Hashing Garbled Circuits for Free

Xiong Fan, **Chaya Ganesh** and Vladimir Kolesnikov

Motivation

- Garbled circuits (GC) – main technique for secure computation

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  - Cut-and-choose for GC-based 2PC
  - Private certified functions
  - Encrypted database – Blind seer

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- Fast hardware AES implementations, fast garbling, SHA bottleneck

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- Eliminating GC hashing cost significantly improves performance in GC applications

Private policy credentials

- Attribute-based credential

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- Certificate Authority (CA) setting – CA certifies the policy function

Certificate Authority (sk, vk)

Prover

Verifier

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$s_1, s_2, \ldots, s_n$

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$GC_i, d_i = \text{Garble}(f ; R_i)$

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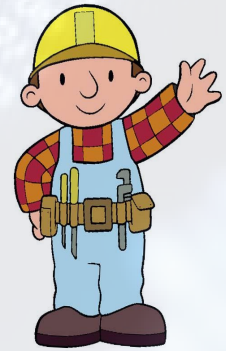
Randomness generated using s_i as seed



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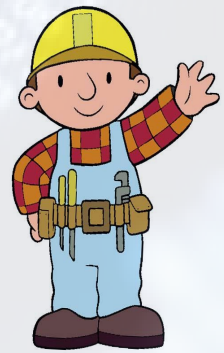

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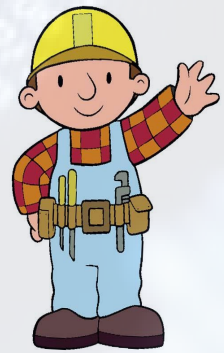

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If Verify $(h_i \| d_i, \boldsymbol{\sigma}_i, vk) \neq 1$, abort

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- Can free hash be used instead?

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Garbling scheme

Tuple of algorithms (Garble, Encode, Eval, Decode)

- $\text{Garble}(C) = (\hat{C}, e, d)$
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  - Verifiability: Additional algorithm Ve, $\text{Ve}(C, \hat{C}, e, d) \in \{0, 1\}$

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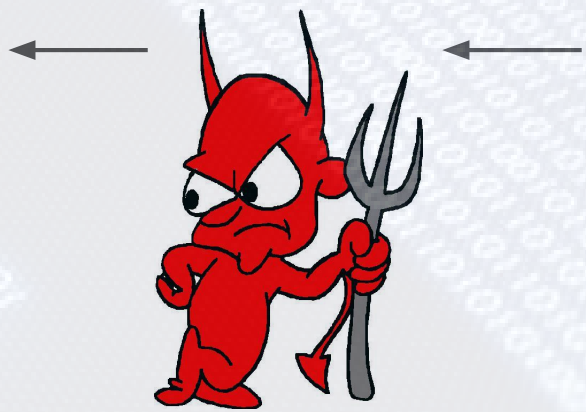
  - $\widehat{GC}$ will fail to evaluate

C

GC, $\mathcal{GC}$, e, e, d, h



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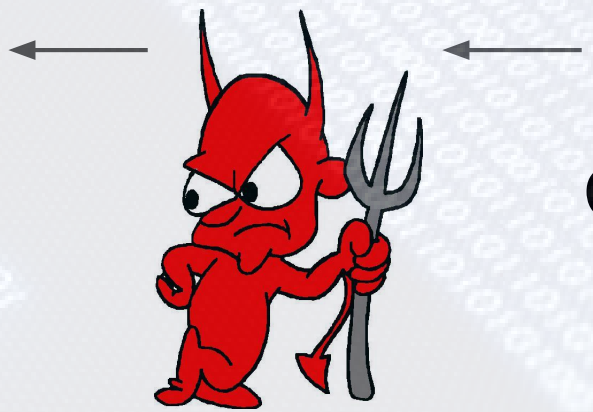

C

H(GC) = H($\mathcal{GC}$) = h

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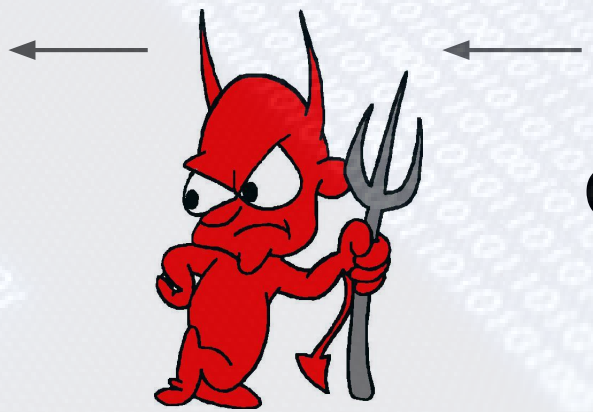

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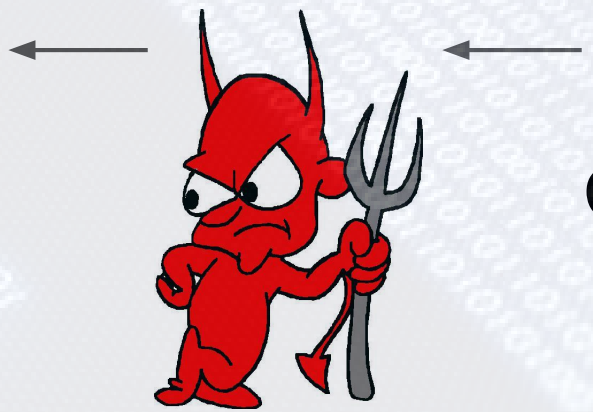

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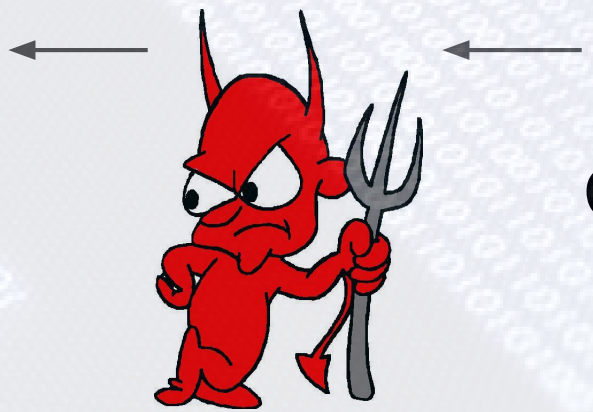

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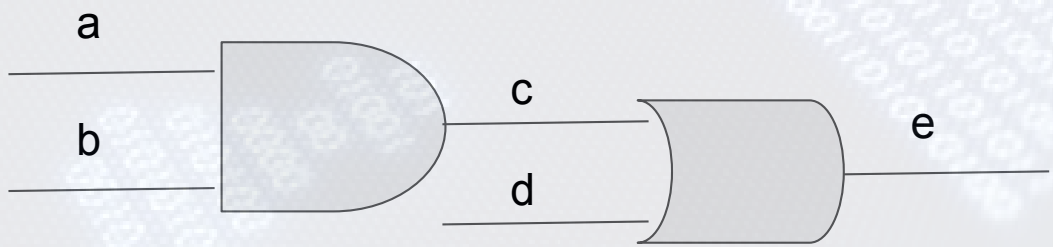
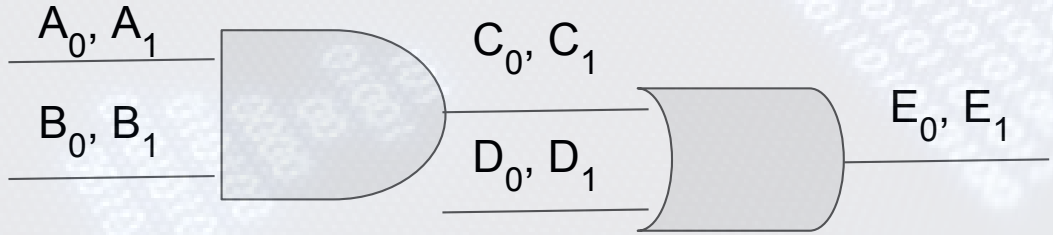
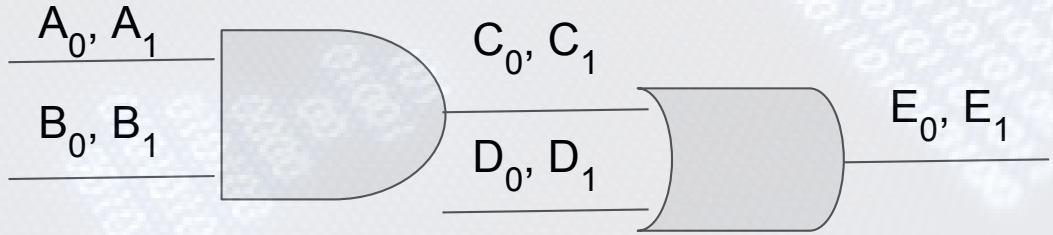
- Attempt 1: $H(GC) = \oplus_i GR_i$


a
b
c
d
e


A_0, A_1
B_0, B_1
C_0, C_1
D_0, D_1
E_0, E_1



GT1

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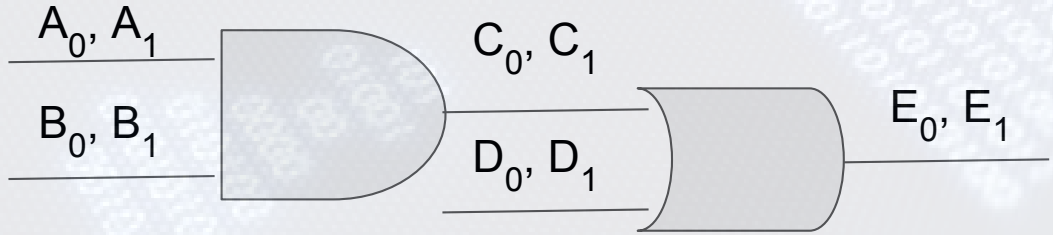

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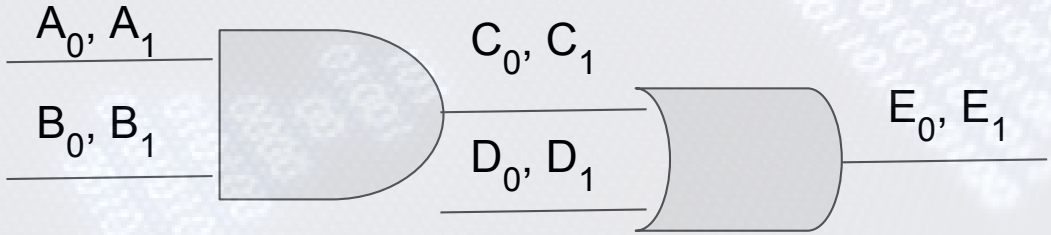

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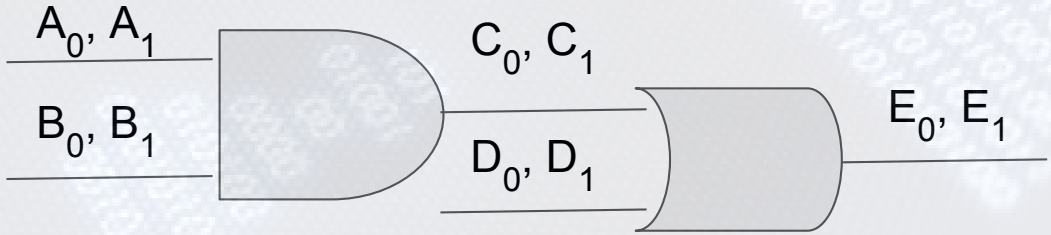

GT1 GT2

$$h = \begin{array}{|c|}\hline E_{A0,B0}(C_0) \\ \hline E_{A0,B1}(C_0) \\ \hline E_{A1,B0}(C_0) \\ \hline E_{A1,B1}(C_1) \\ \hline \end{array} \oplus \begin{array}{|c|}\hline E_{C0,D0}(E_0) \\ \hline E_{C0,D1}(E_1) \\ \hline E_{C1,D0}(E_1) \\ \hline E_{C1,D1}(E_1) \\ \hline \end{array}$$

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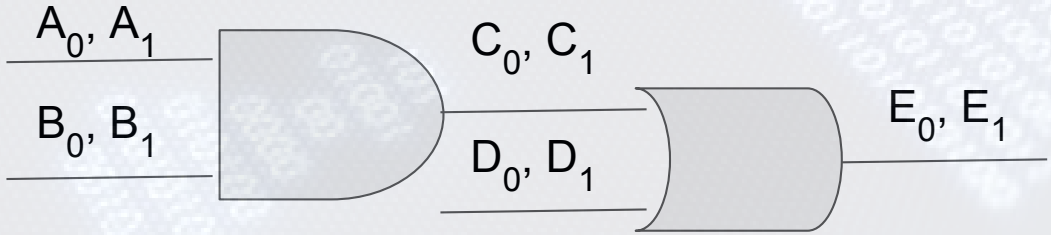

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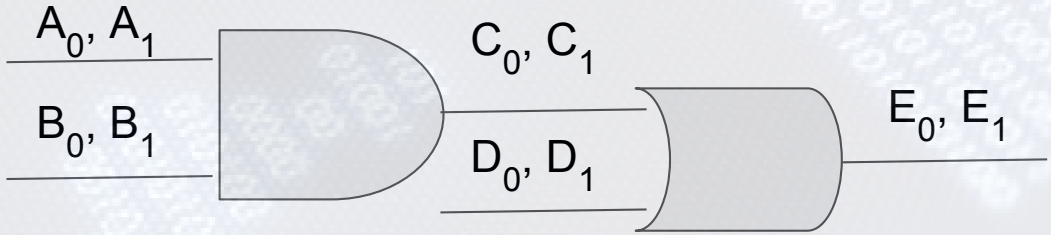
H(GC) = h



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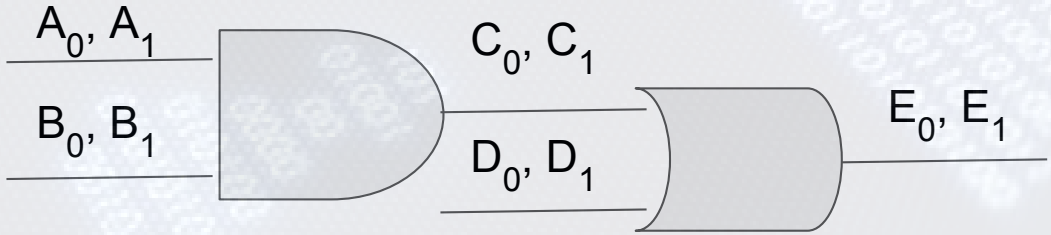

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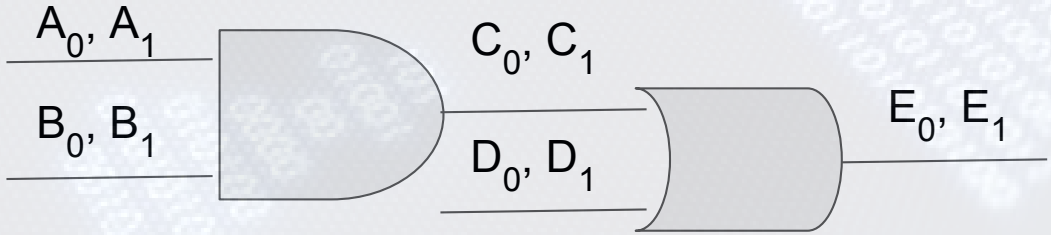

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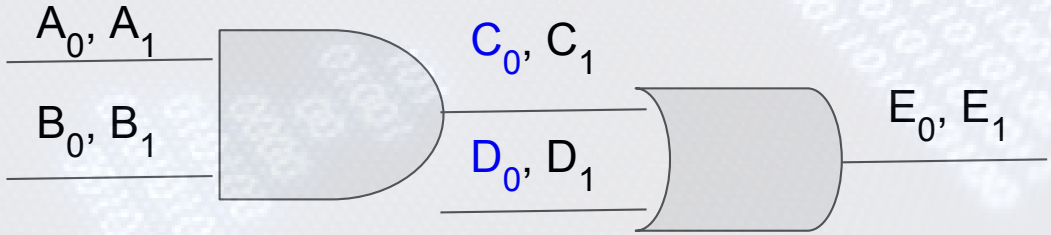
$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h \oplus \Delta$



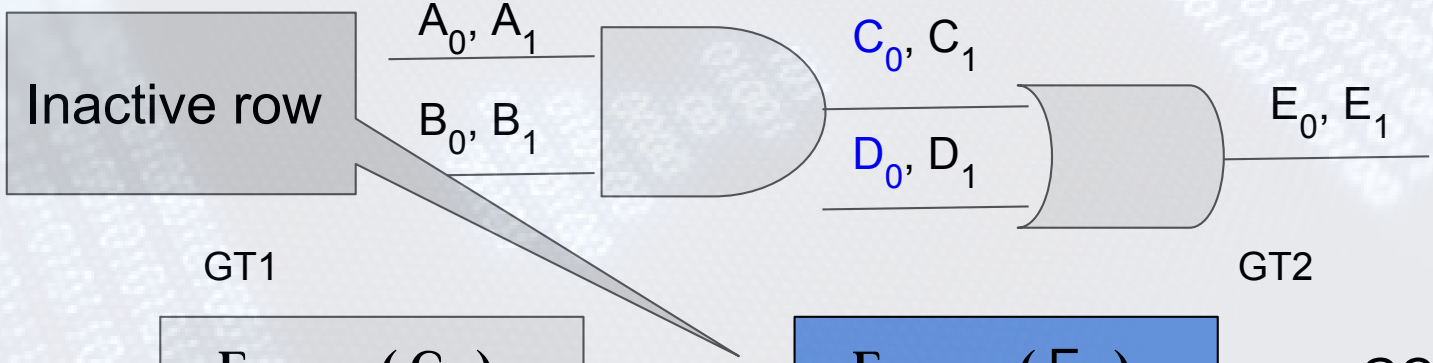
$$h = \begin{array}{|c|}\hline E_{A0,B0}(C_0) \\ \hline E_{A0,B1}(C_0) \\ \hline E_{A1,B0}(C_0) \\ \hline E_{A1,B1}(C_0) \\ \hline \end{array} \oplus \begin{array}{|c|}\hline E_{C0,D0}(E_0) \\ \hline E_{C0,D1}(E_1) \\ \hline E_{C1,D0}(E_1) \\ \hline E_{C1,D1}(E_1) \\ \hline \end{array}$$

GC = (GT1, GT2)

H(GC) = h

$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h \oplus \Delta$



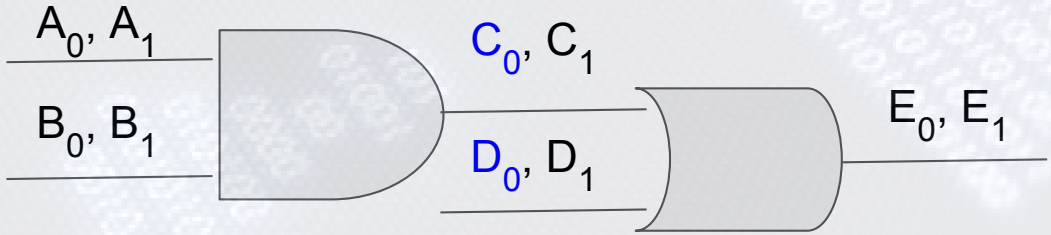
$$h = \begin{matrix} E_{A0,B0}(C_0) \\ E_{A0,B1}(C_0) \\ E_{A1,B0}(C_0) \\ E_{A1,B1}(C_0) \end{matrix} \oplus \begin{matrix} E_{C0,D0}(E_0) \\ E_{C0,D1}(E_1) \\ E_{C1,D0}(E_1) \\ E_{C1,D1}(E_1) \end{matrix}$$

GC = (GT1, GT2)

H(GC) = h

$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h \oplus \Delta$



GT1 GT2

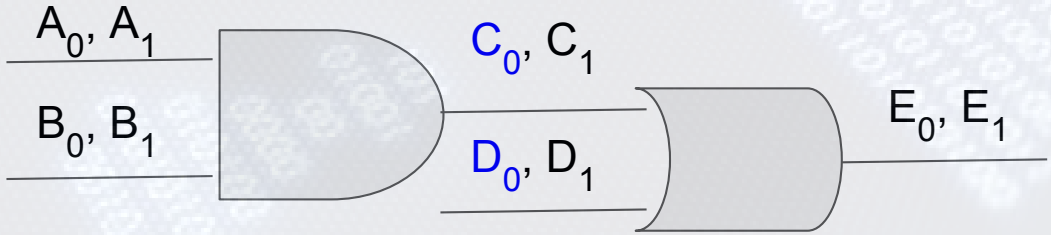
$$h = \begin{array}{|c|} \hline E_{A0,B0}(C_0) \\ \hline E_{A0,B1}(C_0) \\ \hline E_{A1,B0}(C_0) \\ \hline E_{A1,B1}(C_0) \\ \hline \end{array} \oplus \begin{array}{|c|} \hline E_{C0,D0}(E_0) \oplus \Delta \\ \hline E_{C0,D1}(E_1) \\ \hline E_{C1,D0}(E_1) \\ \hline E_{C1,D1}(E_1) \\ \hline \end{array}$$

GC = (GT1, GT2)

H(GC) = h

$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h \oplus \Delta$



GT1 GT2

$h =$

$E_{A0, B0}(C_0)$	$E_{C0, D0}(E_0) \oplus \Delta$
$E_{A0, B1}(C_0)$	$E_{C0, D1}(E_1)$
$E_{A1, B0}(C_0)$	$E_{C1, D0}(E_1)$
$E_{A1, B1}(C_0)$	$E_{C1, D1}(E_1)$

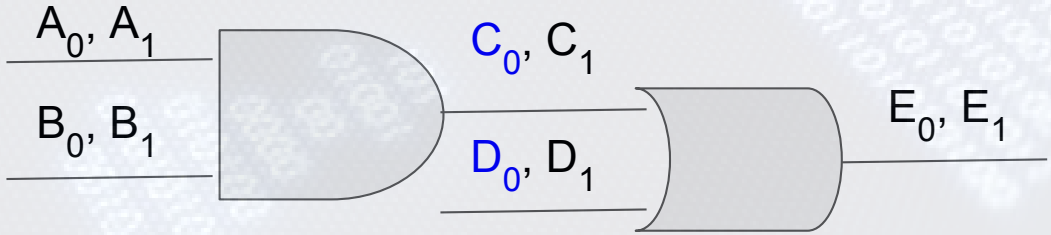
$\oplus$

GC = (GT1, GT2)

H(GC) = h

$\hat{GC}$ = ($\hat{GT1}$, GT2)

H($\hat{GC}$) = $h \oplus \Delta \oplus \Delta$



$$h = \begin{array}{|c|}\hline E_{A0,\,B0}\,(C_0) \\ \hline E_{A0,\,B1}\,(C_0) \\ \hline E_{A1,\,B0}\,(C_0) \\ \hline E_{A1,\,B1}\,(C_0) \\ \hline \end{array} \oplus \begin{array}{|c|}\hline E_{C0,\,D0}(E_0) \oplus \Delta \\ \hline E_{C0,\,D1}\,(E_1) \\ \hline E_{C1,\,D0}\,(E_1) \\ \hline E_{C1,\,D1}\,(E_1) \\ \hline \end{array}$$

GC = (GT1, GT2)

H(GC) = h

$\hat{GC}$ = ($\hat{GT1}$, GT2)
H($\hat{GC}$) = h ✔

GC hash construction

- Make each gate's output wire label depend on *all* entries of GT

GC hash construction

- Make each gate's output wire label depend on *all* entries of GT
- XOR hash correction involves modifying an active GT entry

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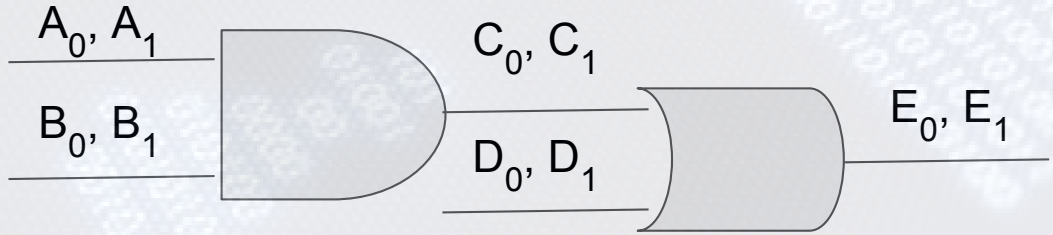
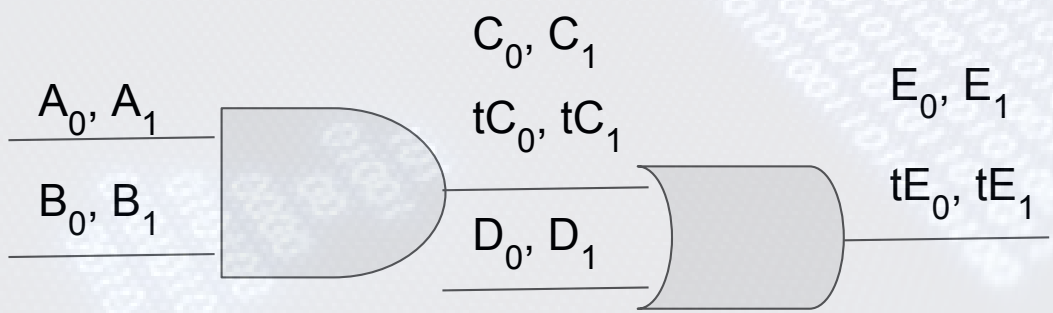
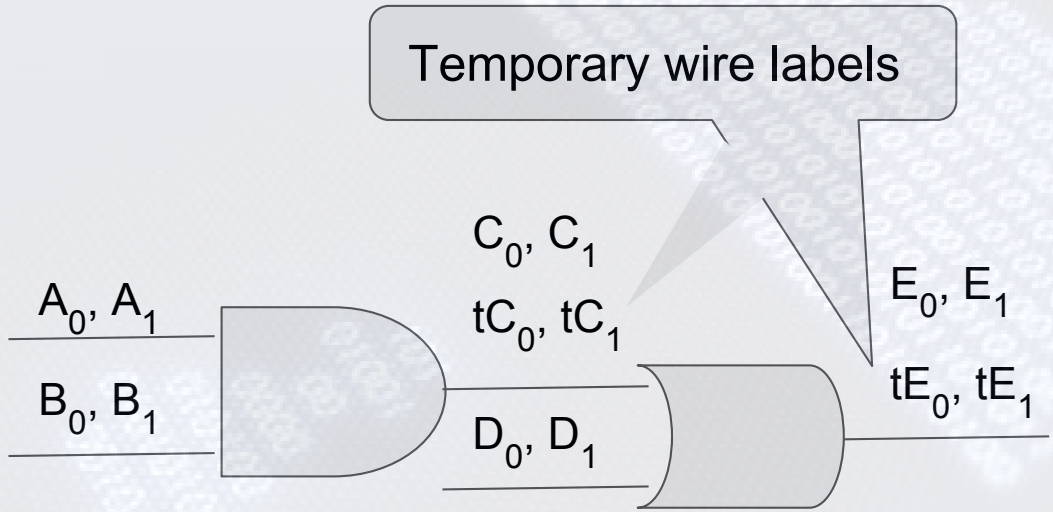
- Make each gate's output wire label depend on *all* entries of GT
- XOR hash correction involves modifying an active GT entry
- This affects the computed output wire label of the gate

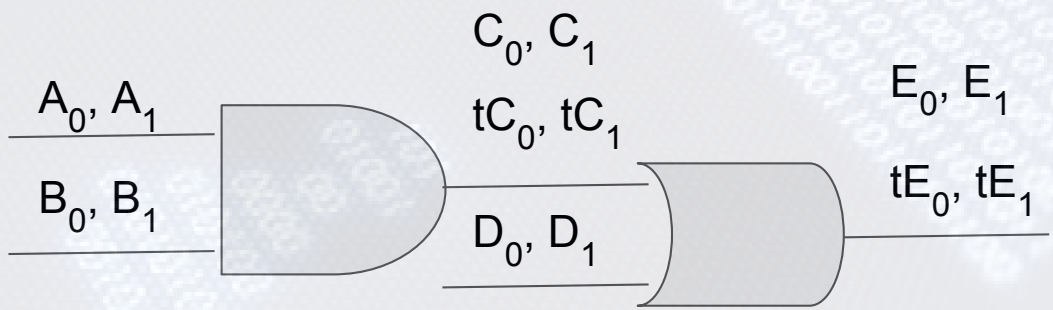
GC hash construction

- Make each gate's output wire label depend on *all* entries of GT
- XOR hash correction involves modifying an active GT entry
- This affects the computed output wire label of the gate
- Does this suffice?


A_0, A_1
B_0, B_1
C_0, C_1
D_0, D_1
E_0, E_1


A_0, A_1
B_0, B_1
C_0, C_1
tC_0, tC_1
D_0, D_1
E_0, E_1
tE_0, tE_1


Temporary wire labels
A_0, A_1
B_0, B_1
C_0, C_1
tC_0, tC_1
D_0, D_1
E_0, E_1
tE_0, tE_1



GT1

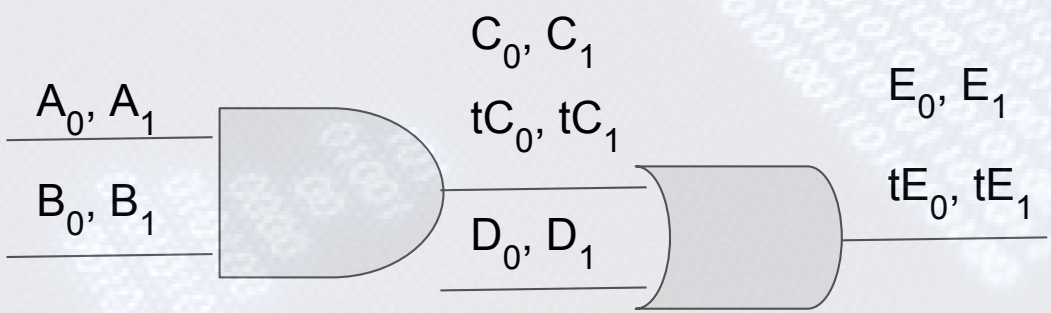
$E_{A0, B0}\ (tC_0)$
$E_{A0, B1}\ (tC_0)$
$E_{A1, B0}\ (tC_0)$
$E_{A1, B1}\ (tC_1)$

GT2

$E_{C0, D0}\ (tE_0)$
$E_{C0, D1}\ (tE_1)$
$E_{C1, D0}\ (tE_1)$
$E_{C1, D1}\ (tE_1)$

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



GT1

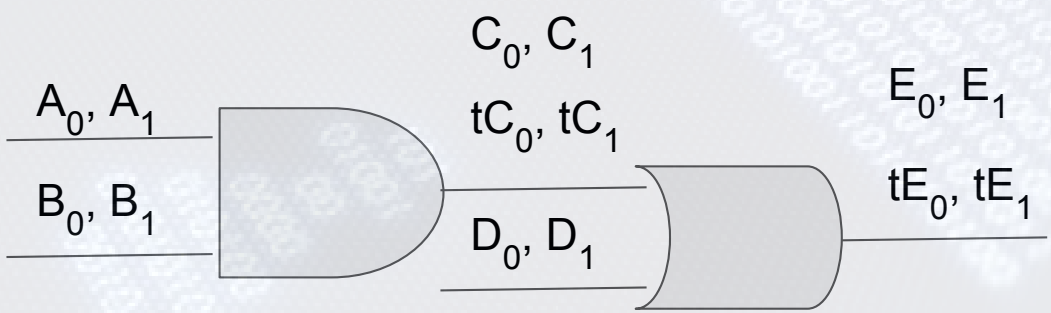
$E_{A0, B0}\ (tC_0)$
$E_{A0, B1}\ (tC_0)$
$E_{A1, B0}\ (tC_0)$
$E_{A1, B1}\ (tC_1)$

GT2

$E_{C0, D0}\ (tE_0)$
$E_{C0, D1}\ (tE_1)$
$E_{C1, D0}\ (tE_1)$
$E_{C1, D1}\ (tE_1)$

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



GT1 GT2

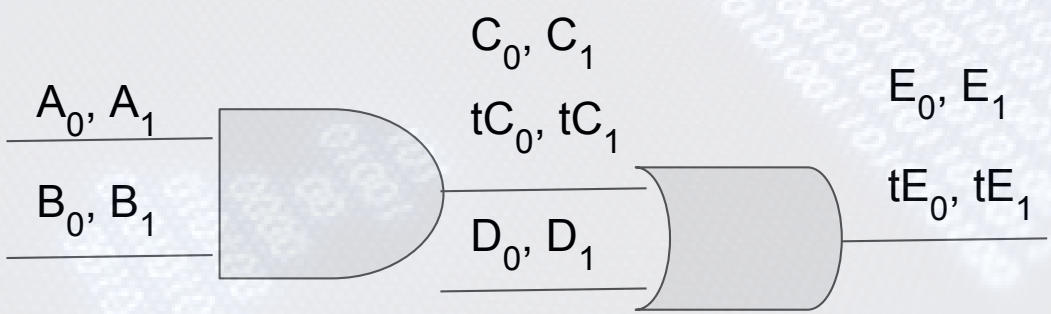
$$h = \begin{array}{|c|}\hline E_{A0,B0}(tC_0) \\ \hline E_{A0,B1}(tC_0) \\ \hline E_{A1,B0}(tC_0) \\ \hline E_{A1,B1}(tC_1) \\ \hline \end{array} \oplus \begin{array}{|c|}\hline E_{C0,D0}(tE_0) \\ \hline E_{C0,D1}(tE_1) \\ \hline E_{C1,D0}(tE_1) \\ \hline E_{C1,D1}(tE_1) \\ \hline \end{array}$$

GC = (GT1, GT2)

H(GC) = h

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



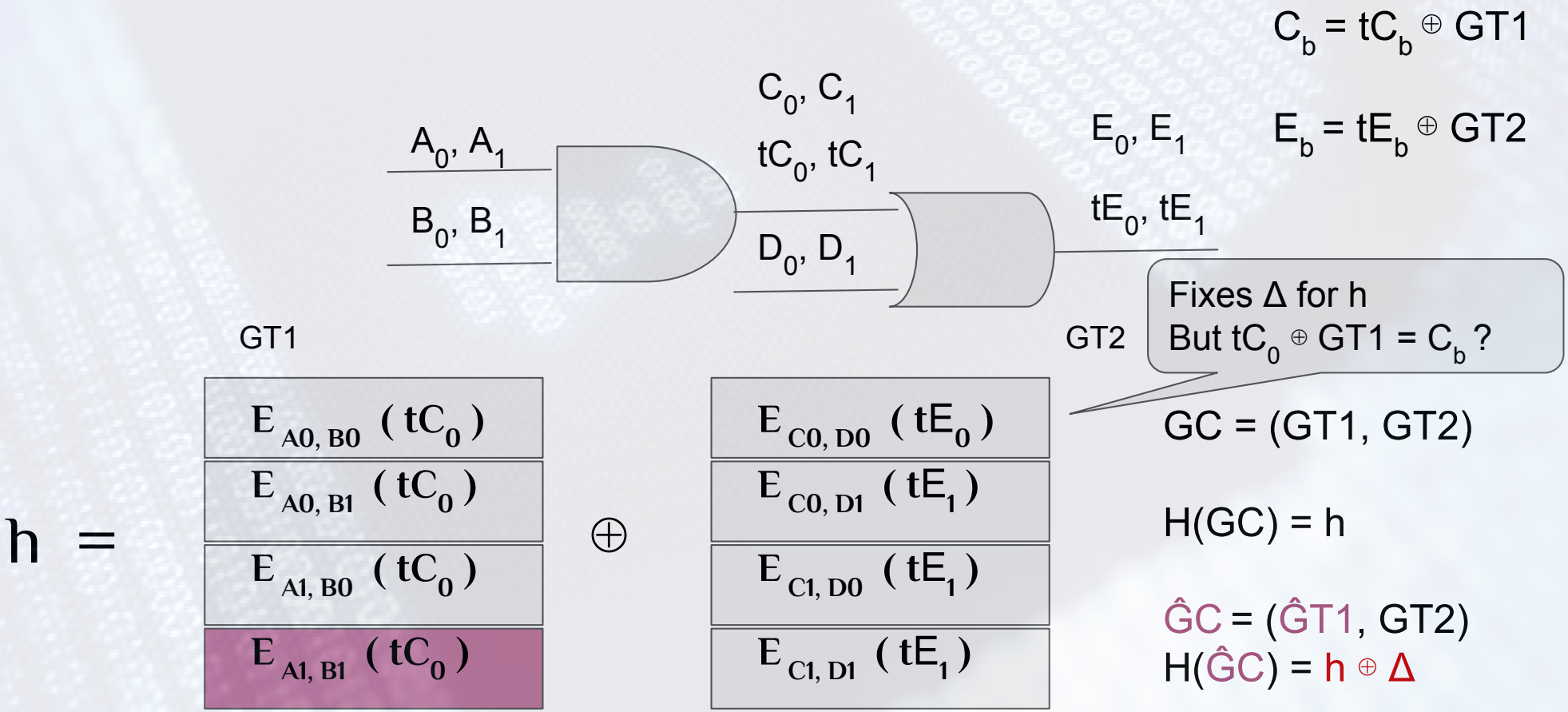
$$h = \begin{array}{|c|}\hline E_{A0,B0}\ (tC_0) \\ \hline E_{A0,B1}\ (tC_0) \\ \hline E_{A1,B0}\ (tC_0) \\ \hline E_{A1,B1}\ (tC_0) \\ \hline \end{array} \oplus \begin{array}{|c|}\hline E_{C0,D0}\ (tE_0) \\ \hline E_{C0,D1}\ (tE_1) \\ \hline E_{C1,D0}\ (tE_1) \\ \hline E_{C1,D1}\ (tE_1) \\ \hline \end{array}$$

$GC = (GT1, GT2)$

$H(GC) = h$

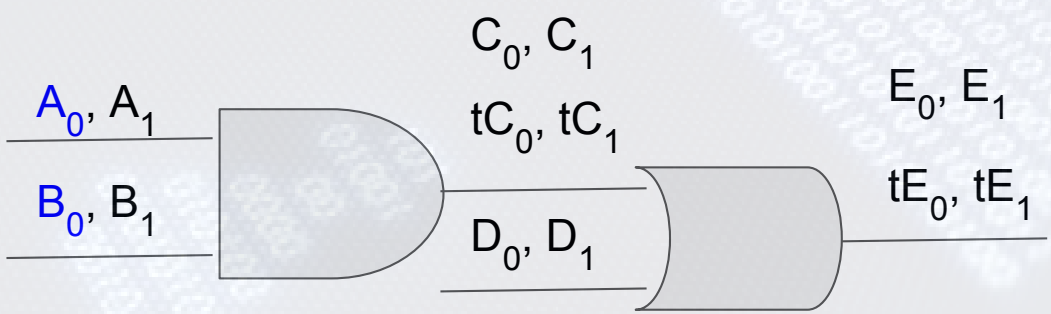
$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h \oplus \Delta$


$C_b = tC_b \oplus GT1$
$E_b = tE_b \oplus GT2$
A_0, A_1
B_0, B_1
C_0, C_1
tC_0, tC_1
D_0, D_1
E_0, E_1
tE_0, tE_1
Fixes Δ for h
But $tC_0 \oplus GT1 = C_b$?
GT1
GT2
$h =$
$E_{A0, B0}\ (tC_0)$
$E_{A0, B1}\ (tC_0)$
$E_{A1, B0}\ (tC_0)$
$E_{A1, B1}\ (tC_0)$
$\oplus$
$E_{C0, D0}\ (tE_0)$
$E_{C0, D1}\ (tE_1)$
$E_{C1, D0}\ (tE_1)$
$E_{C1, D1}\ (tE_1)$
GC = (GT1, GT2)
H(GC) = h
$\hat{GC} = (\hat{GT1}, GT2)$
$H(\hat{GC}) = h \oplus \Delta$

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



GT1 GT2

$$h = \begin{bmatrix} E_{A0,B0}(tC_0) \\ E_{A0,B1}(tC_0) \\ E_{A1,B0}(tC_0) \\ E_{A1,B1}(tC_0) \end{bmatrix} \oplus \begin{bmatrix} E_{C0,D0}(tE_0) \\ E_{C0,D1}(tE_1) \\ E_{C1,D0}(tE_1) \\ E_{C1,D1}(tE_1) \end{bmatrix}$$

$GC = (GT1, GT2)$

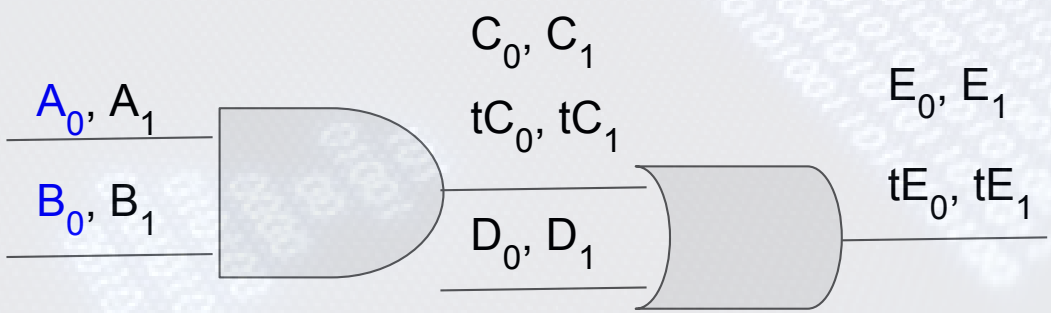
$H(GC) = h$

$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h \oplus \Delta$

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



GT1 GT2

$$h = \begin{array}{|c|}\hline E_{A0,B0}(tC_0) \\ \hline E_{A0,B1}(tC_0) \\ \hline E_{A1,B0}(tC_0) \\ \hline E_{A1,B1}(tC_0) \\ \hline \end{array} \oplus \begin{array}{|c|}\hline E_{C0,D0}(tE_0) \\ \hline E_{C0,D1}(tE_1) \\ \hline E_{C1,D0}(tE_1) \\ \hline E_{C1,D1}(tE_1) \\ \hline \end{array}$$

$GC = (GT1, GT2)$

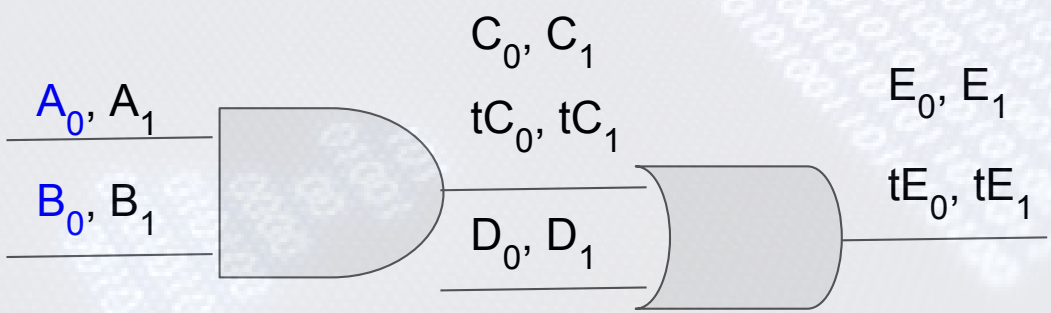
$H(GC) = h$

$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h \oplus \Delta$

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



GT1 GT2

$$h = \begin{array}{|l|}\hline E_{A0,B0}(tC_0) \oplus \Delta \\ \hline E_{A0,B1}(tC_0) \\ \hline E_{A1,B0}(tC_0) \\ \hline E_{A1,B1}(tC_0) \\ \hline \end{array} \oplus \begin{array}{|l|}\hline E_{C0,D0}(tE_0) \\ \hline E_{C0,D1}(tE_1) \\ \hline E_{C1,D0}(tE_1) \\ \hline E_{C1,D1}(tE_1) \\ \hline \end{array}$$

$GC = (GT1, GT2)$

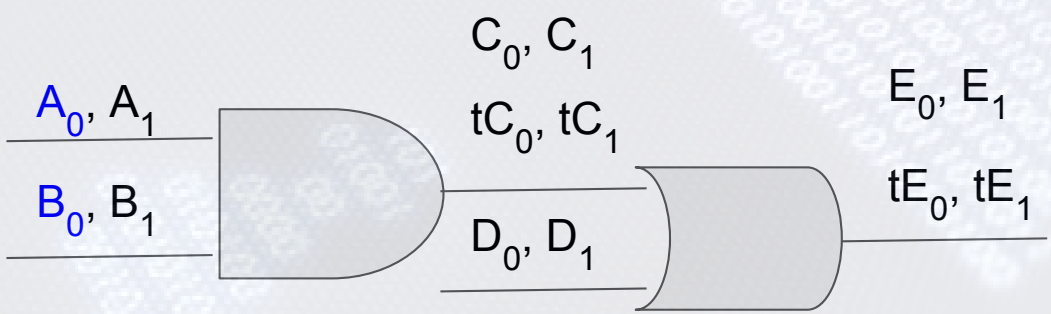
$H(GC) = h$

$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h \oplus \Delta$

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



GT1 GT2

$$h = \begin{array}{|l|}\hline E_{A0,B0}(tC_0) \oplus \Delta \\ \hline E_{A0,B1}(tC_0) \\ \hline E_{A1,B0}(tC_0) \\ \hline E_{A1,B1}(tC_0) \\ \hline \end{array} \oplus \begin{array}{|l|}\hline E_{C0,D0}(tE_0) \\ \hline E_{C0,D1}(tE_1) \\ \hline E_{C1,D0}(tE_1) \\ \hline E_{C1,D1}(tE_1) \\ \hline \end{array}$$

$GC = (GT1, GT2)$

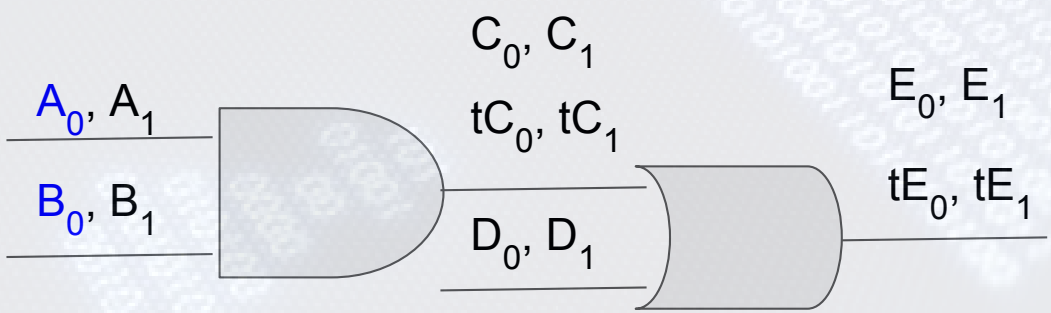
$H(GC) = h$

$\hat{G}C = (\hat{G}T1, GT2)$

$H(\hat{G}C) = h \oplus \Delta \oplus \Delta$

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



$$h = \begin{array}{|l|}\hline E_{A0,B0}(tC_0) \oplus \Delta \\ \hline E_{A0,B1}(tC_0) \\ \hline E_{A1,B0}(tC_0) \\ \hline E_{A1,B1}(tC_0) \\ \hline \end{array} \oplus \begin{array}{|l|}\hline E_{C0,D0}(tE_0) \\ \hline E_{C0,D1}(tE_1) \\ \hline E_{C1,D0}(tE_1) \\ \hline E_{C1,D1}(tE_1) \\ \hline \end{array}$$

$GC = (GT1, GT2)$

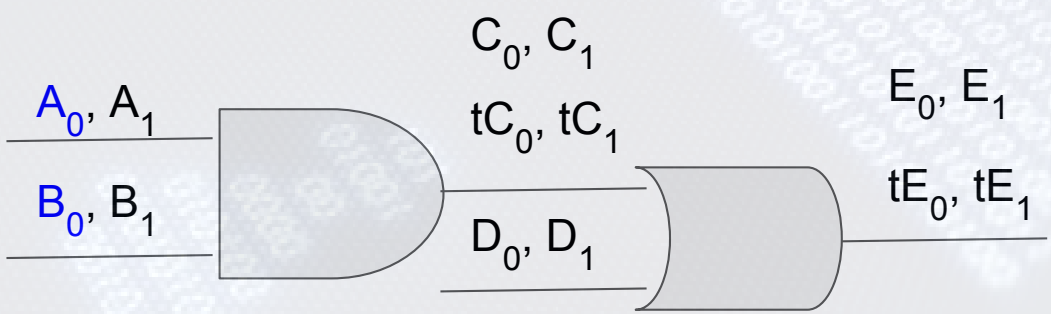
$H(GC) = h$

$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h$ ✔

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



GT1 GT2

$$h = \begin{array}{|l|}\hline E_{A0,B0}(tC_0) \oplus \Delta \\ \hline E_{A0,B1}(tC_0) \\ \hline E_{A1,B0}(tC_0) \\ \hline E_{A1,B1}(tC_0) \\ \hline \end{array} \oplus \begin{array}{|l|}\hline E_{C0,D0}(tE_0) \\ \hline E_{C0,D1}(tE_1) \\ \hline E_{C1,D0}(tE_1) \\ \hline E_{C1,D1}(tE_1) \\ \hline \end{array}$$

$GC = (GT1, GT2)$

$H(GC) = h$

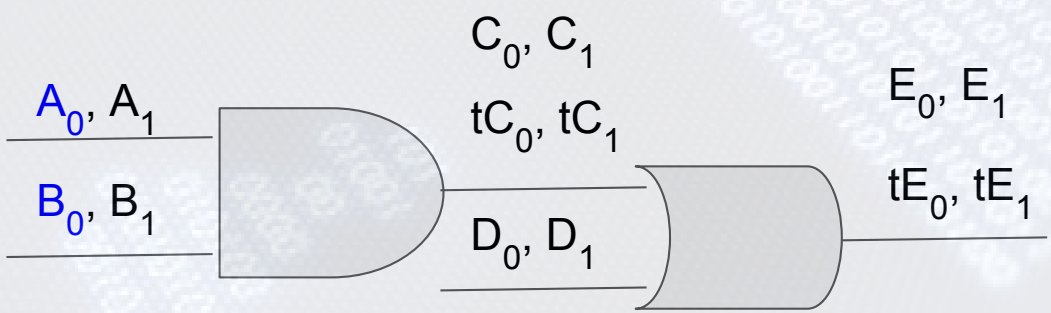
$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h$ ✔

$tC_0 \oplus GT1 = C_0$

$C_b = tC_b \oplus GT1$

$E_b = tE_b \oplus GT2$



GT1 GT2

$$h = \begin{array}{|l|}\hline E_{A0,B0}(tC_0) \oplus \Delta \\ \hline E_{A0,B1}(tC_0) \\ \hline E_{A1,B0}(tC_0) \\ \hline E_{A1,B1}(tC_0) \\ \hline \end{array} \oplus \begin{array}{|l|}\hline E_{C0,D0}(tE_0) \\ \hline E_{C0,D1}(tE_1) \\ \hline E_{C1,D0}(tE_1) \\ \hline E_{C1,D1}(tE_1) \\ \hline \end{array}$$

$GC = (GT1, GT2)$

$H(GC) = h$

$\hat{GC} = (\hat{GT1}, GT2)$

$H(\hat{GC}) = h$ ✔

$tC_0 \oplus GT1 = C_0$ ✔

GC hash construction

- $\mathcal{A}$ modifies a GT entry, and corrects it within the same table

GC hash construction

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- Works since the "fix" for broken hash also fixes the translation from temporary to real wire label

GC hash construction

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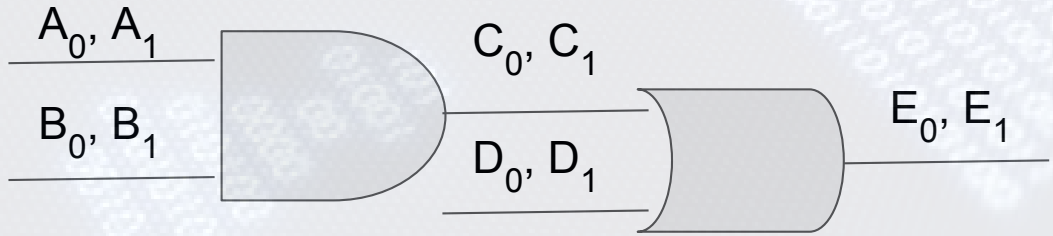
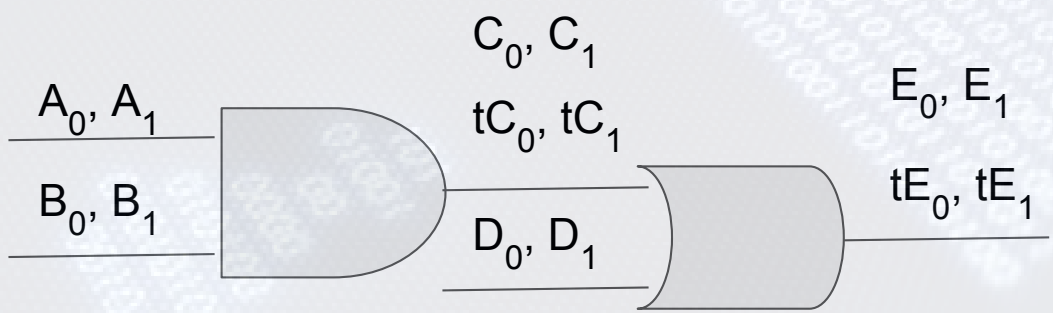
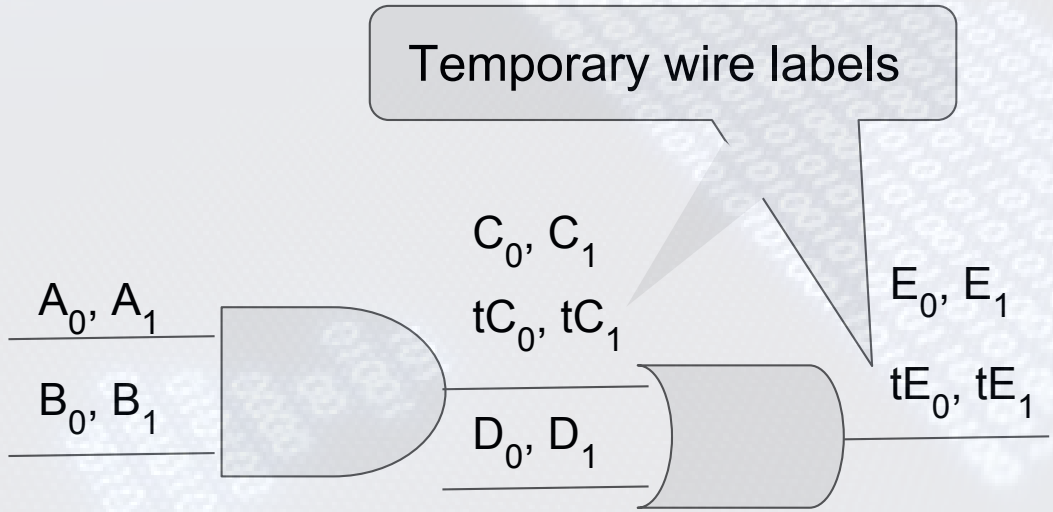
- Works since the "fix" for broken hash also fixes the translation from temporary to real wire label
- Use GT rows for computing wire label and hash in *different ways*

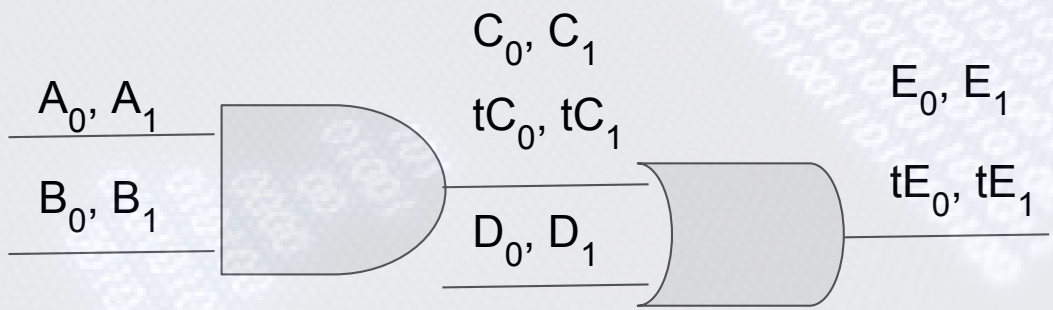
GC hash construction

- $\mathcal{A}$ modifies a GT entry, and corrects it within the same table
- Works since the "fix" for broken hash also fixes the translation from temporary to real wire label
- Use GT rows for computing wire label and hash in *different ways*
- The "fix" for hash will no longer keep the wire label valid


A_0, A_1
B_0, B_1
C_0, C_1
D_0, D_1
E_0, E_1


A_0, A_1
B_0, B_1
C_0, C_1
tC_0, tC_1
D_0, D_1
E_0, E_1
tE_0, tE_1


Temporary wire labels
A_0, A_1
B_0, B_1
C_0, C_1
tC_0, tC_1
D_0, D_1
E_0, E_1
tE_0, tE_1



GT1

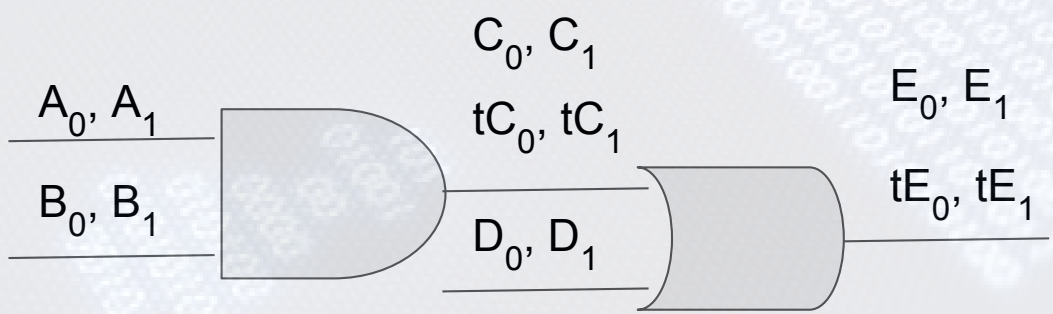
$E_{A0, B0}\ (tC_0)$
$E_{A0, B1}\ (tC_0)$
$E_{A1, B0}\ (tC_0)$
$E_{A1, B1}\ (tC_1)$

GT2

$E_{C0, D0}\ (tE_0)$
$E_{C0, D1}\ (tE_1)$
$E_{C1, D0}\ (tE_1)$
$E_{C1, D1}\ (tE_1)$

$C_b = tC_b \oplus f$ (GT1)

$E_b = tE_b \oplus f$ (GT2)



GT1

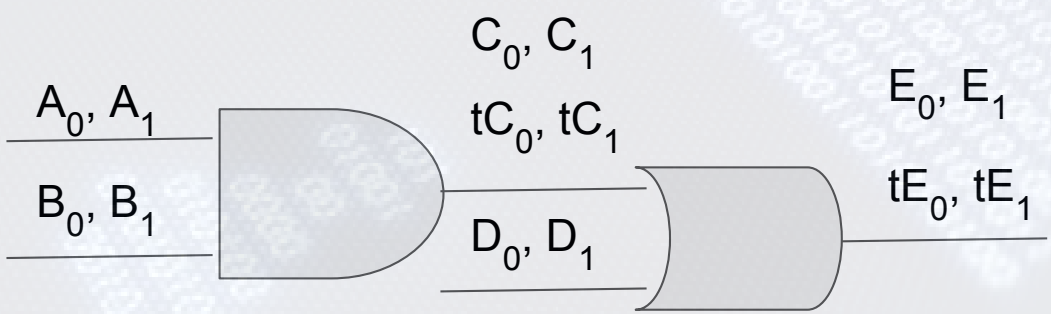
$E_{A0, B0}\ (tC_0)$
$E_{A0, B1}\ (tC_0)$
$E_{A1, B0}\ (tC_0)$
$E_{A1, B1}\ (tC_1)$

GT2

$E_{C0, D0}\ (tE_0)$
$E_{C0, D1}\ (tE_1)$
$E_{C1, D0}\ (tE_1)$
$E_{C1, D1}\ (tE_1)$

$C_b = tC_b \oplus f$ (GT1)

$E_b = tE_b \oplus f$ (GT2)



GT1 GT2

$$h = \begin{array}{|c|}\hline E_{A0,B0}(tC_0) \\ \hline E_{A0,B1}(tC_0) \\ \hline E_{A1,B0}(tC_0) \\ \hline E_{A1,B1}(tC_1) \\ \hline \end{array} \oplus \begin{array}{|c|}\hline E_{C0,D0}(tE_0) \\ \hline E_{C0,D1}(tE_1) \\ \hline E_{C1,D0}(tE_1) \\ \hline E_{C1,D1}(tE_1) \\ \hline \end{array}$$

GC = (GT1, GT2)

$H(GC) = h = GT1 \oplus GT2$

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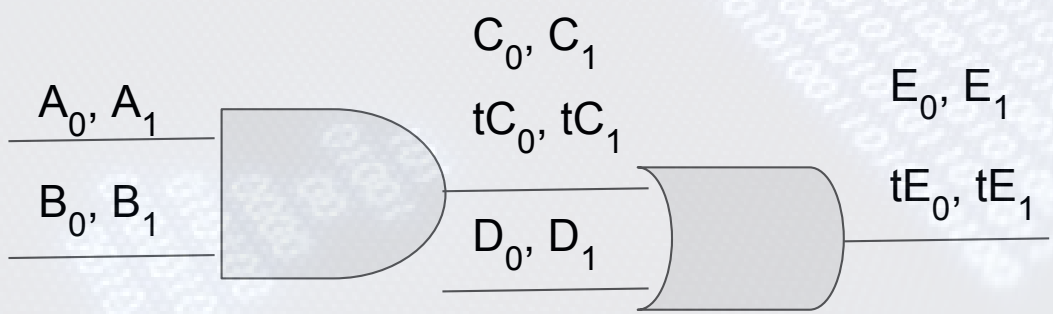

$$h = \begin{array}{l} R_1 \\ R_2 \\ R_3 \\ R_4 \end{array} \begin{array}{|c|} \hline E_{A0,\,B0}\,(tC_0) \\ \hline E_{A0,\,B1}\,(tC_0) \\ \hline E_{A1,\,B0}\,(tC_0) \\ \hline E_{A1,\,B1}\,(tC_1) \\ \hline \end{array} \oplus \begin{array}{|c|} \hline E_{C0,\,D0}\,(tE_0) \\ \hline E_{C0,\,D1}\,(tE_1) \\ \hline E_{C1,\,D0}\,(tE_1) \\ \hline E_{C1,\,D1}\,(tE_1) \\ \hline \end{array}$$

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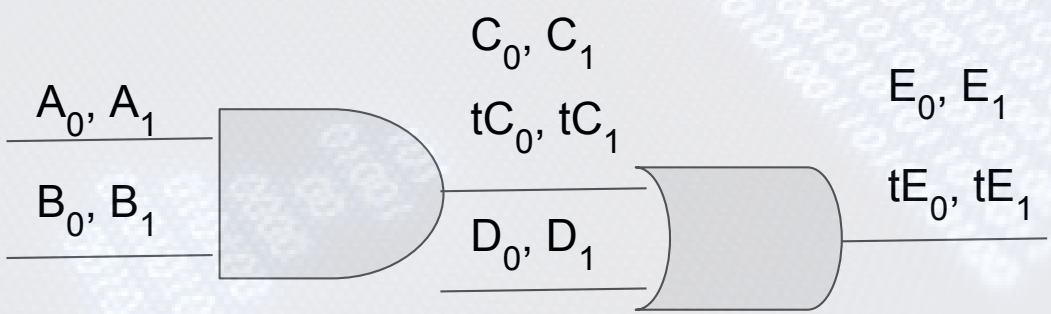

$C_b = tC_b \oplus f\ (GT1)$

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$$h = \begin{matrix} R_1 \\ R_2 \\ R_3 \\ R_4 \end{matrix} \begin{matrix} E_{A0,\,B0}\ (tC_0) \\ E_{A0,\,B1}\ (tC_0) \\ E_{A1,\,B0}\ (tC_0) \\ E_{A1,\,B1}\ (tC_1) \end{matrix} \oplus \begin{matrix} E_{C0,\,D0}\ (tE_0) \\ E_{C0,\,D1}\ (tE_1) \\ E_{C1,\,D0}\ (tE_1) \\ E_{C1,\,D1}\ (tE_1) \end{matrix}$$

$GC = (GT1, GT2)$

$H(GC) = h = GT1 \oplus GT2$

$f\ (GT) = \oplus R_i^{<< i}$

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- Use GT rows as XOR pads in a different manner for computing the GC hash and for offsetting the wire values

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- In general, functions f_i such that, if

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- (i.e. if GC is changed s.t. XOR of GT rows is the same, then w.h.p. XOR of f(GT) will change)

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Half-gate garbling

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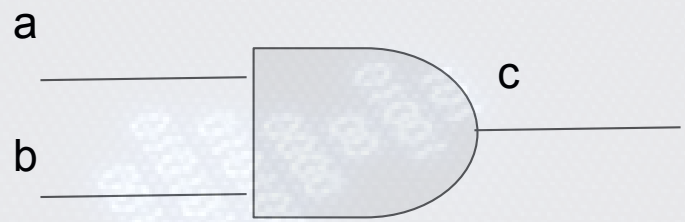
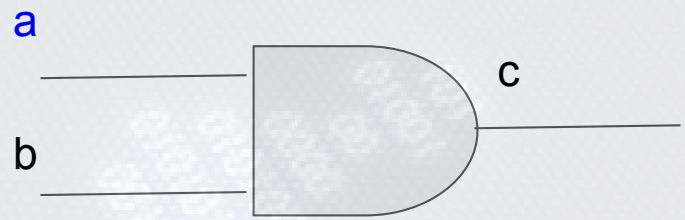
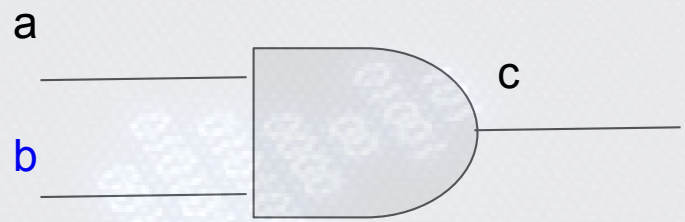
- 2 ciphertexts for AND gate
- Free hash for half-gates garbling?


a
b
c



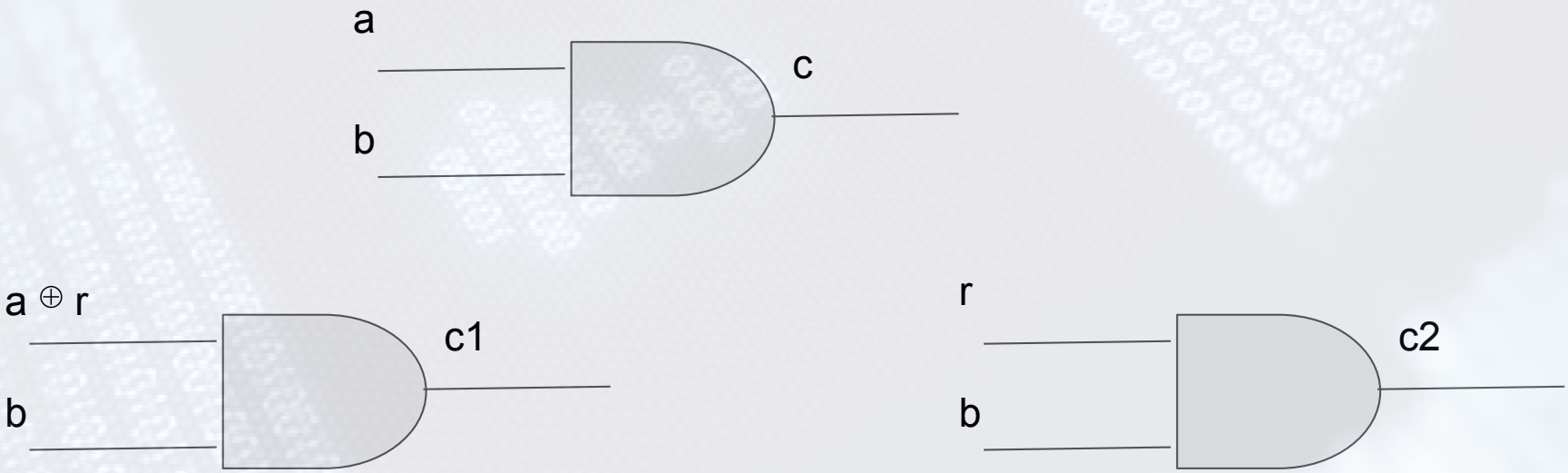
Garbler knows one of the values in the clear

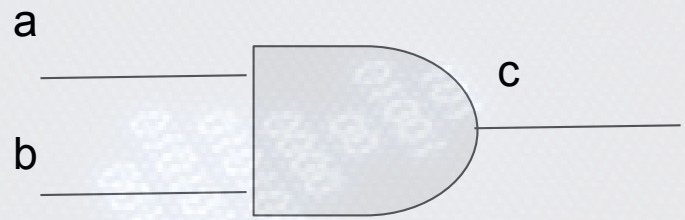
Generator half-gate

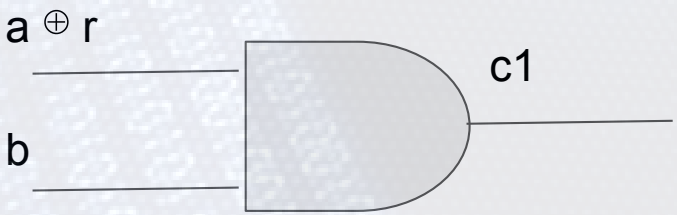


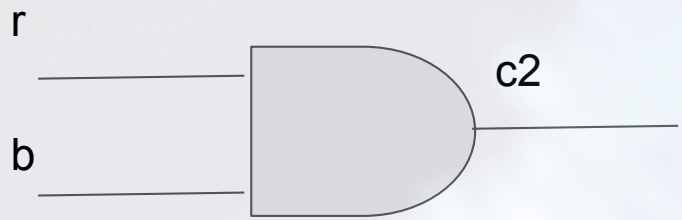
Evaluator knows one of the values in the clear

Evaluator half-gate

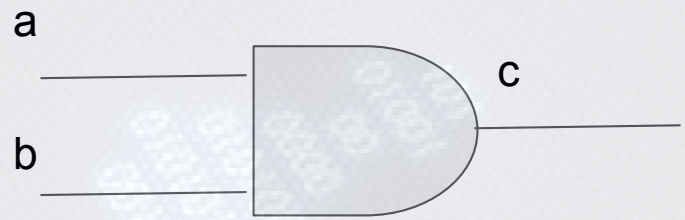

a
b
c
a ⊕ r
b
c1
r
b
c2

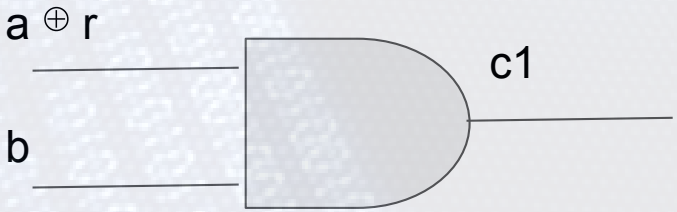


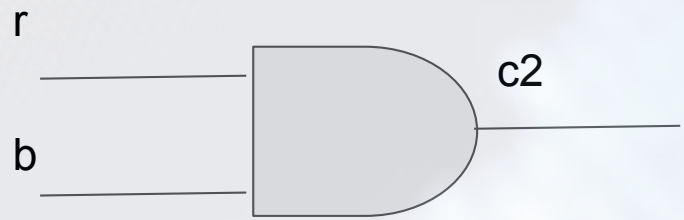




r chosen by the garbler
Evaluator learns a ⊕ r in the clear

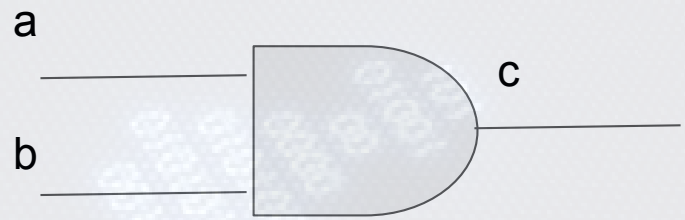


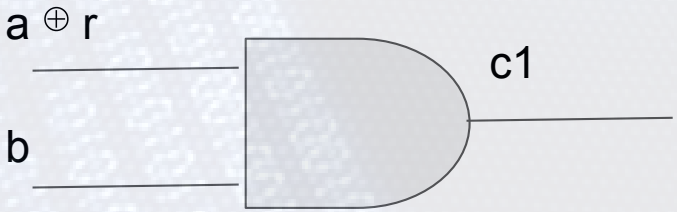


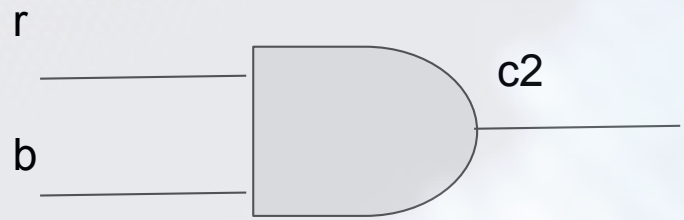


Evaluator half-gate

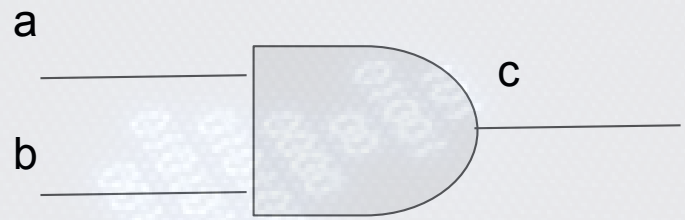
Generator half-gate

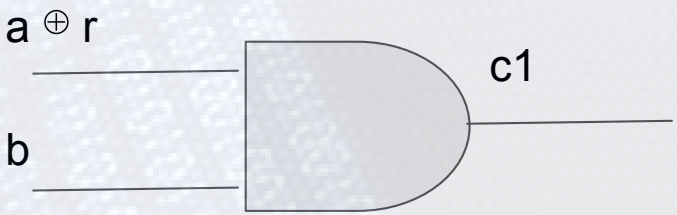


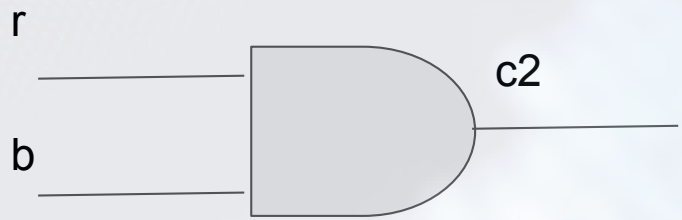




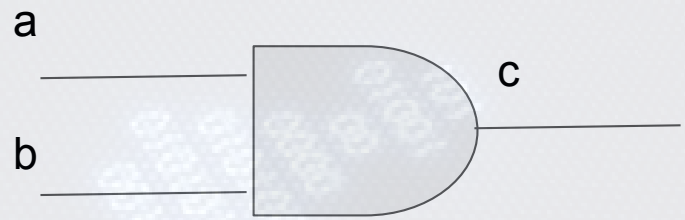
$c1 \oplus c2$

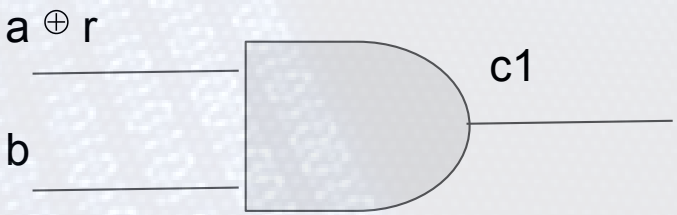


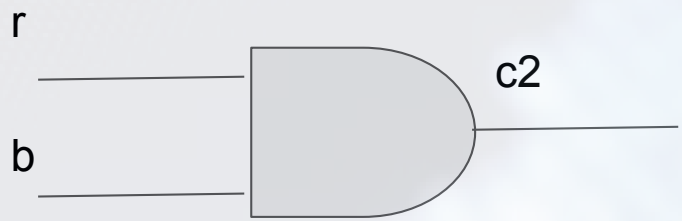




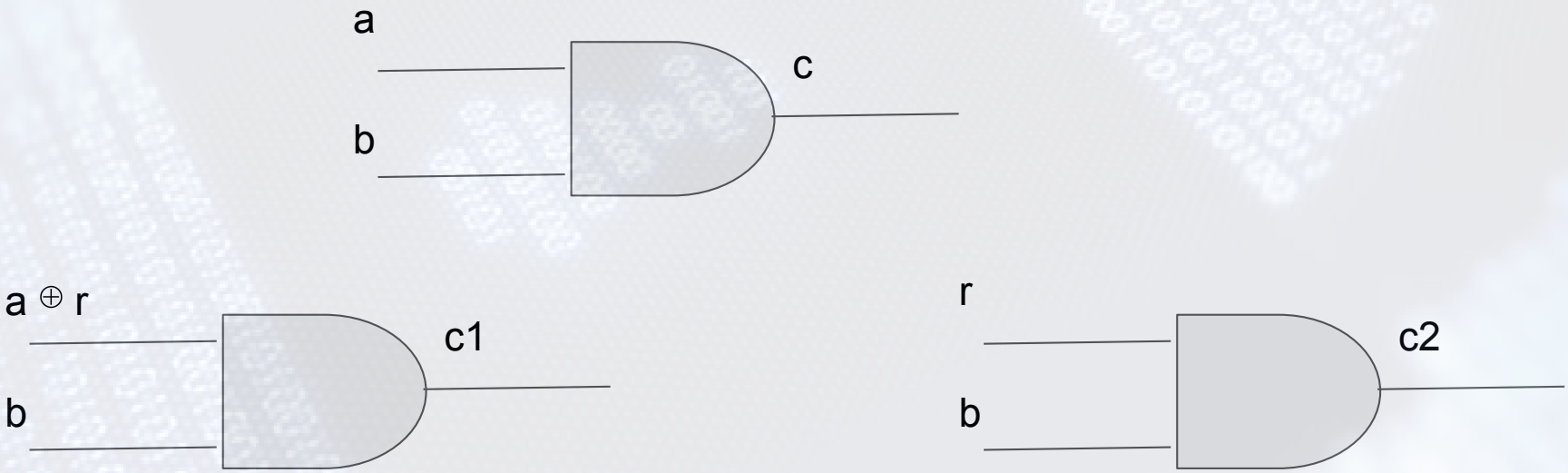
$$c1 \oplus c2 = ((a \oplus r) \wedge b) \oplus (r \wedge b)$$

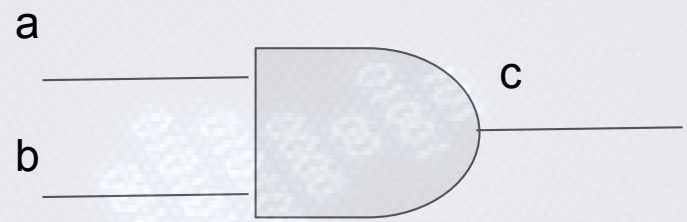


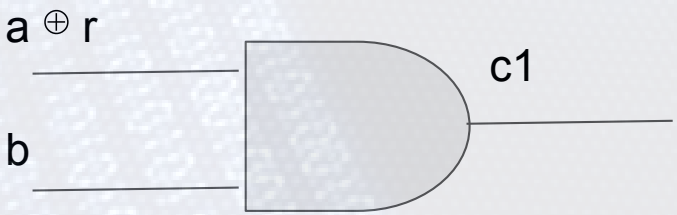


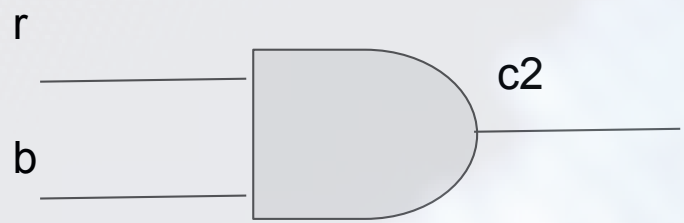


$$c1 \oplus c2 = ((a \oplus r) \wedge b) \oplus (r \wedge b) = a \wedge b$$


a
b
c
a ⊕ r
b
c1
r
b
c2







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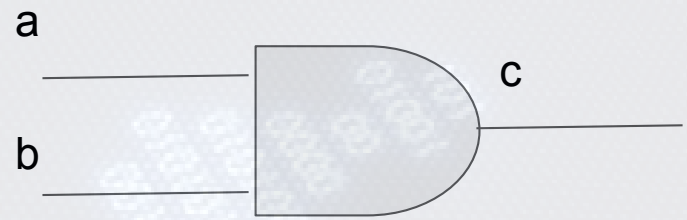

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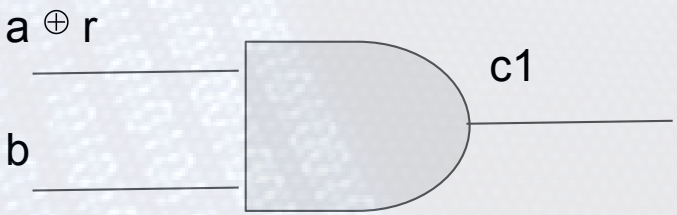

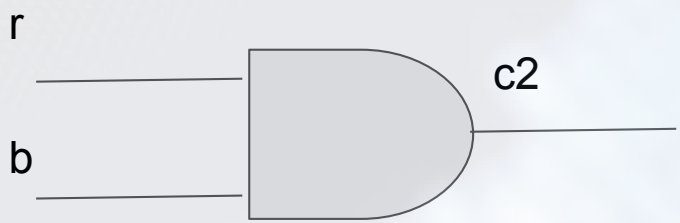

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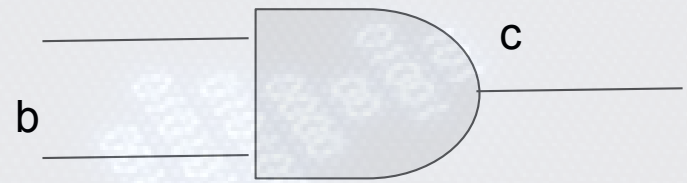

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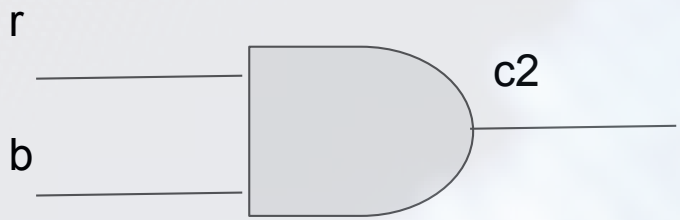

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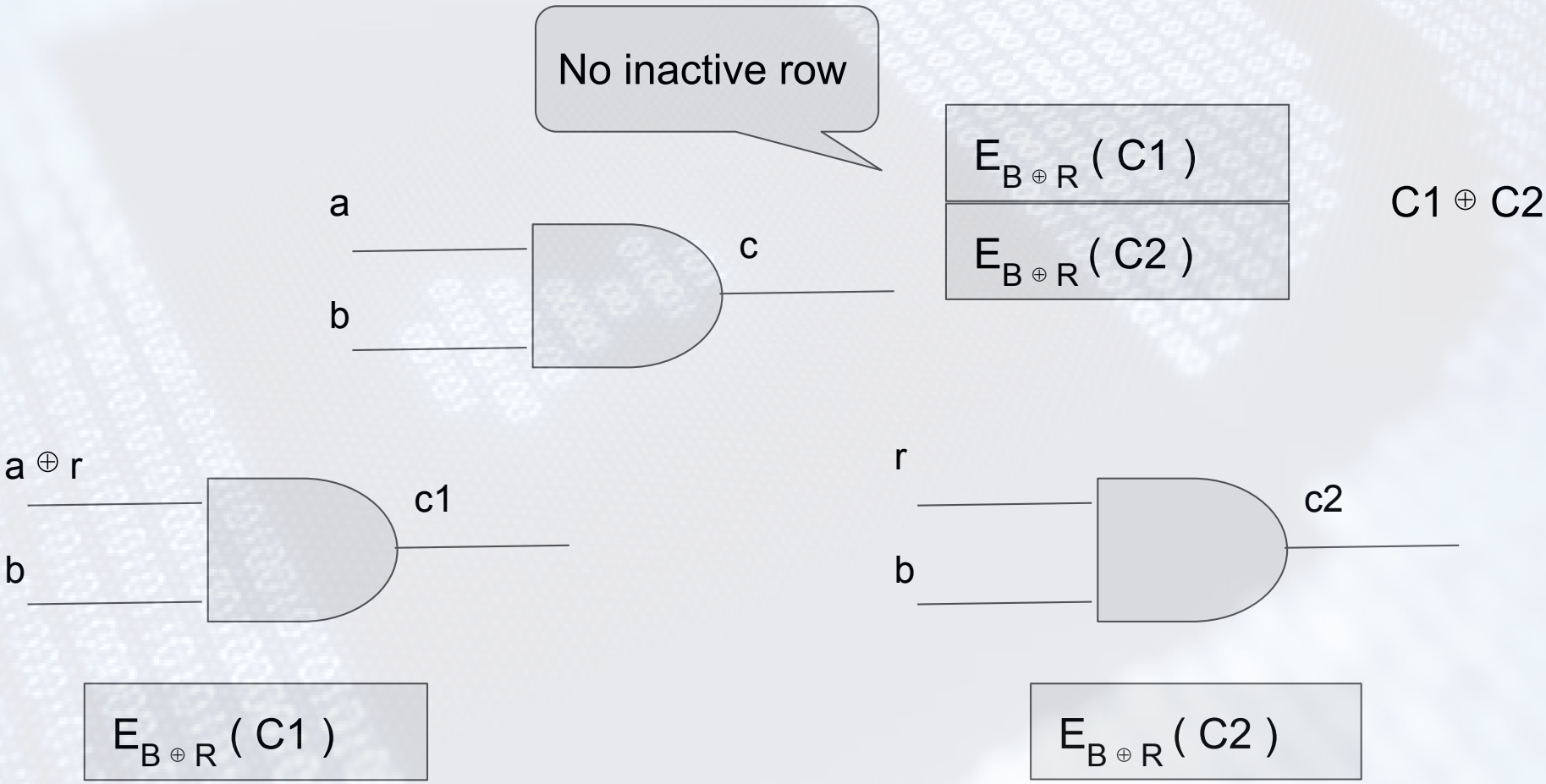
No inactive row
$E_{B \oplus R}(C1)$
$E_{B \oplus R}(C2)$
$C1 \oplus C2$
a
b
c
$a \oplus r$
b
c1
$E_{B \oplus R}(C1)$
r
b
c2
$E_{B \oplus R}(C2)$

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- Hashed garbling constructions – standard garbling and half-gates [ZRE'15]
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Standard Garbling	31.1	226.7	29
Half-gates	26.8	157.7	25.3

- AES circuit garbled, numbers in cycles per gate
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  - When can P_2 abort? (cf. selective failure)

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- Introduced in AL'07, public verifiability (PVC) studied in AO'12, KM'15

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- Total execution time improved for the same deterrence

Covert secure protocols – improving performance

	Total number of circuits	Number of check circuits	Circuits sent**	Time (in secs)
AL'07	10	9	10	3510
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- ** In AL07 and KM15 cheaper to send GC than to compute SHA (GC)

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