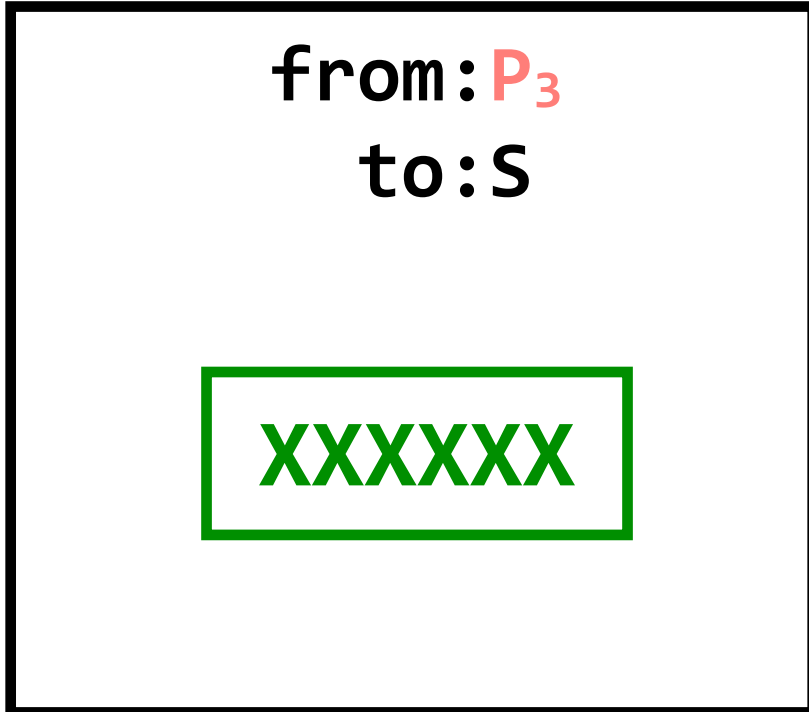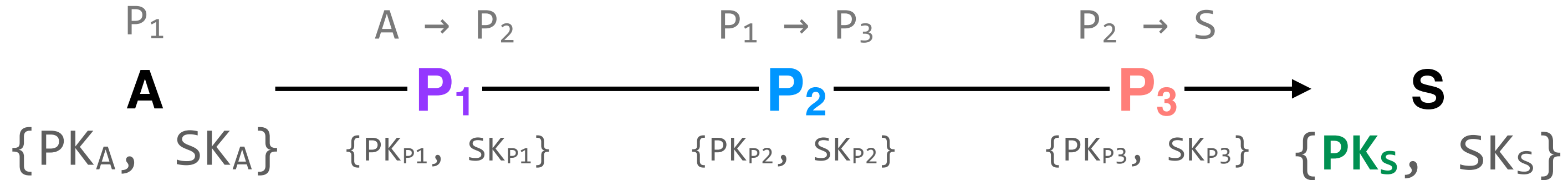data should not appear the same across packets

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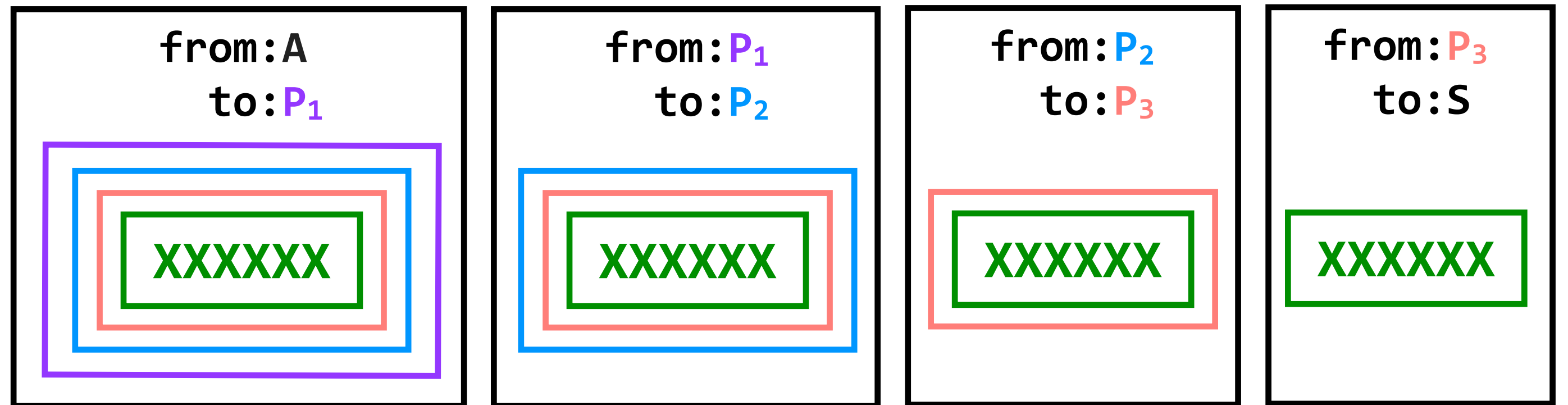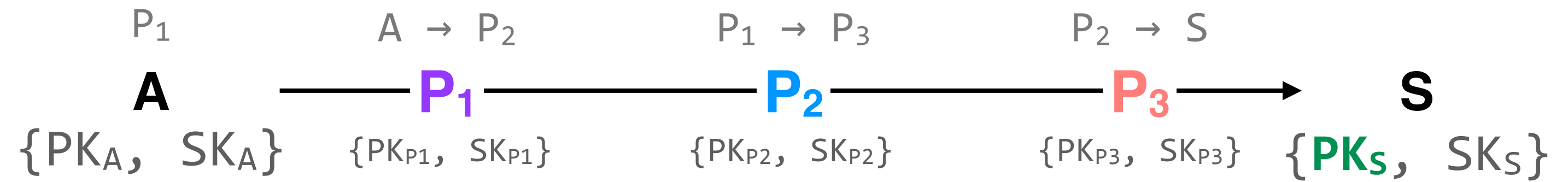data should not appear the same across packets

| P_1 | $A \rightarrow P_2$ | $P_1 \rightarrow P_3$ | $P_2 \rightarrow S$ |

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```
from:A        from:P₁       from:P₂       from:P₃
to:P₁         to:P₂         to:P₃         to:S
XXXXXX        XXXXXX        XXXXXX        XXXXXX
```

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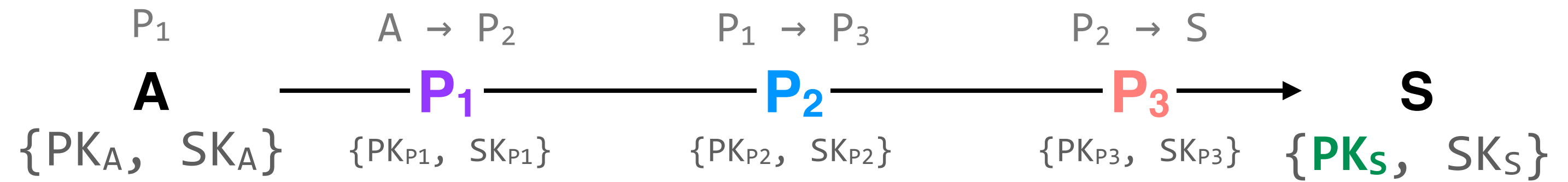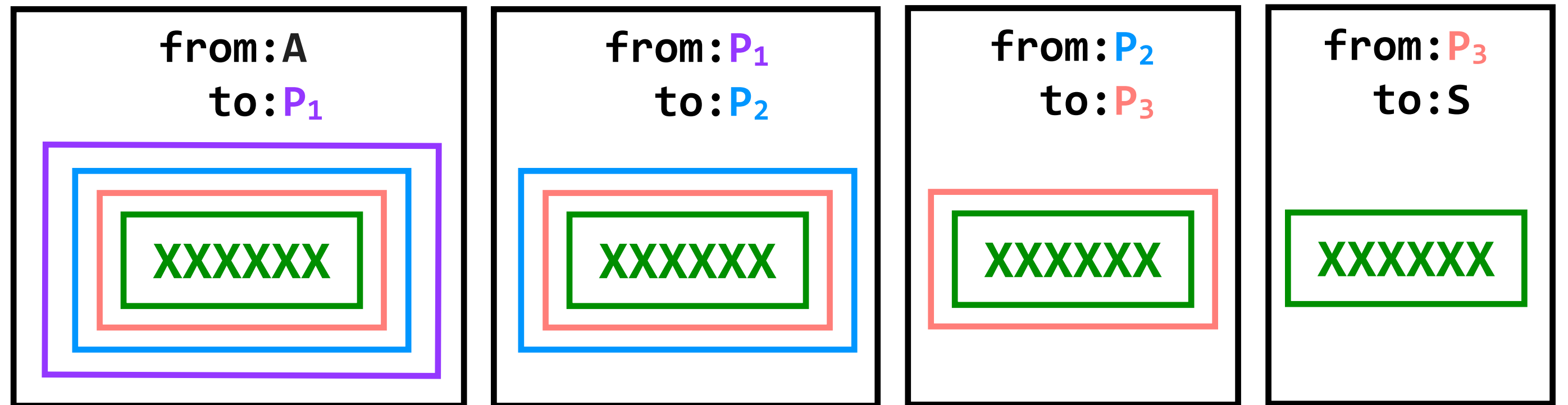data should not appear the same across packets

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```
from:A          from:P₁         from:P₂         from:P₃
to:P₁           to:P₂           to:P₃           to:S

  XXXXXX          XXXXXX          XXXXXX          XXXXXX
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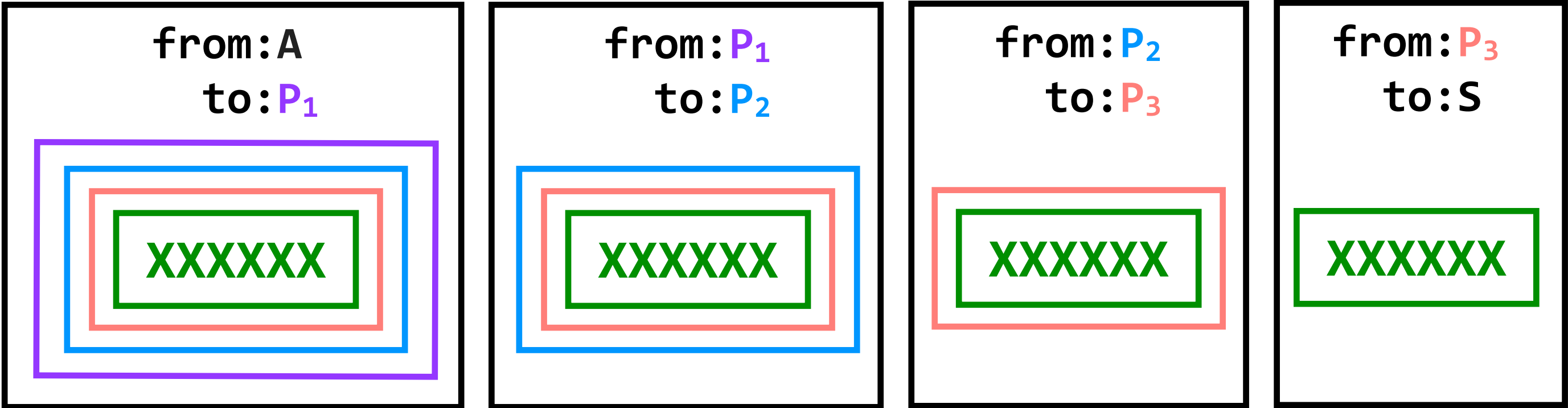**policy:** provide **anonymity** (only the client should know that they're communicating with the server)

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```
from:A          from:P₁          from:P₂          from:P₃
  to:P₁           to:P₂            to:P₃            to:S

  XXXXXX          XXXXXX           XXXXXX           XXXXXX
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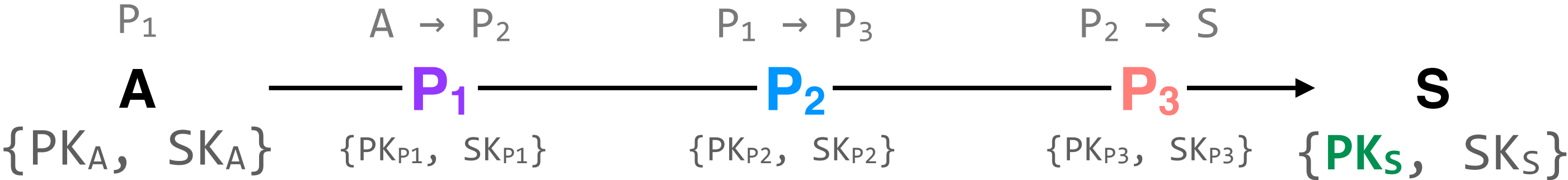
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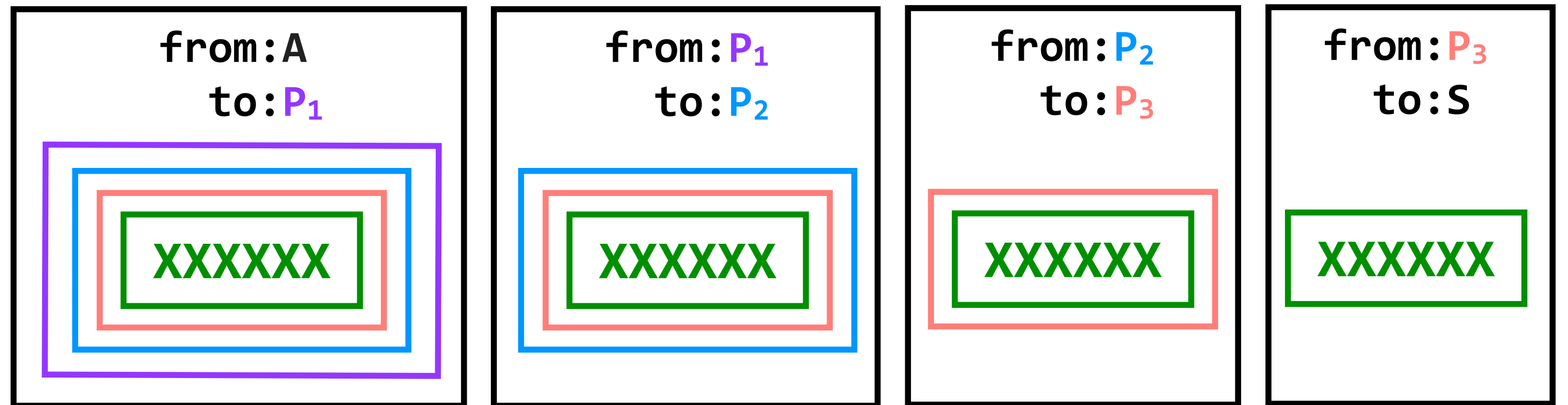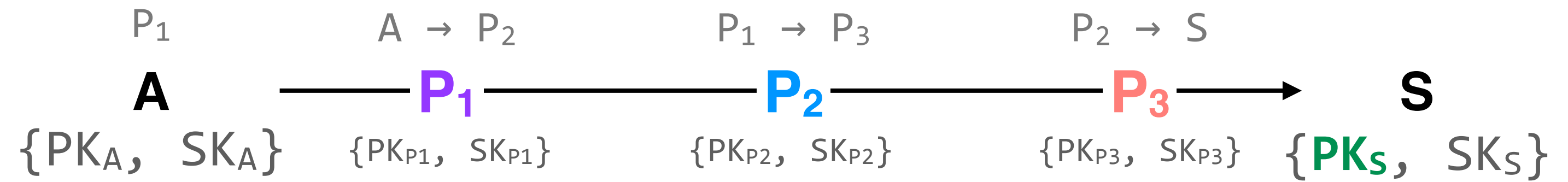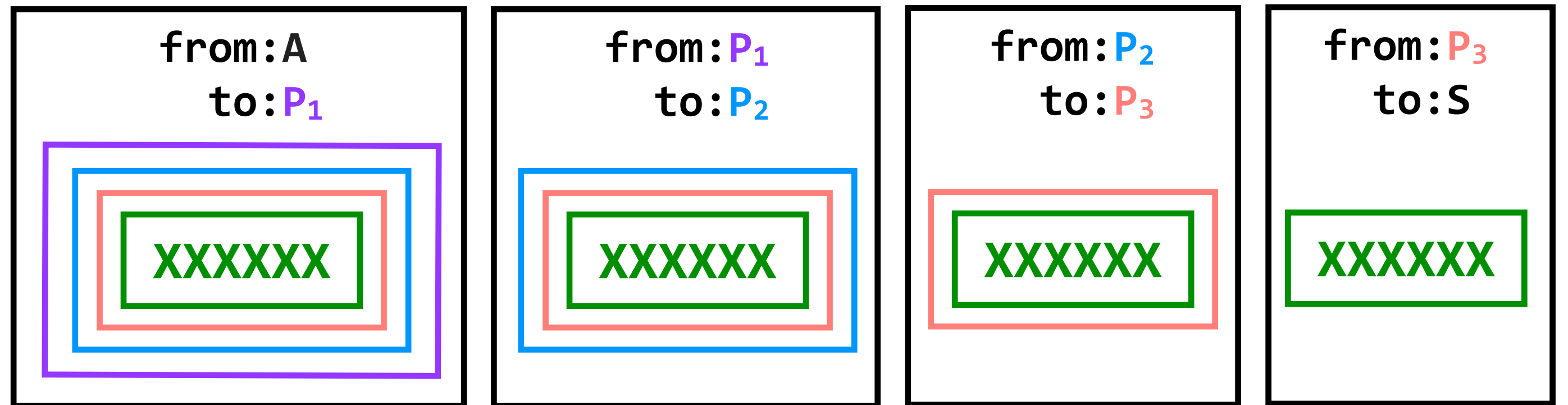
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```
from:A          from:P₁         from:P₂         from:P₃
to:P₁           to:P₂           to:P₃           to:S

XXXXXX          XXXXXX          XXXXXX          XXXXXX
```

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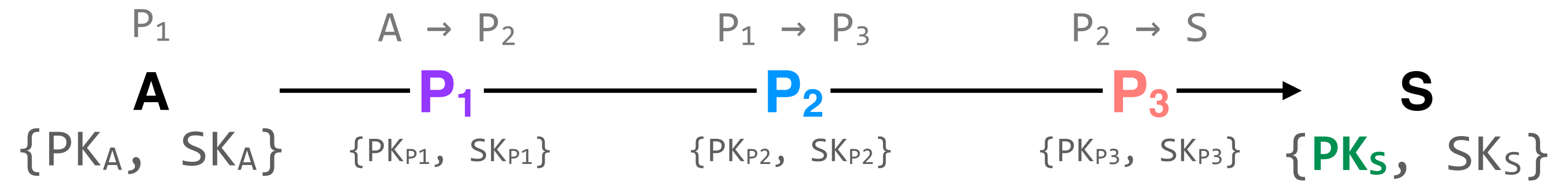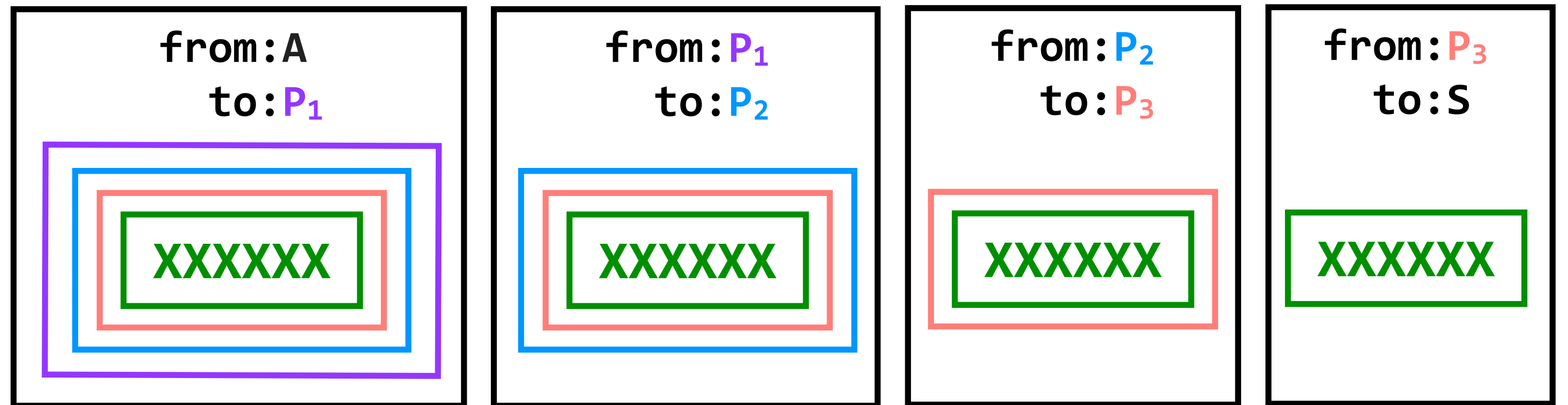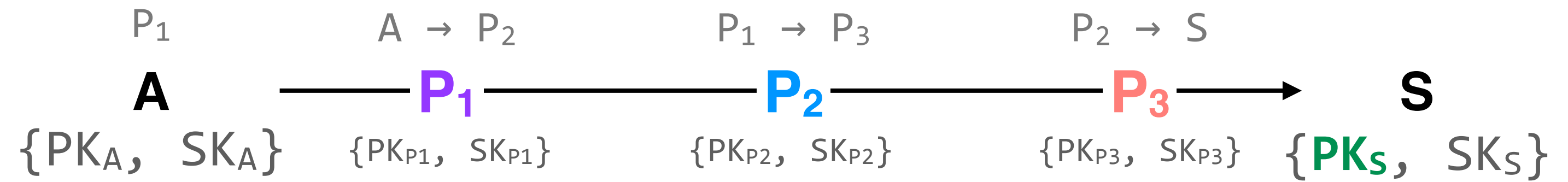
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P_1 $A \rightarrow P_2$ $P_1 \rightarrow P_3$ $P_2 \rightarrow S$

A ———— $\textbf{P}_\textbf{1}$ ———— $\textbf{P}_\textbf{2}$ ———— $\textbf{P}_\textbf{3}$ ⟶ **S**

$\{PK_A,\ SK_A\}$ $\{PK_{P1},\ SK_{P1}\}$ $\{PK_{P2},\ SK_{P2}\}$ $\{PK_{P3},\ SK_{P3}\}$ $\{\textbf{PK}_\textbf{S},\ SK_S\}$

from:A to:P_1	from:P_1 to:P_2	from:P_2 to:P_3	from:P_3 to:S
XXXXXX	XXXXXX	XXXXXX	XXXXXX

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P1   A → P2   P1 → P3   P2 → S

A —— **P₁** —————— **P₂** —————— **P₃** ——→ **S**
{PK_A, SK_A} {PK_P1, SK_P1}   {PK_P2, SK_P2}   {PK_P3, SK_P3} {PK_S, SK_S}

```
from:A        from:P₁        from:P₂        from:P₃
to:P₁          to:P₂          to:P₃          to:S

XXXXXX        XXXXXX        XXXXXX        XXXXXX
```

onion routing adds layers of encryption that nodes on the path can strip off as the packet traverses the network

in practice, **tor** uses public-key cryptography to securely exchange **symmetric keys** between A and each node in the circuit, and the layers of encryption use those symmetric keys; this is what allow traffic to travel in both directions

policy: provide **anonymity** (only the client should know that they're communicating with the server)

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Am I totally anonymous if I use Tor?

Generally it is impossible to have perfect anonymity, even with Tor. Though there are some things you can practice to improve your anonymity while using Tor and offline.

Use Tor Browser and software specifically configured for Tor

Tor does not protect all of your computer's Internet traffic when you run it. Tor only protects applications that are properly configured to send their Internet traffic through Tor.

Web browsing:

- Safe: Tor Browser
- Unsafe: Any other browser configured to use Tor as a proxy

File sharing:

- Safe: OnionShare
- Unsafe: BitTorrent over Tor

policy: provide **anonymity** (only the client should know that they're communicating with the server)

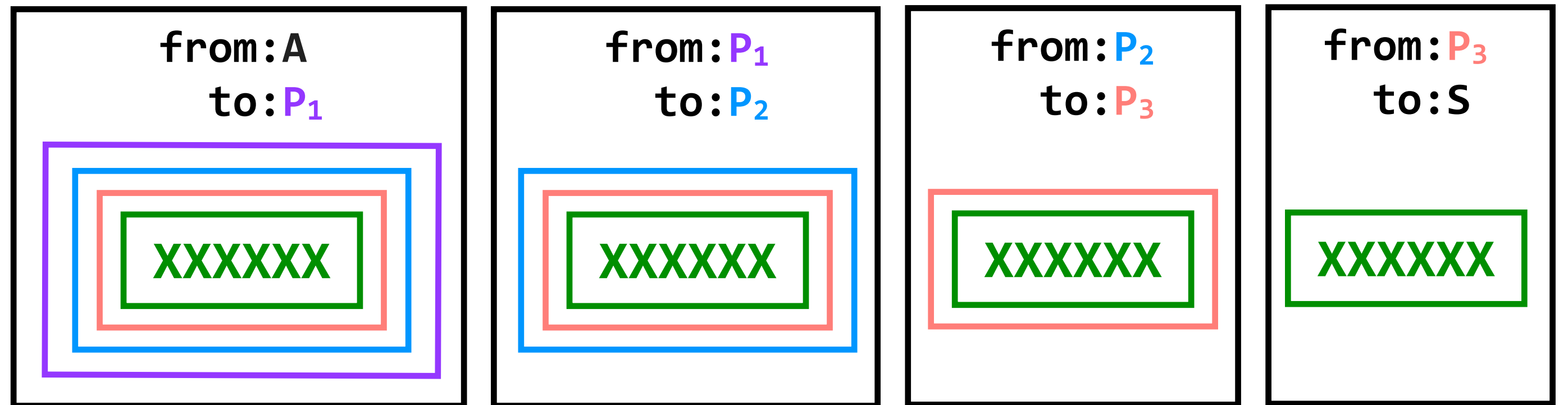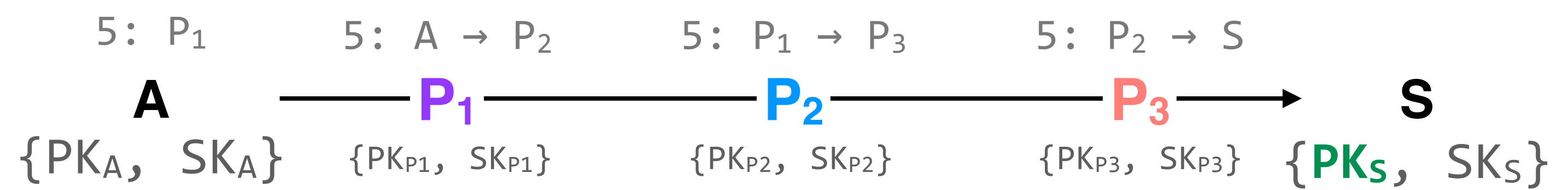**threat model:** adversary is on the path between the client and the server

public-key cryptography: a message to **x** is encrypted with **x**'s public key; only **x**'s secret key can decrypt the message

$$\text{encrypt}(PK_x, m) = c$$

$$\text{decrypt}(SK_x, c) = m$$

things to avoid

👍 no packet should say "from: A; to: S"

👍 no entity in the network should receive a packet from A and send it directly to S

👍 no entity in the network should keep *state* that links A to S

👍 data should not appear the same across packets

5 is the (random) "circuit ID". a proxy may be involved in more than one circuit, so it needs a way to differentiate

5: P_1 5: $A \rightarrow P_2$ 5: $P_1 \rightarrow P_3$ 5: $P_2 \rightarrow S$

A ——— **P₁** ——————— **P₂** ——————— **P₃** ——→ **S**

{PK_A, SK_A}   {PK_{P1}, SK_{P1}}   {PK_{P2}, SK_{P2}}   {PK_{P3}, SK_{P3}} {**PK_S**, SK_S}

from:A to:P_1	from:P_1 to:P_2	from:P_2 to:P_3	from:P_3 to:S
XXXXXX	XXXXXX	XXXXXX	XXXXXX

onion routing adds layers of encryption that nodes on the path can strip off as the packet traverses the network
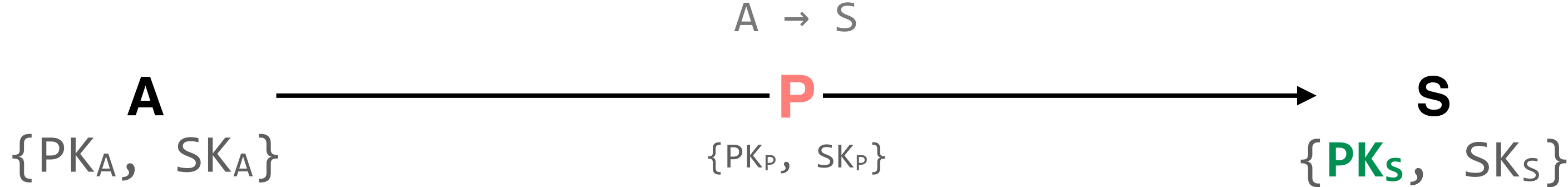
in practice, **tor** uses public-key cryptography to securely exchange **symmetric keys** between A and each node in the circuit, and the layers of encryption use those symmetric keys; this is what allow traffic to travel in both directions

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A → S

A   **P** ────────────▶ **S**
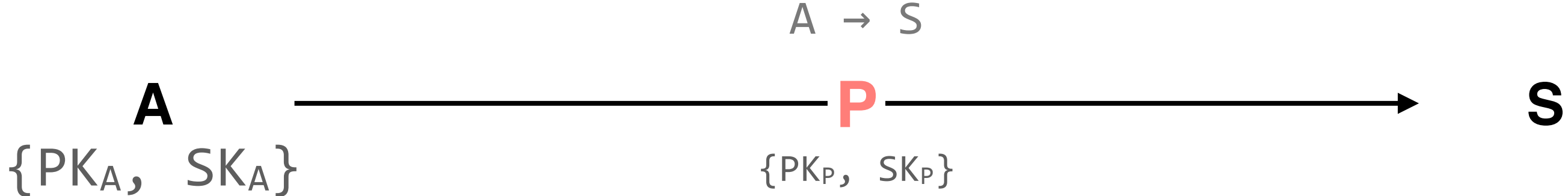$\{PK_A,\ SK_A\}$ $\{PK_P,\ SK_P\}$ $\{PK_S,\ SK_S\}$

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A   **P** ──────────────▶ **S**
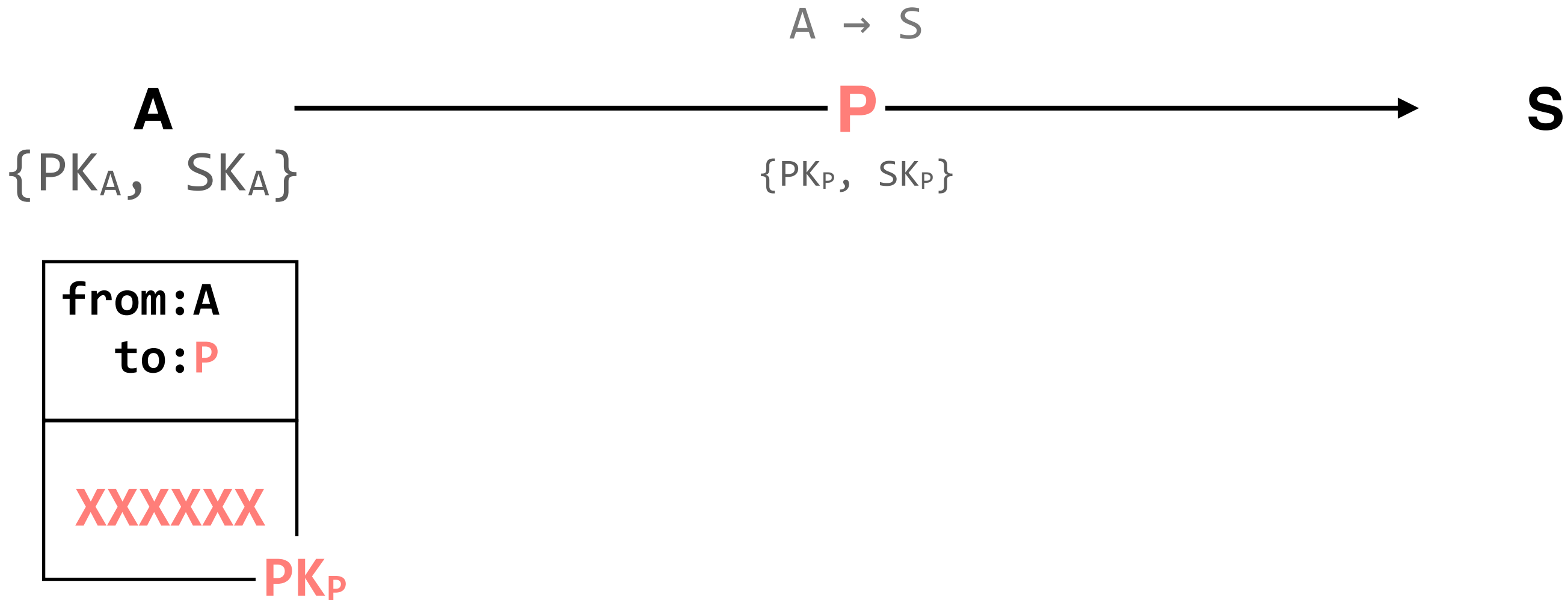$\{PK_A, SK_A\}$ $\{PK_P, SK_P\}$

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A → S

A   **P**   **S**
{PK$_A$, SK$_A$}   {PK$_P$, SK$_P$}
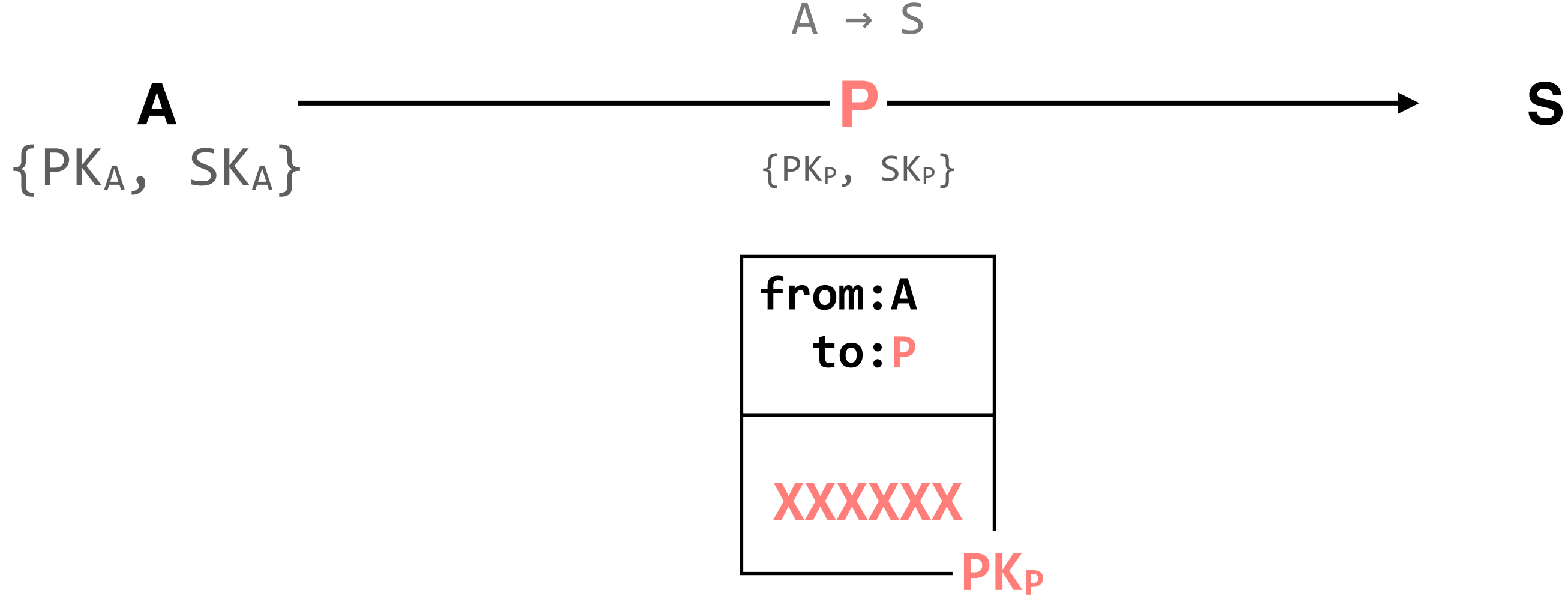
```
from:A
  to:P

XXXXXX
```
—— PK$_P$

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A → S

A
{PK_A, SK_A}

P
{PK_P, SK_P}
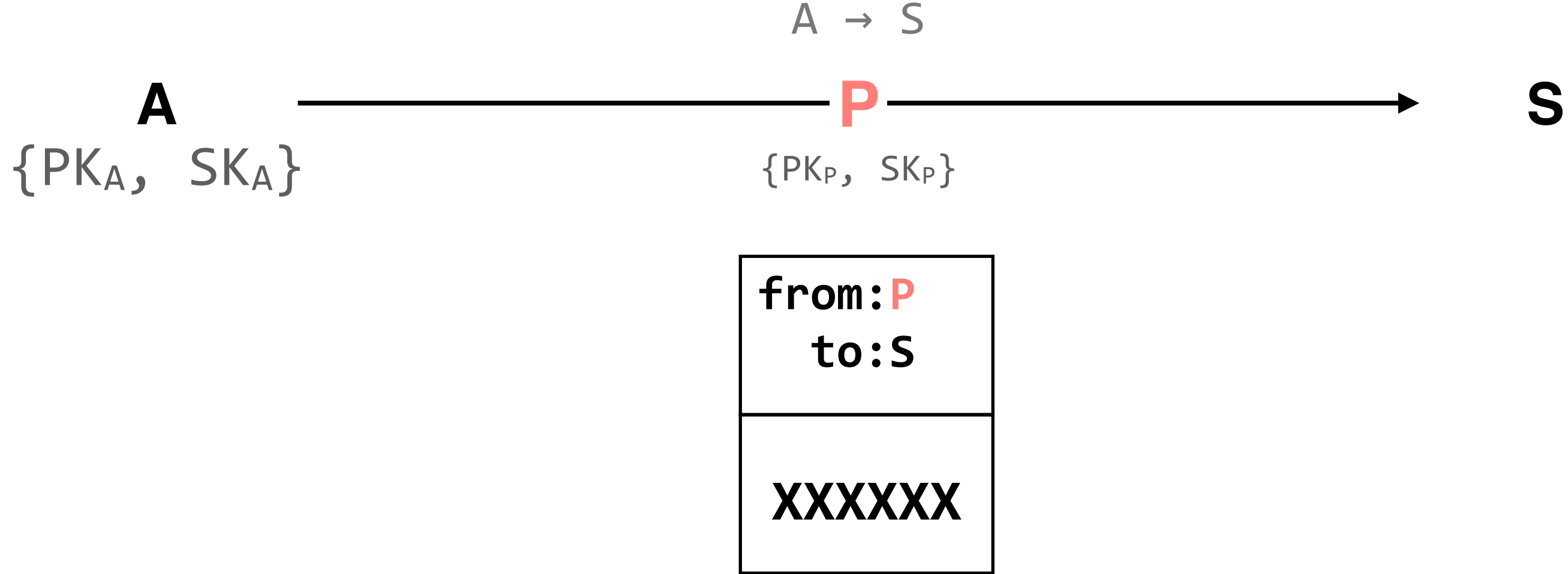
S

```
from:A
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XXXXXX

PK_P

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A → S

A
{PK$_\text{A}$, SK$_\text{A}$}

P
{PK$_\text{P}$, SK$_\text{P}$}
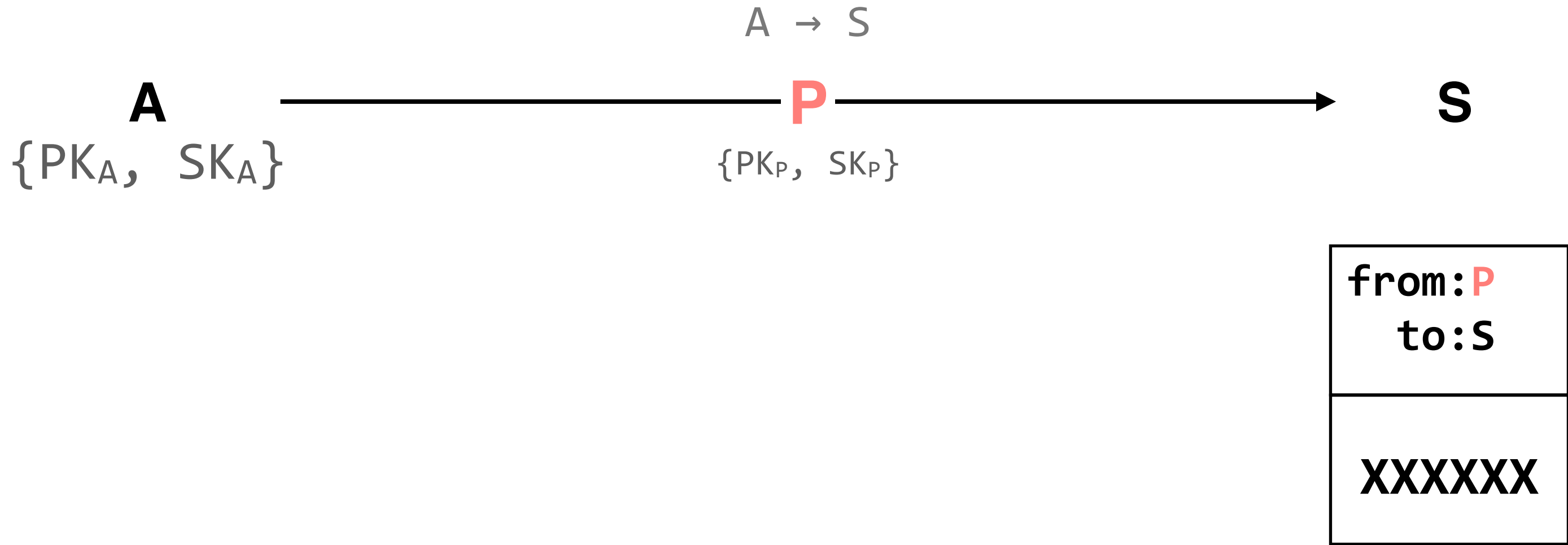
S

```
from:P
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```

```
XXXXXX
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$A \rightarrow S$

A
$\{PK_A, SK_A\}$

P
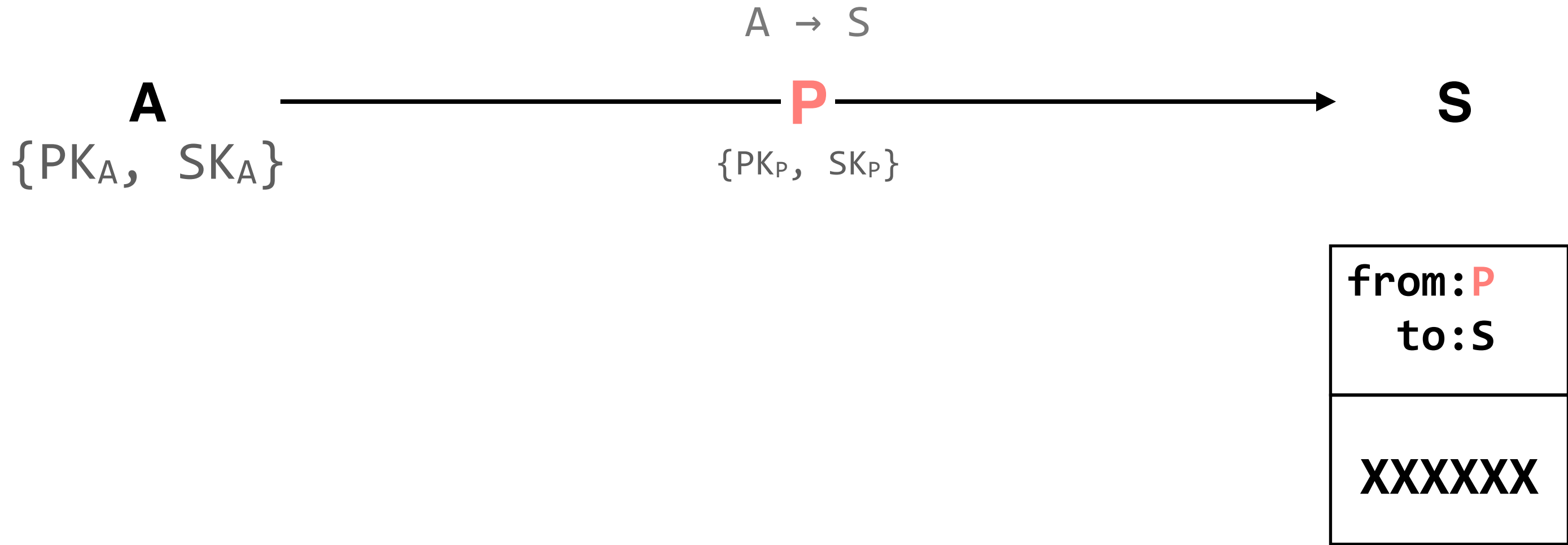$\{PK_P, SK_P\}$

S

| from:P |
| to:S |
| XXXXXX |

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A ───────────────── **P** ────────────────▶ **S**
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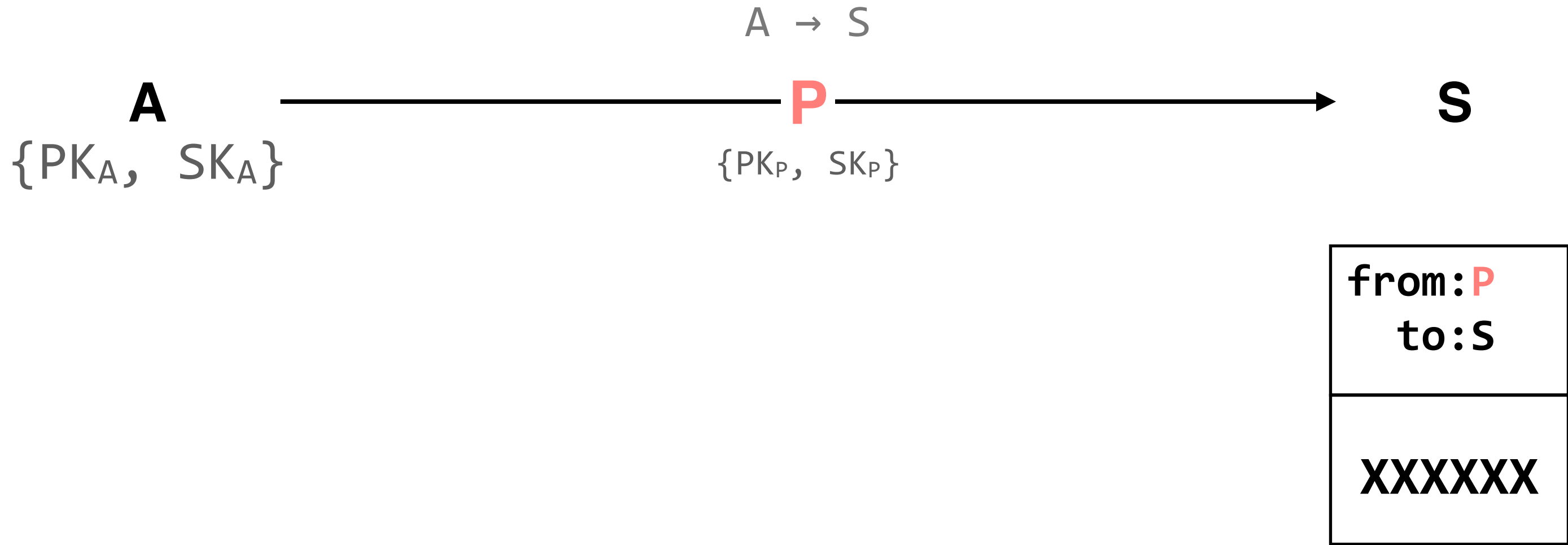
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XXXXXX
```

assuming you trust the proxy, this type of service can be useful if you care about confidentiality on a local network

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A → S

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S

from:P
to:S

XXXXXX

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what we've shown here is a simplified version of some of the functionality you get when you use a VPN

tor provides some level of anonymity for users, preventing adversaries from linking a sender to its receiver

much like when we discussed certificate authorities, there are interesting questions about who should run tor. how do we trust that the relay nodes are behaving as they should?

there are still ways to attack tor, namely by **correlating traffic** from various points in the network

as system designers, it's important to think about what traffic you're sending over the network to clients, and whether that traffic can be sent in a more secure way (and what the trade-offs would be)

a larger takeaway here is that a secure channel alone only provides confidentiality and integrity of the message data; **packet headers can reveal information** that may be sensitive in certain contexts