An Analysis of OpenSSL's Random Number Generator
Eurocrypt 2016

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September 14, 2016

Pseudo Random Number Generation

- Software-based RNG's use pseudo random number generators (PRNGs)
- but are not PRNGs

seed

RAND_add (buffer, estimated entopy)

RNG state

RAND_bytes (buffer),
RAND_pseudo_bytes (buffer)

output

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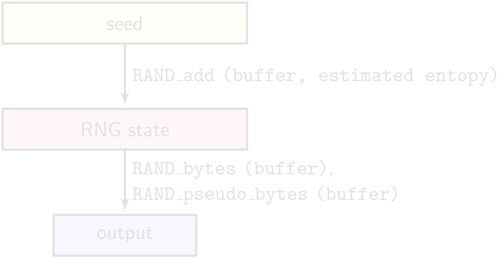

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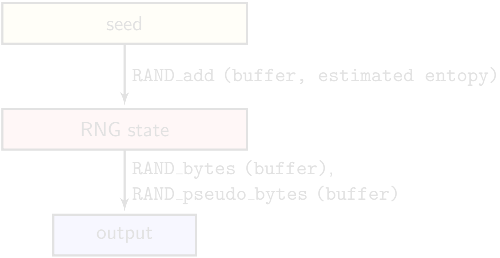

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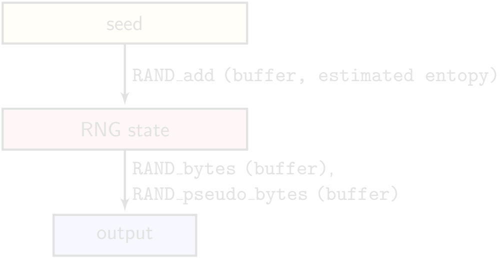
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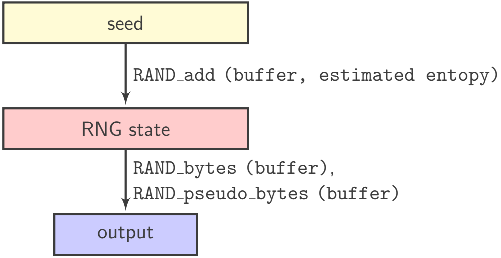
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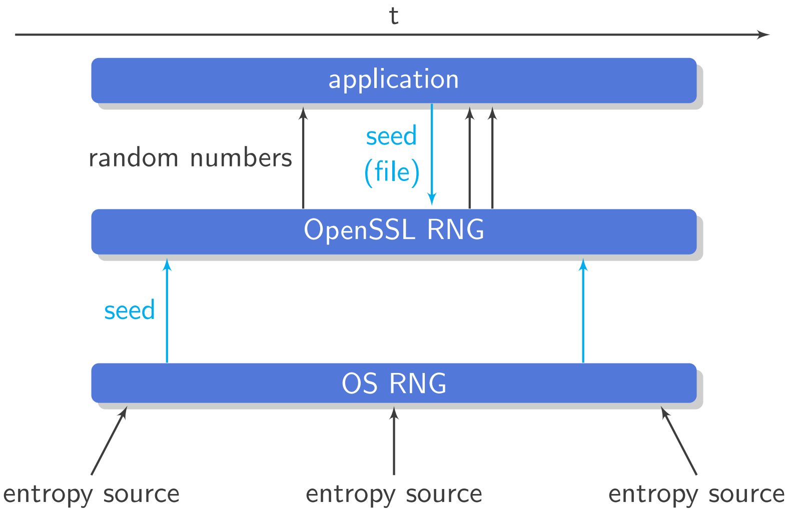
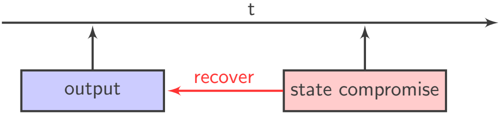
Random Number Generation in Cryptographic Libraries

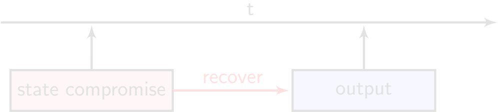


Security Notions for RNGs

- forward security



- backward security



- don't leak any information about state in output

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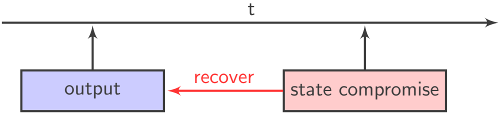

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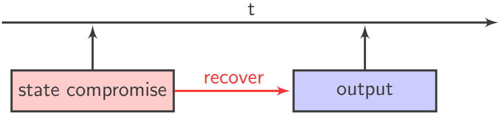

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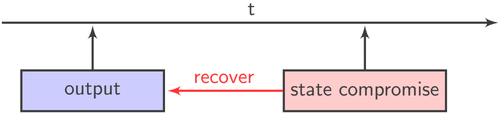

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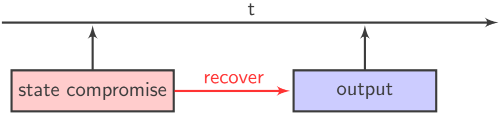

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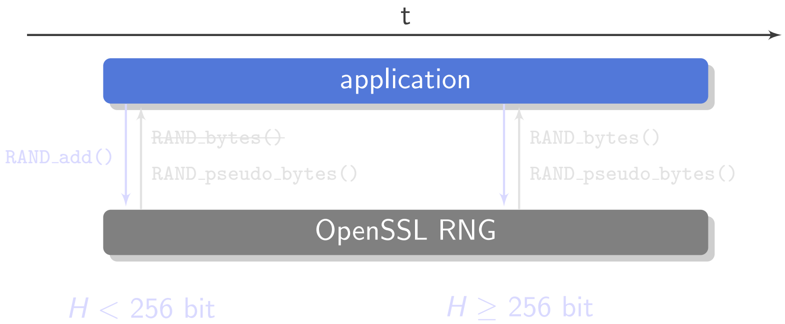
Low Entropy Secret Leakage

Seeding by the Application



t

application

RAND_add()

~~RAND_bytes()~~

RAND_pseudo_bytes()

RAND_bytes()

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OpenSSL RNG

$H < 256$ bit

$H \geq 256$ bit

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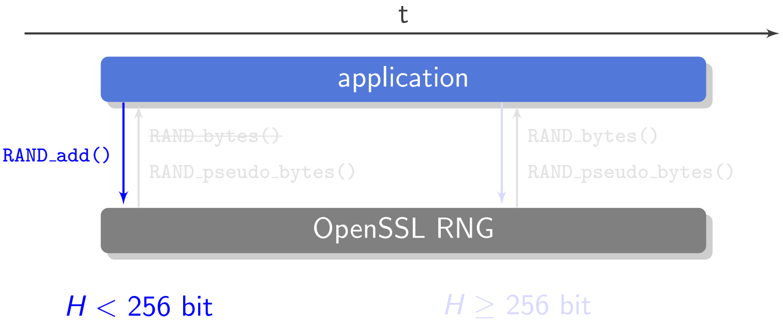

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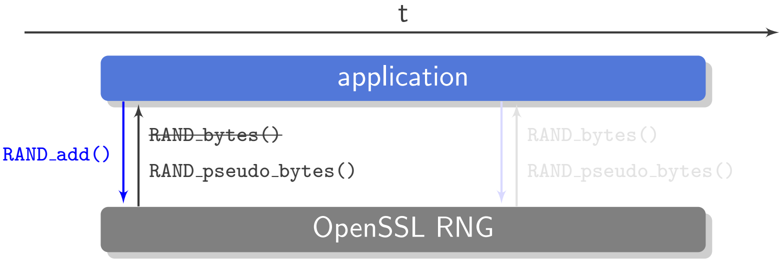

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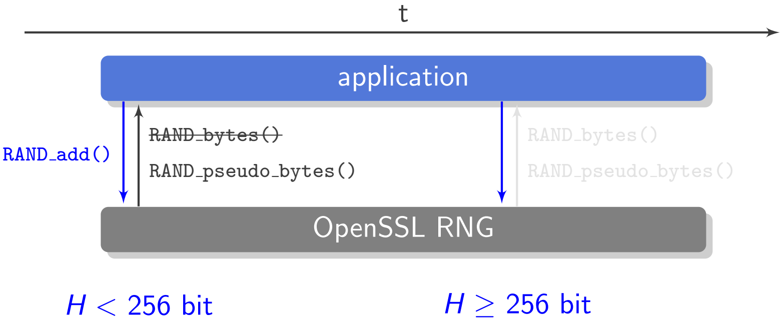

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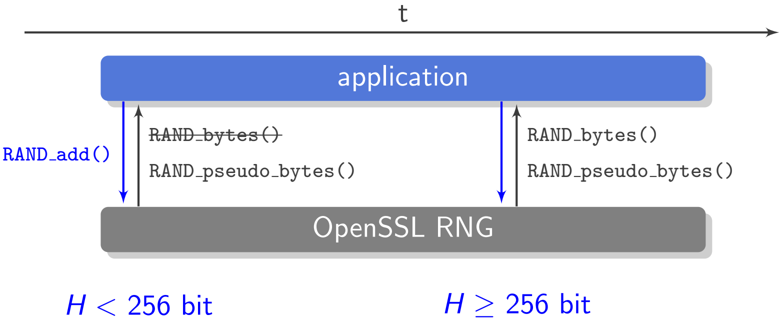

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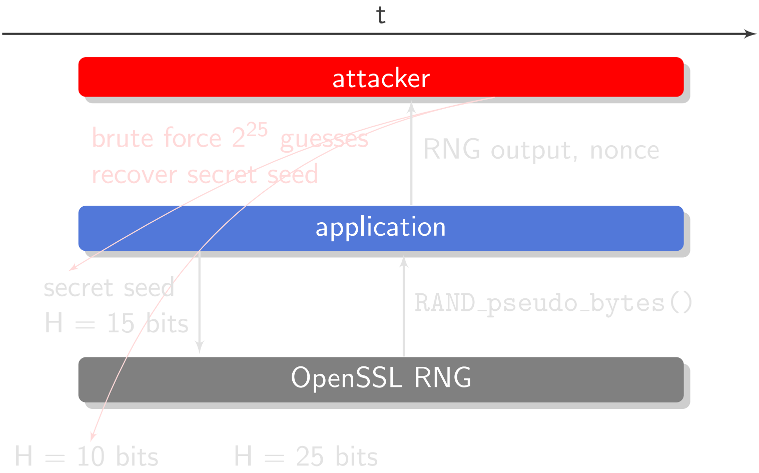
Outputting Random Numbers in Low Entropy States



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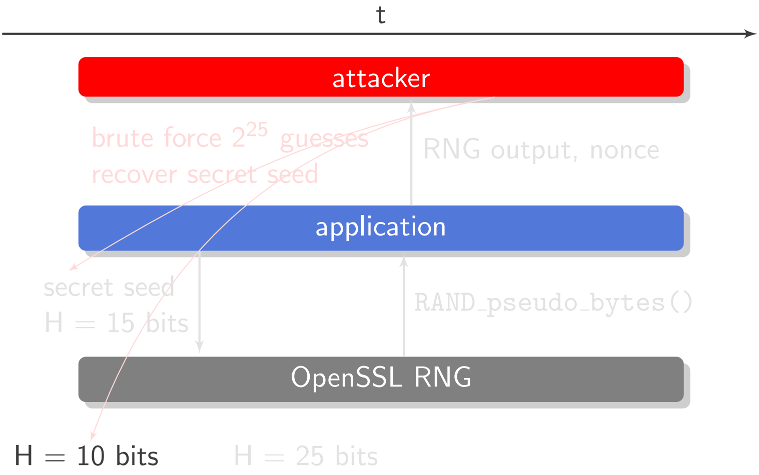

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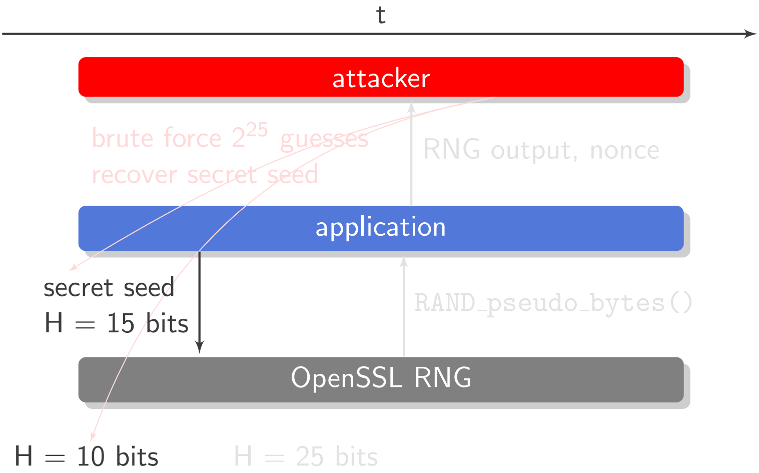

t

attacker

brute force 2^{25} guesses

recover secret seed

RNG output, nonce

application

secret seed

$H = 15$ bits

RAND_pseudo_bytes()

OpenSSL RNG

$H = 10$ bits

$H = 25$ bits

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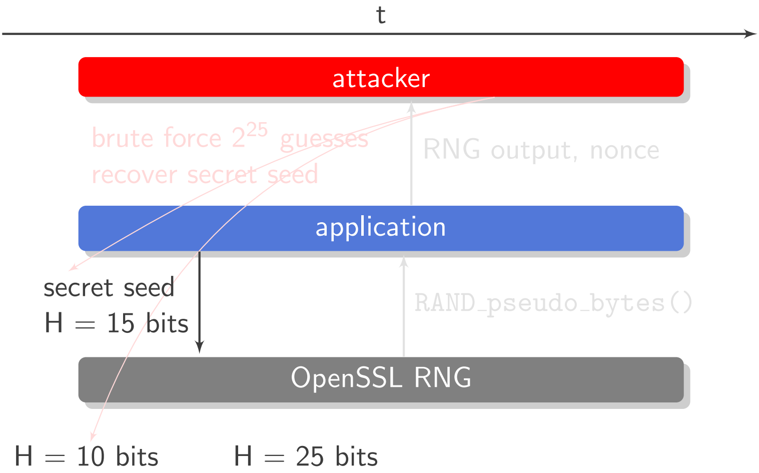

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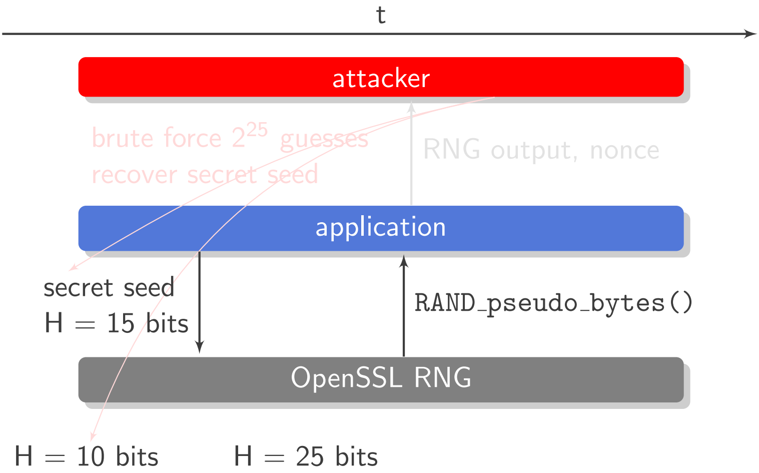

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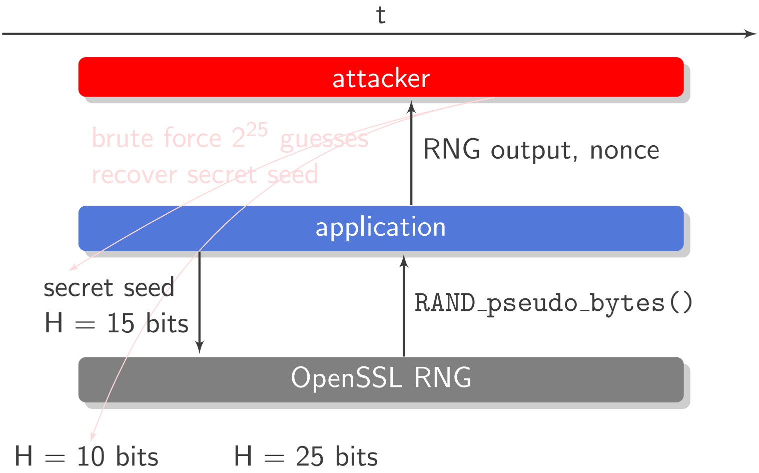

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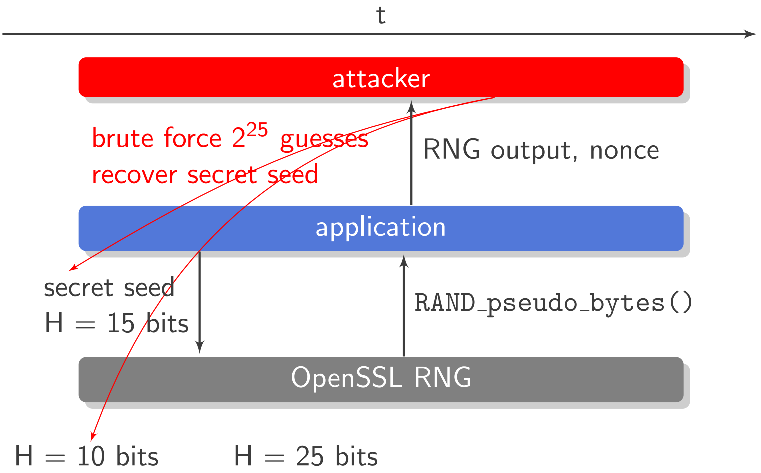

Potentially Leaked Secrets

- RAND_pseudo_bytes generates output in the same way as RAND_bytes
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- OpenSSL feeds the previous contents of buffers to be randomized to RNG state (Debian issue in 2008)
- previous contents could contain low entropy secrets by themselves
- overwriting secrets with random numbers is an established practice
- overwritten low entropy secrets may be leaked in output

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- custom design
- ©1998

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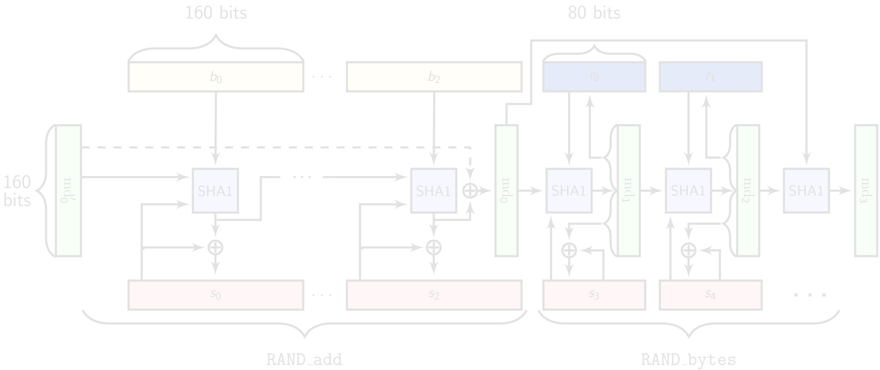

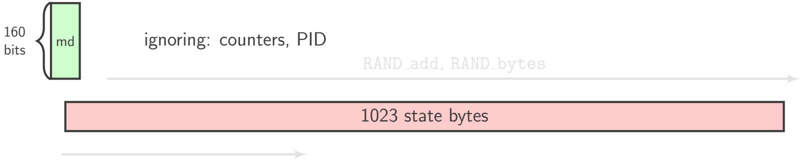

ignoring: counters, PID

1023 state bytes

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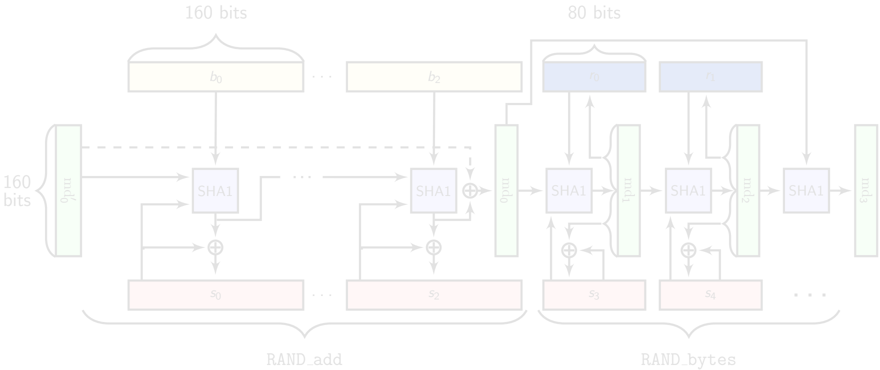

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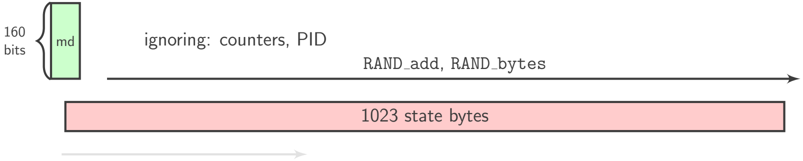

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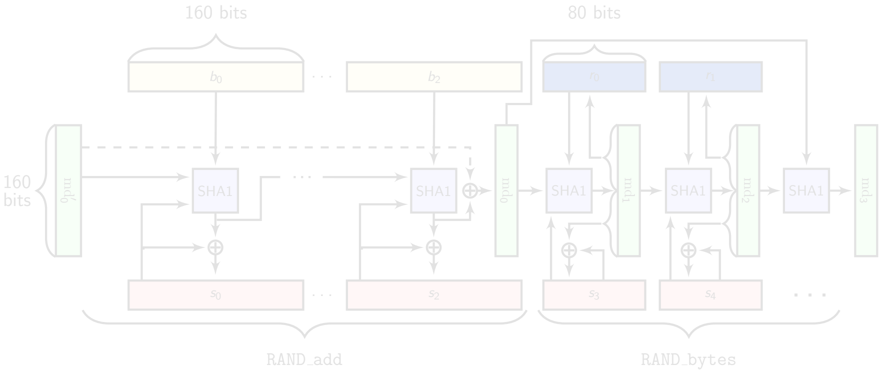

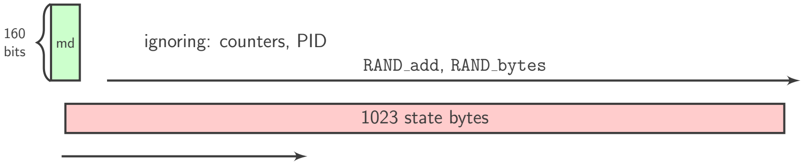

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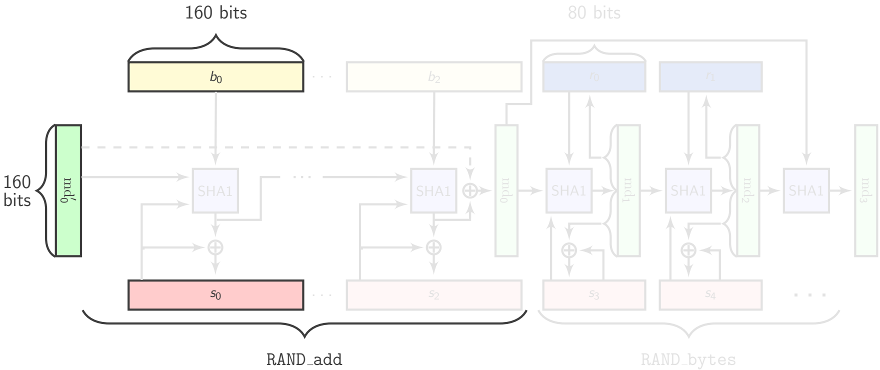

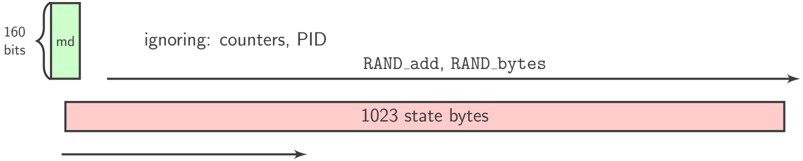

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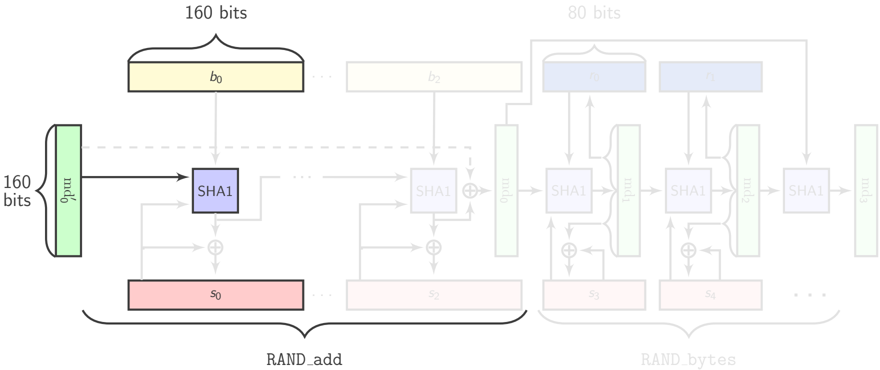

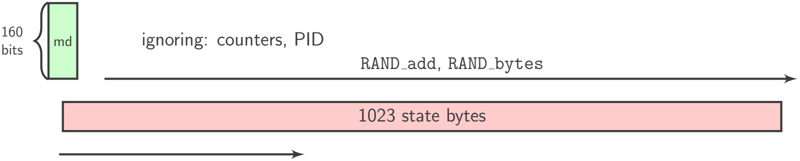

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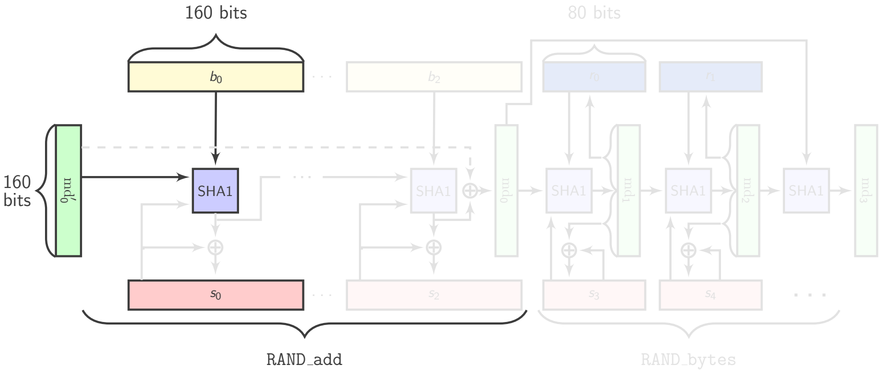

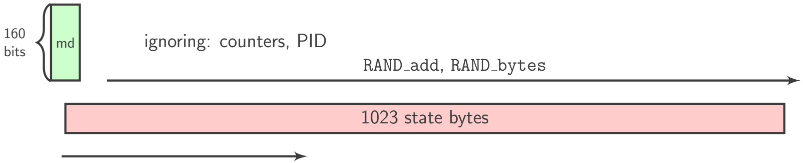

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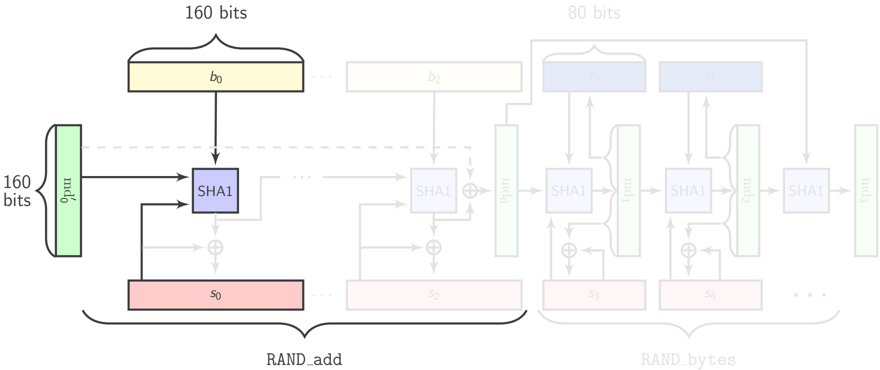

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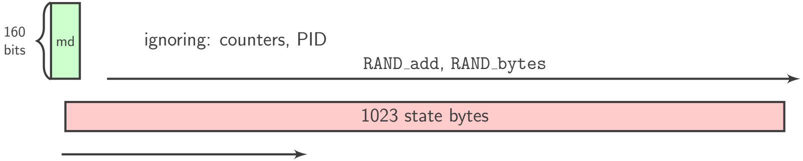

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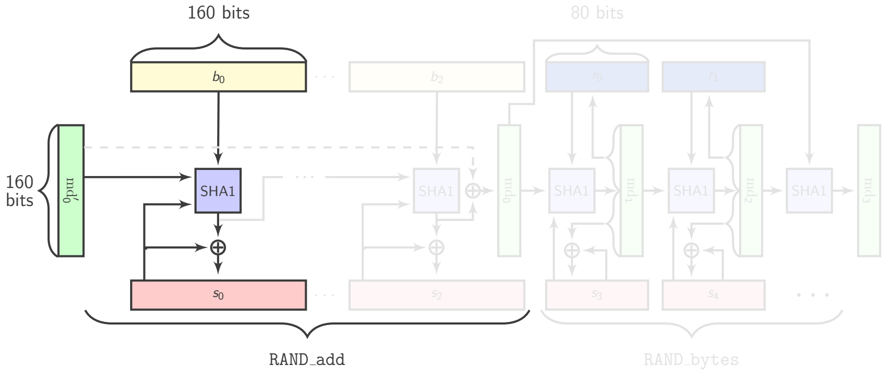

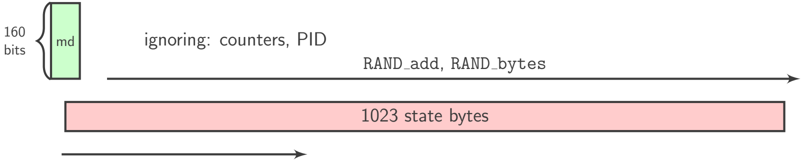

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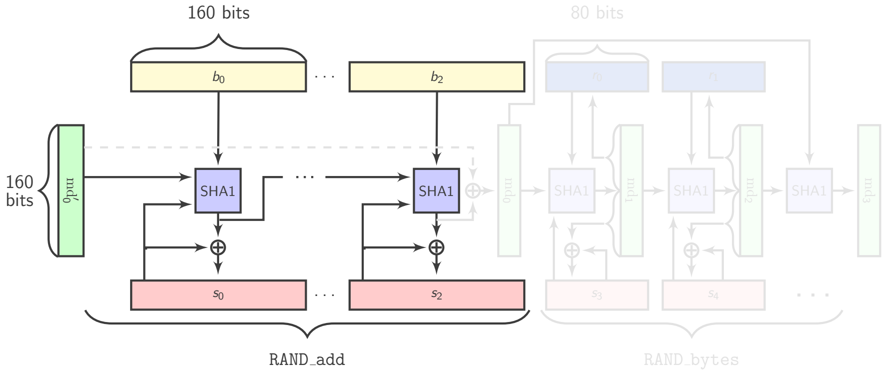

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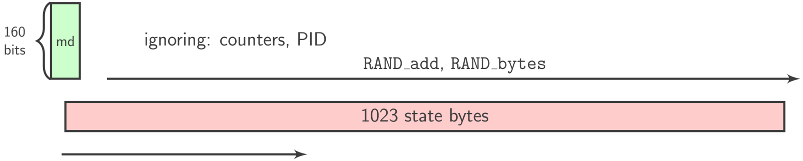

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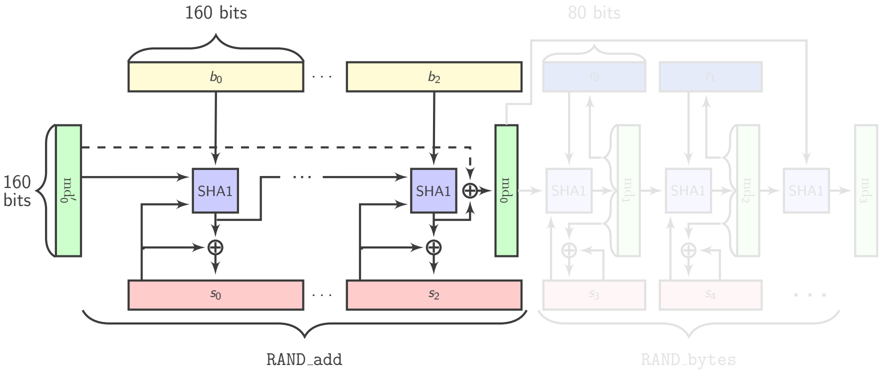

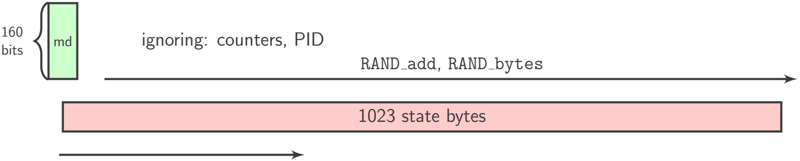

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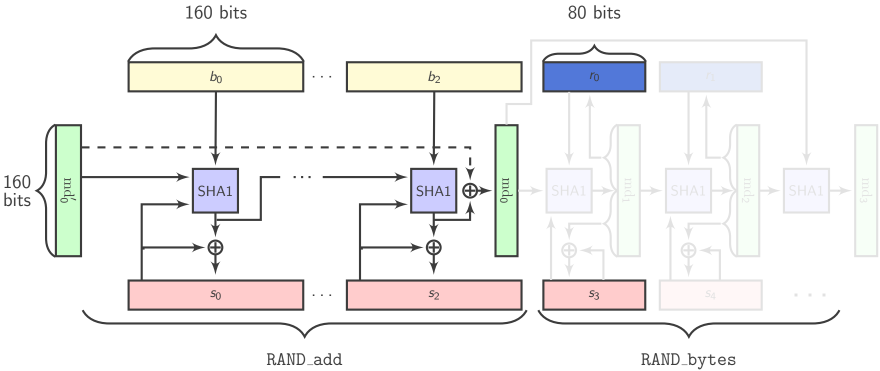

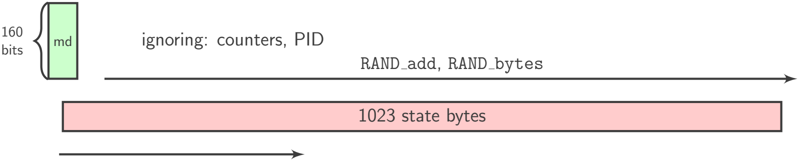

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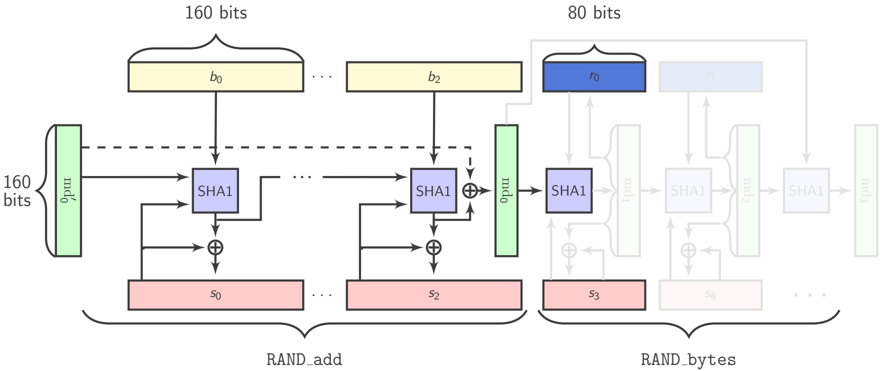

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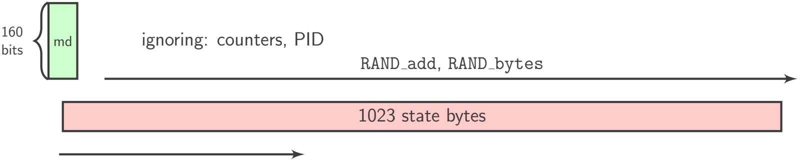

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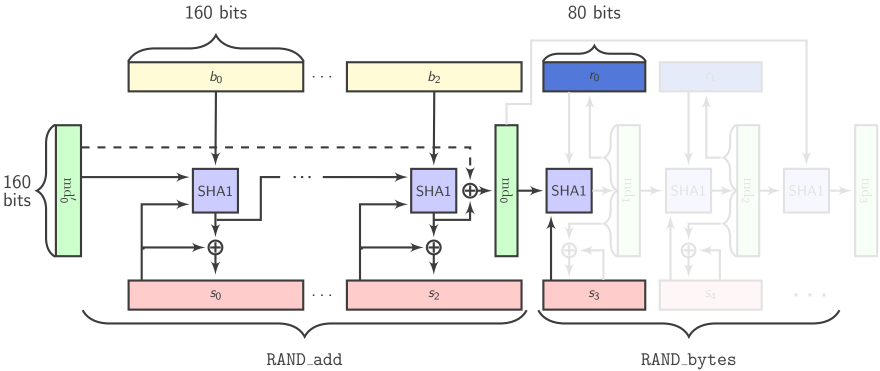

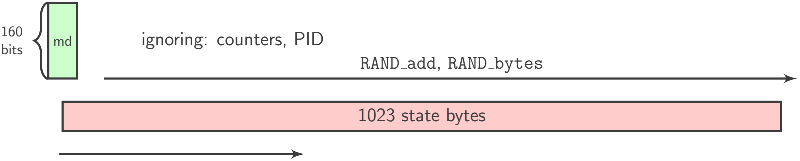

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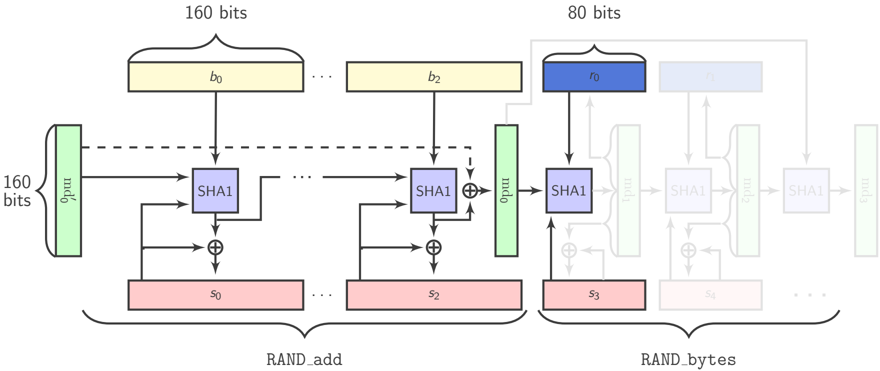

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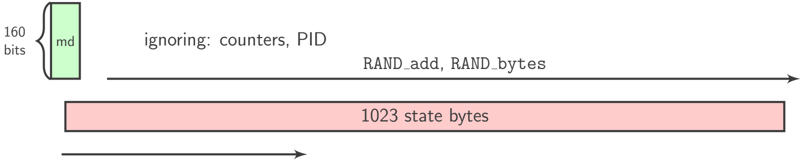

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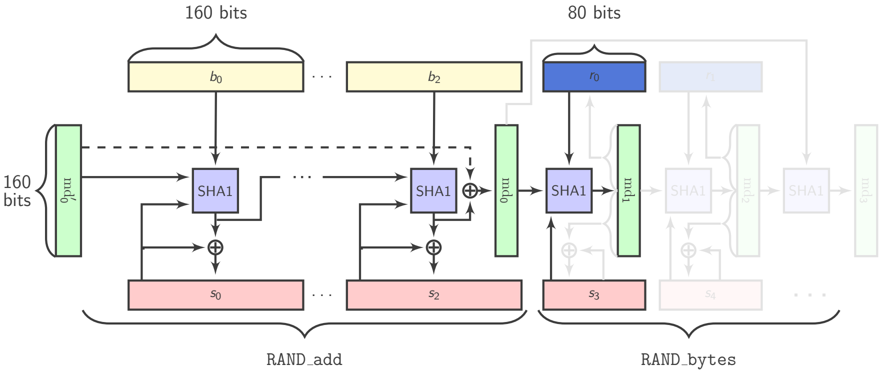

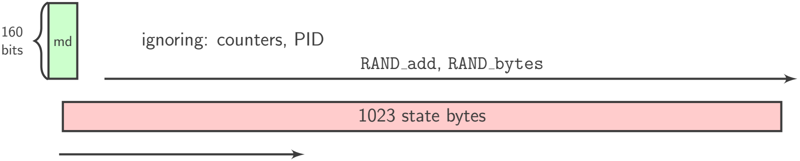

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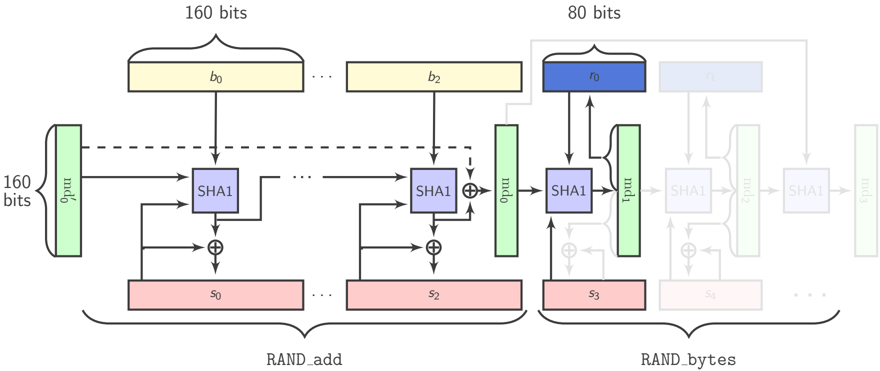

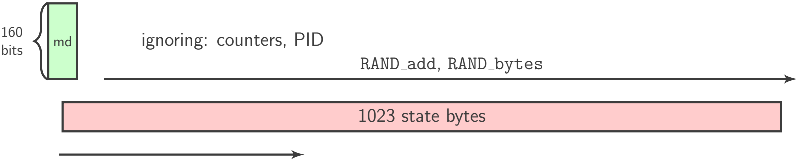

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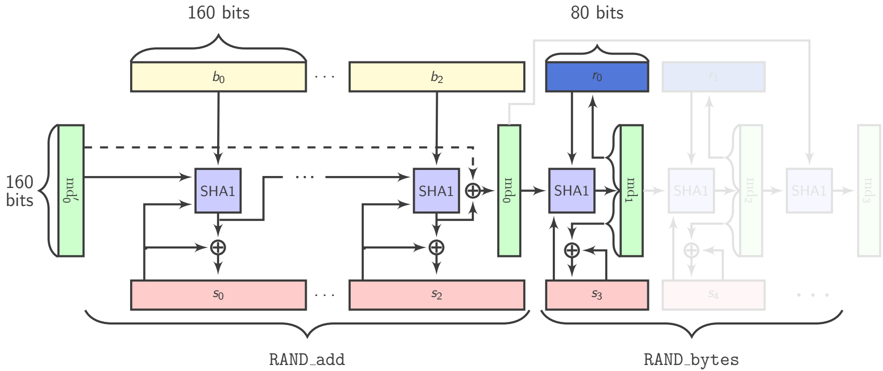

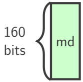

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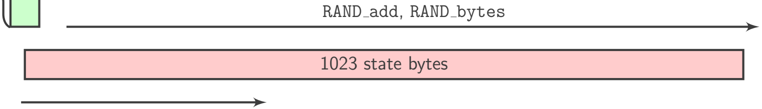
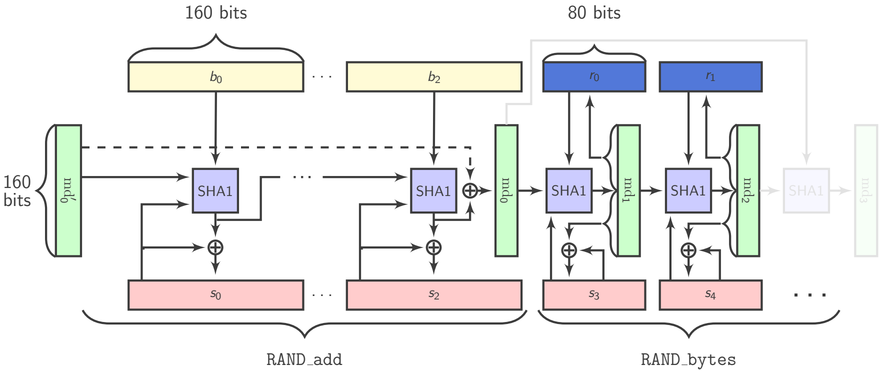
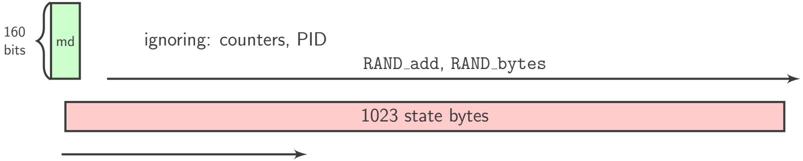


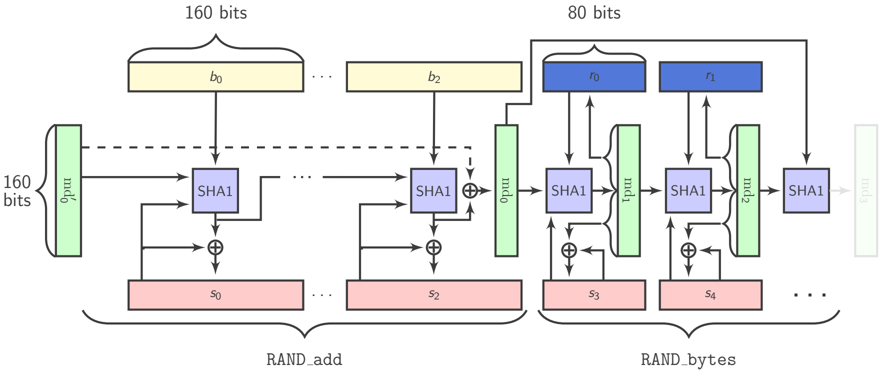
Core Cryptographic Function of OpenSSL's RNG

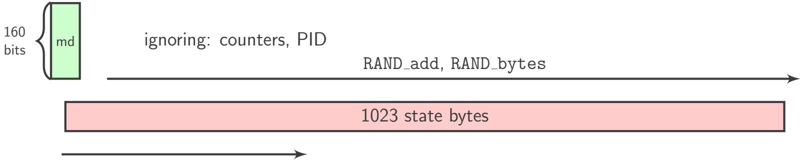




ignoring: counters, PID

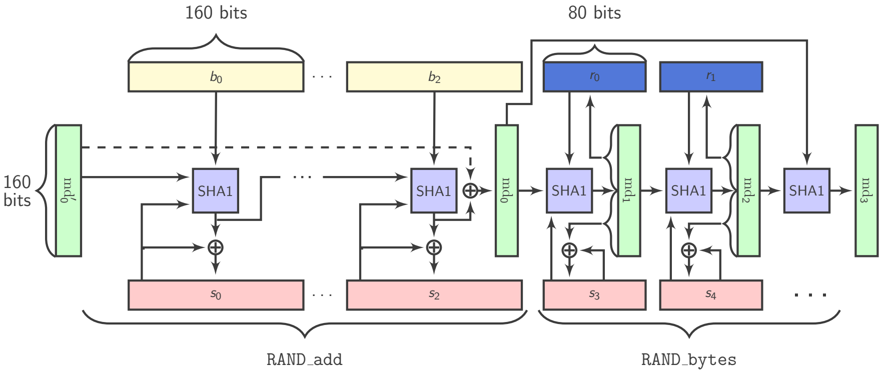
Core Cryptographic Function of OpenSSL's RNG

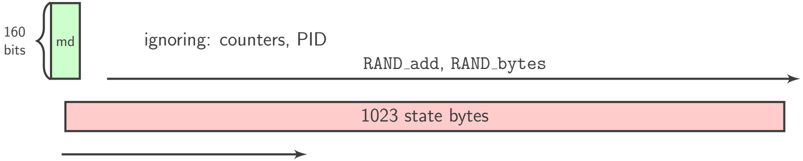




ignoring: counters, PID

Core Cryptographic Function of OpenSSL's RNG

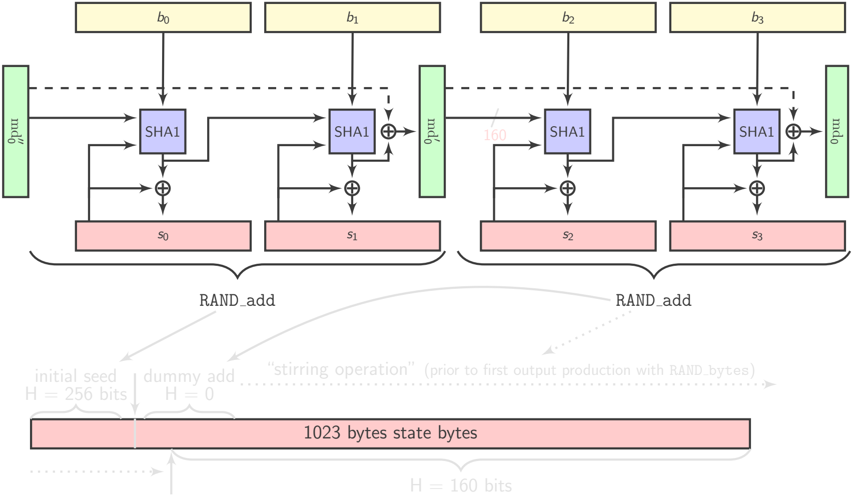




ignoring: counters, PID

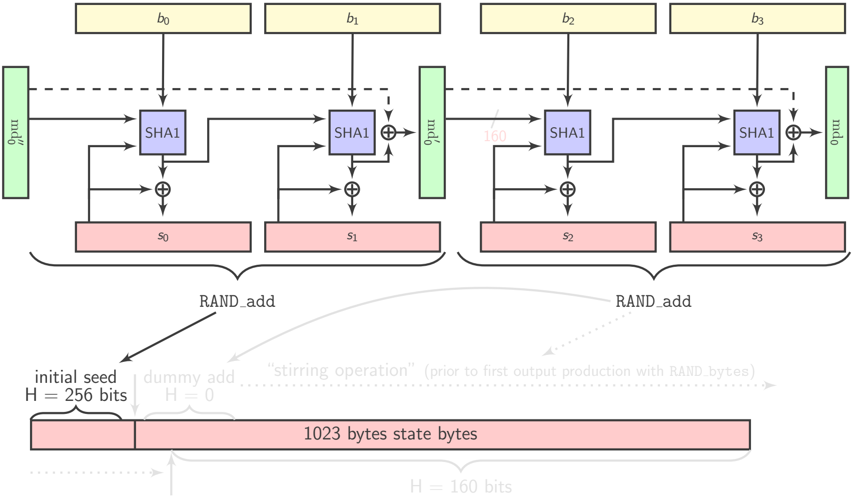
Output Entropy Limitation Vulnerabilities

ELO240



b_0
b_1
b_2
b_3
md_0''
md_0'
md_0
SHA1
SHA1
SHA1
SHA1
160
s_0
s_1
s_2
s_3
RAND_add
RAND_add
initial seed
H = 256 bits
dummy add
H = 0
"stirring operation" (prior to first output production with RAND_bytes)
1023 bytes state bytes
H = 160 bits

ELO240



RAND_add

RAND_add

initial seed
H = 256 bits

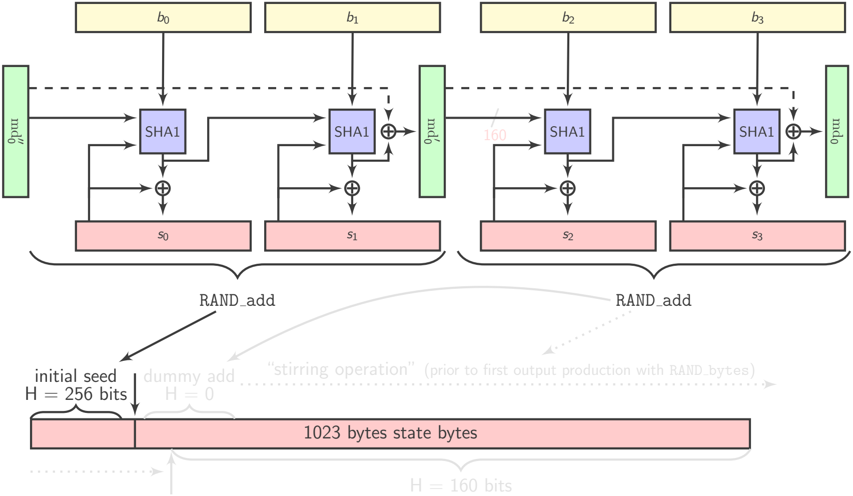
dummy add
H = 0

“stirring operation” (prior to first output production with RAND_bytes)

1023 bytes state bytes

H = 160 bits

ELO240



b_0
b_1
b_2
b_3
md_0''
md_0'
md_0
SHA1
SHA1
SHA1
SHA1
160
s_0
s_1
s_2
s_3
RAND_add
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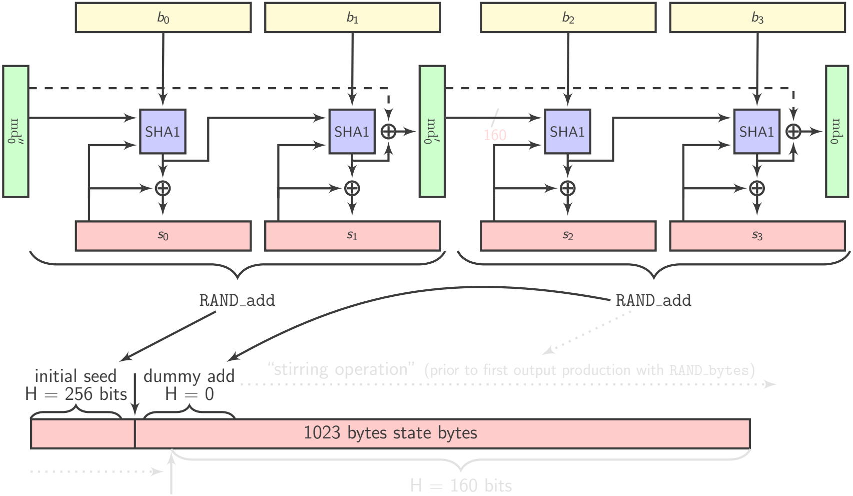
ELO240



b_0
b_1
b_2
b_3
md''
md'
md_0
SHA1
SHA1
SHA1
SHA1
160
s_0
s_1
s_2
s_3
RAND_add
RAND_add
"stirring operation" (prior to first output production with RAND_bytes)
initial seed
H = 256 bits
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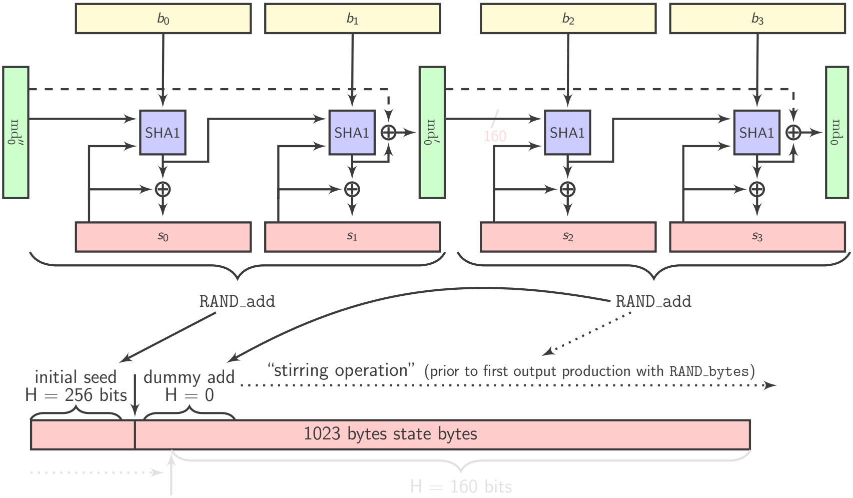
1023 bytes state bytes
H = 160 bits



RAND_add

RAND_add

initial seed
H = 256 bits

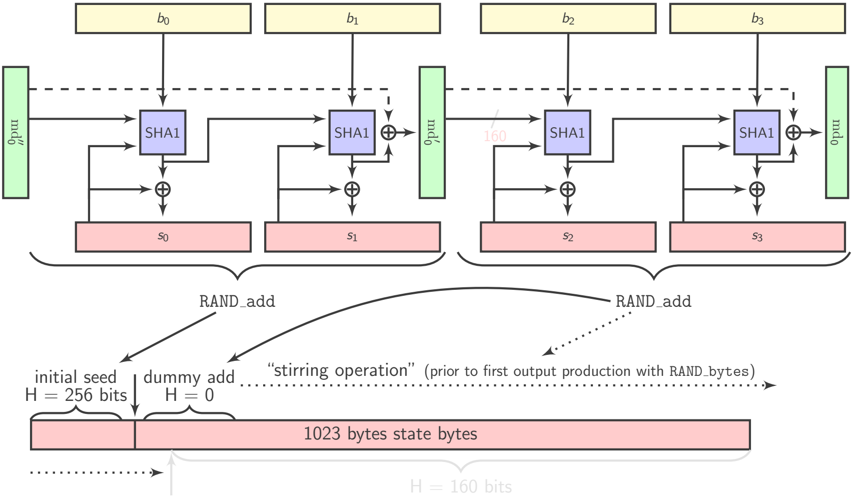
dummy add
H = 0

"stirring operation" (prior to first output production with RAND_bytes)

1023 bytes state bytes

H = 160 bits

ELO240



RAND_add

RAND_add

initial seed
H = 256 bits

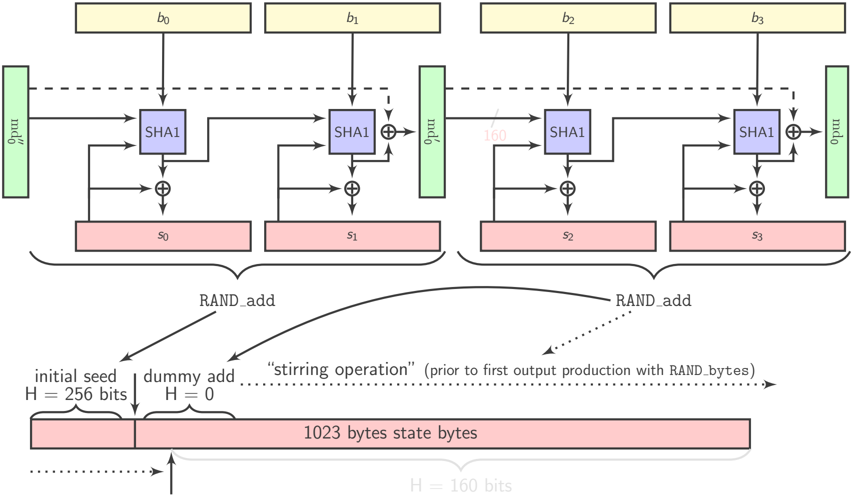
dummy add
H = 0

“stirring operation” (prior to first output production with RAND_bytes)

1023 bytes state bytes

H = 160 bits

ELO240



b_0
b_1
b_2
b_3
md''
SHA1
SHA1
md'
160
SHA1
SHA1
md_0
s_0
s_1
s_2
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RAND_add
RAND_add
initial seed
H = 256 bits
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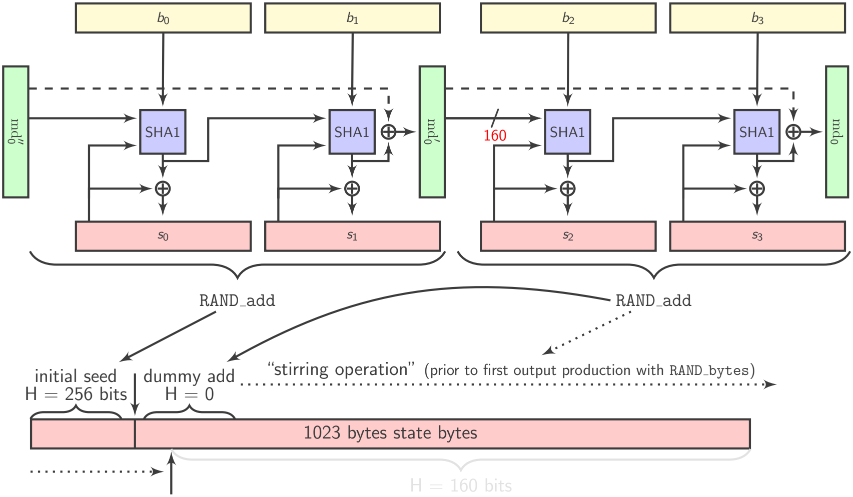
ELO240

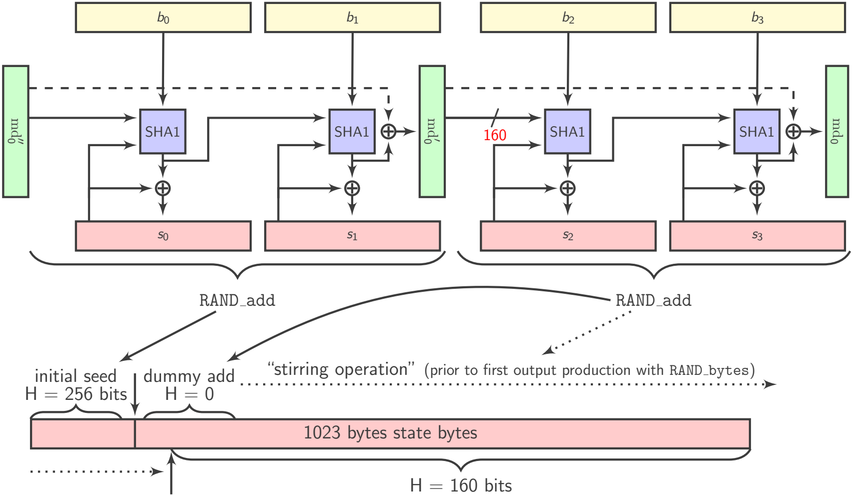


initial seed
H = 256 bits

dummy add
H = 0

"stirring operation" (prior to first output production with RAND_bytes)

H = 160 bits


b_0
b_1
b_2
b_3
md''
md'
md
SHA1
SHA1
SHA1
SHA1
160
s_0
s_1
s_2
s_3
RAND_add
RAND_add
initial seed
H = 256 bits
dummy add
H = 0
"stirring operation" (prior to first output production with RAND_bytes)
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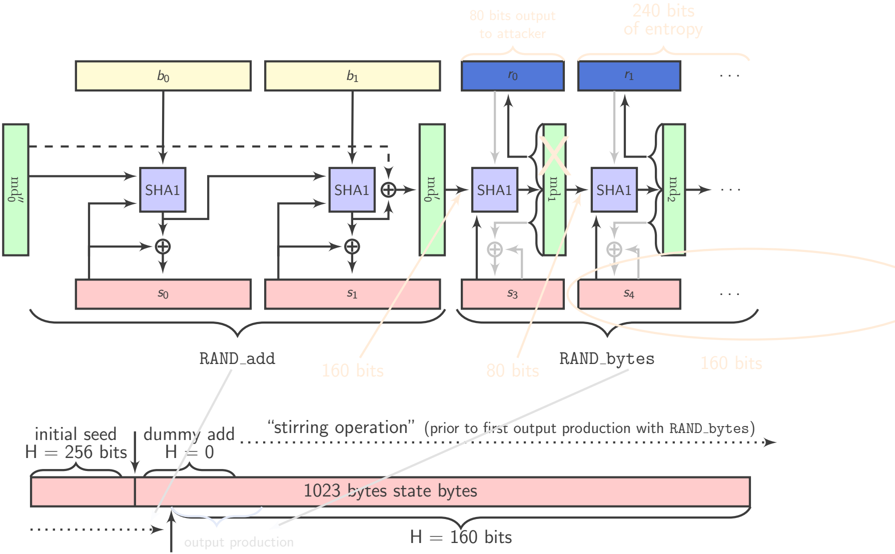
H = 160 bits

ELO240



80 bits output to attacker

240 bits of entropy

b_0 b_1 r_0 r_1 . . .

md_0'' SHA1 SHA1 ⊕ md_0' SHA1 md_1 SHA1 md_2 . . .

s_0 s_1 s_3 s_4 . . .

RAND_add 160 bits 80 bits RAND_bytes 160 bits

initial seed H = 256 bits

dummy add H = 0

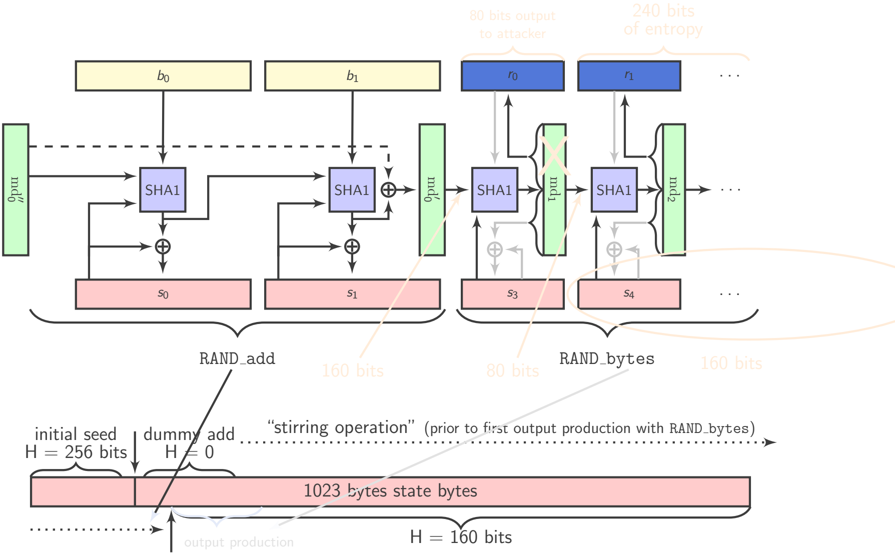
"stirring operation" (prior to first output production with RAND_bytes)

1023 bytes state bytes

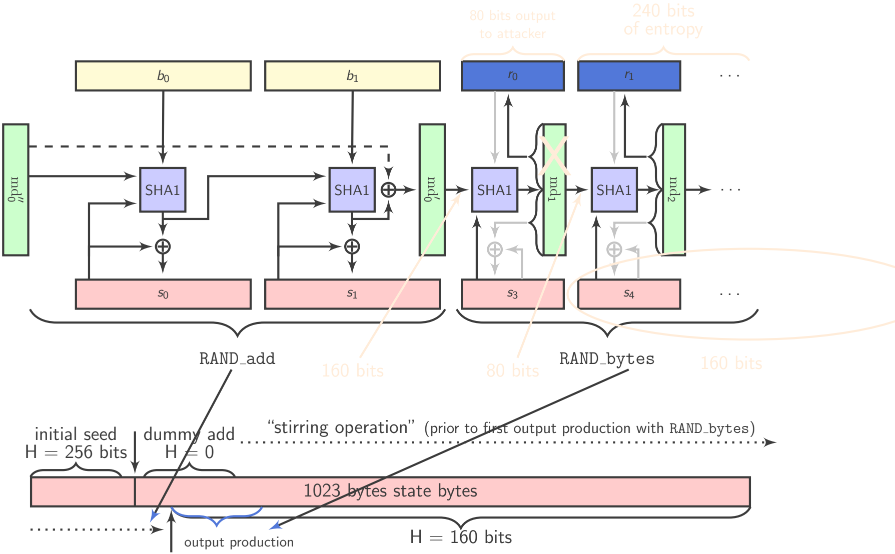
output production

H = 160 bits

ELO240


80 bits output
to attacker
240 bits
of entropy
b_0
b_1
r_0
r_1
. . .
md$''_0$
SHA1
SHA1
md$'_0$
SHA1
md$_1$
SHA1
md$_2$
. . .
s_0
s_1
s_3
s_4
. . .
RAND_add
160 bits
80 bits
RAND_bytes
160 bits
initial seed
H = 256 bits
dummy add
H = 0
"stirring operation" (prior to first output production with RAND_bytes)
1023 bytes state bytes
output production
H = 160 bits

ELO240


80 bits output
to attacker
240 bits
of entropy
b_0
b_1
r_0
r_1
. . .
md_0''
SHA1
SHA1
$\oplus$
md_0'
SHA1
md_1
SHA1
md_2
. . .
$\oplus$
$\oplus$
$\oplus$
$\oplus$
s_0
s_1
s_3
s_4
. . .
RAND_add
160 bits
80 bits
RAND_bytes
160 bits
initial seed
H = 256 bits
dummy add
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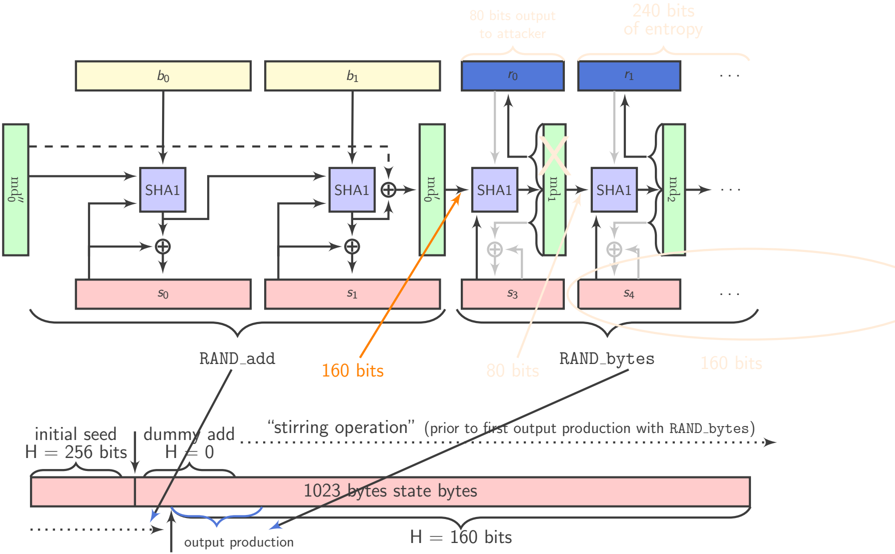
"stirring operation" (prior to first output production with RAND_bytes)
1023 bytes state bytes
output production
H = 160 bits

ELO240


80 bits output
to attacker
240 bits
of entropy
b_0
b_1
r_0
r_1
. . .
md_0''
SHA1
SHA1
⊕
md_0'
SHA1
md_1
SHA1
md_2
. . .
⊕
⊕
⊕
⊕
s_0
s_1
s_3
s_4
. . .
RAND_add
160 bits
80 bits
RAND_bytes
160 bits
initial seed
H = 256 bits
dummy add
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"stirring operation" (prior to first output production with RAND_bytes)
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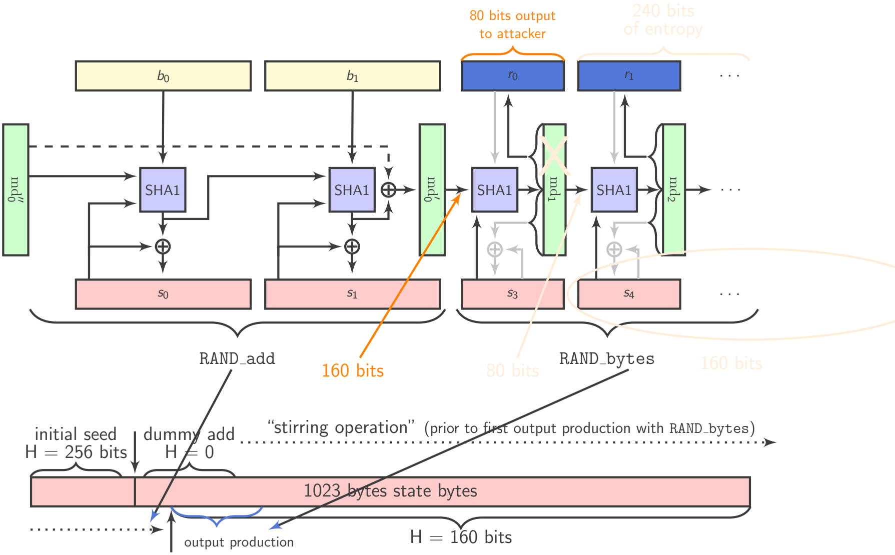
output production
H = 160 bits

ELO240


80 bits output
to attacker
240 bits
of entropy
b_0
b_1
r_0
r_1
. . .
md_0''
SHA1
SHA1
md_0'
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md_1
SHA1
md_2
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s_0
s_1
s_3
s_4
. . .
RAND_add
160 bits
80 bits
RAND_bytes
160 bits
initial seed
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"stirring operation" (prior to first output production with RAND_bytes)
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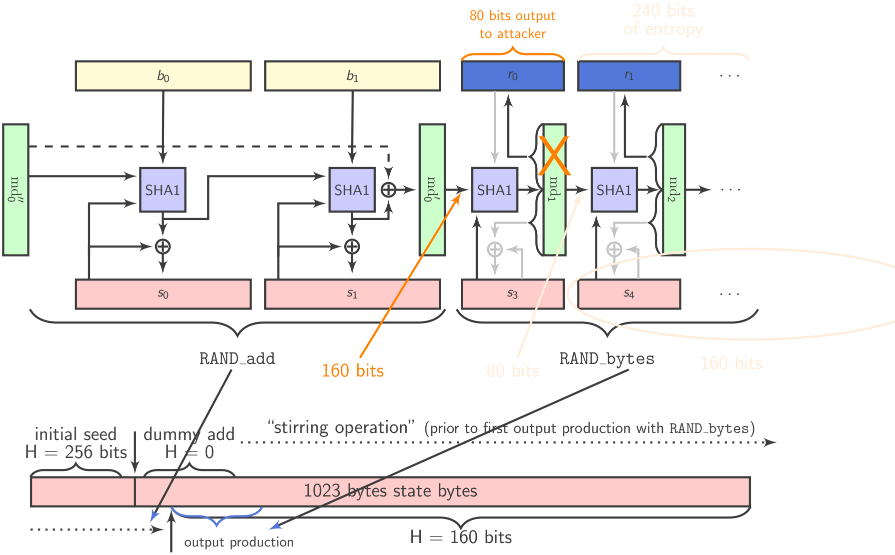
ELO240


80 bits output
to attacker
240 bits
of entropy
b_0
b_1
r_0
r_1
. . .
md$''_0$
SHA1
SHA1
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md$'_0$
SHA1
md$_1$
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s_0
s_1
s_3
s_4
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RAND_add
160 bits
80 bits
RAND_bytes
160 bits
initial seed
H = 256 bits
dummy add
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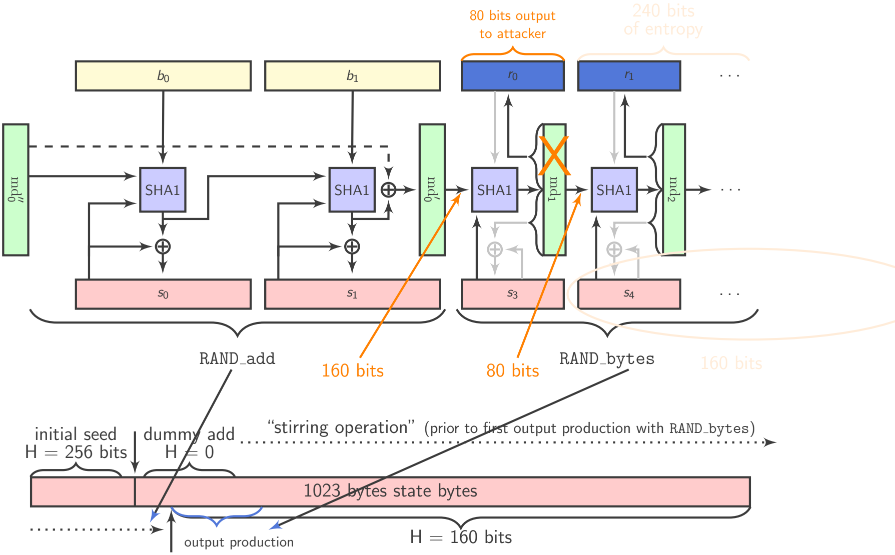
“stirring operation” (prior to first output production with RAND_bytes)
1023 bytes state bytes
output production
H = 160 bits

ELO240



80 bits output
to attacker
240 bits
of entropy
b_0
b_1
r_0
r_1
. . .
md_0''
SHA1
SHA1
md_0'
SHA1
md_1
SHA1
md_2
. . .
s_0
s_1
s_3
s_4
. . .
RAND_add
160 bits
80 bits
RAND_bytes
160 bits
initial seed
H = 256 bits
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"stirring operation" (prior to first output production with RAND_bytes)
1023 bytes state bytes
output production
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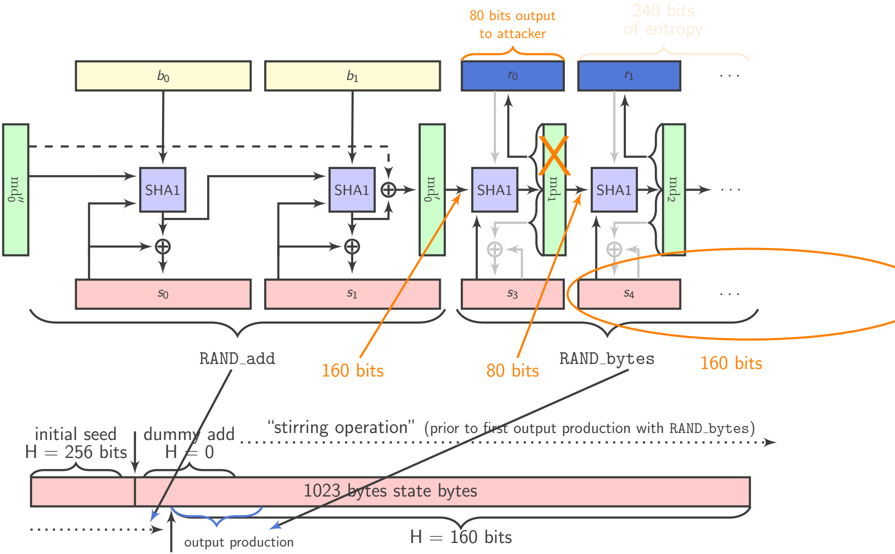
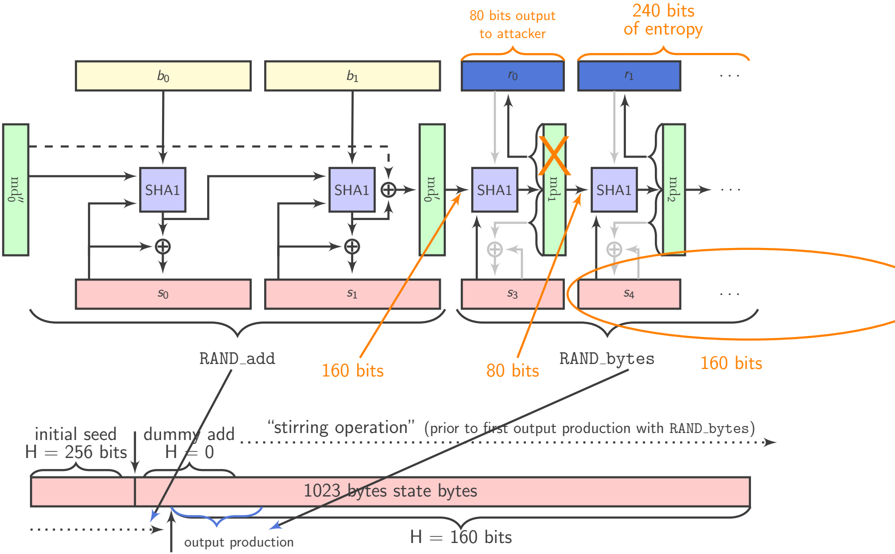
ELO240



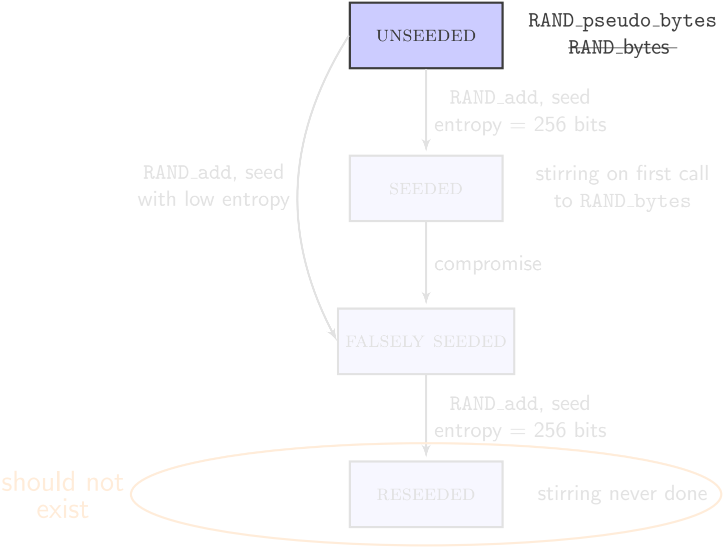
80 bits output
to attacker
240 bits
of entropy
b_0
b_1
r_0
r_1
. . .
md$''_0$
SHA1
SHA1
md$'_0$
SHA1
md$_1$
SHA1
md$_2$
. . .
s_0
s_1
s_3
s_4
. . .
RAND_add
160 bits
80 bits
RAND_bytes
160 bits
initial seed
H = 256 bits
dummy add
H = 0
"stirring operation" (prior to first output production with RAND_bytes)
1023 bytes state bytes
output production
H = 160 bits

ELO240

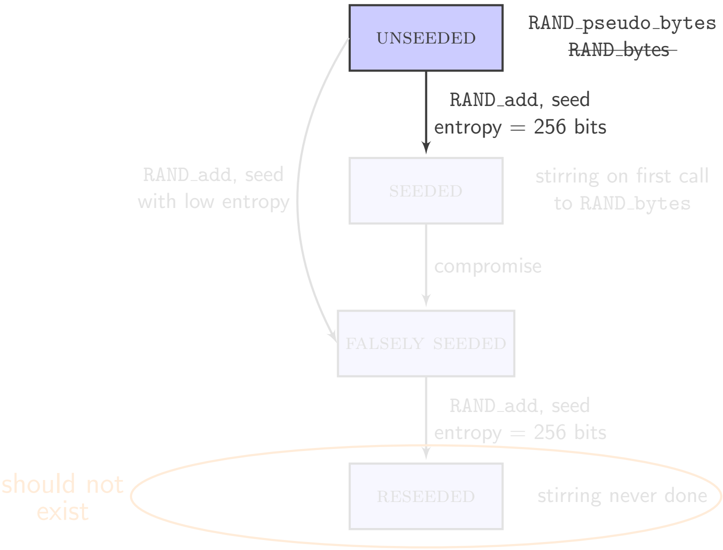


80 bits output to attacker
240 bits of entropy
b_0
b_1
r_0
r_1
. . .
md''_0
SHA1
SHA1
md'_0
SHA1
md_1
SHA1
md_2
X
s_0
s_1
s_3
s_4
RAND_add
160 bits
80 bits
RAND_bytes
160 bits
initial seed
H = 256 bits
dummy add
H = 0
"stirring operation" (prior to first output production with RAND_bytes)
1023 bytes state bytes
output production
H = 160 bits

Life cycle


UNSEEDED
RAND_pseudo_bytes
~~RAND_bytes~~
RAND_add, seed
entropy = 256 bits
RAND_add, seed
with low entropy
SEEDED
stirring on first call
to RAND_bytes
compromise
FALSELY SEEDED
RAND_add, seed
entropy = 256 bits
should not
exist
RESEEDED
stirring never done

Life cycle



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~~RAND_bytes~~

RAND_add, seed
entropy = 256 bits

RAND_add, seed
with low entropy

SEEDED

stirring on first call
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compromise

FALSELY SEEDED

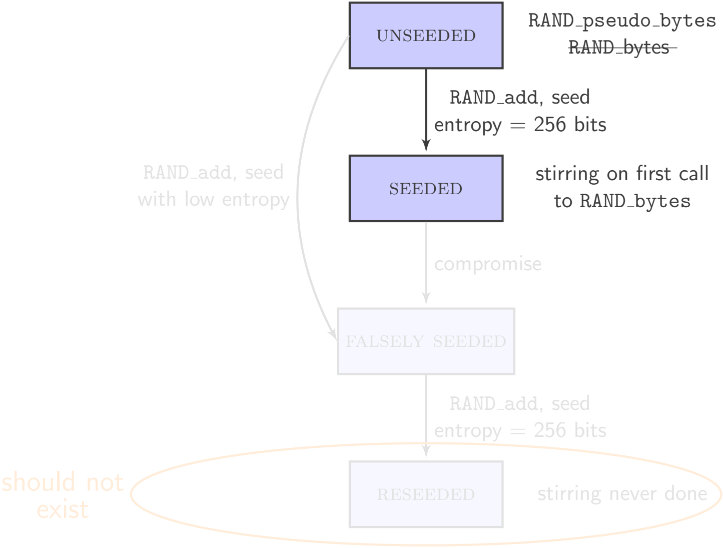
RAND_add, seed
entropy = 256 bits

should not
exist

RESEEDED

stirring never done

Life cycle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~~RAND_bytes~~
RAND_add, seed
entropy = 256 bits
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stirring on first call
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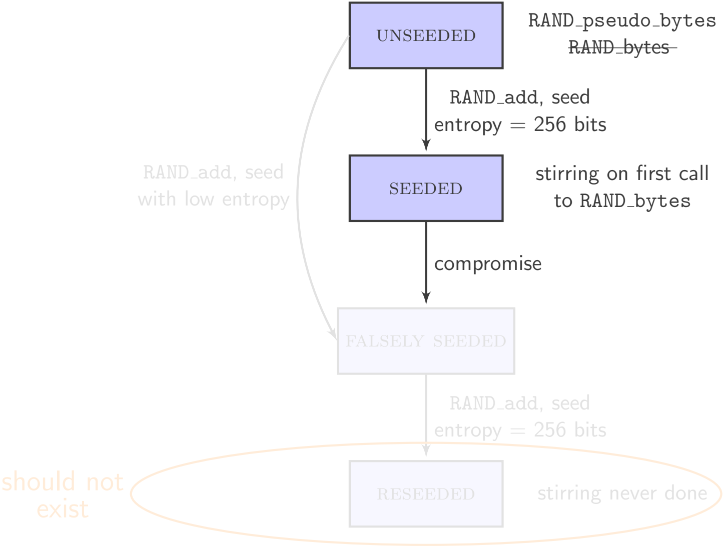
Life cycle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entropy = 256 bits
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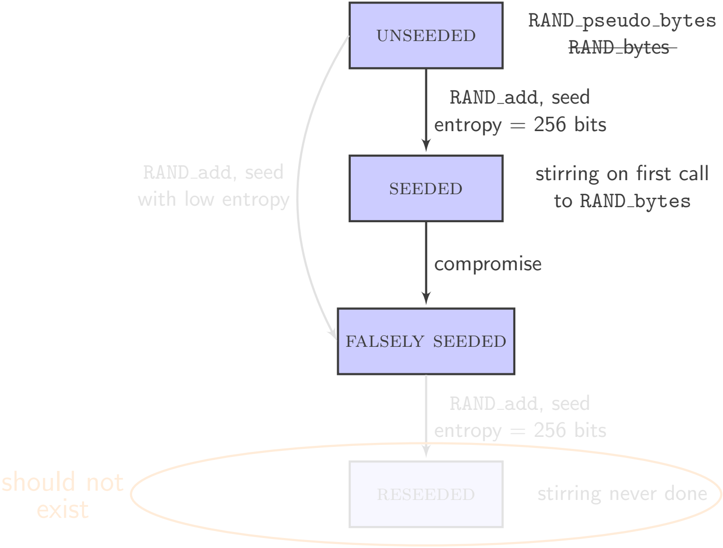
Life cycle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RAND_add, seed
entropy = 256 bits
SEEDED
stirring on first call
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RAND_add, seed
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FALSELY SEEDED
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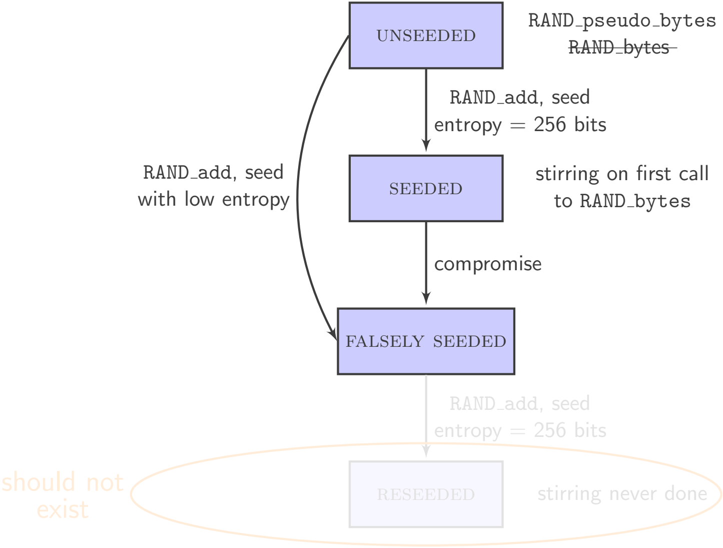
Life cycle


UNSEEDED
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entropy = 256 bits
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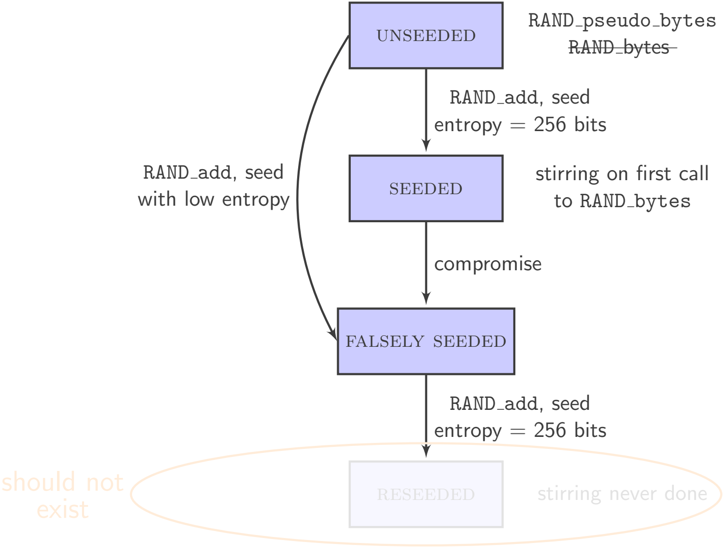
Life cycle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entropy = 256 bits
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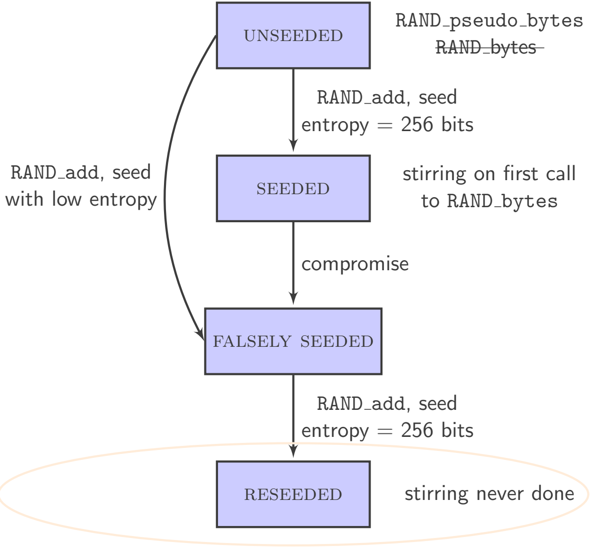
Life cycle



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RAND_pseudo_bytes
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entropy = 256 bits

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stirring on first call
to RAND_bytes

RAND_add, seed
with low entropy

compromise

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entropy = 256 bits

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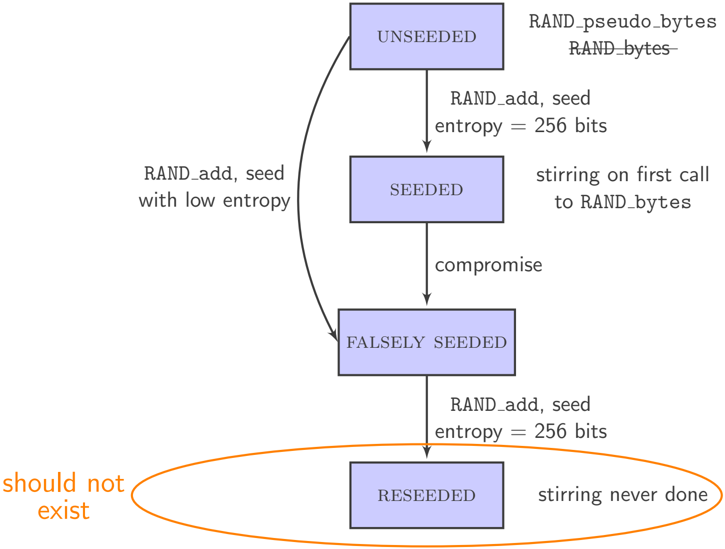
Life cycle



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RAND_add, seed
entropy = 256 bits

SEEDED

stirring on first call
to RAND_bytes

RAND_add, seed
with low entropy

compromise

FALSELY SEEDED

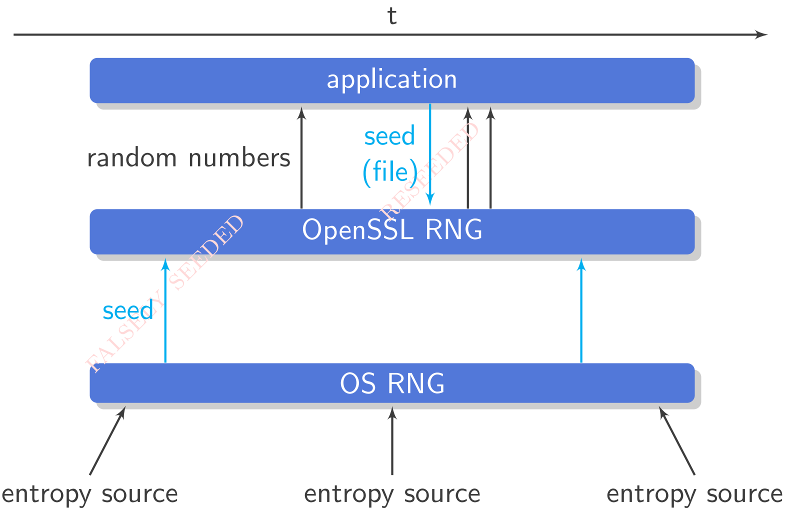
RAND_add, seed
entropy = 256 bits

RESEEDED

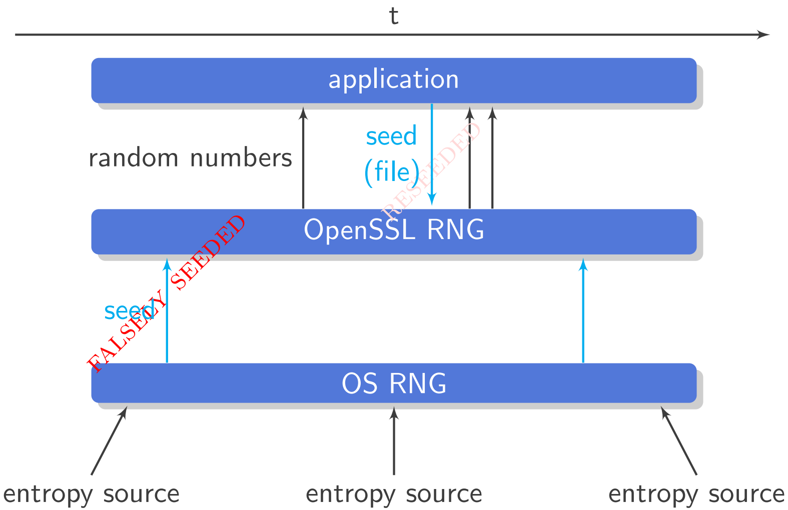
stirring never done

should not
exist

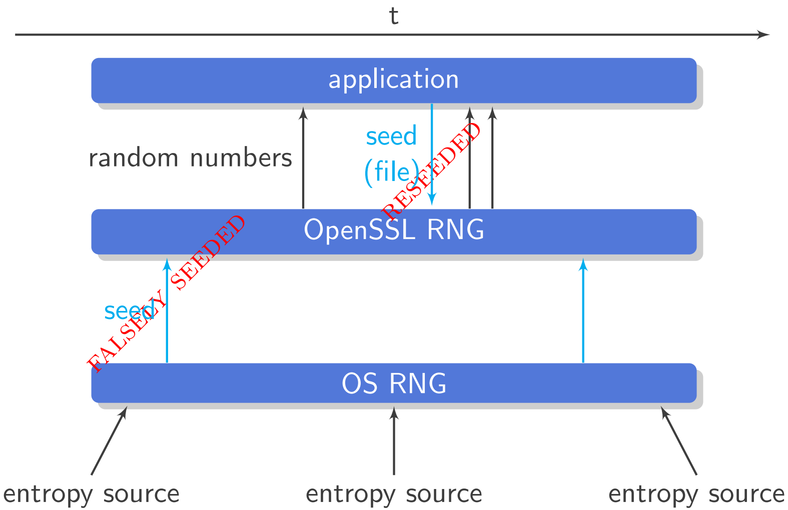
Reseeded State in Practice



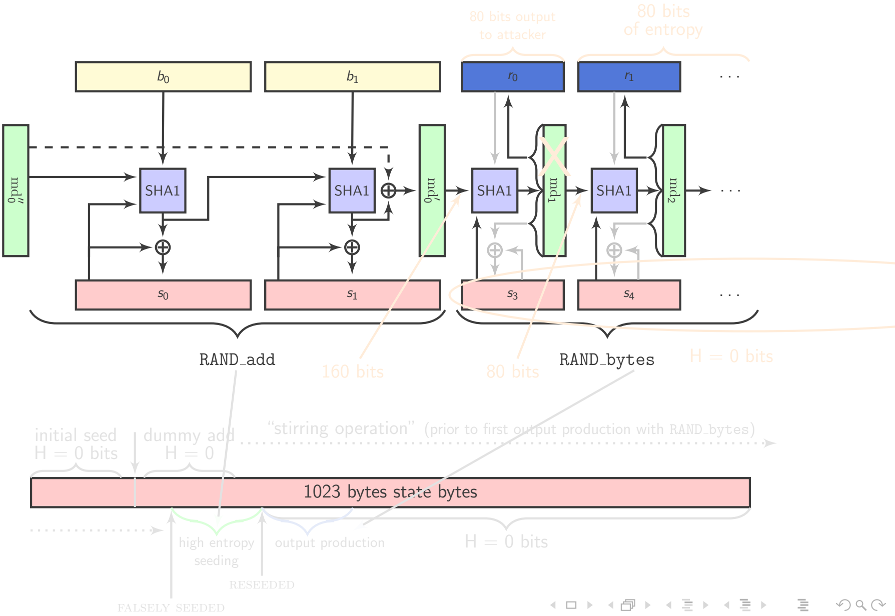
Reseeded State in Practice



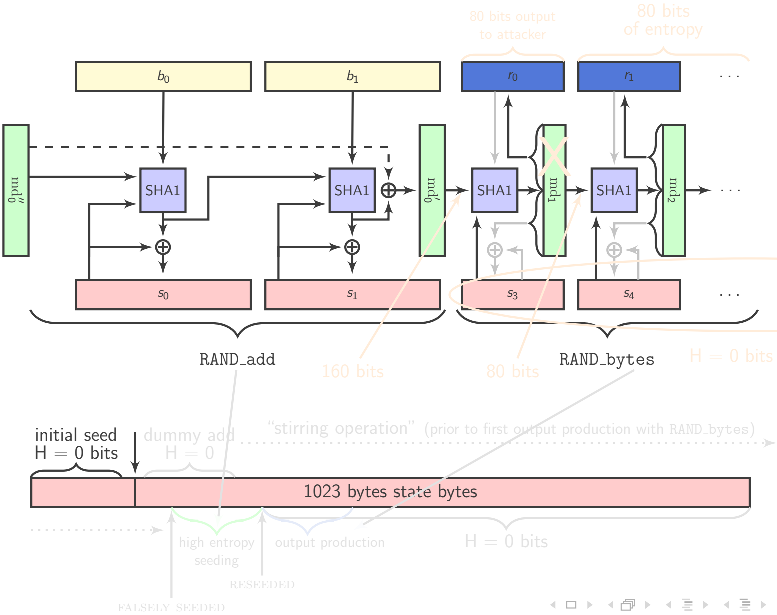
Reseeded State in Practice



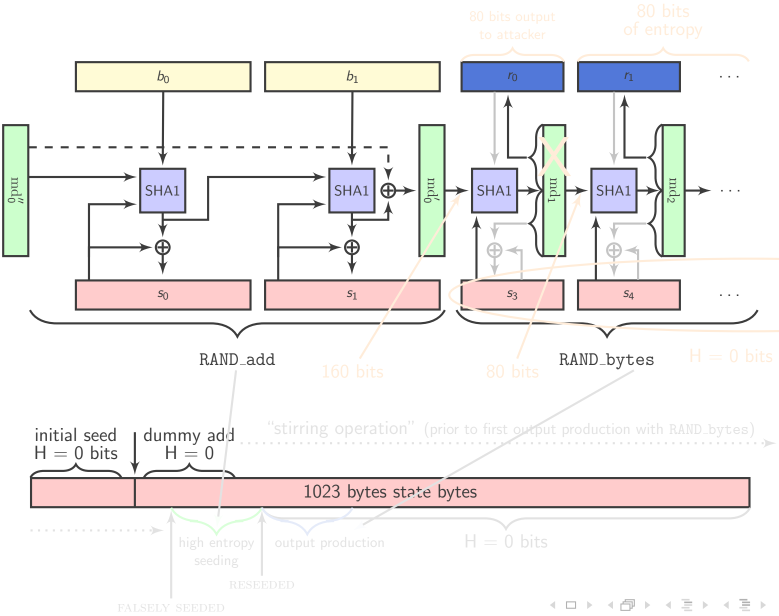
ELO160 / ELO80 in State RESEEDED



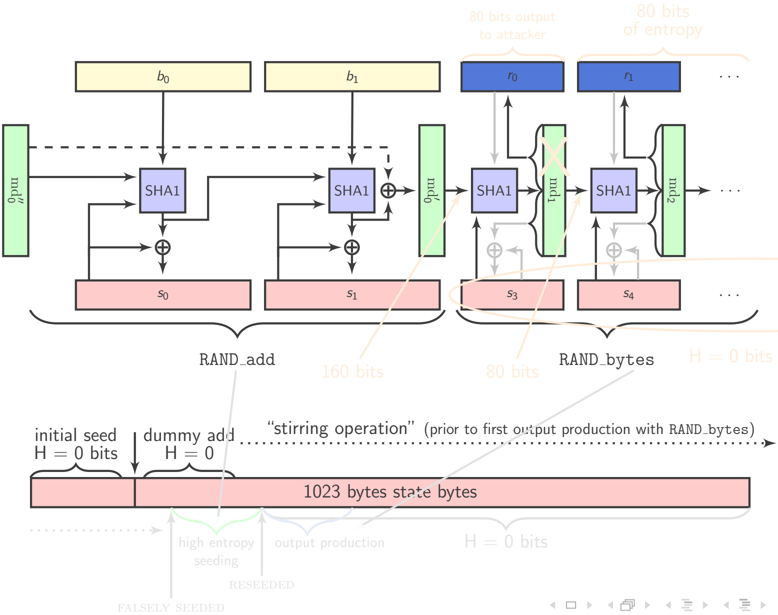
ELO160 / ELO80 in State RESEEDED



ELO160 / ELO80 in State RESEEDED



ELO160 / ELO80 in State RESEEDED



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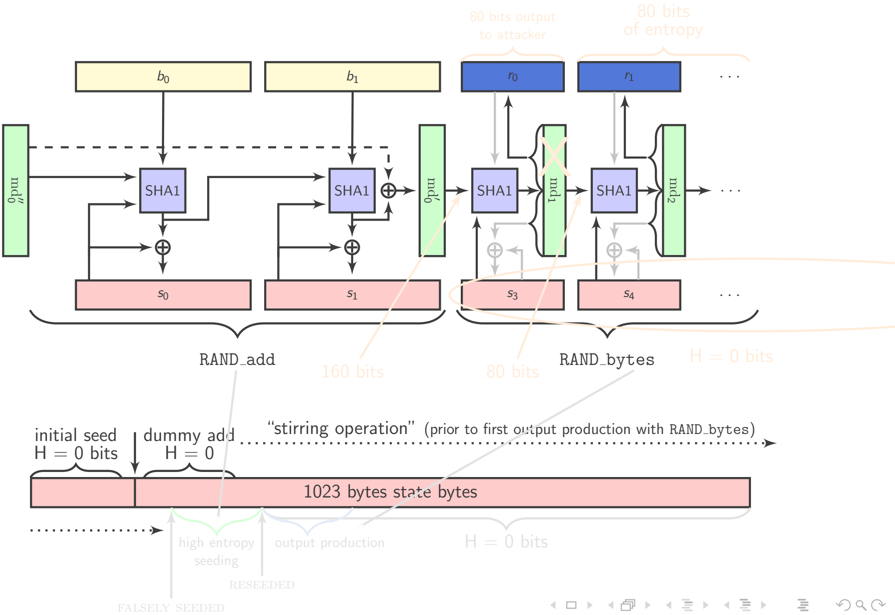

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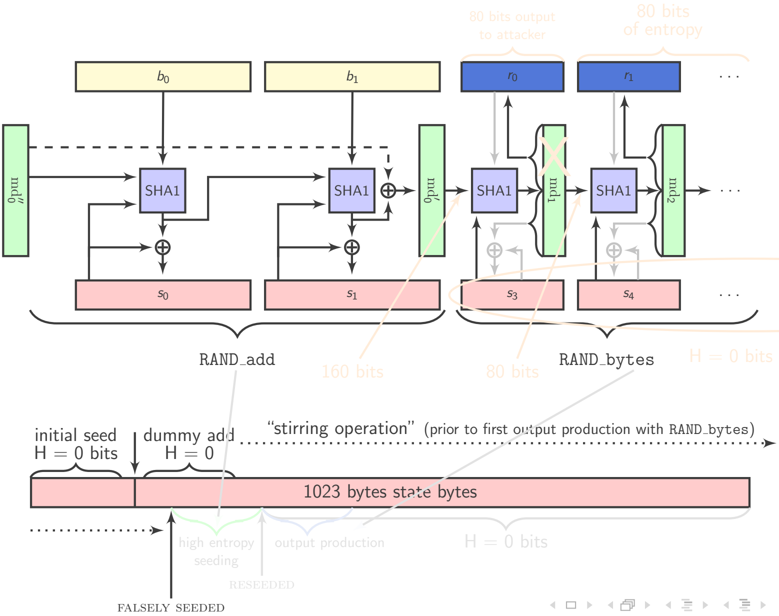

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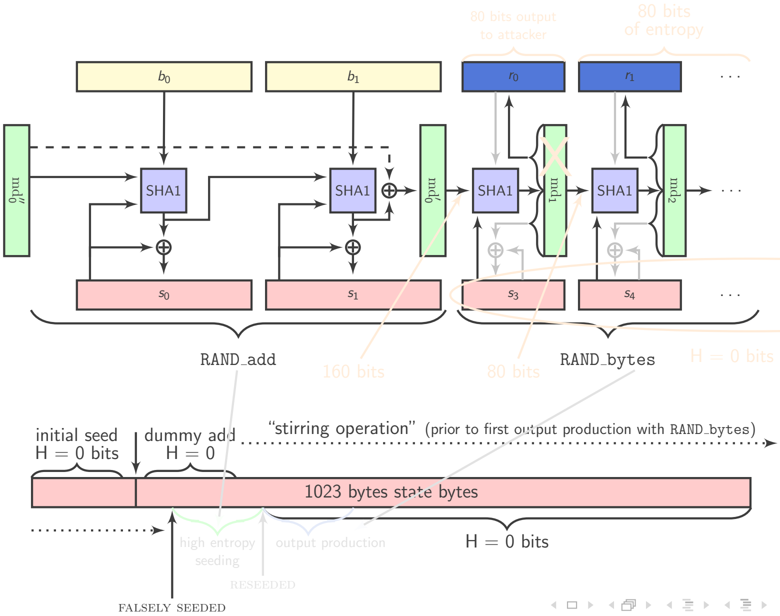

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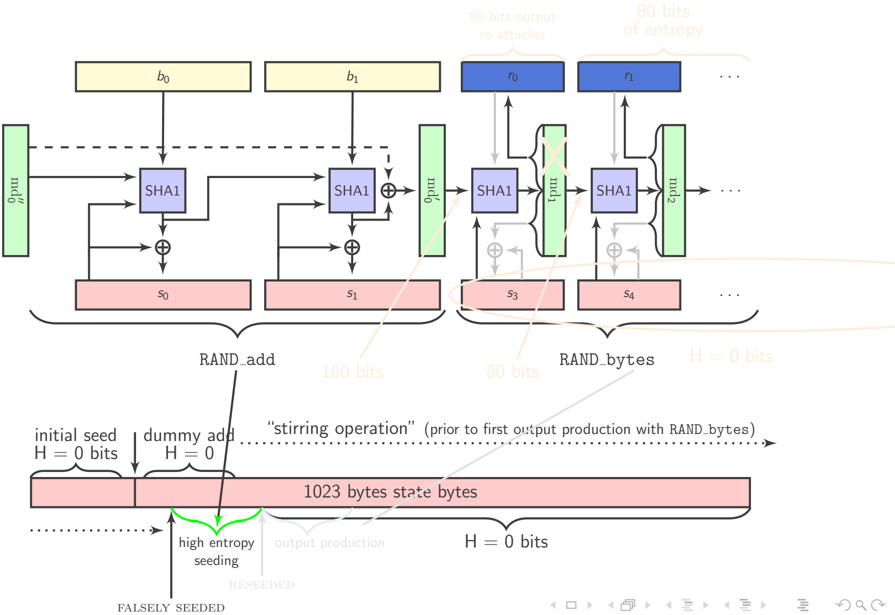

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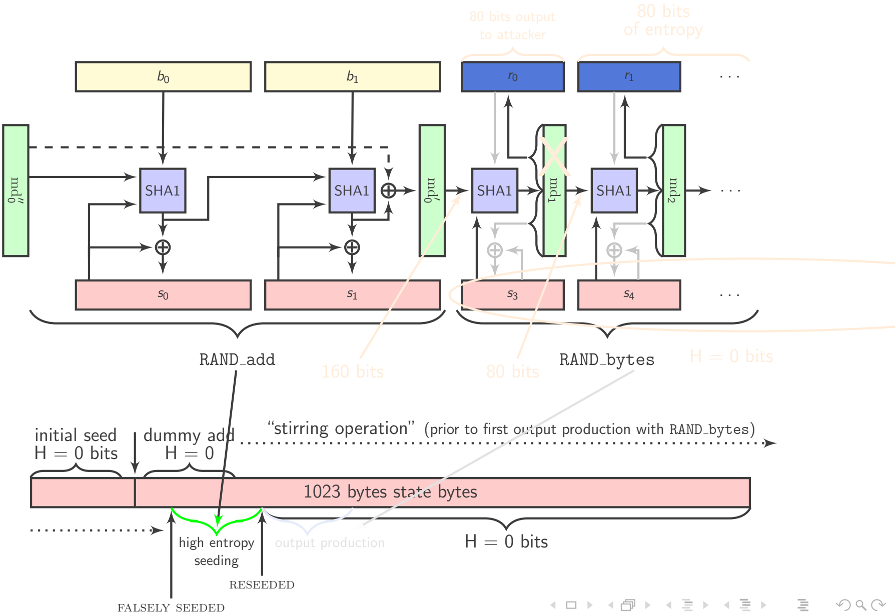

80 bits output to attacker

80 bits of entropy

b_0

b_1

r_0

r_1

. . .

md_0''

SHA1

SHA1

md_0'

SHA1

md_1

SHA1

md_2

. . .

s_0

s_1

s_3

s_4

. . .

RAND_add

160 bits

80 bits

RAND_bytes

H = 0 bits

initial seed
H = 0 bits

dummy add
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“stirring operation” (prior to first output production with RAND_bytes)

1023 bytes state bytes

high entropy seeding

output production

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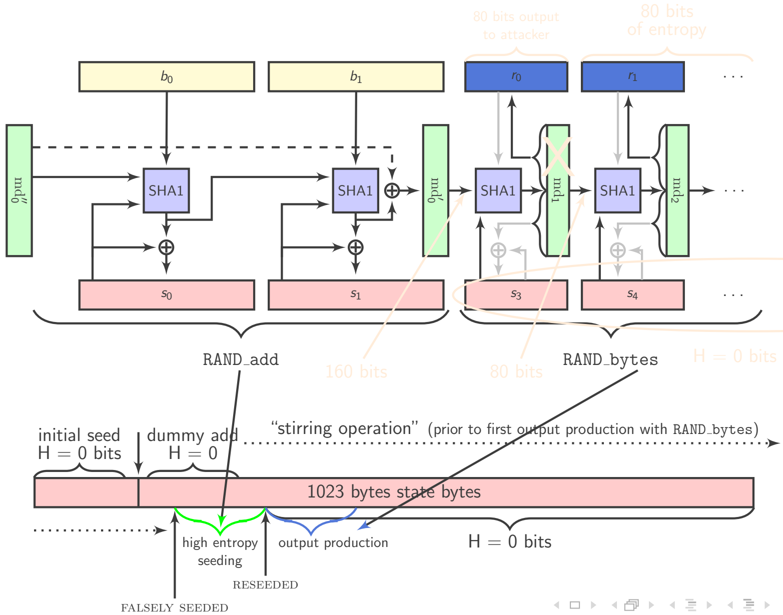

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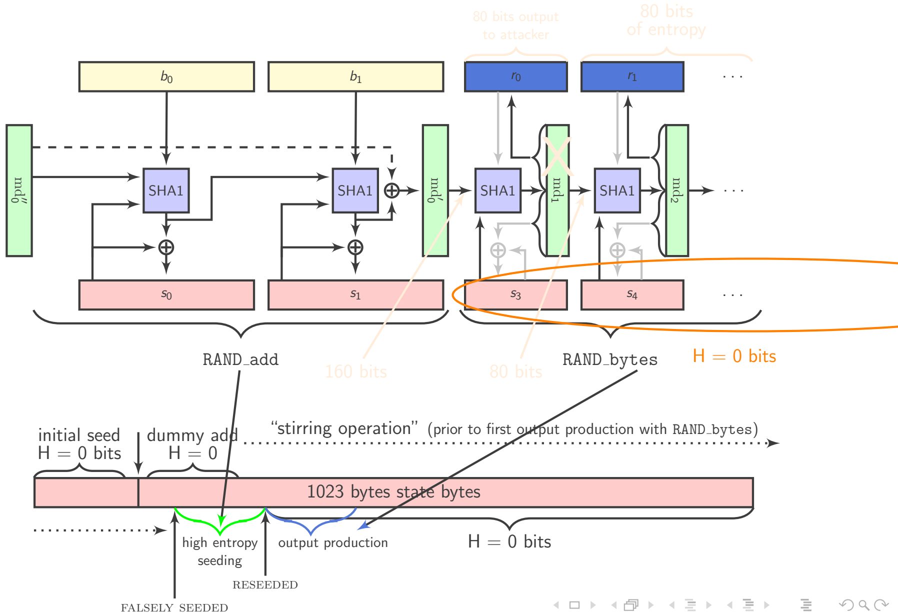

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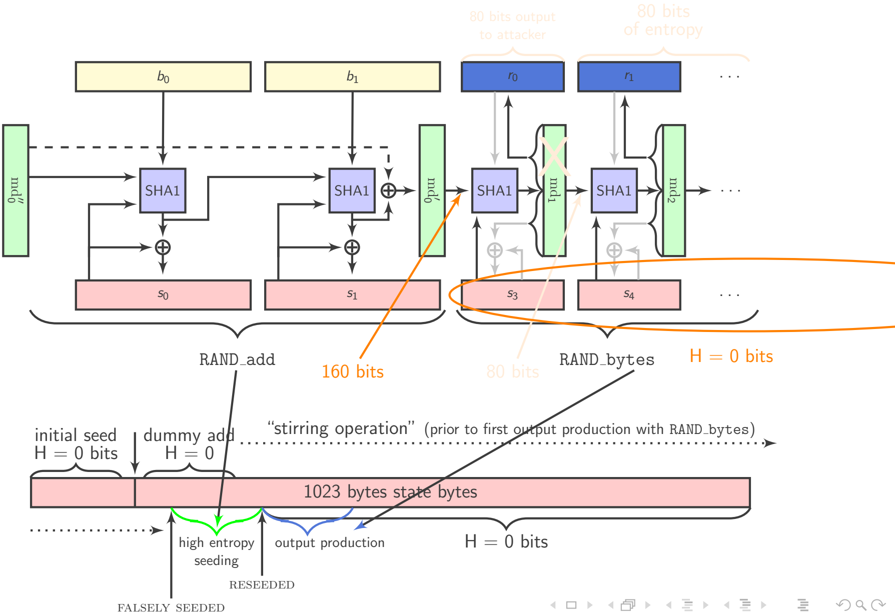

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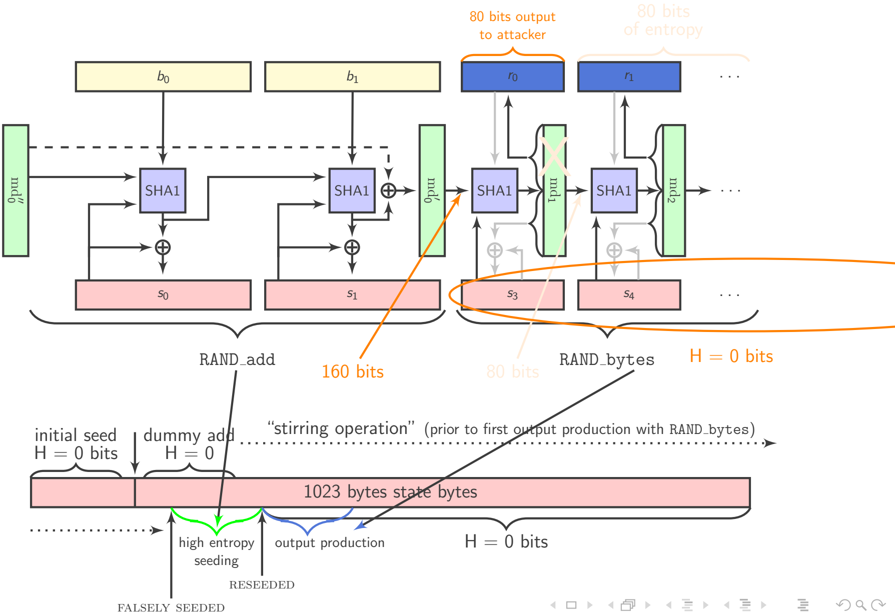

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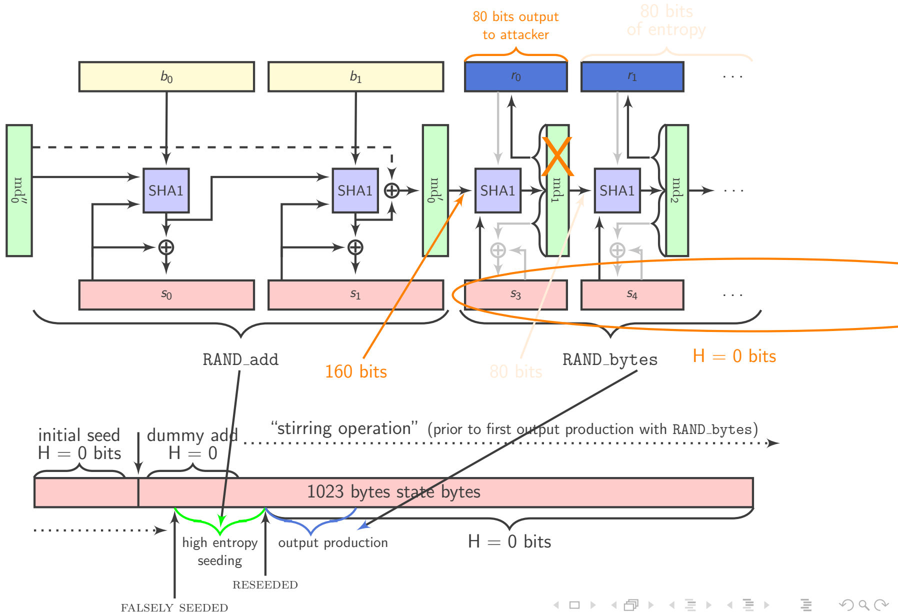

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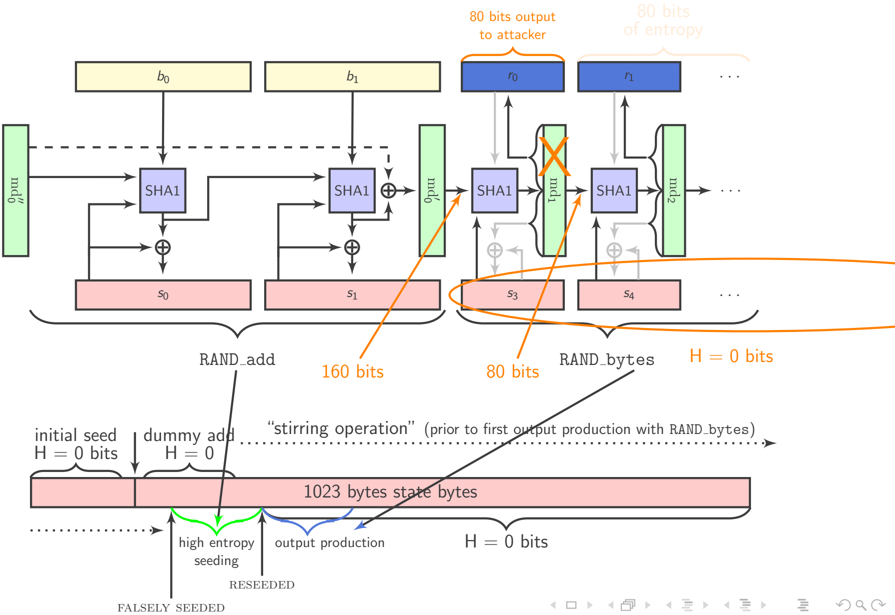

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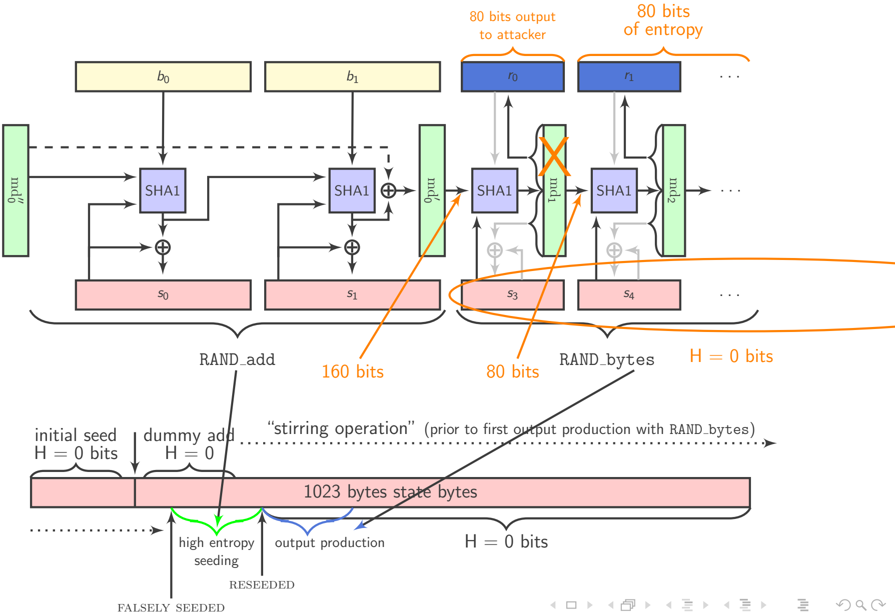

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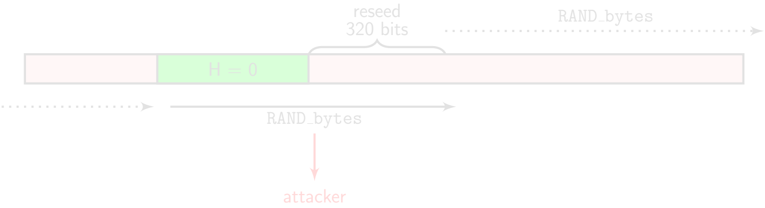

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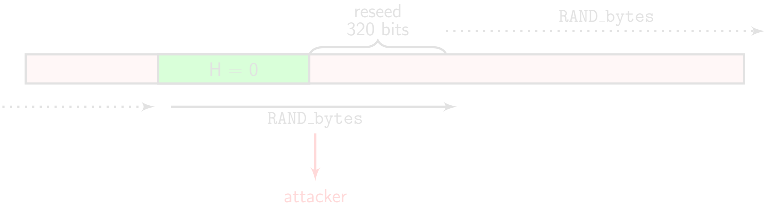

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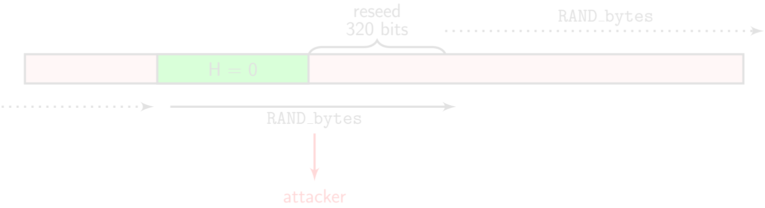

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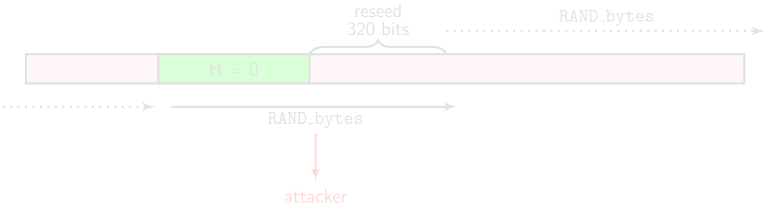

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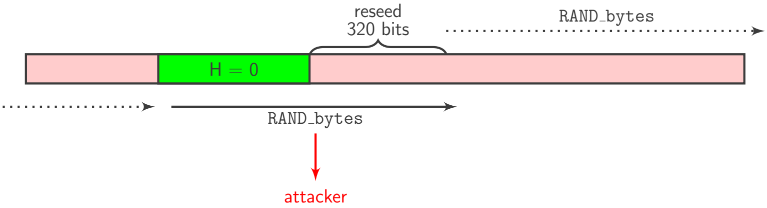

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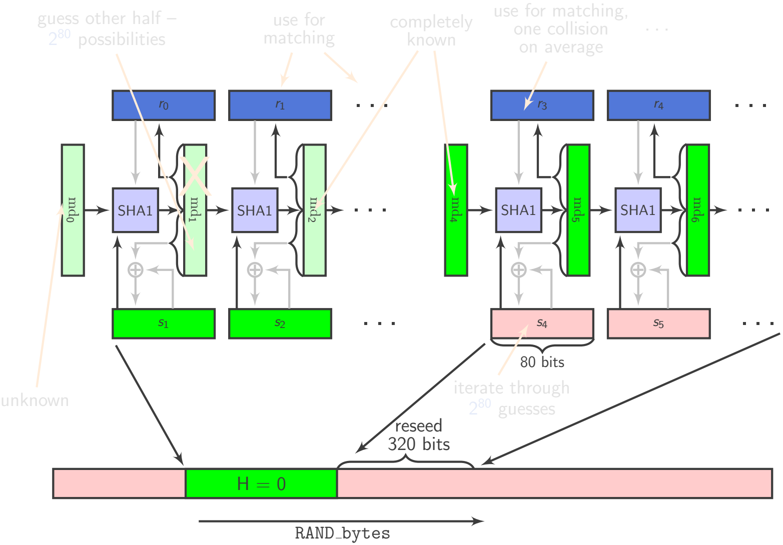

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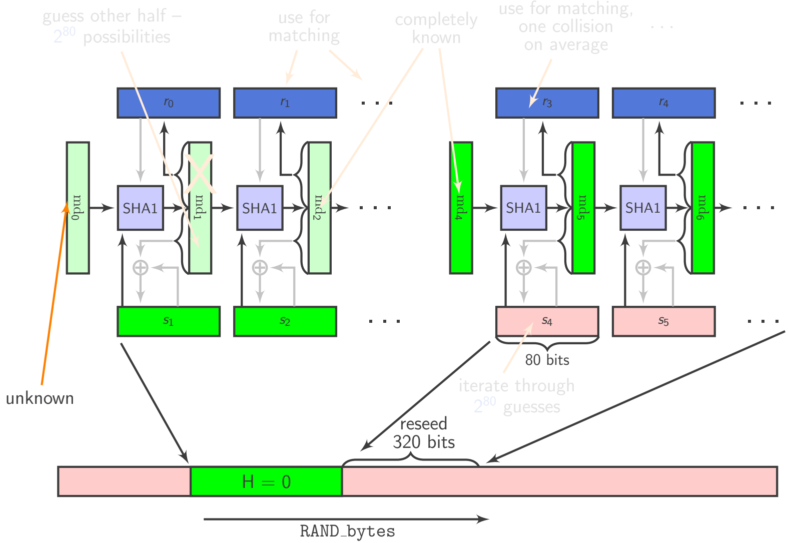

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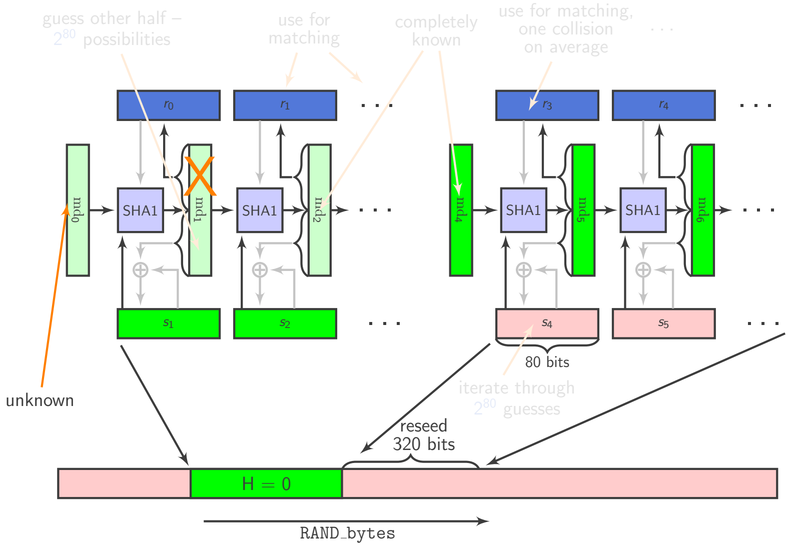

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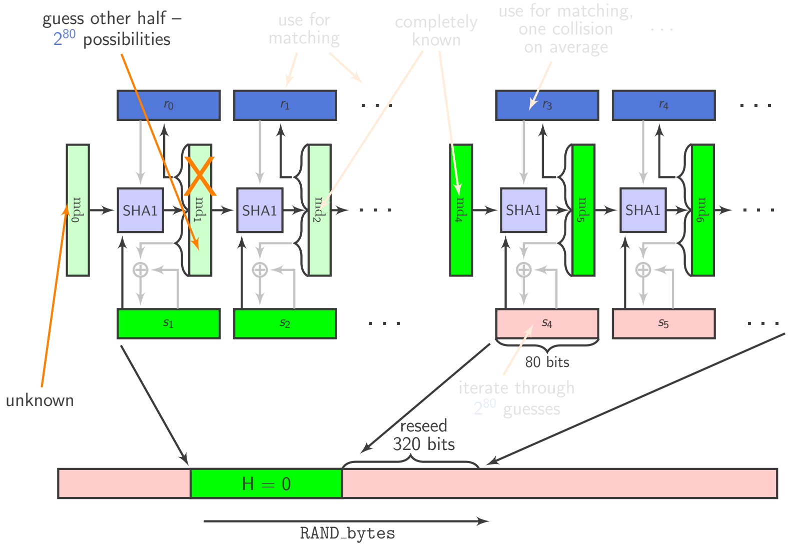

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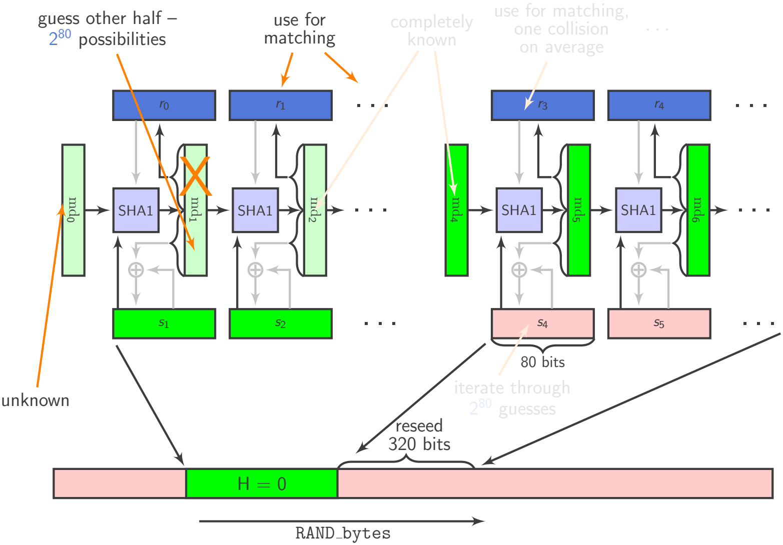

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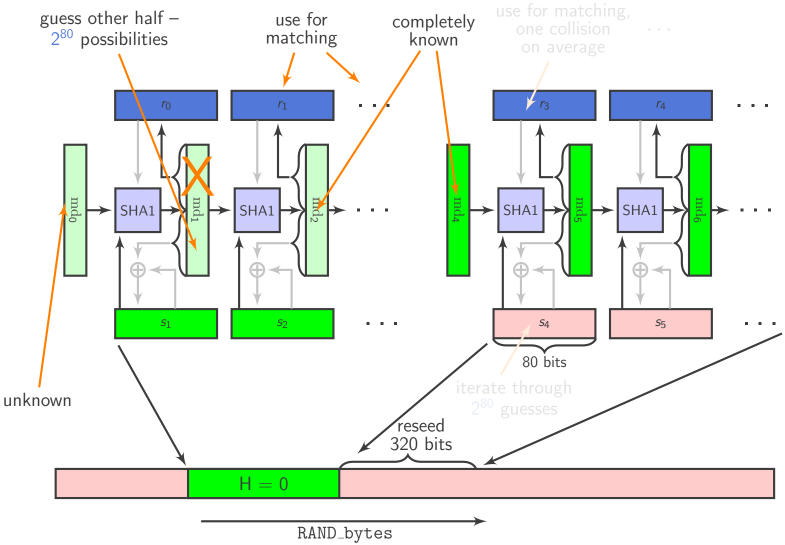

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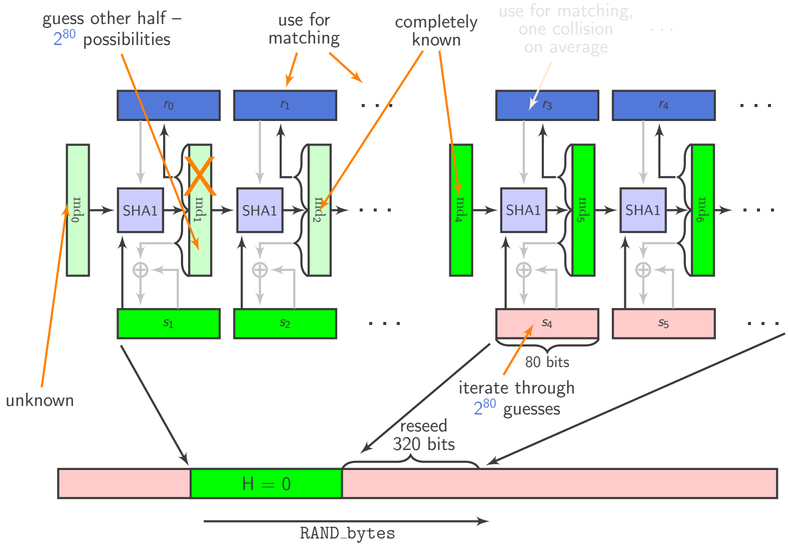

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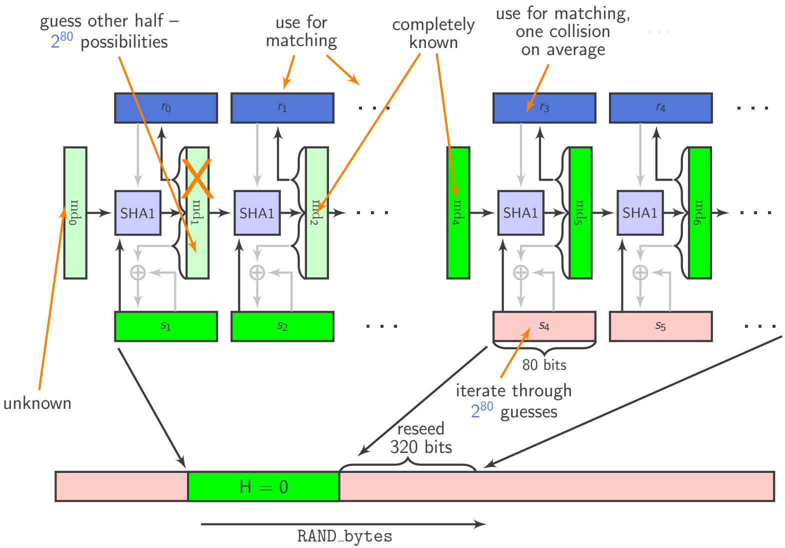

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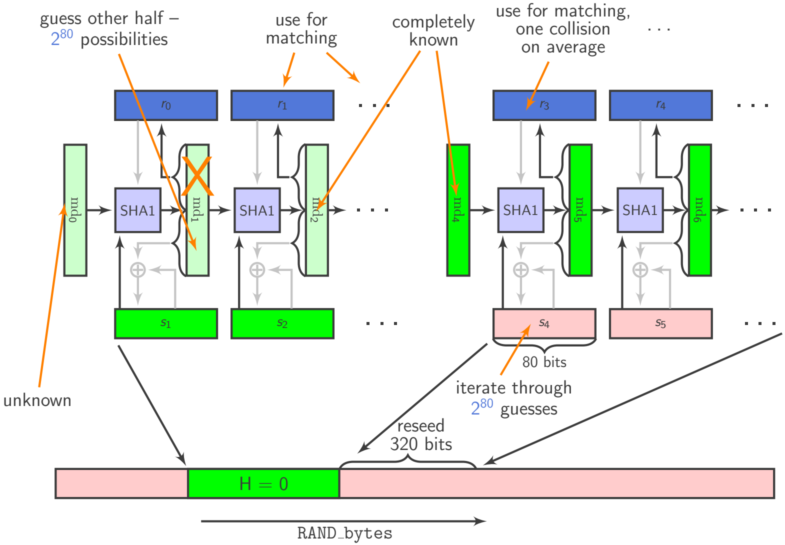

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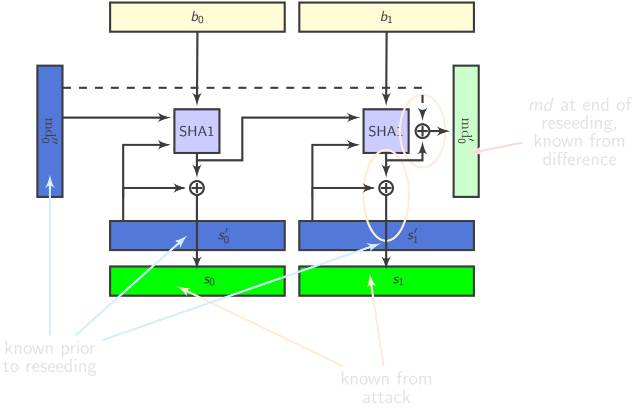

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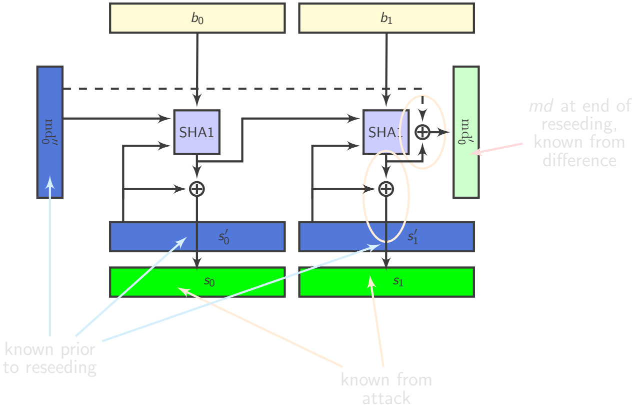

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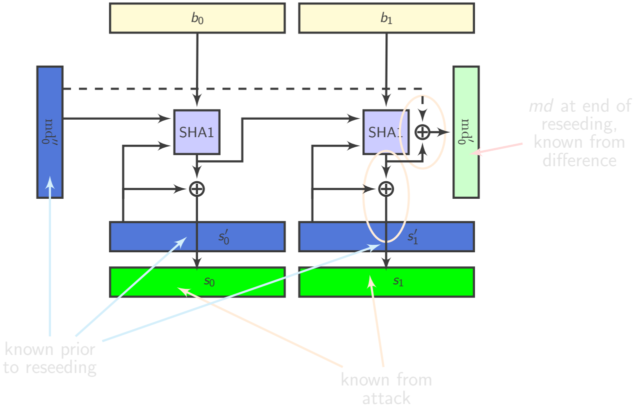

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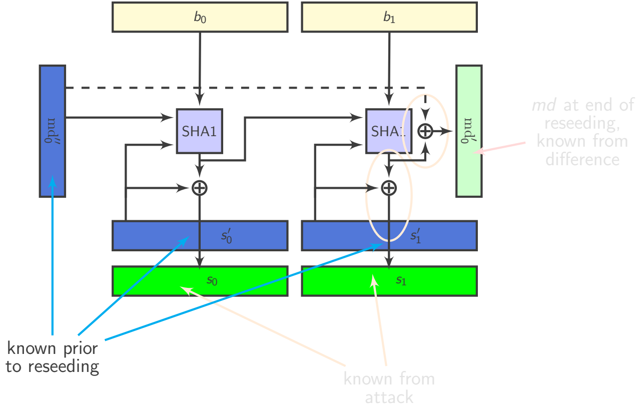

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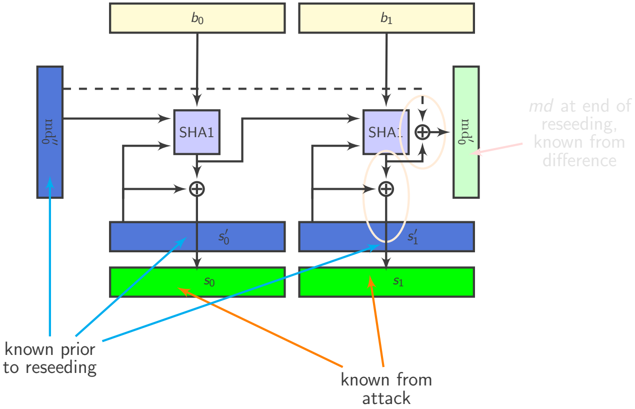

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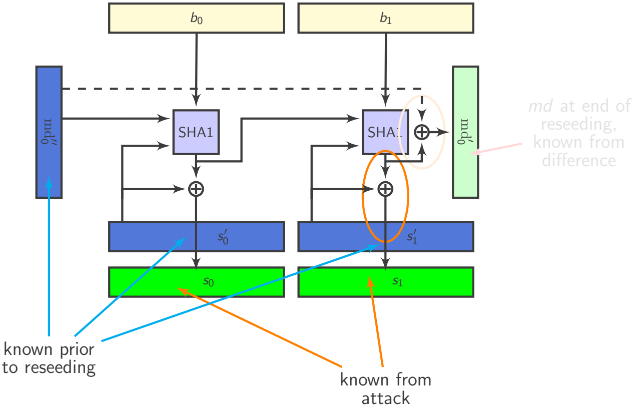

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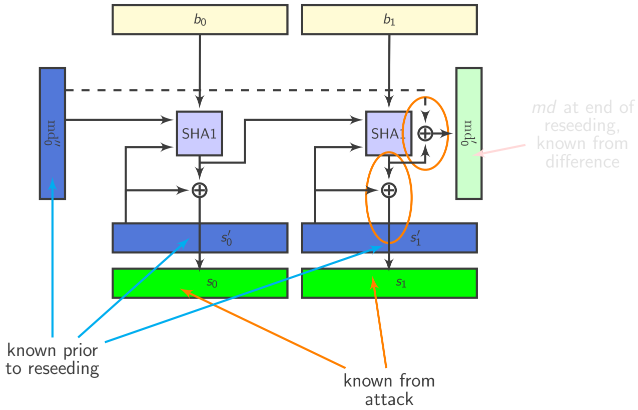

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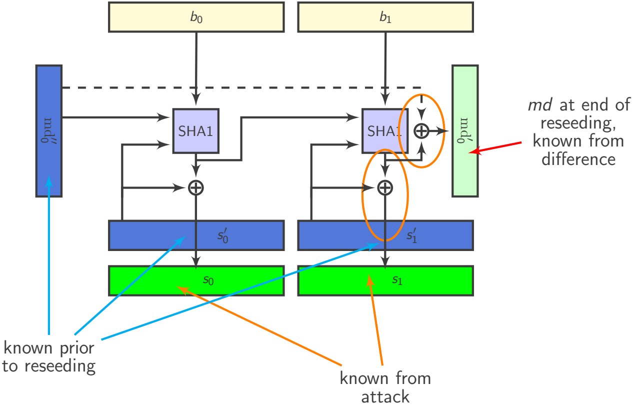

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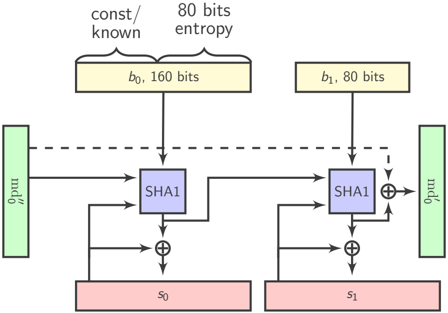

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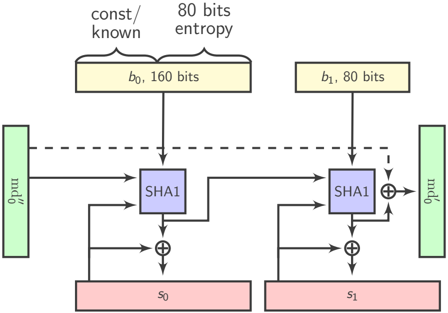

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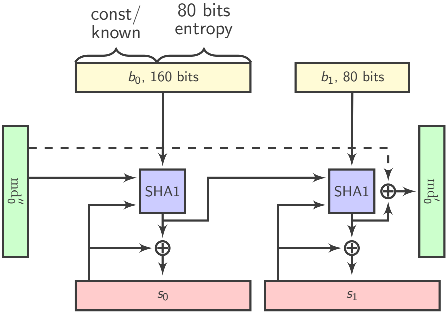

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Theoretical Considerations

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$$H(f(I,S)) \geq H(S) \text{ and } H(f(I,S) \geq H(I)$$

- input I, state S
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- but not effectively
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- but not effectively
- only useful if whole state is used in output production in a **symmetric way**
- need definition which considers **entropy of subsequent output** instead of that of the state

Notion of Mixing Function

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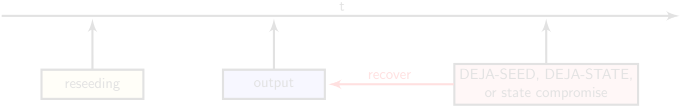
Formal Vulnerabilities of OpenSSL's RNG

- impaired forward security



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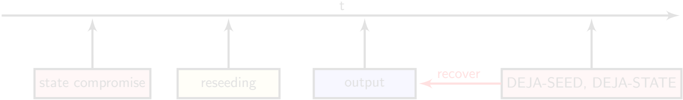

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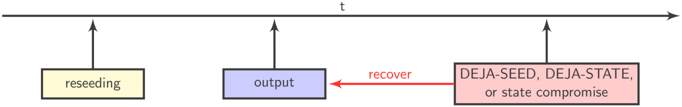

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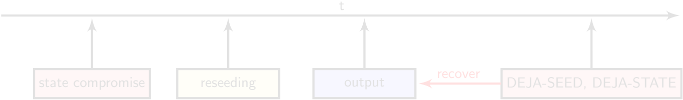

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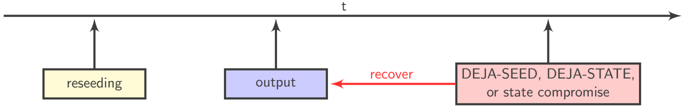

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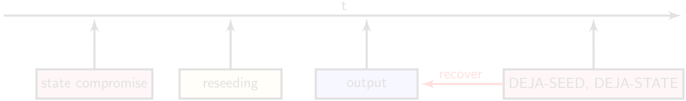

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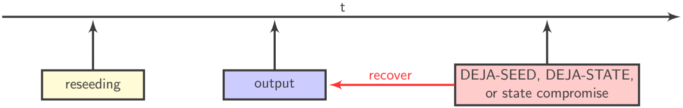

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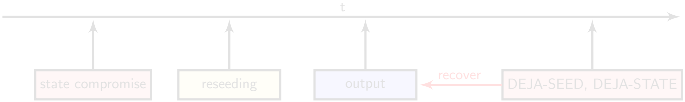

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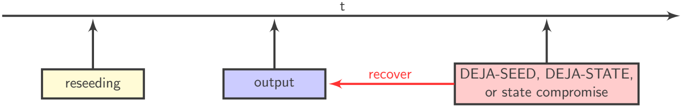

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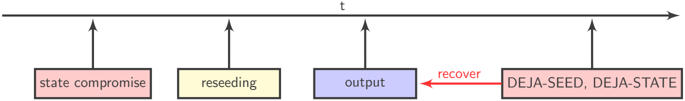

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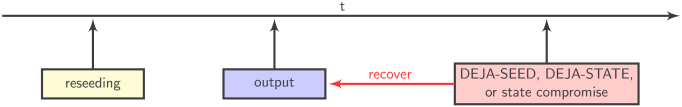

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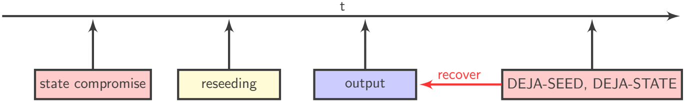

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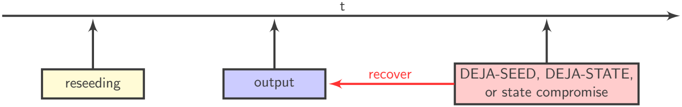

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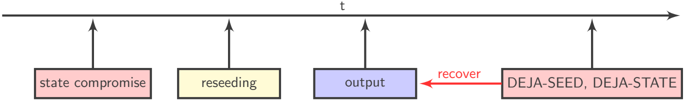

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Repairing OpenSSL's RNG

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  - approved and efficients designs exist

    e.g. AES / counter mode generators
    as realized in the FIPS version of the library!
  - more efficient than hash-based, due to hardware support
- ad-hoc repair
  - increase the "entropy flow" beyond 160 bits
  - remove the leakage of half of md
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- Note: the forks LibreSSL and BoringSSL are even worse

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  - DEJA-STATE, DEJA-SEED
    - effort around 2^{80} hash evaluations
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