General Purpose Frameworks for Secure Multi-party Computation

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Secure multi-party computation (MPC)

MPC allows a group of mutually distrustful parties to compute a function on their joint inputs without revealing anything beyond the output.

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Example: Danish sugar beet auction [BCD+08]

Parties: beet farmers, government buyer, research university

Inputs: Beet prices, yields

Outputs: Market clearing price

Beyond Beets: MPC in practice

Blind auction
[BCD+08]

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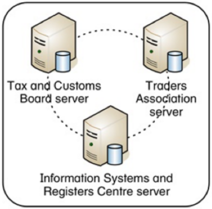

Fraud detection
[BJSV16]

Beyond Beets: MPC in practice

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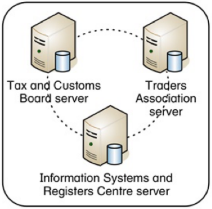

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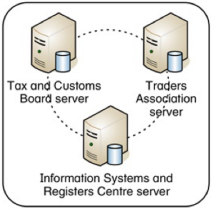

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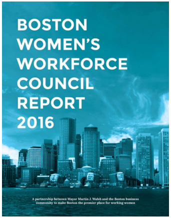

Financial statistics
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Beyond Beets: MPC in practice

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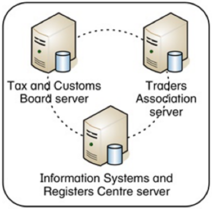

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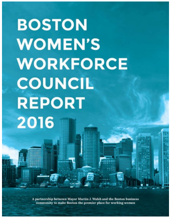
ZCASH

Parameter computation [BGM17]



Financial statistics [BLV17]

CYBERNETICA

PARTISIA

Government applications

BOLT LABS

UNBOUND (MATH OVER MATTER)

Private companies

Motivating end-to-end frameworks for MPC

Custom one-off solutions are unsustainable

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Protocols assumed impractical until Fairplay [MNPS04]

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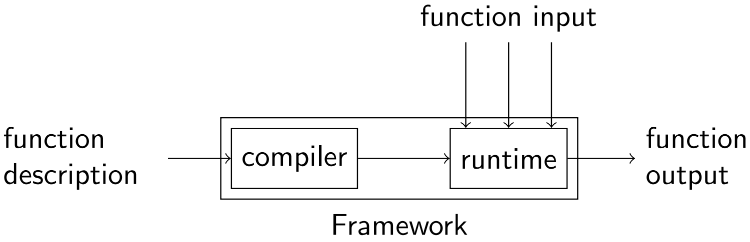
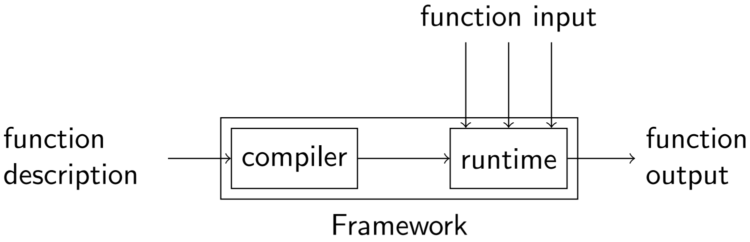
Performance improvements rapidly advanced state-of-the-art

- OT extension [IKNP03]
- Free XOR gates [KS08]
- Half-gates [ZRE15]
- AES-NI

Modern General-Purpose Frameworks



Modern General-Purpose Frameworks



Who are frameworks designed for?

What types of cryptographic settings do they use?

Are they suitable for use in large-scale applications?

Contributions

General purpose frameworks for secure multi-party computation [HHNZ19]

Survey

- Surveyed 9 frameworks and 2 circuit compilers
- Recorded protocol, feature, implementation details
- Evaluated usability criteria

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Survey

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Evaluated usability criteria

Open-source framework repository

Three sample programs in every framework

Docker instances with complete build environments

Documentation on compilation and execution

`github.com/mpc-sok/frameworks`

Findings

Most frameworks are in good shape!

Diverse set of threat models and protocols

Expressive high-level languages

Accessible, open-source, and compilable

Findings

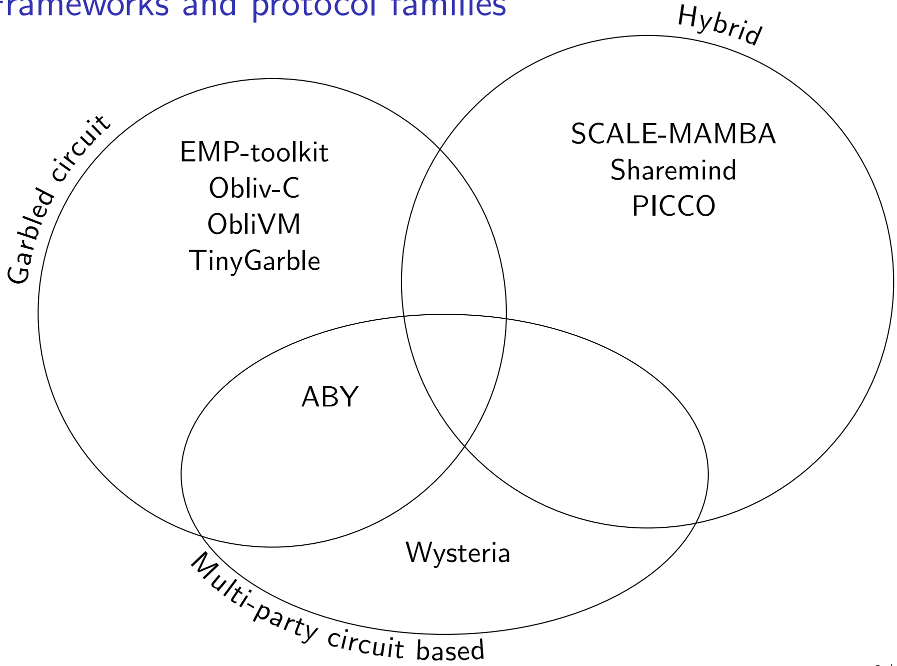
Most frameworks are in good shape!

- Diverse set of threat models and protocols
- Expressive high-level languages
- Accessible, open-source, and compilable

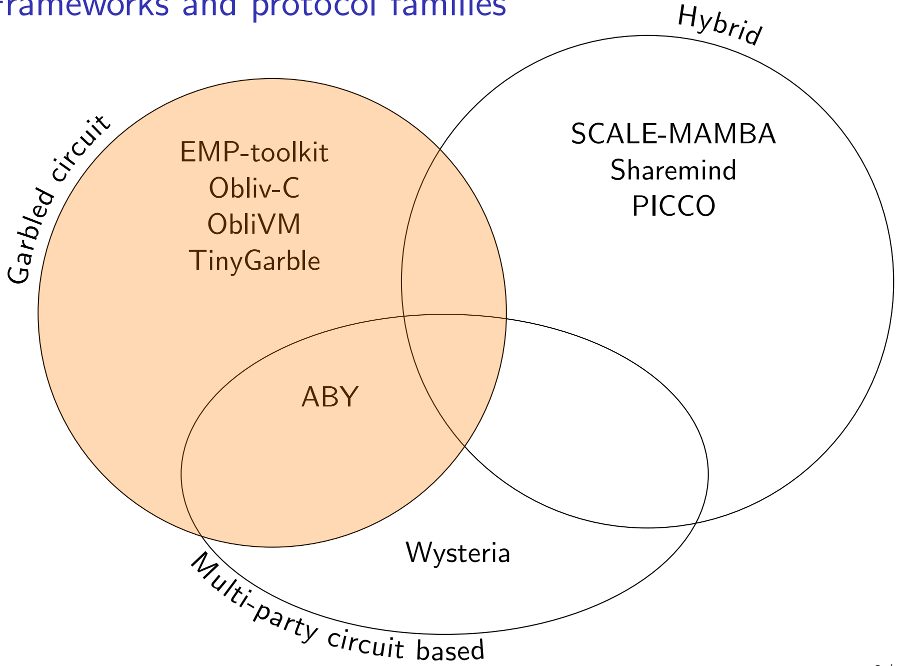
Room for improvement

- Engineering limitations
- Barriers to usability

Frameworks and protocol families

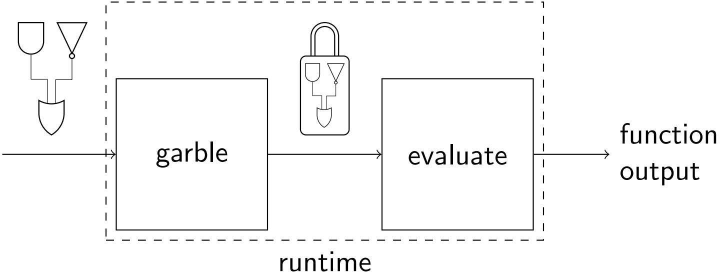


Frameworks and protocol families



Garbled circuit protocols

Introduced by [Yao82, Yao86]

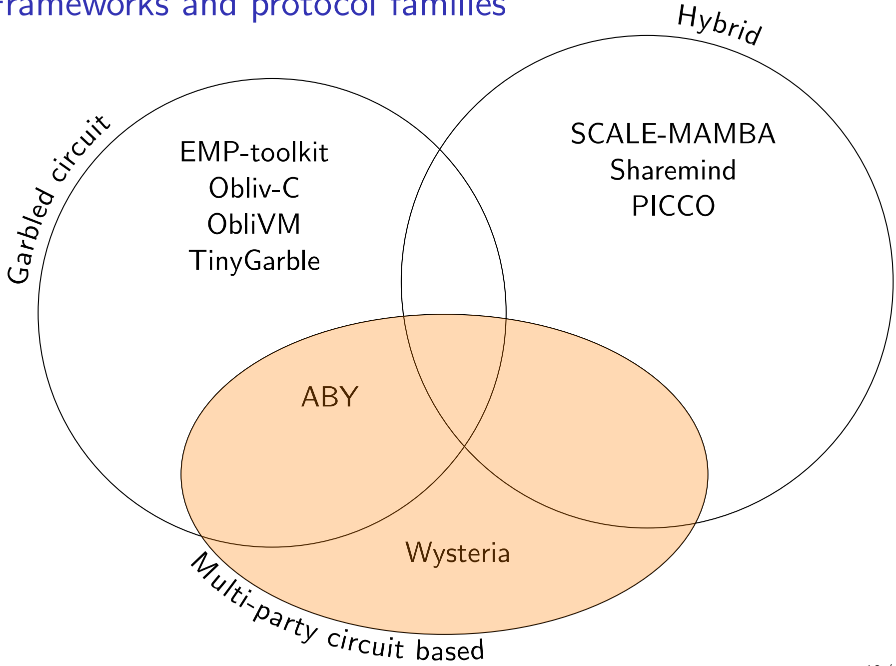


Functions represented as Boolean circuits

Typically semi-honest, 2-party

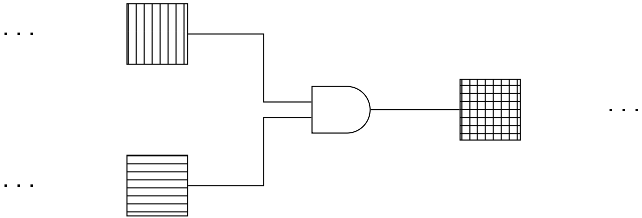
Constant-round communication, volume $\propto$ circuit size

Frameworks and protocol families



Multi-party circuit-based protocols

Introduced by [GMW87, BGW88, CCD88]



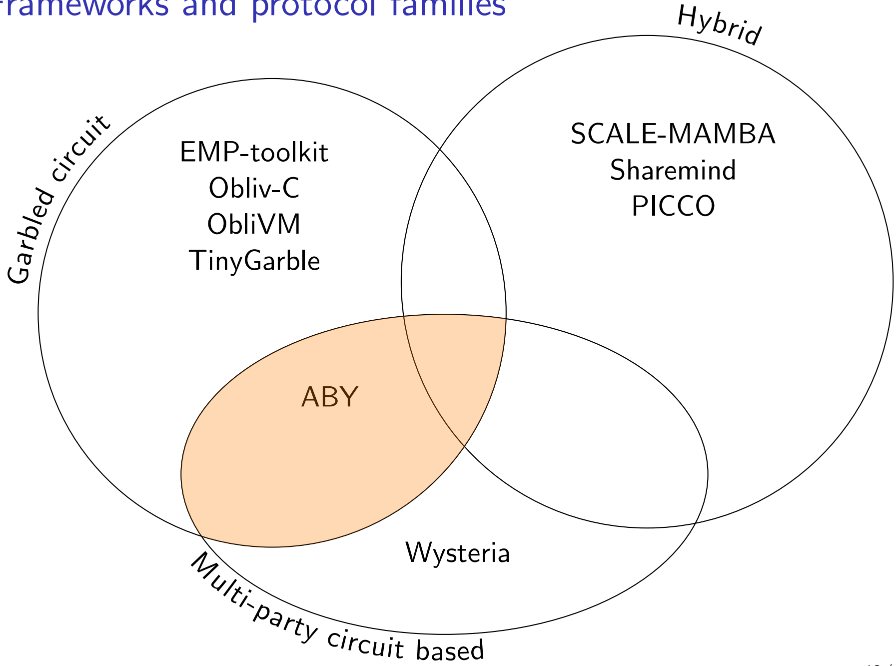
Functions represented as Boolean or arithmetic circuits

Data represented as linear secret shares

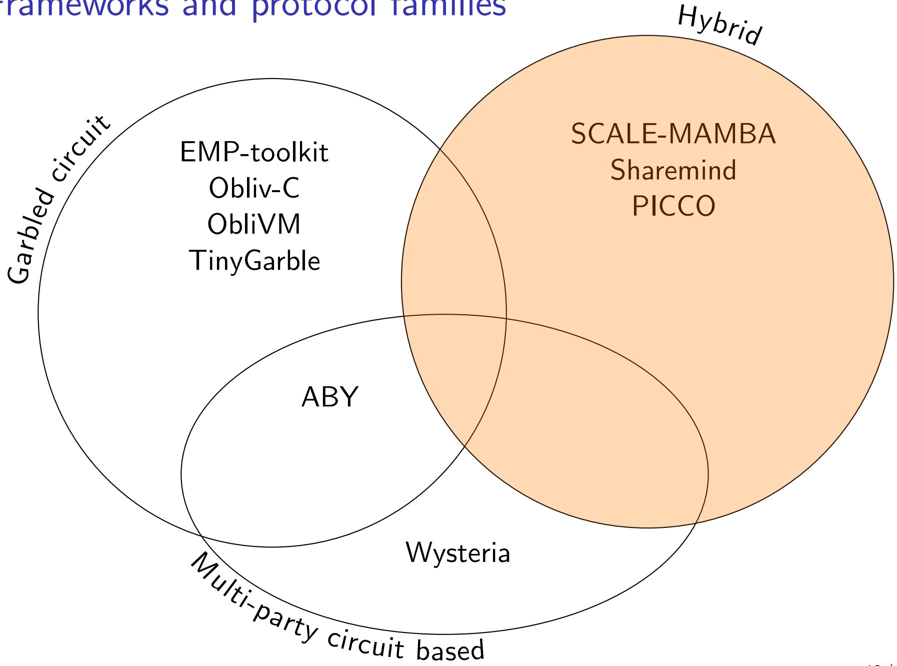
Various threat models and protocol types
(information-theoretic or cryptographic)

Rounds, volume of communication $\propto$ multiplication gates

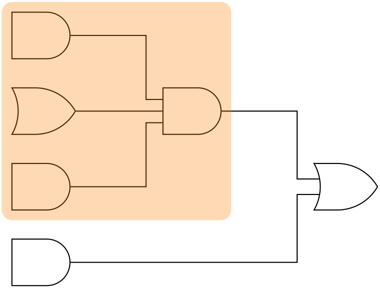
Frameworks and protocol families



Frameworks and protocol families



Hybrid protocols



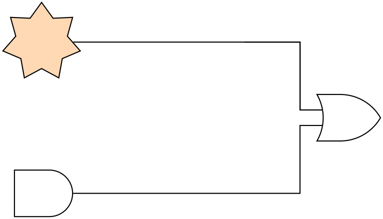
Integrates optimized subprotocols for common functions

- Bitwise operators in arithmetic settings
- Matrix operations

Seamless front-end experience (no explicit protocol selection)

Currently: One-to-one mapping from operations to protocols

Hybrid protocols



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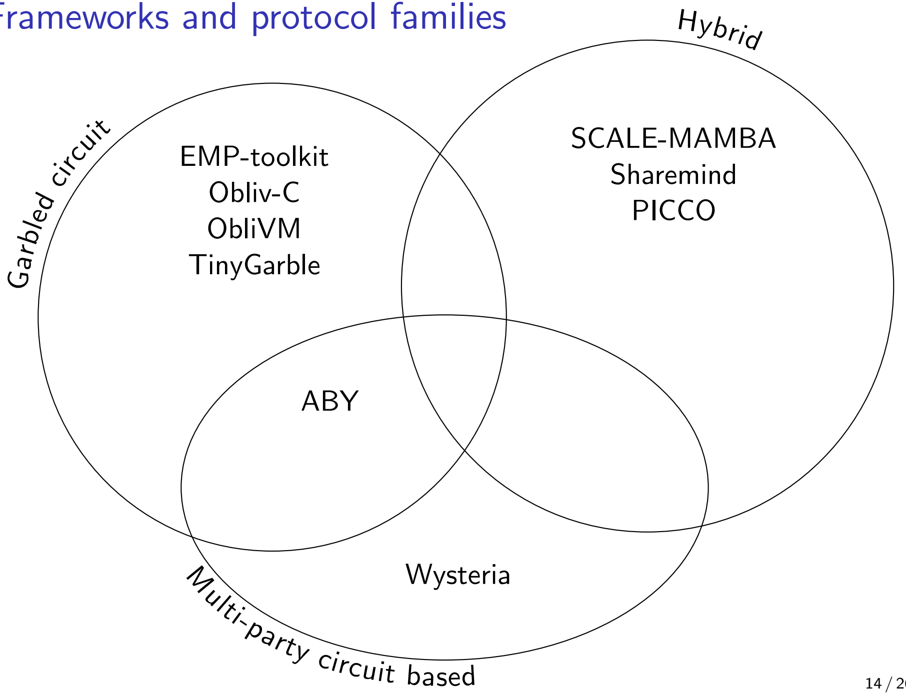
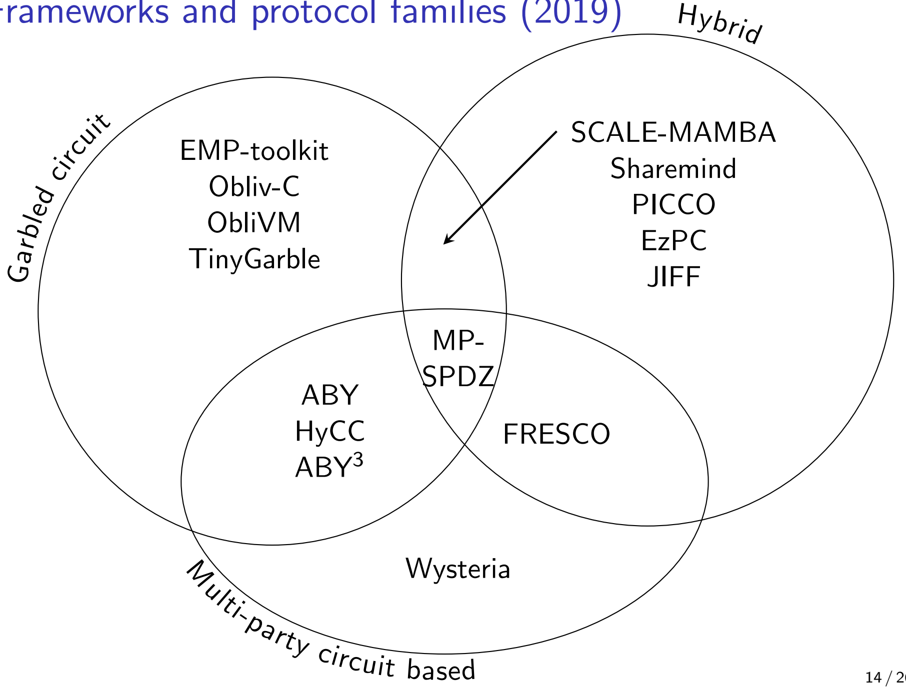


Frameworks and protocol families (2019)



Design decisions

Architecture: system structure and data representation

Circuit model: representing data-independent paradigm

Language accessibility: cryptographic abstraction level

Design decisions: Data-independent construction

Should designers reveal "non-traditional" performance characteristics?

Circuits are a data-independent representation.

Branching programs are <u>flattened</u> in this model.

Non-expert users might not recognize this performance disparity.

Data independence: Private conditionals

Should branching programs reveal atypical performance?

Obliv-C: traditional paradigm

```
obliv int result;
obliv if (a >= b) {
  result = a * a;
} else {
  result = b;
}
```

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EMP-toolkit: explicit branch selection

```
Bit a_bigger = a.geq(b);
Integer result = b.select(a_bigger, a * a);
```

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Bit a_bigger = a.geq(b);
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Recommendation

Depends on your users, but data independence is a good paradigm

Design decisions: Cryptographic abstraction level

Should the user have control over the underlying cryptographic representation?

Frigate: standard (C-style) abstraction

```
int result = 0;
for(int i=0; i<LEN; i++) {
    result = result + (A.data[i] * B.data[i]);
}
```

Design decisions: Cryptographic abstraction level

Should the user have control over the underlying cryptographic representation?

Frigate: standard (C-style) abstraction

```
int result = 0;
for(int i=0; i<LEN; i++) {
    result = result + (A.data[i] * B.data[i]);
}
```

PICCO: custom primitive, high level abstraction

```
int result = A @ B;
```

Design decisions: Cryptographic abstraction level

Should the user have control over the underlying cryptographic representation?

ABY: Low-level access

```
share *A, *B;
A = circ->PutMULGate(A, B);
A = circ->PutSplitterGate(A);
for (uint32_t i = 1; i < LEN; i++) {
    A->set_wire_id(
            0, circ->PutADDGate(A->get_wire_id(0),
                                A->get_wire_id(i)));
}
A->set_bitlength(1);
share *result = circ->PutOUTGate(A, ALL);
```

Software engineering

Complicated, non-trivial build systems

Set up certificate authority or PKI

Compile specific OpenSSL version from source

No dependency lists, manual search for compile errors

Estimated time: 1-2 weeks per framework

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Complicated, non-trivial build systems

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- Compile specific OpenSSL version from source
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Significant software projects

- Cryptographic protocols
- Distributed communication
- Interfacing with other systems

Documentation

Language documentation: How do I write secure code?

Code samples: What does a working example look like?

Code documentation: How does this example work?

Online support: Where can I ask questions?

Open-source: Can I run this without complex licensing?

Half the frameworks have no more than 3 of these ☹

Limited language documentation is frustrating

CBMC-GC:

```
int mpc_main(int alice, int bob) {
  return alice * bob;
}
```

$ make
[...]
Uncaught exception: Unknown literal: 33. Did you forget to return a value or assign a value to a OUTPUT variable?

Limited language documentation is frustrating

CBMC-GC: Arguments must be called INPUT_<*var*>

```
int mpc_main(int INPUT_alice, int INPUT_bob) {
  return INPUT_alice * INPUT_bob;
}
```

$ make
[...]
Gates: 5648 with 1986 Non-XOR and 0 LUTs
Depth: 151 with 32 Non-XOR

Limited language documentation is frustrating

CBMC-GC: Arguments must be called INPUT_*<var>*

ObliVM:

```
int main(int alice, int bob){
  secure int result = alice * bob;
  return result;
}
```

$ ./run-compiler 12345 multiply.lcc

[ERROR] Error: Parsing Error Encountered " "alice" "alice "" at line 3, column 21.

Was expecting one of: ⟨ IDENTIFIER ⟩ ... "[" ... "@" ... "¡" ...

Limited language documentation is frustrating

CBMC-GC: Arguments must be called `INPUT_`*<var>*
ObliVM: `alice` and `bob` are reserved keywords

```
int main(int aaaaa, int bbb){
  secure int result = aaaaa * bbb;
  return result;
}
```

$ ./run-compiler 12345 multiply.lcc
[INFO] The program type checks
[INFO] Compiling mult3.lcc succeeds
[INFO] Compilation finishes successfully.

Limited language documentation is frustrating

CBMC-GC: Arguments must be called `INPUT_<var>`

ObliVM: `alice` and `bob` are reserved keywords

Wysteria:

```
let richer = \x:ps . \w:W x nat .

    let b @ sec(x) =
     wfold x (w, 0, \accum:nat . \p:ps . \n:nat .

        if accum > n then accum
        else n )

    in b

  let all = { !Alice, !Bob } in
  let w = (wire !Alice:10) ++ (wire !Bob:100) in
  richer all w
```

$ wysteria –i-am Alice –gmw-port 9000 examples/tutorial.wy

File examples/fakemill.wy, line 1, character 16: syntax error at ':'

Limited language documentation is frustrating

CBMC-GC: Arguments must be called INPUT_*<var>*

ObliVM: alice and bob are reserved keywords

Wysteria: Language docs don't account for parser limitations

```
let richer = \(x:ps{true}) . \(w:W x nat) .
  let tmp @ par(x) =
    let b @ sec(x) =
      let result = wfold x [w ; 0;
        \(accum:nat) . \(p:ps{true}) . \(n:nat) .
        if accum > n then accum
        else n ]
      in result
    in b
  in wire x:tmp
in let all = { !Alice , !Bob } in
   let w = (wire !Alice:10) ++ (wire !Bob:100) in
   richer all w
```

$ wysteria –i-am Alice –gmw-port 9000 examples/tutorial.wy

done with type checking the program

Limited language documentation is frustrating

CBMC-GC: Arguments must be called `INPUT_`*<var>*

ObliVM: `alice` and `bob` are reserved keywords

Wysteria: Language docs don't account for parser limitations

EMP-toolkit: ∼1 comment per 600 lines of code

Documentation appreciation and recommendations

Frameworks with excellent documentation

- ABY: 35-page language guide; only slightly out-of-date
- SCALE-MAMBA: 100+ pages of documentation
- Sharemind: Auto-generated language guide online

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Two recommendations for maintainers

- Multiple types of documentation drastically increase usability
- Online resources are sustainable and reduce workload
    - Produces a living FAQ
    - Allows users to interact

Good news for usability

Documentation issues aren't fundamental

IARPA HECTOR includes usability criteria

Recent frameworks focus on usability!*

"JIFF is built to be highly flexible with a focus on usability [...] designed so that developers need not be familiar with MPC techniques or know the details of cryptographic protocols in order to build secure applications."

HyCC makes "highly efficient hybrid MPC [...] accessible for developers without cryptographic background."

*Claims made by authors may not be verified by the speaker.

Future directions in MPC frameworks

Continued support for multiple settings

Extend frameworks with different threat models and protocols

Better integration of work in other disciplines

Heavy-duty circuit compilers (TinyGarble)

Formal guarantees about front-ends (Wysteria, ObliVM)

Maintaining the repository

I'm continuing to add modern frameworks

We accept pull requests!

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