Data Is a Stream

Security of Stream-Based Channels

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joint work with Marc Fischlin, Giorgia Azzurra Marson, and Kenneth G. Paterson

Secure Communication Needs Secure Channels

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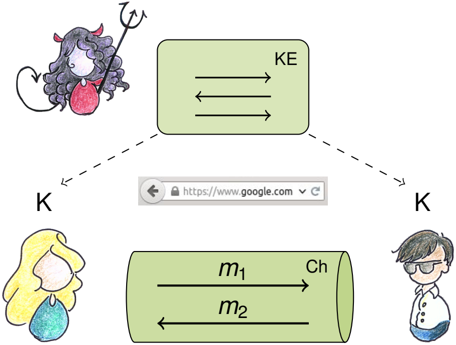
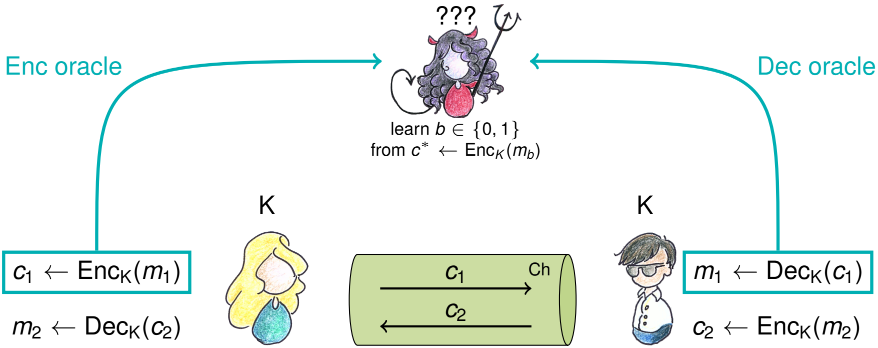


What's that secure channel precisely?

drawings by *Giorgia Azzurra Marson*

On the Origin of Channel Models

Encryption



IND-CPA
(Goldwasser, Micali 1984)

IND-CCA
(Naor, Yung 1990), (Rackoff, Simon 1991)

More formally...

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IND-CPA Security

$\mathsf{Expt}^{\text{IND-CPA}}_{\mathcal{E},\mathcal{A}}(1^n)$:

1. $K \leftarrow_\$ \mathsf{KGen}(1^n)$, $b \leftarrow_\$ \{0,1\}$
2. $b' \leftarrow_\$ \mathcal{A}(1^n)^{\mathcal{O}_{\text{LoR}}(K,\cdot,\cdot)}$
3. return $b = b'$

$\mathcal{O}_{\text{LoR}}(K, m_0, m_1)$ returns $\mathsf{Enc}(K, m_b)$, for $|m_0| = |m_1|$

IND-CCA Security

$\mathsf{Expt}^{\text{IND-CPA}}_{\mathcal{E},\mathcal{A}}(1^n)$:

1. $K \leftarrow_\$ \mathsf{KGen}(1^n)$, $b \leftarrow_\$ \{0,1\}$
2. $b' \leftarrow_\$ \mathcal{A}(1^n)^{\mathcal{O}_{\text{LoR}}(K,\cdot,\cdot),\mathcal{O}_{\text{Dec}}(K,\cdot)}$
3. return $b = b'$

$\mathcal{O}_{\text{Dec}}(K, c)$ returns $\mathsf{Dec}(K, c)$
as long as c not output by $\mathcal{O}_{\text{Enc}}$

$\mathcal{E}$ is IND-CPA/IND-CCA-secure iff $\left|\Pr\left[\mathsf{Expt}^{\text{IND-CPA/IND-CCA}}_{\mathcal{E},\mathcal{A}}(1^n) = 1\right] - \frac{1}{2}\right| \approx 0$

On the Origin of Channel Models

Integrity

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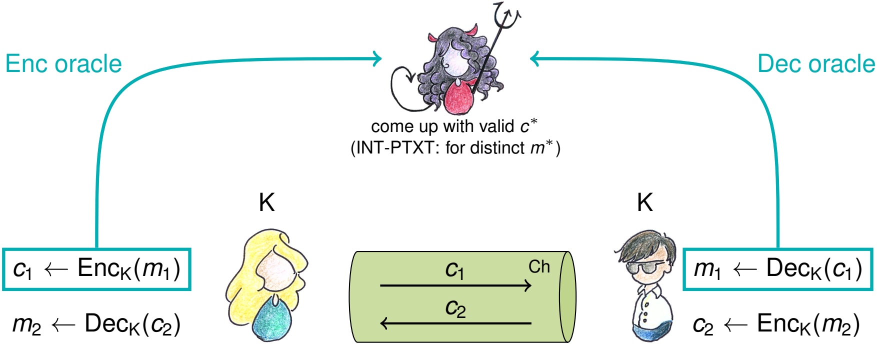

Authenticated Encryption

IND-CPA + INT-CTXT

($\Rightarrow$ IND-CCA)

INT-PTXT

(Bellare, Namprempre 2000)

INT-CTXT

(Bellare, Rogaway 2000)

More formally...

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INT-PTXT Security

$\mathrm{Expt}^{\text{INT-PTXT}}_{\mathcal{E},\mathcal{A}}(1^n)$:

1. $K \leftarrow_\$ \mathrm{KGen}(1^n)$
2. $\mathcal{A}(1^n)^{\mathcal{O}_{\mathrm{Enc}}(K,\cdot),\mathcal{O}_{\mathrm{Dec}}(K,\cdot)}$
3. return 1 if $\mathcal{A}$ queries c to $\mathcal{O}_{\mathrm{Dec}}$ s.t.
   - $\perp \neq m \leftarrow \mathcal{O}_{\mathrm{Dec}}(K, c)$
   - m was never queried to $\mathcal{O}_{\mathrm{Enc}}$

INT-CTXT Security

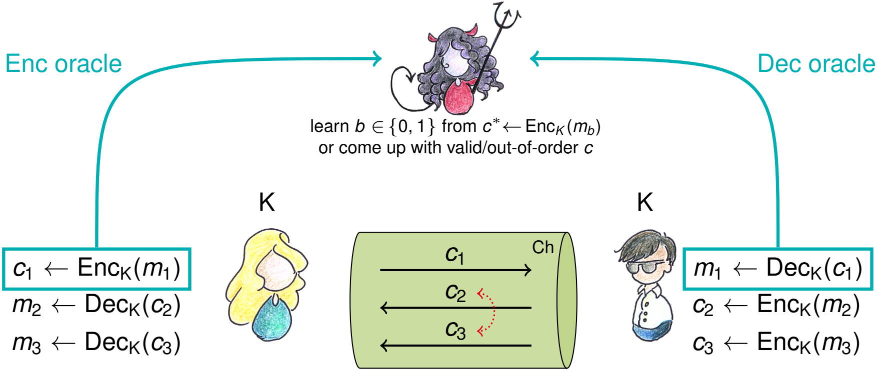
$\mathrm{Expt}^{\text{INT-CTXT}}_{\mathcal{E},\mathcal{A}}(1^n)$:

1. $K \leftarrow_\$ \mathrm{KGen}(1^n)$
2. $\mathcal{A}(1^n)^{\mathcal{O}_{\mathrm{Enc}}(K,\cdot),\mathcal{O}_{\mathrm{Dec}}(K,\cdot)}$
3. return 1 if $\mathcal{A}$ queries c to $\mathcal{O}_{\mathrm{Dec}}$ s.t.
   - $\perp \neq m \leftarrow \mathcal{O}_{\mathrm{Dec}}(K, c)$
   - c was never output by $\mathcal{O}_{\mathrm{Enc}}$

$\mathcal{E}$ is INT-PTXT/INT-CTXT-secure iff $\left|\Pr\left[\mathrm{Expt}^{\text{INT-PTXT/INT-CTXT}}_{\mathcal{E},\mathcal{A}}(1^n) = 1\right]\right| \approx 0$

On the Origin of Channel Models

Stateful Authenticated Encryption



Stateful Authenticated Encryption

used to analyze SSH

IND-sfCCA

(Bellare, Kohno, Namprempre 2002)

INT-sfCTXT

INT-sfPTXT

(Brzuska, Smart, Warinschi, Watson 2013)

More formally…

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IND-sfCCA Security

$\mathsf{Expt}^{\text{IND-sfCCA}}_{\mathcal{E},\mathcal{A}}(1^n)$:

1. $K \leftarrow_\$ \mathsf{KGen}(1^n)$, $b \leftarrow_\$ \{0,1\}$
2. $i, j \leftarrow 0$, $\mathsf{sync} \leftarrow 1$
3. $b' \leftarrow_\$ \mathcal{A}(1^n)^{\mathcal{O}_{\mathsf{LoR}}(K,\cdot,\cdot),\mathcal{O}_{\mathsf{Dec}}(K,\cdot)}$
4. return $b = b'$

$\mathcal{O}_{\mathsf{LoR}}(K, m_0, m_1)$:

1. $i \leftarrow i + 1$
2. return $c_i \leftarrow \mathsf{Enc}(K, m_b)$

$\mathcal{O}_{\mathsf{Dec}}(K, c)$:

1. $j \leftarrow j + 1$
2. if $j > i$ or $c \neq c_j$, then $\mathsf{sync} \leftarrow 0$
3. if $\mathsf{sync} = 0$, return $m \leftarrow \mathsf{Dec}(K, c)$

INT-sfCTXT Security

$\mathsf{Expt}^{\text{INT-sfCTXT}}_{\mathcal{E},\mathcal{A}}(1^n)$:

1. $K \leftarrow_\$ \mathsf{KGen}(1^n)$
2. $i, j \leftarrow 0$, $\mathsf{sync} \leftarrow 1$, $\mathsf{win} \leftarrow 0$
3. $\mathcal{A}(1^n)^{\mathcal{O}_{\mathsf{Enc}}(K,\cdot),\mathcal{O}_{\mathsf{Dec}}(K,\cdot)}$
4. return win

$\mathcal{O}_{\mathsf{Enc}}(K, m)$:

1. $i \leftarrow i + 1$
2. return $c_i \leftarrow \mathsf{Enc}(K, m)$

$\mathcal{O}_{\mathsf{Dec}}(K, c)$:

1. $j \leftarrow j + 1$, $m \leftarrow \mathsf{Dec}(K, c)$
2. if $j > i$ or $c \neq c_j$, then $\mathsf{sync} \leftarrow 0$
3. if $\mathsf{sync} = 0$ and $m \neq \perp$, then $\mathsf{win} \leftarrow 1$

On the Origin of Channel Models

(Stateful) Authenticated Encryption+

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- Authenticated Encryption with **Associated Data** (Rogaway 2002) — AEAD
  - ciphertext carries additional unencrypted, but authenticated data field

- **Length-Hiding** Authenticated Encryption (with AD) (Paterson, Ristenpart, Shrimpton 2011) — LH-AEAD
  - hides message length up to some granularity (padding)
  - used to analyze TLS record layer (within ACCE framework)

Stateful Length-Hiding Authenticated Encryption

is the accepted security notion for channels to date, so we're done?

Attack on SSH

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Albrecht, Paterson, Watson 2009: **plaintext recovery attack against SSH**
(SSH Binary Packet Protocol with CBC-mode Encode-then-Encrypt&MAC)

- basic idea:
  - packet length field encrypted in first ciphertext block
  - MAC verification depends on decrypted length value
  - adversary feeds ciphertext in *block-wise* (via TCP fragmentation)
  - observable MAC failure leaks content of length field
  - put arbitrary ciphertext block as first block to leak $|\text{len}|$ bits
- clearly breaks confidentiality

Wait. . .

- SSH was proven IND-sfCCA and INT-sfCTXT secure! (BKN 2002)
- . . . but these only allow *atomic* ciphertexts in Dec oracle

Boldyreva, Degabriele, Paterson, Stam 2012:

Symmetric Encryption Supporting Fragmentation

- general security model for ciphertext fragmentation
- security notion: IND-sfCFA (chosen-fragment attack)
  - standard Enc algorithm (and left-or-right oracle)
  - Dec algorithm obtains ciphertext fragments, outputs messages separated with ¶
  - (focuses on confidentiality)

Are we there yet?

Attacks on TLS

Truncating Connections and Cutting Cookies

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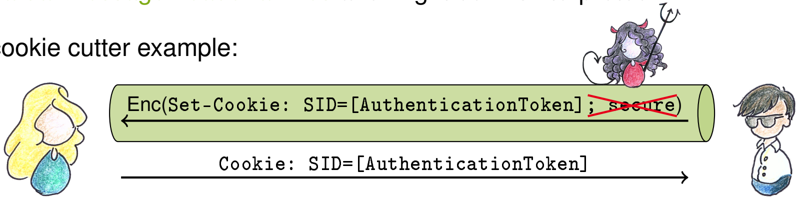
Smyth, Pironti 2013: **truncation attack**

- attacker truncates TLS connection by closing underlying TCP connection
- thereby drops (parts of) messages, potentially corrupting web application logic

Bhargavan, Delignat-Lavaud, Fournet, Pironti, Strub 2014: **cookie cutter attack**

- attacker forces part of the HTTP header (e.g., cookie) to be cut off
- partial message/header arrives and might be misinterpreted
- cookie cutter example:



Wait... deleting message parts within ciphertext—how can this be possible?

Cookie Cutter Attack

A Closer Look

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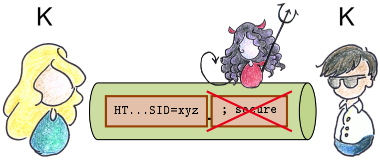
$c \leftarrow$ Enc(`HTTP/1.1 200 OK`

```
    ...
    Set-Cookie: SID=xyz; secure
```
)




```
#include <openssl/ssl.h>
SSL_write("HTTP/1.1 200 OK
        ...
        Set-Cookie: SID=xyz; secure")
```

```
HTTP/1.1 200 OK
...
Set-Cookie: SID=xyz
```

2 TLS records

HTTP/1.1 200 OK ... Set-Cookie: SID=xyz	; secure

adversary can potentially enforce this split at any point
$\rightarrow$ receiver sees arbitrary message fragmentation

Data Is a Stream!

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- That behavior is actually okay—and specified:

  > *6.2.1. Fragmentation*
  > *The record layer fragments information blocks into TLSPlaintext records [...]. Client* ***message boundaries are not preserved*** *in the record layer (i.e., multiple client messages of the same ContentType MAY be coalesced into a single TLSPlaintext record, or a single message MAY be fragmented across several records).*
  >
  > RFC 5246 TLS v1.2

- TLS never promised to treat messages atomically!

- au contraire: 2^{14} bytes maximum message length will lead to fragmentation
- some implementations don't even guarantee to send at all on `SSL_write`, but have a separate `flush` command (e.g., MS.NET)

Data Is a Stream!

. . . and TLS is not alone

- many important channel protocols treat data as a stream
  - TLS
  - SSH tunnel-mode
  - QUIC
- meant as secure drop-in replacement for TCP (which works on streams)
- channel models so far don't capture this behavior exposed to the application

Stream-Based Channels
Overview & Syntax

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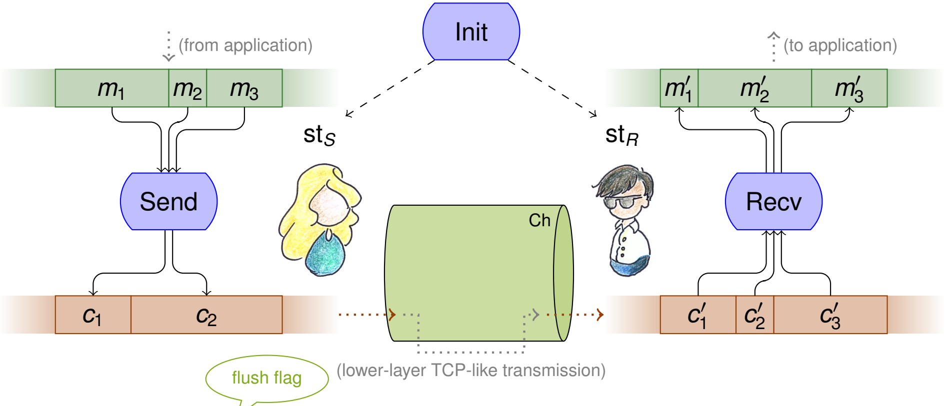
$$\mathsf{Init}(1^n) \to \mathsf{st}_S \in \mathcal{S}_S, \mathsf{st}_R \in \mathcal{S}_R$$

$(K \in \mathsf{st}_S/\mathsf{st}_R)$



$\mathsf{Send}(\mathsf{st}_S, m \in \{0,1\}^*, f \in \{0,1\}) \to c \in \{0,1\}^*$ $\quad$ $\mathsf{Recv}(\mathsf{st}_R, c \in \{0,1\}^*) \to m \in \{0,1\}^* \cup \mathcal{E}$

Stream-Based Channels
Properties

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- no particular input/output behavior stipulated on sender side
  - allow for buffering (e.g., optimization for lower layer)
    output c can even be empty
  - `flush` command modeled with flush flag $f \in \{0,1\}$
    $f = 1 \Rightarrow$ all message fragments sent out instantaneously

Correctness

$$\text{if } ||\mathbf{c} = ||\mathbf{c}' \text{ then } ||\mathbf{m}[1,\ldots,i] \prec ||\mathbf{m}' \prec ||\mathbf{m}$$

received message stream is **prefix** of sent stream

received message stream contains **everything upto last flush**

for
- sent/received ciphertext (fragments) $\mathbf{c}/\mathbf{c}'$
- sent/received message fragments $\mathbf{m}/\mathbf{m}'$
- i-th Send the last flushing call ($f = 1$)

Stream-Based Channels

Confidentiality

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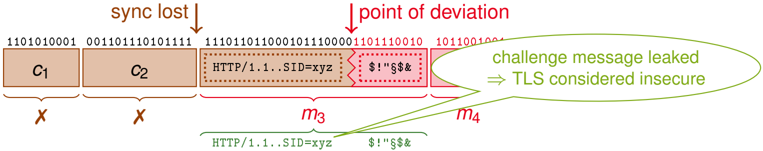
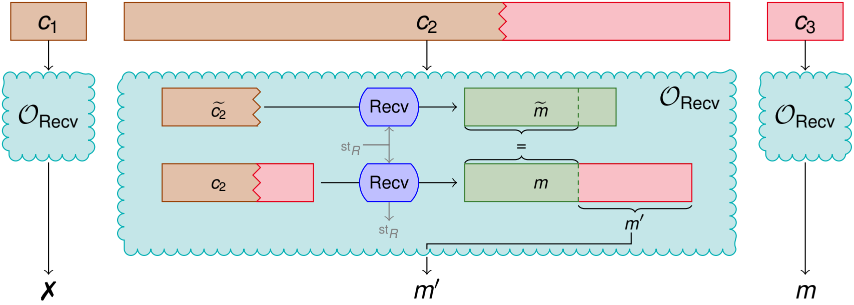
- **CP(F)A** case straightforward: left-or-right oracle allowing to control flush flag
- **CC(F)A** case more complex:
  - general idea: allow as much decryption as possible, but no trivial attacks
  - Bellare-Kohno-Namprempre approach: Recv oracle $\mathcal{O}_{\mathsf{Recv}}$ can be in/out of sync
    - in sync (original ciphertext stream): no output
    - out of sync (deviation from original stream): Recv output given to adversary
  - But where exactly shall $\mathcal{O}_{\mathsf{Recv}}$ / ciphertext stream be considered out-of-sync?
    - BDPS 2012: at ciphertext boundaries



Stream-Based Channels

Confidentiality

- key insight: there is no inherent structure on a stream!
  - think: Send generates ciphertext stream as “message stream $\oplus$ keystream”
- $\mathcal{O}_{\text{Recv}}$ behavior
  - in-sync / already out-of-sync cases as always: output nothing / everything
  - loosing sync: strip longest common prefix with output of genuine ciphertext part



Stream-Based Channels
Integrity

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(first consideration of integrity in non-atomic setting)

- **INT-PST:** plaintext-stream integrity
  no adversary can make received message stream deviate from sent stream

$m' \notin \mathcal{E}^* \Rightarrow \mathcal{A}$ succeeds

- **INT-CST:** ciphertext-stream integrity
  no adversary can make message bits being output after point of deviation

$m' \notin \mathcal{E}^* \Rightarrow \mathcal{A}$ succeeds

consider output beyond longest common prefix with genuine part output (like for confidentiality)

! stream-based confidentiality/integrity allow (genuine) **“partial message” output**
(would be considered as breaking security in atomic (and BDPS 2012) setting)

Relations & Composition Result

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Classic implications hold:

- IND-CCFA $\Rightarrow$ IND-CPFA
- INT-CST $\Rightarrow$ INT-PST

Classic composition result: IND-CPA + INT-CTXT $\Rightarrow$ IND-CCA (BN 2000)

- idea: when $\mathcal{A}$ gets any $\mathcal{O}_{\mathsf{Recv}}$ output, it broke integrity; let $\mathcal{B}$ always return $\perp$
- multi-error setting: need additional “error invariance” property (BDPS 2013)

  at most one error with non-negl. probability

- composition in stream-based setting:
  IND-CPFA + INT-CST $\Rightarrow$ IND-CCFA
  - inherently “multi-error”: Recv output on deviating ciphertext can be $\perp$ *or* empty
  - we require predictability of errors by an efficient algorithm (given sent/received ciphertext stream and next ciphertext fragment)
  - sounds strong, but is achievable by natural constructions
  - also extends to atomic setting with multiple non-negligible errors

Generic Construction

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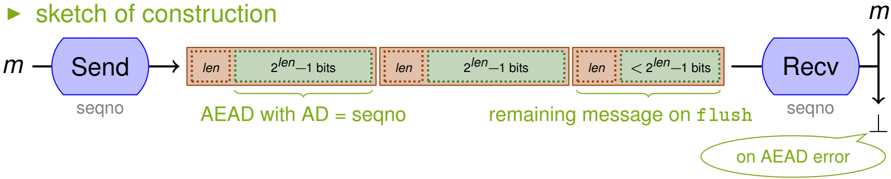
- secure stream-based channels can be built
  - based on authenticated encryption with associated data (AEAD)
  - achieving strong IND-CCFA confidentiality
  - achieving strong INT-CST integrity
- sketch of construction



- example scheme satisfying error predictability (composition theorem used)
  unencrypted length field allows to predict when error $\perp$ is output
- close to TLS record layer design using AEAD (providing some validation)
  - ✓ unsent sequence number as authenticated AD
  - ✓ sent length field, unauthenticated (in TLS 1.3)
  - ✗ TLS additionally includes: version number, content type (sent + authenticated)

Summary

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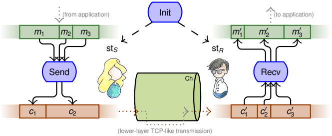
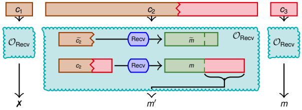
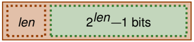
Data is a stream!

We

- formalize stream-based channels
- give adequate security notions and a composition result
- provide an AEAD-based construction







Ongoing / Future Work

- explore exact relation between atomic and stream-based notions
- what is length-hiding on a stream?
- multiplexing several data streams into one channel
- how to safely encode atomic messages in a stream?

Thank You!

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