PALISADE

HOMOMOPHIC ENCRYPTION FOR PALISADE USERS: TUTORIAL WITH APPLICATIONS

Boolean Arithmetic with Applications

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AGENDA

- Boolean Algebra/Logic Review and Circuits
- Basic Examples from PALISADE
- Simple Circuit Examples Using the PALISADE Encrypted Circuit Emulator
- Additional Circuit Examples

Boolean Logic

A quick refresher

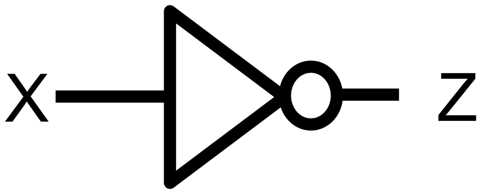
Boolean Algebra

- The basis of all digital logic
- Many equivalent representations:
  - Circuits of Gates
  - Logic Equations
  - Truth tables
- All are equivalent!
- Any logic circuit can be manipulated into many different forms.
  - Minimize # gates
  - Minimize depth
  - Use particular gate types

XOR

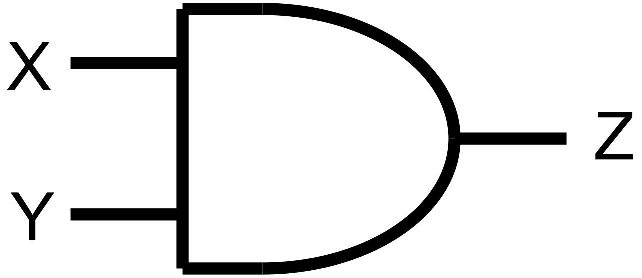
X	Y	Z
0	0	0
0	1	1
1	0	1
1	1	0

NOT



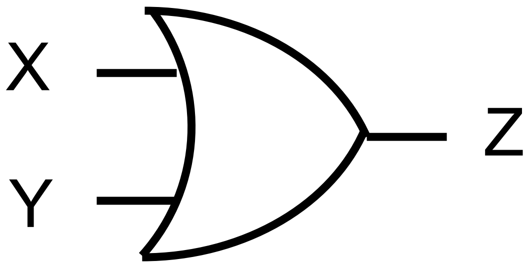
`Z = !X`

AND



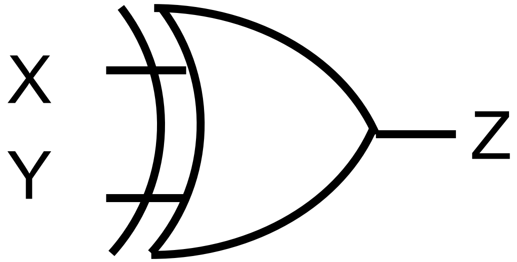
`Z = X & Y`

OR



`Z = X | Y`

XOR



`Z = X ^ Y`

Other gate combinations are easily built from these

Thanks to https://www.secs.oakland.edu/~polis/Lectures/EGR240 D5.1 BasicLogicGates.ppt

Representing Systems of Logic Gates

- Circuit diagrams / Schematics (gates and wires)
- Net lists (BLIF, EDL, Bristol Format) not very readable
- Hardware Design Languages (VHDL, Verilog, System C)
- Other..
  - PALISADE lets you connect gates together via C++
  - Good for simple systems
  - PALISADE Encrypted Circuit Emulator lets you script your own circuits, and reads in some net list formats
    - Good for circuits with 1000's of gates

Basic Examples

From the PALISADE distribution

The “cost” of Encrypted Logic

- Memory (32 bit implementation):
  - AP (STD128): Classical FHEW
    - Bootstrapping key: 1152 MB, Key switching key: 300 MB
  - GINX (STD128): TFHE
    - Bootstrapping key: 64 MB, Key switching key: 300 MB
  - Note that the key switching key size can be reduced if desired (it is a controllable parameter).
  - Each encrypted bit takes ~2KB storage

The “cost” of Encrypted Logic

- Execution time
  - Executing NOT is fast (100 nsec), since no bootstrapping is performed
  - Executing AND, OR has one bootstrap performed
    - 107 msec / thread (AP STD128)
    - 143 msec / thread (GINX STD128)
  - Two options for XOR:
    - XOR - 3x slower than AND (three bootstraps, gives same failure probability as AND $<2^{-32}$)
    - XOR_FAST - = AND but higher failure probability $<2^{-15}$
    - For more details, see https://eprint.iacr.org/2020/086
- The execution time of an encrypted circuit is strictly a function of the gate time
  - Manipulating circuit to minimize # of gates (other than NOT) gives fastest runtime

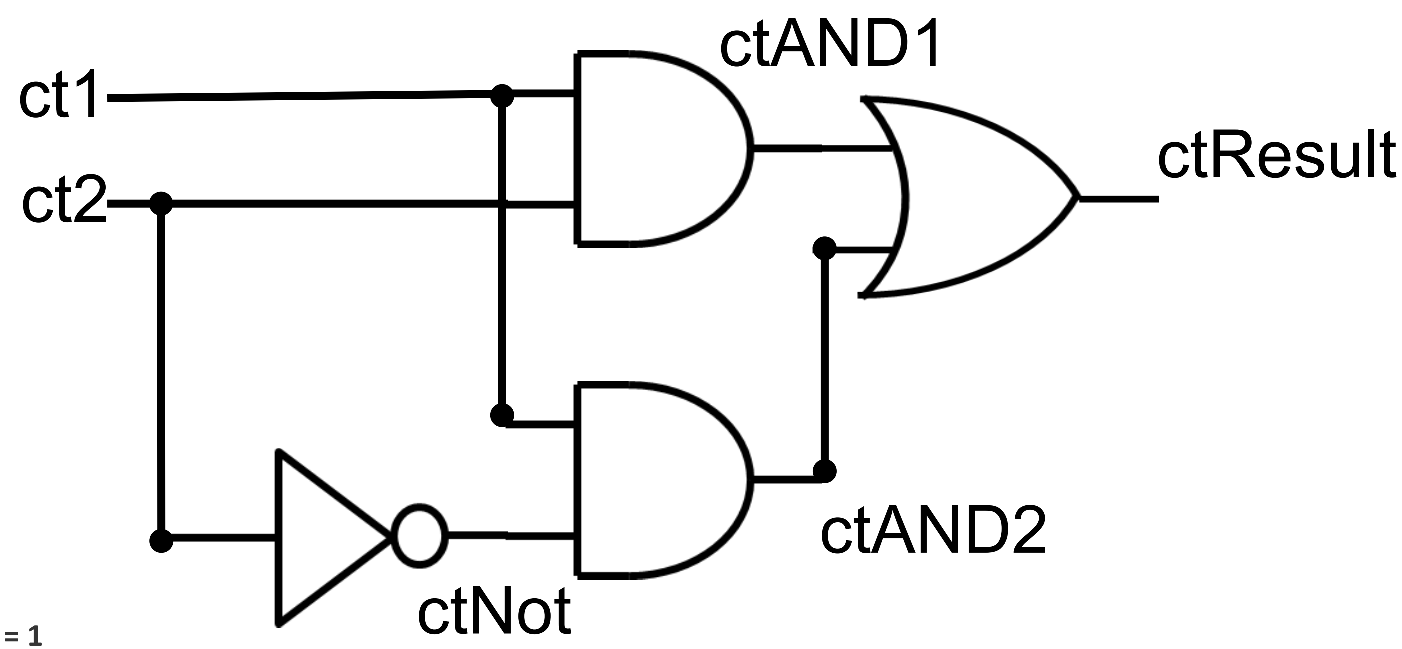
C++ Examples provided in the PALISADE release

- Sample executables are in **${root}/build/bin/examples/binfhe**
- C++ source code for these examples are in **${root}/binfhe/examples**
  - **boolean** : simple collection of gates using the GINX method.
  - **boolean-ap** : same as above except using AP method.
  - **boolean-truth-tables** : example showing basic gate output for all input combinations
  - **boolean-serial-json** : how to serialize (save to disk) the components of a binfhe crypto-system (various keys and ciphertext)
  - **boolean-serial-binary** : same as above though with binary vs json storage (much smaller files)
- Source code for sample benchmarks are in **${root}/benchmark/src/binfhe*.cpp**

Listing of boolean.cpp

```
#include "binfhecontext.h"
using namespace lbcrypto;
using namespace std;
int main() {

  // Step 1: Set CryptoContext
  auto cc = BinFHEContext();
  cc.GenerateBinFHEContext(STD128, AP);   //set 128 bits of security,  AP

  // Step 2: Key Generation
  auto sk = cc.KeyGen();          // Generate the secret key
  cc.BTKeyGen(sk);                // Generate the bootstrapping keys

  // Step 3: Encryption
  // Encrypt two ciphertexts representing Boolean True (1)
  auto ct1 = cc.Encrypt(sk, 1);
  auto ct2 = cc.Encrypt(sk, 1);

  // Step 4: Evaluation
  auto ctAND1 = cc.EvalBinGate(AND, ct1, ct2);        // Compute (1 AND 1) = 1
  auto ct2Not = cc.EvalNOT(ct2);                      // Compute (NOT 1) = 0
  auto ctAND2 = cc.EvalBinGate(AND, ct2Not, ct1);    // Compute (1 AND (NOT 1)) = 0
  // Computes OR of the results in ctAND1 and ctAND2 = 1
  auto ctResult = cc.EvalBinGate(OR, ctAND1, ctAND2);

  // Step 5: Decryption
  LWEPlaintext result;
  cc.Decrypt(sk, ctResult, &result);
}
```

Equivalent Circuit Representation



Each "wire" is a ciphertext
Each "gate" is a function call
Inputs are "encrypted"
Outputs are "decrypted"

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Simple Circuit Examples

From the PALISADE Encrypted Circuit Emulation repository

PALISADE Encrypted Circuit Emulator

- GitLab repo: https://gitlab.com/palisade/palisade-encrypted-circuit-emulator
  - Build instructions are in README.md, requires you to install PALISADE
- Contains prototype C++ code to
  - Parse circuit representation input files
  - Analyze and Assemble them into an intermediate form for circuit emulation (*.out file)
  - Run C++ test fixtures to generate input and test output for various circuits
  - Executes resulting logic circuit in plaintext and encrypted form – uses Open MP to evaluate encrypted gates in parallel on all available threads.
  - Stores minimum number of circuit ciphertexts
    - once all gates have fired that are fed by a node, it is deleted.

PALISADE Encrypted Circuit Emulator

- Current limitations (Aug 2020)
  - Input currently limited to “Bristol Format Circuits” https://homes.esat.kuleuven.be/~nsmart/MPC/old-circuits.html
    - Format is primarily used for Garbled Circuit R&D
    - As a result it has limited I/O, limited gate types, and these circuits prefer XOR over all other gates – also not the smallest circuits possible but are a good representation.
  - Intermediate file format (*.out) is a bit primitive and fiddly, but you can use it to write your own circuits
  - Circuit management / scheduling code is done brute force
    - Executes encrypted gates on parallel threads, minimize circuit ciphertext
    - Overhead high for small circuits, negligible (2%) on large circuits.

PALISADE Encrypted Circuit Emulator

- Planned extensions
  - Add New Bristol Fashion Circuit format
  - Improve I/O definitions to allow more complex circuits
  - Optimize circuit management and internal netlist generation (currently takes a long time for large circuits)
  - Follow improvements in PALISADE binfhe performance as they get released

Example Simple Circuits

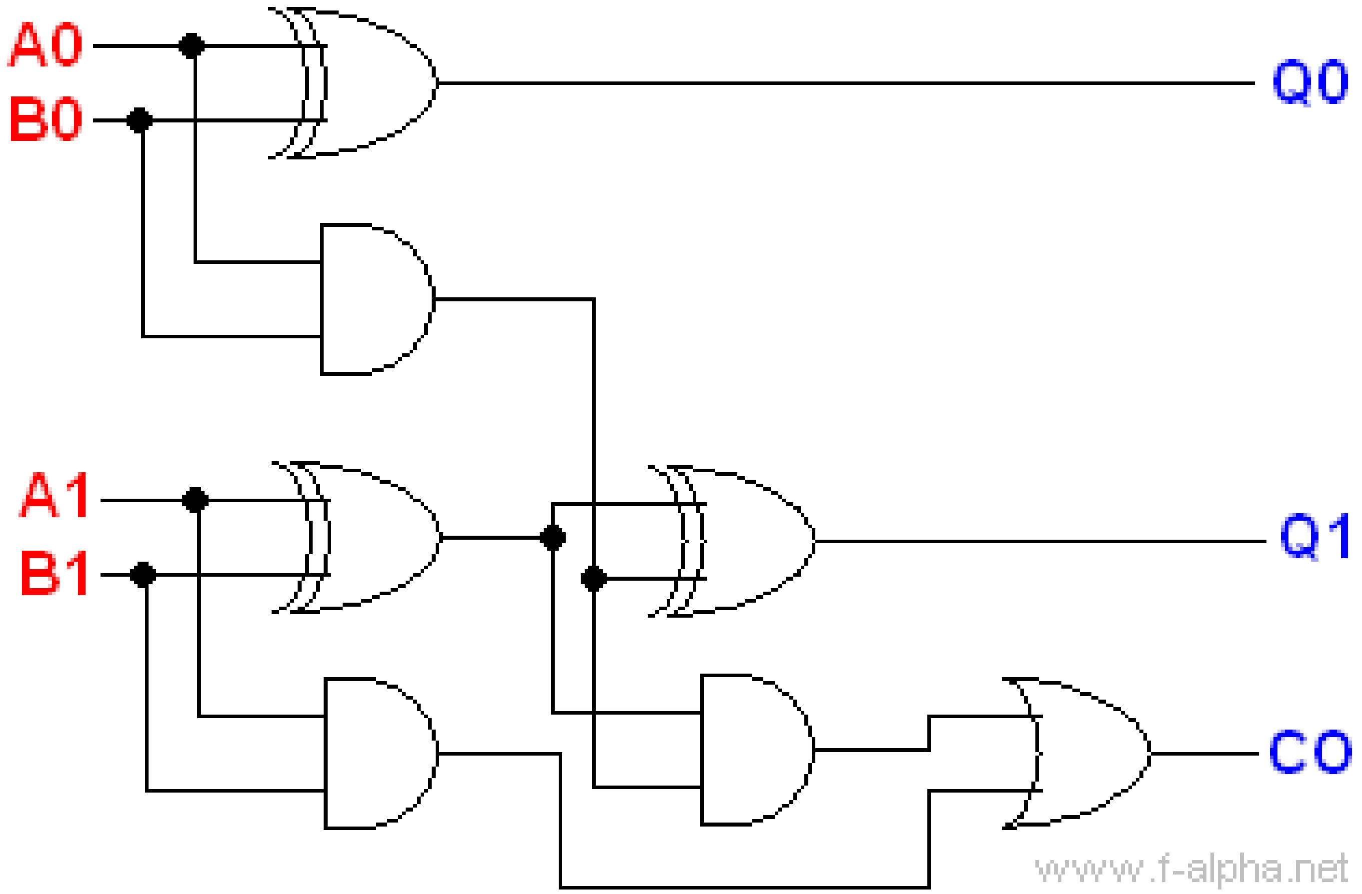
- There are two simple circuits that are provided in the distribution examples folder that we will review in this session
  - Simple Circuits - examples/simple_ckts/*
- Hand assembled circuits that demonstrate capability with minimal run time
  - **adder_2bit** - 4 bit input, three bit output adder with carry
  - **parity** - 8 bit parity generator/checker
- We will next review the process of building the description by hand

adder_2bit circuit

- Start with basic circuit

Q = a + b

CO is carry out



https://i.stack.imgur.com/TpBpr.gif

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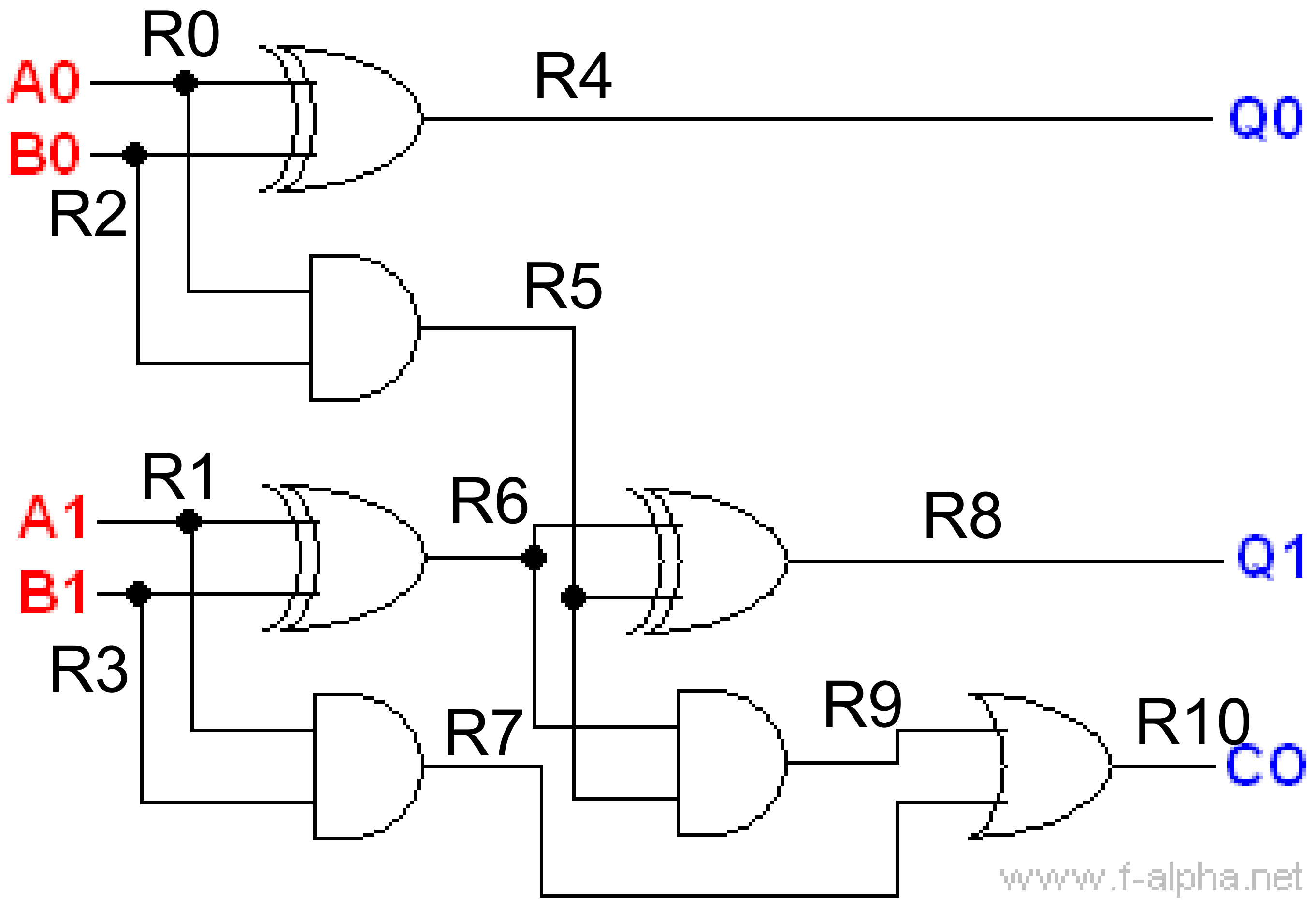
adder_2bit circuit

- Start with basic circuit
- Label nodes
  - Input nodes need to be numbered sequentially
  - Nodes need to be R# starting from zero, but can be any order



https://i.stack.imgur.com/TpBpr.gif

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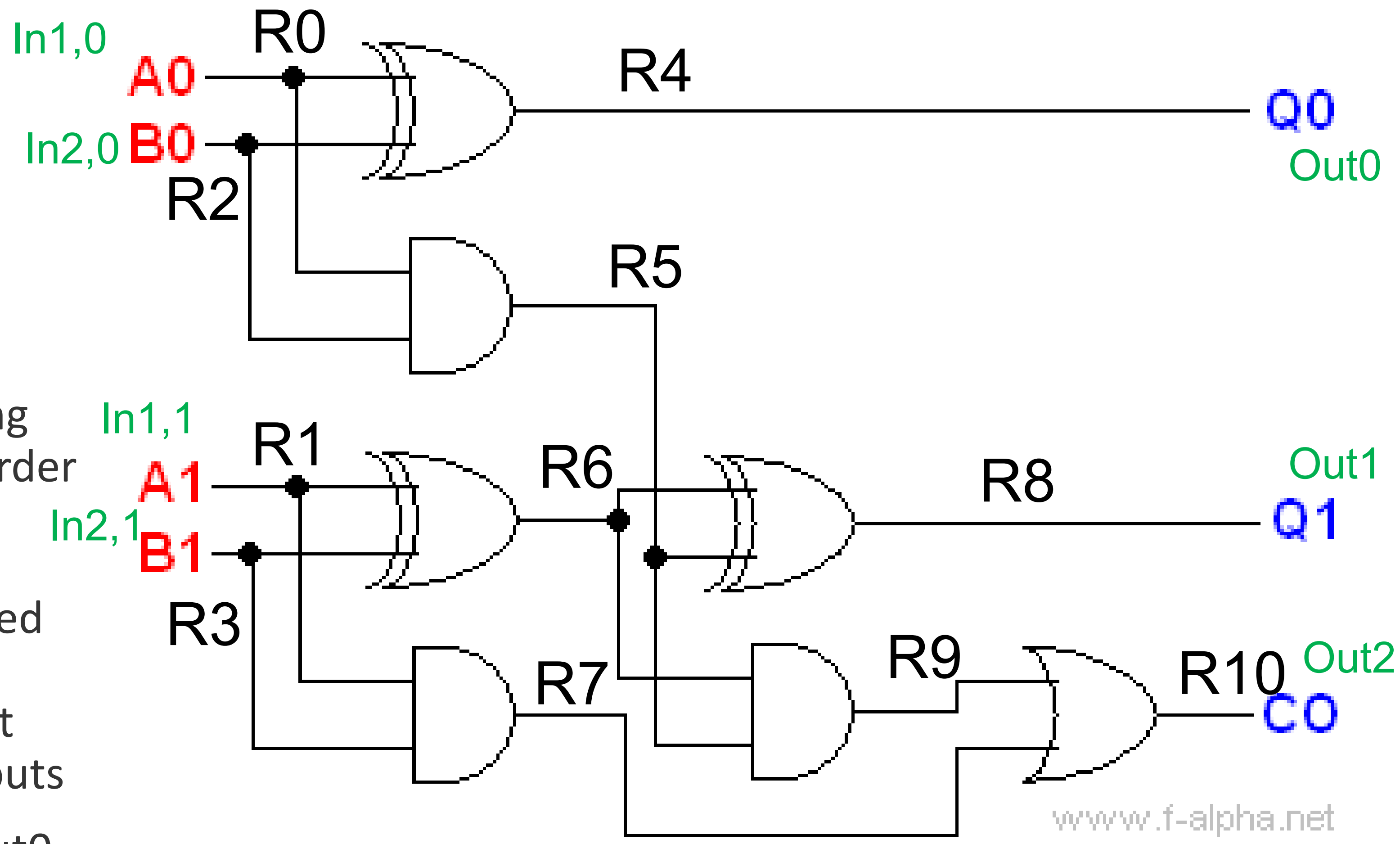
adder_2bit circuit

- Start with basic circuit
- Label nodes
  - Input nodes need to be numbered sequentially
  - Nodes need to be R# starting from zero, but can be any order
- Label Inputs and Outputs
  - Input registers are numbered In1,0 is bit 0 of first input In2,1 is bit 1 of second input there can be one or two inputs
  - Outputs bits are labeled Out0, Out1, etc. -- there is only one output register
- These constraints are based on historical requirements of the Bristol circuit format and will be lifted in future revisions.



https://i.stack.imgur.com/TpBpr.gif

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Resulting adder_2bit assembly code:

```
# number input1 bits 2
# number input2 bits 2
# number output1 bits 3
# Do not edit the top 3 lines!
# 2 bit adder
# Q = a + b
# CO is carry out
#
# inputs:
# In0,0 In0,1 are a0 , b0
# In1,0 In1,1 are a1 , b1
# outputs
# Out0 is Q0, Out1 is Q1, Out2 is CO
```

```
R0 = LOAD(In1,0)
R1 = LOAD(In1,1)
R2 = LOAD(In2,0)
R3 = LOAD(In2,1)

R4 = XOR(R0, R2)
R5 = AND(R0, R2)
Out0 = STORE(R4)

R6 = XOR(R1, R3)
R7 = AND(R1, R3)
R8 = XOR(R5, R6)
Out1 = STORE(R8)

R9 = AND(R5, R6)
R10 = OR(R9, R7)
Out2 = STORE(R10)
```

The first 3 lines need to list the
Number of bits for inputs and outputs
Comment lines have # in column 1

LOAD and STORE are used to
Indicate inputs and outputs into the
Circuit (they trigger encrypt/decrypt)

Use this format, no extra spaces

adder_2bit sample output

- Program name bin/TB_adder_2bit
- Size of input and output registers.
- Number of internal nodes
- Security parameters used
- Test input and correct output
- Plaintext circuit runtime **1 msec**
-

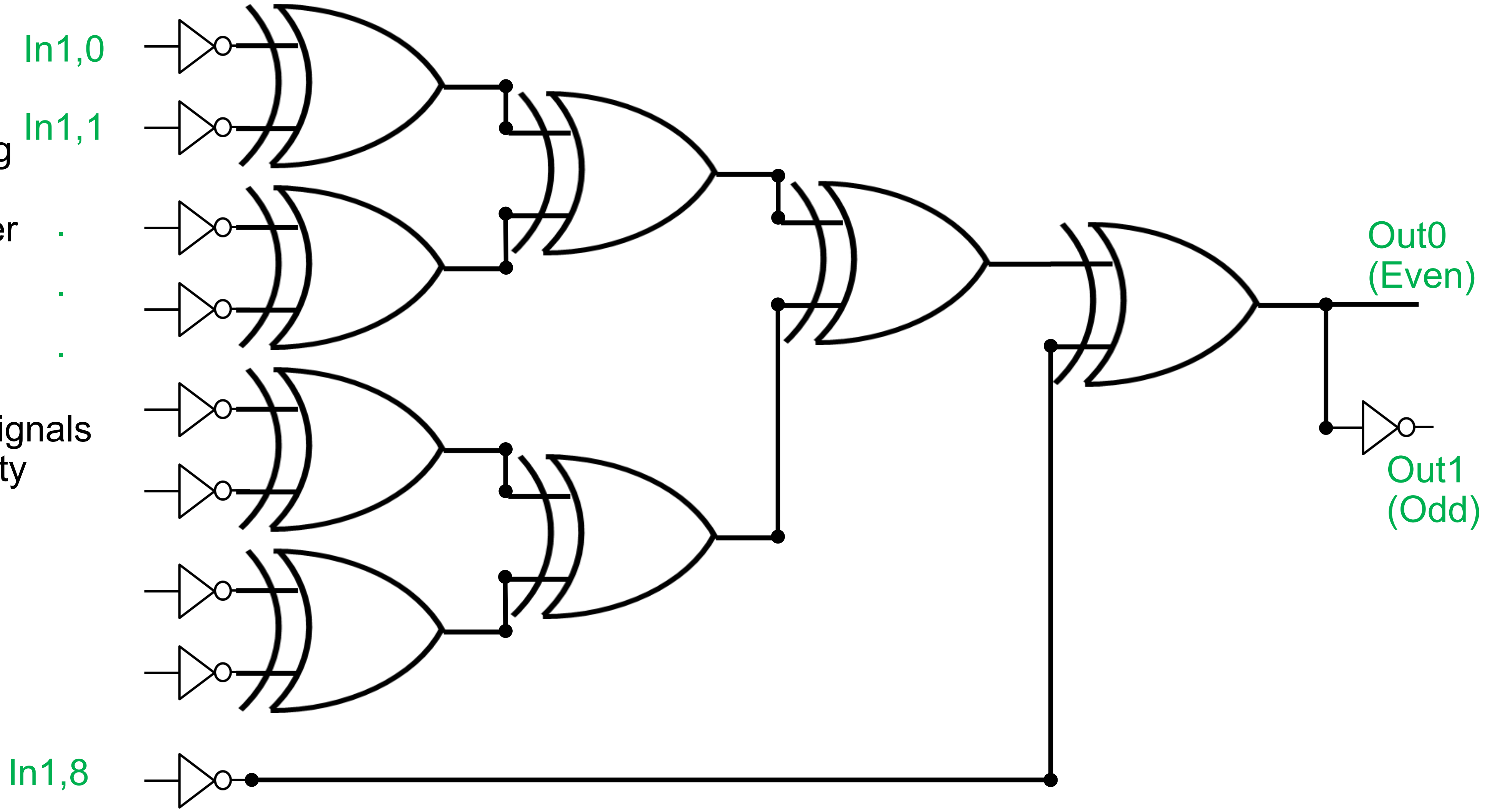
- Circuit size
- Encrypted circuit run time
  2113 msec, Efficiency 99.9053%
- Circuit verified correctly

```
palisade:ECE$ bin/TB_adder_2bit
Test bench for 2bit adder
test_adder: Opening file examples/simple_ckts/adder_2bit/adder_2bit.out for test
_adder parameters
using 2 bits for input 1
using 2 bits for input 2
using 3 bits for output 1
using 10 registers
end of file
Generating crypto context
STD 128 Security used
AP used
Generating crypto keys
Done
Loading circuit description examples/simple_ckts/adder_2bit/adder_2bit.out

generating output nbits 3
circuit out size 1
circuit[0] out size 3
generating netlist
Done
testing 10 iterations
test 0
 input 1:   11
 input 2:   10
 output : 101
executing circuit
Processing: 10 of 10
### Total time 1 msec

efficiency 100%
program done
Number of input gates 4
Number of output gates 3
Number of not gates 0
Number of and gates 3
Number of or gates 1
Number of xor gates 3
output match
executing encrypted circuit
Processing: 10 of 10
### Total time 2113 msec

efficiency 99.9053%
program done
output match
```

Parity generator circuit

8 bits for input
(9th bit can be set to 0 or used for chaining multiple circuits together for wider words)

2 bits output appropriate bit signals even or odd parity



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Parity assembly code: examples/simple_ckts/parity

```
# number input1 bits 9
# number input2 bits 0
# number output1 bits 2
# Do not edit the top 3 lines!
# parity generator/checker 8 bits
# inputs:
# In0,0 .. In0,7 are 8 bits input with
In0,8 as 0 for input (or cascade)
# outputs
# Out0 is even Out1 is odd

R0 = LOAD(In1,0)
R1 = LOAD(In1,1)
R2 = LOAD(In1,2)
R3 = LOAD(In1,3)
R4 = LOAD(In1,4)
R5 = LOAD(In1,5)
R6 = LOAD(In1,6)
R7 = LOAD(In1,7)
R8 = LOAD(In1,8)
```

```
R9 = NOT(R0)
R10 = NOT(R1)
R11 = NOT(R2)
R12 = NOT(R3)
R13 = NOT(R4)
R14 = NOT(R5)
R15 = NOT(R6)
R16 = NOT(R7)
R17 = NOT(R8)

R18 = XOR(R9, R10)
R19 = XOR(R11, R12)

R20 = XOR(R13, R14)
R21 = XOR(R15, R16)

R22 = XOR(R18, R19)
R23 = XOR(R20, R21)

R24 = XOR(R22, R23)

R25 = XOR(R24, R17)
R26 = NOT(R25)

Out0 = STORE(R25)
Out1 = STORE(R26)
```


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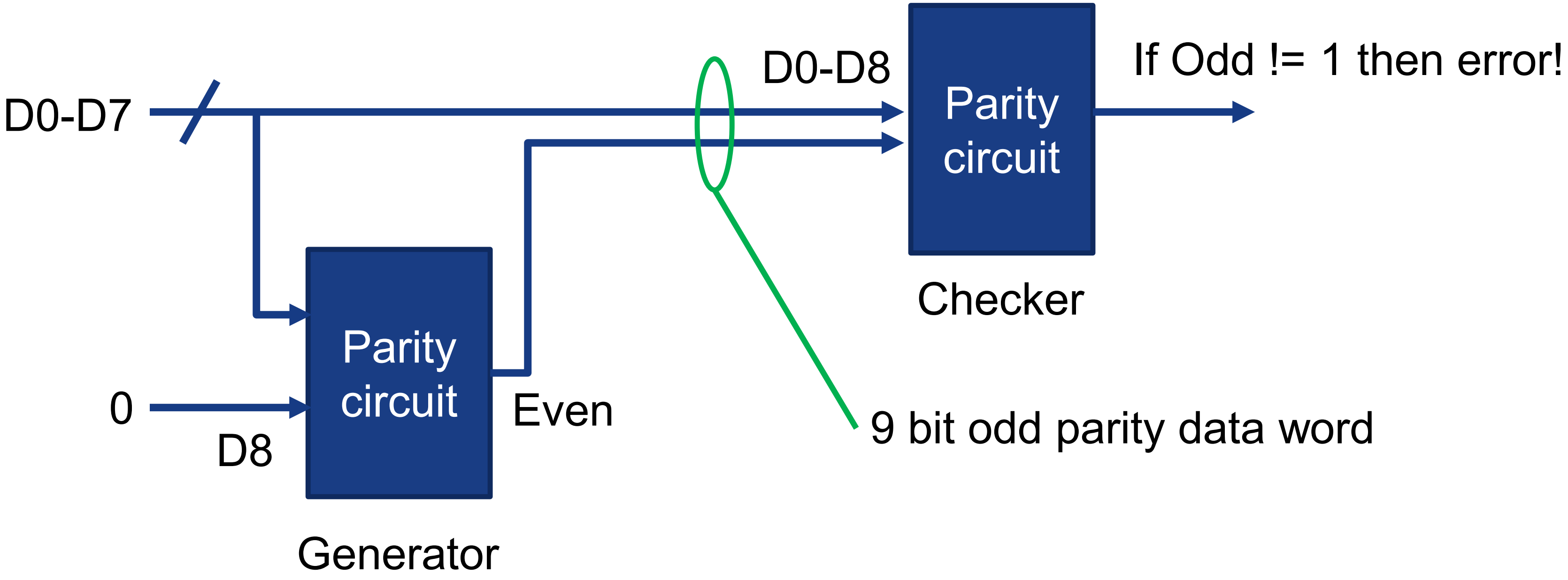
Parity test: examples/simple_ckts/parity

- Test program performs the following operations, using the same circuit as both a parity generator and parity checker. Note all data is encrypted. Decrypting the output determines the parity of the encrypted word.



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Parity sample output

- Program name bin/TB_parity

- Circuit size 10 NOT, 8 XOR
- Encrypted circuit run time

  3648 msec, Efficiency 99.9%
- Circuit verified correctly

```
palisade:ECE$ bin/TB_parity
Test bench for simple parity circuit
test_parity: Opening file examples/simple_ckts/parity/parity.out for test_parity
 parameters
using 9 bits for input 1
using 0 bits for input 2
using 2 bits for output 1
end of file
Generating crypto context
STD 128 Security used
AP used
Generating crypto keys
Done
Loading circuit description examples/simple_ckts/parity/parity.out

generating output nbits 2
circuit out size 1
circuit[0] out size 2
generating netlist
Done
testing 10 iterations
test 0
 input 1:  000111101 = 61

 output : 10 odd
executing circuit
Processing: 20 of 20
### Total time 1 msec

efficiency 100%
program done
Number of input gates 9
Number of output gates 2
Number of not gates 10
Number of and gates 0
Number of or gates 0
Number of xor gates 8
output match
executing encrypted circuit
Processing: 20 of 20
### Total time 3648 msec

efficiency 99.9178%
program done
output match
```

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Additional Complex Circuit Examples

From the PALISADE Encrypted Circuit Emulation repository

Complex Circuit Examples for Further Exploration

Currently the repository has examples taken from https://homes.esat.kuleuven.be/~nsmart/MPC/old-circuits.html

- The arithmetic examples are relatively quick, crypto examples have >10K gates so can take a long time to process and run

Arithmetic					
Function	File	# ANDs	# XORs	# NOTs	# ORs
32-bit Adder	TB_adders	127	61	187	0
64-bit Adder	TB_adders	256	115	379	0
32x32-bit Multiplier	TB_multipliers	5926	1069	5379	0
32-bit comparisons	TB_comparators	150	0	150/162	0
Crypto					
Md5 hash	TB_crypto	29084	14150	34627	0
SHA-256	TB_crypto	90825	42029	103258	0
AES 128 (No Key Expansion)	TB_aes	6800	25124	1692	0
AES 128 (Key Expanded)	TB_aes	5440	20325	1927	0

THANK YOU

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