Session 2: The Yao and BMR Protocols for Secure Computation

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Tradition of Excellence

The Yao and BMR Protocols

- Yao presented the first protocol for secure (two-party) computation
- Yao's protocol was followed by several protocols for the multi-party setting
  - Goldreich-Micali-Wigderson (GMW)
  - Ben Or-Goldwasser-Wigderson (BGW), Chaum-Crepeau-Damgård (CCD)
- Beaver-Micali-Rogaway (BMR) presented a multi-party protocol using a similar approach to Yao's, and with only O(1) communication rounds.

Yao's Protocol

Yao's Protocol

- **A protocol for general secure two-party computation**
  - Constant number of rounds
  - The basic protocol is secure only for semi-honest adversaries
  - Many applications of the methodology beyond secure computation
- **General secure computation**
  - Can securely compute *any* functionality
  - Based on a representation of the functionality as a **Boolean circuit**

Representing functions as Boolean circuits???

- In some cases the circuits are small
  - Adding numbers
  - Comparing numbers
  - Multiplying numbers?
  - Computing AES?
  - Working with indirect addressing (A[i]) ?

- We can efficiently do secure computation of millions and billions of gates

Basic ideas

- **A *plain* circuit is evaluated by**
  - Setting values to its input gates
  - For each gate, computing the value of the outgoing wire as a function of the wires going into the gate
- **Secure computation:**
  - No party should learn the values of any internal wires
- **Yao's protocol**
  - A compiler which takes a circuit and transforms it to a circuit which hides all information but the final output

Outline

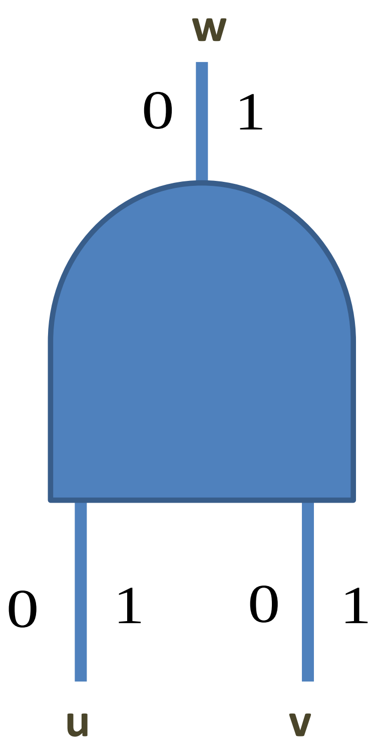
- **Garbled circuit**
  - An encrypted circuit together with a pair of keys (k_0,k_1) for every wire so that for any gate, given one key on every input wire:
    - It is possible to compute the key of the corresponding gate output
    - It is impossible to learn anything else
- **Tool: oblivious transfer**
  - Input: sender has x_0,x_1; receiver has b
  - Receiver obtains x_b only
  - Sender learns nothing

A Garbled Circuit

- For the entire circuit, assign independent random values/keys to each wire (key k_0 for 0, key k_1 for 1)
  - These keys are also called "garbled values"

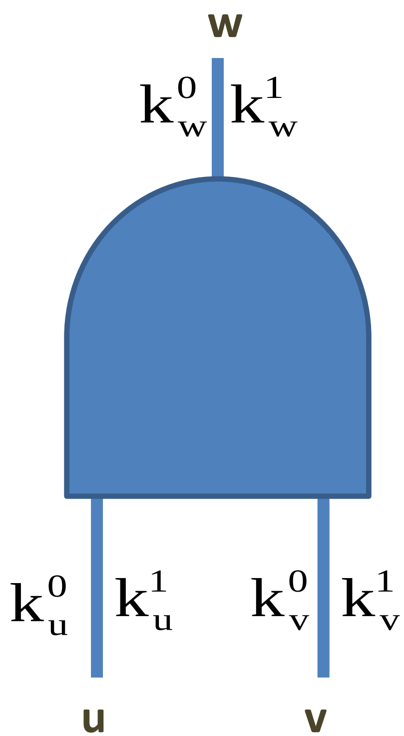
- Encrypt each gate, so that given one key for each input wire, can compute the appropriate key on the output wire

An AND Gate



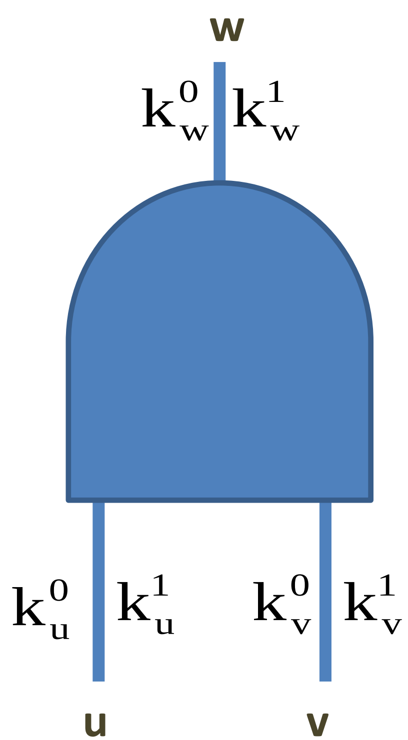
u	v	w
0	0	0
0	1	0
1	0	0
1	1	1

An AND Gate with Garbled Values



u	v	w
k_u^0	k_v^0	k_w^0
k_u^0	k_v^1	k_w^0
k_u^1	k_v^0	k_w^0
k_u^1	k_v^1	k_w^1

A Garbled AND Gate

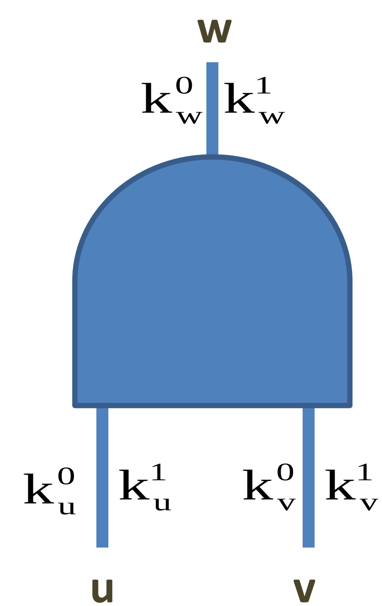


u	v	w
k_u^0	k_v^0	$E_{k_u^0}(E_{k_v^0}(k_w^0))$
k_u^0	k_v^1	$E_{k_u^0}(E_{k_v^1}(k_w^0))$
k_u^1	k_v^0	$E_{k_u^1}(E_{k_v^0}(k_w^0))$
k_u^1	k_v^1	$E_{k_u^1}(E_{k_v^1}(k_w^1))$

A Garbled AND Gate

- **The actual garbled gate**

$$\text{in permuted order}\left\{\begin{array}{l} E_{k_u^1}(E_{k_v^0}(k_w^0)) \\ E_{k_u^0}(E_{k_v^1}(k_w^0)) \\ E_{k_u^1}(E_{k_v^1}(k_w^1)) \\ E_{k_u^0}(E_{k_v^0}(k_w^0)) \end{array}\right.$$

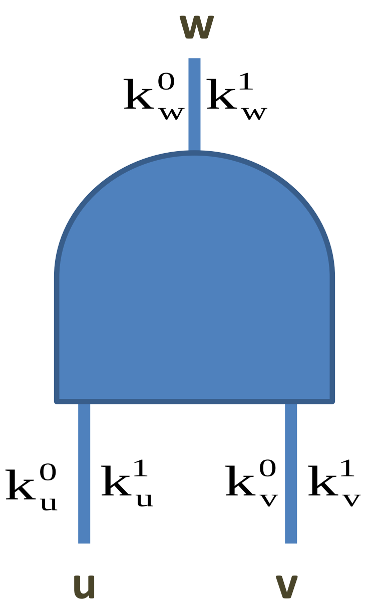


- Given K_u^0 and K_v^1 can obtain only K_w^0
- Furthermore, since the order of the rows is permuted, the party has no idea if it obtained the 0 or 1 key

Output Translation

- If the gate is an output gate, also need to provide the “decryption” of the output wire
- Output translation table:

  $[(0,k_w^0),(1,k_w^1)]$

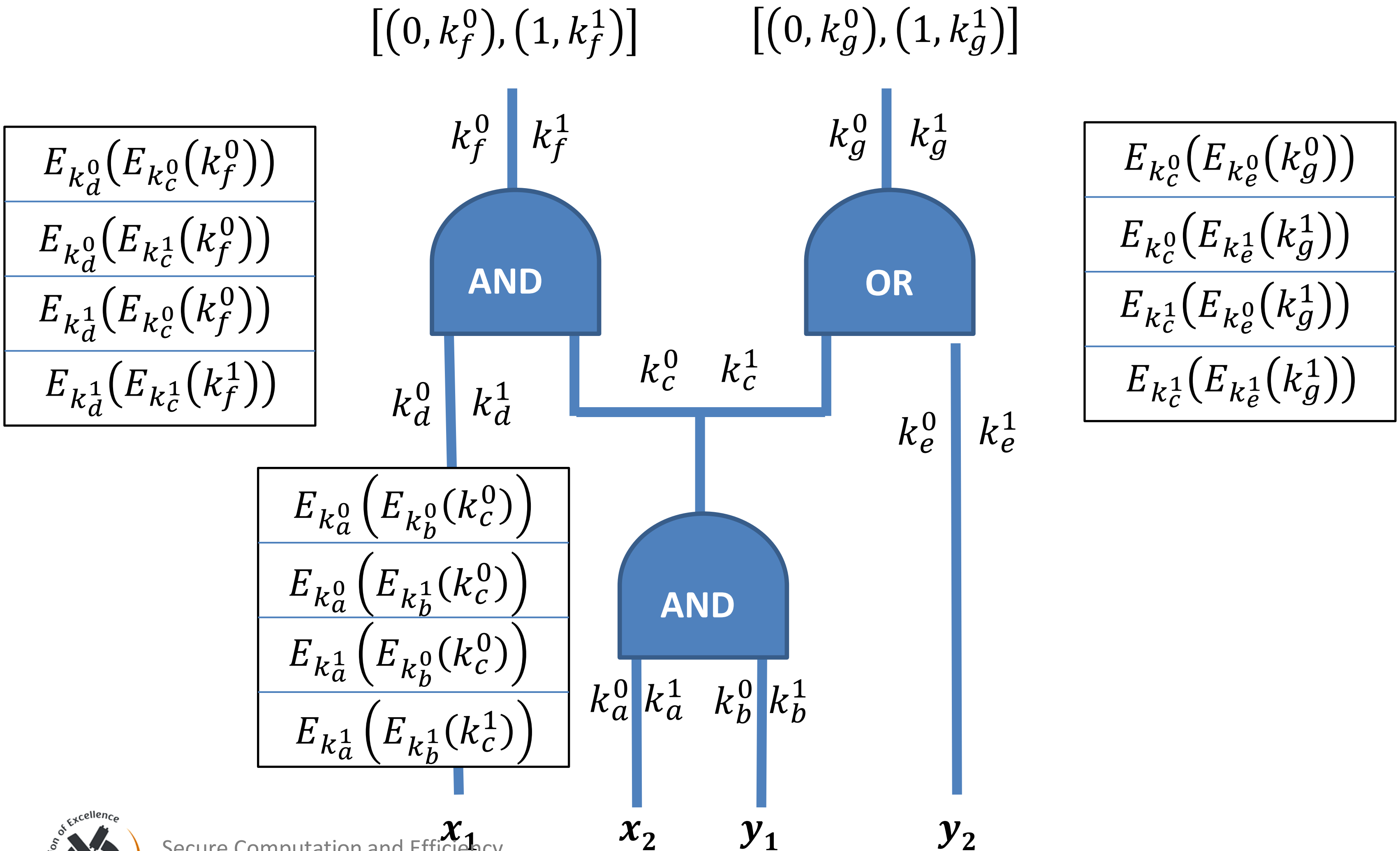


- (Note: this table is insecure if the wire w is used as an input wire to any other gate. It is better to use a table of the form $[(0, H(k_w^0)), (1,H(k_w^1))]$ but this complicates the security proof.)

Constructing a Garbled Circuit

- **Given a Boolean circuit**
  - Assign garbled values to all wires
  - Construct garbled gates using the garbled values
- **Central property:**
  - Given a garbled value for each input wire, can compute the entire circuit, and obtain garbled values for the output wires
  - Given a translation table for the output wires, can obtain output
  - Nothing but the final output is learned!

An Example Circuit



Computing a Garbled Circuit

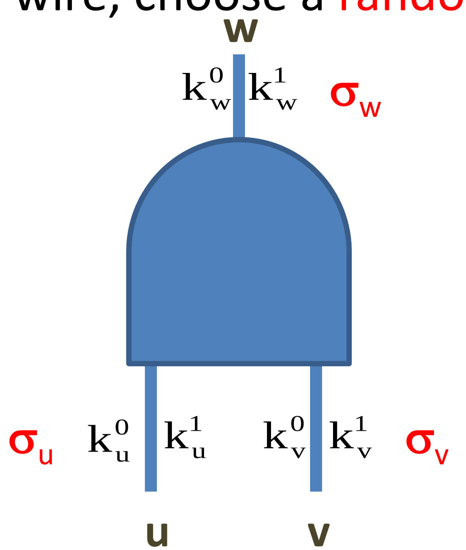
- **How does the party computing the circuit know that it decrypted the "correct" entry?**
  - A gate table has four entries in permuted order
  - The keys known to the evaluator can decrypt only a single entry, but symmetric encryption may decrypt "correctly" even with incorrect keys
- **Two possibilities** (actually many…)
  - Add redundant zeroes to the plaintext; only correct keys give redundant block
  - Add a bit to signal which ciphertext to decrypt

Computing a Garbled Circuit

- **Option 1:**
  - Encryption: $\mathbf{E_K(m)} = [\mathbf{r}\ ,\ \mathbf{F_K(r)} \oplus \mathbf{(m||0^n)}]$
  - By the pseudo-randomness of **F**, the probability of obtaining $\mathbf{0^n}$ with an incorrect **K** is negligible

any drawbacks?

- **Option 2:**
  - For every wire, choose a random signal bit together with the keys



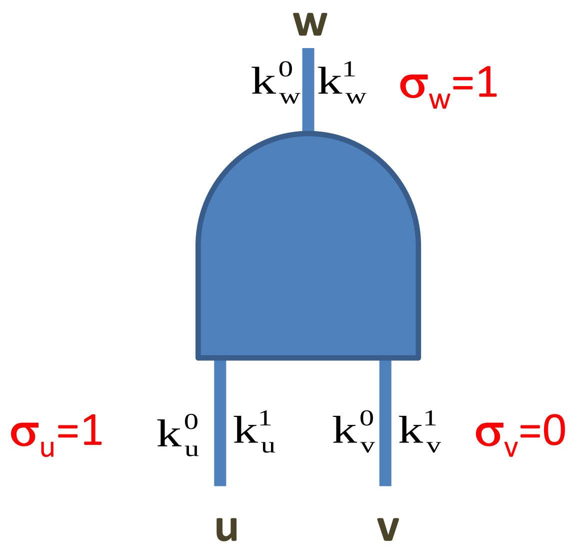
- Each wire has an "internal value" bit which must be kept secret
- It also has an "external value" bit which the evaluator can see
- External value is equal to (internal value xor signal bit)

Computing a Garbled Circuit with a Signal Bit

- **The actual garbled gate**

table ordered based on external values

$$(0,0) \rightarrow E_{k_u^1}(E_{k_v^0}(k_w^0 \,\|\, 1))$$
$$(0,1) \rightarrow E_{k_u^1}(E_{k_v^1}(k_w^1 \,\|\, 0))$$
$$(1,0) \rightarrow E_{k_u^0}(E_{k_v^0}(k_w^0 \,\|\, 1))$$
$$(1,1) \rightarrow E_{k_u^0}(E_{k_v^1}(k_w^0 \,\|\, 1))$$



- **Advantage**
  - Evaluator knows external values and therefore which entry to decrypt. Computing the circuit requires just two decryptions per gate (rather than an average of 5 if 0^n is appended to plaintext)

Yao's protocol

- P_1 sends to P_2
  - Tables encoding each circuit gate.
  - The keys corresponding to P_1's input values.

- If P_2 gets the keys corresponding to its input values, it can compute the output of the circuit, and nothing else.
  - Why can't P_1 provide P_2 with the keys corresponding to both 0 and 1 for P_2's input wires?

Yao's protocol

- For every wire i of P_2's input:
  - The parties run an OT protocol
  - P_2's input is her input bit (y_i).
  - P_1's input is k_i^0, k_i^1
  - P_2 learns $k_i^{y_i}$

- The OTs for all input wires can be run in parallel.
- Afterwards P_1 can compute the circuit by itself.

Yao's Protocol

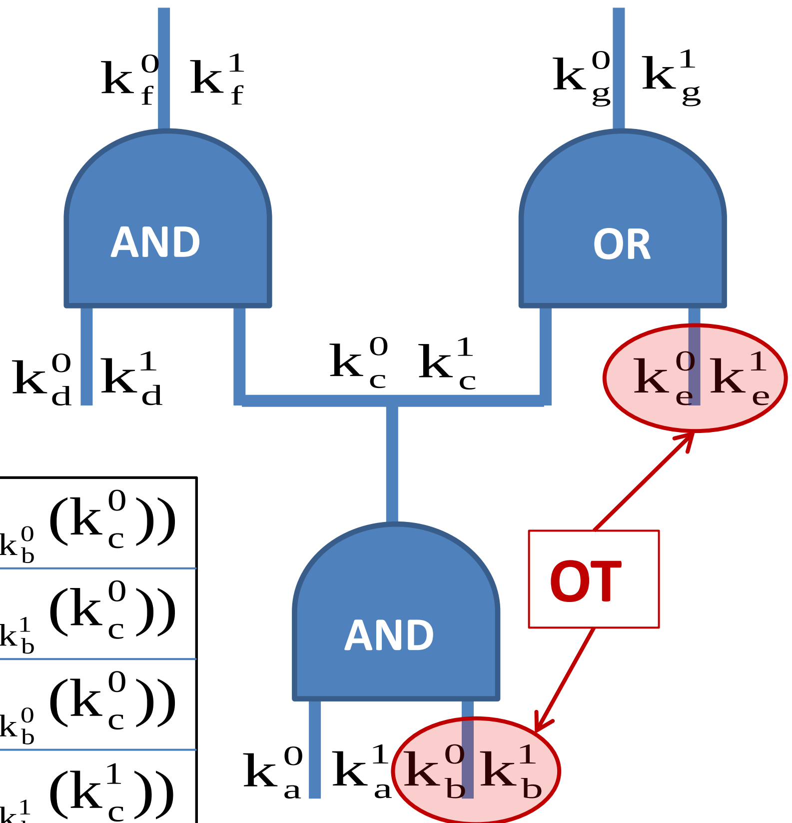
- **Input:** **x** and **y** of length **n**
- P_1 generates a garbled circuit **G**(**C**)
  - $\mathbf{k_L^0, k_L^1}$ are the keys on wire $\mathbf{w_L}$
  - Let $w_1,\ldots,w_n$ be the input wires of P_1 and $w_{n+1},\ldots,w_{2n}$ be the input wires of P_2
- P_1 sends to P_2 **G(C)** and the strings $\mathbf{k_1^{x_1}},\ldots,\mathbf{k_n^{x_n}}$
- P_1 and P_2 run **n** OTs in parallel
  - P_1 inputs ($\mathbf{k_{n+i}^0}$, $\mathbf{k_{n+i}^1}$)
  - P_2 inputs $\mathbf{y_i}$
- Given all keys, P_2 computes **G**(**C**) and obtains **C**(**x**,**y**)
  - P_2 sends result to P_1

The Example Circuit

(input wires P_1= d,a; P_2 = b,e)

$$\left[\left(0, k_f^0\right), \left(1, k_f^1\right)\right] \qquad \left[\left(0, k_g^0\right), \left(1, k_g^1\right)\right]$$

$E_{k_d^0}(E_{k_c^0}(k_f^0))$
$E_{k_d^0}(E_{k_c^1}(k_f^0))$
$E_{k_d^1}(E_{k_c^0}(k_f^0))$
$E_{k_d^1}(E_{k_c^1}(k_f^1))$



$E_{k_c^0}(E_{k_e^0}(k_g^0))$
$E_{k_c^0}(E_{k_e^1}(k_g^1))$
$E_{k_c^1}(E_{k_e^0}(k_g^1))$
$E_{k_c^1}(E_{k_e^1}(k_g^1))$

$E_{k_a^0}(E_{k_b^0}(k_c^0))$
$E_{k_a^0}(E_{k_b^1}(k_c^0))$
$E_{k_a^1}(E_{k_b^0}(k_c^0))$
$E_{k_a^1}(E_{k_b^1}(k_c^1))$

Double-Encryption Security

- Need to formally prove that given 4 encryptions of a garbled gate and only 2 keys
  - Nothing is learned beyond one output
- Actually, in order to simulate the protocol, we need something stronger
- Notation:
  - Double encryption: $\overline{\mathrm{E}}(\mathrm{k}_{\mathrm{u}}, \mathrm{k}_{\mathrm{v}}, \mathrm{m}) = \mathrm{E}_{\mathrm{k}_{\mathrm{u}}}(\mathrm{E}_{\mathrm{k}_{\mathrm{v}}}(m))$
  - Oracles: $\overline{\mathrm{E}}(\cdot, \mathrm{k}_{\mathrm{v}}, \cdot), \overline{\mathrm{E}}(\mathrm{k}_{\mathrm{u}}, \cdot, \cdot)$

Double-Encryption Security

$\text{Expt}_{\mathcal{A}}^{\text{double}}(n, \sigma)$

1. The adversary $\mathcal{A}$ is invoked upon input 1^n and outputs two keys k_0 and k_1 of length n and two triples of messages (x_0, y_0, z_0) and (x_1, y_1, z_1) where all messages are of the same length.
2. Two keys $k'_0, k'_1 \leftarrow G(1^n)$ are chosen for the encryption scheme.
3. $\mathcal{A}$ is given the challenge ciphertext $\langle \overline{E}(k_0, k'_1, x_\sigma), \overline{E}(k'_0, k_1, y_\sigma), \overline{E}(k'_0, k'_1, z_\sigma) \rangle$ as well as oracle access to $\overline{E}(\cdot, k'_1, \cdot)$ and $\overline{E}(k'_0, \cdot, \cdot)$
4. $\mathcal{A}$ outputs a bit b and this is taken as the output of the experiment.

Enabling *A* to access these oracles gives it more power

The encryption is secure if the adversary cannot identify which one of the two triples as encrypted

Proof of Security – P_1 is Corrupted

- P_1's view consists only of the messages it receives in the oblivious transfers
- In the OT-hybrid model, P_1 receives no messages in the oblivious transfers
- Simulation:
  - Generate an empty transcript

Proof of Security – P_2 is Corrupted

- **More difficult case**
  - Need to construct a fake garbled circuit **G**(**C′**) that looks indistinguishable to **G**(**C**)
  - Simulated view contains keys to input wires and **G**(**C′**)
  - **G**(**C′**) together with the keys computes **f**(**x,y**)
  - But the simulator does not know **x**, so cannot generate a real garbled circuit

Proof of Security – P_2 is Corrupted

- **The simulator**
  - Given **y** and **z = f**(**x,y**), construct a fake garbled circuit **G′**(**C**) that always outputs **z**
    - Do this by choosing wire keys as usual, but encrypting the **same output key** in all ciphertexts, e.g.

$$E_{k_u^1}(E_{k_v^0}(k_w^0)) \quad E_{k_u^1}(E_{k_v^1}(k_w^0))$$
$$E_{k_u^0}(E_{k_v^1}(k_w^0)) \quad E_{k_u^0}(E_{k_v^0}(k_w^0))$$

    - This ensures that no matter the input, the same known garbled values on the output wires are received

Proof of Security – P_2 is Corrupted

- **Simulator (continued)**
  - Simulation of output translation tables
    - Let **k,k′** be the keys on the **i**th output wire; let **k** be the key encrypted in all 4 entries of the gate which outputs this wire
    - If $\mathbf{z_i = 0}$, write **[(0,k)**,**(1,k′)]**
    - If $\mathbf{z_i = 1}$, write **[(0,k′)**,**(1,k)]**
  - Simulation of input keys phase
    - Input wires associated with P_1's input: send any one of the two keys on the wire
    - Input wires associated with P_2's input: simulate output of OT to be any one of the two keys on the wire

Proof of Security – P_2 is Corrupted

- Need to prove that the simulation is indistinguishable from the real execution
- First step – modify simulator as follows
  - Given circuit inputs x and y (just for the sake of the proof), label all keys on the wires as active or inactive
    - active: key is obtained on this wire upon inputs (x,y)
    - inactive: key is not obtained on wire upon inputs (x,y)
  - Make sure that the single key encrypted in each gate is the active one
- This simulation is identical to the previous one

Proof of Security – P_2 is Corrupted

- Proven by a hybrid argument
  - Consider a garbled circuit $G_L(C)$ for which:
    - The first L gates are generated as in the (alternative) simulation
    - The rest of the gates are generated honestly
- Claim: $G_{L-1}(C)$ is indistinguishable from $G_L(C)$
- Proof:
  - Difference is in L^{th} gate
  - Intuition: use indistinguishability of encryptions to say that cannot distinguish real garbled gate from one where the same active key is encrypted in all entries

Proof of Security – P_2 Corrupted

- Observation – L^{th} gate
  - The encryption under both active keys is identical in both cases
  - The difference is encryptions where one or both of the keys are inactive keys
    - Must show that these three encryptions are indistinguishable from the encryptions in real execution
- The problem
  - The inactive keys in this gate may appear in other gates as well
    - We needed the oracles to generate these other encryptions…

The Example Circuit

(input wires P_1= d,a; P_2 = b,e)

$$\left[(0, k_f^0),(1, k_f^1)\right] \qquad \left[(0, k_g^0),(1, k_g^1)\right]$$

$E_{k_d^0}(E_{k_c^0}(k_f^0))$
$E_{k_d^0}(E_{k_c^1}(k_f^0))$
$E_{k_d^1}(E_{k_c^0}(k_f^0))$
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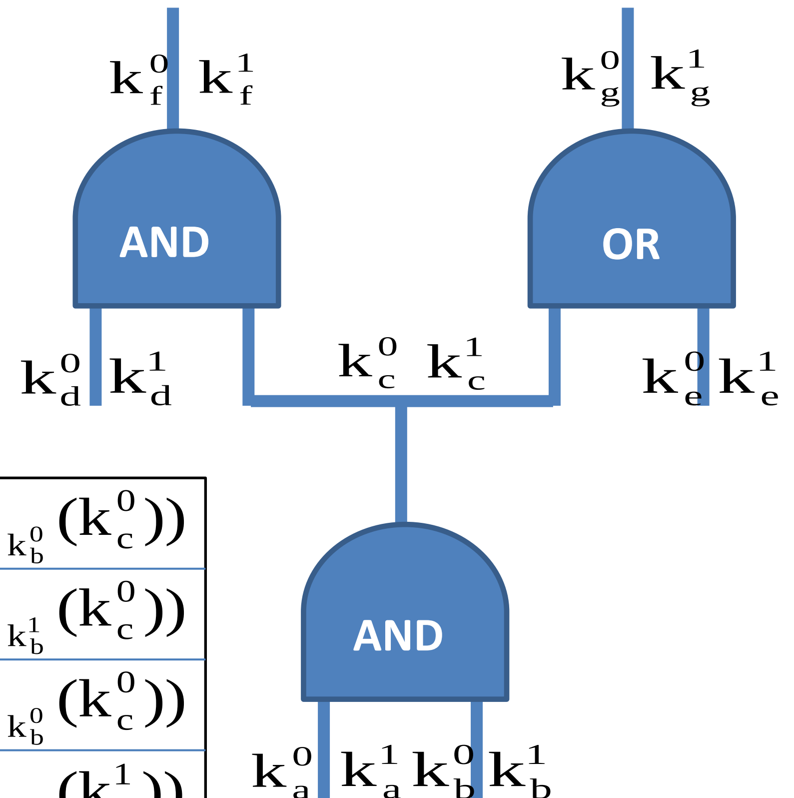


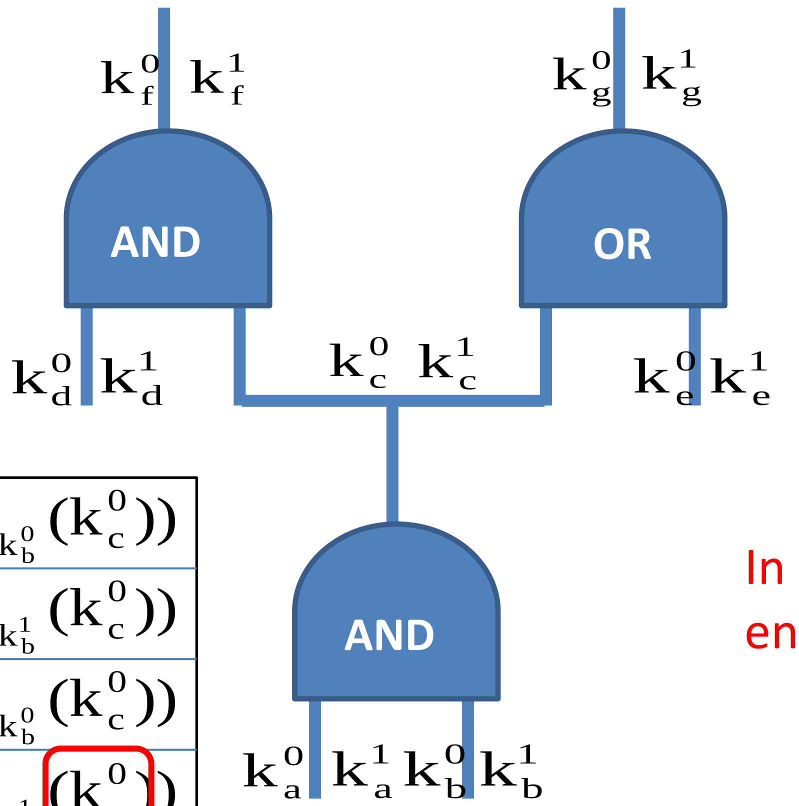
$E_{k_c^0}(E_{k_e^0}(k_g^0))$
$E_{k_c^0}(E_{k_e^1}(k_g^1))$
$E_{k_c^1}(E_{k_e^0}(k_g^1))$
$E_{k_c^1}(E_{k_e^1}(k_g^1))$

$E_{k_a^0}(E_{k_b^0}(k_c^0))$
$E_{k_a^0}(E_{k_b^1}(k_c^0))$
$E_{k_a^1}(E_{k_b^0}(k_c^0))$
$E_{k_a^1}(E_{k_b^1}(k_c^1))$

Simulator’s Circuit (Output 01)

$$[(0, \boxed{k_f^0}), (1, k_f^1)] \qquad [(0, k_g^0), (1, \boxed{k_g^1})]$$

$E_{k_d^0}(E_{k_c^0}(k_f^0))$
$E_{k_d^0}(E_{k_c^1}(k_f^0))$
$E_{k_d^1}(E_{k_c^0}(k_f^0))$
$E_{k_d^1}(E_{k_c^1}(\boxed{k_f^0}))$



$E_{k_c^0}(E_{k_e^0}(\boxed{k_g^1}))$
$E_{k_c^0}(E_{k_e^1}(k_g^1))$
$E_{k_c^1}(E_{k_e^0}(k_g^1))$
$E_{k_c^1}(E_{k_e^1}(k_g^1))$

$E_{k_a^0}(E_{k_b^0}(k_c^0))$
$E_{k_a^0}(E_{k_b^1}(k_c^0))$
$E_{k_a^1}(E_{k_b^0}(k_c^0))$
$E_{k_a^1}(E_{k_b^1}(\boxed{k_c^0}))$

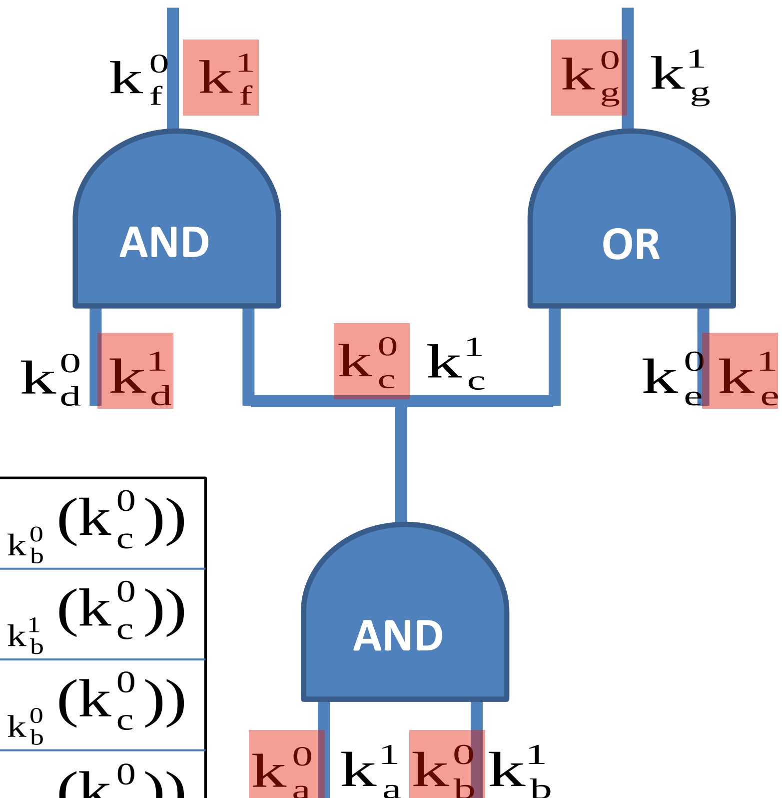
In each gate, all table entries are identical

Inactive Keys

Assuming input is (da=01,be=10), output is (fg=01)

$$\left[(0, k_f^0), (1, \boxed{k_f^1})\right] \qquad \left[(0, \boxed{k_g^0}), (1, k_g^1)\right]$$

$E_{k_d^0}(E_{k_c^0}(k_f^0))$
$E_{k_d^0}(E_{k_c^1}(k_f^0))$
$E_{k_d^1}(E_{k_c^0}(k_f^0))$
$E_{k_d^1}(E_{k_c^1}(k_f^0))$



$E_{k_c^0}(E_{k_e^0}(k_g^1))$
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$E_{k_c^1}(E_{k_e^0}(k_g^1))$
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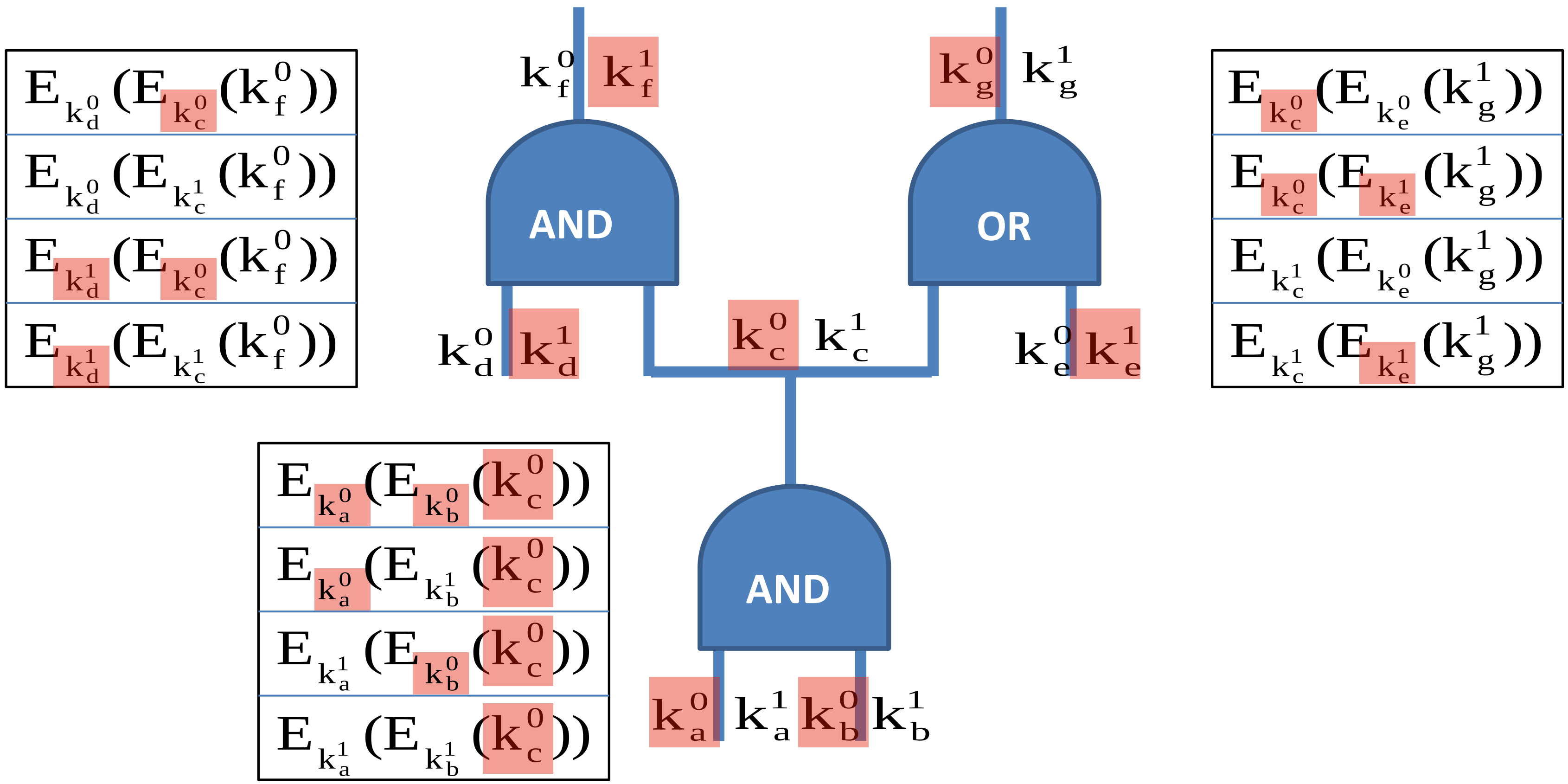
$E_{k_a^0}(E_{k_b^0}(k_c^0))$
$E_{k_a^0}(E_{k_b^1}(k_c^0))$
$E_{k_a^1}(E_{k_b^0}(k_c^0))$
$E_{k_a^1}(E_{k_b^1}(k_c^0))$

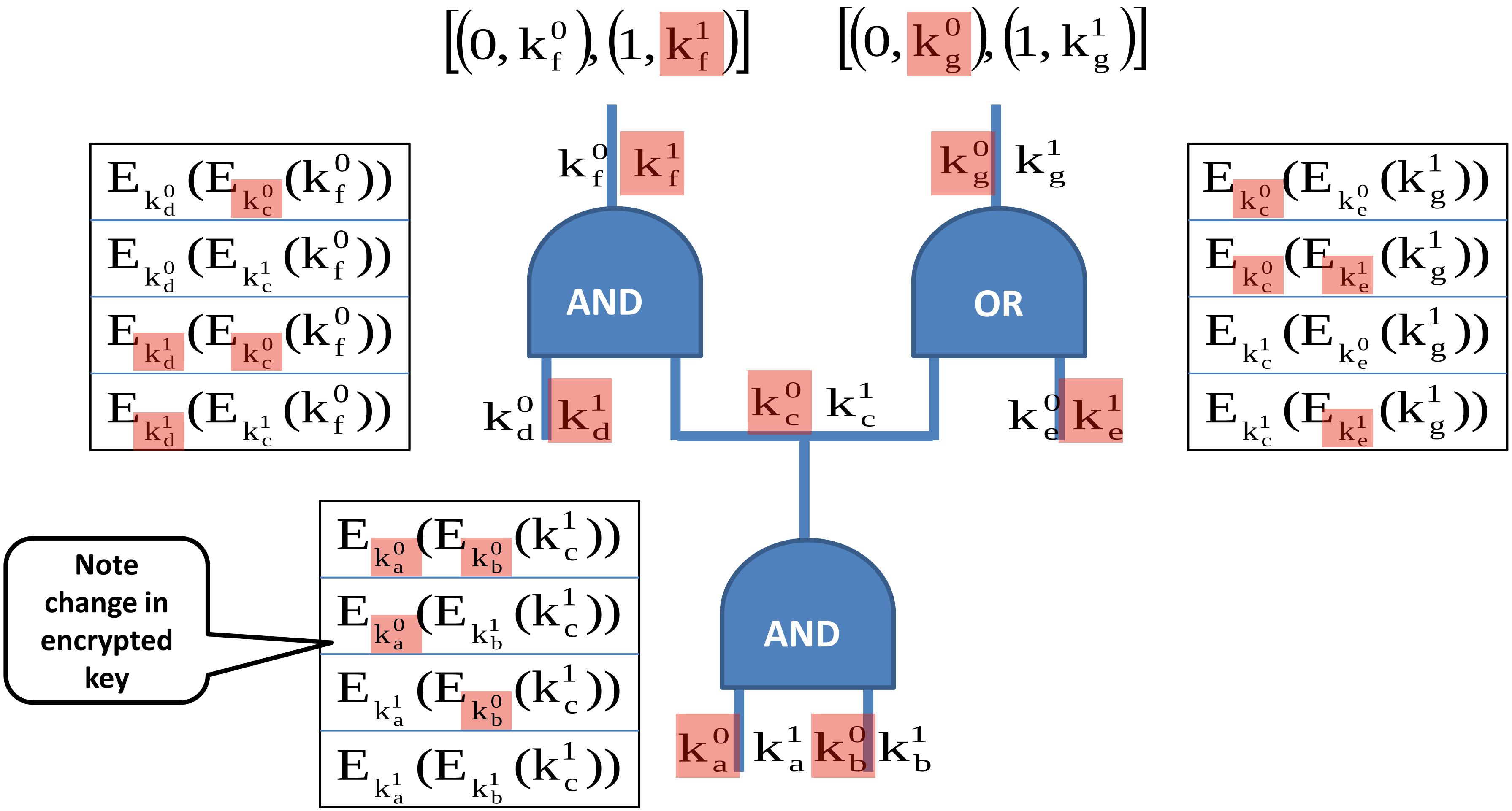
Inactive Keys

Assuming input is (da=01,be=10), output is (fg=01)

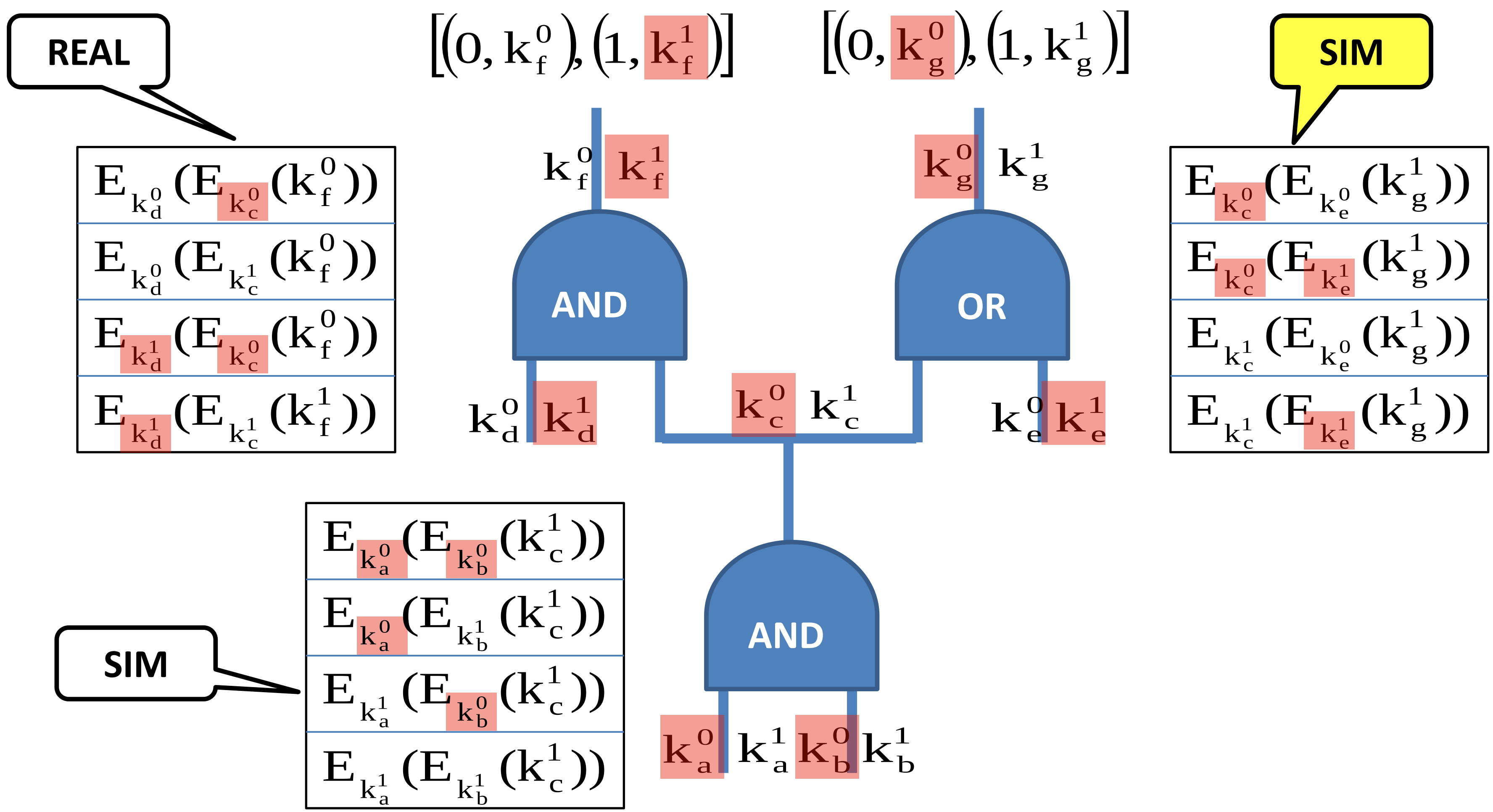
$[(0, k_f^0), (1, k_f^1)]$ $[(0, k_g^0), (1, k_g^1)]$



Modify Simulator
(Encrypt Active Keys Only)



Hybrid on OR Gate – Simulated OR

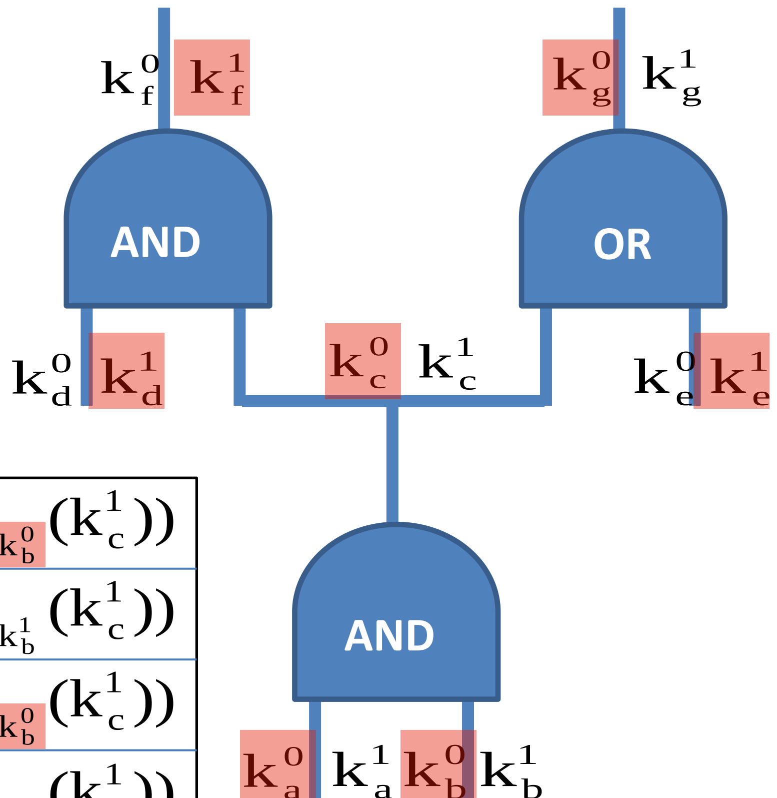


Hybrid on OR Gate – Real OR

REAL

$E_{k_d^0}(E_{k_c^0}(k_f^0))$
$E_{k_d^0}(E_{k_c^1}(k_f^0))$
$E_{k_d^1}(E_{k_c^0}(k_f^0))$
$E_{k_d^1}(E_{k_c^1}(k_f^1))$

$[(0, k_f^0), (1, k_f^1)]$ $[(0, k_g^0), (1, k_g^1)]$



REAL

$E_{k_c^0}(E_{k_e^0}(k_g^0))$
$E_{k_c^0}(E_{k_e^1}(k_g^1))$
$E_{k_c^1}(E_{k_e^0}(k_g^1))$
$E_{k_c^1}(E_{k_e^1}(k_g^1))$

SIM

$E_{k_a^0}(E_{k_b^0}(k_c^1))$
$E_{k_a^0}(E_{k_b^1}(k_c^1))$
$E_{k_a^1}(E_{k_b^0}(k_c^1))$
$E_{k_a^1}(E_{k_b^1}(k_c^1))$

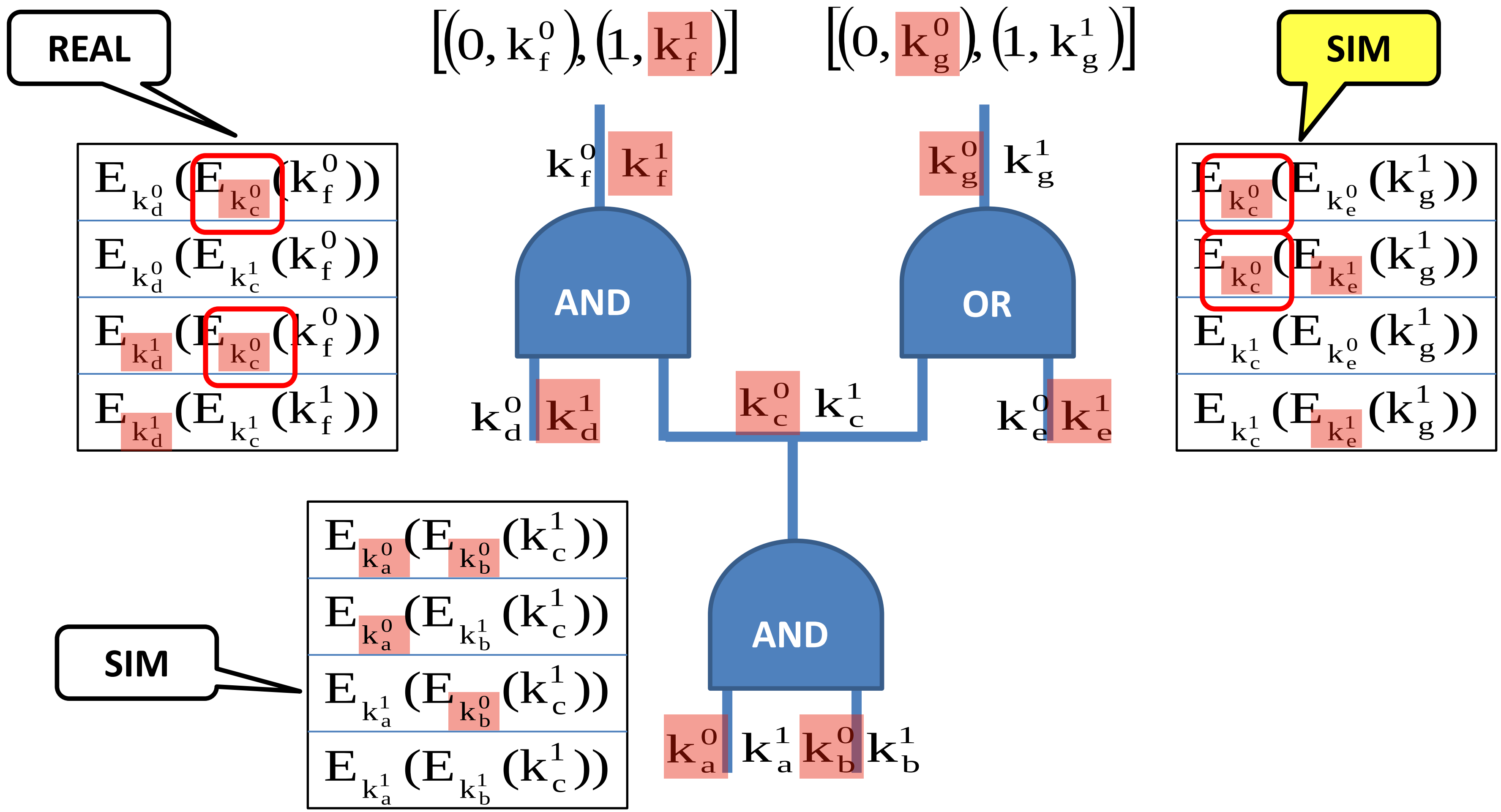
What's the Difference

- In the simulated OR case, the inactive key $\mathbf{k_c^0}$ encrypts the key $\mathbf{k_g^1}$
- In the real OR case, the inactive key $\mathbf{k_c^0}$ encrypts the key $\mathbf{k_g^0}$
- Indistinguishability follows from the indistingushability of encryptions under the **inactive key** $\mathbf{k_c^0}$

Proving Indistinguishability

- Follows from the indistingushability of encryptions under the **inactive key** $\mathbf{k_c^0}$
- **The good news**
  - Key $\mathbf{k_c^0}$ is not encrypted anywhere (as data) because prior gates are simulated
- **The bad news**
  - The key $\mathbf{k_c^0}$ needs to be used to construct the real AND gate for the hybrid
- **The solution**
  - The special double-encryption CPA game

The problem: inactive key used in another gate



Double-Encryption Security

$\mathsf{Expt}^{\mathsf{double}}_{\mathcal{A}}(n, \sigma)$

1. The adversary $\mathcal{A}$ is invoked upon input 1^n and outputs two keys k_0 and k_1 of length n and two triples of messages (x_0, y_0, z_0) and (x_1, y_1, z_1) where all messages are of the same length.
2. Two keys $k'_0, k'_1 \leftarrow G(1^n)$ are chosen for the encryption scheme.
3. $\mathcal{A}$ is given the challenge ciphertext $\langle \overline{E}(k_0, k'_1, x_\sigma), \overline{E}(k'_0, k_1, y_\sigma), \overline{E}(k'_0, k'_1, z_\sigma)\rangle$ as well as oracle access to $\overline{E}(\cdot, k'_1, \cdot)$ and $\overline{E}(k'_0, \cdot, \cdot)$.[5]
4. $\mathcal{A}$ outputs a bit b and this is taken as the outp t of the experiment.

- k_0,k_1 (i.e., k_c^1,k_e^0) are active keys
- k'_0,k'_1 (i.e, k_c^0,k_e^1) are inactive keys
  - Can use oracle to generate the REAL AND gate

Proof of Security – P_2 is Corrupted

- Since each gate-replacement is indistinguishable, using a hybrid argument we have that the distributions are indistinguishable (see paper for details)

- QED

Efficiency

- 2-4 rounds (depending on OT and if one party or both parties receive output)
- $|y|$ oblivious transfers
- $8|C|$ symmetric encryptions to generate circuit and $2|C|$ to compute it (using the signal bit)
- For a circuit of 33,000 gates, about 528 Kbytes with 128bit AES encryption

Malicious Adversaries

- **Assume that the OT is secure for malicious adv:**
  - A corrupted $\mathbf{P_1}$ cannot learn **anything** (it receives no messages in the protocol, in the hybrid-OT model)
    - Thus, we have **privacy**
  - We can prove **full security** for the case of a corrupted $\mathbf{P_2}$
- **This can be useful, but…**
  - This does not ensure that the parties compute the required functionality
  - E.g., consider P_1 that builds circuit so that if P_2's first bit is 0, the circuit doesn't decrypt
    - If P_1 can detect this in the real world, privacy is lost
  - Proving full security against a malicious P1 is hard

The BMR Protocol

The BMR protocol

- Beaver-Micali-Rogaway
- A multi-party version of Yao's protocol
- Works in O(1) communication rounds, regardless of the depth of the Boolean circuit. (The GMW,BGW, CCD protocol have O(d) rounds)

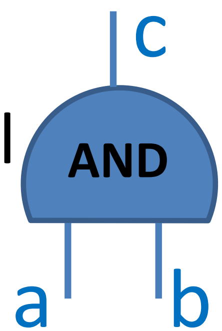
  – D. Beaver, S. Micali and P. Rogaway, "The round complexity of secure protocols", 1990.
  – A. Ben-David, N. Nisan and B. Pinkas, "FairplayMP – A System for Secure Multi-Party Computation", 2010.

The BMR protocol: the basic idea

- Two random seeds (aka keys, garbled values) are set for every wire of the Boolean circuit:
  - Each seed is a concatenation of seeds generated by all players and secretly shared among them.
- The parties securely compute together a 4x1 table for every gate (in parallel):
  - Given a 0/1 seed to each of the two input wires, the table reveals the seed of the resulting value of the output wire.

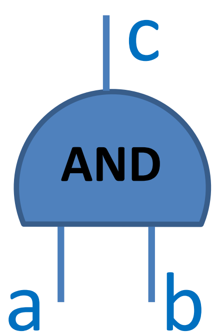
Encoding Gates

- Wire a has seeds $s_{a,1}^0, s_{a,1}^1, \ldots, s_{a,n}^0, s_{a,n}^1$ of parties $P_1, \ldots, P_n$.
- Every wire has similar seeds.
- Each wire has a secret bit λ. If $\lambda_a=0$ then $s_{a,i}^0$ corresponds to an internal value of 0 and $s_{a,i}^1$ corresponds to an internal value of 1. Otherwise $s_{a,i}^0$ corresponds to 1 and $s_{a,i}^1$ to 0.
- The λ values are random and shared between the parties, so no one knows to which internal value the 0 seeds correspond.



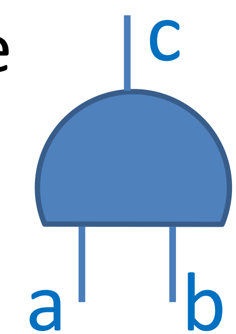
Encoding Gates

- Suppose that $\lambda_a=0$, $\lambda_b=1$ and $\lambda_c=0$.
- The seeds $s_{a,1}^0,\ldots, s_{a,n}^0$ and $s_{b,1}^0,\ldots, s_{b,n}^0$
  - Correspond to internal values of $a=0$, $b=1$, and consequently to $c=0$.
  - Since $\lambda_c=0$ they will encrypt the corresponding seeds of wire c, $s_{c,1}^0,\ldots, s_{c,n}^0$
- Can similarly decide which seed of wire c must be encrypted by each combination of the seeds of wires a,b.



Encoding Gates

- For each gate, the table encrypting the outputs of the gate is a function of
  - $\lambda_a=0$, $\lambda_b=1$, $\lambda_c=0$ (these values are shared by the parties)
  - The seeds $s_{a,1}^{0}, s_{a,1}^{1},\ldots, s_{a,n}^{0}, s_{a,n}^{1}, s_{b,1}^{0}, s_{b,1}^{1},\ldots, s_{b,n}^{0}, s_{b,n}^{1}$, and $s_{c,1}^{0}, s_{c,1}^{1},\ldots, s_{c,n}^{0}, s_{c,n}^{1}$
  - Gate type (AND, OR, etc.)
- The size of this function is independent of the circuit size
- The parties can run a secure computation to compute the table (using, e.g., GMW etc.)



The BMR protocol

- Offline: The parties securely compute together a 4x1 table for every gate (in parallel for all gates):
  - This is essentially a secure computation of the table
  - All tables are computed in parallel. Therefore overall O(1) rounds.
  - This is the main bottleneck of the BMR protocol (FairplayMP optimizes this computation).
- Online: Given the tables and the seeds of the input values, compute the circuit as in Yao.

Summary

- Can compute any functionality securely in presence of semi-honest adversaries.
- The Yao and BMR protocols are efficient, for circuits that are not too large.
- Obtaining security against malicious adversaries is hard.