FHE Transpiler

- By Google

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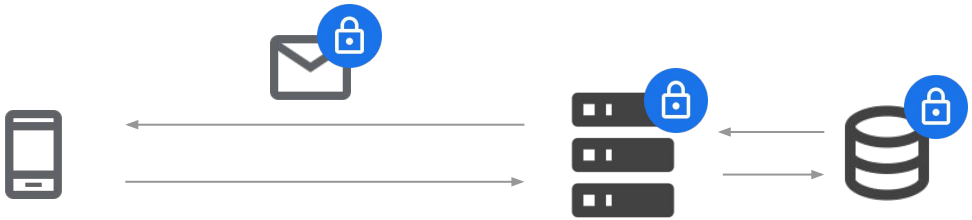
AGENDA

1. FHE
2. FHE Challenges
3. FHE Transpiler building blocks
4. FHE Transpiler architecture
5. Future directions

Fully Homomorphic Encryption (FHE) makes computations on encrypted data possible.

Without FHE



With FHE

Challenges

Ease of Use

Speed

Challenges

Ease of Use

Speed

FHE Programming

Need to abstract away cryptographic details from engineers

Cryptography

Engineering

Reference: SoK: Fully Homomorphic Encryption Compilers, Viand et al

FHE Programming : Cryptographic challenges

01
Parameter selection

02
Noise tracking

03
Bootstrapping

04
Circuit depth analysis

Reference: SoK: Fully Homomorphic Encryption Compilers, Viand et al

FHE Programming : Engineering challenges

01 If / else needs to be written as controlled multiplexer

02 No variable length loops and jumps based on data

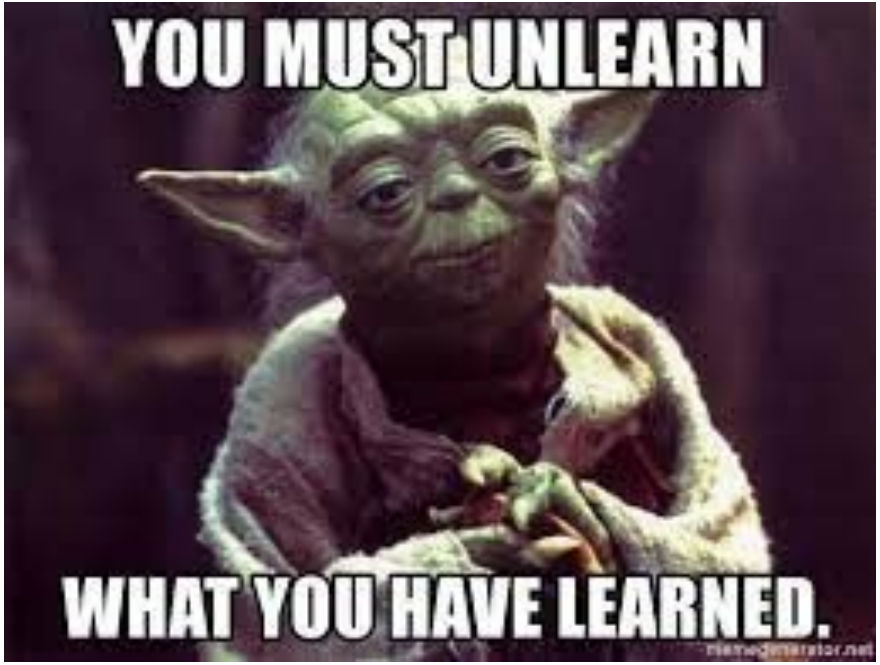
03 No branch and bound optimizations

04 Using the right scheme for the right type of computation

Example: approximate computations don't work for string processing

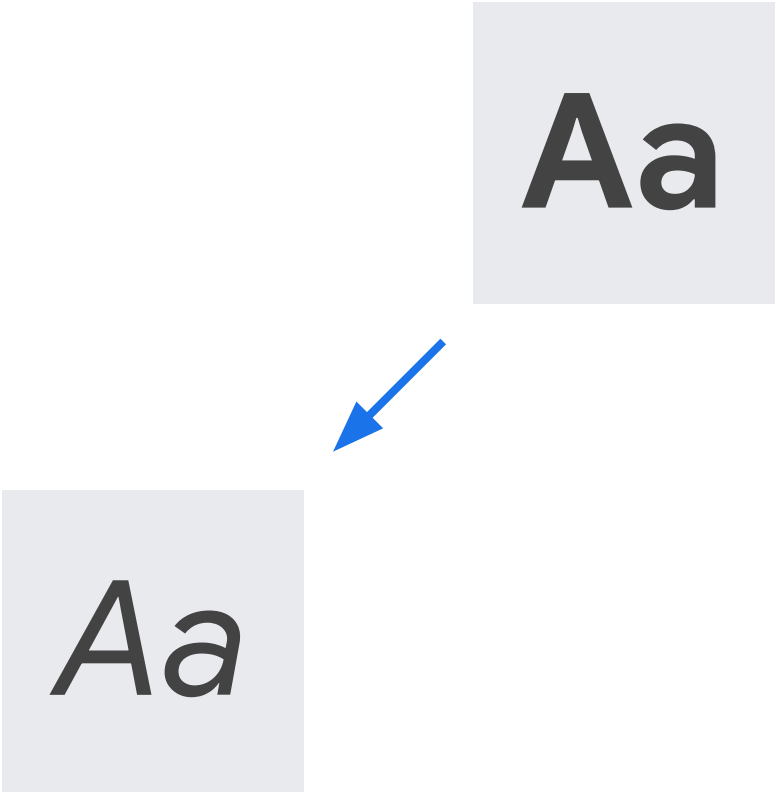
Reference: SoK: Fully Homomorphic Encryption Compilers, Viand et al

Adding FHE to an existing application



FHE transpiler

Allows us to easily convert existing code
that works on plaintext to work on ciphertext.



FHE Transpiler Building Blocks

FHE Schemes

Levelled schemes

BGV, BFV, CKKS

Composable schemes

FHEW, TFHE

General purpose FHE compilers

Cingulata

Armadillo: a compilation chain for privacy preserving applications

- Carpov et al

E3

A Framework for Compiling C++ Programs with Encrypted Operands

- Chielle et al

General purpose FHE compilers

Cingulata

Armadillo: a compilation chain for privacy preserving applications

- Carpov et al

Uses boolean circuit

E3

A Framework for Compiling C++ Programs with Encrypted Operands

- Chielle et al


FHE Programming
Hardware Design

High-Level Synthesis (HLS) Tools

Composable FHE

FHEW

FHEW: Bootstrapping Homomorphic Encryption in Less Than a Second

- Ducas, Micciancio

CGGI/TFHE

Faster fully homomorphic encryption: Bootstrapping in less than 0.1 seconds

- Chilloti et al

TFHE API

```
void bootsNOT(LweSample* result, const LweSample* ca,
              const TFheGateBootstrappingCloudKeySet* bk);
void bootsNAND(LweSample* result, const LweSample* ca, const LweSample* cb,
               const TFheGateBootstrappingCloudKeySet* bk);
void bootsOR(LweSample* result, const LweSample* ca, const LweSample* cb,
             const TFheGateBootstrappingCloudKeySet* bk);
void bootsAND(LweSample* result, const LweSample* ca, const LweSample* cb,
              const TFheGateBootstrappingCloudKeySet* bk);
void bootsXOR(LweSample* result, const LweSample* ca, const LweSample* cb,
              const TFheGateBootstrappingCloudKeySet* bk);
void bootsNOR(LweSample* result, const LweSample* ca, const LweSample* cb,
              const TFheGateBootstrappingCloudKeySet* bk);
void bootsMUX(LweSample* result, const LweSample* a, const LweSample*b,
              const LweSample* c, const TFheGateBootstrappingCloudKeySet* bk);
```

FHE transpiler

Convert any C++ code to work on ciphertext.

```
int sum(int a, int b) {
        return (a + b);
}
```

```
#include <tfhe.h>

void sum(LweSample* result, const LweSample* a, const LweSample* b,
const int nb_bits, const TFheKeySet* bk) {
  LweSample* carry = new_ciphertext(bk->params);
  LweSample* temp = new_ciphertext(bk->params);
  // Initialize the carry to 0
  bootsCONSTANT(&carry, 0, bk);
  // Compute bitwise addition
  for (int i = 0; i < nb_bits; i++) {
    // Compute Sum
    bootsXOR(&temp, &a[i], &b[i], bk);
    bootsXOR(&result[i], &temp, &carry, bk);
    // Compute carry
    bootsAND(&carry, &carry, &temp, bk);
    bootsAND(&temp, &a[i], &b[i], bk);
    bootsOR(&carry, &temp, &carry, bk);
  }
  delete_ciphertext(carry);
  delete_ciphertext(temp);
}
```

FHE Transpiler Architecture

FHE Applications

Client

- Encryption
- Decryption
- Key generation

Server

- Homomorphic evaluation of computational circuit

Transpiler Design

Frontend: Parser

Middle-end: FHE Optimizer

Backend: Execution Engine

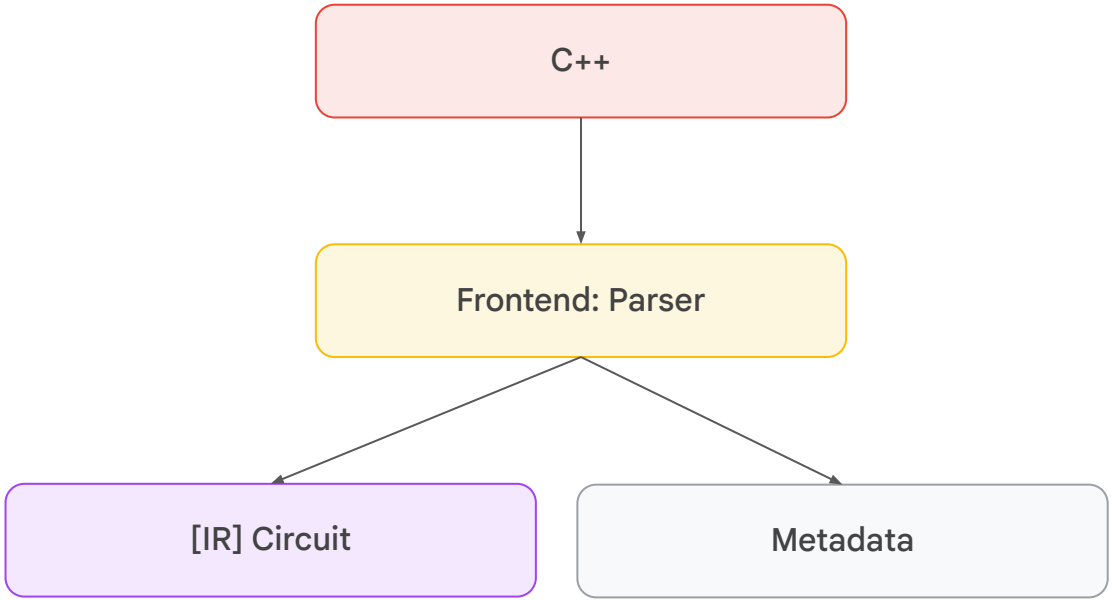
Transpiler Design

Frontend: Parser

Middle-end: FHE Optimizer

Backend: Execution Engine

Transpiler Frontend: Parser



Basic Example: String Capitalization

The following code capitalizes words in a string and is written using standard C++ syntax.

```
#include "string_cap.h"
State::State()
 : last_was_space_(true) {
}

unsigned char State::process(unsigned char c) {
      unsigned char ret = c;

      if(last_was_space_ && (c >= 'a') && (c <= 'z'))
            ret -= ('a' - 'A');

      last_was_space_ = (c == ' ');
      return ret;
}

// Note: Way to mark State::process() as main function
char my_package(State &st, char c) {
      return st.process(c);
}
```

XLS IR

Intermediate representation

```
package my_package
fn _ZN5State7processEh(this: (bits[1]), c: bits[8]) -> (bits[8], (bits[1])) {
 literal.20: bits[8] = literal(value=97, pos=1,10,2)
 literal.31: bits[8] = literal(value=97, pos=1,11,3)
 …
 …
 …
 ret tuple.44: (bits[8], (bits[1])) = tuple(sel.36, tuple.43, pos=1,7,1)
}

fn my_package(st: (bits[1]), c: bits[8]) -> (bits[8], (bits[1])) {
invoke.45: (bits[8], (bits[1])) = invoke(st, c, to_apply=_ZN5State7processEh,
pos=1,19,2)
 tuple_index.46: bits[8] = tuple_index(invoke.45, index=0, pos=1,19,2)
 tuple_index.47: (bits[1]) = tuple_index(invoke.45, index=1, pos=1,19,2)
 ret tuple.48: (bits[8], (bits[1])) = tuple(tuple_index.46, tuple_index.47,
pos=1,18,1)
}
```

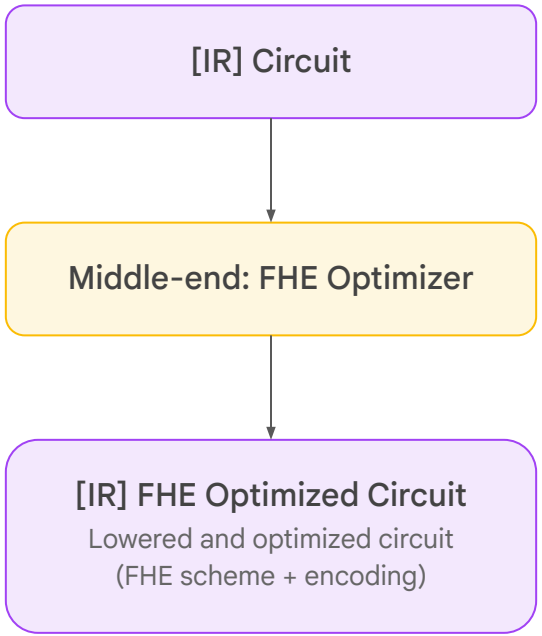
Transpiler Design

Frontend: Parser

Middle-end: FHE Optimizer

Backend: Execution Engine

Transpiler Middle-end: FHE Optimizer



Booleanized XLS IR

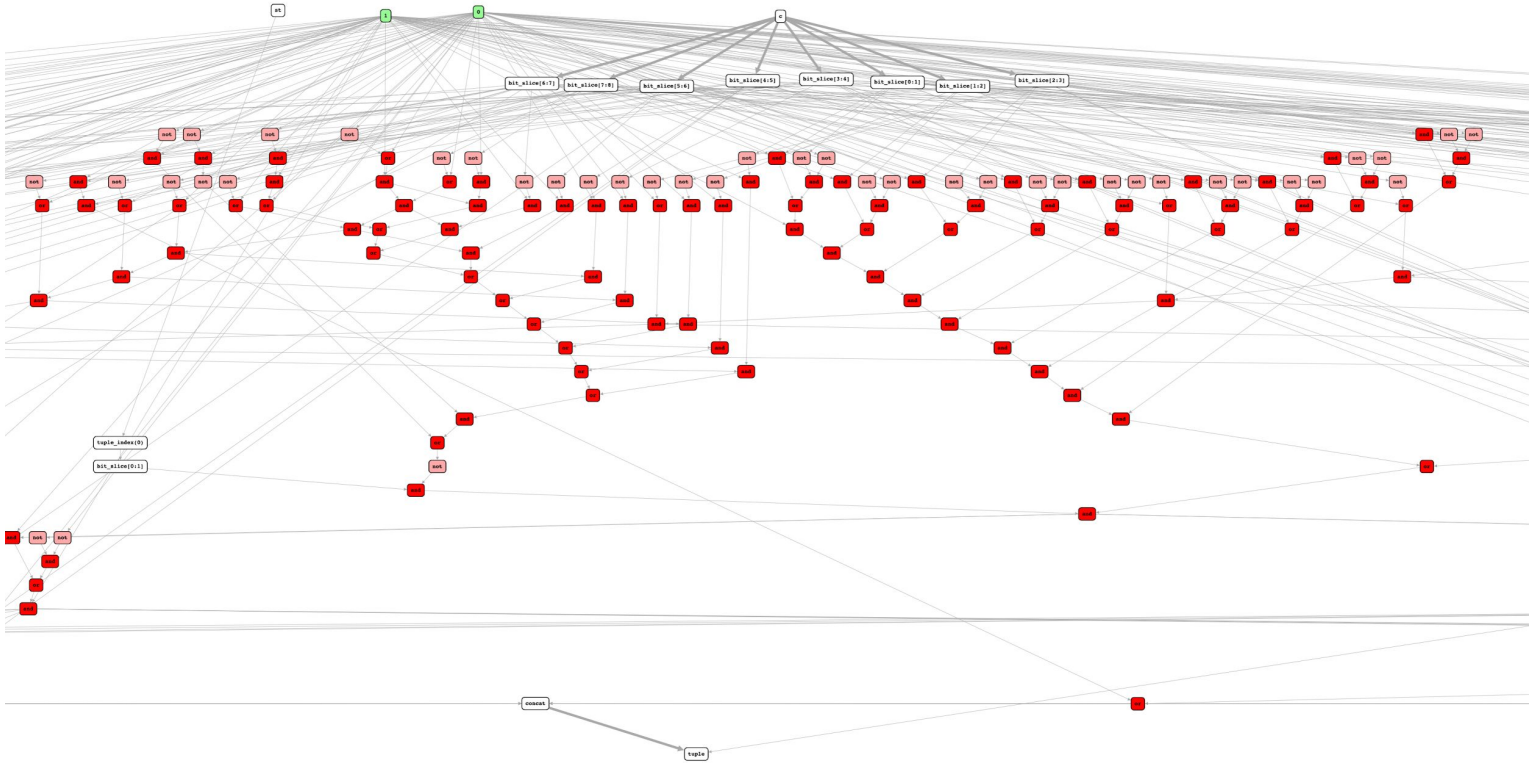
IR after running through the booleanifier.

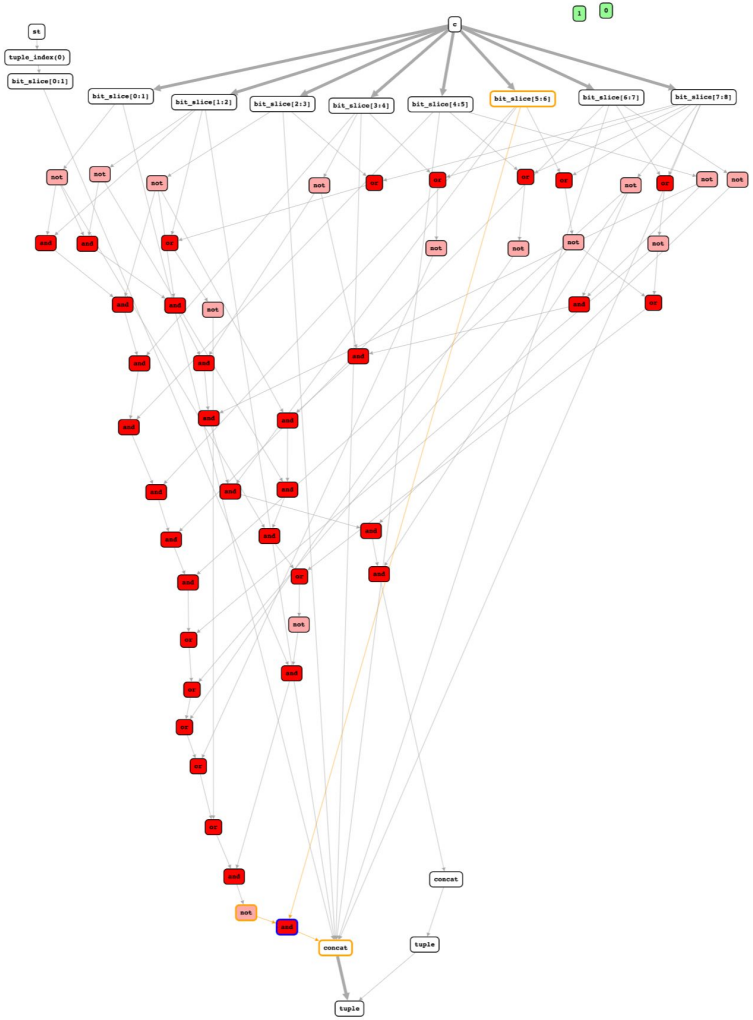
Now it only contains AND, OR, and NOT gates.

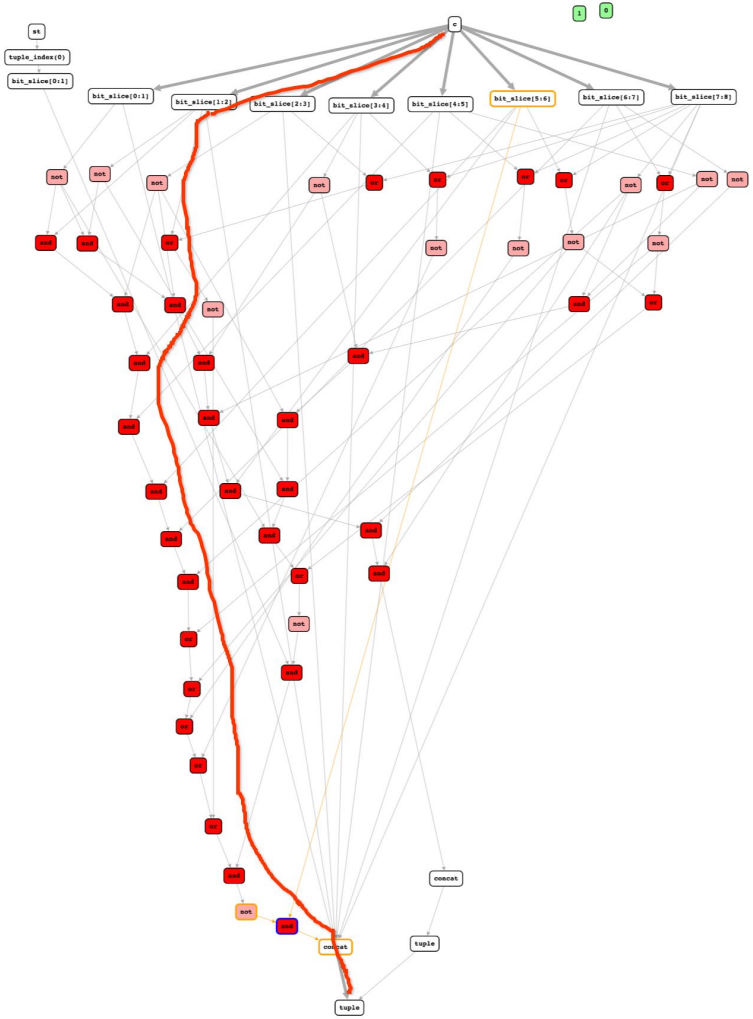
```
Boolean-ized IR:
package p

fn my_package_boolean(st: (bits[1]), c: bits[8]) -> (bits[8], (bits[1])) {
  literal.115: bits[8] = literal(value=1)
  shrl.117: bits[8] = shrl(c, literal.115)
  shrl.119: bits[8] = shrl(shrl.117, literal.115)
  shrl.121: bits[8] = shrl(shrl.119, literal.115)
  shrl.123: bits[8] = shrl(shrl.121, literal.115)
  shrl.125: bits[8] = shrl(shrl.123, literal.115)
  shrl.127: bits[8] = shrl(shrl.125, literal.115)
  ...
  ...
  ...

  shrl.131: bits[8] = shrl(shrl.129, literal.115)
  and.196: bits[1] = and(and.189, or.195)
  and.263: bits[1] = and(and.256, or.262)
  or.346: bits[1] = or(or.345, and.342)
  ret tuple.468: (bits[8], (bits[1])) = tuple(concat.465, tuple.467)
}
```


a1
1
0
c
bit_slice[6:7]
bit_slice[7:8]
bit_slice[5:6]
bit_slice[4:5]
bit_slice[3:4]
bit_slice[0:1]
bit_slice[1:2]
bit_slice[2:3]
tuple_index(0)
bit_slice[0:1]
concat
tuple


st
tuple_index(0)
bit_slice(0:1)
c
1
0
bit_slice(0:1)
bit_slice(1:2)
bit_slice(2:3)
bit_slice(3:4)
bit_slice(4:5)
bit_slice(5:6)
bit_slice(6:7)
bit_slice(7:8)
not
and
or
concat
tuple


st
tuple_index(0)
bit_slice(0:1)
c
1
0
bit_slice(0:1)
bit_slice(1:2)
bit_slice(2:3)
bit_slice(3:4)
bit_slice(4:5)
bit_slice(5:6)
bit_slice(6:7)
bit_slice(7:8)
not
and
or
xor
concat
tuple

JSON Cytoscape graph

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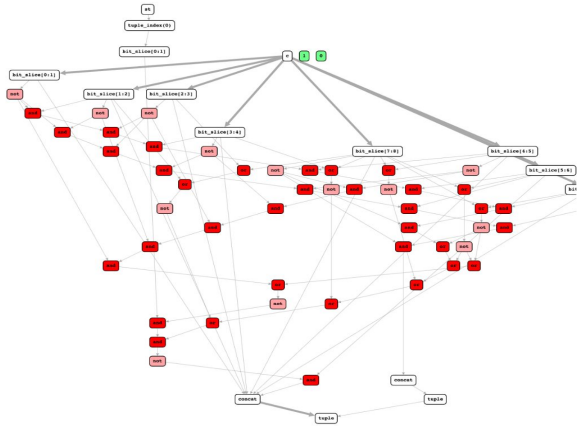
enchmarks... Opt lev Load

```
ckage my_package

 my_package_boolean(st: (bits[1]), c: bits[8]) -> (bits[8], (bits[1]))

  bit_slice.1075: bits[1] = bit_slice(c, start=0, width=1, id=1075)
  not.1088: bits[1] = not(bit_slice.1075, id=1088)
  bit_slice.1076: bits[1] = bit_slice(c, start=1, width=1, id=1076)
  bit_slice.1077: bits[1] = bit_slice(c, start=2, width=1, id=1077)
  and.1102: bits[1] = and(not.1088, bit_slice.1076, id=1102)
  not.1086: bits[1] = not(bit_slice.1077, id=1086)
  and.1103: bits[1] = and(and.1102, not.1086, id=1103)
  bit_slice.1078: bits[1] = bit_slice(c, start=3, width=1, id=1078)
  bit_slice.1082: bits[1] = bit_slice(c, start=7, width=1, id=1082)
  bit_slice.1079: bits[1] = bit_slice(c, start=4, width=1, id=1079)
  and.1104: bits[1] = and(and.1103, bit_slice.1078, id=1104)
  not.1083: bits[1] = not(bit_slice.1082, id=1083)
  not.1084: bits[1] = not(bit_slice.1079, id=1084)
  and.1105: bits[1] = and(and.1104, bit_slice.1079, id=1105)
  bit_slice.1080: bits[1] = bit_slice(c, start=5, width=1, id=1080)
  and.1093: bits[1] = and(not.1083, not.1084, id=1093)
  not.1085: bits[1] = not(bit_slice.1078, id=1085)
  and.1106: bits[1] = and(and.1105, bit_slice.1080, id=1106)
  bit_slice.1081: bits[1] = bit_slice(c, start=6, width=1, id=1081)
  and.1094: bits[1] = and(and.1093, not.1085, id=1094)
  and.1107: bits[1] = and(and.1106, bit_slice.1081, id=1107)
  or.1089: bits[1] = or(bit_slice.1082, bit_slice.1081, id=1089)
  or.1091: bits[1] = or(bit_slice.1082, bit_slice.1080, id=1091)
  and.1095: bits[1] = and(and.1094, not.1086, id=1095)
  not.1087: bits[1] = not(bit_slice.1076, id=1087)
  and.1108: bits[1] = and(and.1107, not.1083, id=1108)
  not.1090: bits[1] = not(or.1089, id=1090)
  not.1092: bits[1] = not(or.1091, id=1092)
  and.1096: bits[1] = and(and.1095, not.1087, id=1096)
  or.1117: bits[1] = or(and.1108, not.1090, id=1117)
  or.1109: bits[1] = or(bit_slice.1082, bit_slice.1079, id=1109)
  and.1127: bits[1] = and(not.1088, not.1087, id=1127)
  or.1100: bits[1] = or(not.1090, not.1092, id=1100)
  and.1097: bits[1] = and(and.1096, not.1088, id=1097)
  or.1118: bits[1] = or(or.1117, not.1092, id=1118)
  not.1110: bits[1] = not(or.1109, id=1110)
  or.1111: bits[1] = or(bit_slice.1082, bit_slice.1078, id=1111)
  or.1113: bits[1] = or(bit_slice.1082, bit_slice.1077, id=1113)
  and.1128: bits[1] = and(and.1127, not.1086, id=1128)
```

OK



ew Graph Critical Path Show only selected nodes

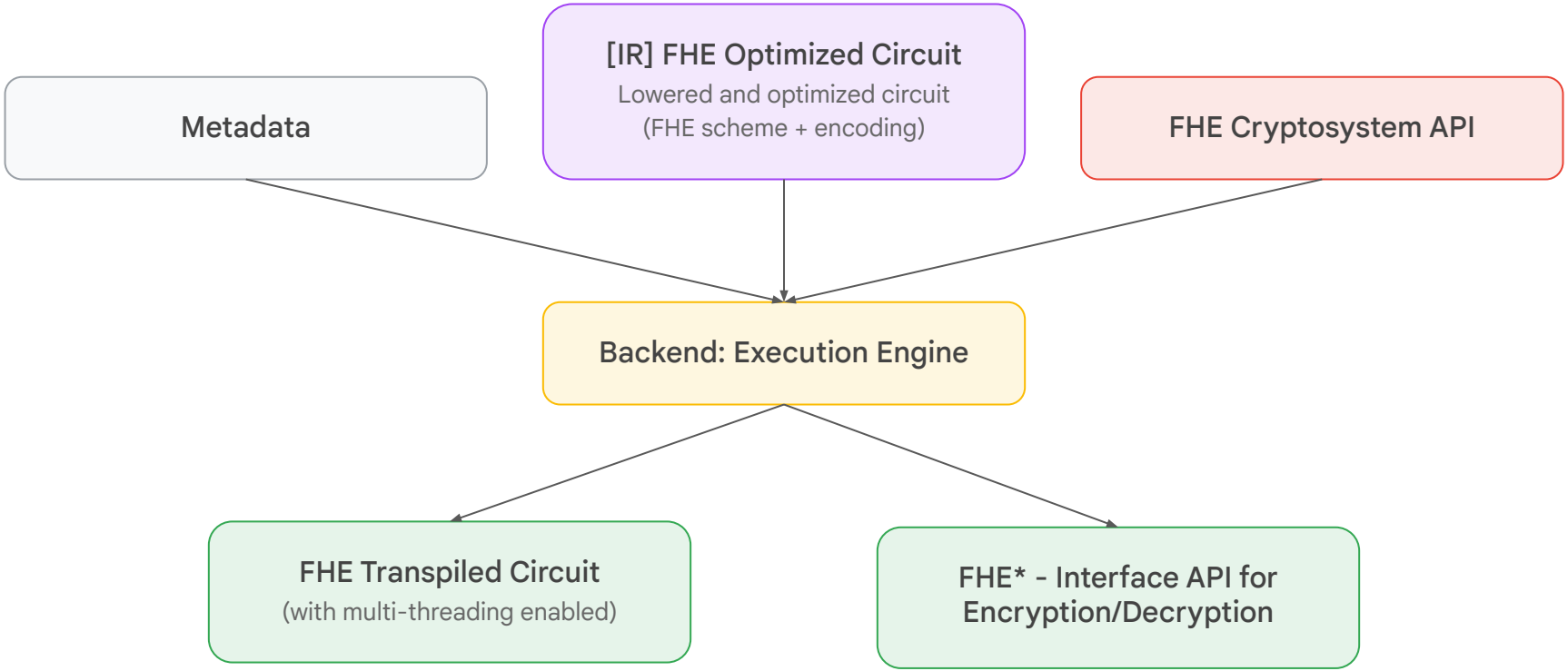
Transpiler Design

Frontend: Parser

Middle-end: FHE Optimizer

Backend: Execution Engine

Transpiler Backend: Execution Engine



```
plaintext(28):do or do not there is no try
Encryption done
Sanity check by decryption:
do or do not there is no try
```

```
Server side computation:
char 0 done.
char 1 done.
char 2 done.
char 3 done.
char 4 done.
char 5 done.
char 6 done.
char 7 done.
char 8 done.
char 9 done.
char 10 done.
char 11 done.
char 12 done.
char 13 done.
char 14 done.
char 15 done.
char 16 done.
char 17 done.
char 18 done.
char 19 done.
char 20 done.
char 21 done.
char 22 done.
char 23 done.
char 24 done.
char 25 done.
char 26 done.
char 27 done.
Total time : 28 secs
Computation done
```

```
Decrypted result: Do Or Do Not There Is No Try
Decryption done
```

```
plaintext(28):do or do not there is no try
Encryption done
Sanity check by decryption:
do or do not there is no try
                                        Server side computation:
                                        char 0 done.
                                        char 1 done.
                                        char 2 done.
                                        char 3 done.
                                        char 4 done.
                                        char 5 done.
                                        char 6 done.
                                        char 7 done.
                                        char 8 done.
                                        char 9 done.
                                        char 10 done.
                                        char 11 done.
                                        char 12 done.
                                        char 13 done.
                                        char 14 done.
                                        char 15 done.
                                        char 16 done.
                                        char 17 done.
                                        char 18 done.
                                        char 19 done.
                                        char 20 done.
                                        char 21 done.
                                        char 22 done.
                                        char 23 done.
                                        char 24 done.
                                        char 25 done.
                                        char 26 done.
                                        char 27 done.
                                        Total time : 28 secs
                                        Computation done
Decrypted result: Do Or Do Not There Is No Try
Decryption done
```

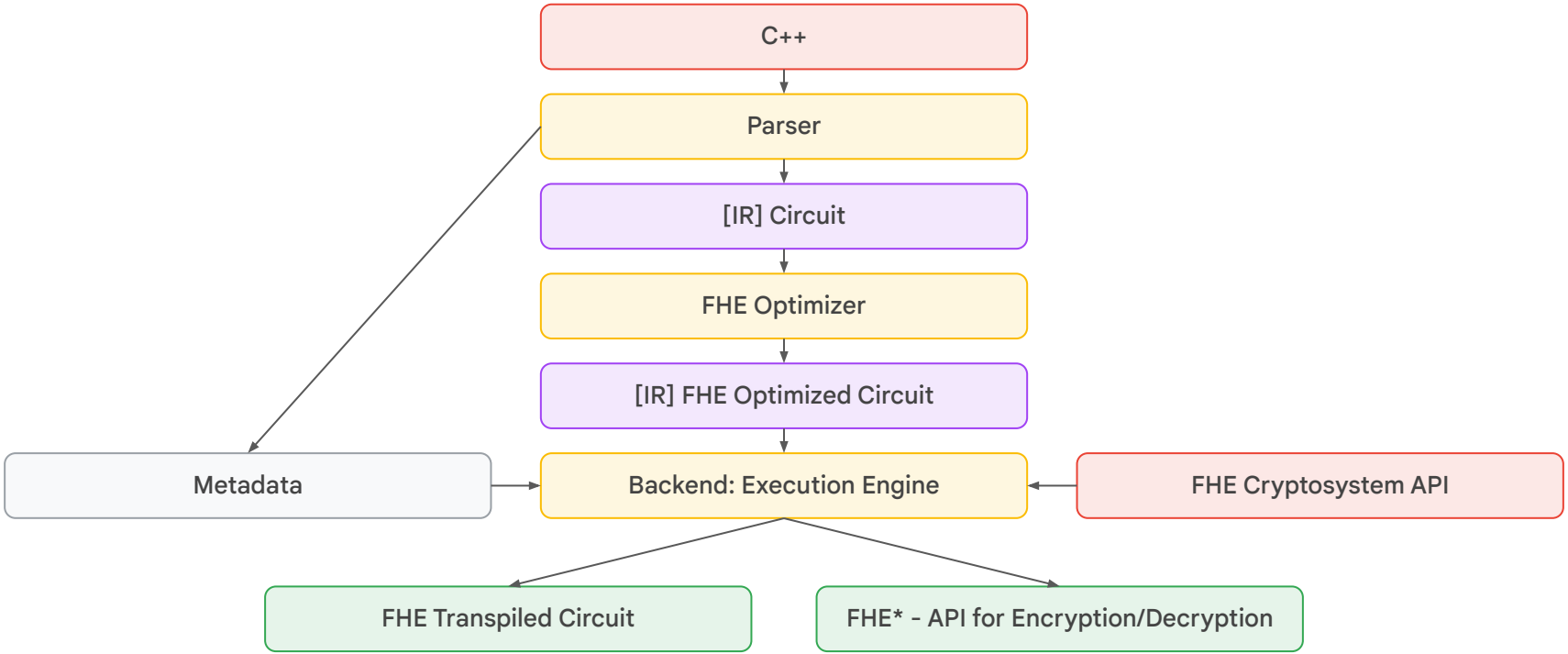
Execution engine: Multi-threaded Interpreter

```
plaintext size: 32
plaintext: 'do or do not there is no try'
Encryption done
Initial state check by decryption:
do or do not there is no try


                                        Server side computation:
Starting!

                                        Total time: 0.756137 secs
                                          CPU time: 46.4172 secs
                                        Computation done
Decrypted result: Do Or Do Not There Is No Try
Decryption done
```

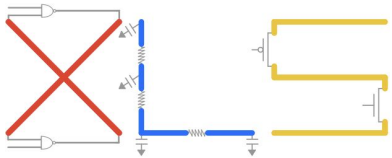
Transpiler: Putting it all together



Modular architecture

FHE cryptosystems

Optimizers



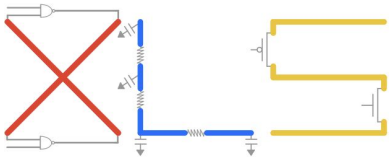
XLS: Accelerated HW Synthesis

Modular architecture

Present

FHE cryptosystems

Optimizers



XLS: Accelerated HW Synthesis

Yosys: Yosys Open SYnthesis Suite

Modular architecture

Future

FHE cryptosystems

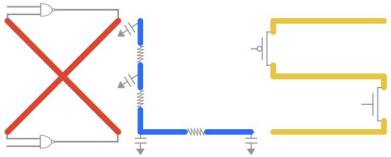
TFHE

OpenFHE

ZAMA
Concrete

CuFHE

Optimizers



XLS: Accelerated HW Synthesis

Yosys: Yosys Open SYnthesis Suite

Future Directions

Hardware

ZAMA
Concrete

CuFHE

GPU

Intel
HEXL

Future Directions

Supporting Arithmetic Programs

Parser

Tensorflow

FHE Optimizer : Ciphertext maintenance

Rescaling, Relinearization, Bootstrapping

Intermediate representations

MLIR, EVA-IR

Levelled schemes

BGV, BFV, CKKS

Framework for Benchmarks

Applications

FHE libraries

Hardware

Optimizers

Get involved

google/fully-homomorphic-encryption

fhe-team@google.com