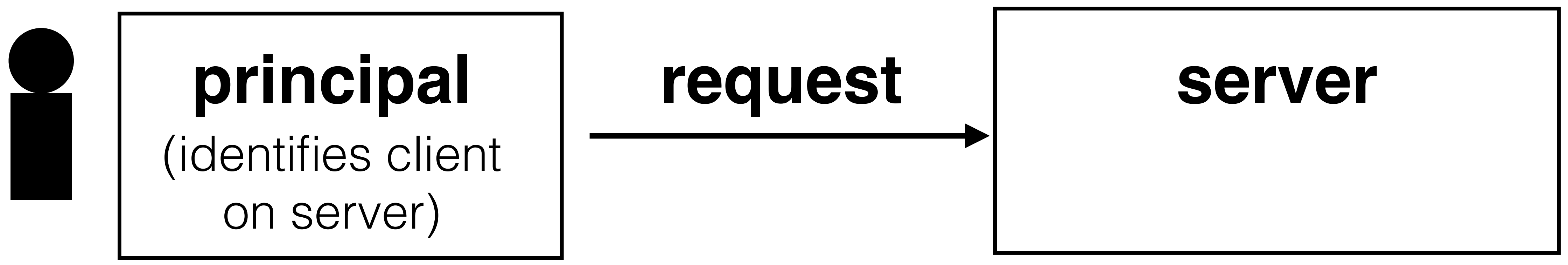
6.1800 Spring 2025

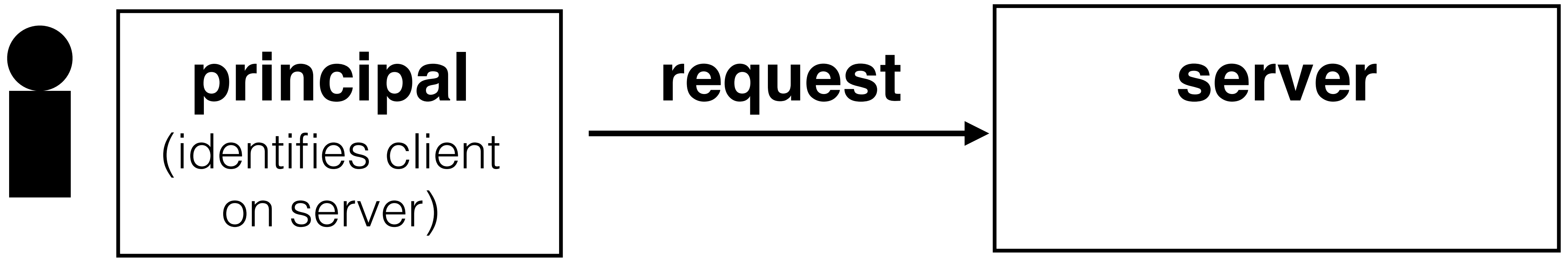
Lecture #23: Secure Channels

confidentiality and integrity through the magic of cryptography

Katrina LaCurts | lacurts@mit.edu | 6.1800 2025


principal
(identifies client on server)
request
server

so far, we've dealt with adversaries that were trying to access data on a server



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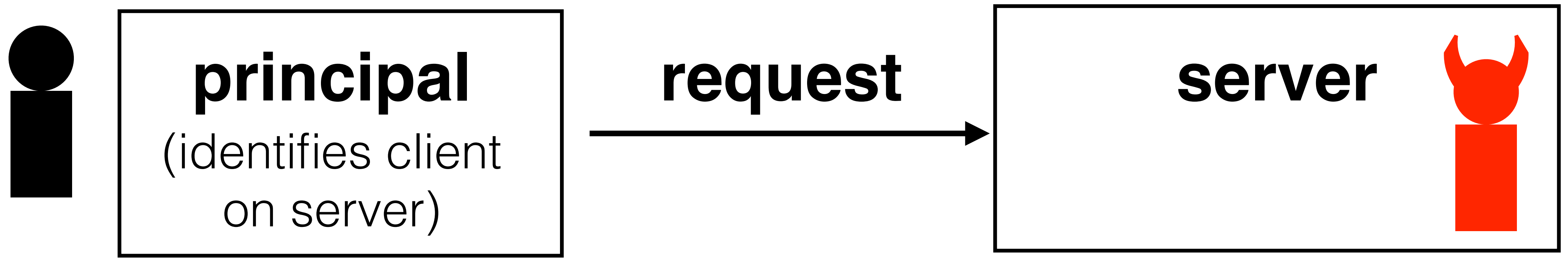
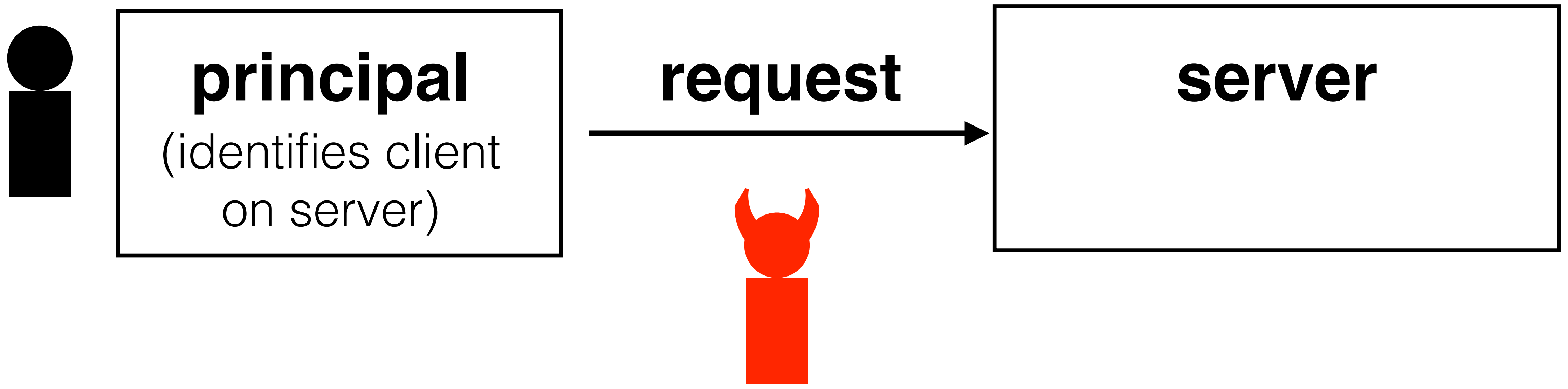


this week, we're going to turn to adversaries that are observing data on the network



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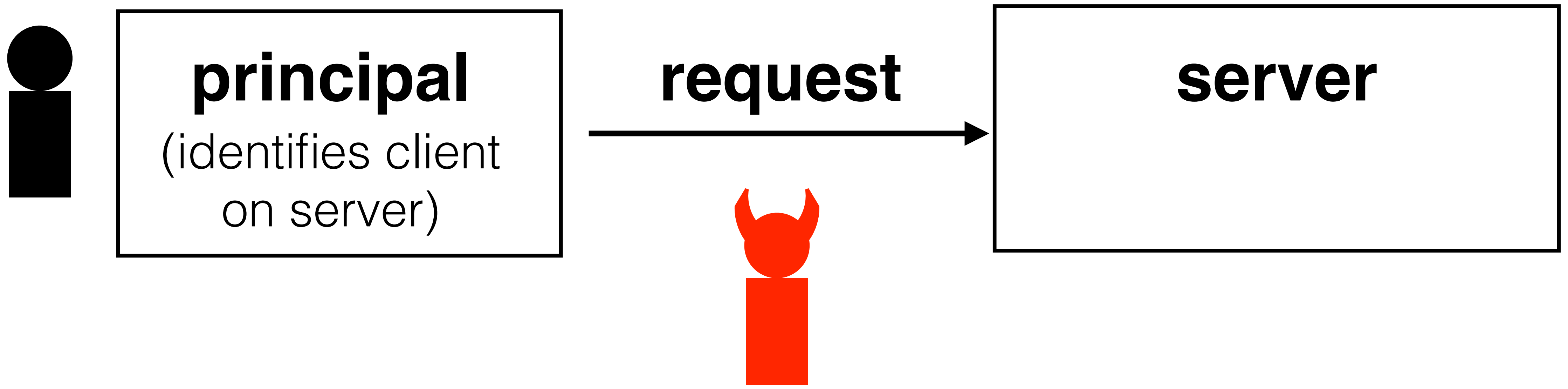

some network traffic is difficult to interpret

e.g., IP addresses are private or resolve to Akamai or Amazon servers

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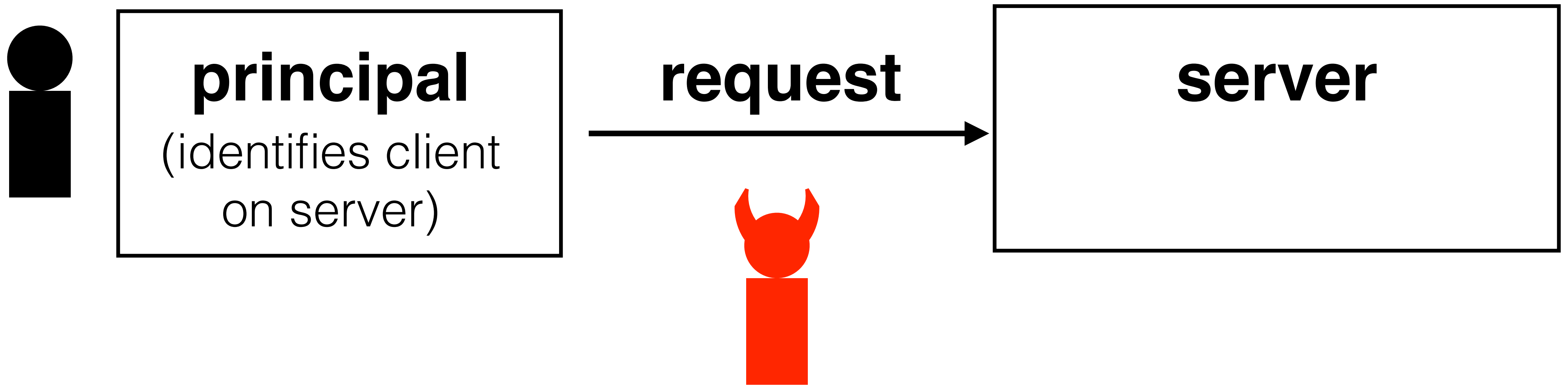

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e.g., IP addresses are private or resolve to Akamai or Amazon servers

```
14:05:31.983557 34392425us tsft -62dB signal -98dB noise antenna 1 5785 MHz 11a
ht/20 [bit 20] CF +QoS IP 184.28.89.95.443 > 10.189.86.146.41204: Flags [P.], seq
1643649202:1643649233, ack 1215791031, win 285, options [nop,nop,TS val 2235675295
ecr 95087166], length 31
        0x0000:  aaaa 0300 0000 0800 4548 0053 b11e 4000  ........EH.S..@.
        0x0010:  3506 2174 b81c 595f 0abd 5692 01bb a0f4  5.!t..Y_..V.....
        0x0020:  61f8 18b2 4877 7fb7 8018 011d 835f 0000  a...Hw......._..
        0x0030:  0101 080a 8541 b29f 05aa ea3e 1503 0300  .....A.....>....
        0x0040:  1ac6 d28d 46ab 64f6 36a3 4efb edd1 f693  ....F.d.6.N.....
        0x0050:  5cf0 0132 65f2 0b0d 21dd 66              \..2e...!.f
```

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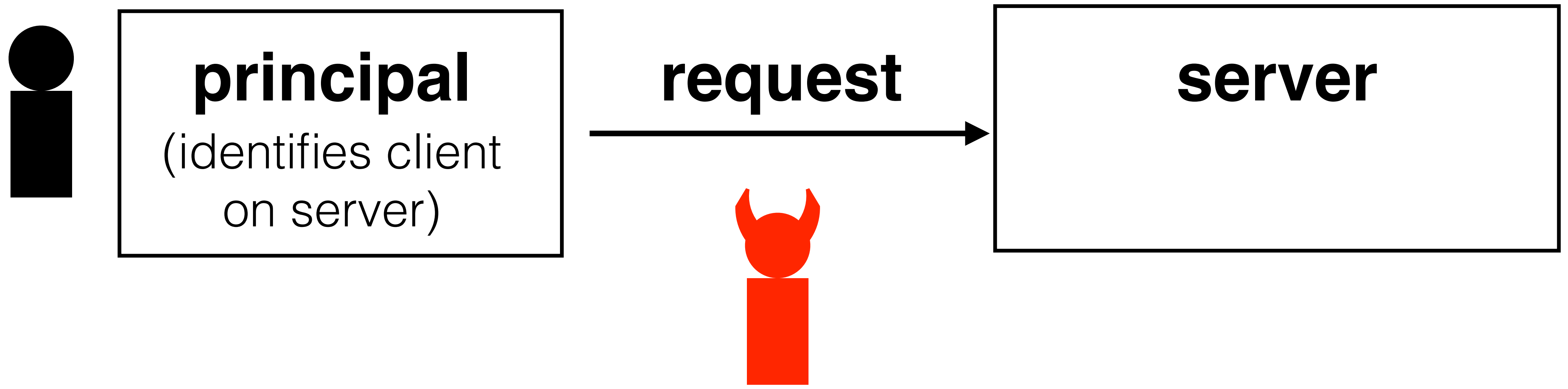

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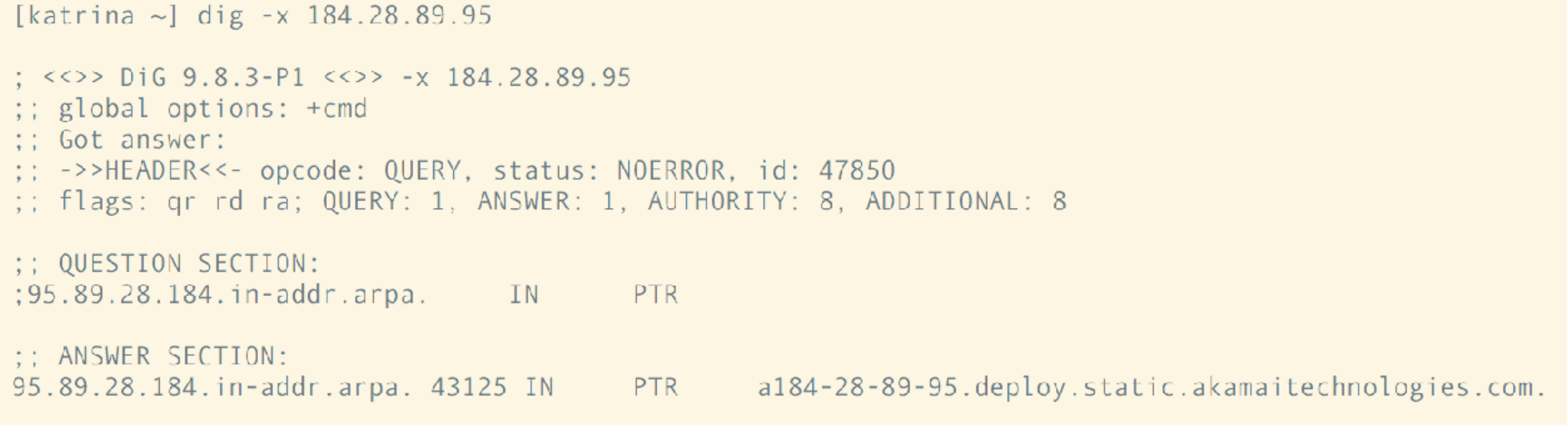
        0x0000:  aaaa 0300 0000 0800 4548 0053 b11e 4000  ........EH.S..@.
        0x0010:  3506 2174 b81c 595f 0abd 5692 01bb a0f4  5.!t..Y_..V.....
        0x0020:  61f8 18b2 4877 7fb7 8018 011d 835f 0000  a...Hw......._..
        0x0030:  0101 080a 8541 b29f 05aa ea3e 1503 0300  .....A.....>....
        0x0040:  1ac6 d28d 46ab 64f6 36a3 4efb edd1 f693  ....F.d.6.N.....
        0x0050:  5cf0 0132 65f2 0b0d 21dd 66              \..2e...!.f
```



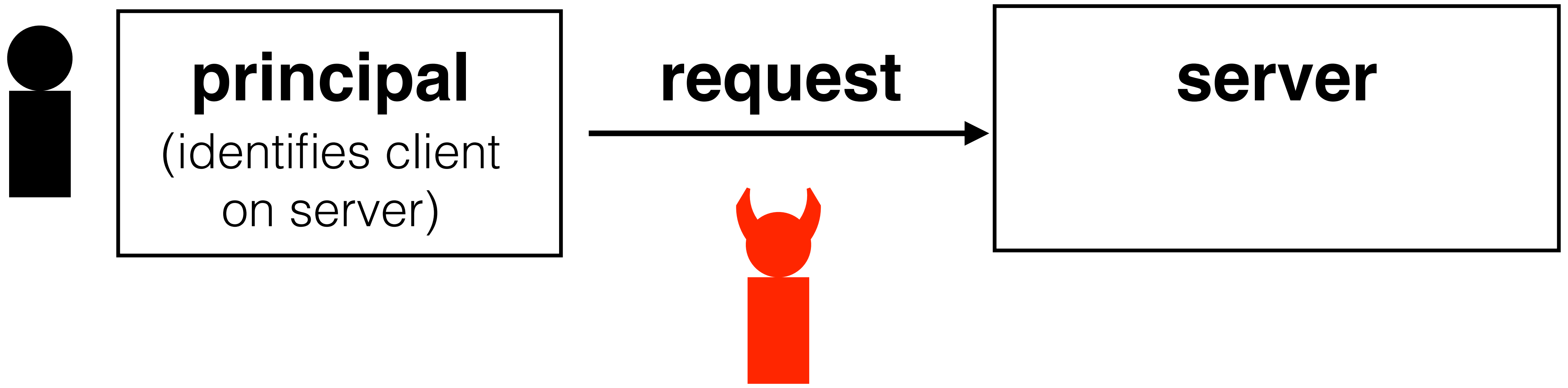
```
[katrina ~] dig -x 184.28.89.95

; <<>> DiG 9.8.3-P1 <<>> -x 184.28.89.95
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 47850
;; flags: qr rd ra; QUERY: 1, ANSWER: 1, AUTHORITY: 8, ADDITIONAL: 8

;; QUESTION SECTION:
;95.89.28.184.in-addr.arpa.     IN      PTR

;; ANSWER SECTION:
95.89.28.184.in-addr.arpa. 43125 IN     PTR     a184-28-89-95.deploy.static.akamaitechnologies.com.
```

this week, we're going to turn to adversaries that are observing data on the network



some packet data can reveal what you're doing even if the packet headers are difficult to interpret

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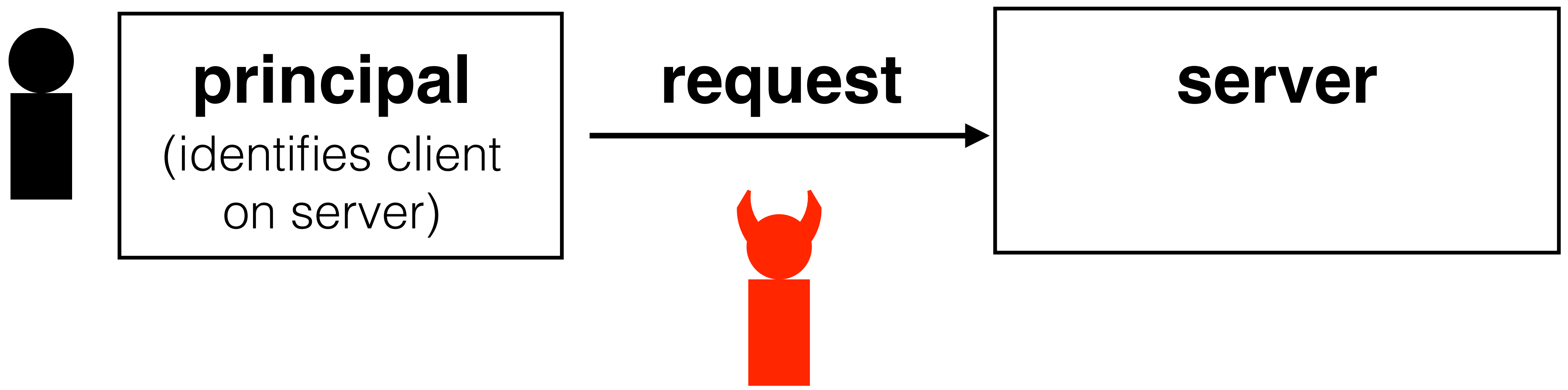

some packet data can reveal what you’re doing even if the packet headers are difficult to interpret

```
0x0130:  5f47 414d 455f 4556 454e 5425 3236 6a73  _GAME_EVENT%26js
0x0140:  6f6e 5f76 616c 2533 4425 3742 2532 3261  on_val%3D%7B%22a
0x0150:  7070 496e 666f 2532 3225 3341 2537 4225  ppInfo%22%3A%7B%
0x0160:  3232 6170 7069 6425 3232 2533 4125 3232  22appid%22%3A%22
0x0170:  636f 6d2e 7469 6e79 636f 7270 2e70 6f74  com.tinycorp.pot
0x0180:  7465 7225 3232 2532 4325 3232 636f 7265  ter%22%2C%22core
0x0190:  7325 3232 2533 4132 2532 4325 3232 6465  s%22%3A2%2C%22de
0x01a0:  7669 6365 5f69 6425 3232 2533 4125 3232  vice_id%22%3A%22
0x01b0:  4533 3346 3230 3642 2d33 3336 302d 3444  E33F206B-3360-4D
0x01c0:  3736 2d42 4236 422d 3742 4144 3043 4130  76-BB6B-7BAD0CA0
0x01d0:  3746 4541 2532 3225 3243 2532 3264 6576  7FEA%22%2C%22dev
0x01e0:  6963 655f 6d6f 6465 6c25 3232 2533 4125  ice_model%22%3A%
0x01f0:  3232 6950 686f 6e65 3925 3243 3225 3232  22iPhone9%2C2%22
0x0200:  2532 4325 3232 6875 6d61 6e5f 6964 2532  %2C%22human_id%2
0x0210:  3225 3341 2532 3225 3232 2532 4325 3232  2%3A%22%22%2C%22
0x0220:  6964 6661 2532 3225 3341 2532 3231 4237  idfa%22%3A%221B7
0x0230:  3646 4643 362d 4130 3432 2d34 4530 312d  6FFC6-A042-4E01-
0x0240:  4239 3934 2d42 4245 3135 3443 3738 4645  B994-BBE154C78FE
0x0250:  3625 3232 2532 4325 3232 696e 7374 616c  6%22%2C%22instal
0x0260:  6c5f 6964 2532 3225 3341 2d36 3135 3437  l_id%22%3A-61547
0x0270:  3635 3033 2532 4325 3232 6c61 6e67 7561  6503%2C%22langua
0x0280:  6765 2532 3225 3341 2532 3265 6e2d 5553  ge%22%3A%22en-US
0x0290:  2532 3225 3243 2532 326c 6f63 616c 6525  %22%2C%22locale%
0x02a0:  3232 2533 4125 3232 656e 5f55 5325 3232  22%3A%22en_US%22
0x02b0:  2532 4325 3232 6f73 5f74 7970 6525 3232  %2C%22os_type%22
0x02c0:  2533 4125 3232 6950 686f 6e65 2b4f 5325  %3A%22iPhone+OS%
0x02d0:  3232 2532 4325 3232 6f73 5f76 6572 7369  22%2C%22os_versi
```

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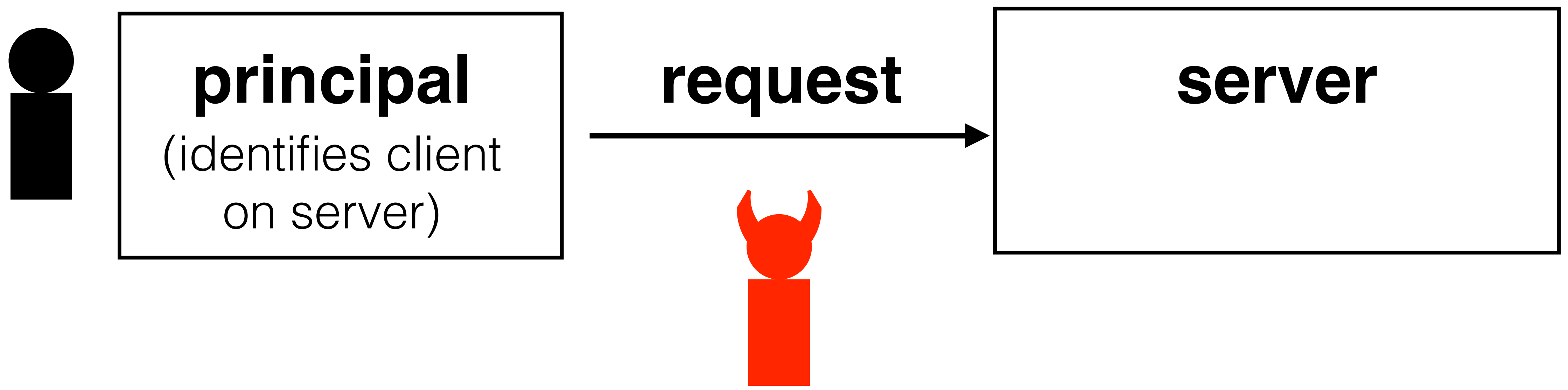

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```
0x0400:  2532 3225 3243 2532 3261 7474 5f63 6f75  %22%2C%22att_cou
0x0410:  7261 6765 2532 3225 3341 3131 2532 4325  rage%22%3A11%2C%
0x0420:  3232 6174 745f 656d 7061 7468 7925 3232  22att_empathy%22
0x0430:  2533 4131 3125 3243 2532 3261 7474 5f6b  %3A11%2C%22att_k
0x0440:  6e6f 776c 6564 6765 2532 3225 3341 3132  nowledge%22%3A12
0x0450:  2532 4325 3232 6176 6174 6172 5f68 6f75  %2C%22avatar_hou
0x0460:  7365 2532 3225 3341 2532 3273 6c79 7425  se%22%3A%22slyt%
0x0470:  3232 2532 4325 3232 6176 6174 6172 5f79  22%2C%22avatar_y
0x0480:  6561 7225 3232 2533 4132 2532 4325 3232  ear%22%3A2%2C%22
0x0490:  6563 686f 2532 3225 3341 2537 4225 3232  echo%22%3A%7B%22
0x04a0:  6625 3232 2533 4125 3232 636f 6d2e 7469  f%22%3A%22com.ti
0x04b0:  6e79 636f 7270 2e70 6f74 7465 7225 3232  nycorp.potter%22
0x04c0:  2532 4325 3232 7025 3232 2533 4166 616c  %2C%22p%22%3Afal
0x04d0:  7365 2532 4325 3232 7225 3232 2533 4174  se%2C%22r%22%3At
0x04e0:  7275 6525 3744 2532 4325 3232 656e 6572  rue%7D%2C%22ener
0x04f0:  6779 5f62 616c 616e 6365 2532 3225 3341  gy_balance%22%3A
0x0500:  3025 3243 2532 3265 7665 6e74 5f74 7970  0%2C%22event_typ
0x0510:  6525 3232 2533 4125 3232 6261 636b 6772  e%22%3A%22backgr
0x0520:  6f75 6e64 5365 7373 696f 6e25 3232 2532  oundSession%22%2
0x0530:  4325 3232 6576 656e 745f 756e 6978 5f74  C%22event_unix_t
0x0540:  6d25 3232 2533 4131 3535 3635 3631 3131  m%22%3A155656111
0x0550:  3225 3243 2532 3267 7569 6425 3232 2533  2%2C%22guid%22%3
0x0560:  4125 3232 3263 6433 6433 3336 2d35 3463  A%222cd3d336-54c
0x0570:  642d 3433 6538 2d39 3539 332d 3961 6537  d-43e8-9593-9ae7
0x0580:  3563 6430 3433 3938 2532 3225 3243 2532  5cd04398%22%2C%2
0x0590:  3268 635f 6261 6c61 6e63 6525 3232 2533  2hc_balance%22%3
0x05a0:  4131 3131 2532 4325 3232 6875 6d61 6e5f  A111%2C%22human_
```

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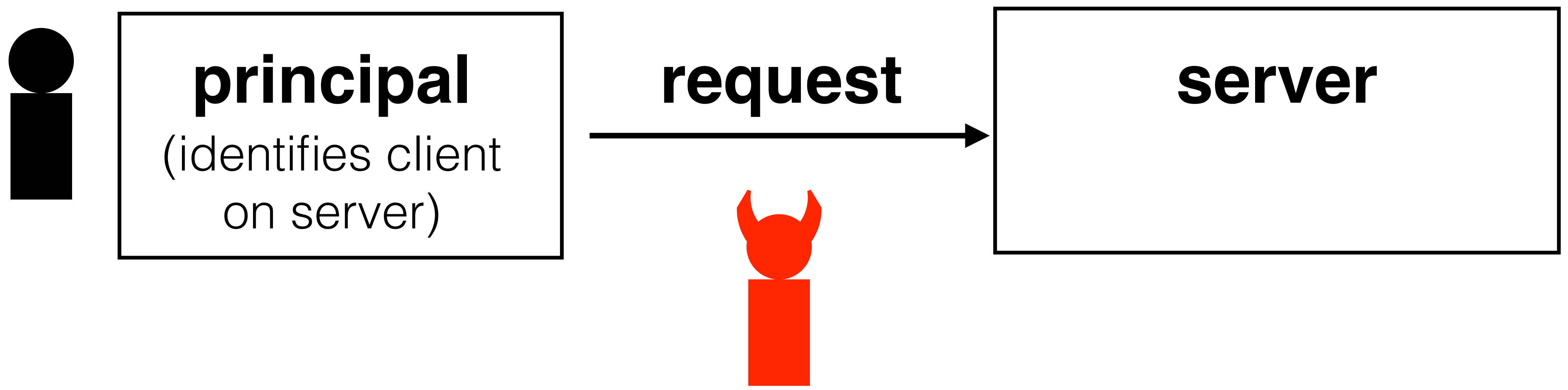

principal

(identifies client on server)

request

server

some packet data can reveal what you're doing even if the packet headers are difficult to interpret

```
14:10:28.658392 331061605us tsft -98dB noise antenna 1 5785 MHz 11a ht/20 [bit 20]
+QoS IP 18.4.86.46.80 > 18.21.134.133.59071: Flags [.], seq 9009:10457, ack 1, win
options [nop,nop,TS val 1469784939 ecr 1030694527], length 1448: HTTP
        0x0040:  0d0a 0a09 0909 3c6f 7074 696f 6e20 7661  ......<option.va
        0x0050:  6c75 653d 2234 3439 223e 266e 6273 703b  lue="449">&nbsp;
        0x0060:  2026 6e62 7370 3b54 6f77 6e20 5371 7561  .&nbsp;Town.Squa
        0x0070:  7265 3c2f 6f70 7469 6f6e 3e0a 0909 0a09  re</option>.....
        0x0080:  0909 3c6f 7074 696f 6e20 7661 6c75 653d  ..<option.value=
        0x0090:  2234 3430 223e 4426 616d 703b 4420 4d79  "440">D&amp;D.My
        0x00a0:  7374 6572 7920 4d61 6669 613c 2f6f 7074  stery.Mafia</opt
        0x00b0:  696f 6e3e 0a09 090a 0909 093c 6f70 7469  ion>.......<opti
        0x00c0:  6f6e 2076 616c 7565 3d22 3434 3122 3e26  on.value="441">&
        0x00d0:  6e62 7370 3b20 266e 6273 703b 4d6f 6e73  nbsp;.&nbsp;Mons
        0x00e0:  7465 7220 4d61 6e75 616c 3c2f 6f70 7469  ter.Manual</opti
        0x00f0:  6f6e 3e0a 0909 0a09 0909 3c6f 7074 696f  on>.......<optio
        0x0100:  6e20 7661 6c75 653d 2234 3432 223e 266e  n.value="442">&n
        0x0110:  6273 703b 2026 6e62 7370 3b50 6c61 7965  bsp;.&nbsp;Playe
        0x0120:  7227 7320 4861 6e64 626f 6f6b 3c2f 6f70  r's.Handbook</op
        0x0130:  7469 6f6e 3e0a 0909 0a09 0909 3c6f 7074  tion>.......<opt
        0x0140:  696f 6e20 7661 6c75 653d 2234 3433 223e  ion.value="443">
        0x0150:  266e 6273 703b 2026 6e62 7370 3b44 756e  &nbsp;.&nbsp;Dun
        0x0160:  6765 6f6e 204d 6173 7465 7227 7320 4775  geon.Master's.Gu
        0x0170:  6964 653c 2f6f 7074 696f 6e3e 0a09 090a  ide</option>....
```

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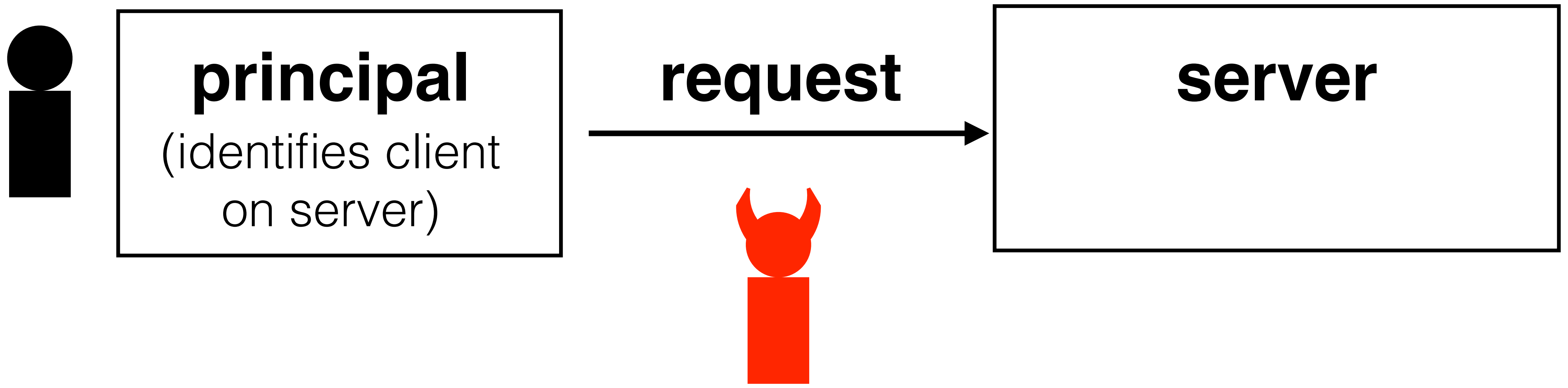
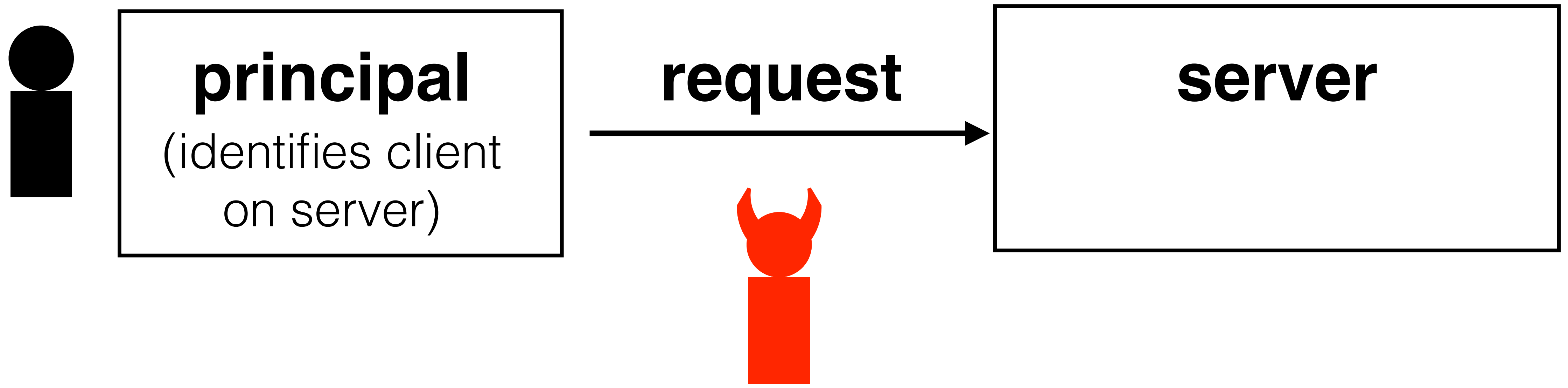


sometimes traffic can be easily tied to individuals

either in packet headers or packet data

this week, we're going to turn to adversaries that are observing data on the **network**



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```
14:05:29.947459 104653458us tsft -70dB signal -92dB noise antenna 0 2412 MHz 11g
ht/20 39.0 Mb/s MCS 10 20 MHz lon GI mixed BCC FEC [bit 20] CF +QoS IP
10.189.6.135.5353 > 224.0.0.251.5353: 0*- [0q] 2/0/3 (Cache flush) PTR Bobs-
iPhone.local., (Cache flush) PTR Bobs-iPhone.local. (217)

          0x0000:  aaaa 0300 0000 0800 4500 00f5 2053 0000  ........E....S..
          0x0010:  ff11 a865 0abd 0687 e000 00fb 14e9 14e9  ...e............
          0x0020:  00e1 5867 0000 8400 0000 0002 0000 0003  ..Xg............
          0x0030:  0137 0135 0144 0133 0139 0130 0138 0133  .7.5.D.3.9.0.8.3
          0x0040:  0135 0135 0139 0144 0144 0141 0143 0130  .5.5.9.D.D.A.C.0
          0x0050:  0130 0130 0130 0130 0130 0130 0130 0130  .0.0.0.0.0.0.0.0
          0x0060:  0130 0130 0130 0130 0130 0138 0145 0146  .0.0.0.0.0.8.E.F
          0x0070:  0369 7036 0461 7270 6100 000c 8001 0000  .ip6.arpa.......
          0x0080:  0078 0015 0d44 3139 8b64 432d 6950 686f  .x.....Bobs-iPho
          0x0090:  6e65 056c 6f63 616c 0003 3133 3501 3603  ne.local..135.6.
          0x00a0:  3138 3902 3130 0769 6e2d 6164 6472 c050  189.10.in-addr.P
          0x00b0:  000c 8001 0000 0078 0002 c060 c00c 002f  .......x...`.../
          0x00c0:  8001 0000 0078 0006 c00c 0002 0008 c075  .....x.........u
          0x00d0:  002f 8001 0000 0078 0006 c075 0002 0008  ./.....x...u....
          0x00e0:  0000 2905 a000 0011 9400 1200 0400 0e00  ..).............
          0x00f0:  256e 8dc1 7d01 b16c 8dc1 7d01 b1         %n..}..l..}..
```

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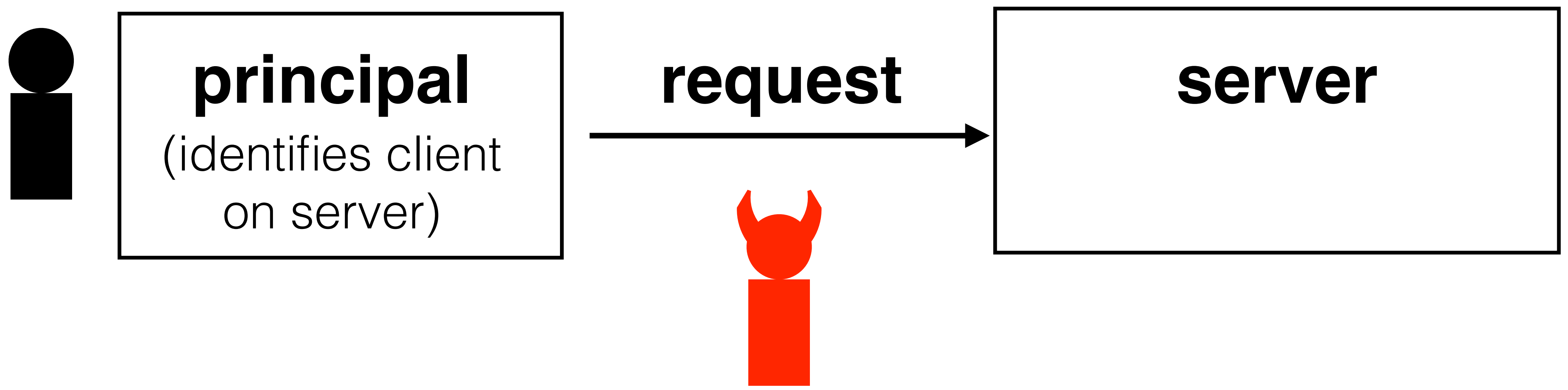

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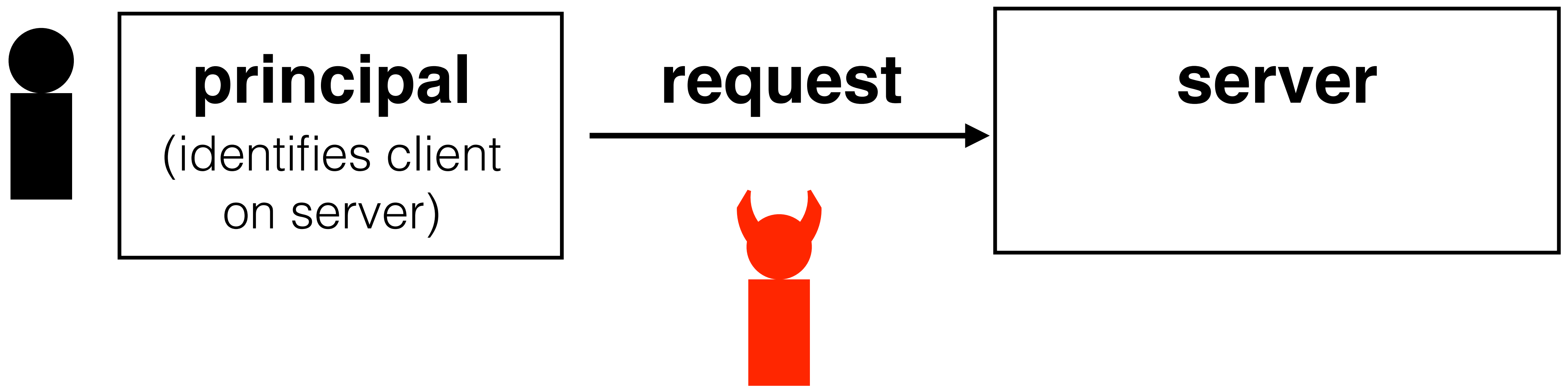
```
0x0000:  aaaa 0300 0000 0800 4500 009b 2acb 0000  ........E...*...
0x0010:  ff11 d8b2 1215 c4c3 e000 00fb 14e9 14e9  ................
0x0020:  0087 a623 0000 0000 0002 0000 0000 0001  ...#............
0x0030:  184d 6174 74e2 8099 7320 4d61 6342 6f6f  .XXXX...s.MacBoo
0x0040:  6b20 4169 7220 2833 290f 5f63 6f6d 7061  k.Air.(3)._compa
0x0050:  6e69 6f6e 2d6c 696e 6b04 5f74 6370 056c  nion-link._tcp.l
0x0060:  6f63 616c 0000 1000 0116 5468 6f6d 6173  ocal......XXXXXX
0x0070:  e280 9973 204d 6163 426f 6f6b 2041 6972  ...s.MacBook.Air
0x0080:  c025 0010 8001 0000 2905 a000 0011 9400  .%......).......
0x0090:  1200 0400 0e00 81a6 4167 2f68 dc84 4167  ........Ag/h..Ag
0x00a0:  2f68 dc                                  /h.
0x0000:  aaaa 0300 0000 0800 4500 00e2 338a 0000  ........E...3...
0x0010:  ff11 cfac 1215 c4c3 e000 00fb 14e9 14e9  ................
0x0020:  00ce 5a25 0000 0000 0005 0000 0000 0001  ..Z%............
0x0030:  114d 6f68 616e e280 9973 204d 6163 2050  .XXXXX...s.Mac.P
0x0040:  726f 0f5f 636f 6d70 616e 696f 6e2d 6c69  ro._companion-li
0x0050:  6e6b 045f 7463 7005 6c6f 6361 6c00 0010  nk._tcp.local...
0x0060:  0001 154d 6f68 616e e280 9973 204d 6163  ...XXXXX...s.Mac
0x0070:  2050 726f 2028 3229 c01e 0010 0001 1566  .Pro.(2).......X
0x0080:  6572 6761 736f 6ee2 8099 7320 4375 7465  XXXXXXX...s..Mac
0x0090:  426f 6f6b c01e 0010 0001 184d 6174 74e2  Book.......XXXX.
0x00a0:  8099 7320 4d61 6342 6f6f 6b20 4169 7220  ..s.MacBook.Air.
0x00b0:  2833 29c0 1e00 1000 010d 4d61 7961 e280  (3).......XXXX..
0x00c0:  9973 2069 5061 64c0 1e00 1000 0100 0029  .s.iPad........)
0x00d0:  05a0 0000 1194 0012 0004 000e 0081 a641  ...............A
0x00e0:  672f 68dc 8441 672f 68dc                 g/h..Ag/h.
0x0000:  aaaa 0300 0000 0800 4500 007a 3ea9 0000  ........E..z>...
```

this week, we're going to turn to adversaries that are observing data on the network



principal

(identifies client on server)

request

server

sometimes traffic can be easily tied to individuals

either in packet headers or packet data

today we're going to focus on how to protect packet data from an adversary

next time, we'll talk about how you can protect meta-information (e.g., packet headers) from an adversary

```
0x0000:  aaaa 0300 0000 0800 4500 009b 2acb 0000  ........E...*...
0x0010:  ff11 d8b2 1215 c4c3 e000 00fb 14e9 14e9  ................
0x0020:  0087 a623 0000 0000 0002 0000 0000 0001  ...#............
0x0030:  184d 6174 74e2 8099 7320 4d61 6342 6f6f  .XXXX...s.MacBoo
0x0040:  6b20 4169 7220 2833 290f 5f63 6f6d 7061  k.Air.(3)._compa
0x0050:  6e69 6f6e 2d6c 696e 6b04 5f74 6370 056c  nion-link._tcp.l
0x0060:  6f63 616c 0000 1000 0116 5468 6f6d 6173  ocal......XXXXXX
0x0070:  e280 9973 204d 6163 426f 6f6b 2041 6972  ...s.MacBook.Air
0x0080:  c025 0010 8001 0000 2905 a000 0011 9400  .%......).......
0x0090:  1200 0400 0e00 81a6 4167 2f68 dc84 4167  ........Ag/h..Ag
0x00a0:  2f68 dc                                  /h.
0x0000:  aaaa 0300 0000 0800 4500 00e2 338a 0000  ........E...3...
0x0010:  ff11 cfac 1215 c4c3 e000 00fb 14e9 14e9  ................
0x0020:  00ce 5a25 0000 0000 0005 0000 0000 0001  ..Z%............
0x0030:  114d 6f68 616e e280 9973 204d 6163 2050  .XXXXX...s.Mac.P
0x0040:  726f 0f5f 636f 6d70 616e 696f 6e2d 6c69  ro._companion-li
0x0050:  6e6b 045f 7463 7005 6c6f 6361 6c00 0010  nk._tcp.local...
0x0060:  0001 154d 6f68 616e e280 9973 204d 6163  ...XXXXX...s.Mac
0x0070:  2050 726f 2028 3229 c01e 0010 0001 1566  .Pro.(2).......X
0x0080:  6572 6761 736f 6ee2 8099 7320 4375 7465  XXXXXXX...s..Mac
0x0090:  426f 6f6b c01e 0010 0001 184d 6174 74e2  Book.......XXXX.
0x00a0:  8099 7320 4d61 6342 6f6f 6b20 4169 7220  ..s.MacBook.Air.
0x00b0:  2833 29c0 1e00 1000 010d 4d61 7961 e280  (3).......XXXX..
0x00c0:  9973 2069 5061 64c0 1e00 1000 0100 0029  .s.iPad........)
0x00d0:  05a0 0000 1194 0012 0004 000e 0081 a641  ...............A
0x00e0:  672f 68dc 8441 672f 68dc                 g/h..Ag/h.
0x0000:  aaaa 0300 0000 0800 4500 007a 3ea9 0000  ........E..z>...
```

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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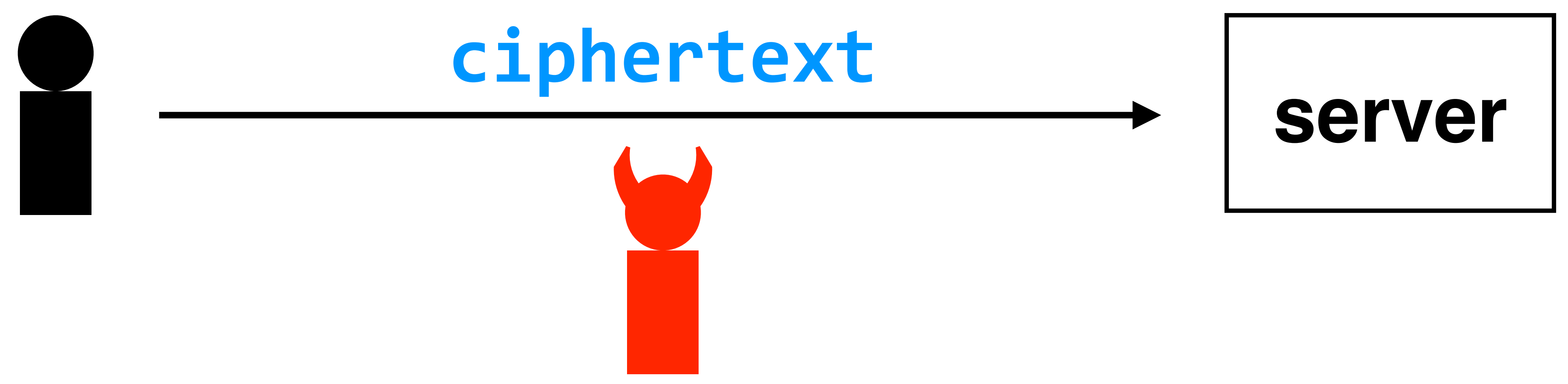

ciphertext

server

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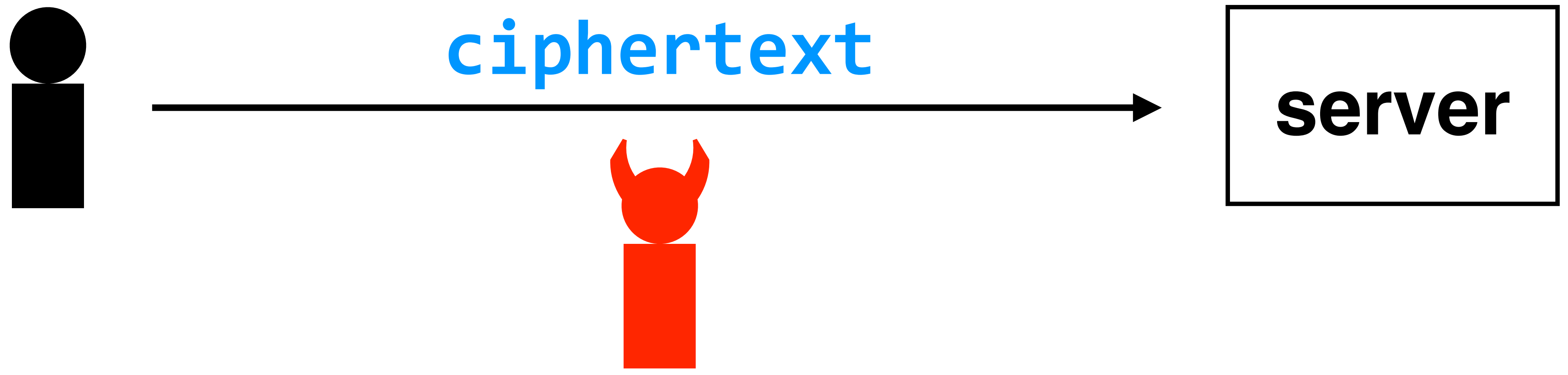

`ciphertext`

server

adversary can't determine `message`, *but* might be able to cleverly alter `ciphertext` so that it decrypts to a different message

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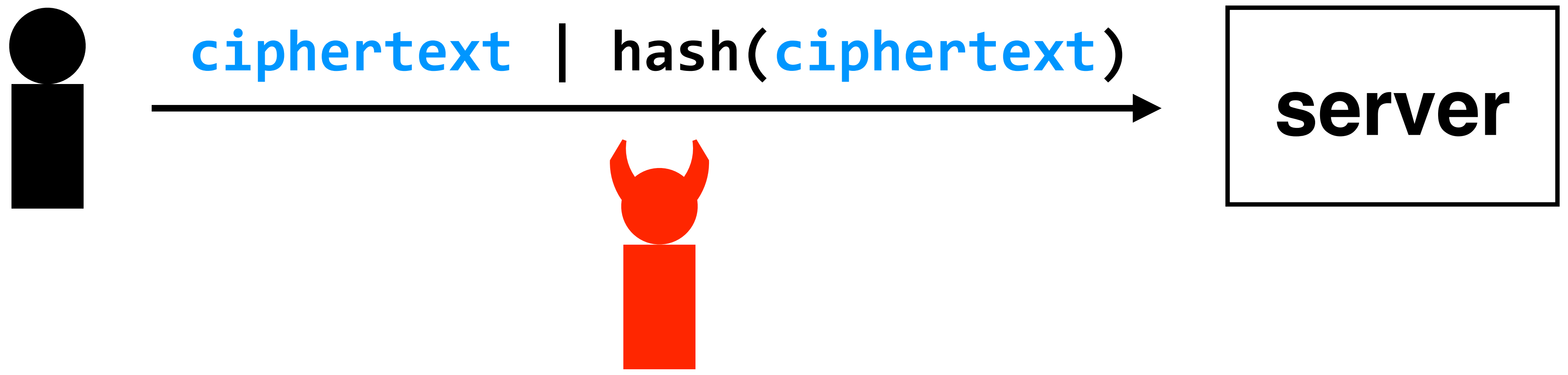

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```
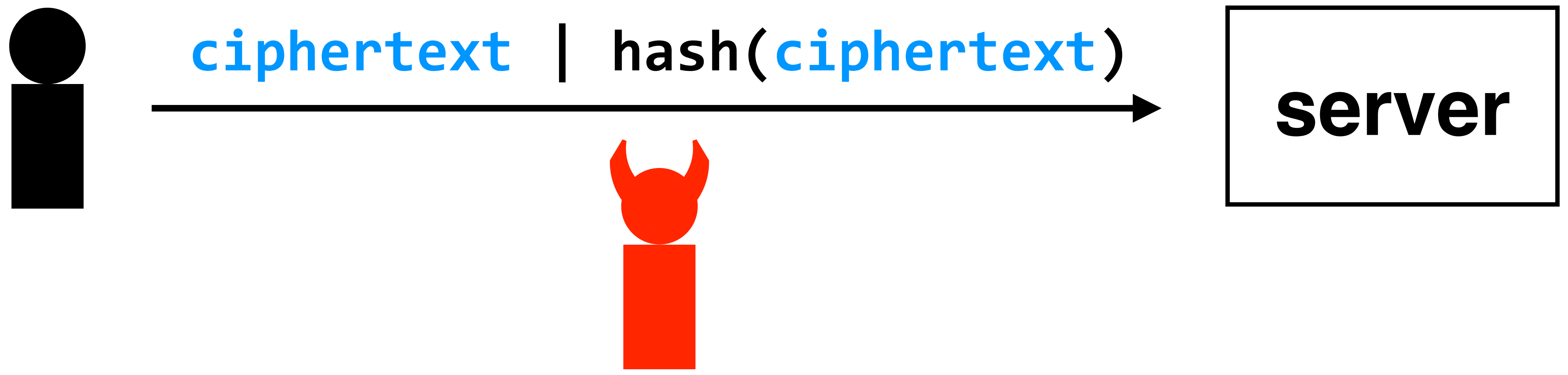

property: given the ciphertext, it is (virtually) impossible to obtain the message without knowing the key



no good — if the adversary changes ciphertext, it can also (correctly) update the hash

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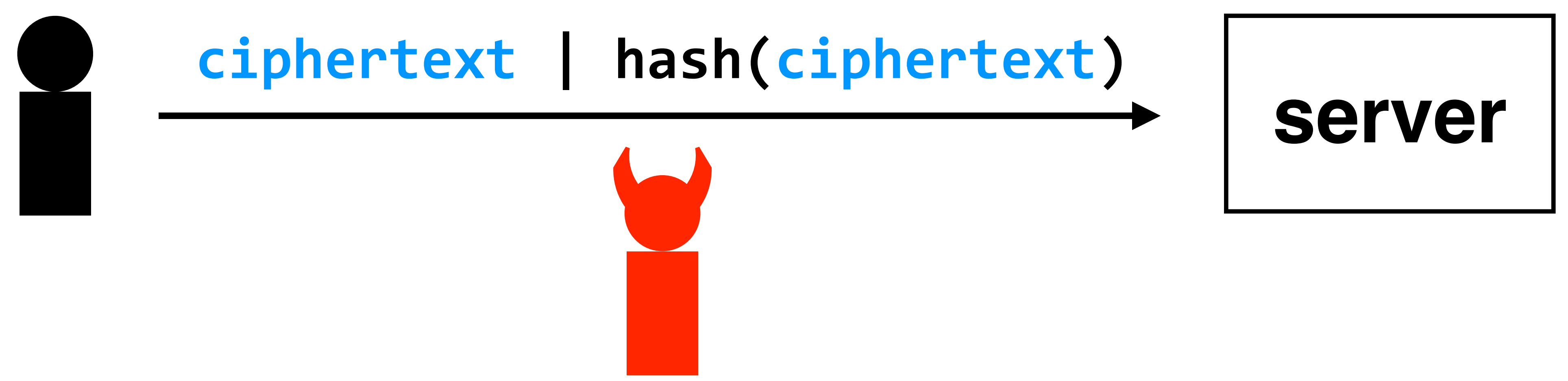
property: given the `ciphertext`, it is (virtually) impossible to obtain the `message` without knowing the `key`

```
MAC(key, message) → token
```



no good — if the adversary changes `ciphertext`, it can also (correctly) update the hash

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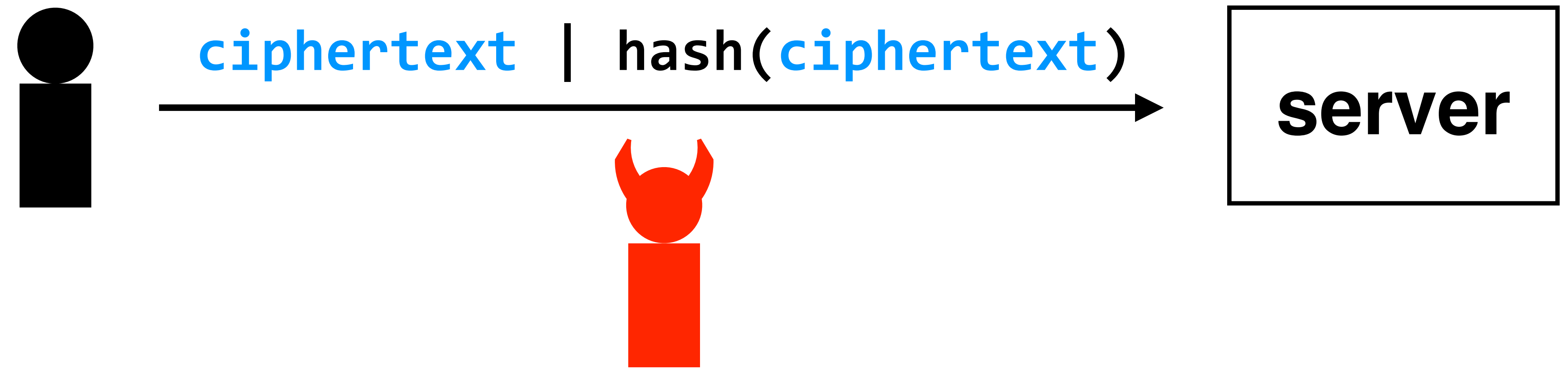
property: given the `ciphertext`, it is (virtually) impossible to obtain the `message` without knowing the `key`

```
MAC(key, message) → token
   MAC(34fbcbd1, “hello, world”) =
  0x59cccc95723737f777e62bc756c8da5c
```



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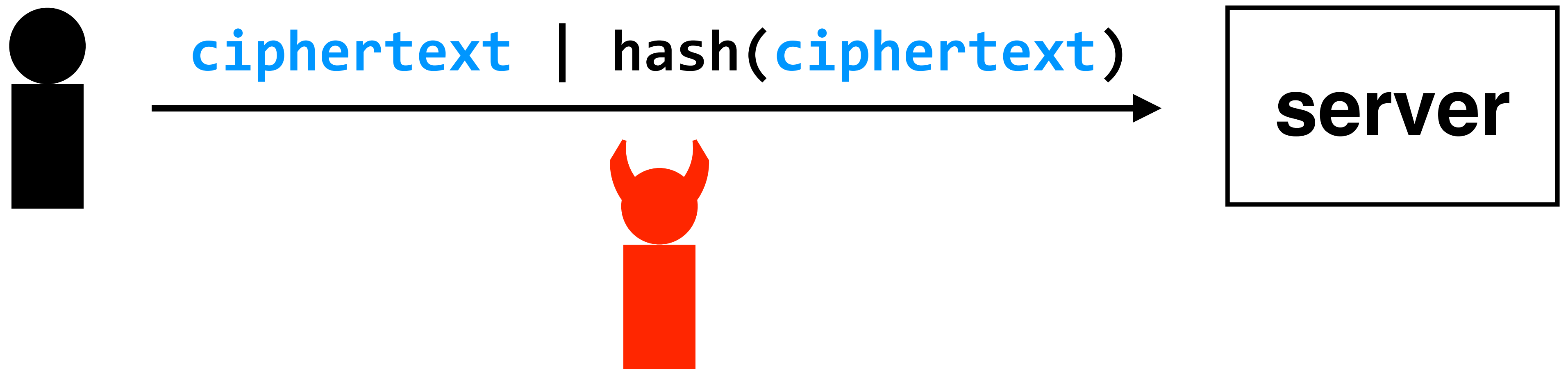
property: given the `message`, it is (virtually) impossible to obtain the `token` without knowing the `key`

it is also impossible to go in the reverse direction: given `token`, you can’t get `message` even with the `key`



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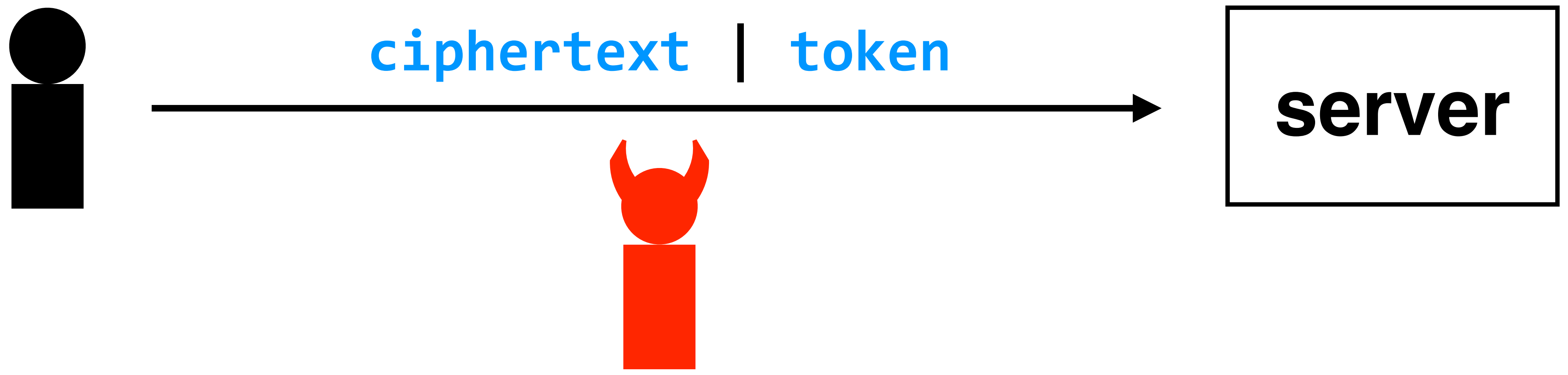

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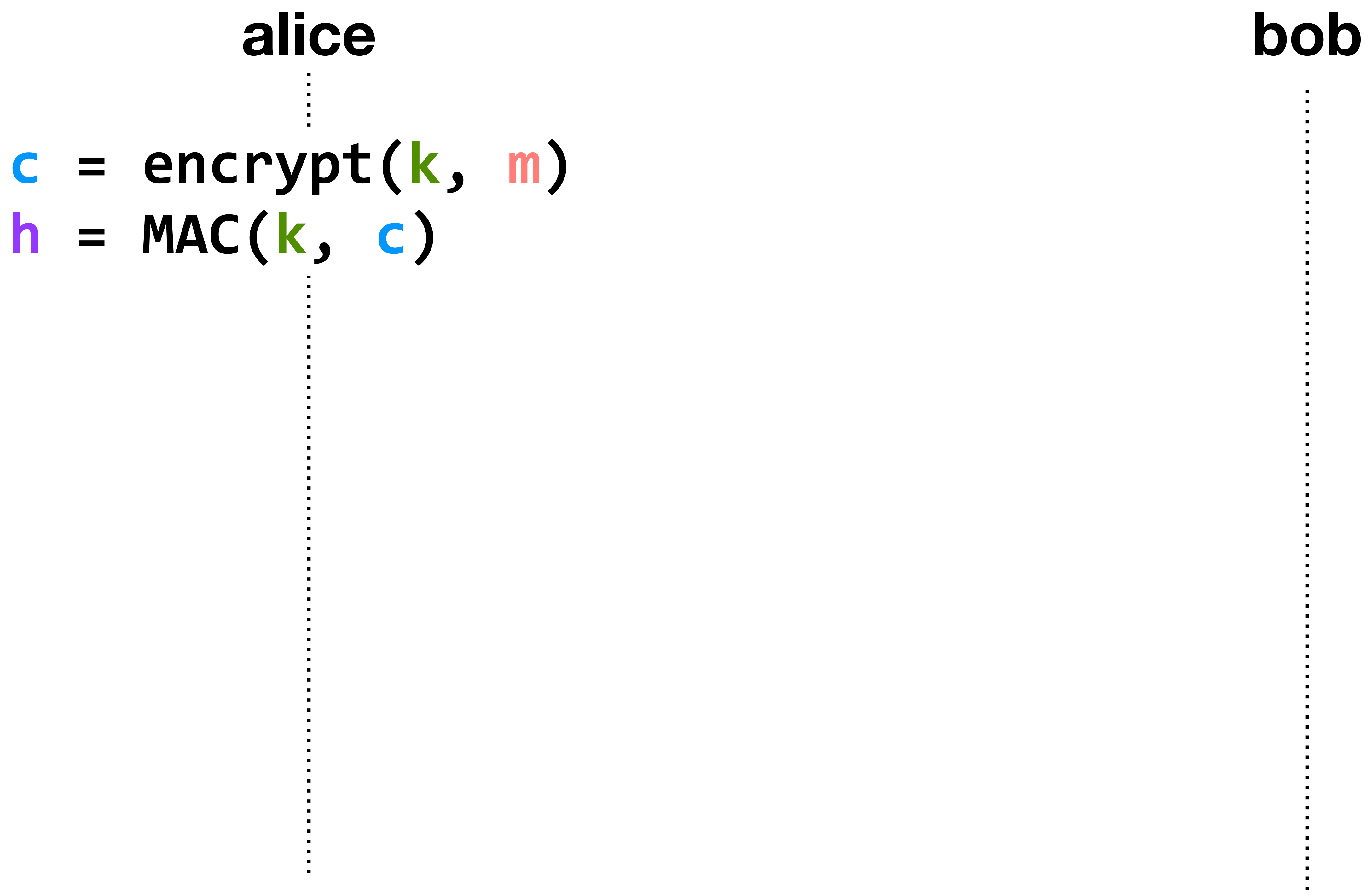

```
c = encrypt(k, m)
h = MAC(k, c)
```

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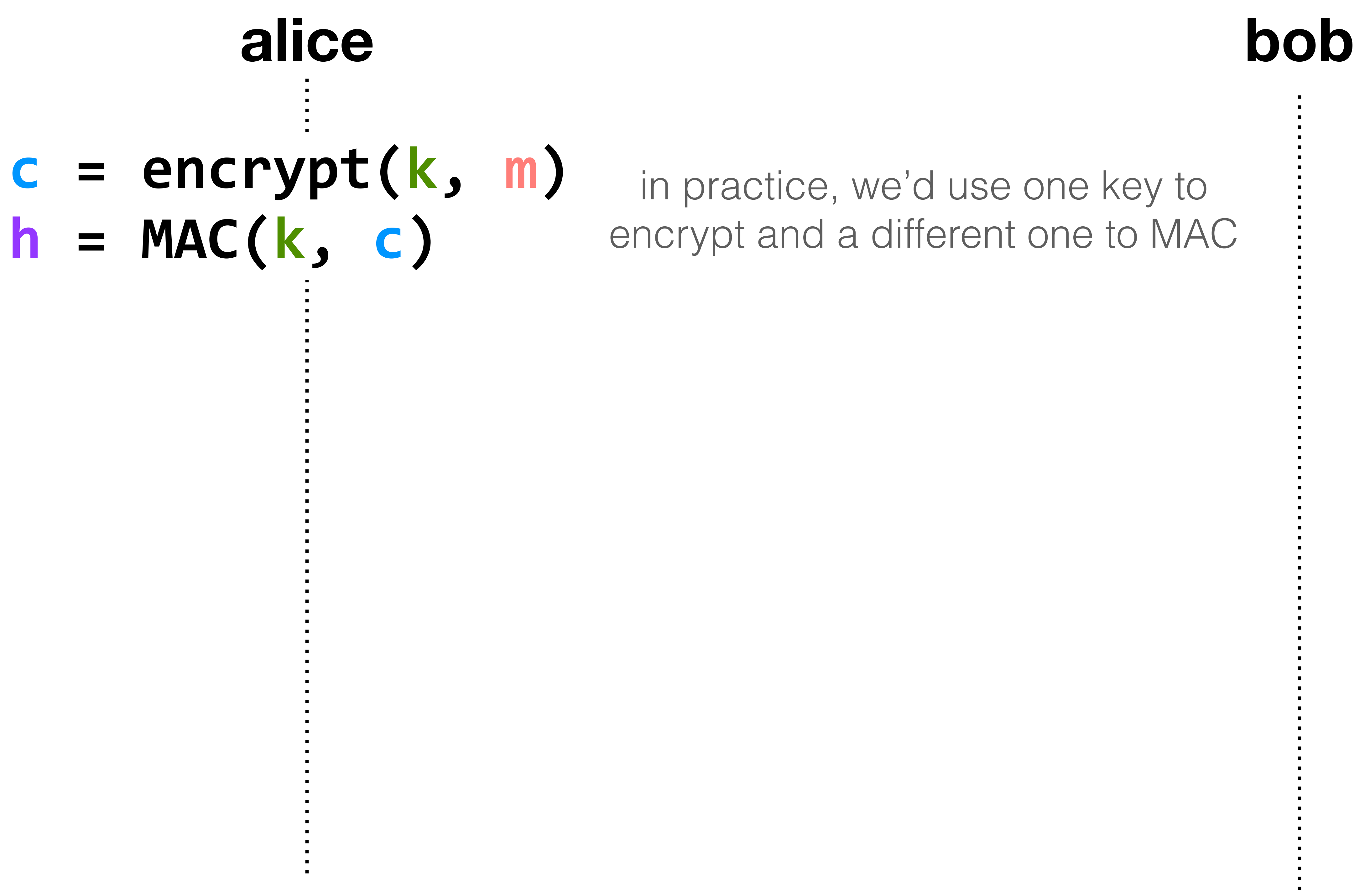

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c = encrypt(k, m)
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in practice, we’d use one key to encrypt and a different one to MAC

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8c”) = hello, world
```

property: given the ciphertext, it is (virtually) impossible to obtain the message without knowing the key

MAC(key, message) → token

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MAC(34fbcbd1, “hello, world”) =
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```
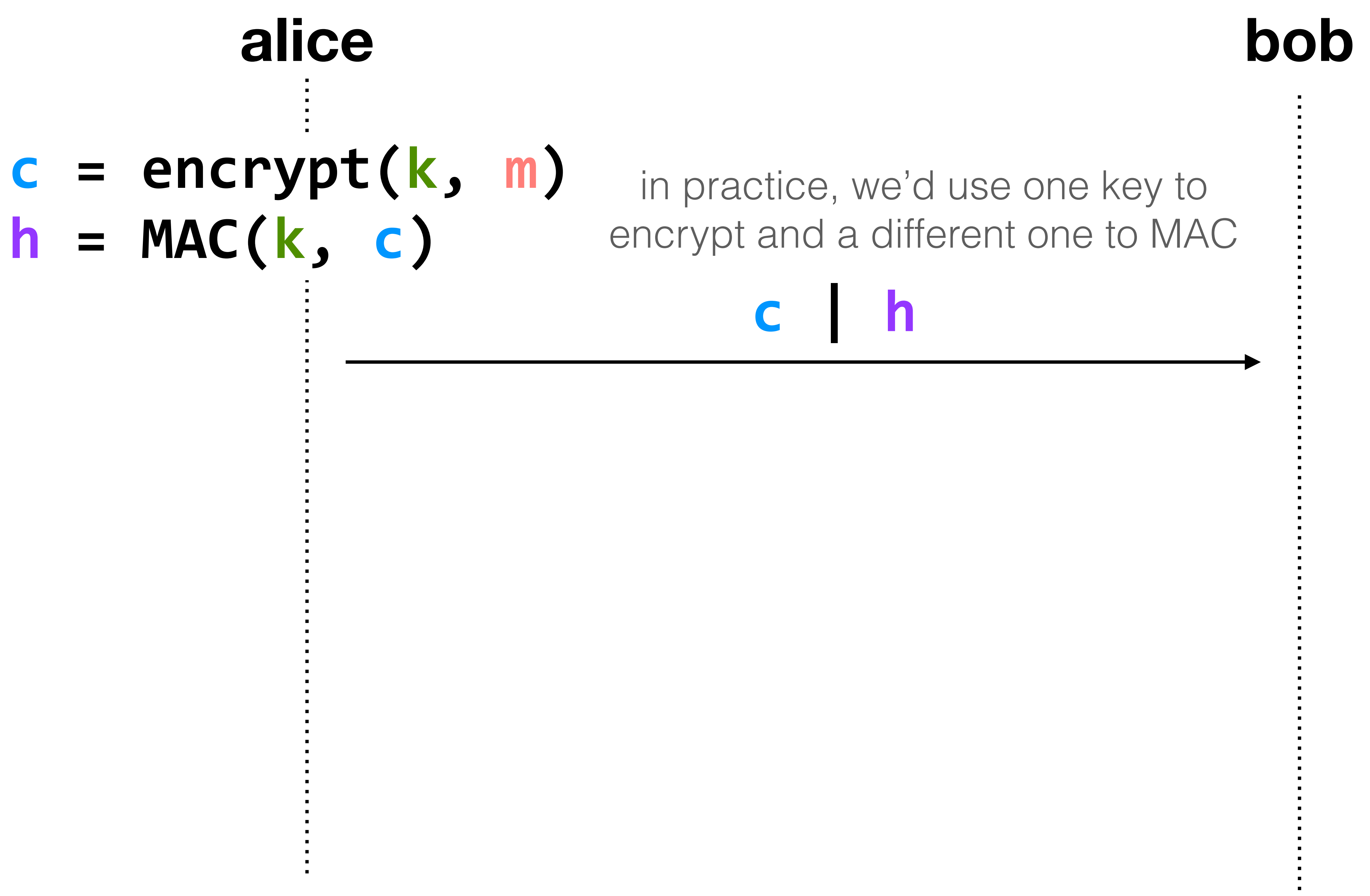

property: given the message, it is (virtually) impossible to obtain the token without knowing the key

it is also impossible to go in the reverse direction: given token, you can't get message even with the key



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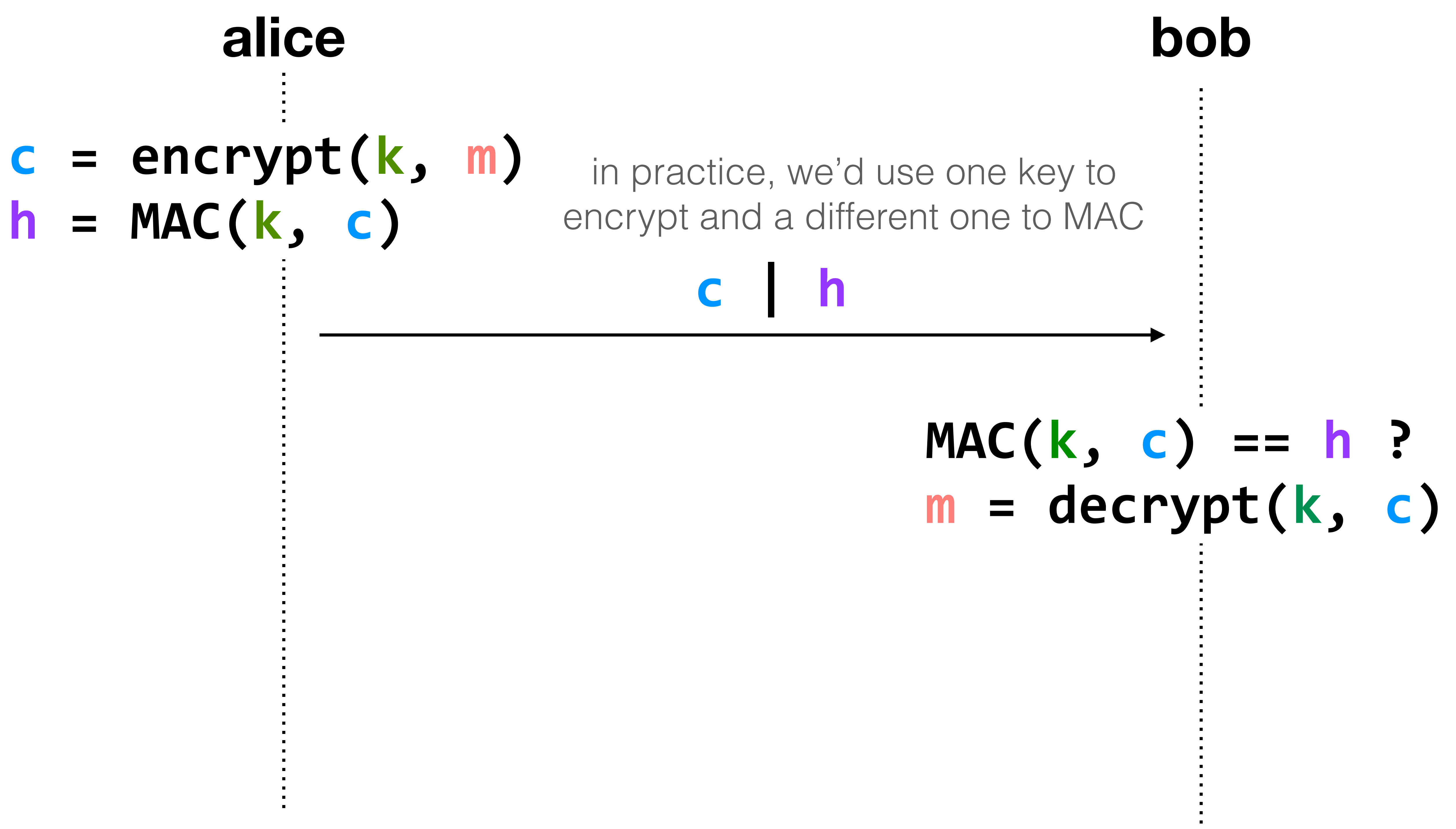

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c = encrypt(k, m)
h = MAC(k, c)
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in practice, we’d use one key to encrypt and a different one to MAC

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

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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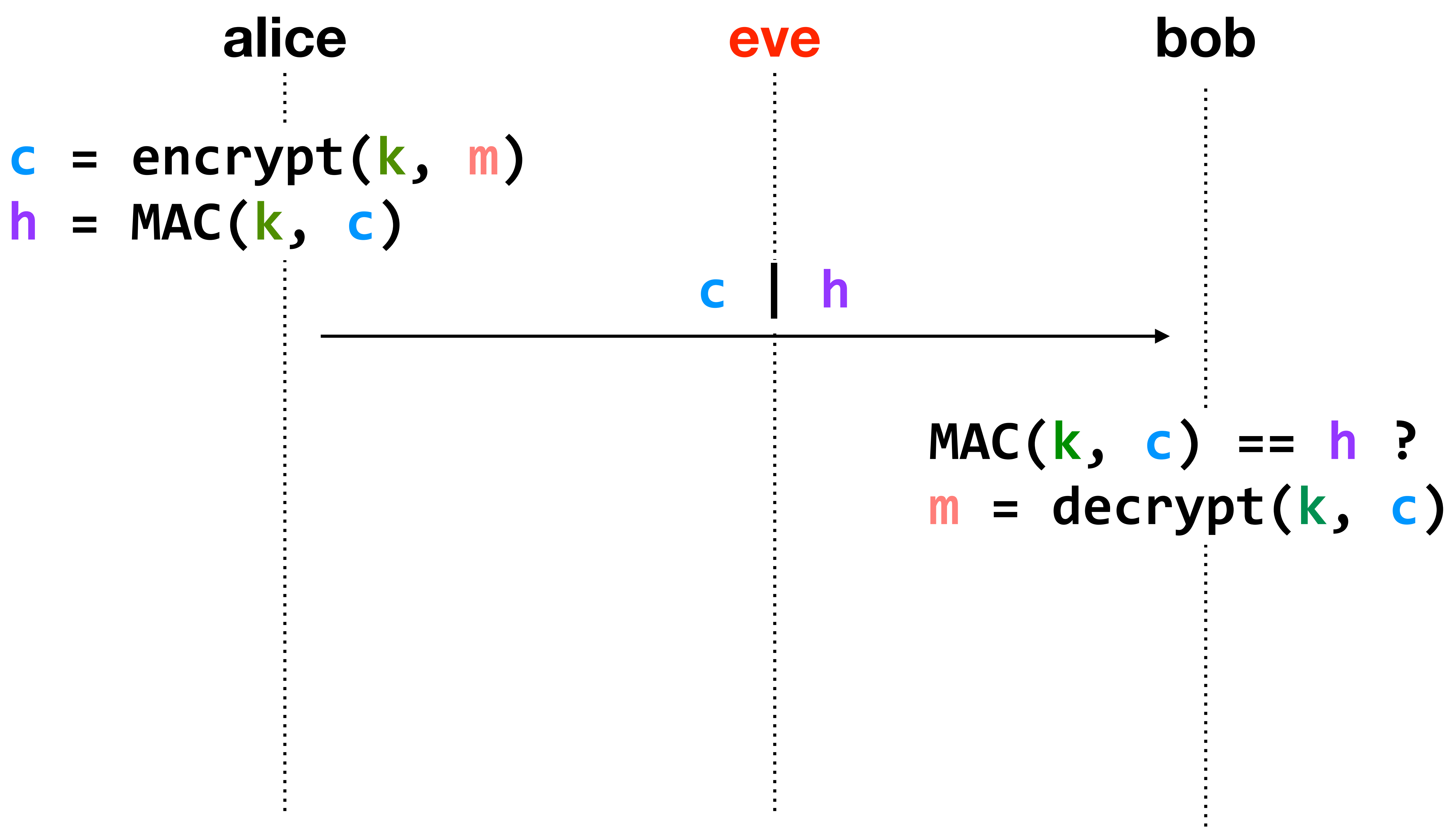

`c = encrypt(k, m)`
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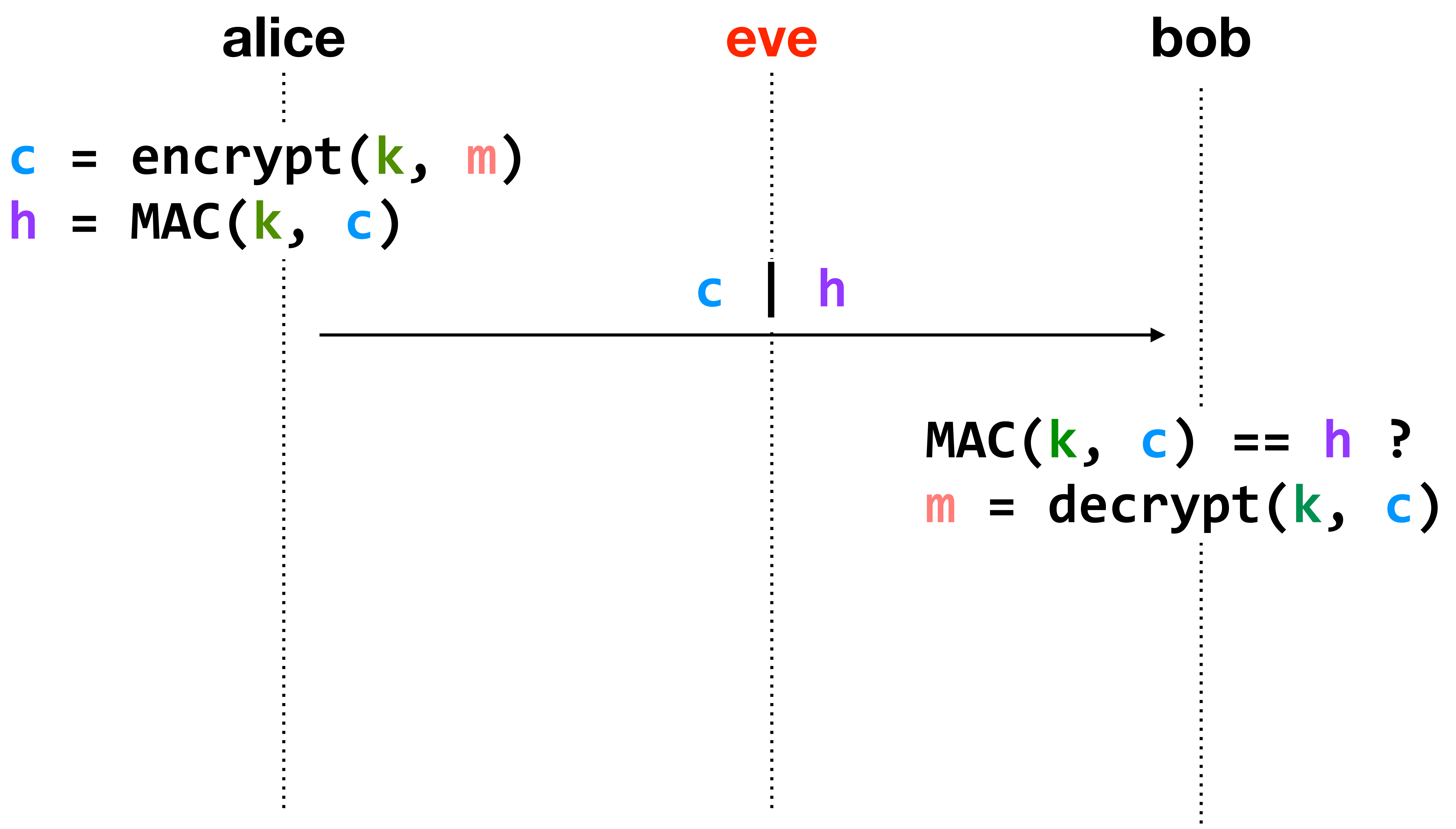

```
c = encrypt(k, m)
h = MAC(k, c)
```

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

eve can neither read `m` nor tamper with `c`

(without going unnoticed)

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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MAC(key, message) → token
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0x59cccc95723737f777e62bc756c8da5c
```

property: given the `message`, it is (virtually) impossible to obtain the `token` without knowing the `key`

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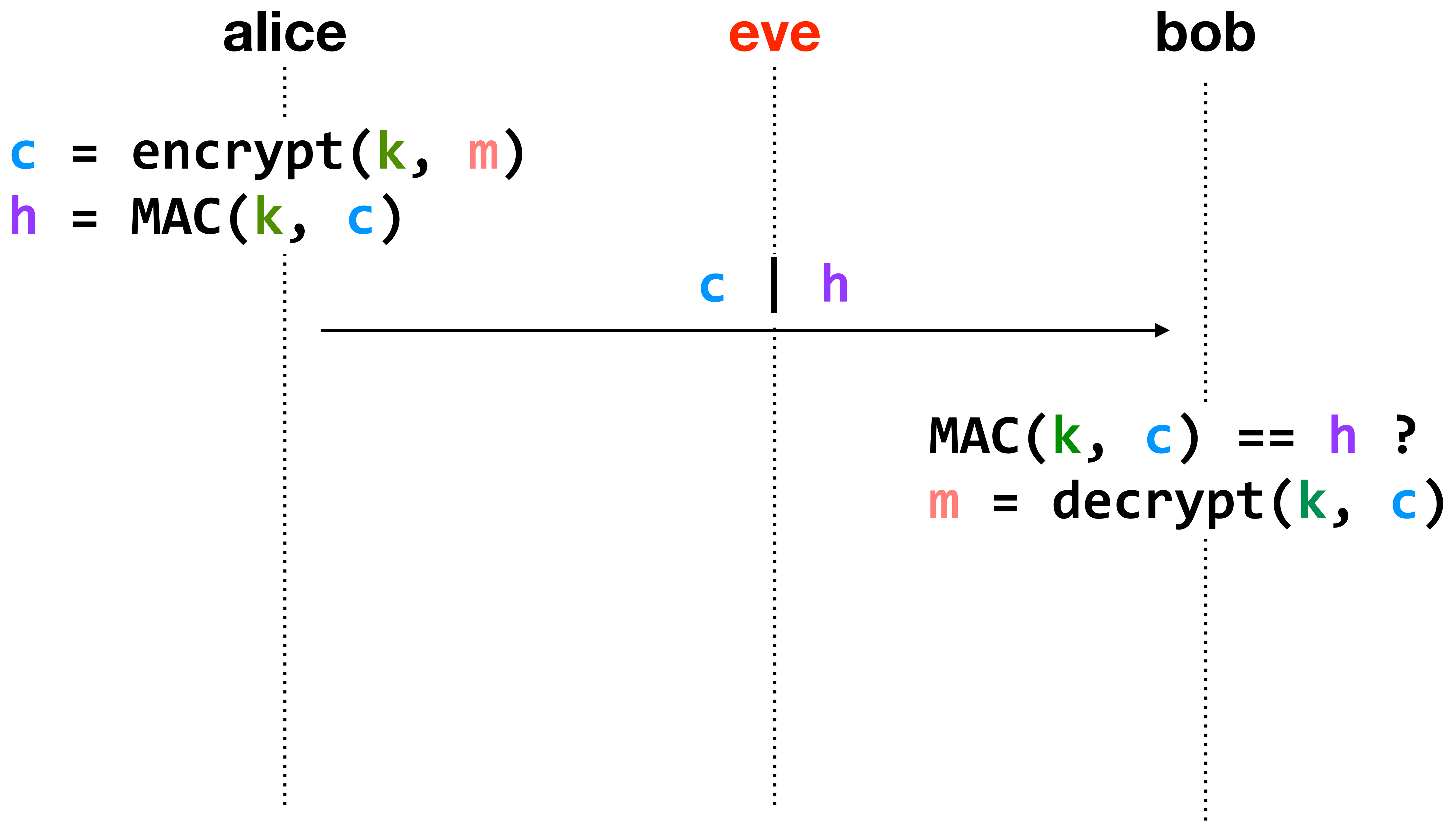

```
c = encrypt(k, m)
h = MAC(k, c)
```

```
c | h
```

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

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

threat model: adversary can observe network data, tamper with packets, and insert its own packets

encrypt(key, message) → ciphertext
decrypt(key, ciphertext) → message

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encrypt(34fbcbd1, “hello, world”) = 0x47348f63a679
26cd393d4b93c58f78c
decrypt(34fbcbd1, “0x47348f63a67926cd393d4b93c58f7
8c”) = hello, world
```

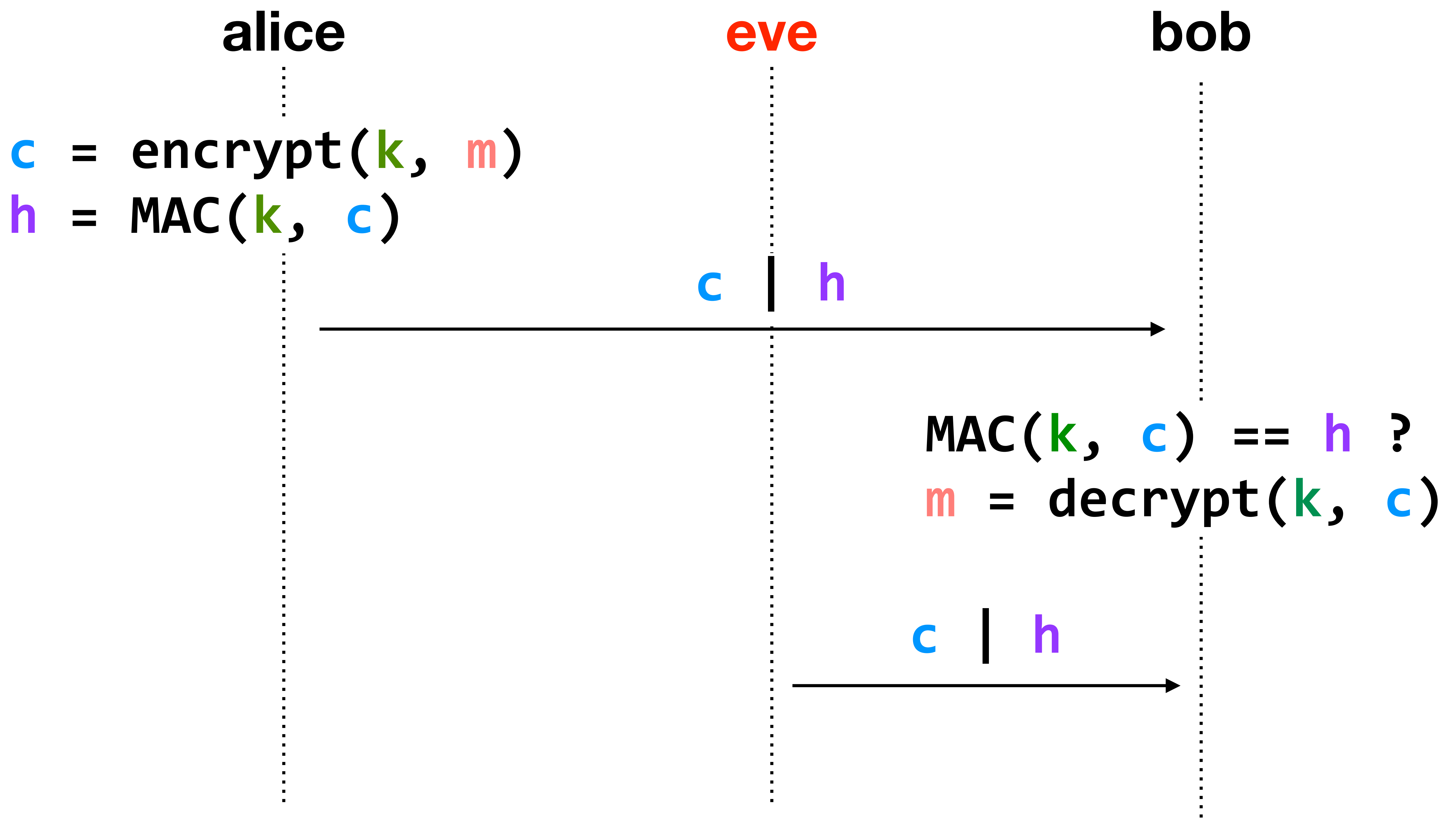
property: given the ciphertext, it is (virtually) impossible to obtain the message without knowing the key

MAC(key, message) → token

```
MAC(34fbcbd1, “hello, world”) =
0x59cccc95723737f777e62bc756c8da5c
```

property: given the message, it is (virtually) impossible to obtain the token without knowing the key

it is also impossible to go in the reverse direction: given token, you can’t get message even with the key



alice

eve

bob

c = encrypt(k, m)
h = MAC(k, c)

c | h

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

c | h

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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8c”) = hello, world
```

property: given the `ciphertext`, it is (virtually) impossible to obtain the `message` without knowing the `key`

```
MAC(key, message) → token
```

```
MAC(34fbcbd1, “hello, world”) =
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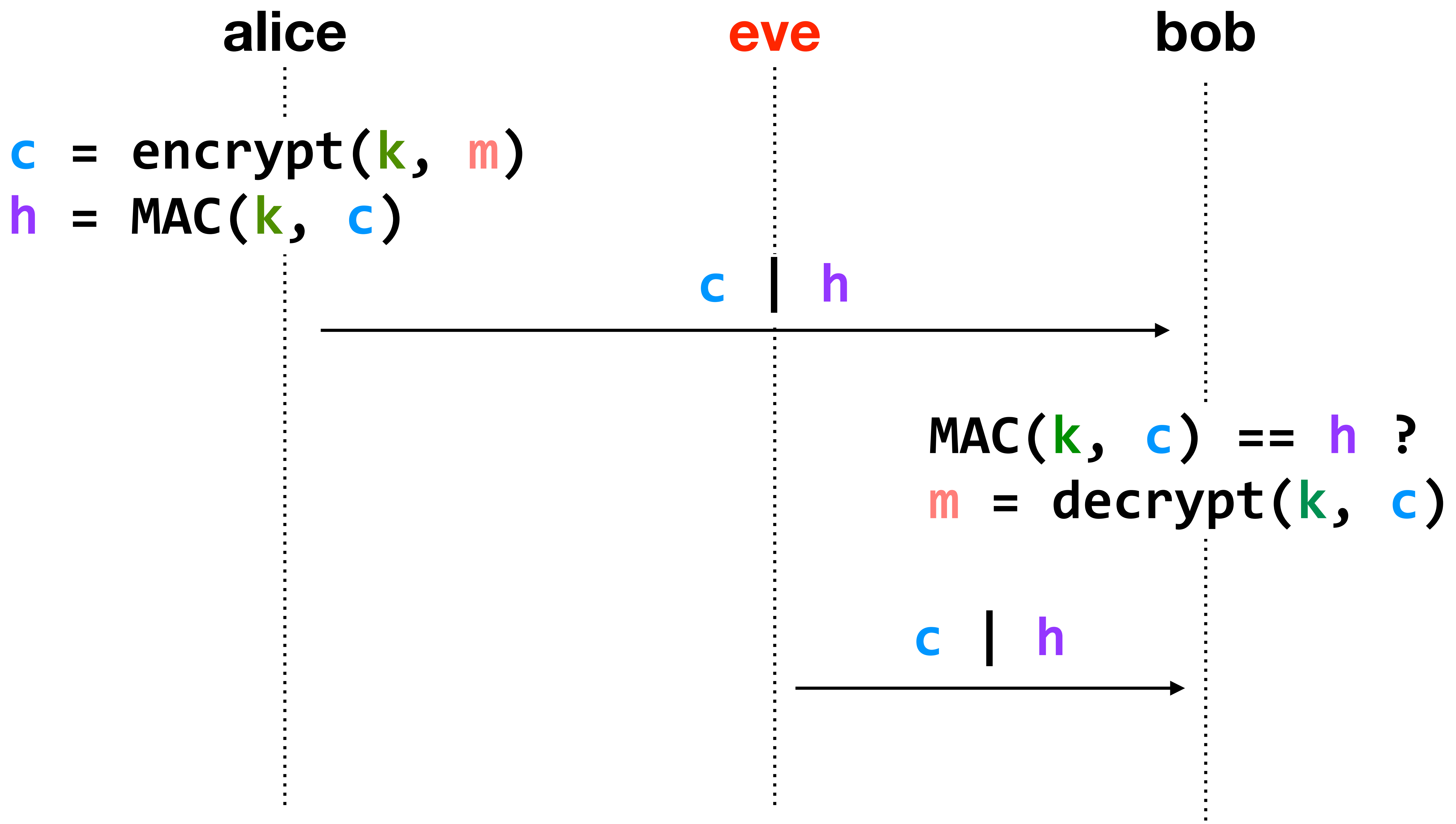
```

property: given the `message`, it is (virtually) impossible to obtain the `token` without knowing the `key`

it is also impossible to go in the reverse direction: given `token`, you can’t get `message` even with the `key`



problem: replay attacks

eve could intercept a message, re-send it at a later time

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

threat model: adversary can observe network data, tamper with packets, and insert its own packets

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encrypt(key, message) → ciphertext
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```

property: given the `ciphertext`, it is (virtually) impossible to obtain the `message` without knowing the `key`

```
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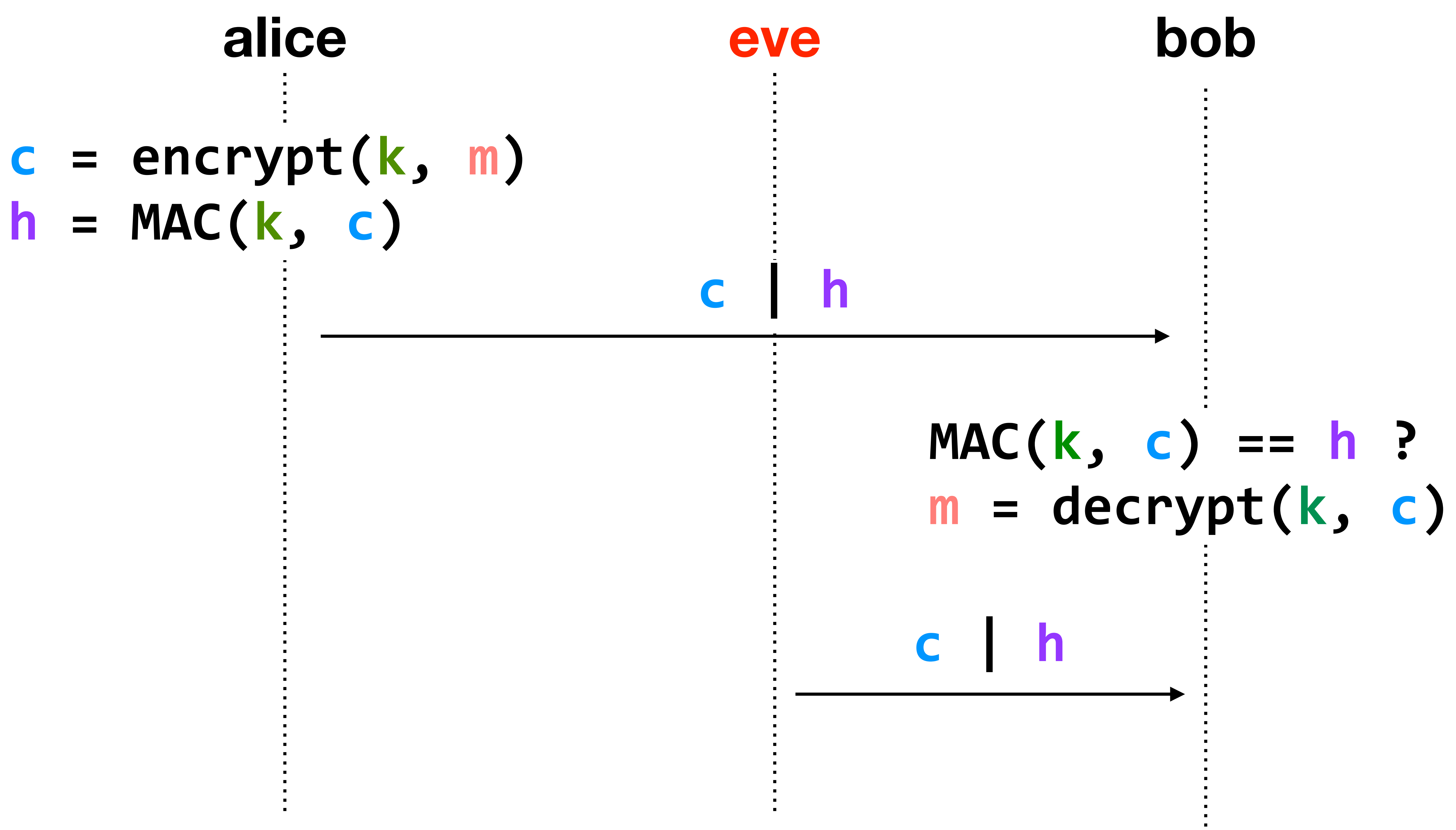
it is also impossible to go in the reverse direction: given `token`, you can’t get `message` even with the `key`



question: why would eve do this?

can you think of times when re-sending a message would cause damage?

bonus question: do you know any techniques to mitigate this attack?

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

threat model: adversary can observe network data, tamper with packets, and insert its own packets

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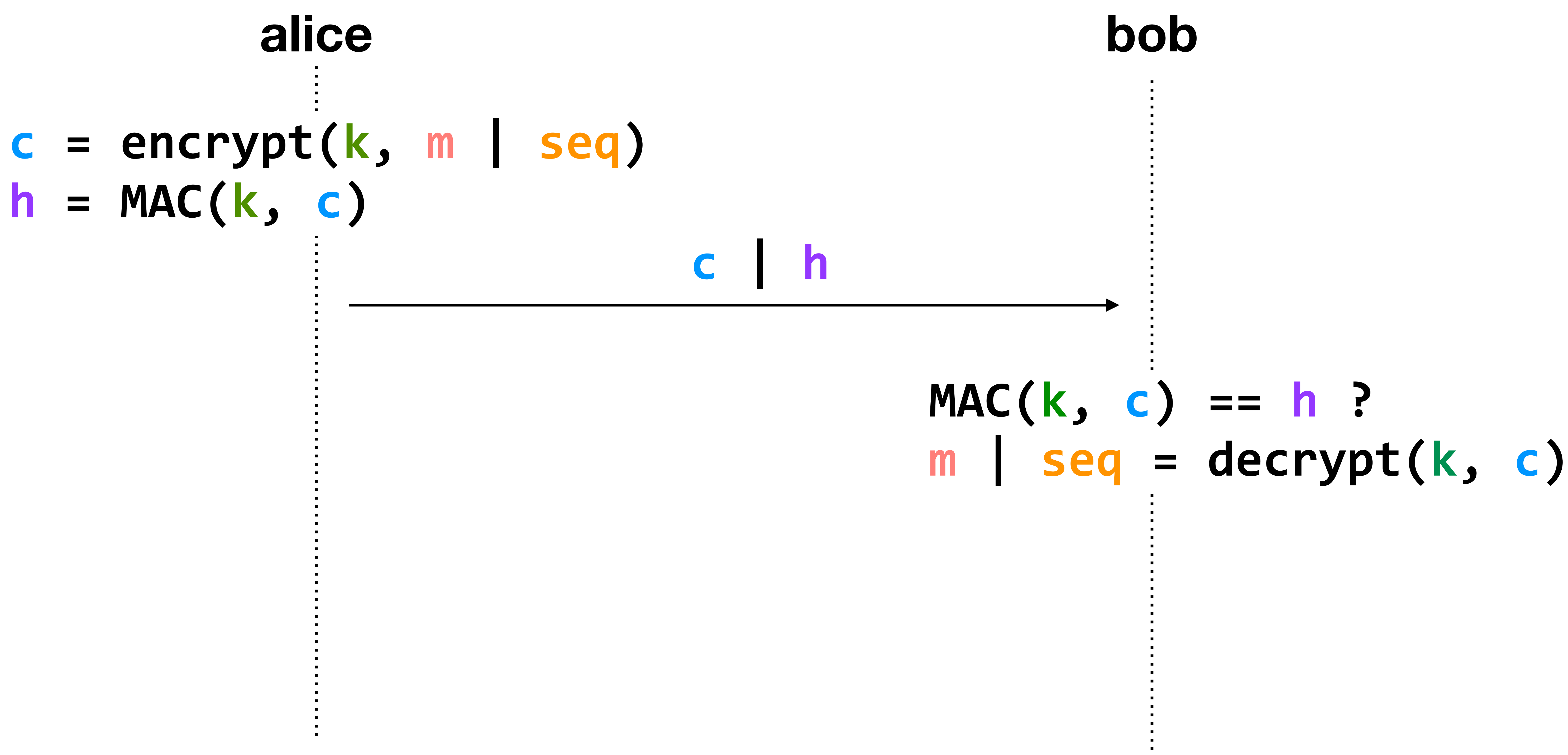

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```
MAC(k, c) == h ?
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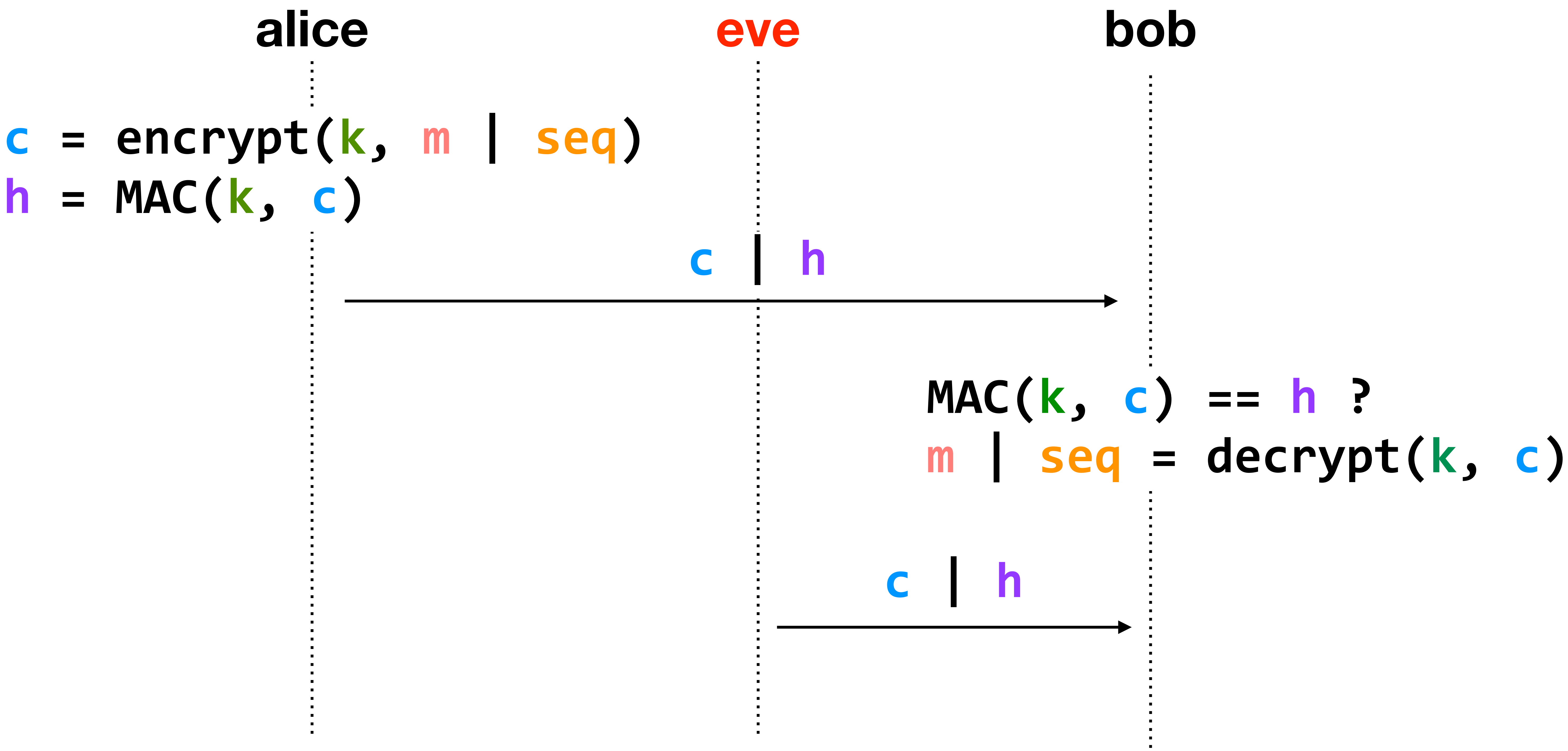

alice

eve

bob

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c | h

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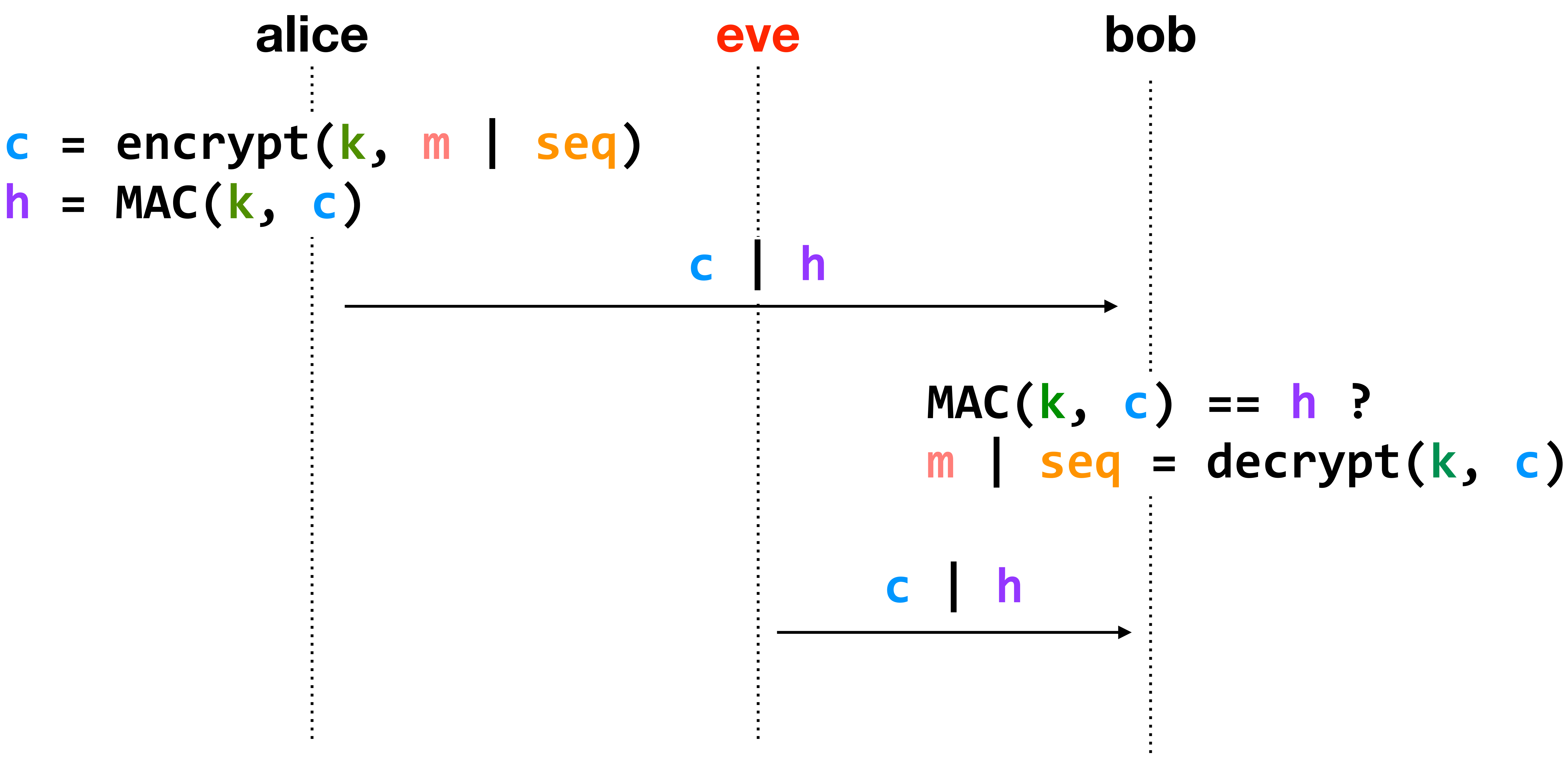

if eve replays the message, bob will notice
because bob has already seen this sequence number

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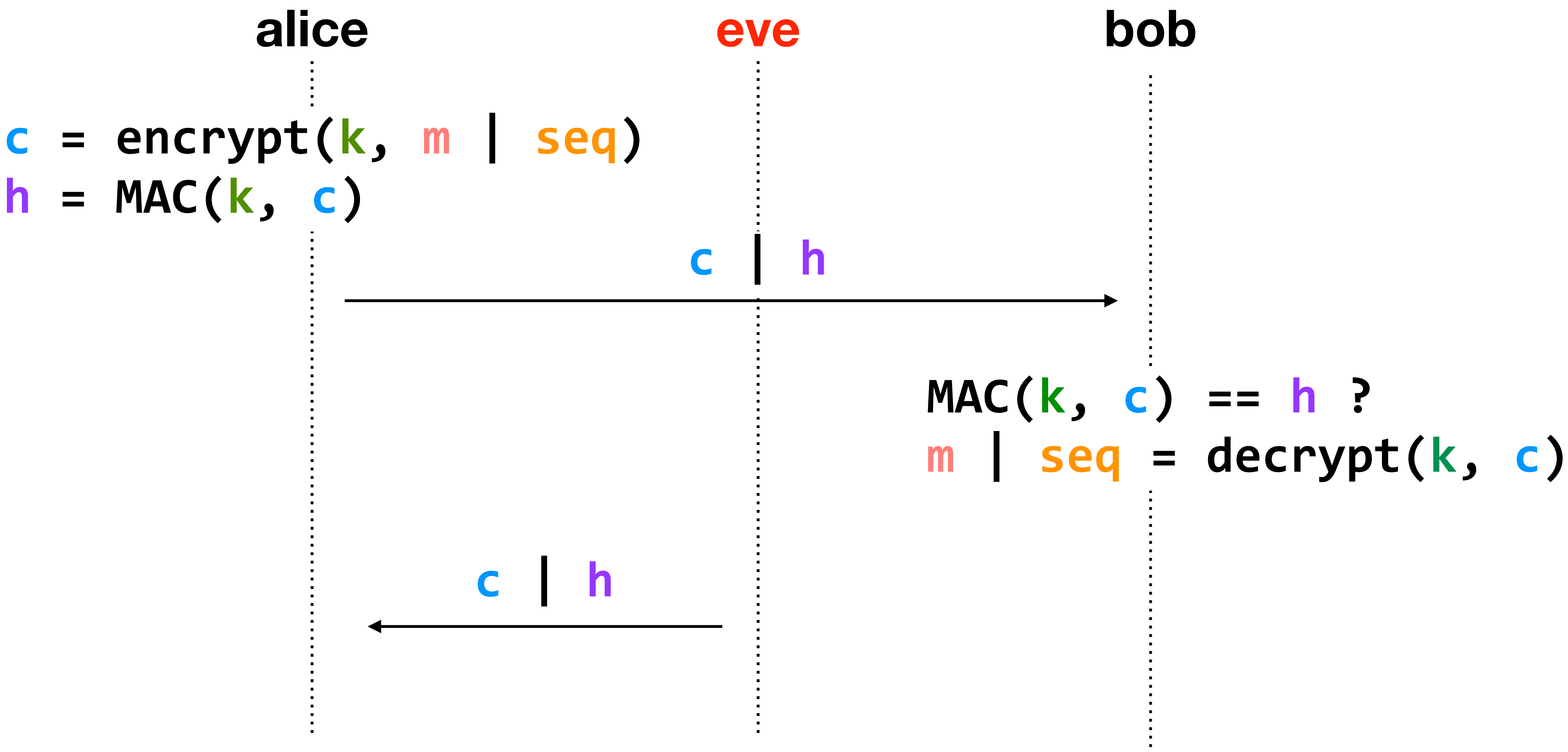

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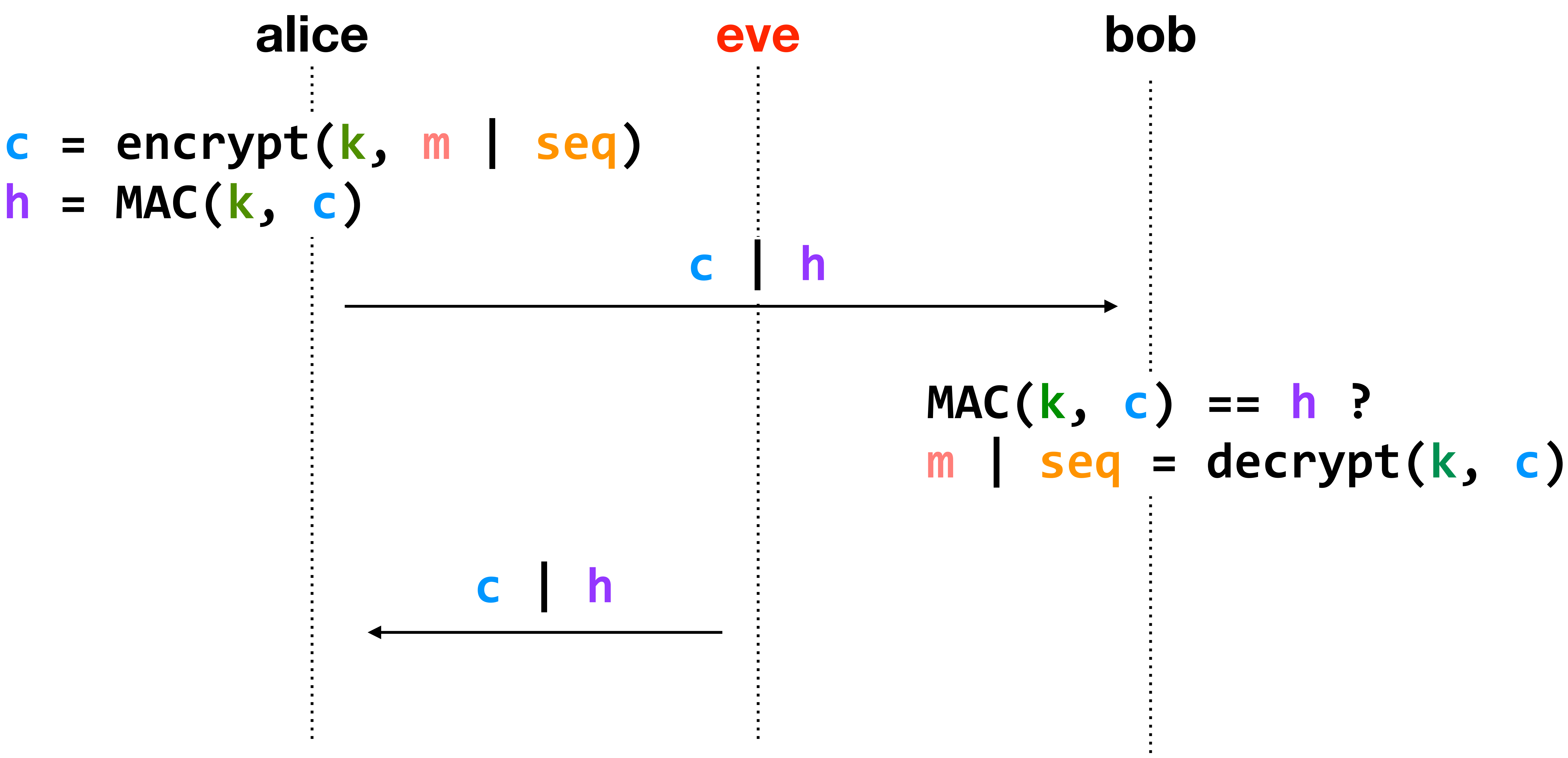

alice **eve** **bob**

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```

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

c | h

problem: reflection attacks

eve could intercept a message, re-send it at a later time in the opposite direction

Katrina LaCurts | lacurts@mit.edu | 6.1800 2025

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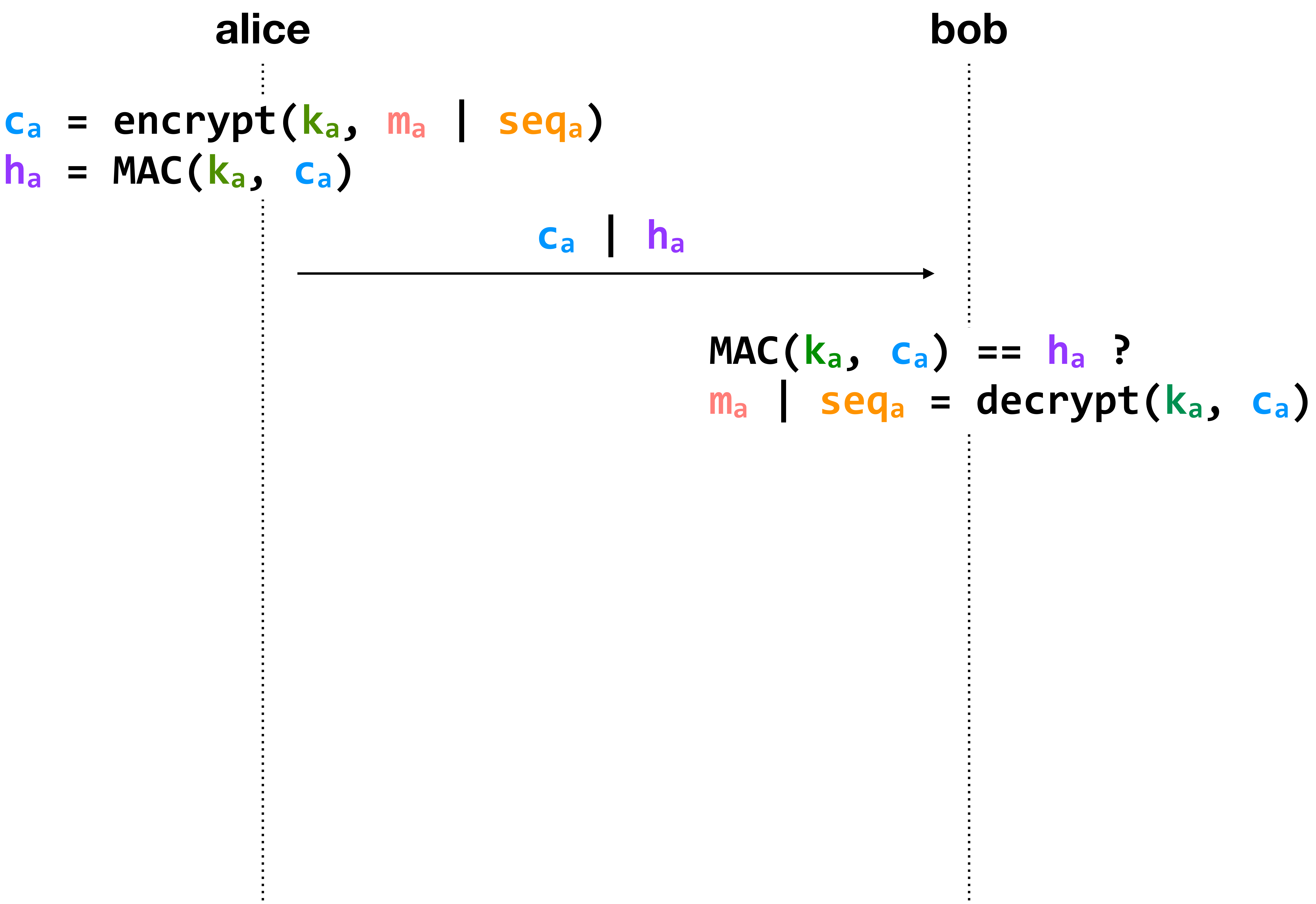

alice
bob
c_a = encrypt(k_a, m_a | seq_a)
h_a = MAC(k_a, c_a)
c_a | h_a
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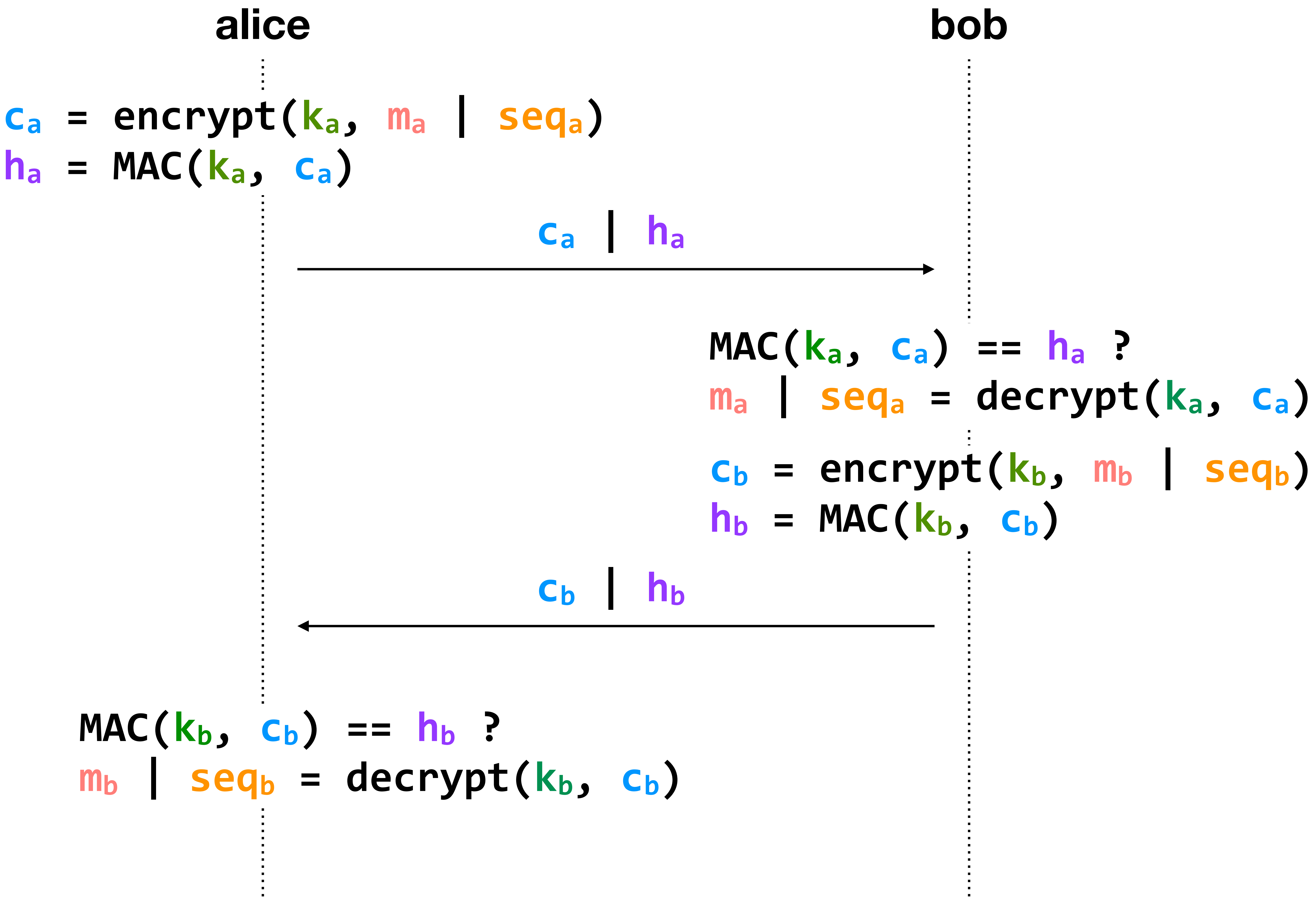

$c_a = \text{encrypt}(k_a, m_a \mid seq_a)$

$h_a = \text{MAC}(k_a, c_a)$

$c_a \mid h_a$

$\text{MAC}(k_a, c_a) == h_a$?

$m_a \mid seq_a = \text{decrypt}(k_a, c_a)$

$c_b = \text{encrypt}(k_b, m_b \mid seq_b)$

$h_b = \text{MAC}(k_b, c_b)$

$c_b \mid h_b$

$\text{MAC}(k_b, c_b) == h_b$?

$m_b \mid seq_b = \text{decrypt}(k_b, c_b)$

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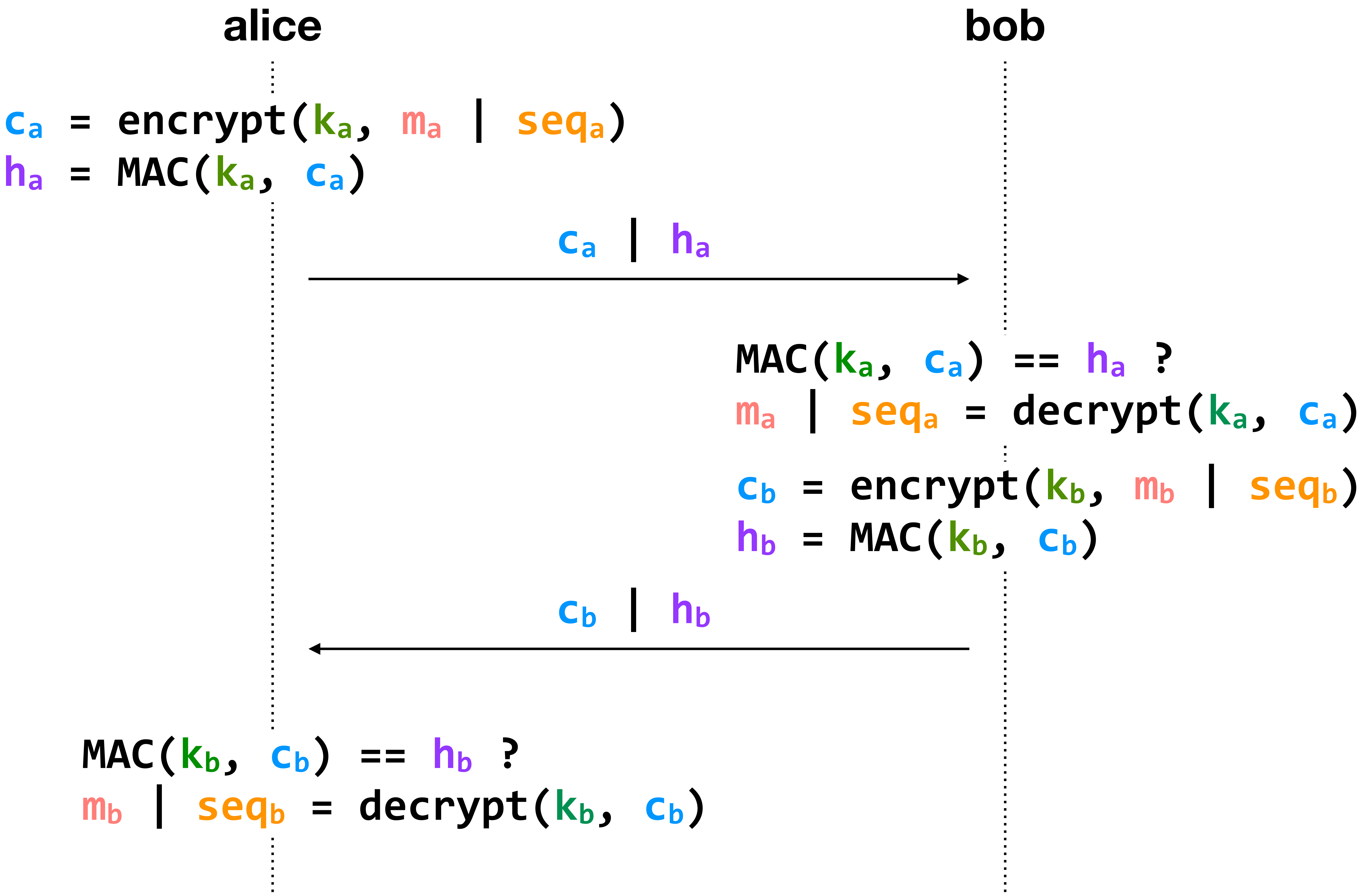

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h_b = MAC(k_b, c_b)

c_b | h_b

MAC(k_b, c_b) == h_b ?
m_b | seq_b = decrypt(k_b, c_b)

problem: how do the parties know the keys?

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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e.g., 10 mod 8 = 2; 23 mod 10 = 3

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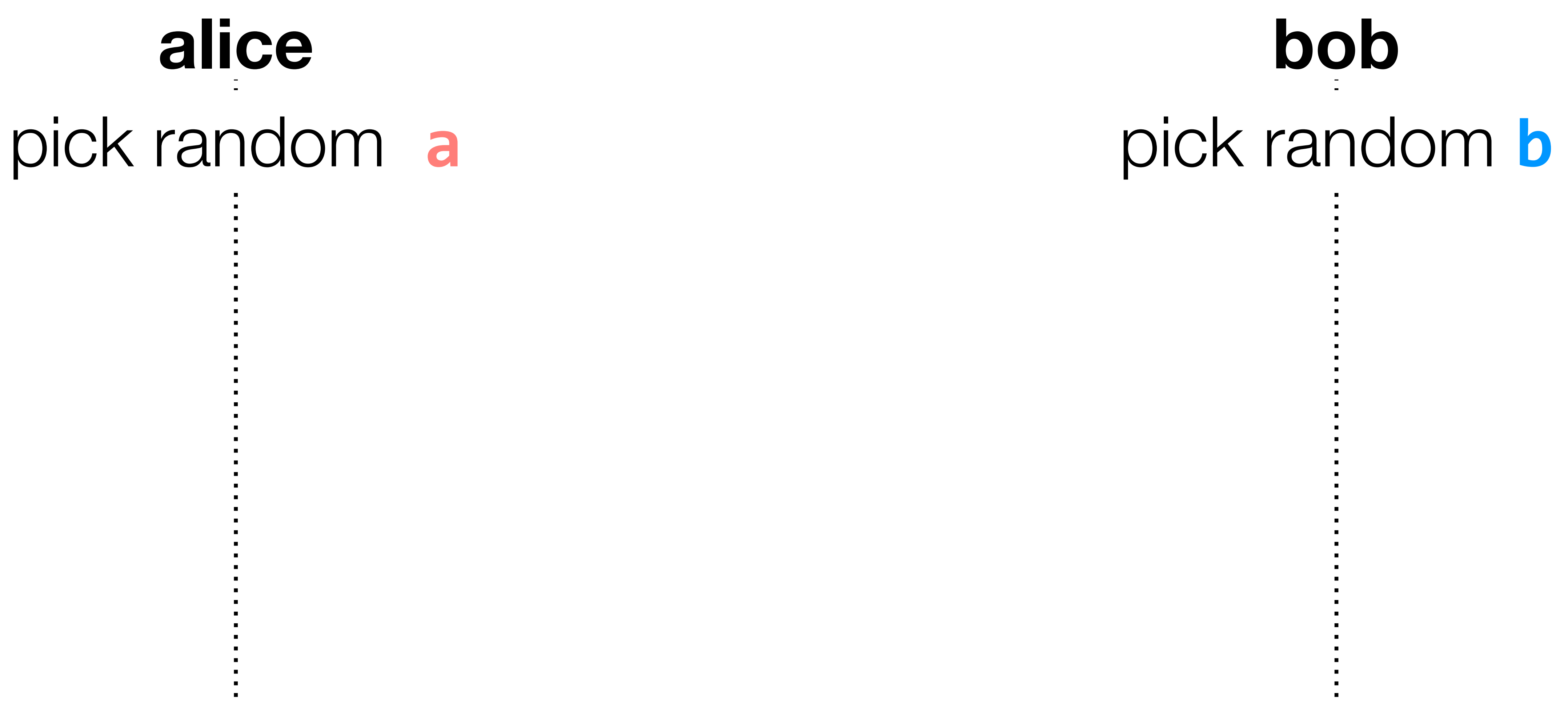

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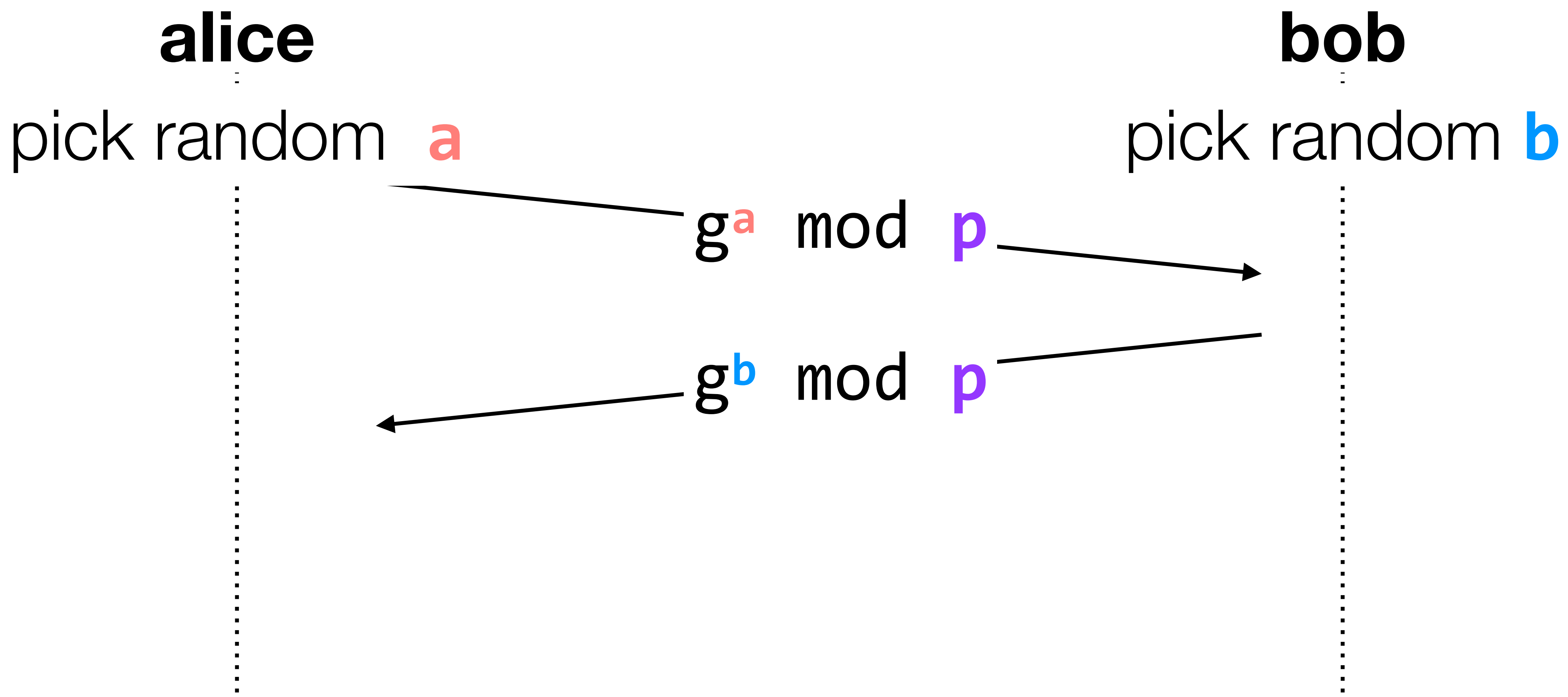

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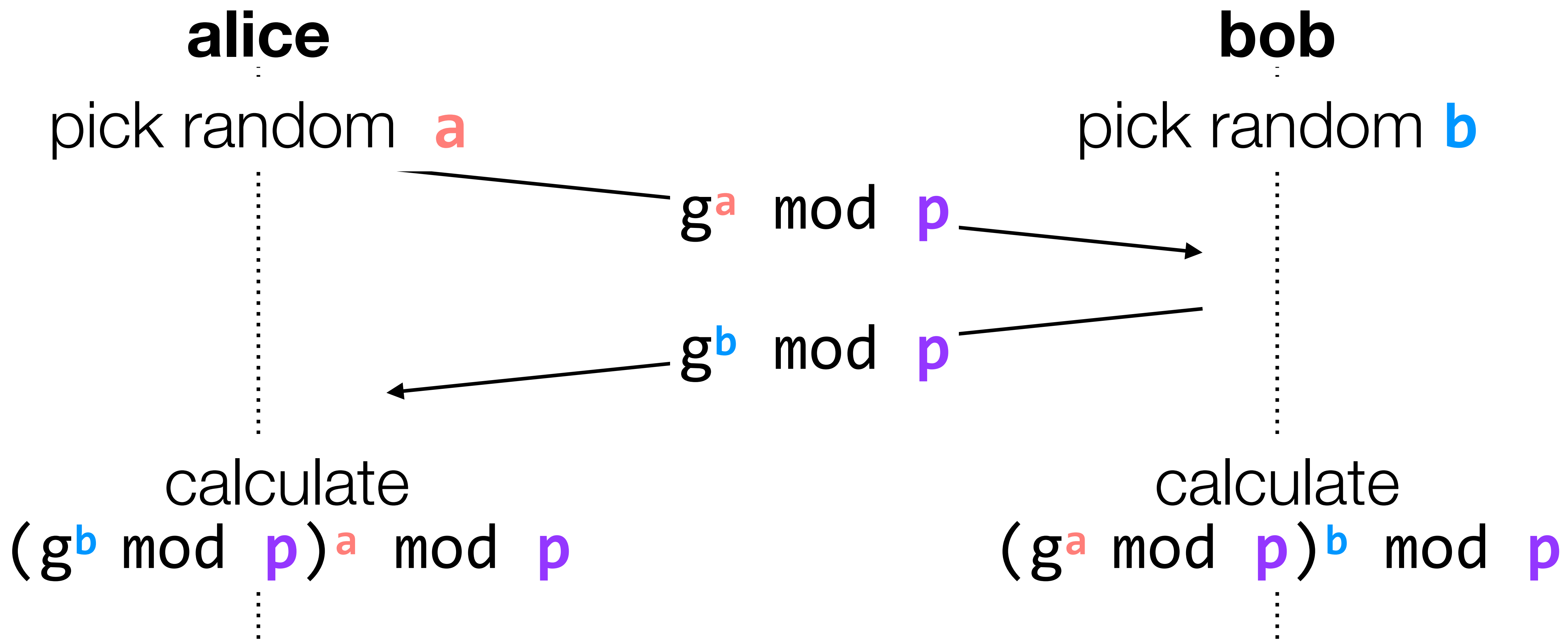

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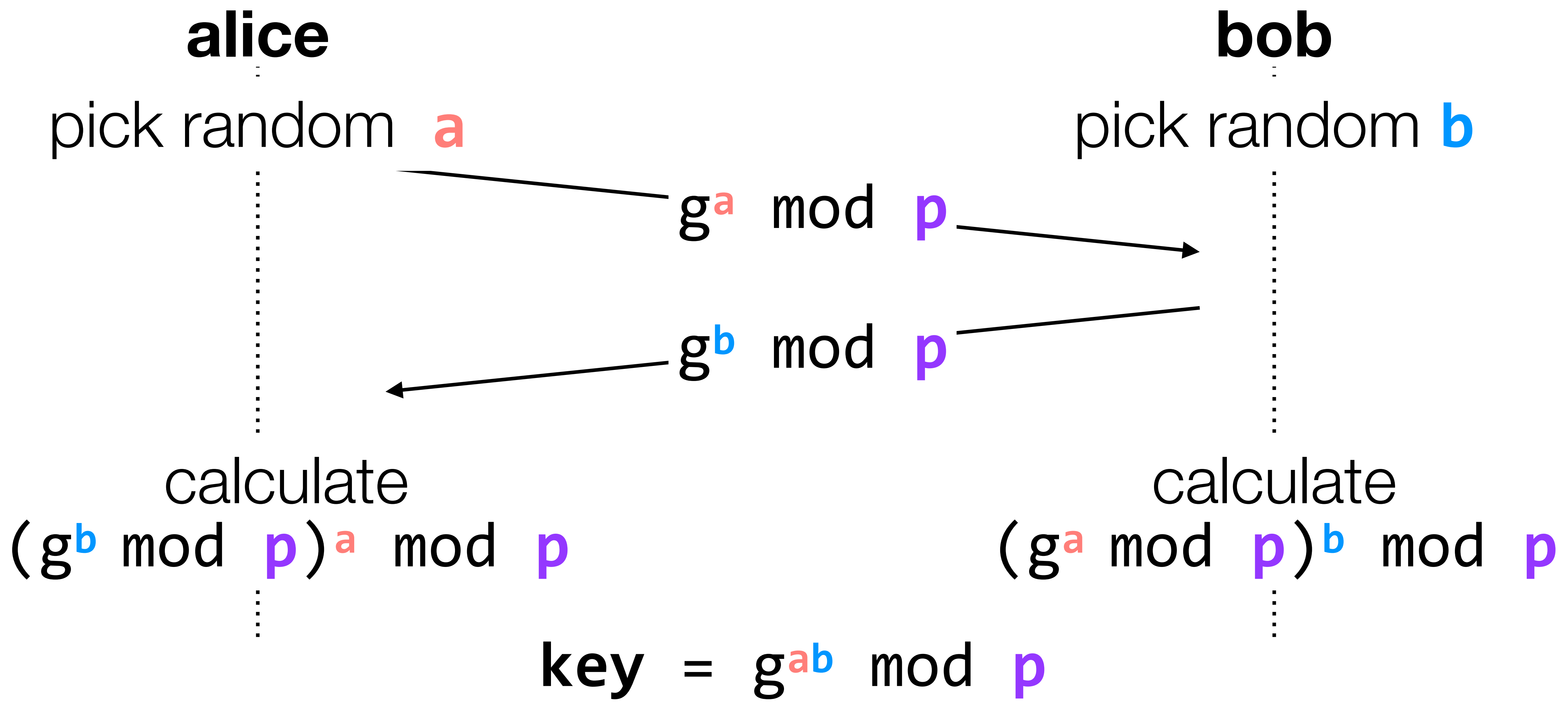

key = $g^{ab} \bmod p$

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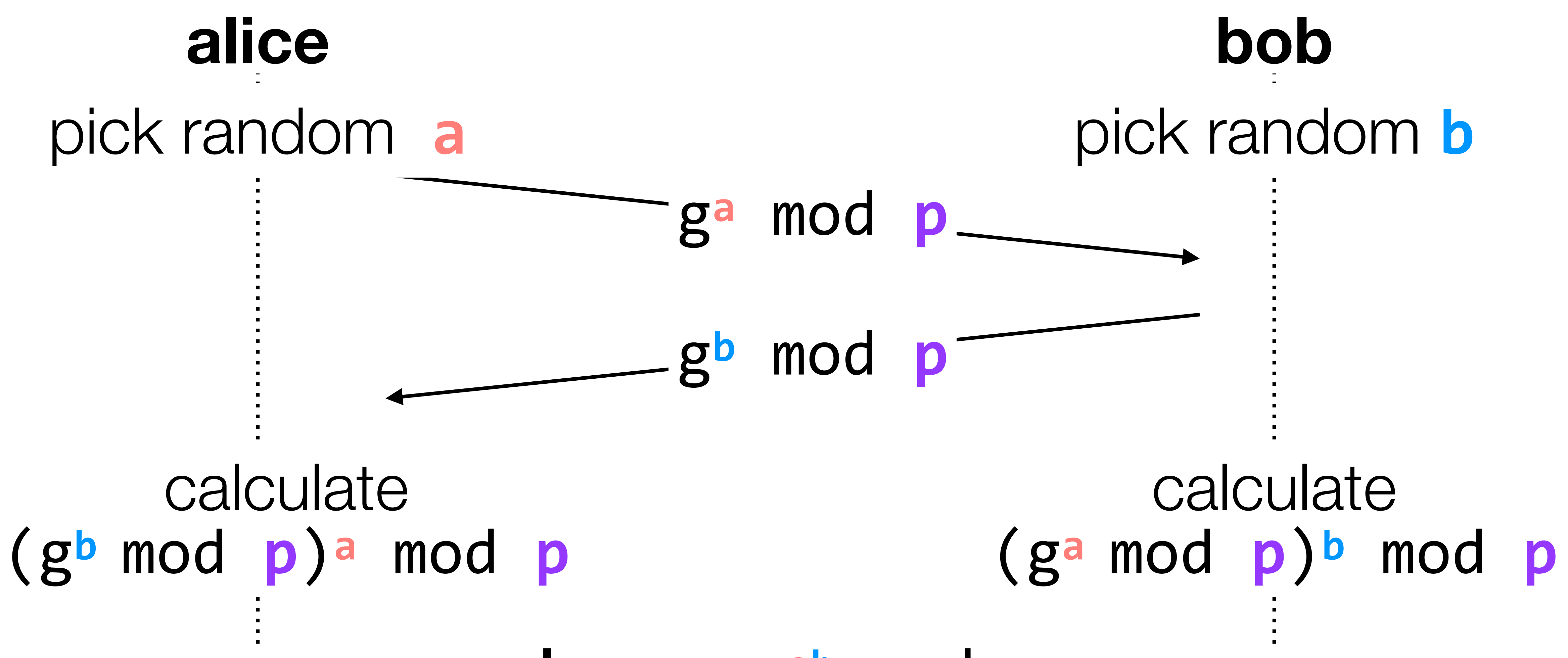

key $= g^{ab} \bmod p$

$(g^x \bmod p)^y \bmod p = (g^y \bmod p)^x \bmod p = g^{xy} \bmod p$

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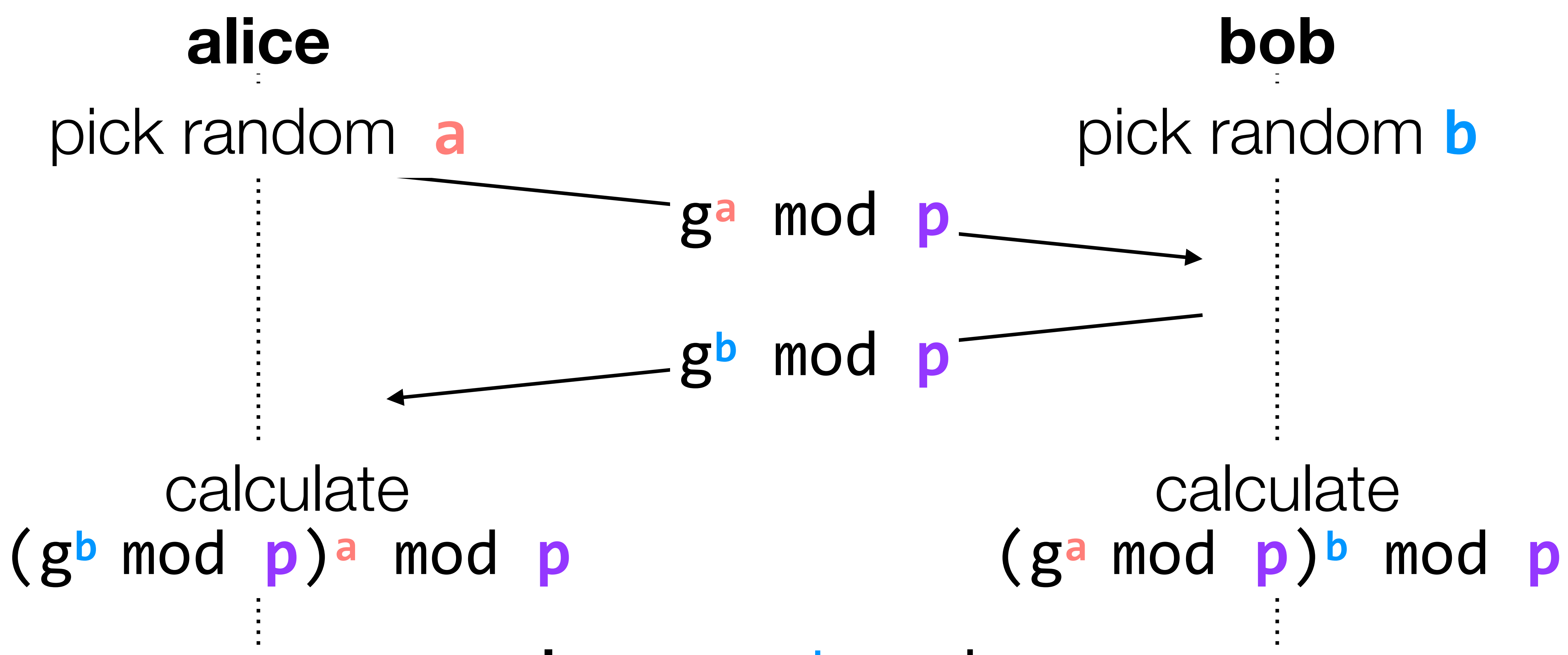

$$\mathtt{key} = \mathtt{g^{ab}\ mod\ p}$$

$(g^x \text{ mod } p)^y \text{ mod } p = (g^y \text{ mod } p)^x \text{ mod } p = g^{xy} \text{ mod } p$

an observer on the network knows p, g, $\mathtt{g^a\ mod\ p}$, and $\mathtt{g^b\ mod\ p}$, but cannot use that information to learn a or b

and thus cannot calculate the key

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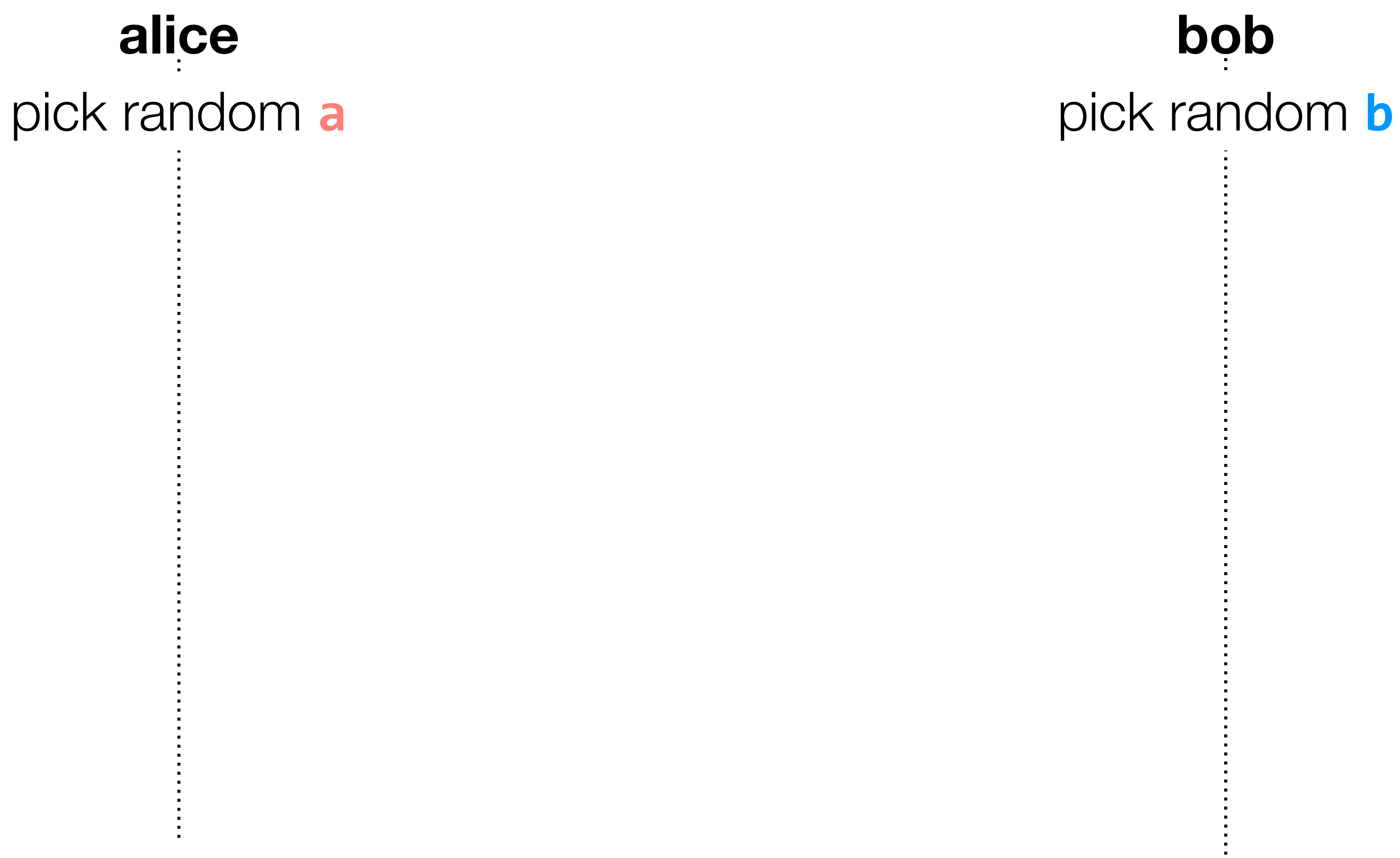

alice

pick random a

bob

pick random b

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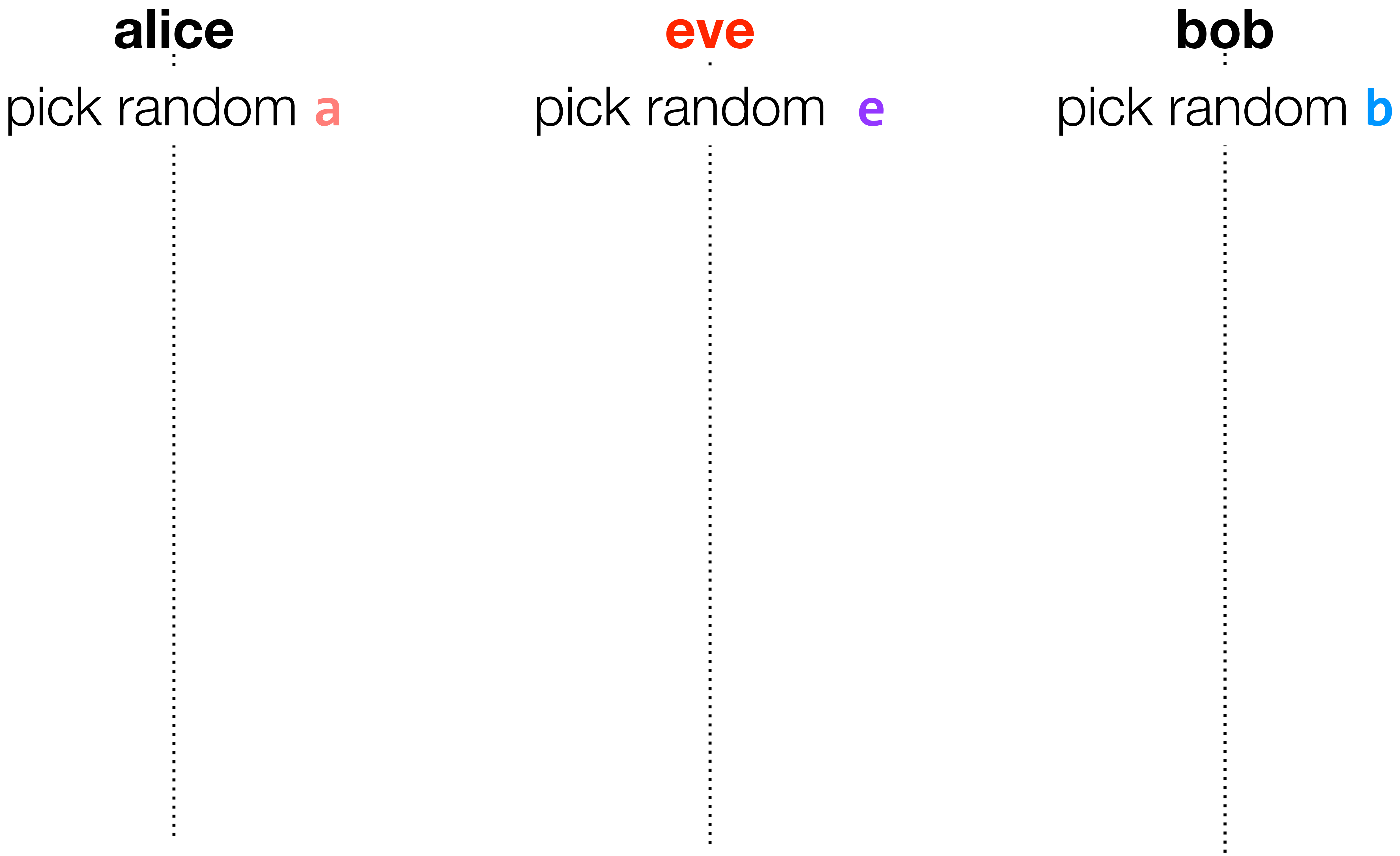

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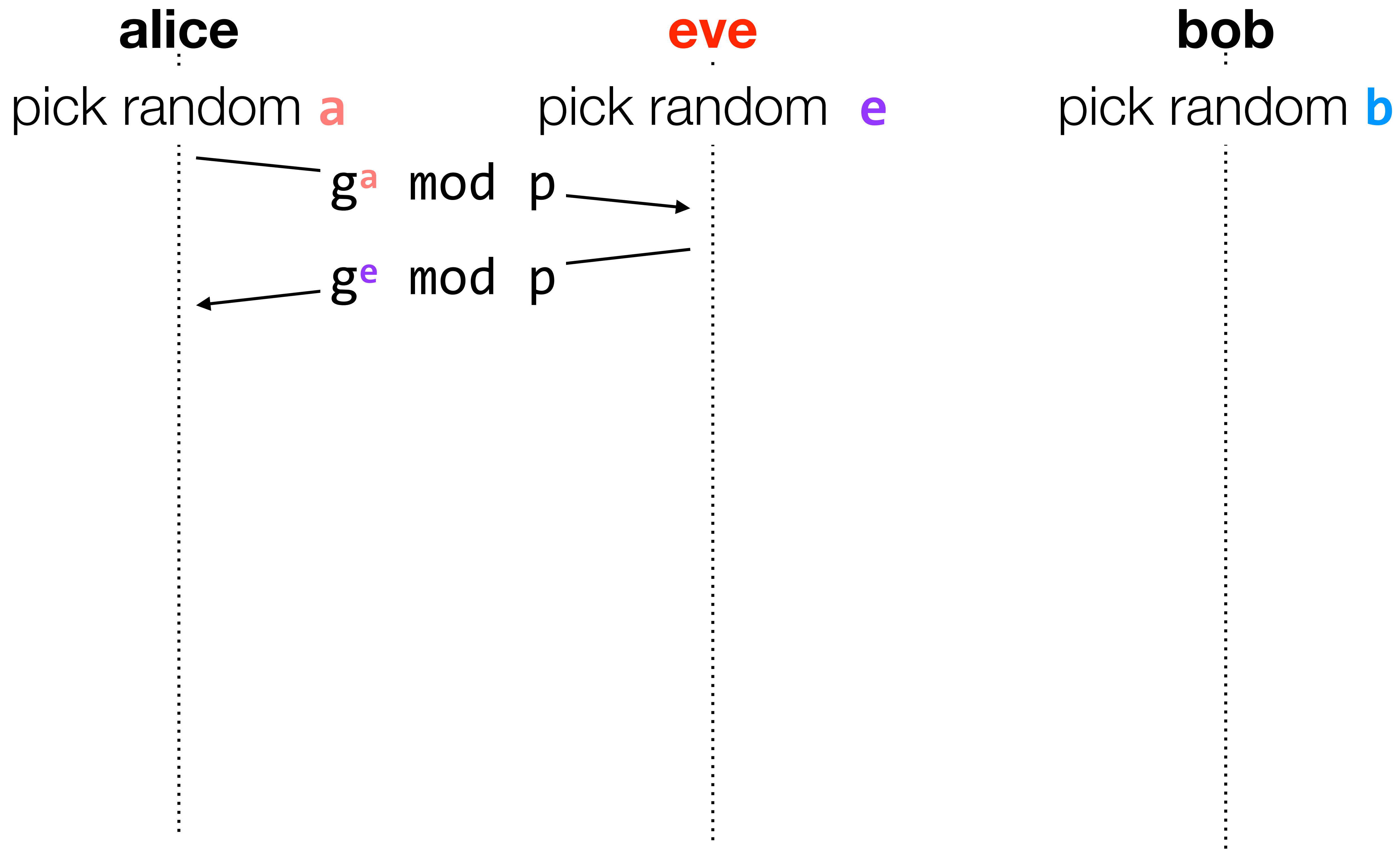

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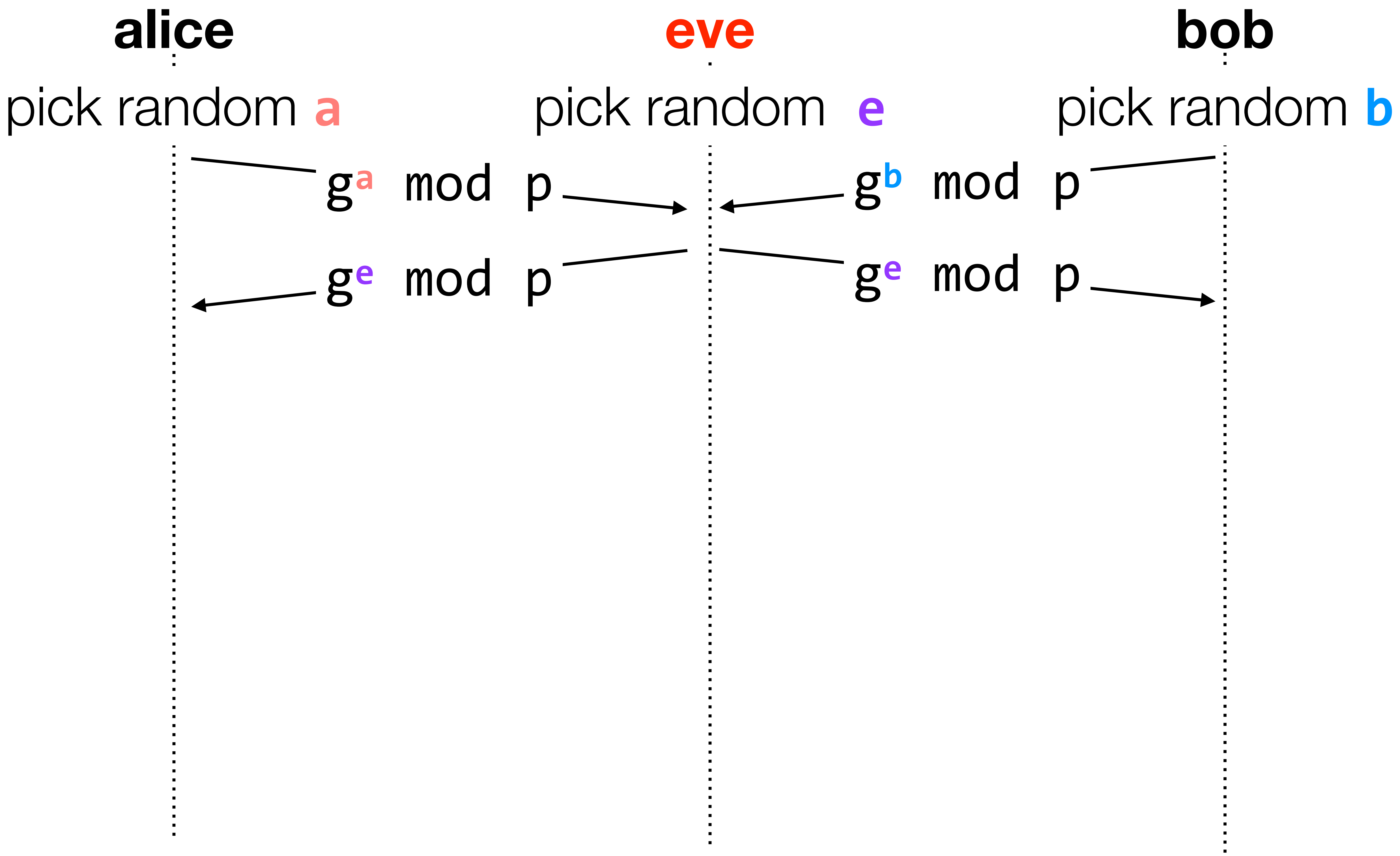

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

threat model: adversary can observe network data, tamper with packets, and insert its own packets

`x mod y` is the remainder when **`x`** is divided by **`y`**

e.g., 10 mod 8 = 2; 23 mod 10 = 3

known to everyone: p (prime), g

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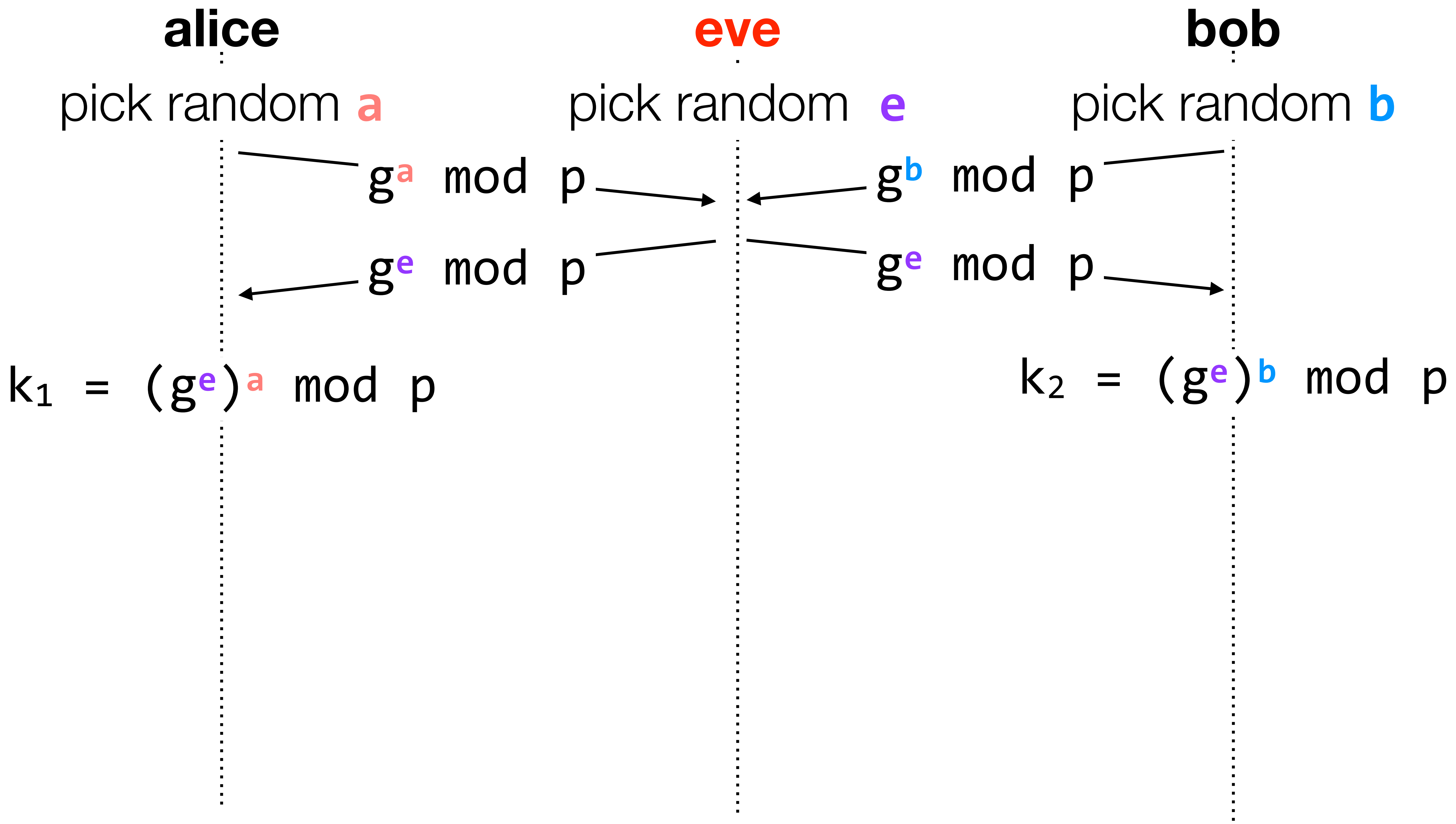

alice

eve

bob

pick random a

pick random e

pick random b

$g^a \bmod p$

$g^b \bmod p$

$g^e \bmod p$

$g^e \bmod p$

$k_1 = (g^e)^a \bmod p$

$k_2 = (g^e)^b \bmod p$

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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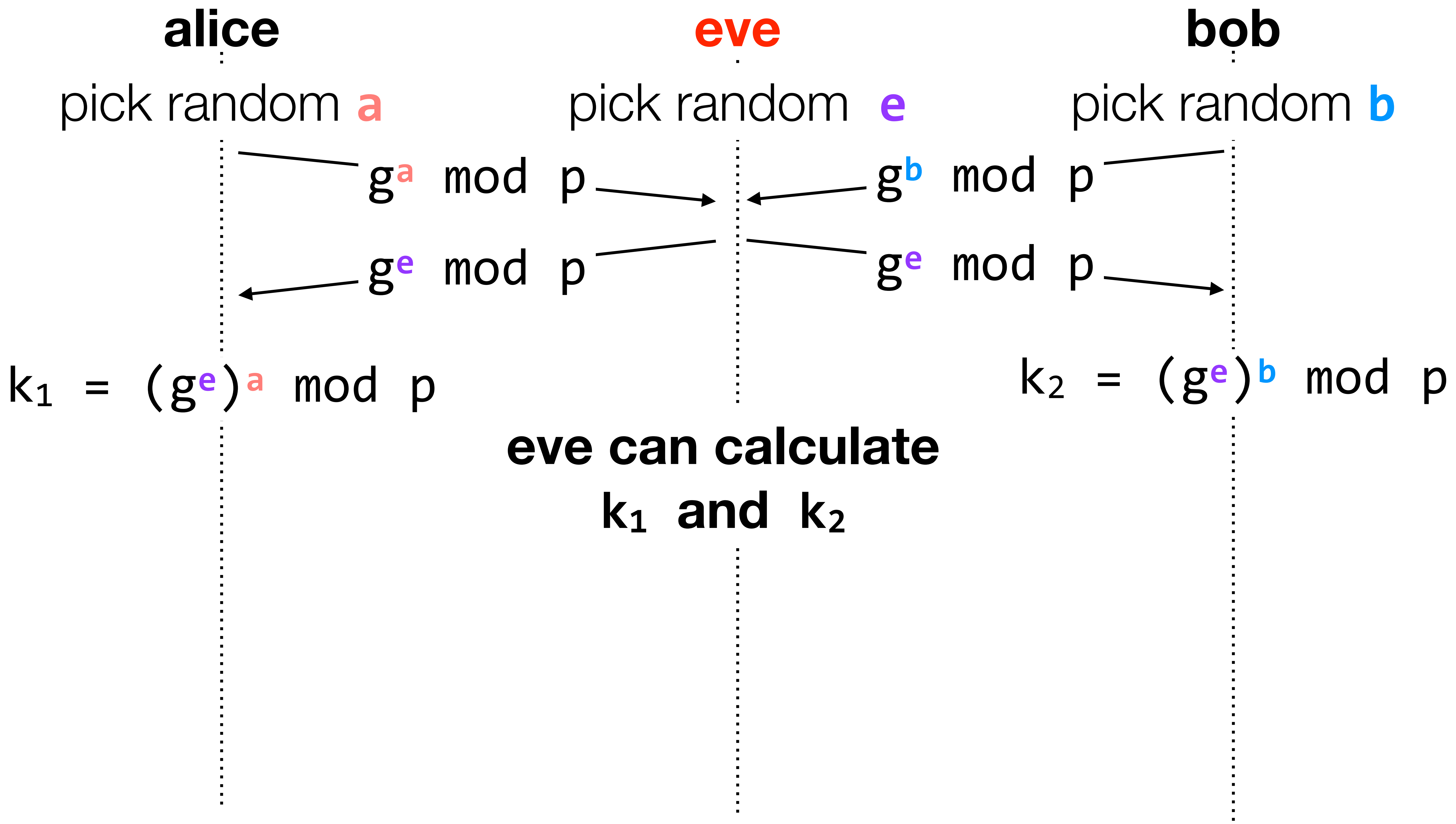

eve can calculate k_1 and k_2

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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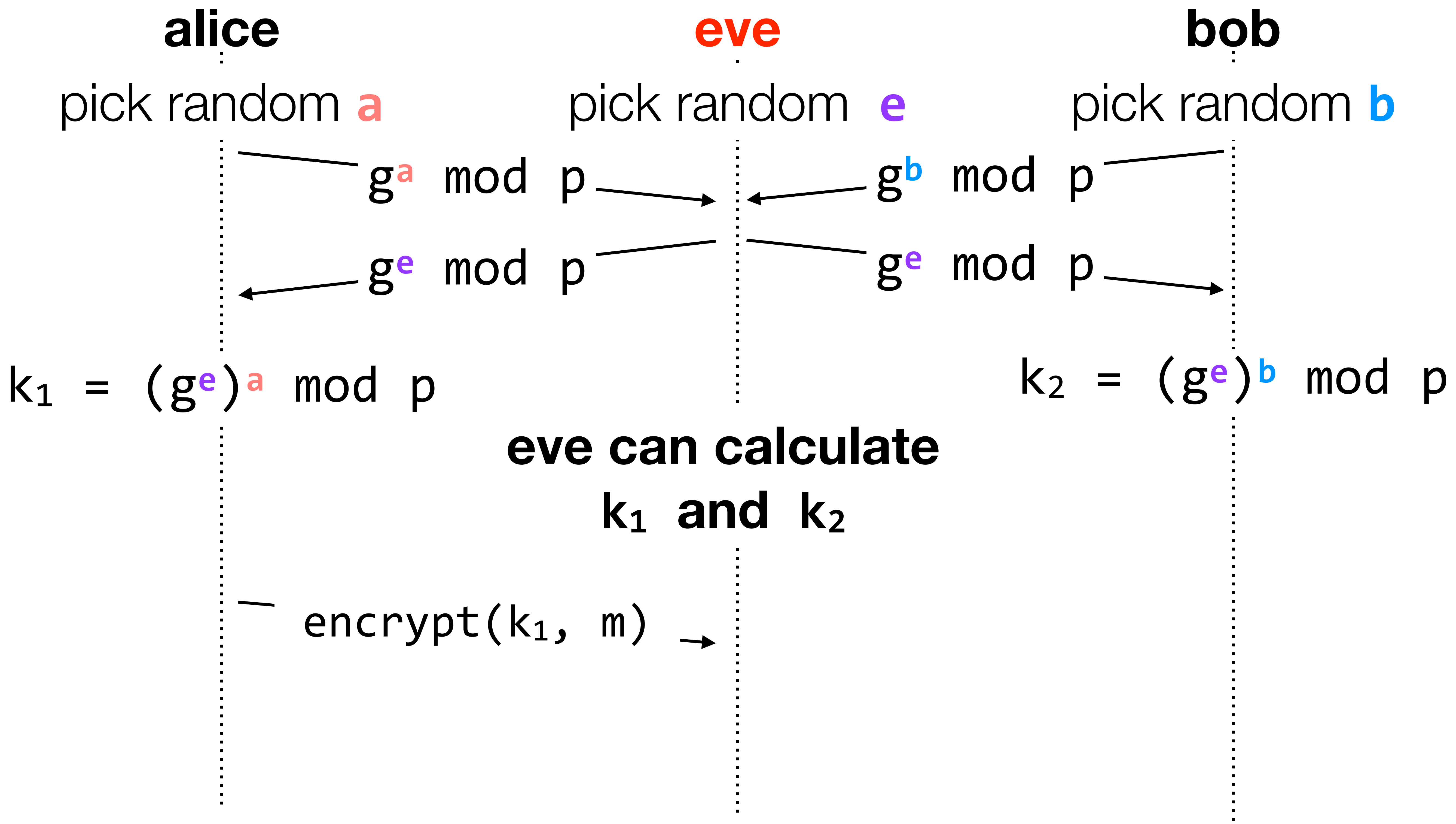

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$g^e \bmod p$

$k_1 = (g^e)^a \bmod p$

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eve can calculate k_1 and k_2

encrypt(k_1, m)

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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e.g., 10 mod 8 = 2; 23 mod 10 = 3

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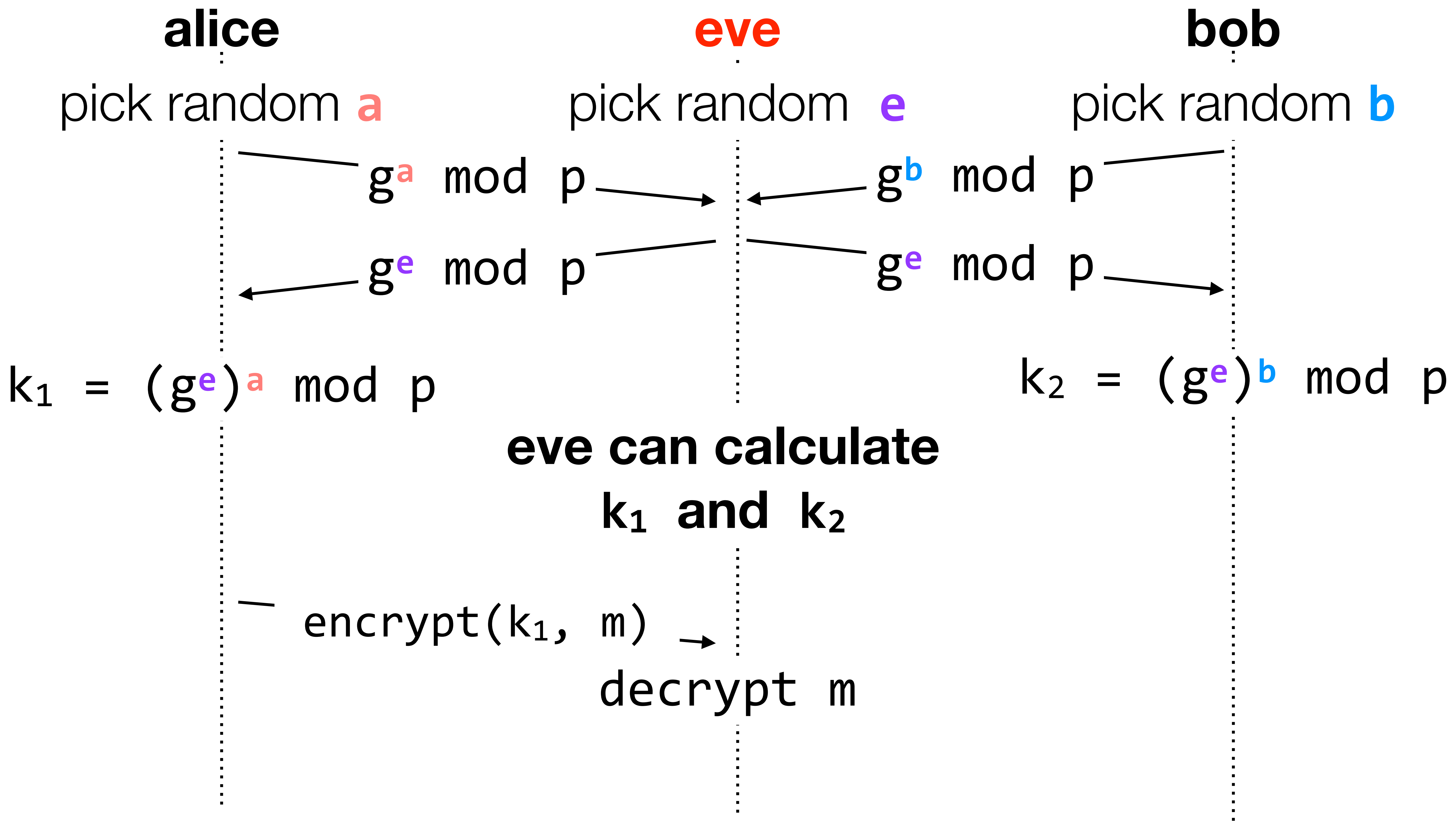
g and p are related mathematically (g is a “primitive root” mod p). this relationship makes the next property possible.

property: given g^r **mod p**, it is (virtually) impossible to determine **r** *even if* you know **g** *and* **p**



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g^a mod p

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$k_1 = (g^e)^a$ mod p

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eve can calculate k_1 and k_2

encrypt(k_1, m)

decrypt m

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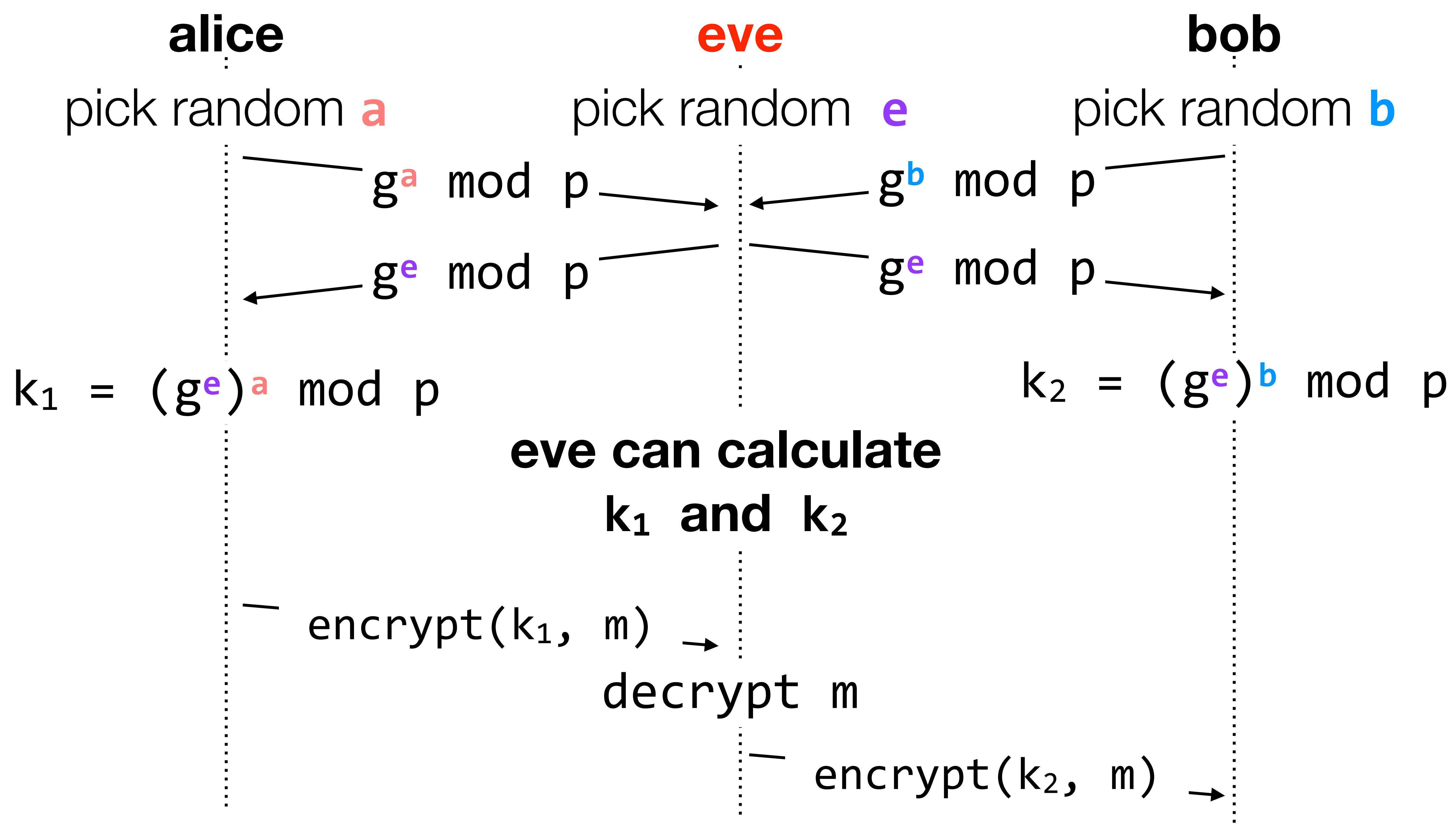

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decrypt m

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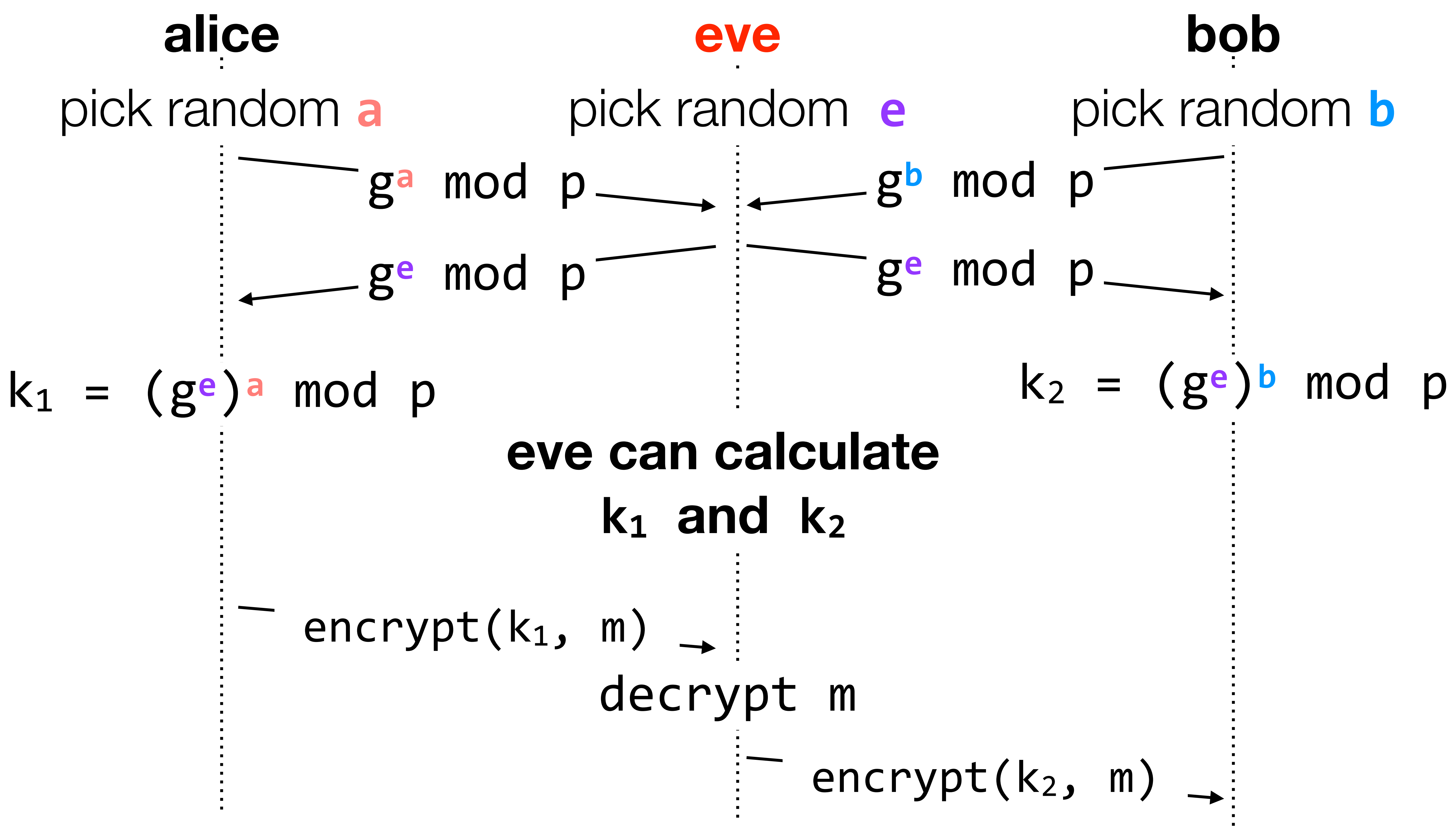

problem: alice and bob don't know they're not communicating directly

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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cryptographic signatures allow users to verify identities using public-key cryptography

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`{public_key, secret_key}`

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```
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  yes/no
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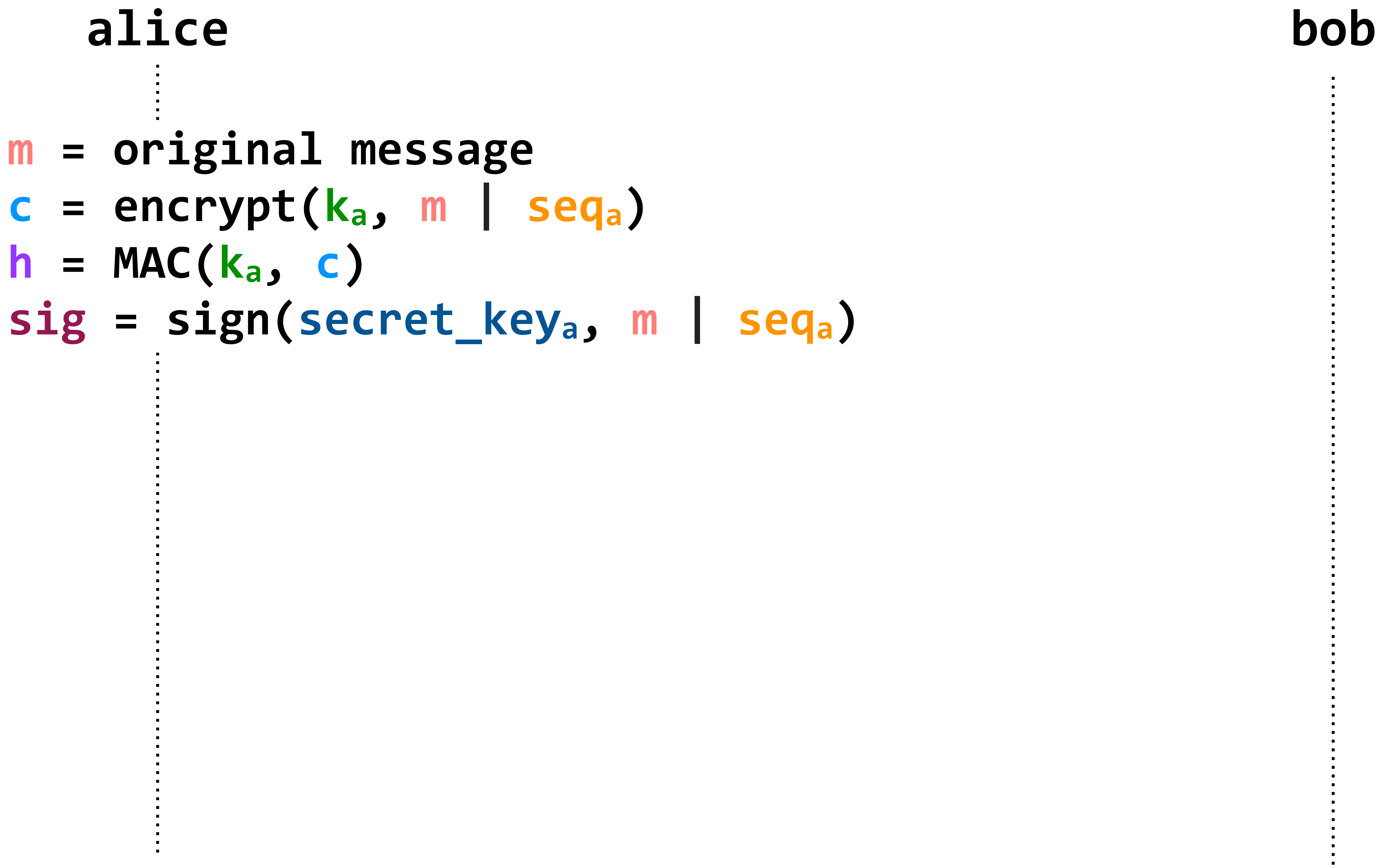

m = original message

c = encrypt(k_a, m | seq_a)

h = MAC(k_a, c)

sig = sign($secret\_key_a$, m | seq_a)

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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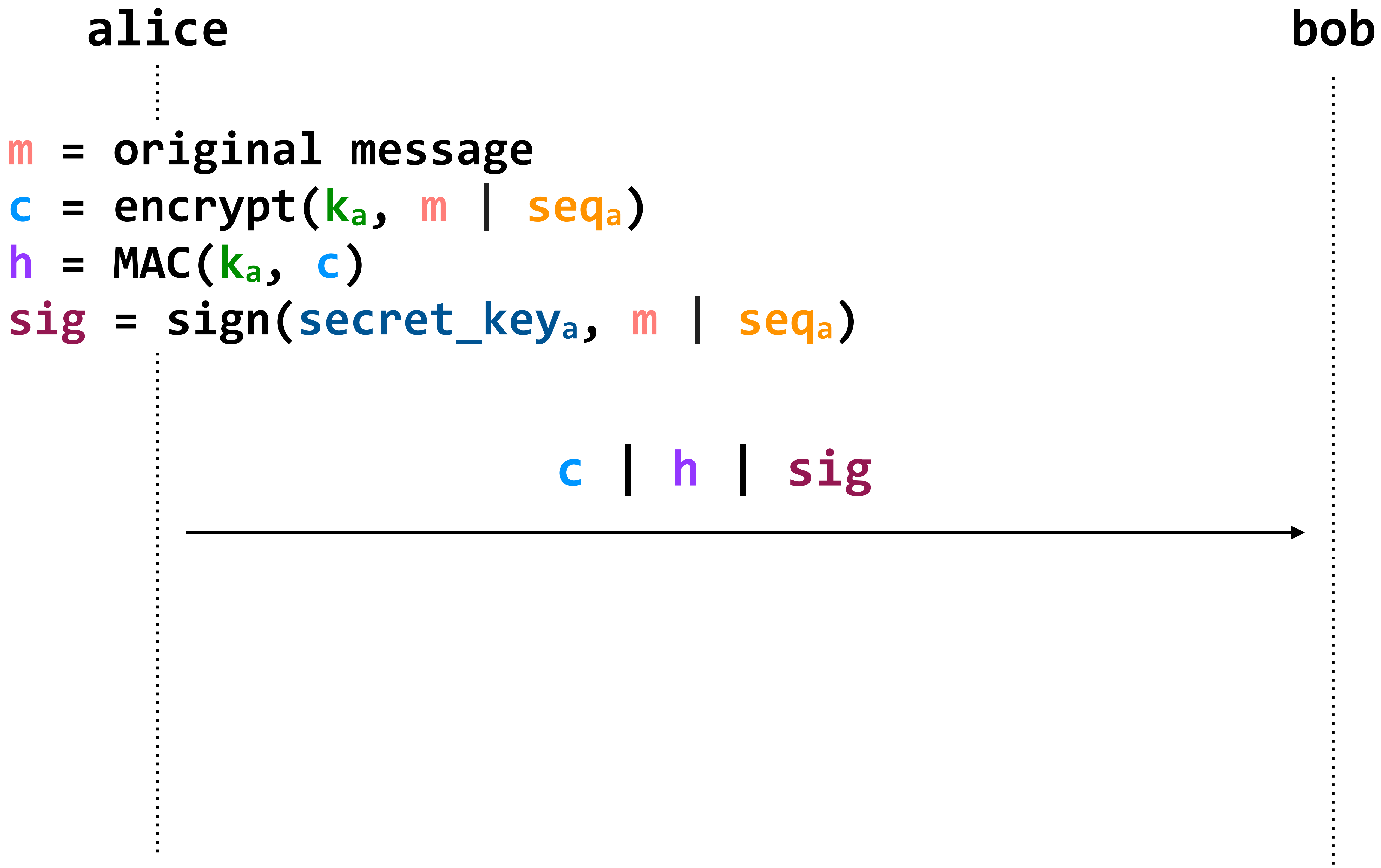

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c | h | sig

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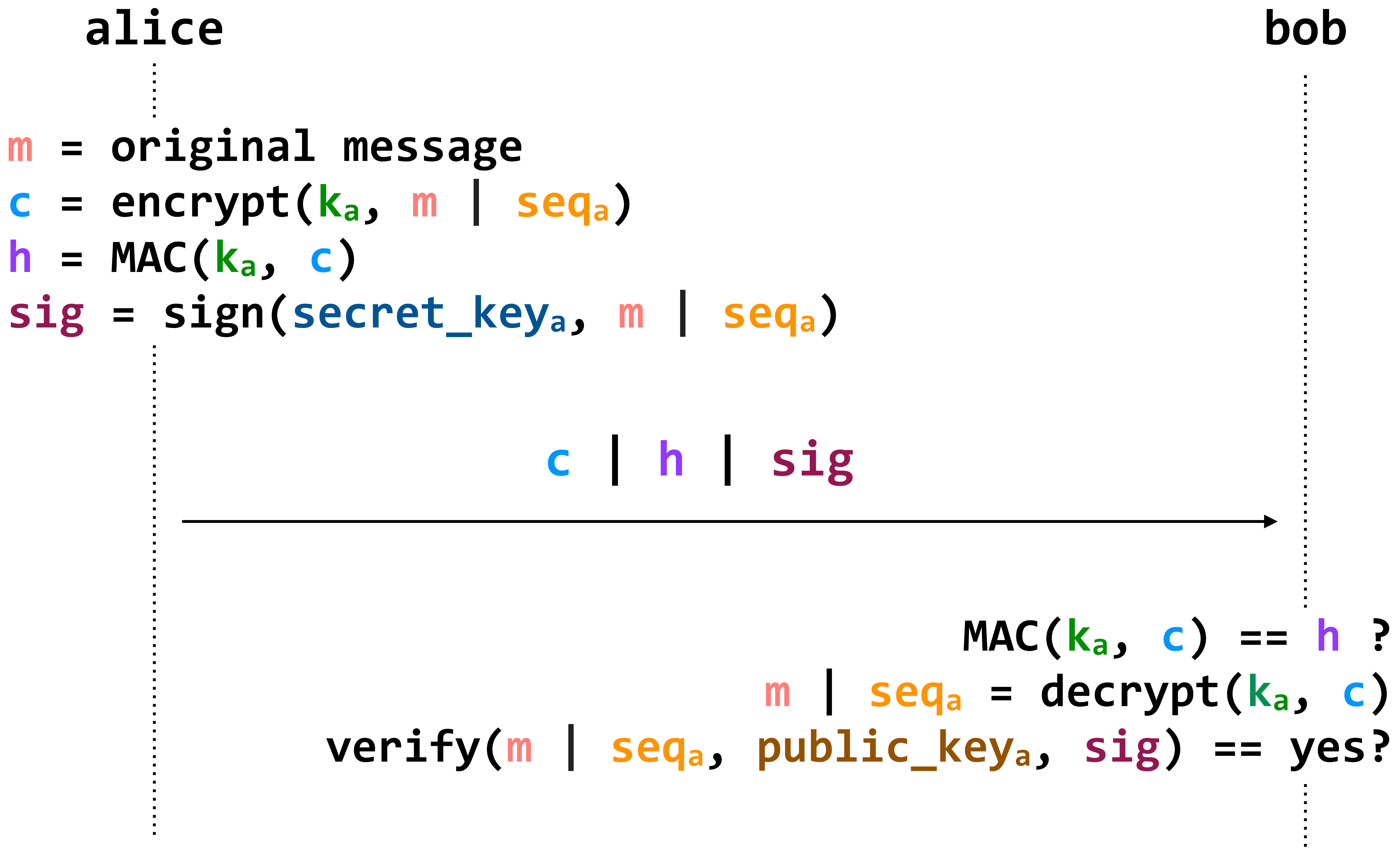

alice

bob

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sig = sign($secret\_key_a$, m | seq_a)

c | h | sig

MAC(k_a, c) == h ?

m | seq_a = decrypt(k_a, c)

verify(m | seq_a, $public\_key_a$, sig) == yes?

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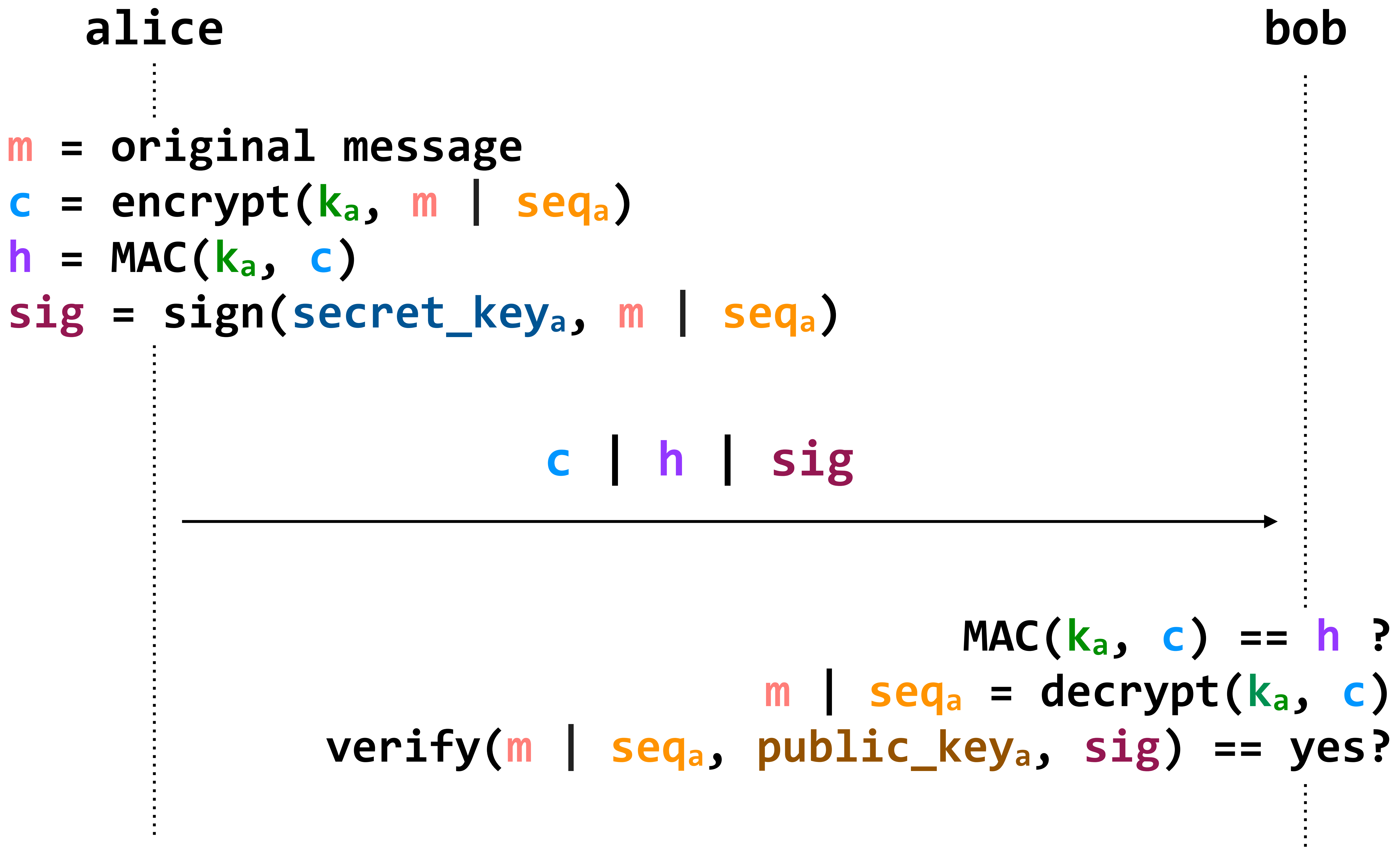

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this is a *rough outline* of how to think about public signatures in the context of this lecture. in reality, things work a bit differently; you'll see an example in a few minutes

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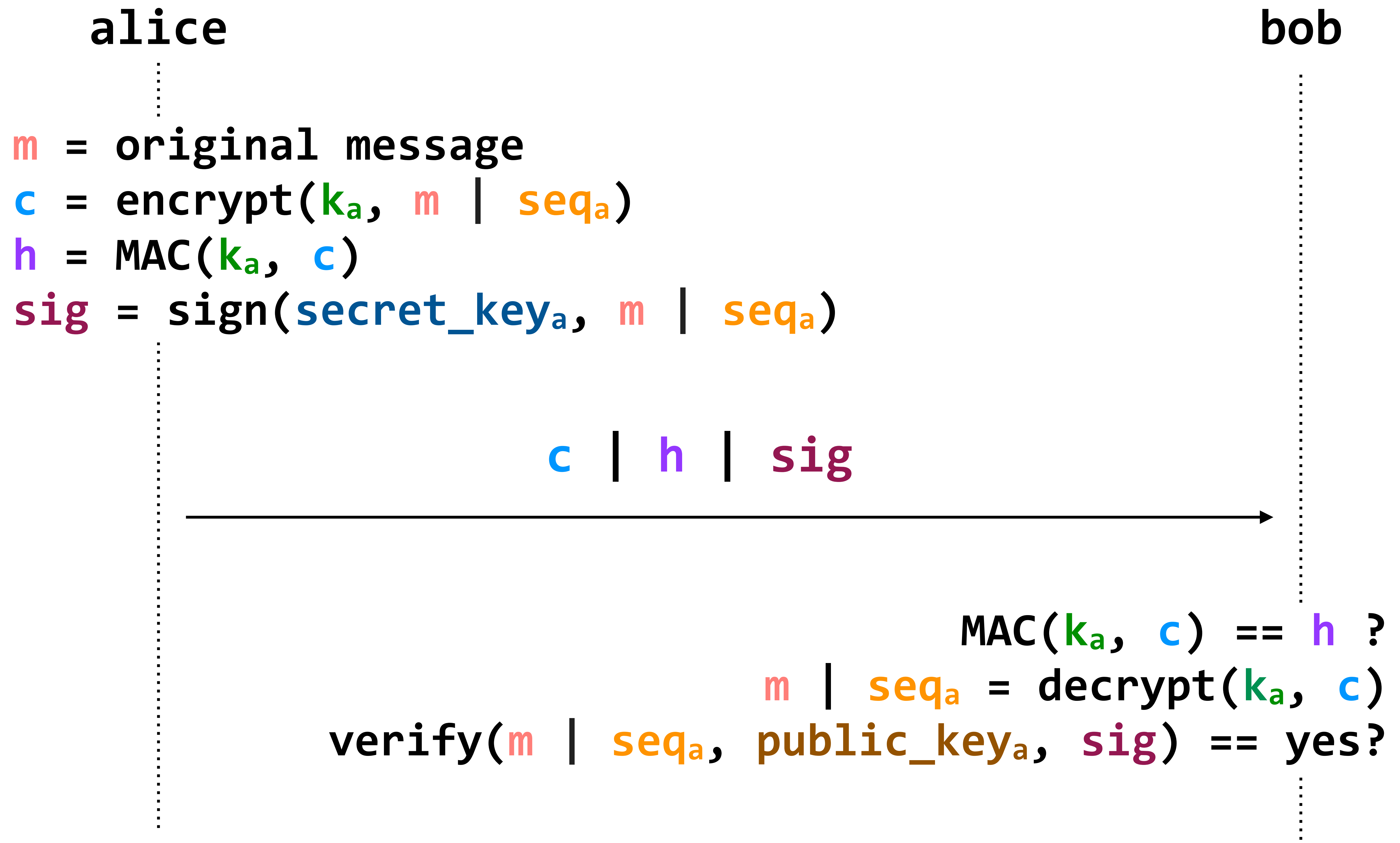

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how do we distribute public keys?

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alice

$\texttt{alice}_{\texttt{sk}}$

bob

$\texttt{bob}_{\texttt{sk}}$

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  yes/no
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alice
alice_{sk}

bob
bob_{sk}

x_{pk} = x’s public key

x_{sk} = x’s secret key (known only to x)

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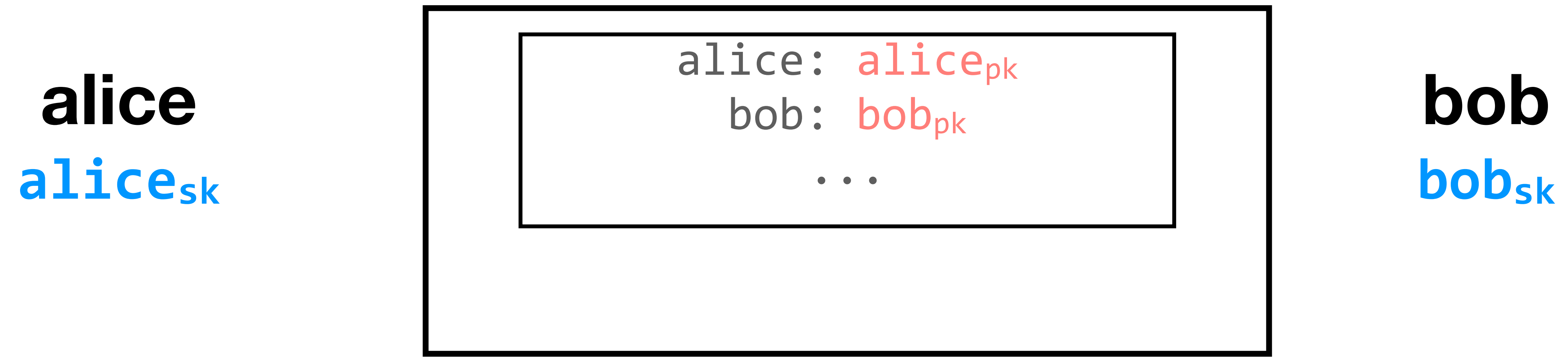

alice

$\texttt{alice}_{sk}$

alice: $\texttt{alice}_{pk}$
bob: $\texttt{bob}_{pk}$
...

bob

$\texttt{bob}_{sk}$

x_{pk} = x’s public key
x_{sk} = x’s secret key (known only to x)

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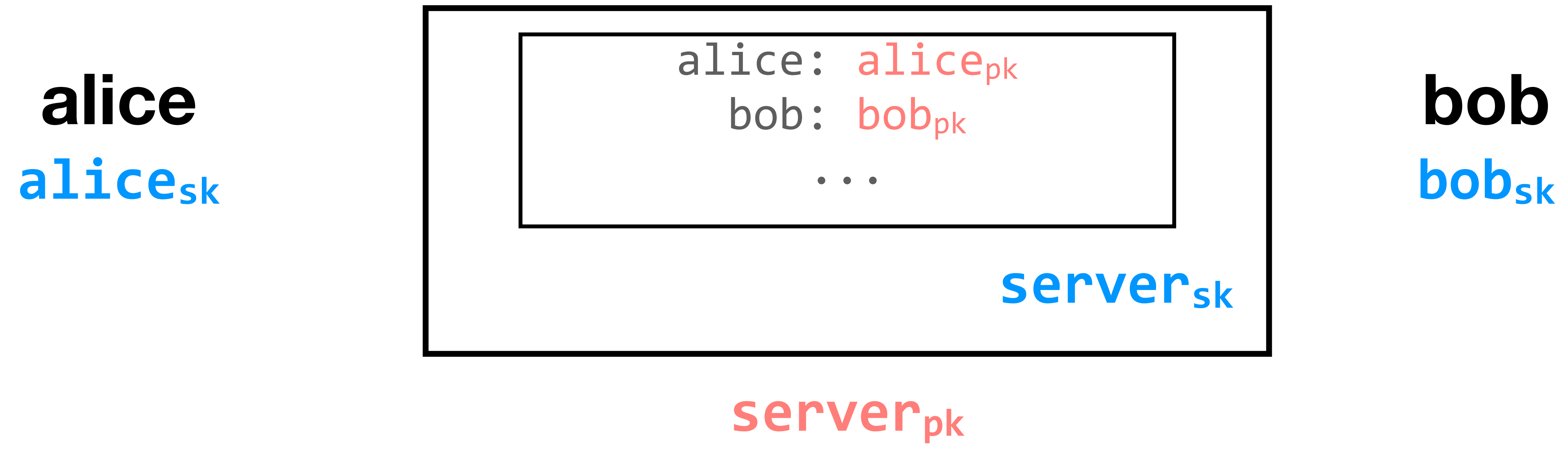

alice

$alice_{sk}$

alice: $alice_{pk}$

bob: bob_{pk}

...

$server_{sk}$

$server_{pk}$

bob

bob_{sk}

x_{pk} = x’s public key

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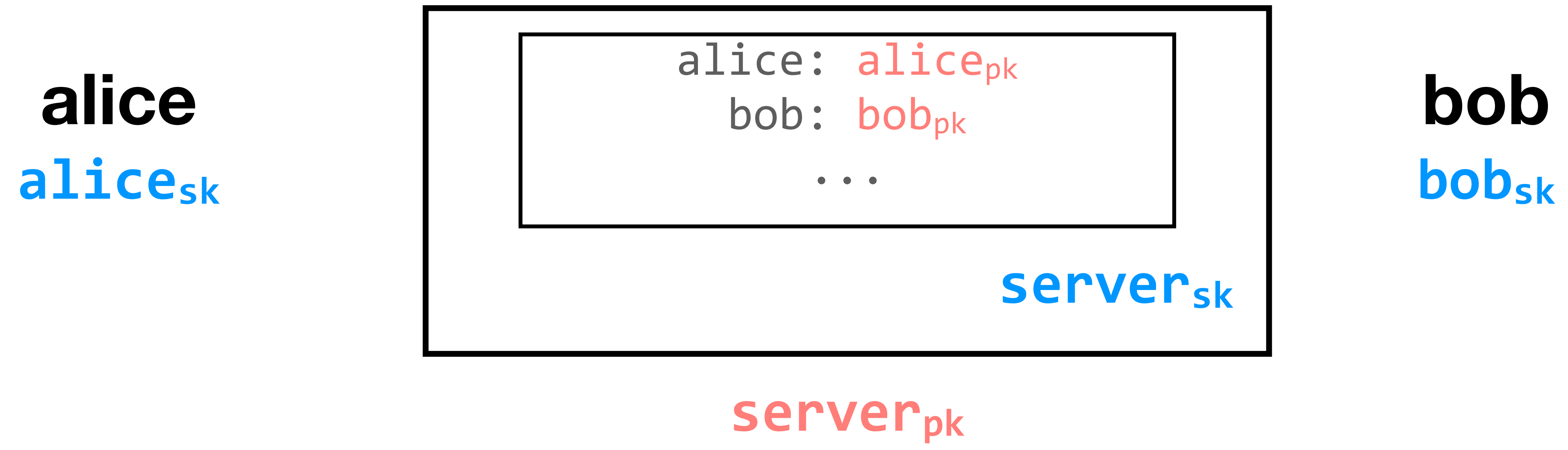

alice and bob could ask the server for any public keys they need, but that doesn't scale, and we also have to figure out how to distribute the server's public key

x_{pk} = x's public key

x_{sk} = x's secret key (known only to x)

how do we distribute public keys?

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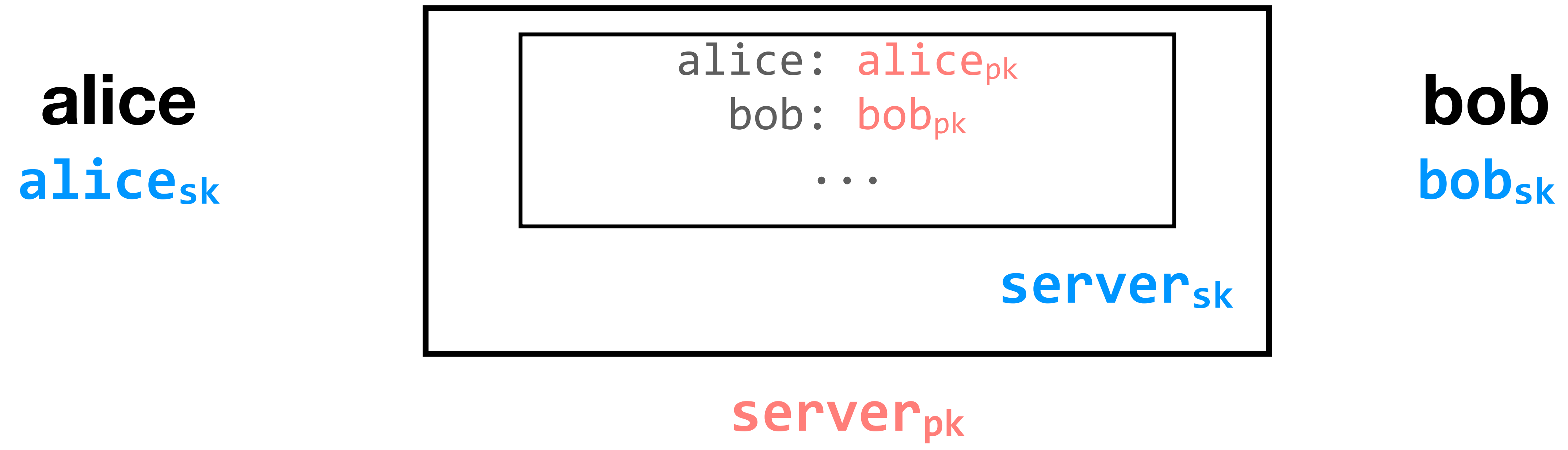

alice

alice_{sk}

alice: alice_{pk}
bob: bob_{pk}
...

server_{sk}

server_{pk}

bob

bob_{sk}

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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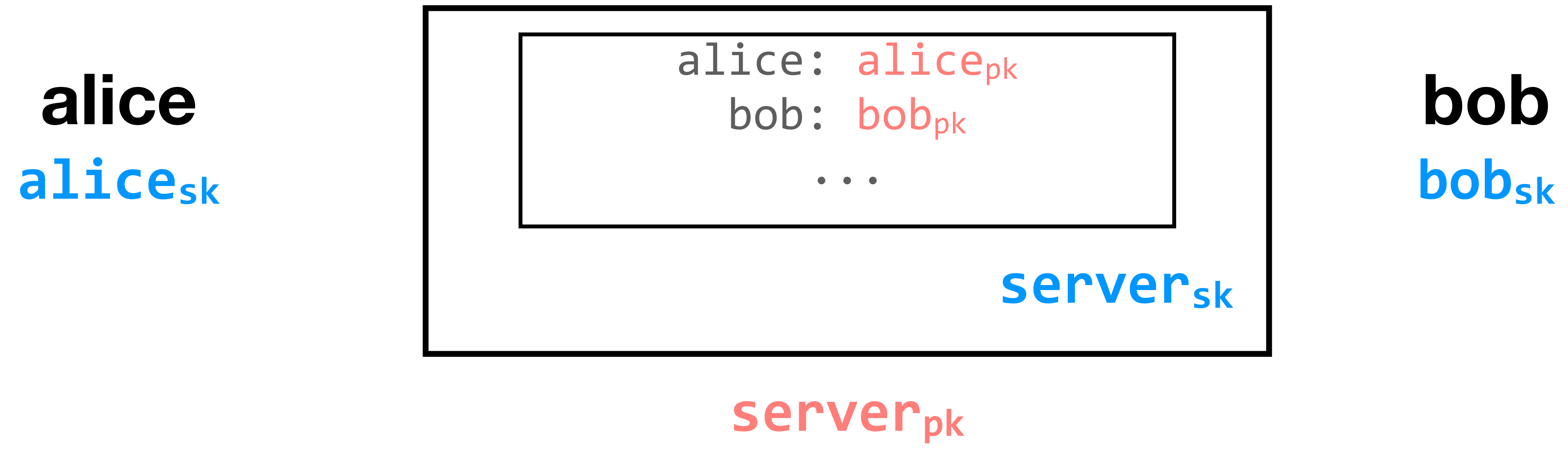

server pre-computes **signed** messages that map names to their public keys

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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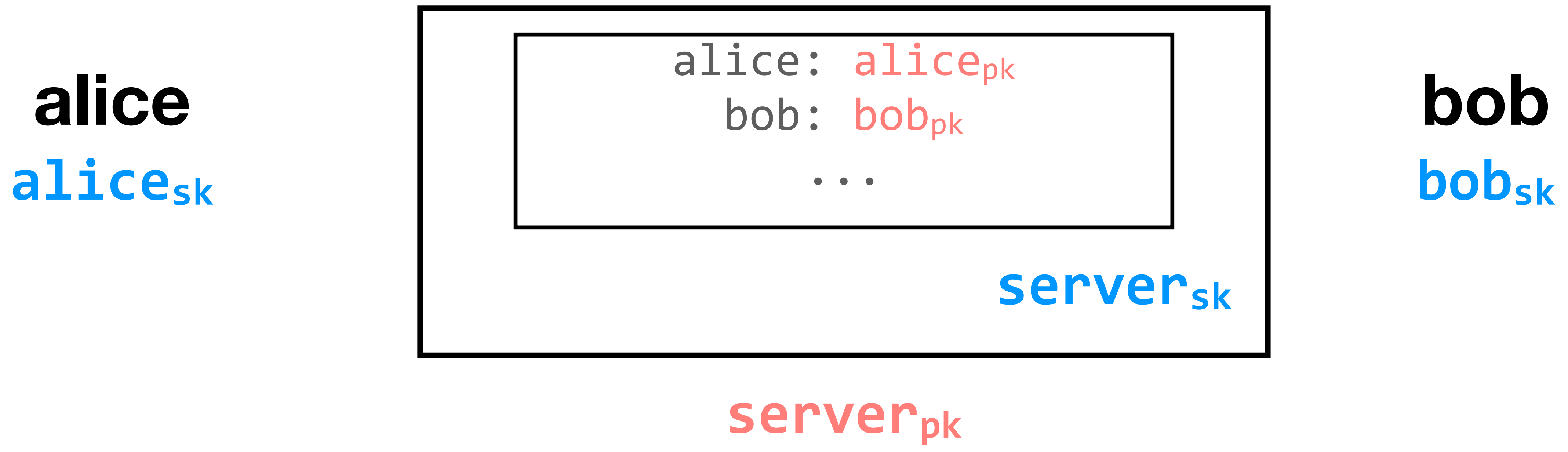

server pre-computes **signed** messages that map names to their public keys

sign(server_{sk}, “alice: alice_{pk}”) → sig

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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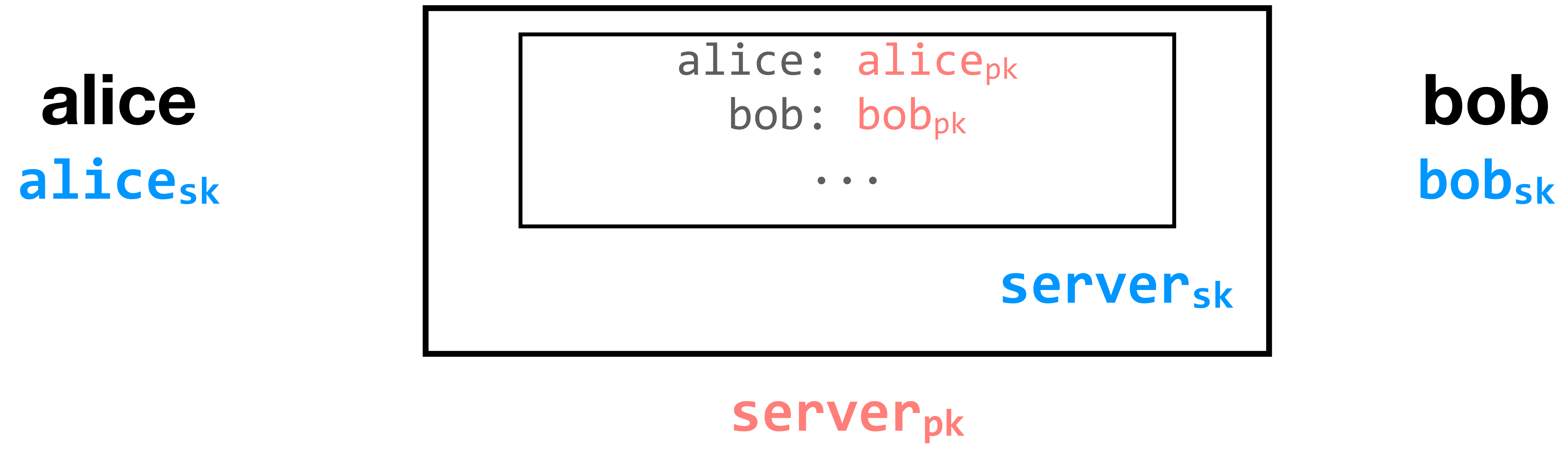

alice
$\texttt{alice}_{\texttt{sk}}$
alice: $\texttt{alice}_{\texttt{pk}}$
bob: $\texttt{bob}_{\texttt{pk}}$
...
$\texttt{server}_{\texttt{sk}}$
$\texttt{server}_{\texttt{pk}}$
bob
$\texttt{bob}_{\texttt{sk}}$

server pre-computes **signed** messages that map names to their public keys

$\texttt{sign}(\texttt{server}_{\texttt{sk}}, \text{“}\texttt{alice: alice}_{\texttt{pk}}\text{”}) \rightarrow \texttt{sig}$

$\texttt{alice, alice}_{\texttt{pk}}\texttt{, sig}$

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

threat model: adversary can observe network data, tamper with packets, and insert its own packets

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`{public_key, secret_key}`

```
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verify(public_key, message, sig) →
  yes/no
```
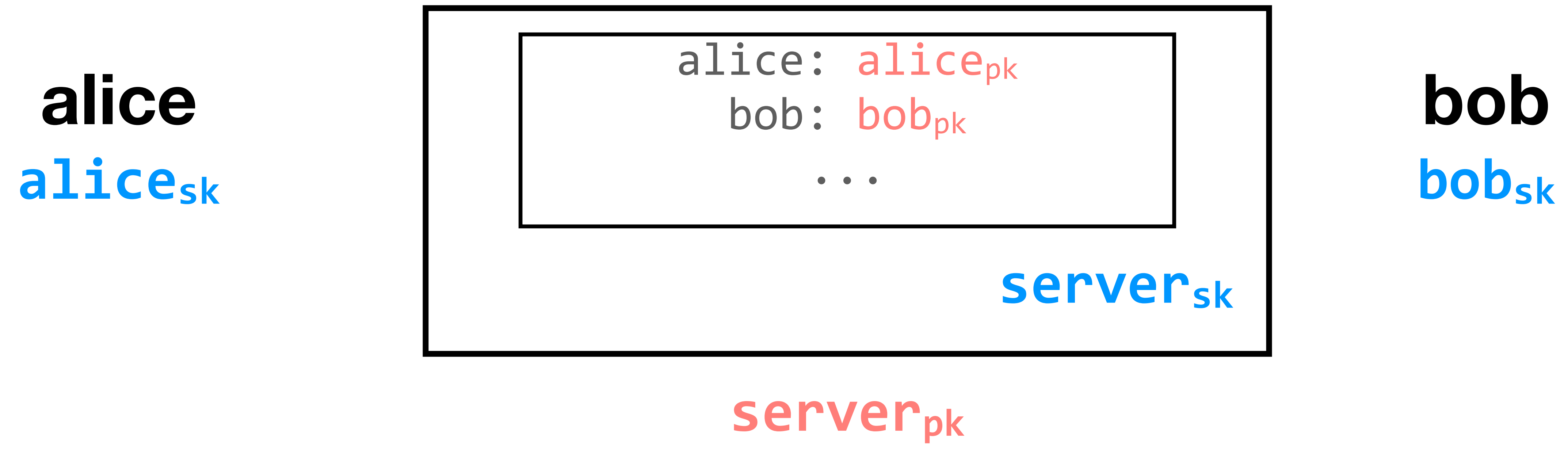

property: it is (virtually) impossible to compute `sig` without `secret_key`



server pre-computes **signed** messages that map names to their public keys

sign(server$_{\text{sk}}$, “alice: alice$_{\text{pk}}$”) → sig

alice, alice$_{\text{pk}}$, sig

anyone can verify that the authority signed this message given server$_{\text{pk}}$, but the server itself doesn’t have to distribute the signed messages

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

threat model: adversary can observe network data, tamper with packets, and insert its own packets

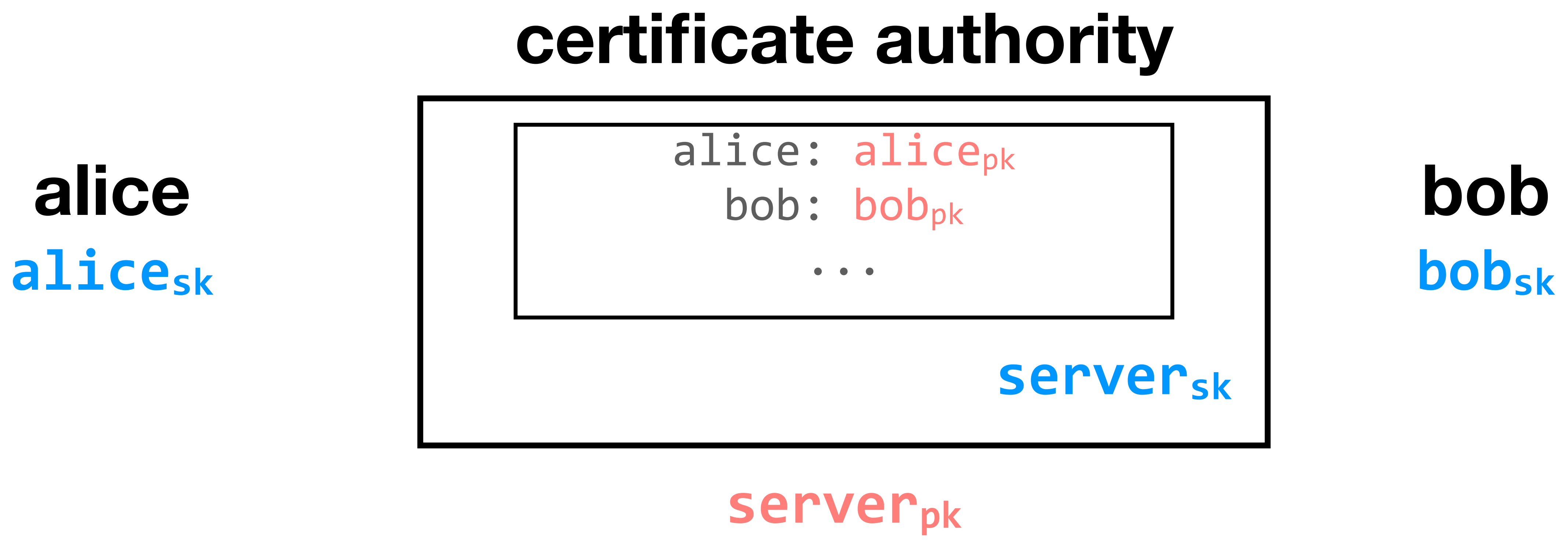
cryptographic signatures allow users to verify identities using public-key cryptography

users generate **key pairs;** the two keys in the pair are related mathematically

`{public_key, secret_key}`

```
sign(secret_key, message) → sig
verify(public_key, message, sig) →
  yes/no
```

property: it is (virtually) impossible to compute `sig` without `secret_key`


certificate authority
alice
$\texttt{alice}_{\texttt{sk}}$
$\texttt{alice: alice}_{\texttt{pk}}$
$\texttt{bob: bob}_{\texttt{pk}}$
...
$\texttt{server}_{\texttt{sk}}$
bob
$\texttt{bob}_{\texttt{sk}}$
$\texttt{server}_{\texttt{pk}}$

server pre-computes **signed** messages that map names to their public keys

$\texttt{sign(server}_{\texttt{sk}}\texttt{, “alice: alice}_{\texttt{pk}}\texttt{”)} \rightarrow \texttt{sig}$

$\texttt{alice, alice}_{\texttt{pk}}\texttt{, sig}$

certificate

anyone can verify that the authority signed this message given $\texttt{server}_{\texttt{pk}}$, but the server itself doesn’t have to distribute the signed messages

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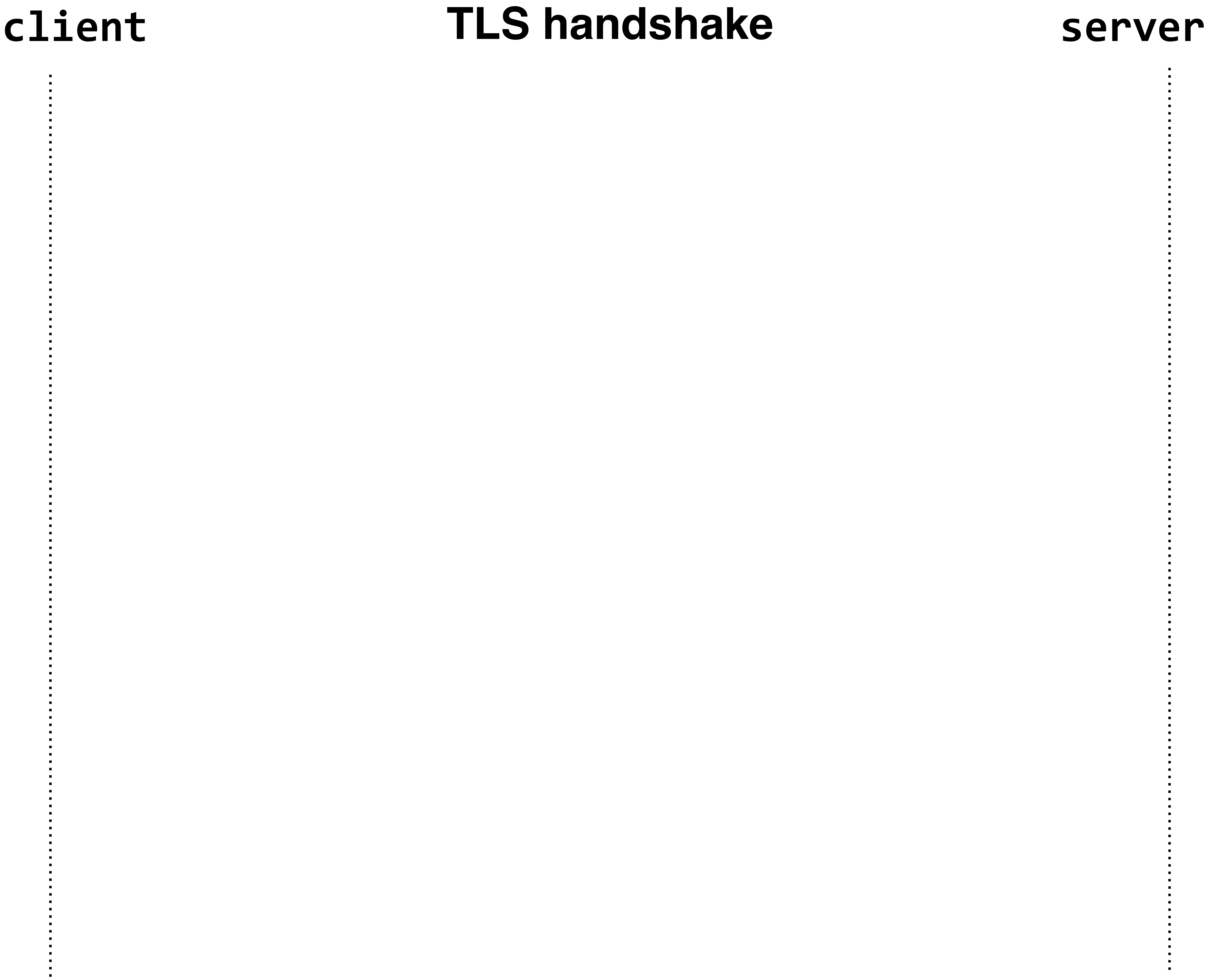

TLS handshake

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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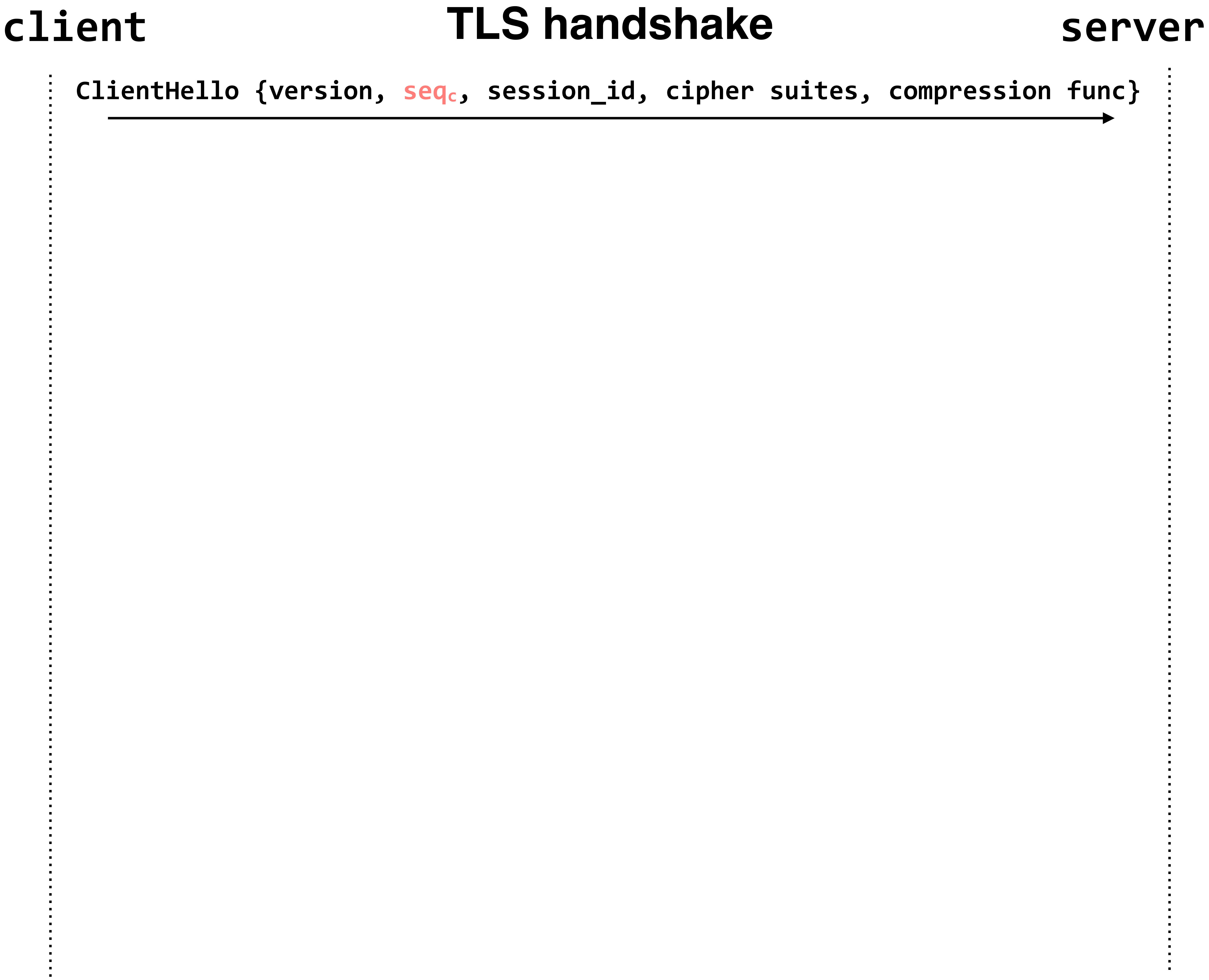
client
TLS handshake
server
ClientHello {version, seq_c, session_id, cipher suites, compression func}

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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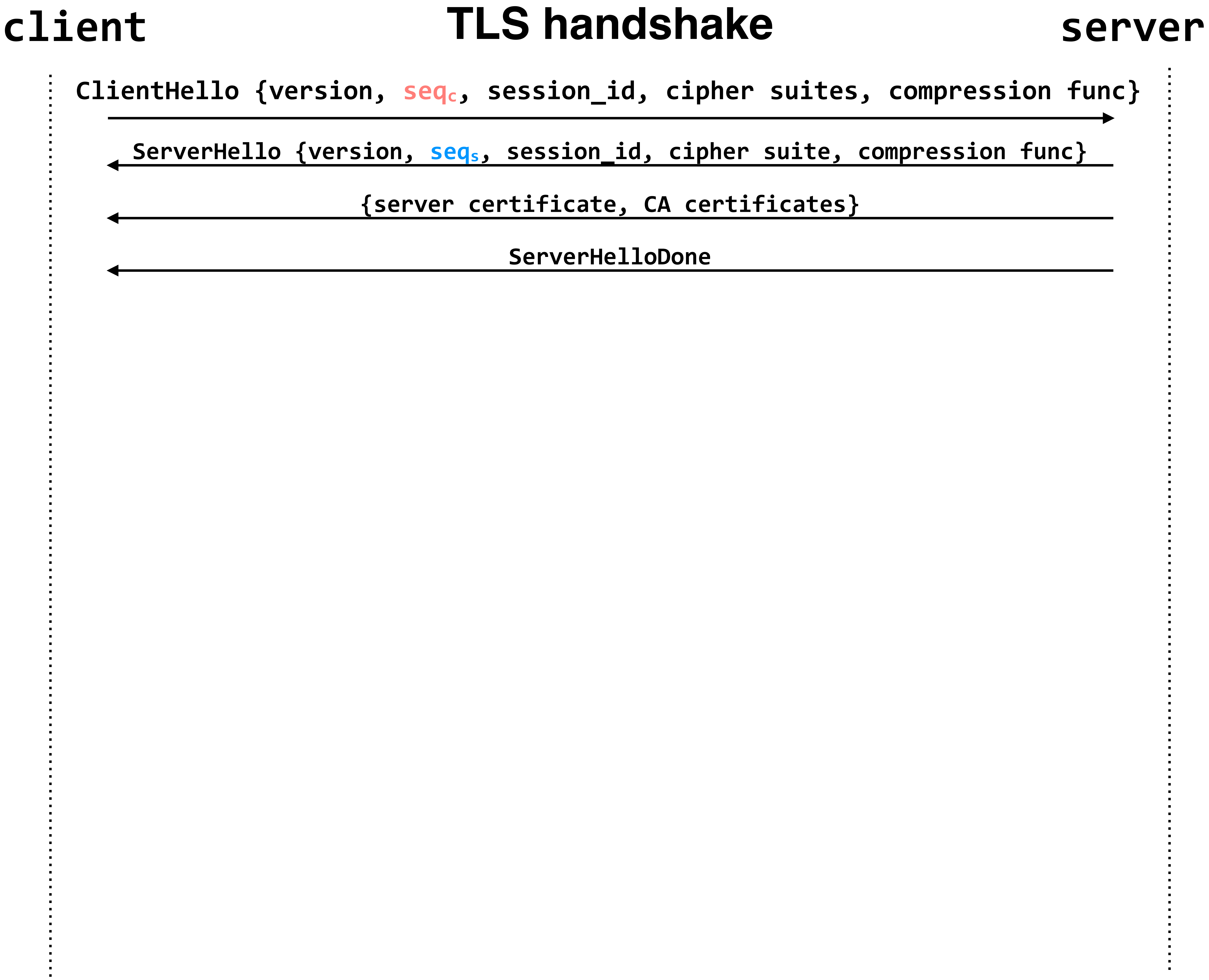
TLS handshake



client

server

ClientHello {version, seq_c, session_id, cipher suites, compression func}

ServerHello {version, seq_s, session_id, cipher suite, compression func}

{server certificate, CA certificates}

ServerHelloDone

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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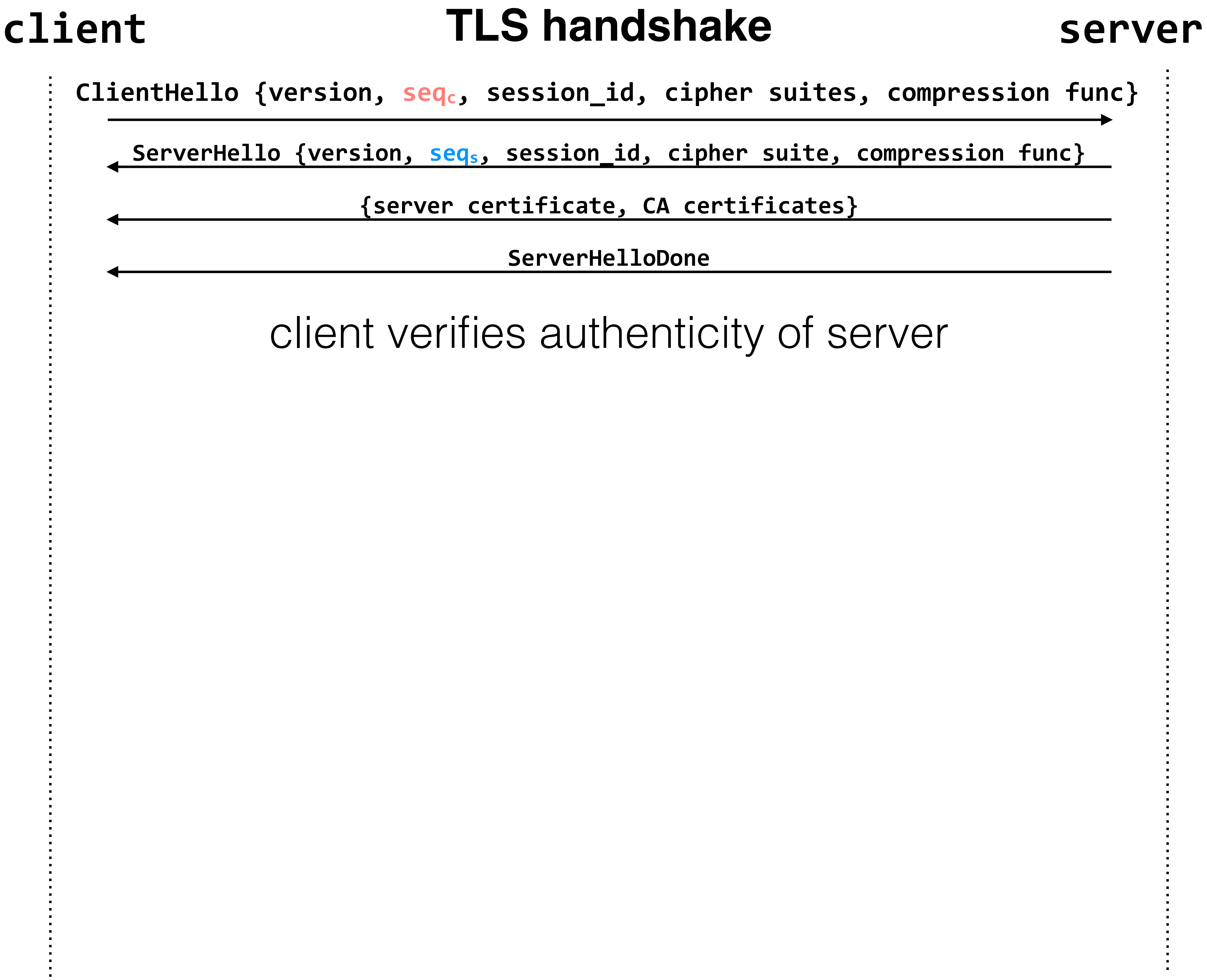

client **TLS handshake** **server**

ClientHello {version, seq$_c$, session_id, cipher suites, compression func}

ServerHello {version, seq$_s$, session_id, cipher suite, compression func}

{server certificate, CA certificates}

ServerHelloDone

client verifies authenticity of server

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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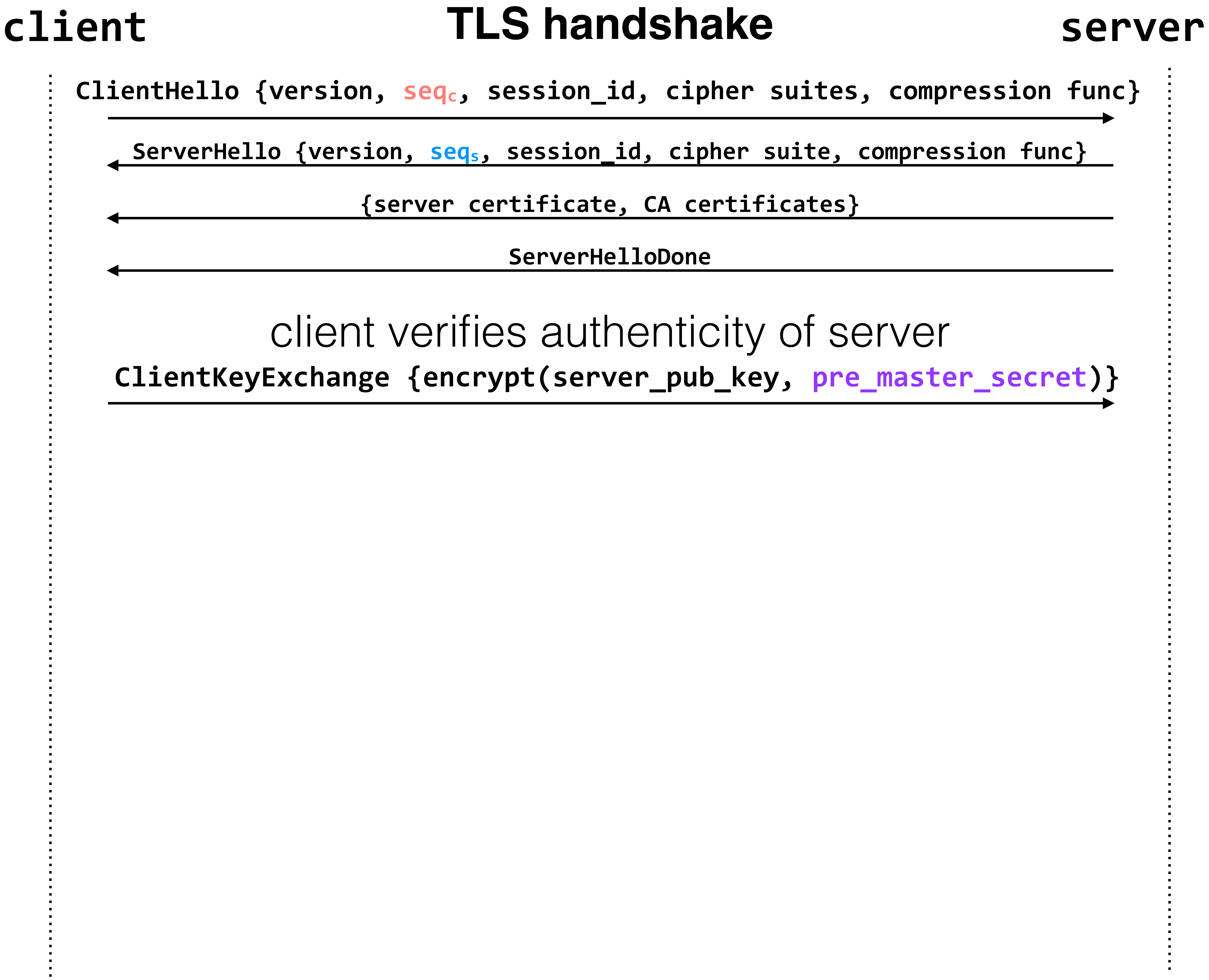
TLS handshake



`ClientHello {version, seq`$_c$`, session_id, cipher suites, compression func}`

`ServerHello {version, seq`$_s$`, session_id, cipher suite, compression func}`

`{server certificate, CA certificates}`

`ServerHelloDone`

client verifies authenticity of server

`ClientKeyExchange {encrypt(server_pub_key, pre_master_secret)}`

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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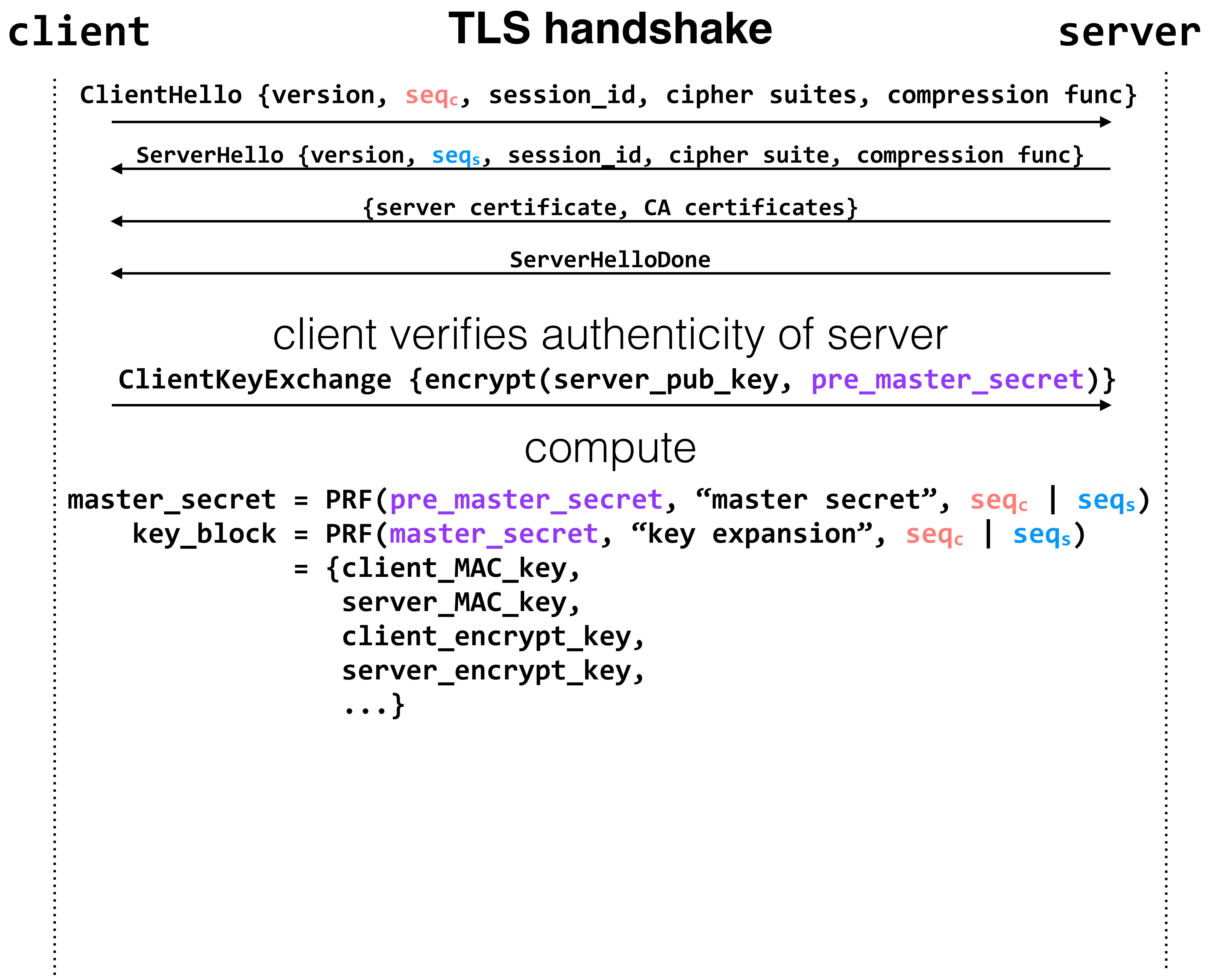

TLS handshake

client

server

ClientHello {version, seq$_c$, session_id, cipher suites, compression func}

ServerHello {version, seq$_s$, session_id, cipher suite, compression func}

{server certificate, CA certificates}

ServerHelloDone

client verifies authenticity of server

ClientKeyExchange {encrypt(server_pub_key, pre_master_secret)}

compute

master_secret = PRF(pre_master_secret, “master secret”, seq$_c$ | seq$_s$)

key_block = PRF(master_secret, “key expansion”, seq$_c$ | seq$_s$)

= {client_MAC_key,
server_MAC_key,
client_encrypt_key,
server_encrypt_key,
...}

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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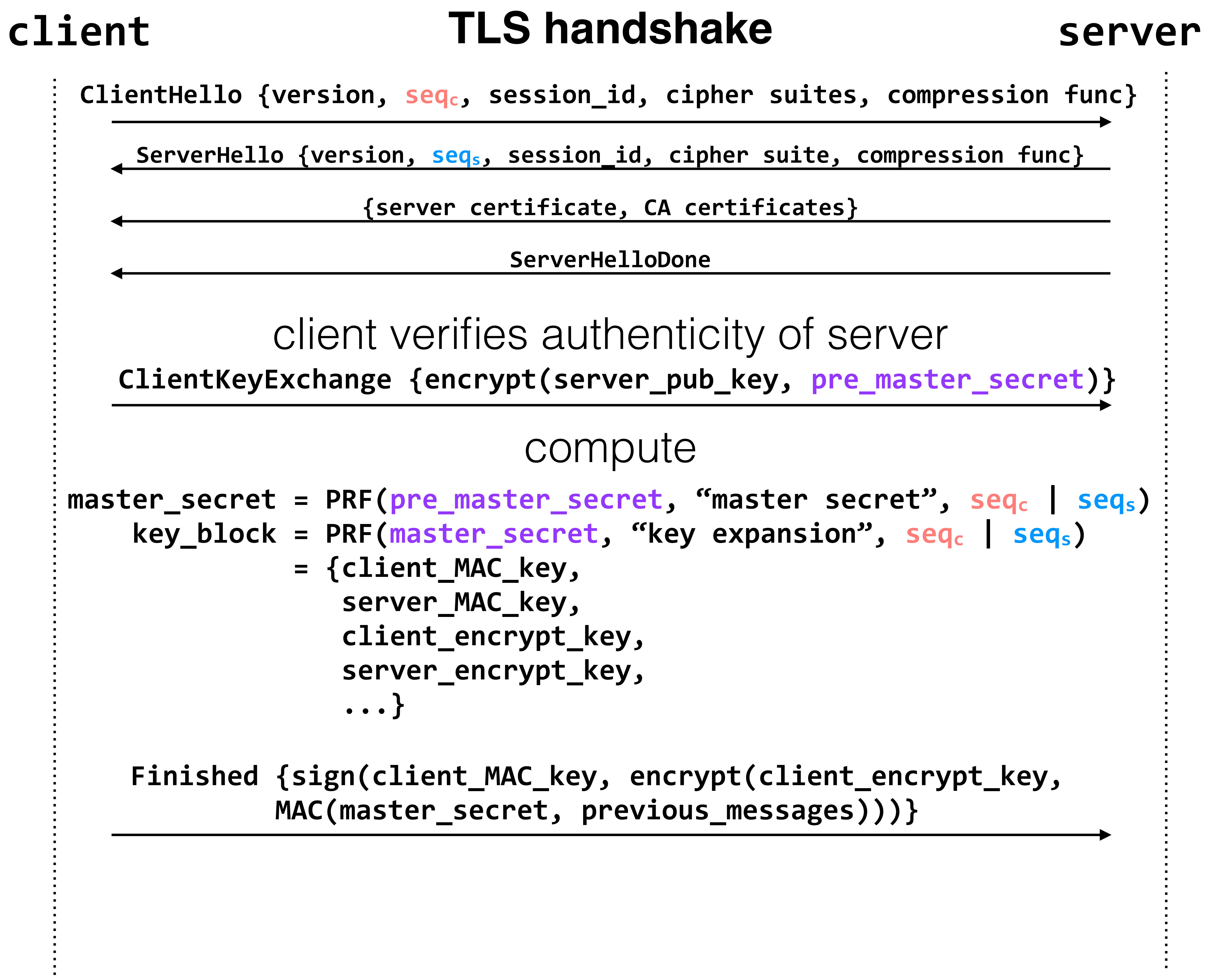

client

TLS handshake

server

ClientHello {version, seq_c, session_id, cipher suites, compression func}

ServerHello {version, seq_s, session_id, cipher suite, compression func}

{server certificate, CA certificates}

ServerHelloDone

client verifies authenticity of server

ClientKeyExchange {encrypt(server_pub_key, pre_master_secret)}

compute

master_secret = PRF(pre_master_secret, “master secret”, seq_c | seq_s)
key_block = PRF(master_secret, “key expansion”, seq_c | seq_s)
= {client_MAC_key,
server_MAC_key,
client_encrypt_key,
server_encrypt_key,
...}

Finished {sign(client_MAC_key, encrypt(client_encrypt_key,
MAC(master_secret, previous_messages)))}

policy: provide **confidentiality** (adversary cannot learn message contents) and **integrity** (adversary cannot tamper with packets and go undetected)

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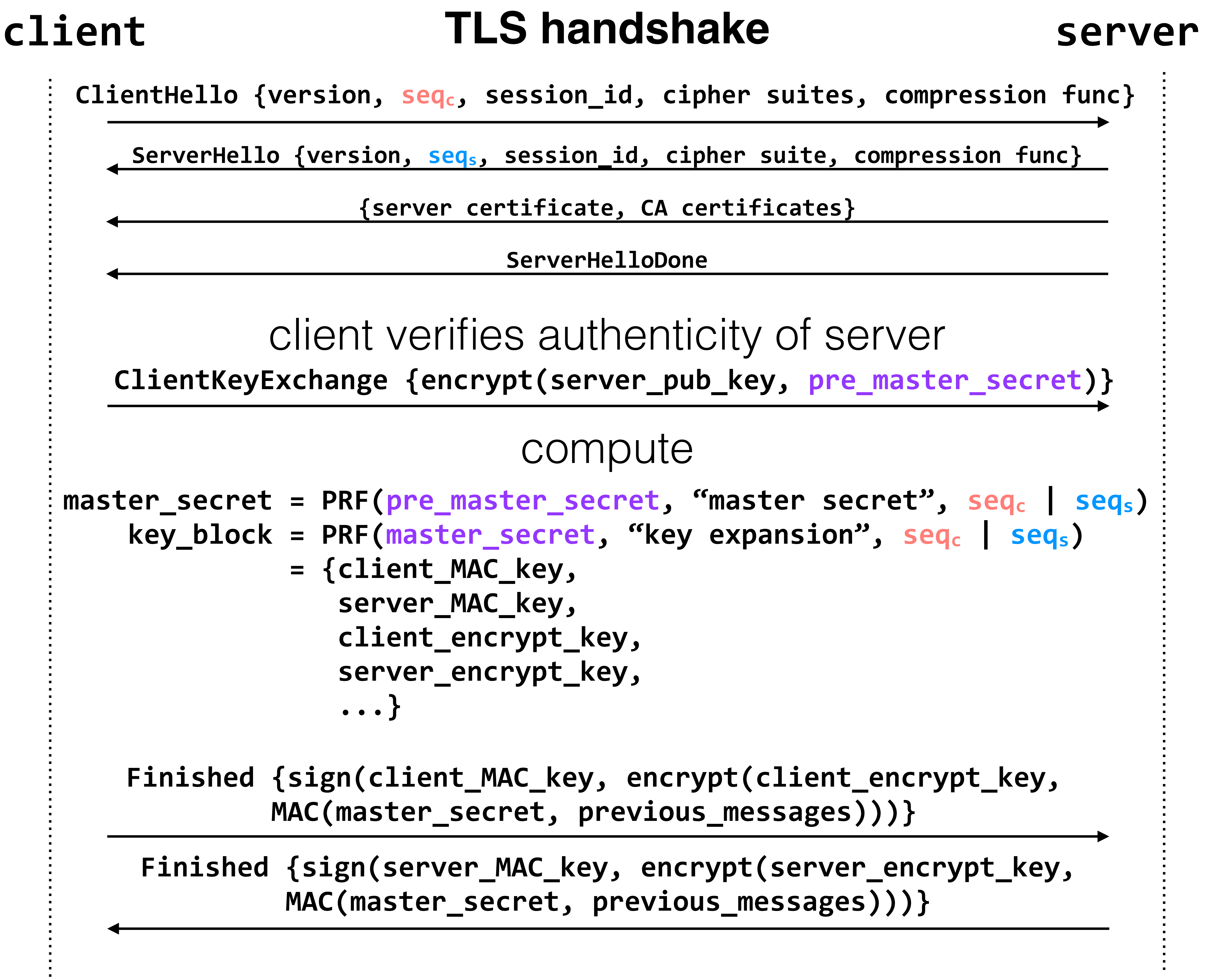


client

TLS handshake

server

ClientHello {version, seq$_c$, session_id, cipher suites, compression func}

ServerHello {version, seq$_s$, session_id, cipher suite, compression func}

{server certificate, CA certificates}

ServerHelloDone

client verifies authenticity of server

ClientKeyExchange {encrypt(server_pub_key, pre_master_secret)}

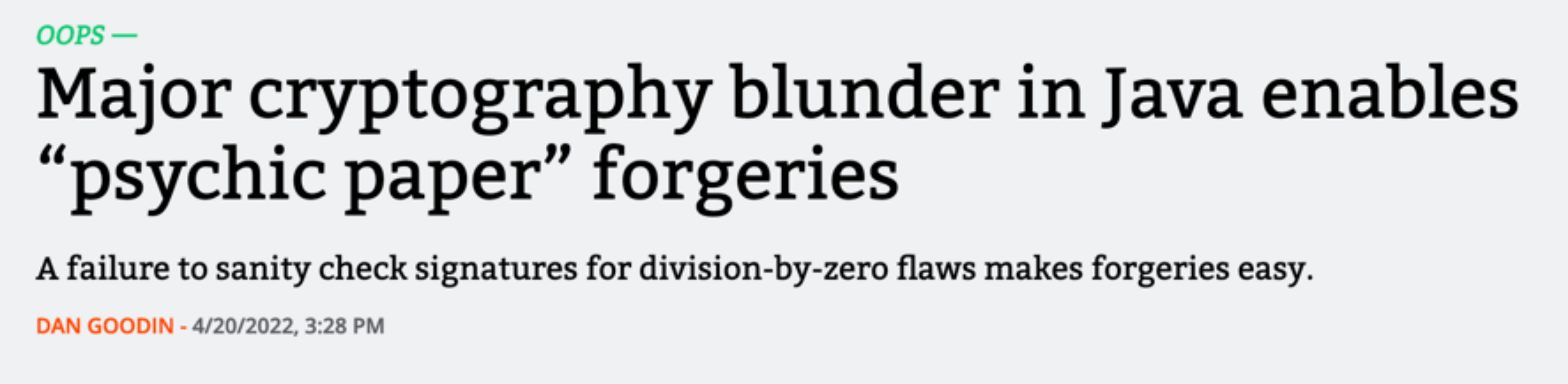
compute

```
master_secret = PRF(pre_master_secret, “master secret”, seqc | seqs)
    key_block = PRF(master_secret, “key expansion”, seqc | seqs)
              = {client_MAC_key,
                 server_MAC_key,
                 client_encrypt_key,
                 server_encrypt_key,
                 ...}
```

Finished {sign(client_MAC_key, encrypt(client_encrypt_key, MAC(master_secret, previous_messages)))}

Finished {sign(server_MAC_key, encrypt(server_encrypt_key, MAC(master_secret, previous_messages)))}

6.1800 in the news

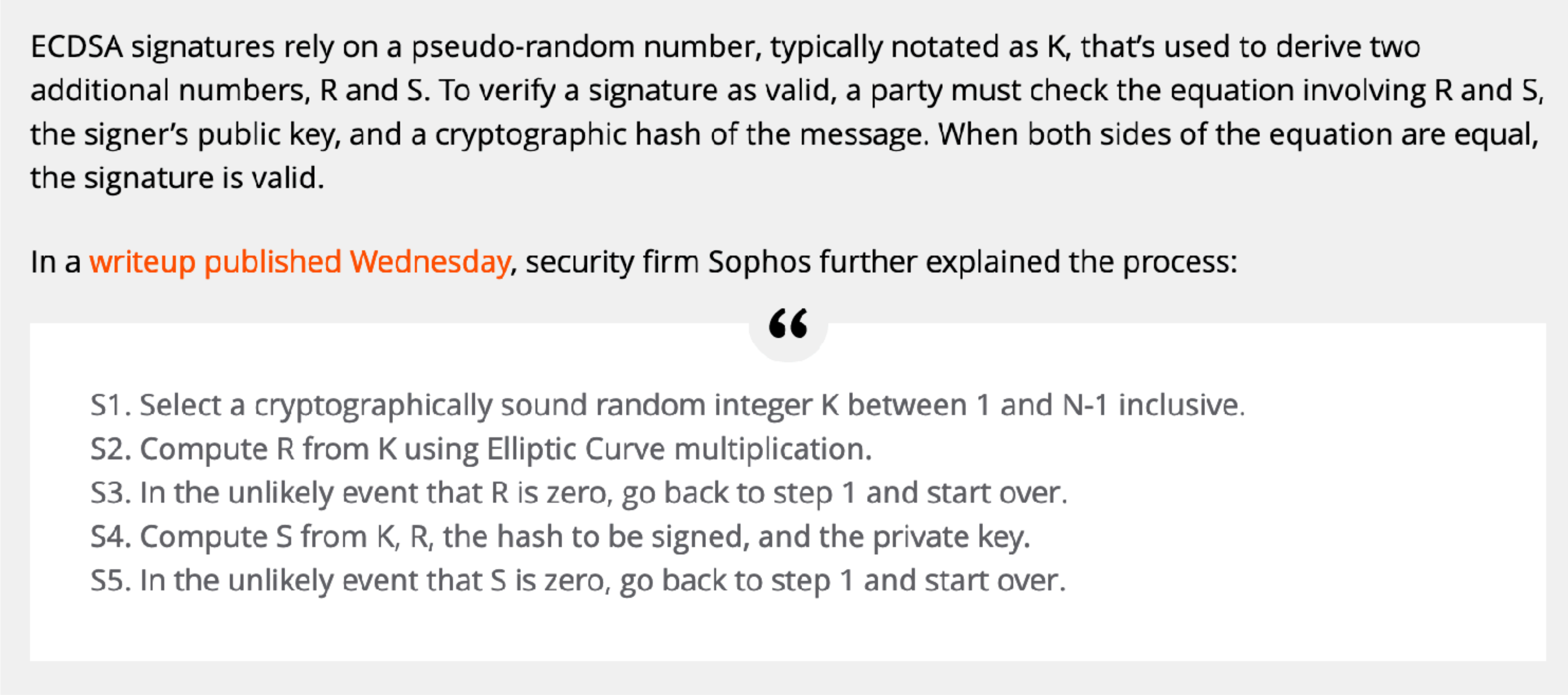


OOPS —

Major cryptography blunder in Java enables "psychic paper" forgeries

A failure to sanity check signatures for division-by-zero flaws makes forgeries easy.

DAN GOODIN - 4/20/2022, 3:28 PM



ECDSA signatures rely on a pseudo-random number, typically notated as K, that's used to derive two additional numbers, R and S. To verify a signature as valid, a party must check the equation involving R and S, the signer's public key, and a cryptographic hash of the message. When both sides of the equation are equal, the signature is valid.

In a writeup published Wednesday, security firm Sophos further explained the process:

> "
>
> S1. Select a cryptographically sound random integer K between 1 and N-1 inclusive.
> S2. Compute R from K using Elliptic Curve multiplication.
> S3. In the unlikely event that R is zero, go back to step 1 and start over.
> S4. Compute S from K, R, the hash to be signed, and the private key.
> S5. In the unlikely event that S is zero, go back to step 1 and start over.

https://arstechnica.com/information-technology/2022/04/major-crypto-blunder-in-java-enables-psychic-paper-forgeries/

6.1800 in the news

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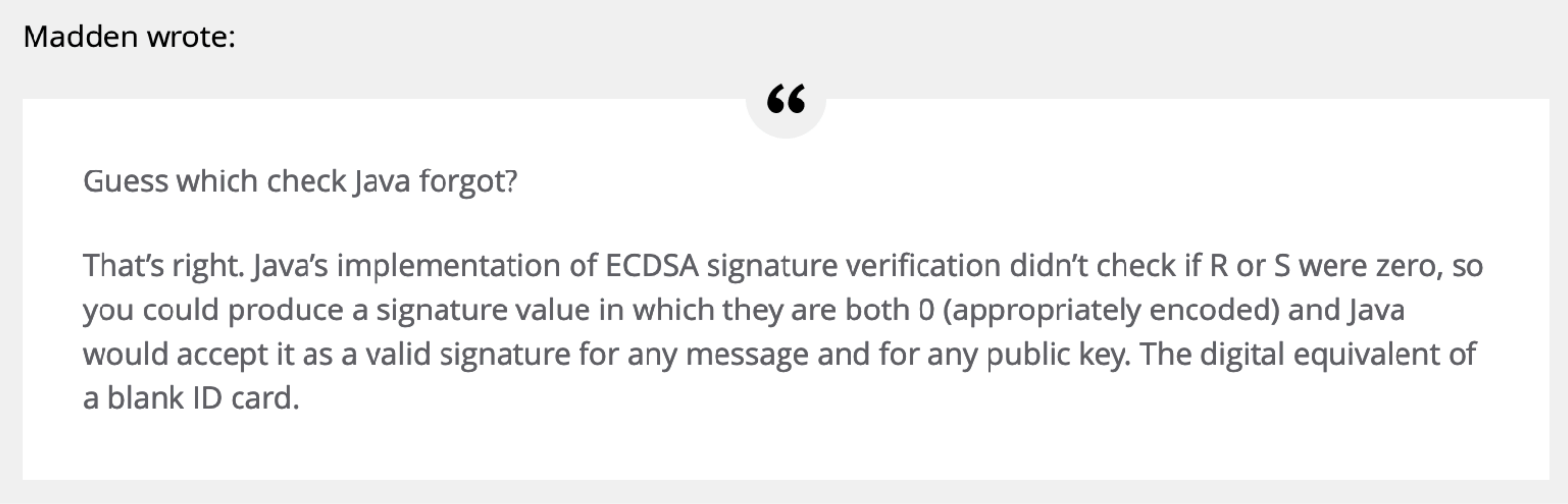

Madden wrote:

> Guess which check Java forgot?
>
> That's right. Java's implementation of ECDSA signature verification didn't check if R or S were zero, so you could produce a signature value in which they are both 0 (appropriately encoded) and Java would accept it as a valid signature for any message and for any public key. The digital equivalent of a blank ID card.

https://arstechnica.com/information-technology/2022/04/major-crypto-blunder-in-java-enables-psychic-paper-forgeries/

encryption provides confidentiality

here, we are using symmetric-key encryption: the same key is used to encrypt *and* decrypt

```
encrypt(key, message) → ciphertext
decrypt(key, ciphertext) → message
```

```
encrypt(34fbcbd1, “hello, world”) = 0x47348f63a679
26cd393d4b93c58f78c
decrypt(34fbcbd1, “0x47348f63a67926cd393d4b93c58f7
8c”) = hello, world
```

property: given the `ciphertext`, it is (virtually) impossible to obtain the `message` without knowing the `key`

MACs provides integrity

```
MAC(key, message) → token
MAC(34fbcbd1, “hello, world”) =
0x59cccc95723737f777e62bc756c8da5c
```

property: given the `message`, it is (virtually) impossible to obtain the `token` without knowing the `key`

it is also impossible to go in the reverse direction: given `token`, you can’t get `message` even with the `key`

in the next lecture, we are going to use a different style of encryption — public-key encryption — to provide confidentiality in a different system

cryptographic signatures allow users to verify identities using public-key cryptography

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```
{public_key, secret_key}
```

```
sign(secret_key, message) → sig
verify(public_key, message, sig) →
  yes/no
```

property: it is (virtually) impossible to compute `sig` without `secret_key`

secure channels protect us from adversaries that can observe and tamper with packets in the network

because a secure channel requires an agreement between the client and the server, system designers must think about whether to provide this abstraction, and who is **impacted** if they do (or do not) provide it

encrypting with **symmetric keys** provides confidentiality, and using **MACs** provides integrity. **Diffie-Hellman key exchange** lets us exchange the symmetric key securely

to verify identities, we use **public-key cryptography** and cryptographic **signatures**. we often distributed public keys via **certificate authorities**, though this method is not perfect