Google | Privacy, Safety & Security

Unlocking the potential of Fully Homomorphic Encryption

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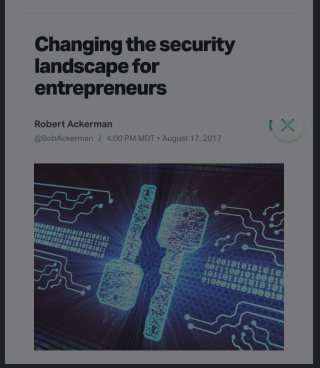
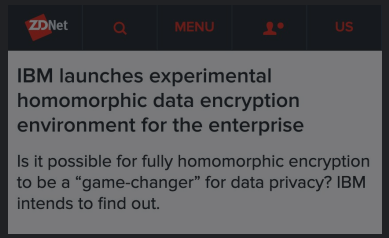
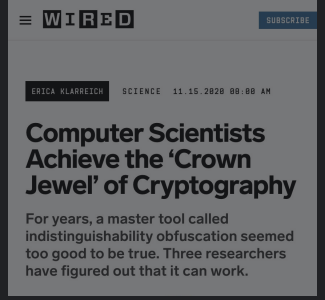
October 30, 2023

Agenda

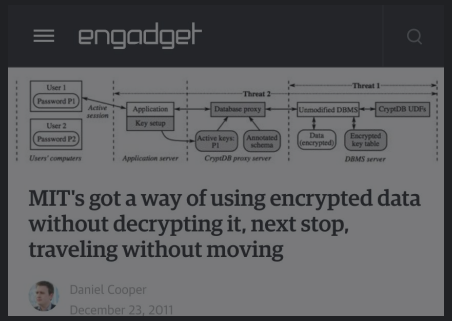
1. What is FHE
2. Brief history of FHE
3. FHE Transpiler
4. HEIR - Foundation for FHE Compilers
5. Questions



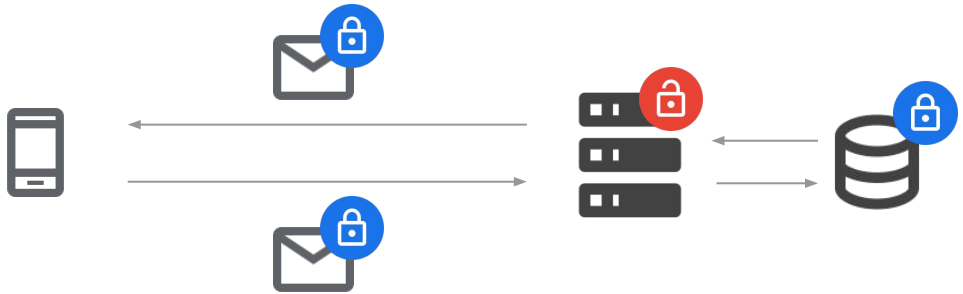




Fully Homomorphic Encryption (FHE) makes computations on encrypted data possible.

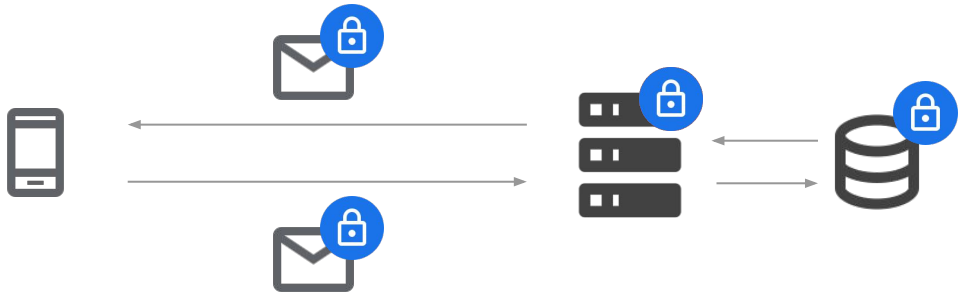


Privacy At Compute-time



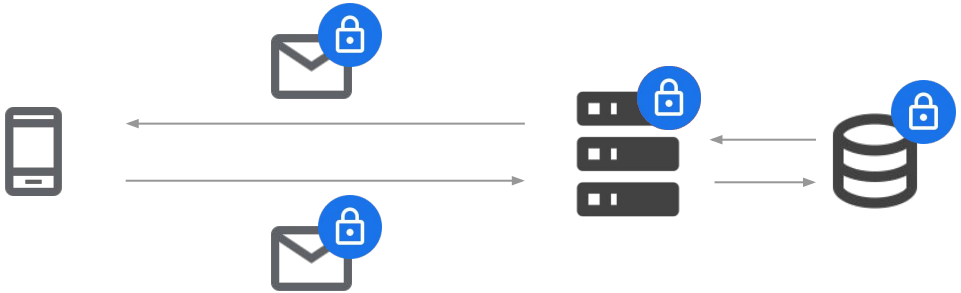
Without FHE

Privacy At Compute-time



With FHE

Privacy At Compute-time



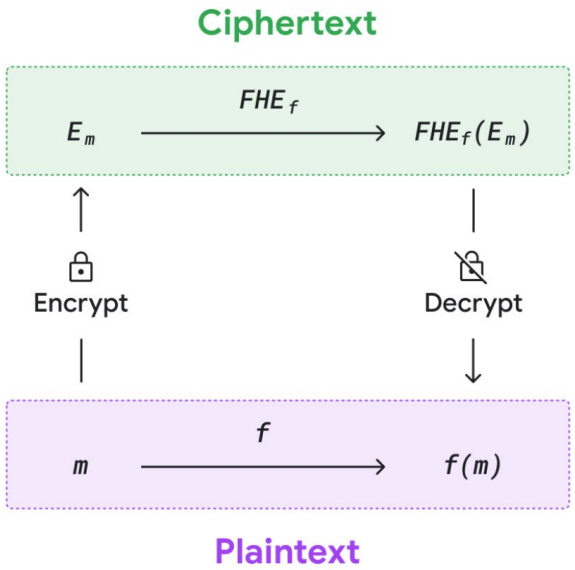
With FHE

Insider risk

Policy compliance

Data minimization

What is Fully Homomorphic Encryption

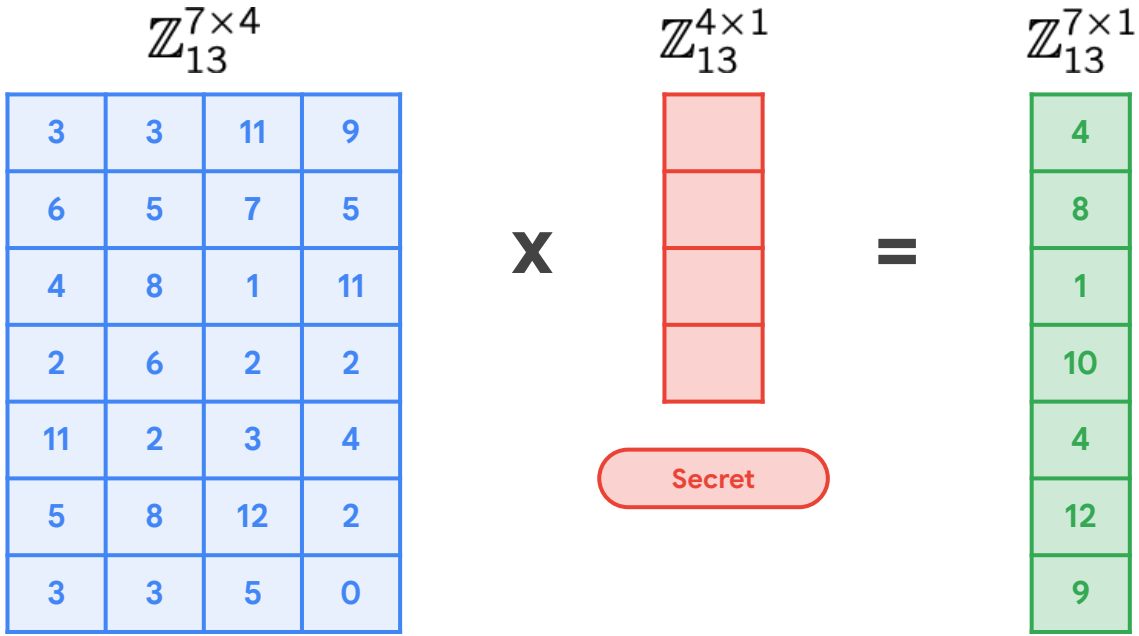


Problem

Learning with Errors (LWE)

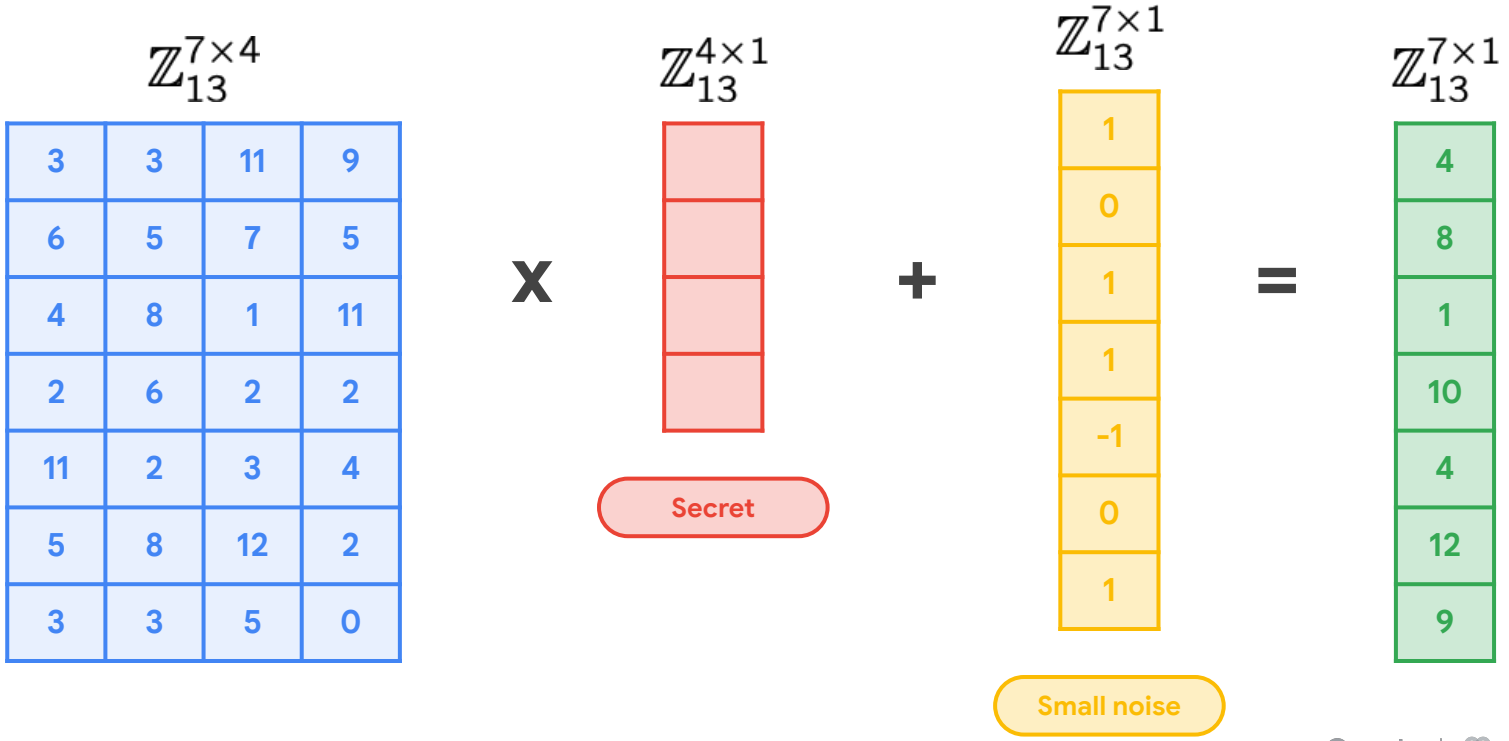
Solving systems of linear equations

Linear system problem: given blue and green, find red

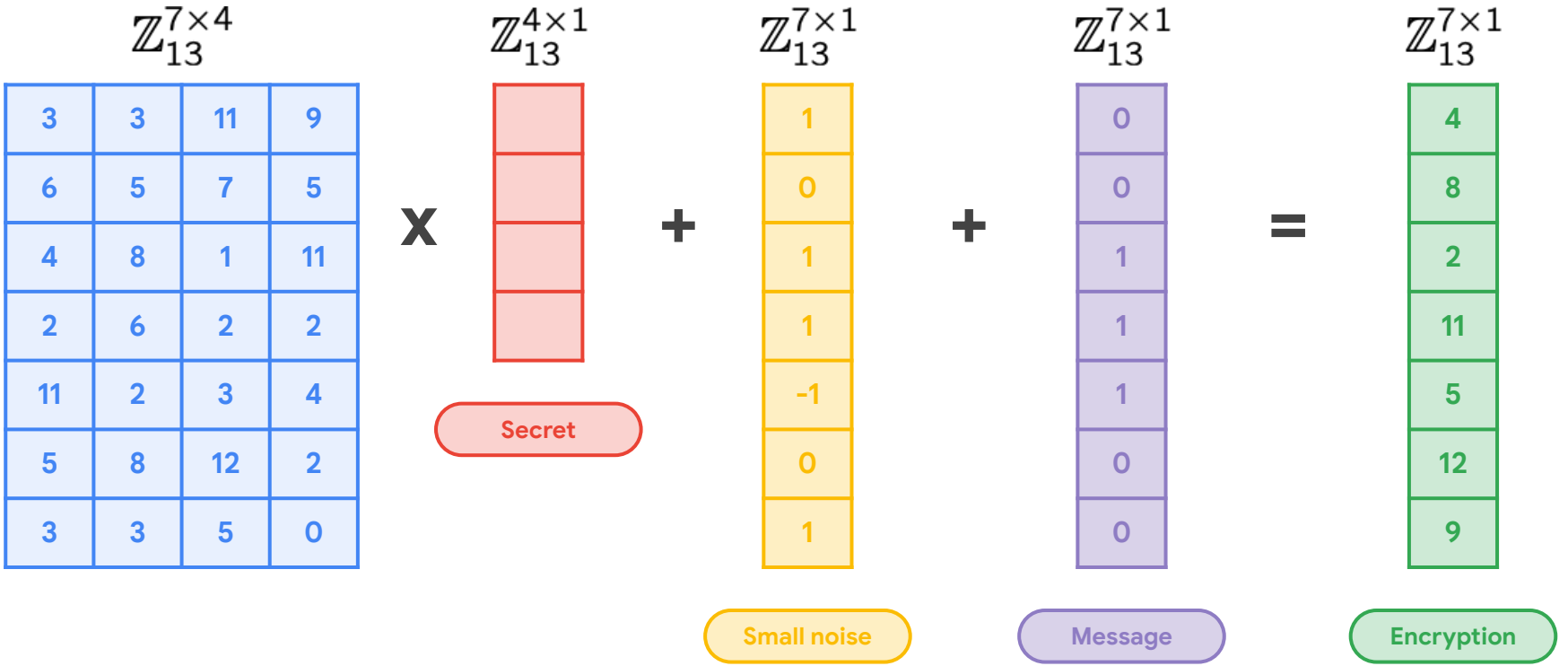


Learning with Errors (LWE) problem

(Search) LWE problem: given blue and green, find red (or yellow)



Encrypting with LWE



Encrypting with LWE

Toy world

$\mathbb{Z}_{13}^{7\times 4}$

4	1	11	10
5	5	9	5
3	9	0	10
1	3	3	2
12	7	3	4
6	5	11	4
3	3	5	0

Real world

$\mathbb{Z}_{2^{15}}^{2430\times 750}$

3673	12393	11334	...
5484	599	9200	...
13455	9830	0	...
19321	3948	383	...
...	...	...	...
...	...	...	...

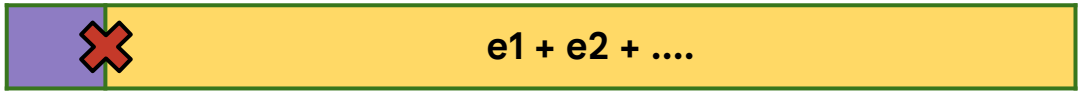
Rule of thumb (bit encryption): dimension more than 750, modulus 16+ bits.
Rule of thumb (homomorphic encryption): dimension >2000, modulus >60 bits.

FHE Computations and Noise

Decryption fails if error grows too large

Noise Management

Problem: Decryption fails if error grows too large



Solution: Choose **large parameters** to fit the entire computation

Solution : Track noise and perform **ciphertext-refresh operations**

Challenges

Usability

Speed

FHE Programming

Need to abstract away cryptographic details from engineers

Cryptography

Engineering

FHE Programming : Cryptographic challenges

01
Circuit depth analysis

02
Noise tracking

03
Bootstrapping

04
Parameter selection

FHE Programming challenges

01 No if/else (well.. sort of)

```
if (condition) {
  return a;
} else {
  return b;
}
```

```
return
      condition.a +
      (1-condition).b;
```

FHE Programming : Engineering challenges

01 No if/else (well.. sort of)

02 Loops need static upper bounds

03 No branch and bound optimizations

04 Using the right FHE scheme for the right type of computation.

2. FHE - A Brief History

FHE over the years

FHE is possible

30 mins for a single MUL

(Craig Gentry's Thesis)

1978 — **2009**

FHE over the years : Ring LWE

FHE is possible

30 mins for a single MUL

1978 — **2009** — 2016

FHE over the years : FHE Schemes

1978 — **2009** — 2016

FHE is possible

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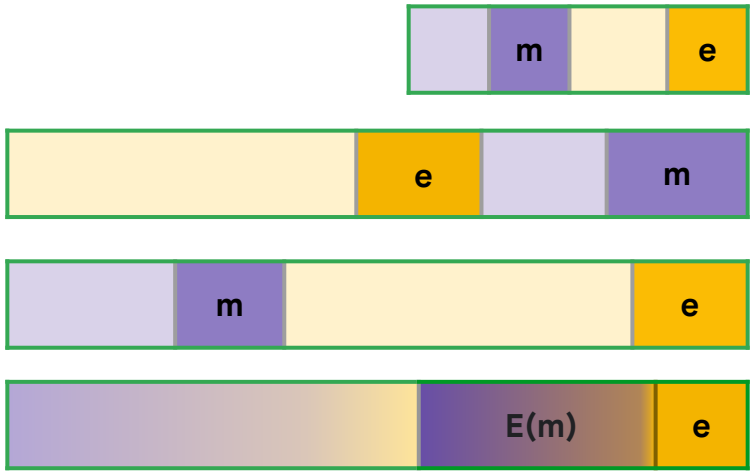


TFHE / DM / CGGI / FHEW
Gates and LUT

BGV
Integer Arithmetic

BFV
Integer Arithmetic

CKKS
Approx fixed point arithmetic

FHE over the years

1978

2009

FHE is possible

30 mins for a single MUL

2016

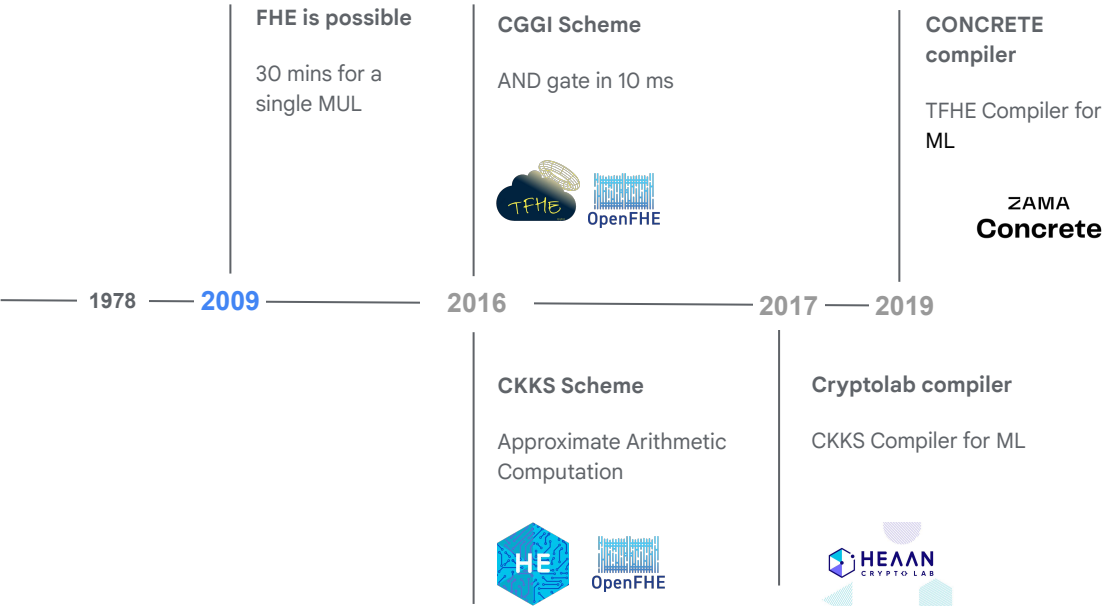
CGGI Scheme

AND gate in 10 ms

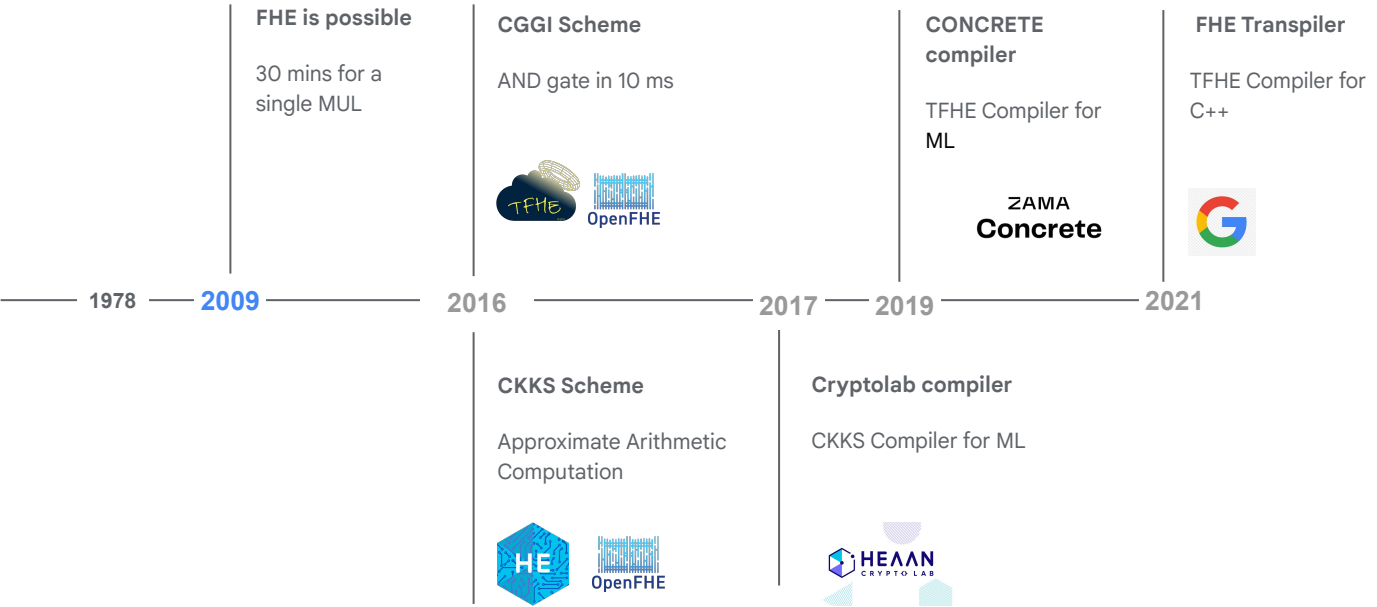
CKKS Scheme

Approximate Arithmetic Computation

FHE over the years



FHE over the years



FHE over the years

1978

2009 — **FHE is possible**

30 mins for a single MUL

2016 — **CGGI Scheme**

AND gate in 10 ms

2017 — **CKKS Scheme**

Approximate Arithmetic Computation

2019 — **CONCRETE compiler**

TFHE Compiler for ML

ZAMA
Concrete

Cryptolab compiler

CKKS Compiler for ML

2021 — **FHE Transpiler**

TFHE Compiler for C++

Video processing

2023 — **Hardware Accelerators**

FPT: Gates in 0.03 ms (FPGA)

Jaxite: FHE on CPU/GPU/TPU

HEIR

Foundation for FHE Compilers

FHE over the years

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Hardware Accelerators

FPT: Gates in 0.03 ms (FPGA)

COSIC

Jaxite: FHE on CPU/GPU/TPU

Claim: 10000x speedup (Photonics)

Optalysys

2025 and beyond

Hardware Accelerators

Claim: 10000x speedup (ASIC)

galois | Duality intel

MIT Massachusetts Institute of Technology SRI International

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SRI International

3. FHE Transpiler

github.com/google/fully-homomorphic-encryption

FHE transpiler

Convert C++ code that works on plaintext to work on ciphertext.

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

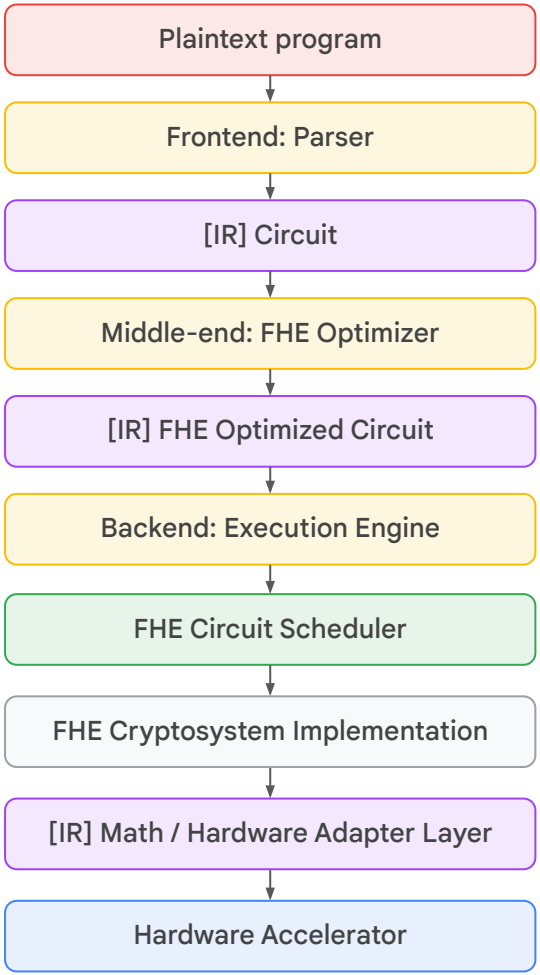
```
#include <tfhe.h>

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

FHE C++ Compilation

Modular
Interoperable
Reusable



Plaintext Program

String Capitalization

```
#include "string_cap.h"

#pragma hls_top
void CapitalizeString(char my_string[MAX_LENGTH]) {
 bool last_was_space = true;
#pragma hls_unroll yes
 for (int i = 0; i < MAX_LENGTH; i++) {
   char c = my_string[i];
   if (last_was_space && c >= 'a' && c <= 'z') {
     my_string[i] = c - ('a' - 'A');
   }
   last_was_space = (c == ' ');
 }
}
```

Parser : Data Independent Programming

XLScc : High Level Synthesis applied to FHE

01

No if/else

(well... sort of)

02

Loops need static upper bounds

03

No branch and bound optimizations

```
if (condition) {
  return a;
} else {
  return b;
}
```

```
return
      condition.a +
      (1-condition).b;
```

Circuit : XLS IR

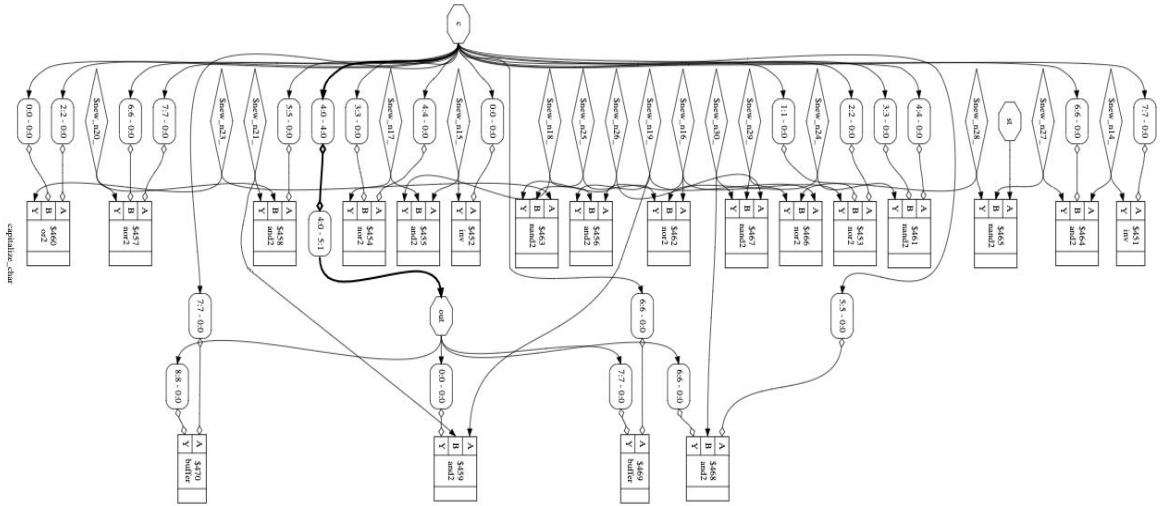
Intermediate Representations - Modularity & Interoperability

```
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)
}
```

FHE Optimizer : Netlist IR

Yosys ABC optimizations: reduces circuit size by 40 - 80%



Execution Engine : Transpiler Codegen

Server : Scheduler

```
#include <tfhe/tfhe.h>
#include <tfhe/tfhe_io.h>
#include <unordered_map>

void my_package_boolean(LweSample* result, LweSample* st, LweSample* c,
                        const TFheGateBootstrappingCloudKeySet* bk) {
  std::unordered_map<int, LweSample*> temp_nodes;

  temp_nodes[115] = new_gate_bootstrapping_ciphertext(bk->params);
  bootsCONSTANT(temp_nodes[115], 1, bk);
  ...
  bootsAND(&temp_nodes[4], temp_nodes[461], temp_nodes[256], bk);
  ...
  bootsCOPY(&result[4], temp_nodes[461], bk);
  bootsCOPY(&result[5], temp_nodes[462], bk);
  for (auto it = temp_nodes.begin(); it != temp_nodes.end(); ++it) {
    delete_gate_bootstrapping_ciphertext(it->second);
  }
}
```

Execution Engine : Transpiler Codegen

Client: Encryption/Decryption API

```
#include <tfhe/tfhe.h>
#include <tfhe/tfhe_io.h>
#include <unordered_map>

absl::Status SumSimpleStruct_SCHEDULER(absl::Span<LweSample> result,
       absl::Span<const LweSample> value,
       const TFheGateBootstrappingCloudKeySet* bk);

absl::Status SumSimpleStruct(TfheRef<signed int> result
       const TfheRef<SimpleStruct> value,
       const TFheGateBootstrappingCloudKeySet* bk) {
  return SumSimpleStruct_SCHEDULER(result.get(), value.get(), bk);
}
```

```
#include <tfhe_simple_struct>

Tfhe<SimpleStruct> fhe_simple_struct(SimpleStruct(2, 3, 4));
fhe_simple_struct.SetEncrypted(simple_struct, key);
```

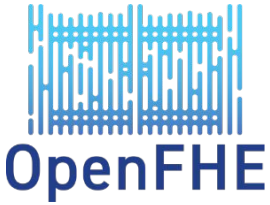
Circuit Schedulers

Computer Architecture & Distributed Systems

- Simple Single Threaded Scheduler
- Multi-core CPU: Multi threaded Scheduler
- GPU: SIMD Scheduler
- TPU: SPMD Scheduler
- Fleet: Distributed Scheduler?

FHE Library

Cryptosystem Library Implementation

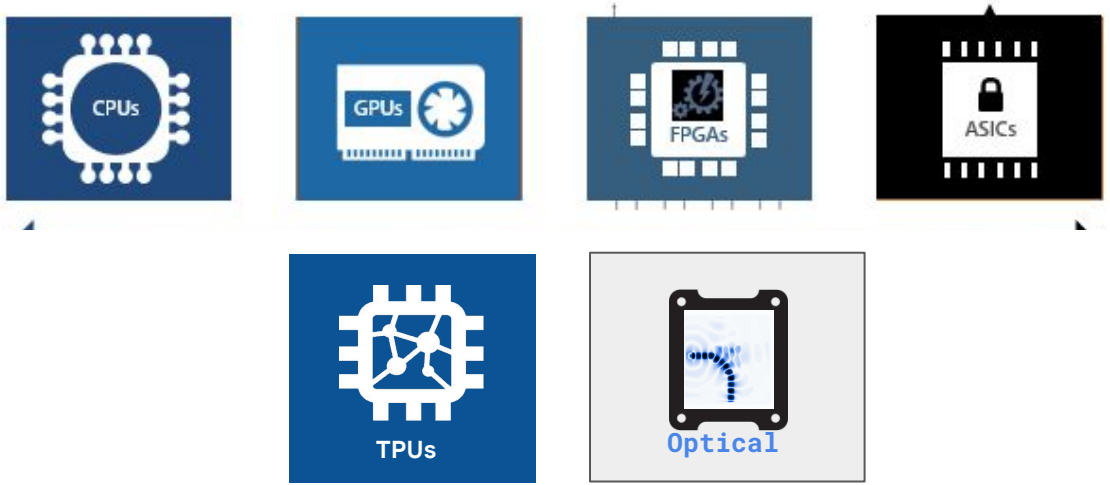


ZAMA
Concrete

Micro Instruction Scheduler

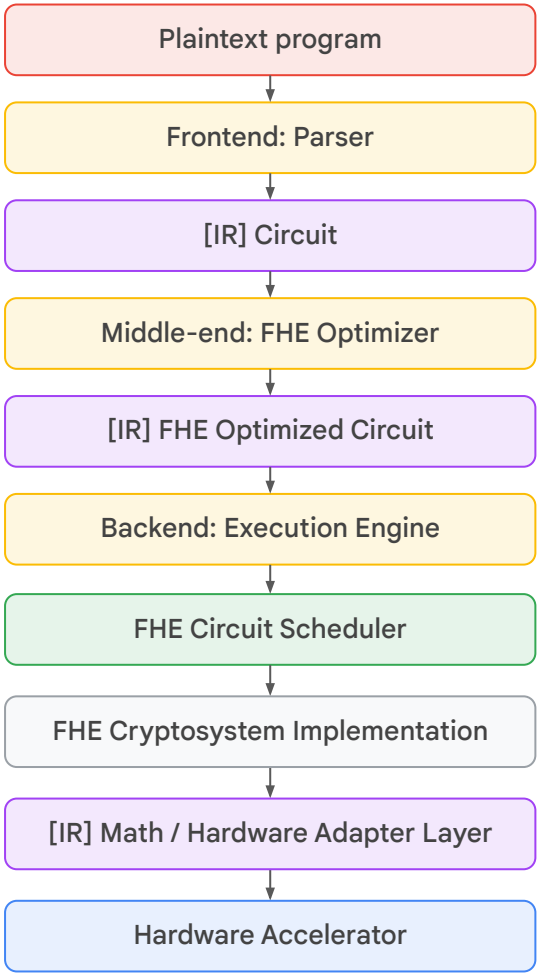
Computer Architecture & Hardware Co-design

- Accelerate Math/Crypto Primitives: Polynomial Math
- Benchmark across Hardware accelerators

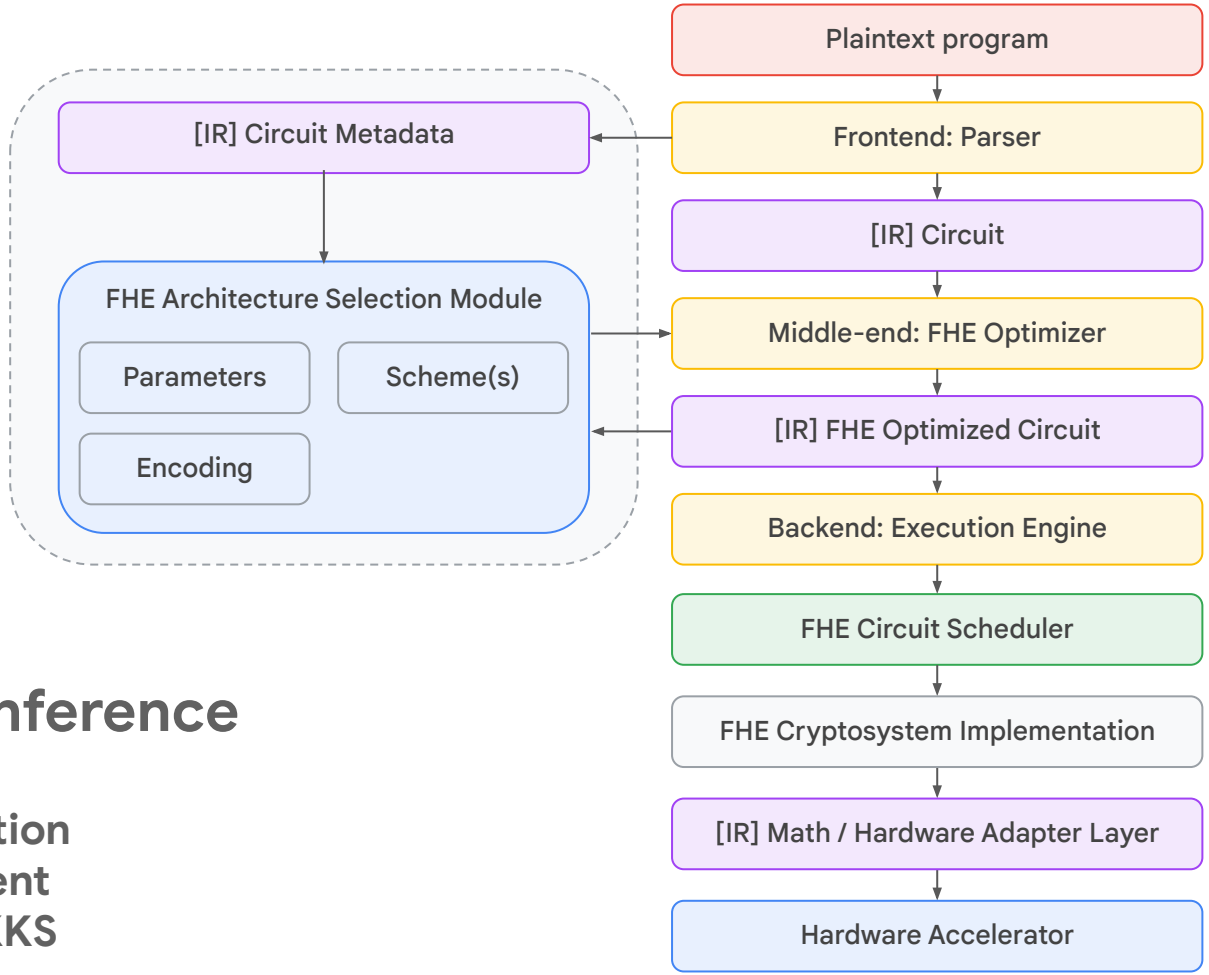


FHE Transpiler

C++ Compilation



FHE Stack



Private ML Inference

Parameter Selection
Noise Management
TFHE-LUTs or CKKS

Blocker to FHE Stack

Extensible Intermediate Representations

4. HEIR

Homomorphic Encryption Intermediate Representation

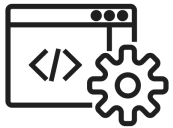
What is HEIR?

- Compiler toolchain for FHE (+ more!)
- Benchmarking platform
- Built in LLVM's MLIR framework

MLIR: Multi Level Intermediate Representation

A collection of ***modular and reusable*** software components that enables the ***progressive lowering*** of operations, to efficiently ***target hardware in a common way,*** *built at Google for TensorFlow.*

MLIR : A great fit for FHE

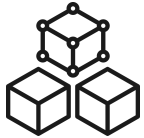


Multi-Level Abstraction

Shared abstractions and specialized expertise

Not Opinionated

Choose level of abstractions for different targets

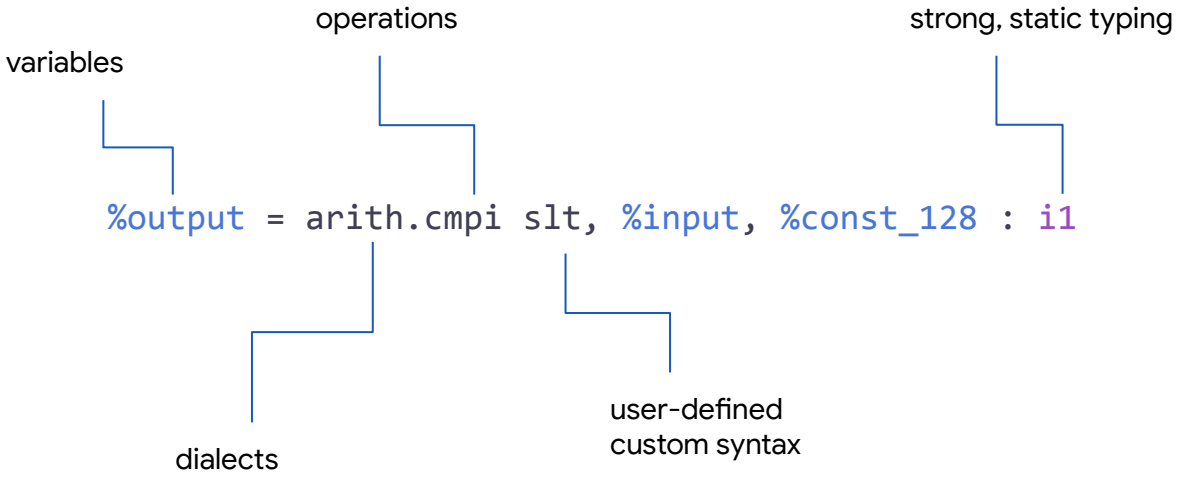


Modular & Extensible

Adapt to new research and mix and match

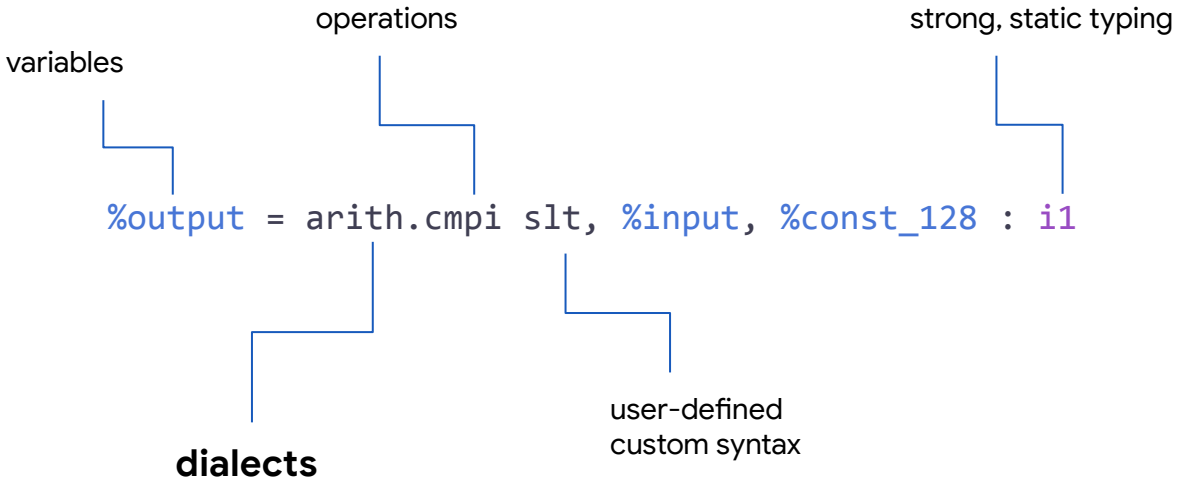
MLIR: Multi Level Intermediate Representation

Common Syntax, basic building blocks

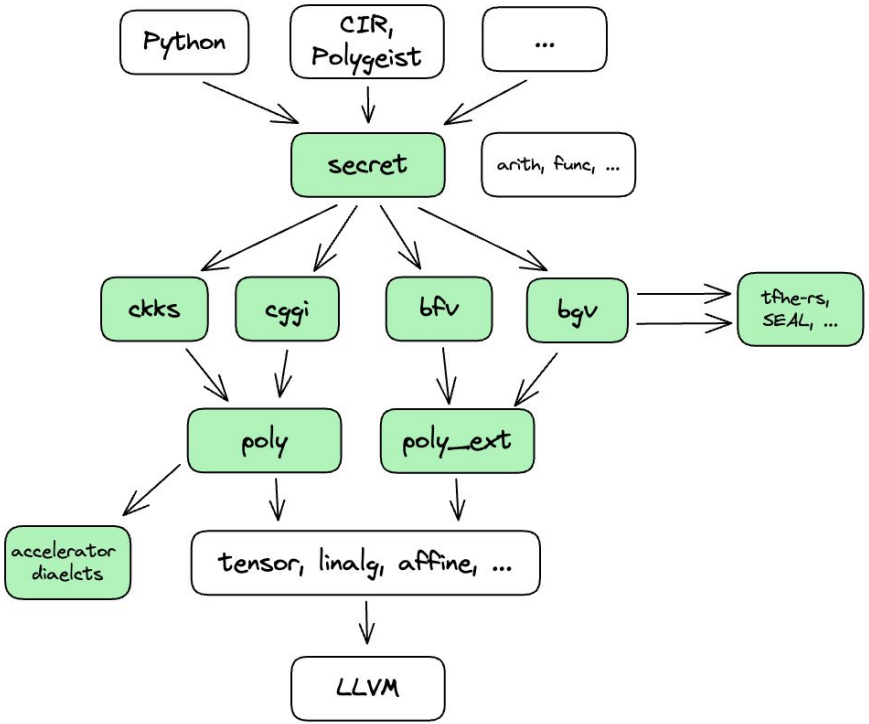


MLIR: Multi Level Intermediate Representation

Common Syntax, basic building blocks



What we're working on in HEIR



4.1 HEIR Goal

To build a compiler toolchain

with all the established ideas in FHE

to accelerate FHE research

and lower the barrier to production FHE

Using the MLIR framework

We're building a compiler toolchain

with all the established ideas in FHE

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Using the MLIR framework

We're building a compiler toolchain

Every FHE scheme, fast polynomial math, optimizations, noise models, ...

with all the established ideas in FHE

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Using the MLIR framework

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Every FHE scheme, fast polynomial math, optimizations, noise models, ...

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Focus on your novel idea, not compiler infra

to accelerate FHE research

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Using the MLIR framework

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Focus on your novel idea, not compiler infra

to accelerate FHE research

Benchmarking, hardware targets, frontends (C++, Python, Tensorflow)

and lower the barrier to production FHE

Working group!

- github.com/google/heir
- Open design meeting every two weeks
- Participants from across industry and academia
  - Bigco: Google, Intel
  - Startups: Zama, Cryptolab
  - University: ETH Zurich, KU Leuven
  - Hardware startups: Optalysys, Niobium
  - **you?**

Meeting calendar

galois | Duality | ZAMA | HEAAN CRYPTO LAB | Google

Thank you

google/heir

[Working Group]

https://google.github.io/heir/community