02244 Language-Based Security
Security Protocols:
Channels and Composition

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Roadmap

1. **Channels as Assumptions**
2. **Channels as Goals**
3. **Channel Calculus**
4. **Pseudonymous Channels**
5. **Protocol Composition**

Motivation

Example (NSL)

$$\begin{array}{lcll} A & \rightarrow & B: & \{NA, A\}_{\mathsf{pk}(B)} \\ B & \rightarrow & A: & \{NA, NB, B\}_{\mathsf{pk}(A)} \\ A & \rightarrow & B: & \{NB\}_{\mathsf{pk}(B)} \end{array}$$

- Public-key cryptography is used here to ensure confidential transmission of messages.

Motivation

Example (NSL)

$$\begin{array}{lcll} A & \to\bullet & B: & NA, A \\ B & \to\bullet & A: & NA, NB, B \\ A & \to\bullet & B: & NB \end{array}$$

- Public-key cryptography is used here to ensure confidential transmission of messages.
- Abstraction: use a confidential channel.

Motivation

The Diffie-Hellman assumes an authentic exchange of the half-keys:

$$\begin{array}{lcll} A & \bullet\!\!\rightarrow & B: & \exp(g, X) \\ B & \bullet\!\!\rightarrow & A: & \exp(g, Y) \end{array}$$

- How this exchange is authenticated is not relevant for Diffie-Hellman!
- Many protocols use Diffie-Hellman, e.g. Station2Station, IKE/IKEv2/JFK, Kerberos, TLS, device-pairing. . . .
- Many different ways to authenticate the key-exchange:

  Cryptographically Digital signatures, symmetric/asymmetric encryption, MACs.

  Non-Cryptographically using a trusted third party, meeting face to face, using additional channels (SMS etc.)
- Using an authentic channel abstracts from the realization.

Motivation

- Channels can be both assumptions and goals of a protocol:

Example

$$
\begin{array}{cccll}
A & \bullet\!\!\rightarrow & B & : & \mathrm{exp}(g,X) \\
B & \bullet\!\!\rightarrow & A & : & \mathrm{exp}(g,Y) \\
A & \rightarrow & B & : & \{\!|Payload|\!\}_{\mathrm{exp}(\mathrm{exp}(g,X),Y)} \\
\hline
A & \bullet\!\!\rightarrow\!\!\bullet & B & : & Payload
\end{array}
$$

"Diffie-Hellman creates a secure channel from authentic channels."

- Actually, public-key cryptography could be defined in a broad sense as a mechanism to obtain secure channels from authentic channels.
- Very general way to see Diffie-Hellman.
- Good for system design and verification: reason about small components with a well-defined interface.

Towards a well-defined interface

What exactly does “authentic”, “confidential” and “secure” mean?

- Indeed there is not one right answer, there are many meaningful ways to define these notions.
- We define them here using asymmetric cryptography.
- There are many other ways to define them, e.g. by their behavior.

Realizing Channels with Cryptography

- Assume every agent A has two key pairs:
  - ★ $\langle \mathsf{ck}(A), \mathsf{inv}(\mathsf{ck}(A)) \rangle$ for asymmetric encryption.
  - ★ $\langle \mathsf{ak}(A), \mathsf{inv}(\mathsf{ak}(A)) \rangle$ for digital signatures.
- Assume that every agent knows the public keys $\mathsf{ck}(A)$ and $\mathsf{ak}(A)$ of every other agent A.
- Encode channels by encryption and signing:

Definition

$$\begin{array}{lllllllll}
A & \bullet\!\!\rightarrow & B: & M & \text{for} & A & \rightarrow & B: & \{\mathsf{atag}, B, M\}_{\mathsf{inv}(\mathsf{ak}(A))} \\
A & \rightarrow\!\!\bullet & B: & M & \text{for} & A & \rightarrow & B: & \{\mathsf{ctag}, M\}_{\mathsf{ck}(B)} \\
A & \bullet\!\!\rightarrow\!\!\bullet & B: & M & \text{for} & A & \rightarrow & B: & \{\{\mathsf{stag}, B, M\}_{\mathsf{inv}(\mathsf{ak}(A))}\}_{\mathsf{ck}(B)}
\end{array}$$

- atag, ctag, and stag are tags to distinguish the channel-encodings from other encryptions.

A Cryptographic Realization

Definition

$$
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A & \bullet\!\!\rightarrow\!\!\bullet & B: & M & \text{for} & A & \rightarrow & B: \{\{\mathsf{stag}, B, M\}_{\mathsf{inv}(\mathsf{ak}(A))}\}_{\mathsf{ck}(B)}
\end{array}
$$

- This ensures the basic properties of channels:
  - ★ Only A can produce messages on the channel $A \bullet\!\!\rightarrow B$.
  - ★ Only B can read messages on the channel $A \rightarrow\!\!\bullet B$.
  - ★ Both restrictions on a secure channel.
- Note that the intruder can still intercept and replay messages!
- This model of channels can be used with all models and tools without extensions!

Authenticated Recipient

Definition

$$
\begin{array}{lllllllll}
A & \bullet\!\!\rightarrow & B: & M & \text{for} & A & \rightarrow & B: & \{\mathsf{atag}, B, M\}_{\mathsf{inv}(\mathsf{ak}(A))} \\
A & \rightarrow\!\!\bullet & B: & M & \text{for} & A & \rightarrow & B: & \{\mathsf{ctag}, M\}_{\mathsf{ck}(B)} \\
A & \bullet\!\!\rightarrow\!\!\bullet & B: & M & \text{for} & A & \rightarrow & B: & \{\{\mathsf{stag}, B, M\}_{\mathsf{inv}(\mathsf{ak}(A))}\}_{\mathsf{ck}(B)}
\end{array}
$$

Why is the recipient B contained in the signatures?

- Including the name B means to authenticate the intended recipient.
- This avoids a classical problem:
  - ★ Recall that $\{\{M\}_{\mathsf{inv}(\mathsf{ak}(A))}\}_{\mathsf{ck}(B)}$ does not give you a secure transmission.

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- This avoids a classical problem:
  - ★ Recall that $\{\{M\}_{\mathsf{inv}(\mathsf{ak}(A))}\}_{\mathsf{ck}(B)}$ does not give you a secure transmission.
  - ★ Think of a dishonest B!
- We want $\bullet\!\!\rightarrow + \rightarrow\!\!\bullet = \bullet\!\!\rightarrow\!\!\bullet$, so the intended recipient should be part of the authentication.
- Also later: relevant when relating to authentic channels as a goal.

Channels as Goals

- Consider payload messages in a protocol; the goal is the authentic and/or secure transmission of the payload:

Example

$$\begin{array}{cccll} A & \bullet\!\!\to & B & : & \mathrm{exp}(g, X) \\ B & \bullet\!\!\to & A & : & \mathrm{exp}(g, Y) \\ A & \to & B & : & \{\!|\mathit{Payload}|\!\}_{\mathrm{exp}(\mathrm{exp}(g,X),Y)} \\ \hline A & \bullet\!\!\to\!\!\bullet & B & : & \mathit{Payload} \end{array}$$

- Authentic transmission $A \bullet\!\!\to B : \mathit{Payload}$: standard non-injective authentication/agreement on *Payload*.
- Confidential transmission $A \to\!\!\bullet B : \mathit{Payload}$: standard secrecy goal (with earliest possible claim by the A).
- Secure transmission: both authentication and secrecy.
- In general, protocols will transmit many payload messages; here we consider only protocols with one payload per session.

Compositionality

Our Aim: A Compositionality Result

- Protocol P_1 realizes channel C as a goal.
- Protocol P_2 assumes channel C.
- Both P_1 and P_2 have been verified individually.
- Some conditions on P_1 and P_2 hold (details later).
- Then we can "plug" P_1 into P_2 to realize the channel C,
- and the resulting protocol $P_2[P_1]$ is correct.

Compositionality: Example

Example (P_1)

$$\begin{array}{rl} A \to s: & A, B, Payload, mac(sk(A,s), A, B, Payload) \\ s \to B: & A, B, Payload, mac(sk(B,s), A, B, Payload) \\ \hline Goal: \ A \bullet\!\!\to B: & Payload \end{array}$$

Example (P_2)

$$\begin{array}{rl} A \bullet\!\!\to B: & \exp(g, X) \\ B \bullet\!\!\to A: & \exp(g, Y) \\ A \to B: & \{\!|ApplicationPayload|\!\}_{\exp(\exp(g,X),Y)} \\ \hline Goal: \ A \bullet\!\!\to\!\!\bullet B: & ApplicationPayload \end{array}$$

Compositionality: Example

Example ($P_2[P_1]$)

$$
\begin{array}{rl}
A \to s: & A, B, \exp(g, X), mac(sk(A, s), A, B, \exp(g, X)) \\
s \to B: & A, B, \exp(g, X), mac(sk(B, s), A, B, \exp(g, X)) \\
B \to s: & B, A, \exp(g, Y), mac(sk(B, s), B, A, \exp(g, Y)) \\
s \to A: & B, A, \exp(g, Y), mac(sk(A, s), B, A, \exp(g, Y)) \\
A \to B: & \{\!|ApplicationPayload|\!\}_{\exp(\exp(g,X),Y)} \\
\hline
Goal: \; A \bullet\!\!\to\!\!\bullet B: & ApplicationPayload
\end{array}
$$

Authentication as an Assumption and as a Goal

Consider an alternative definition of an authentic channel as an assumption:

Definition (*)

$$A \bullet\!\!\rightarrow B : M \text{ for } A \rightarrow B : \{\mathsf{atag}, M\}_{\mathsf{inv}(\mathsf{ak}(A))}$$

This definition of an authentic channel as an assumption is not "compatible" with our definition of a channel as a goal, e.g.:

$$\frac{A \bullet\!\!\rightarrow B : \quad M}{Goal : \; A \bullet\!\!\rightarrow B : \quad M}$$

This protocol has an attack when using definition (*)!

Channel Calculus

Channel Game

- Given a set of channels between agents
- There is no further security relationship between the agents (no public/private keys, passwords,...)
- You can define a protocol to establish new channels between the agents that may use
  - the existing channels
  - create new keys, nonces, and
  - use standard cryptographic primitives
- Question: What new channels between agents can be achieved this way?

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- Question: What new channels between agents can be achieved this way?

- We can turn around the direction of any channel, e.g. given $A \bullet\!\!\rightarrow B$, we can achieve $B \rightarrow\!\!\bullet A$.
- From $A \bullet\!\!\rightarrow B$ and $A \rightarrow\!\!\bullet B$ we get $A \bullet\!\!\rightarrow\!\!\bullet B$.
- Nothing else.

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- From $A \bullet\!\!\rightarrow B$ and $A \rightarrow\!\!\bullet B$ we get $A \bullet\!\!\rightarrow\!\!\bullet B$.
- Nothing else.

Additional question: what if we can assume some parties are honest?

TLS

Consider the TLS handshake (simplified):

$$
\begin{array}{rl}
A \rightarrow B: & A, NA, Sid, PA \\
B \rightarrow A: & NB, Sid, PB, cert_B \\
A \rightarrow B: & cert_A, \{PMS\}_{\mathsf{pk}(B)}, \{hash(NB, B, PMS)\}_{\mathsf{inv}(\mathsf{pk}(A))}, \\
 & \{|hash(prf(PMS, NA, NB), msgs)|\}_{clientK(NA,NB,prf(PMS,NA,NB))} \\
B \rightarrow A: & \{|hash(prf(PMS, NA, NB), msgs)|\}_{serverK(NA,NB,prf(PMS,NA,NB))}
\end{array}
$$

where $msgs$ are all the previous messages of the protocol, $cert_A = \{A, pk(A), \ldots\}_{\mathsf{inv}(\mathsf{pk}(s))}$ is a public key certificate, and $hash$, prf, $clientK$, $serverK$ are hash functions.
Consider also the transmission of a payload with the created keys:

$$
\begin{array}{lrl}
 & A \rightarrow B: & \{|Payload_A|\}_{clientK(NA,NB,prf(PMS,NA,NB))} \\
 & B \rightarrow A: & \{|Payload_B|\}_{serverK(NA,NB,prf(PMS,NA,NB))} \\
\hline
Goal: & A \bullet\!\!\rightarrow\!\!\bullet B: & Payload_A \\
 & B \bullet\!\!\rightarrow\!\!\bullet A: & Payload_B
\end{array}
$$

TLS

$$
\begin{array}{rl}
A \to B : & A, NA, Sid, PA \\
B \to A : & NB, Sid, PB, cert_B \\
A \to B : & cert_A, \{PMS\}_{\mathsf{pk}(B)}, \{hash(NB, B, PMS)\}_{\mathsf{inv}(PK)}, \\
 & \{\!|hash(prf(PMS, NA, NB), msgs)|\!\}_{clientK(NA,NB,prf(PMS,NA,NB))} \\
B \to A : & \{\!|hash(prf(PMS, NA, NB), msgs)|\!\}_{serverK(NA,NB,prf(PMS,NA,NB))}
\end{array}
$$

- While a trustworthy server certificate is (not too un-) realistic, users usually do not have a client certificate!

TLS

$$
\begin{array}{ll}
A \to B: & A, NA, Sid, PA \\
B \to A: & NB, Sid, PB, cert_B \\
A \to B: & PK, \{PMS\}_{\mathrm{pk}(B)}, \{hash(NB, B, PMS)\}_{\mathrm{inv}(PK)}, \\
 & \{\!|hash(prf(PMS, NA, NB), msgs)|\!\}_{clientK(NA,NB,prf(PMS,NA,NB))} \\
B \to A: & \{\!|hash(prf(PMS, NA, NB), msgs)|\!\}_{serverK(NA,NB,prf(PMS,NA,NB))}
\end{array}
$$

- While a trustworthy server certificate is (not too un-) realistic, users usually do not have a client certificate!
- We model now that B has no way to authenticate A's public key:
- A simply generates a fresh public key PK
- What kind of channel do we get from this?

TLS

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A \to B: & PK, \{PMS\}_{\mathsf{pk}(B)}, \{hash(NB, B, PMS)\}_{\mathsf{inv}(PK)}, \\
& \{\!|hash(prf(PMS, NA, NB), msgs)|\!\}_{clientK(NA,NB,prf(PMS,NA,NB))} \\
B \to A: & \{\!|hash(prf(PMS, NA, NB), msgs)|\!\}_{serverK(NA,NB,prf(PMS,NA,NB))}
\end{array}
$$

- While a trustworthy server certificate is (not too un-) realistic, users usually do not have a client certificate!
- We model now that B has no way to authenticate A's public key:
- A simply generates a fresh public key PK
- What kind of channel do we get from this?
- The intruder can impersonate the client A towards B.
- But we still get something like a secure channel:
  - ★ B has a secure channel with the owner of PK, i.e., whoever knows $\mathsf{inv}(PK)$!
  - ★ Is is just not proved that this owner is A.

Secure Pseudonymous Channels

- Consider the public key $\mathsf{pk}(A)$ of agent A as a pseudonym of A.
- The link between A and $\mathsf{pk}(A)$ can be achieved by certificates.
- One can create any number of public keys/pseudonyms, which are a priori unlinkable to the creator/owner.
- One can authenticate as the owner of a pseudonym P by signing with $\mathsf{inv}(P)$.
- The pseudonym P cannot be stolen/hijacked because ownership is the knowledge of $\mathsf{inv}(P)$.

Secure Pseudonymous Channels

- Without authentication of the client, we can obtain secure channels with respect to a pseudonym.
- For the example of TLS w/o client authentication, we denote this as follows:

$$
\begin{array}{rrl}
 & \dots & \\
 & A \to B : & \{\!|Payload_A|\!\}_{clientK(NA,NB,prf(PMS,NA,NB))} \\
 & B \to A : & \{\!|Payload_B|\!\}_{serverK(NA,NB,prf(PMS,NA,NB))} \\
\hline
Goal: & [A] \bullet\!\!\to\!\!\bullet\, B : & Payload_A \\
 & B \bullet\!\!\to\!\!\bullet\, [A] : & Payload_B
\end{array}
$$

This is sometimes called sender/receiver invariance: B cannot be sure about A's real identity, but that it is the same entity in several transmissions (namely the owner of a certain key pair).

Good enough . . .

This kind of channel is good enough for many applications such as transmitting credit card data:

[A] $\bullet\!\!\rightarrow\!\!\bullet$ B : Order & Credit Card Data

The intruder can also make orders, or, as a dishonest merchant B receive credit card data, but cannot see the credit card data from an honest A sent to an honest B.
Example: B is a movie-server, we can ensure that the content is delivered to the paying customer (who sent the credit card data):

B $\bullet\!\!\rightarrow\!\!\bullet$ [A]: The-Movie

This does not prevent a dishonest A from sharing the movie with her friends, of course.

Good enough ...

The secure pseudonymous channel is also good enough for a login protocol:

$$\begin{array}{rrl} & [A] \bullet\!\!\rightarrow\!\!\bullet B : & A, password(A, B) \\ & B \bullet\!\!\rightarrow\!\!\bullet [A] : & Payload \\ \hline Goal : & B \bullet\!\!\rightarrow\!\!\bullet A : & Payload \end{array}$$

where $password(A, B)$ is A's password at server B.

- We establish a "classical" secure channel in two steps:
  1. We establish a secure pseudonymous channel $[A] \bullet\!\!\rightarrow\!\!\bullet B$ using TLS without client authentication.
  2. We use this channel to authenticate the client by a shared secret (which possibly has low entropy).
- Further replies (e.g. the data of client A stored on server B) are bound to this authentication.

Other realizations & applications

- Purpose-built keys (PBK): in mobile IP, a device creates a public key when entering a domain, so one can later prove to be the same device when leaving the domain.
- Protocol between a smart card and a card reader:
  - ★ The card is initially not authenticated.
  - ★ But an intruder cannot interfere between card and card reader.
  - ★ Thus $[Card] \bullet\!\!\rightarrow\!\!\bullet\, CardReader$ is an appropriate model of the communication channel!

Cryptographic Model of Secure Pseudonymous Channels

We can extend our cryptographic model to secure pseudonymous channels:

Definition

$$
\begin{array}{cccccccccc}
[A]_P & \bullet\!\!\rightarrow & B: & M & \text{for} & A & \rightarrow & B: & \{\mathsf{atag}, B, M\}_{\mathsf{inv}(P)} \\
A & \rightarrow\!\!\bullet & [B]_P: & M & \text{for} & A & \rightarrow & B: & \{\mathsf{ctag}, M\}_P \\
[A]_P & \bullet\!\!\rightarrow\!\!\bullet & B: & M & \text{for} & A & \rightarrow & B: & \{\{\mathsf{stag}, B, M\}_{\mathsf{inv}(P)}\}_{\mathsf{ck}(B)} \\
A & \bullet\!\!\rightarrow\!\!\bullet & [B]_P: & M & \text{for} & A & \rightarrow & B: & \{\{\mathsf{stag}, P, M\}_{\mathsf{inv}(\mathsf{ak}(A))}\}_P
\end{array}
$$

where we explicitly annotate the pseudonym/public-key P being used. By default, we have a fresh public-key P for every protocol session and agent.

Channels out of thin air?

- TLS is an example for another rule for the channel calculus: From $A {\rightarrow}\!\bullet B$ we can get $[A] \bullet\!{\rightarrow}\!\bullet B$ (but not $A \bullet\!{\rightarrow}\!\bullet B$!)
- In general we can make secure channels with unauthenticated endpoints:
  - ★ From $A \rightarrow B$ we can get $[A] \bullet\!{\rightarrow}\!\bullet [B]$.
- We get this out of thin air, but it is only giving a weak property: sender/receiver invariance (we can be sure that we talk to the same end-point).
- This channel can easily be over-estimated as the following attack shows...

TLS Renegotiation Attack

A TLS Renegotiation Scenario

- When participants have established a TLS connection where the client is not authenticated
- The client issues a command that requires authentication
- Renegotiation: Run a new TLS handshake over the existing channel, producing new keys.
- After successful handshake, switch to the new keys.
- Now the server executes the command.

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In Channel Notation:

- $[A] \bullet\!\!\to\!\!\bullet\ B$: critical command
- $B \bullet\!\!\to\!\!\bullet\ [A]$: require re-negotiate with client auth
- $[A] \bullet\!\!\leftrightarrow\!\!\bullet\ B$: $\boxed{\text{TLS-Handshake with client auth}}$
- B : execute command

Attack

- $[a(i)] \bullet\!\!\rightarrow\!\!\bullet\, b$: critical command
- $b \bullet\!\!\rightarrow\!\!\bullet [a(i)]$: require re-negotiate with client auth
- $a \leftrightarrow [a(i)] \bullet\!\!\leftrightarrow\!\!\bullet D$: $\boxed{\text{TLS-Handshake with client auth}}$
  - ★ The real a wants to start a session with b, the intruder relays every message from a into his channel with b and vice versa.
- b : execute command
  - ★ Even though a has never issued the command.

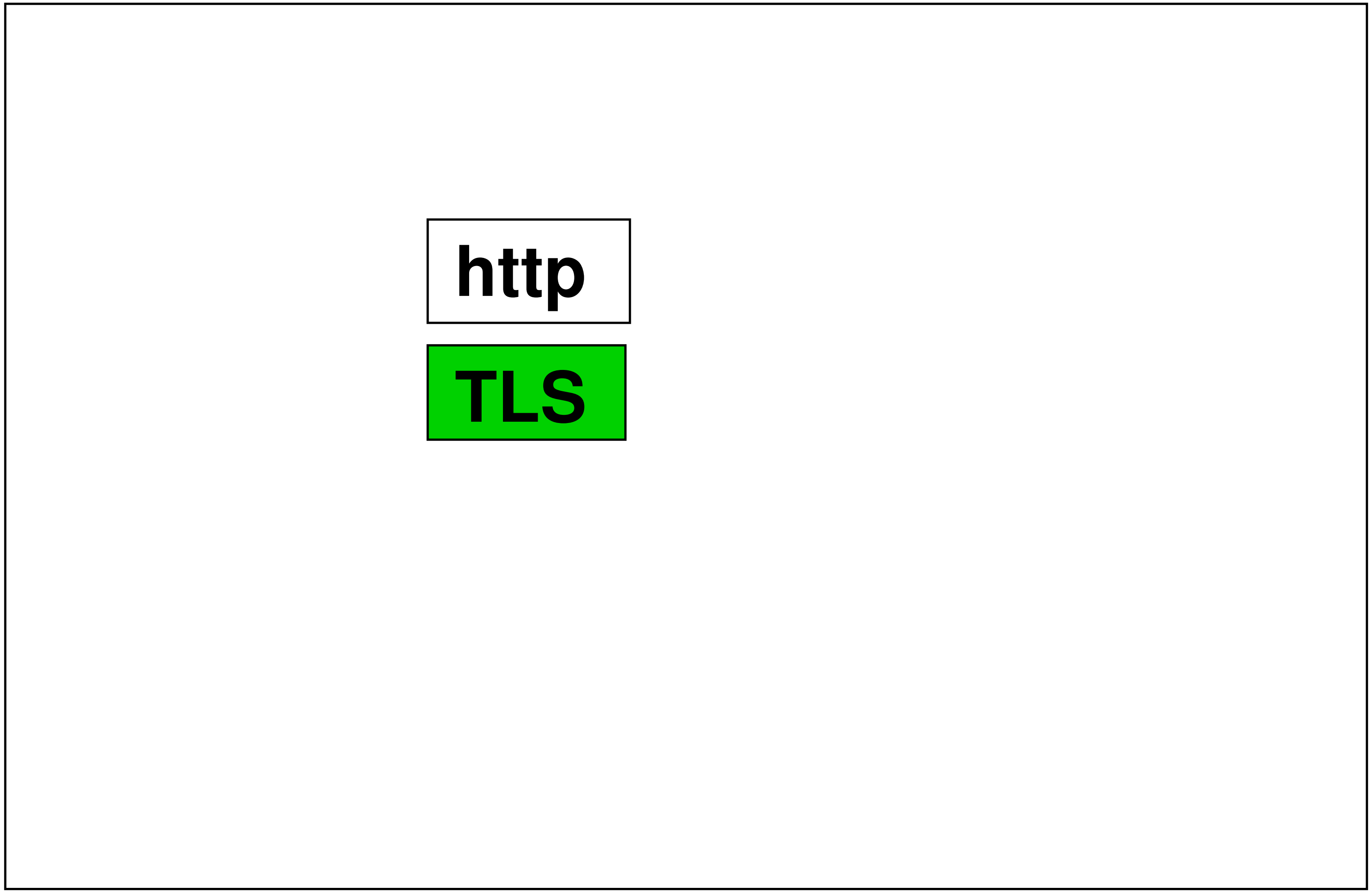
Similar for standard TLS channels (without client authentication) where the intruder is just able to *prefix* a session.

General Problem

The re-negotiation gives no guarantee on messages exchanged before the re-negotiation.

In fact, this is not really a fault of TLS, but the way it is deployed!

Example of Horizontal and Vertical Composition



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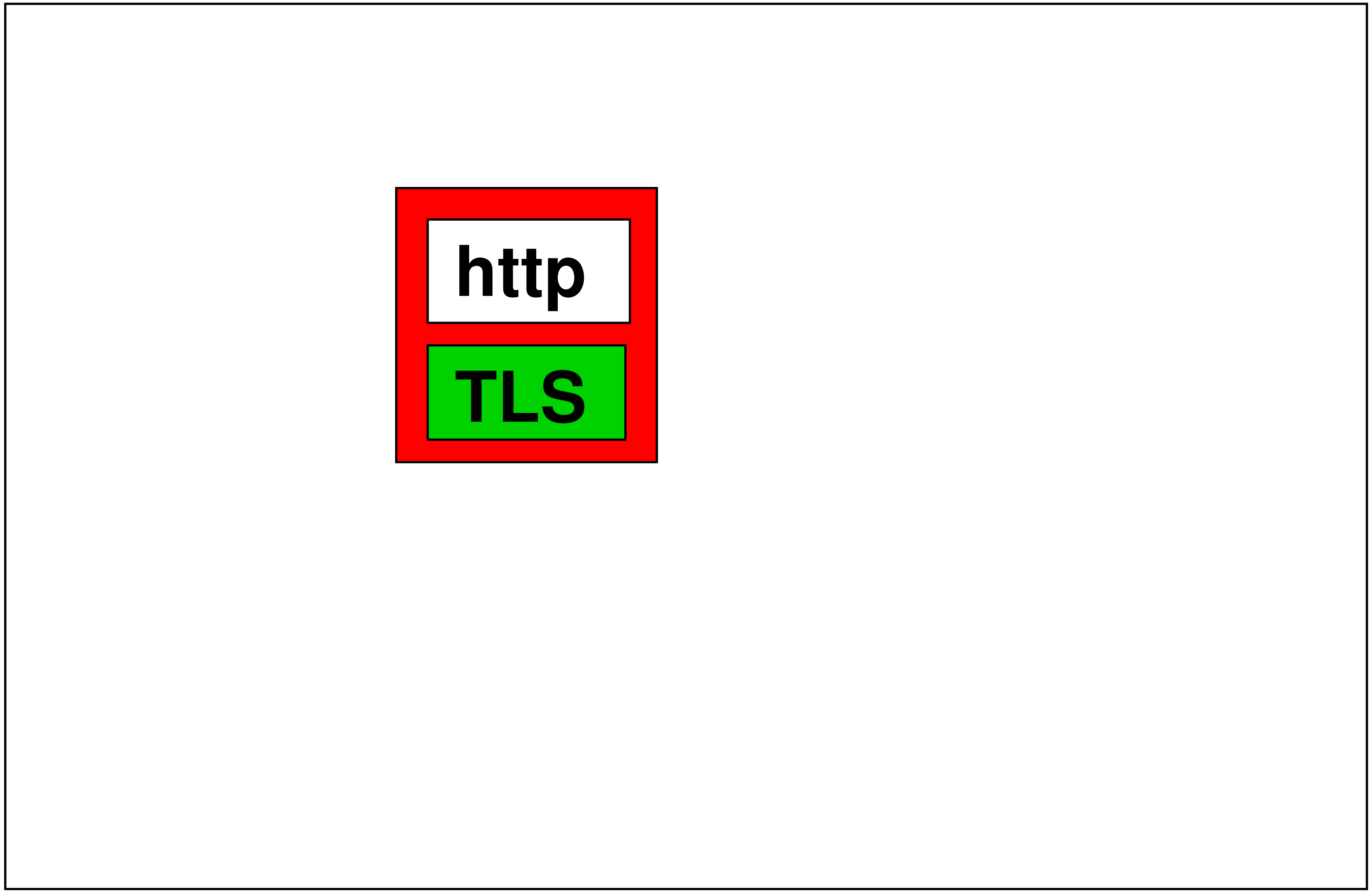

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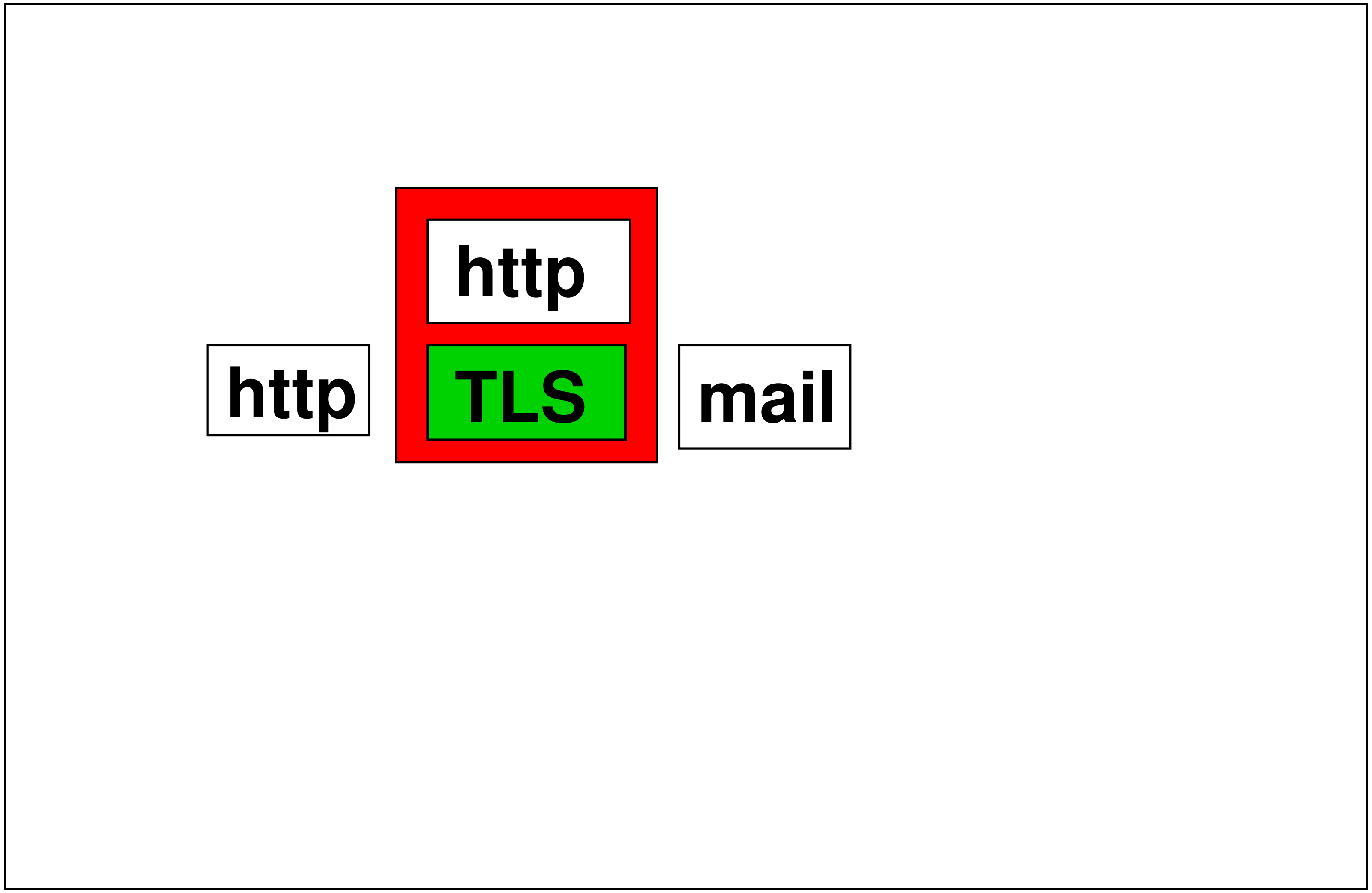

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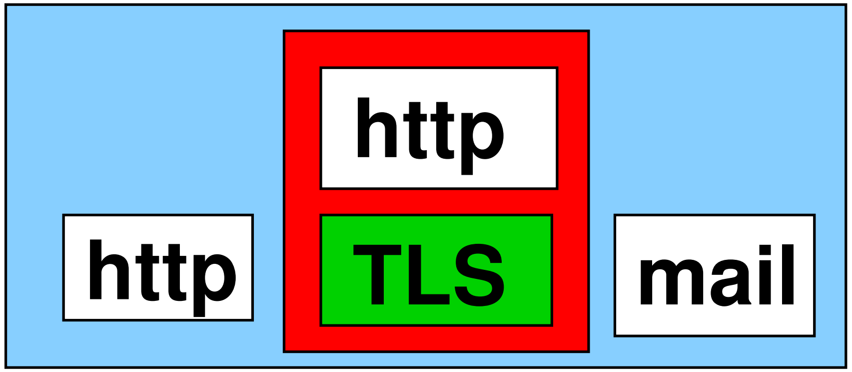

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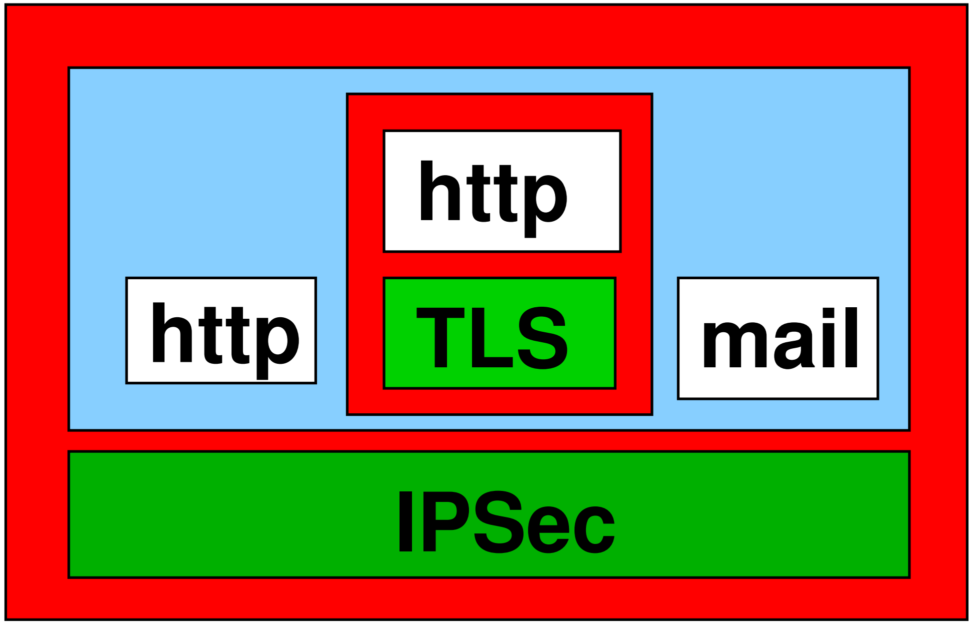

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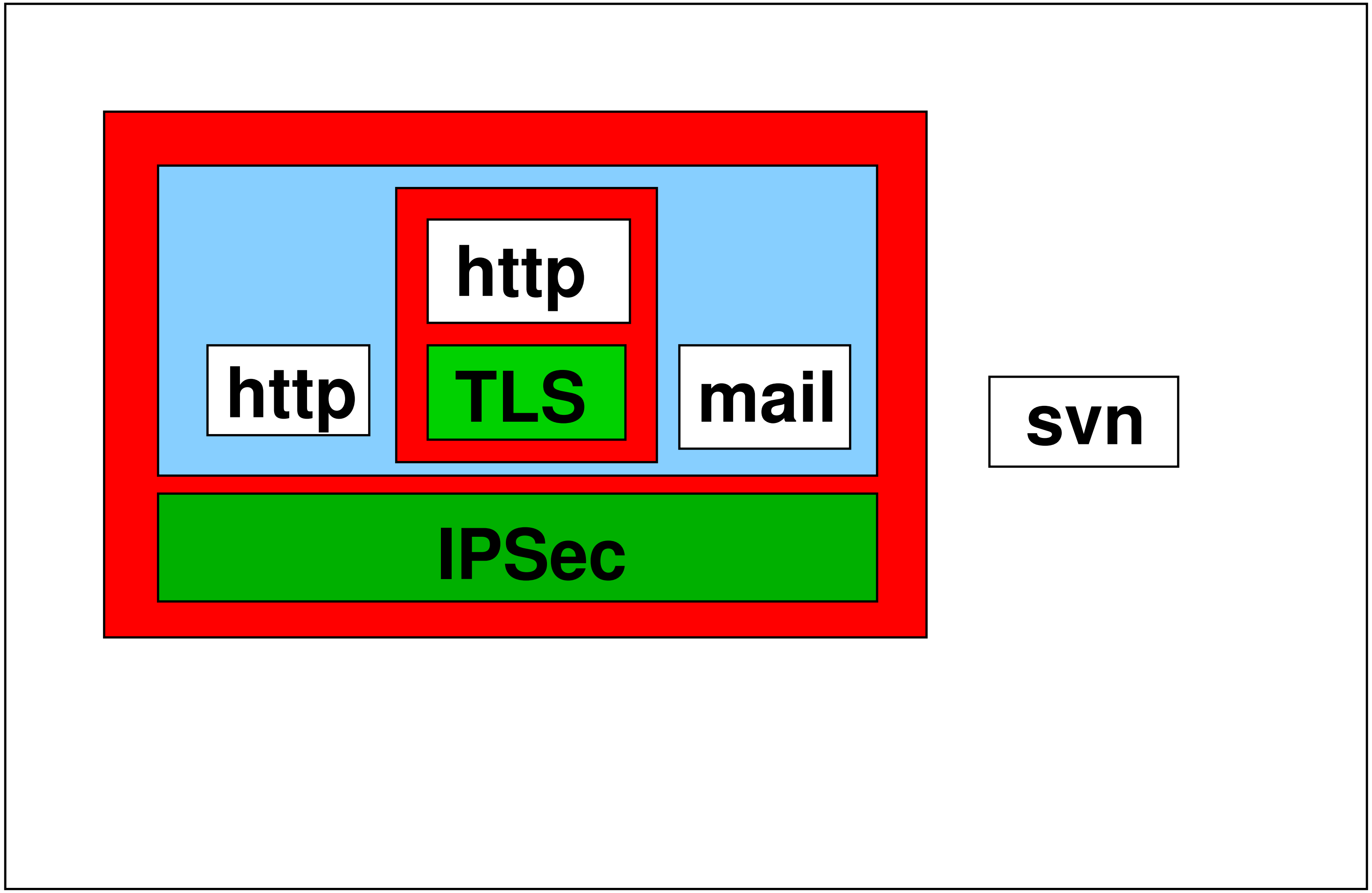

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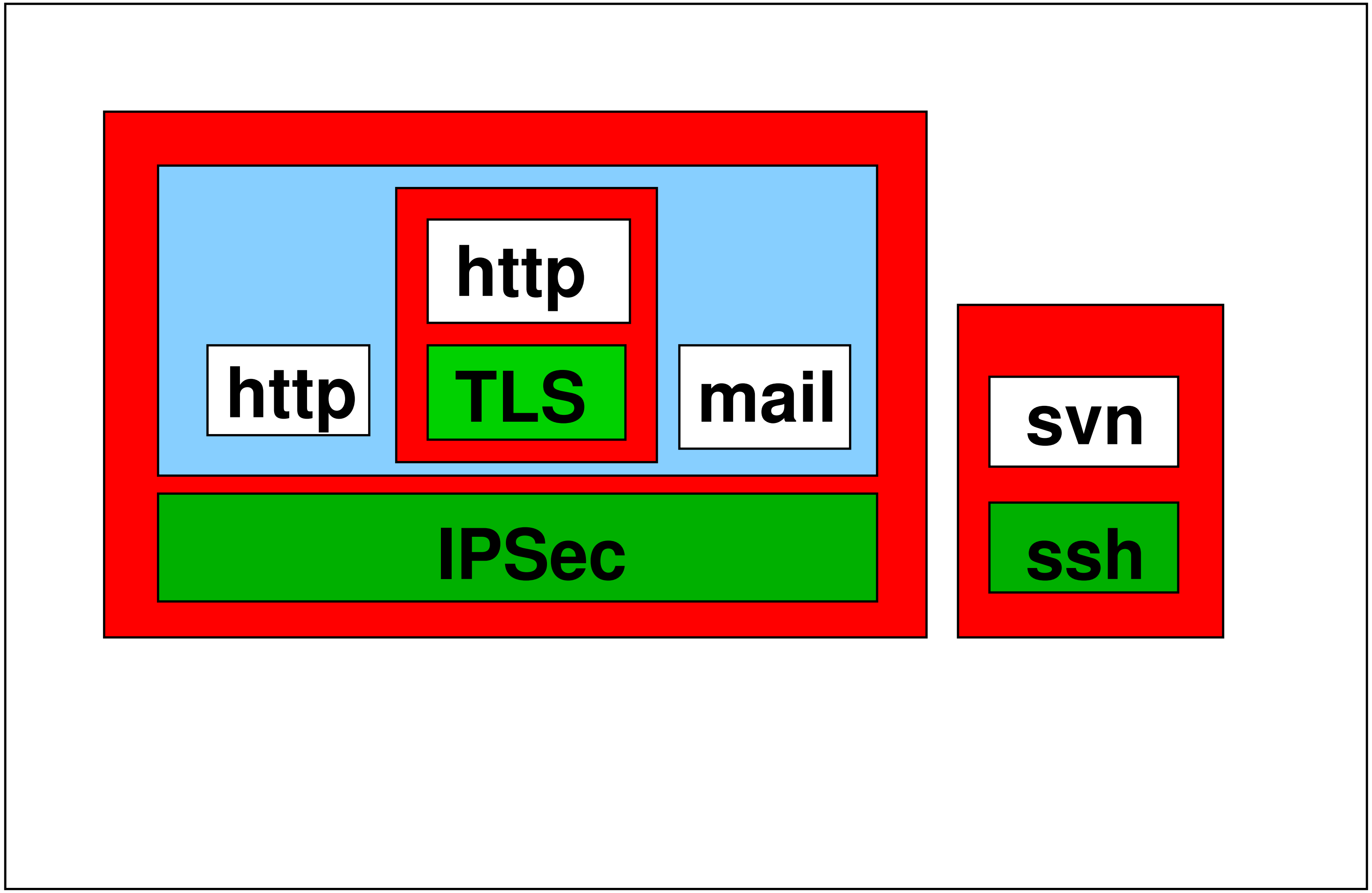

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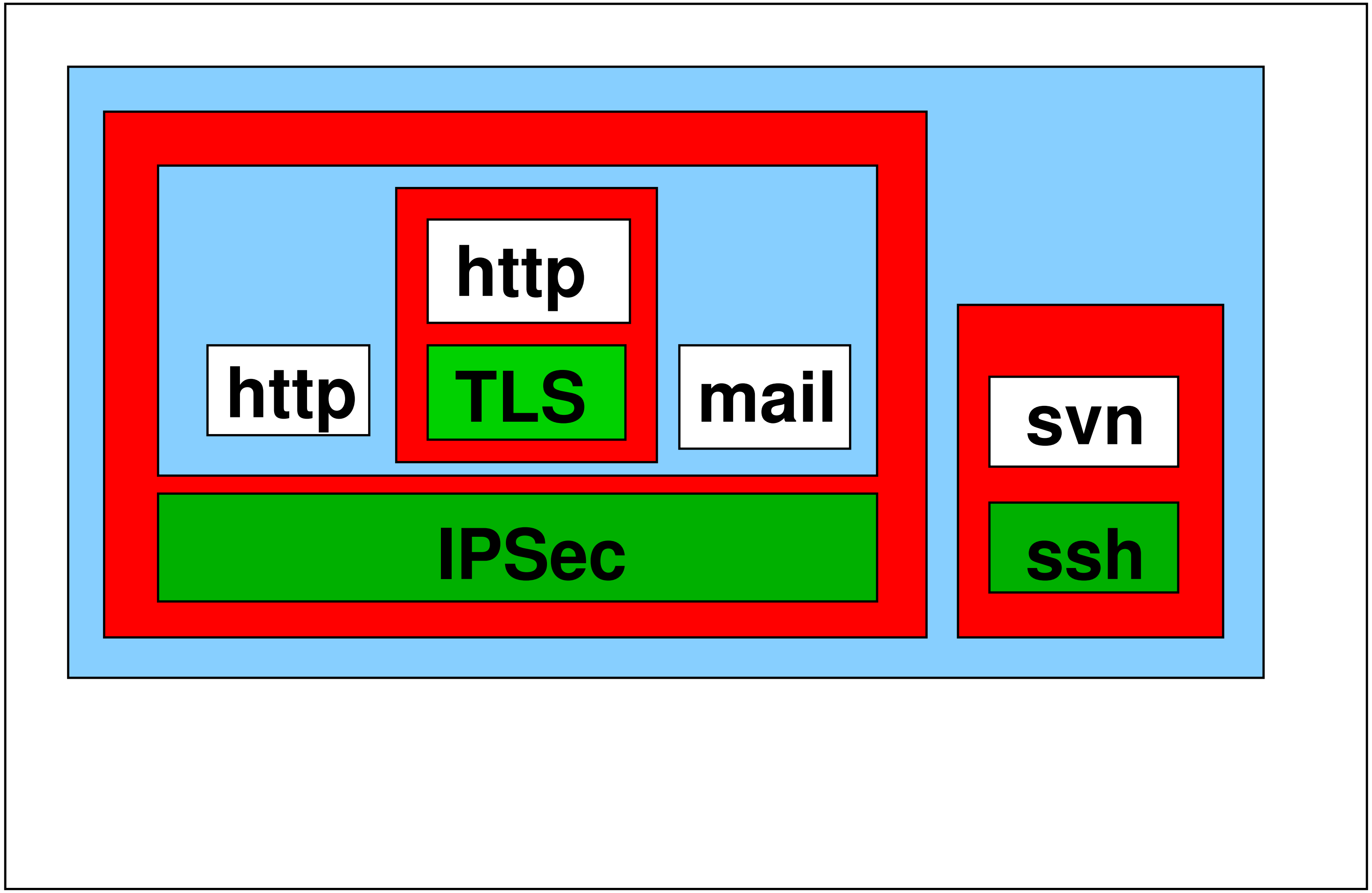

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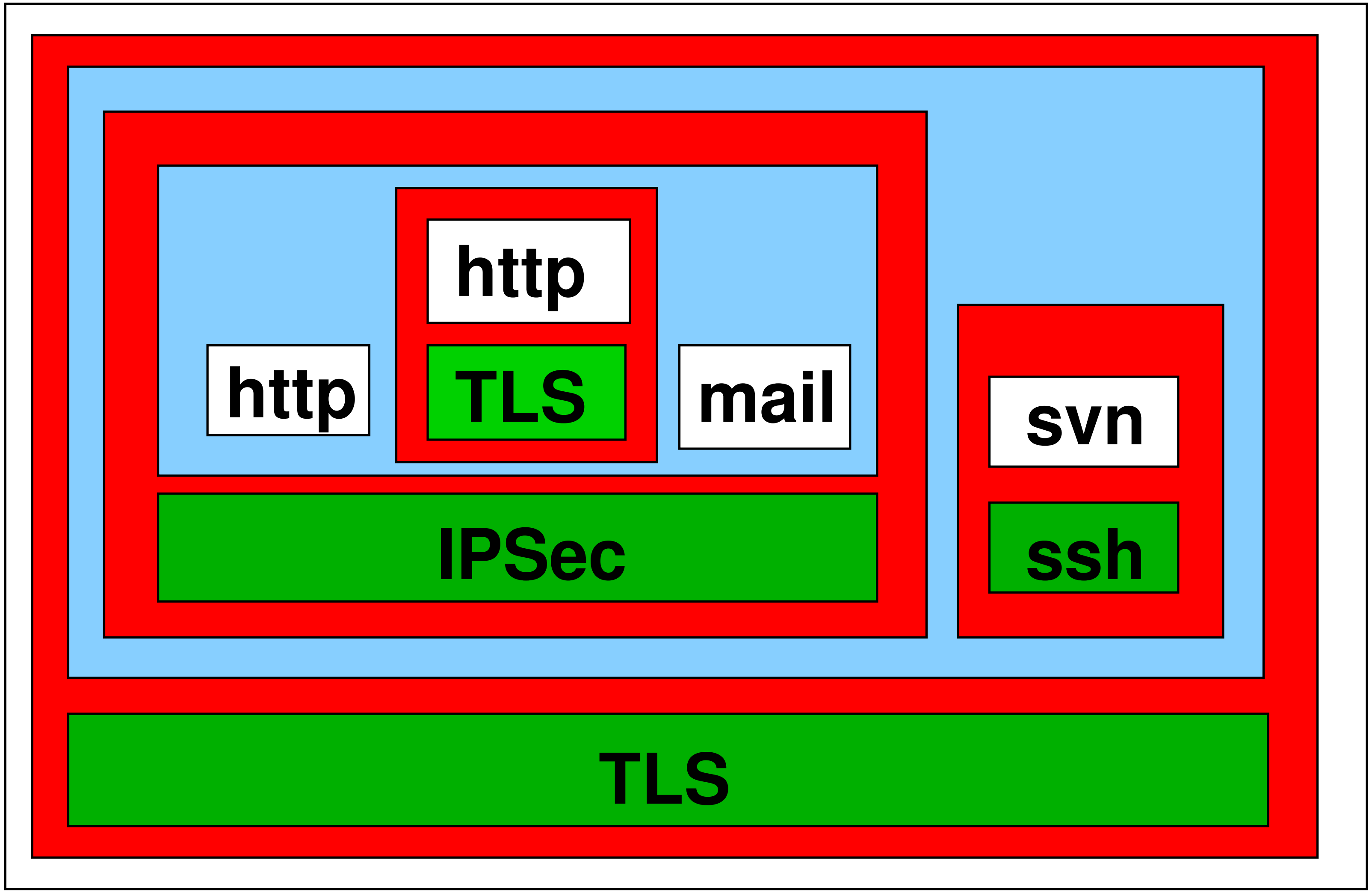

Is this secure?

Compositionality in General

- Design and analyze/verify small systems in isolation.
- Compose them to a secure system using compositionality results
- Ideally, the designer of an application does not need to worry about security—it follows from composition with a security layer
- Can we really achieve this ideal situation?
  - ★ The designer needs to understand what properties a secure channel gives (and which not).
  - ★ Problem: endpoints may still be dishonest and try to attack on the application layer (e.g. injection)
- However, systematic verified solutions tend to reduce the vulnerabilities.