Programming Cryptography without Programming Cryptography

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In 2014, I taught **smart contract programming** to undergraduate students.

UNIVERSITY OF MARYLAND

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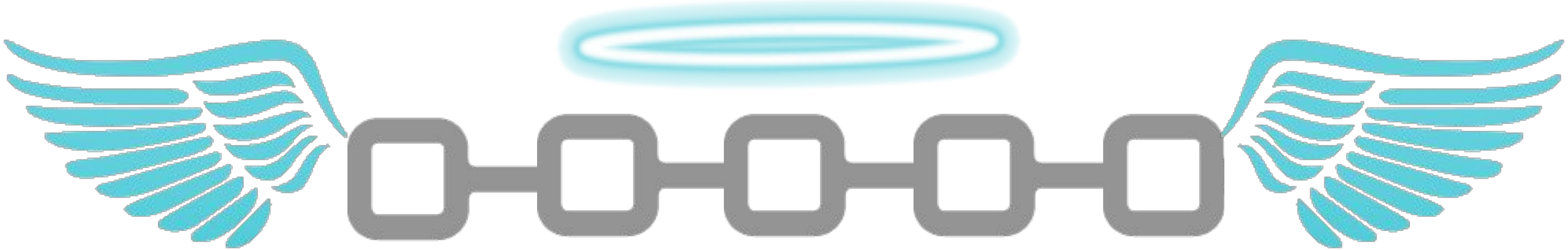
Smart contract programming: you are programming a distributed system

Smart contract



Smart contract

Rock-paper-scissors:

“**Hello World**” for smart contract programming

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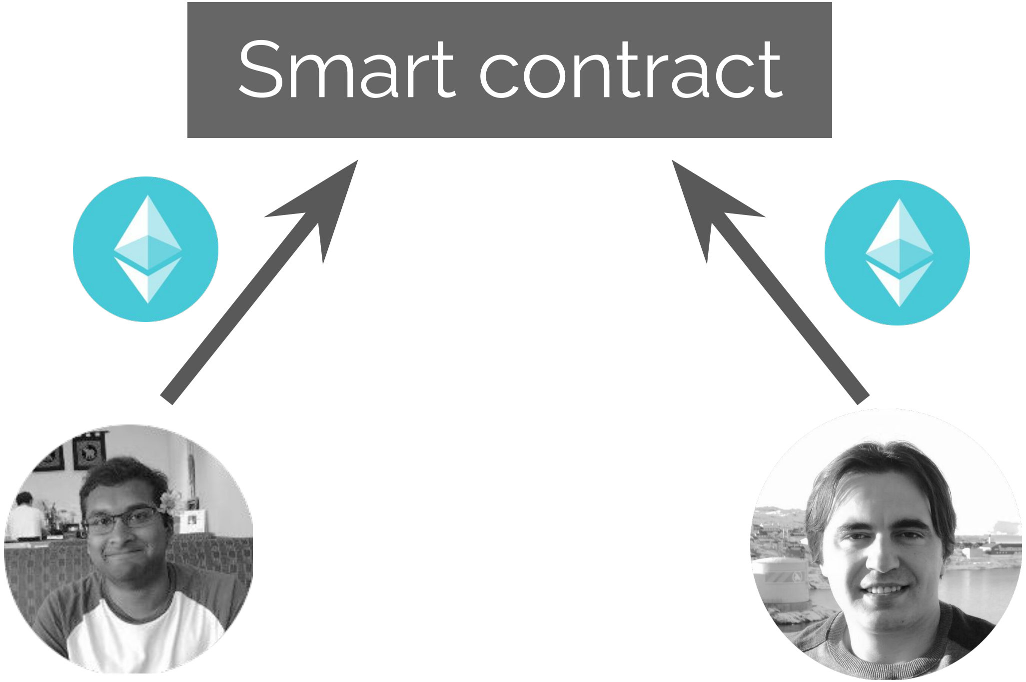
Smart contract

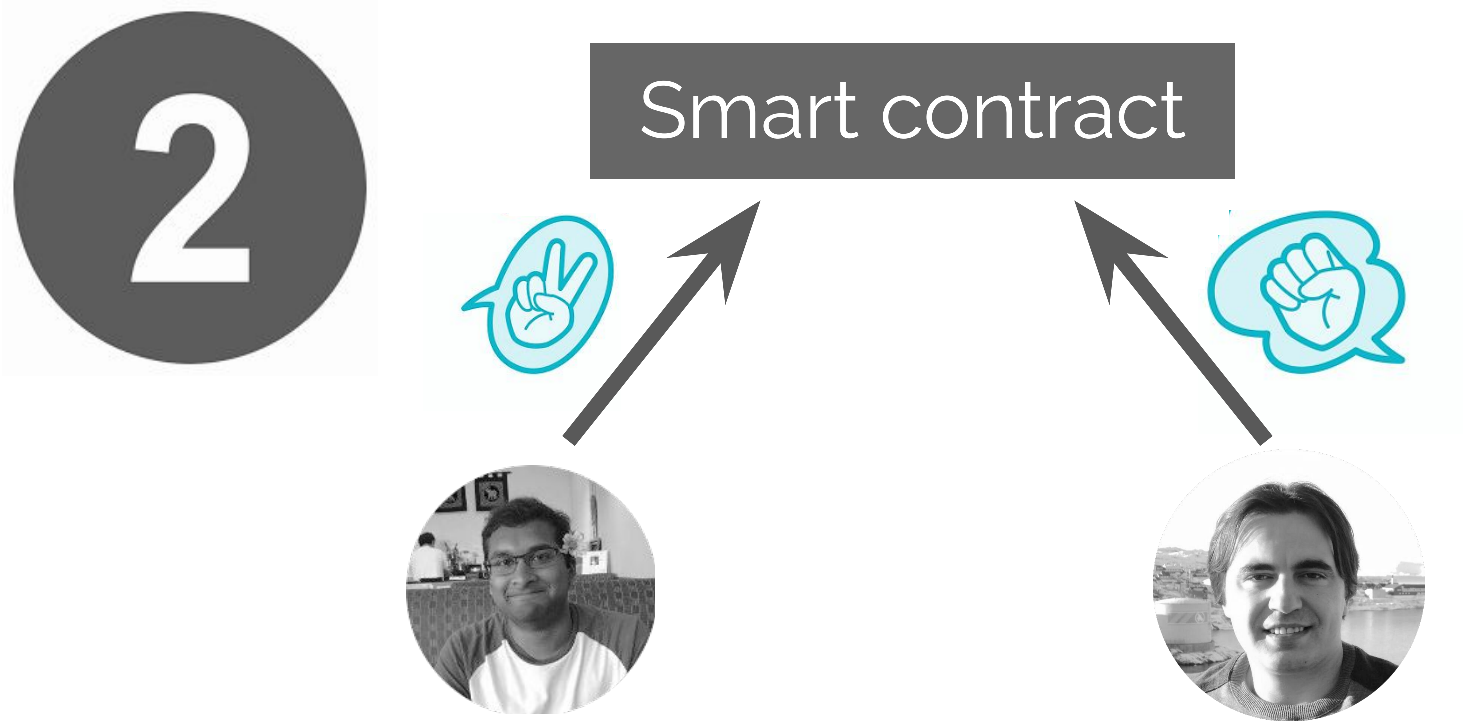
Rock-paper-scissors:

“**Hello World**” for smart contract programming

1



Rock-paper-scissors:
“Hello World” for smart contract programming



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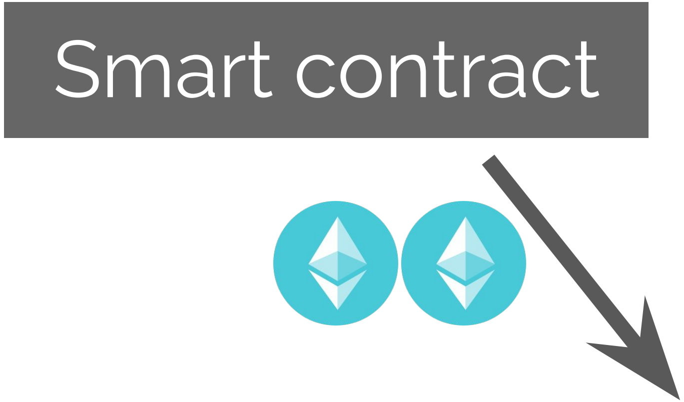
Smart contract

Rock-paper-scissors:
"Hello World" for smart contract programming

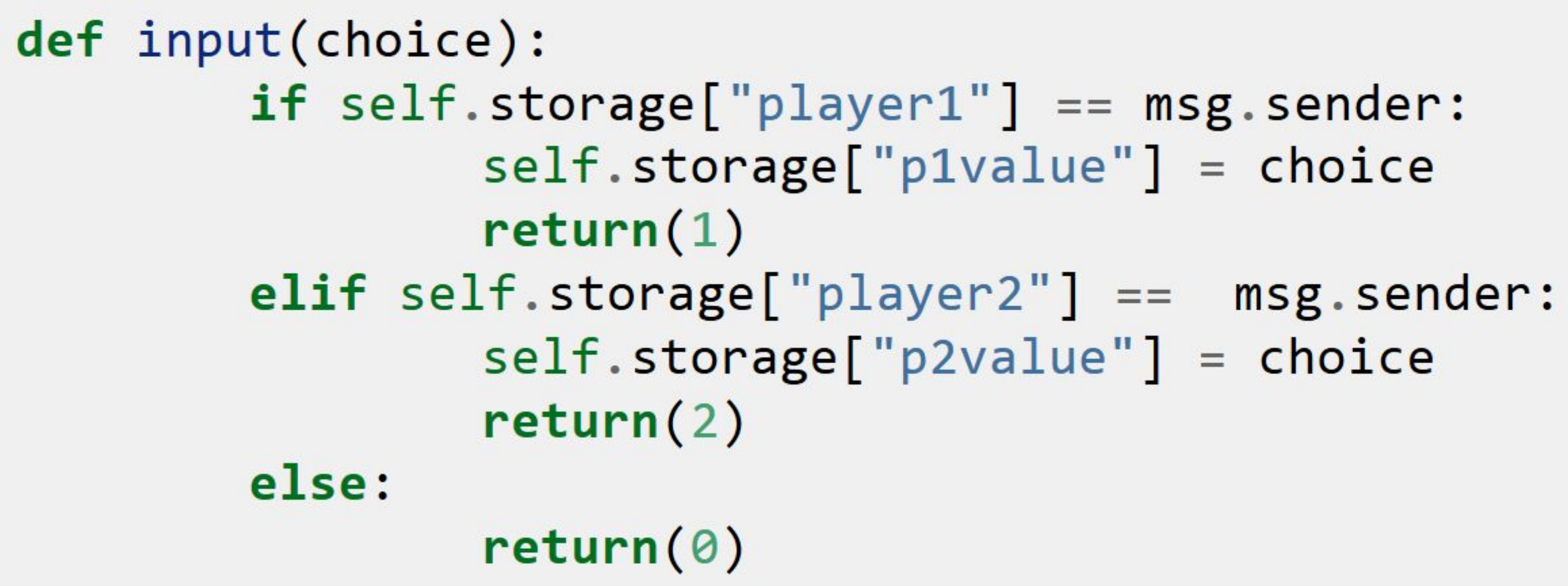
3



Smart contract

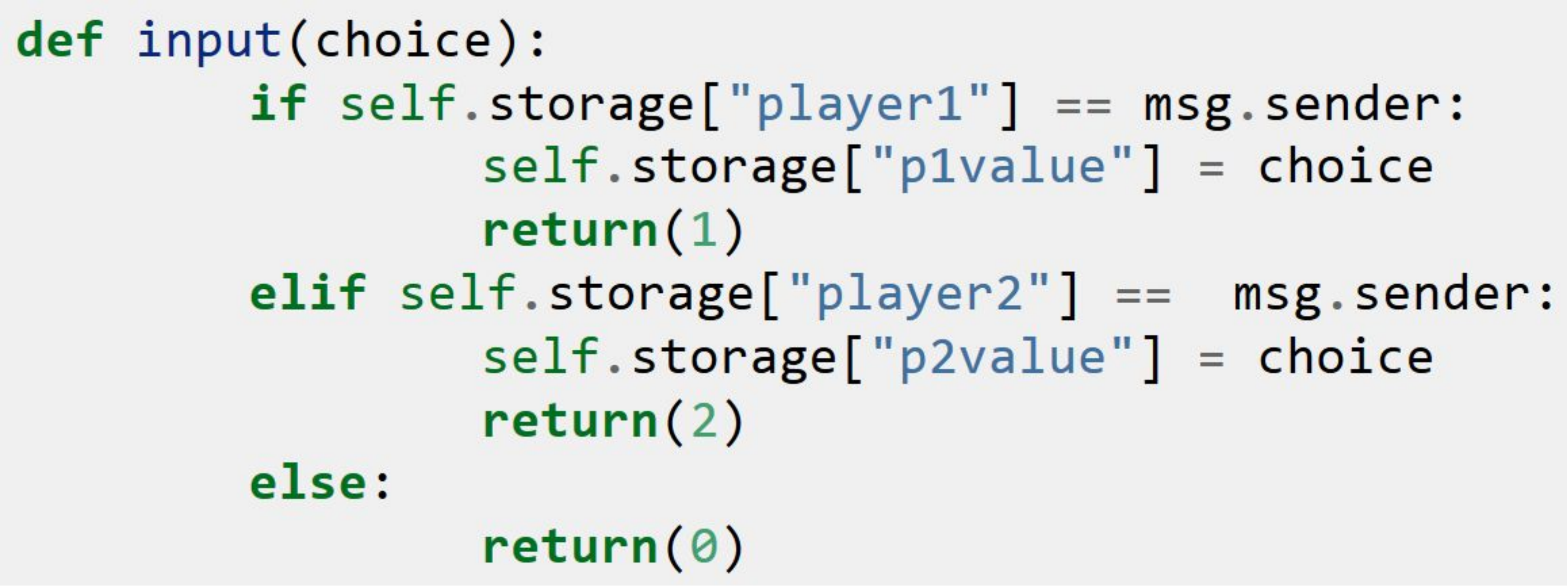
Rock-paper-scissors:

students’ solution



```
def input(choice):
        if self.storage["player1"] == msg.sender:
                self.storage["p1value"] = choice
                return(1)
        elif self.storage["player2"] ==  msg.sender:
                self.storage["p2value"] = choice
                return(2)
        else:
                return(0)
```

Is this secure?



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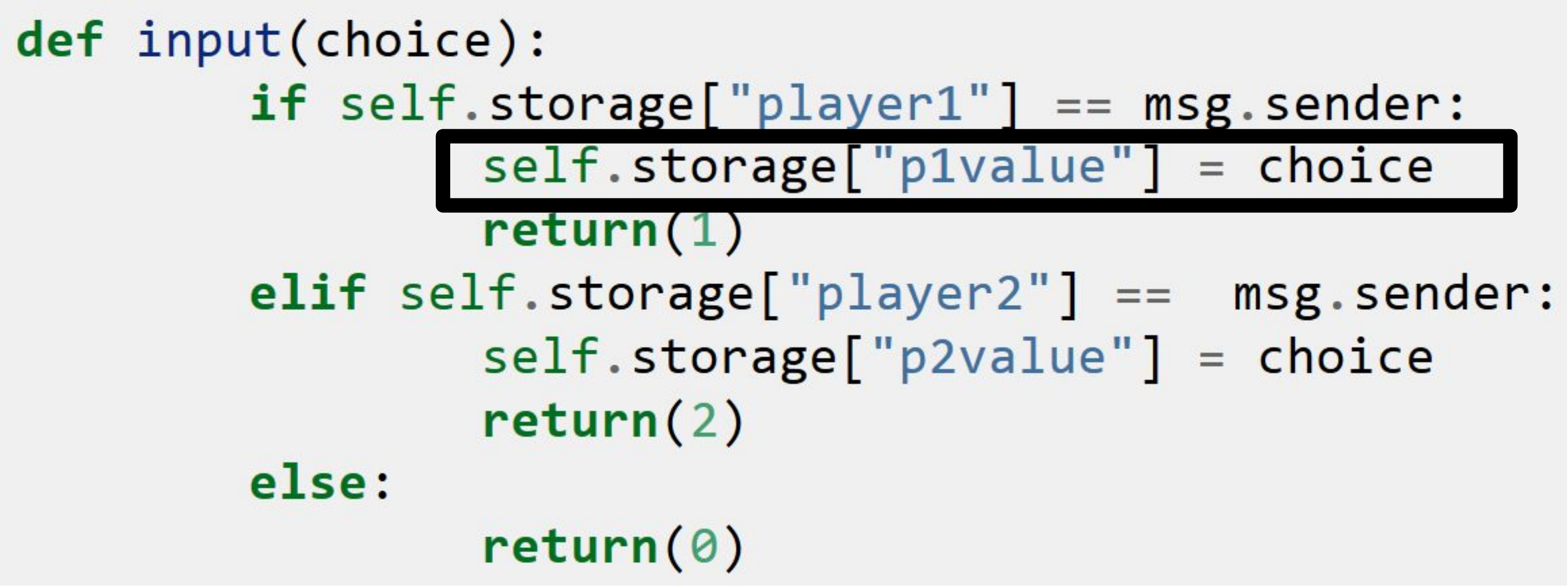
```

 can choose input based on  's input



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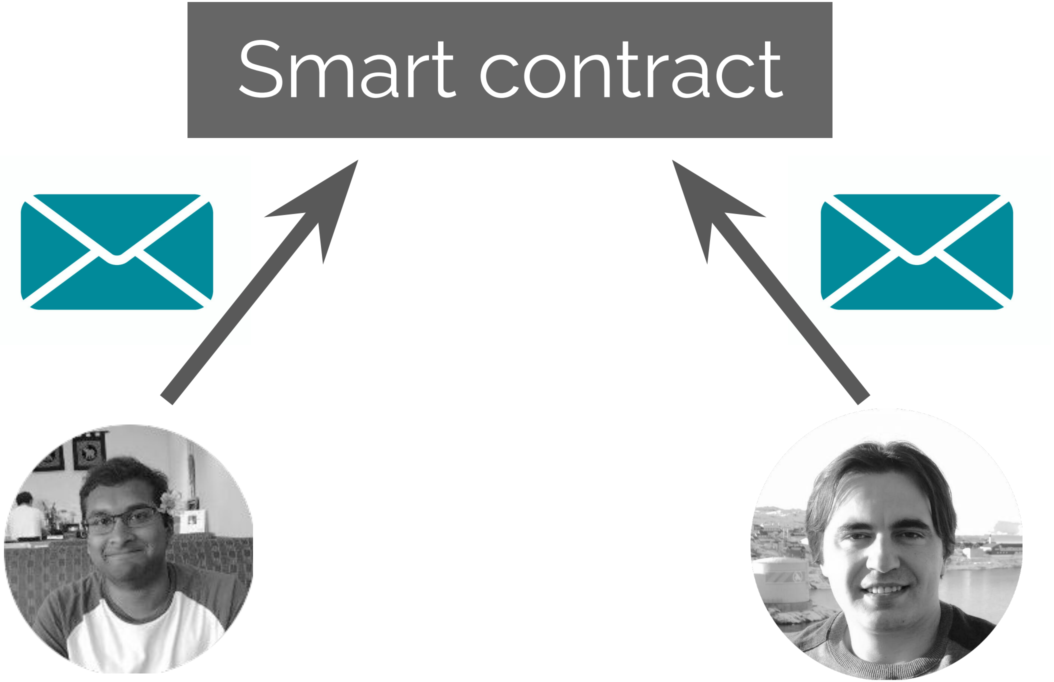
```

Use a **commit-and-open** protocol

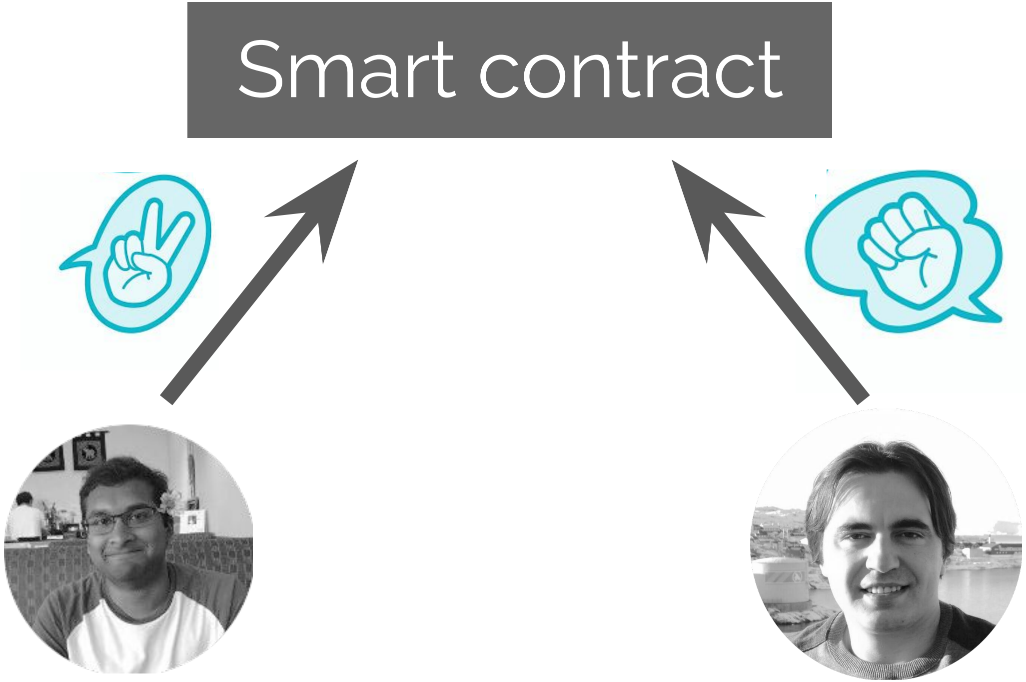
… commitment should be non-malleable

Commit phase



Smart contract

Open phase



Smart contract

Lesson learned:

- Distributed programming often involves cryptography.
- Even the “Hello World” for distributed programming is hard!

Can we let ordinary programmers program cryptography without programming cryptography

Our dream:

- Programmer gives a high-level specification with **security annotations**
- **Synthesize** an **efficient** cryptographic protocol

Two Challenges

- **Cryptography speaks the circuits, not programs**

  e.g., multi-party computation, zero-knowledge proofs

- **Choosing the right and most efficient cryptographic primitive**

Two Challenges

- **Cryptography speaks the circuits, not programs**

  e.g., multi-party computation, zero-knowledge proofs

- **Choosing the right and most efficient cryptographic primitive**

Compiling programs to multi-party computation (MPC) protocols

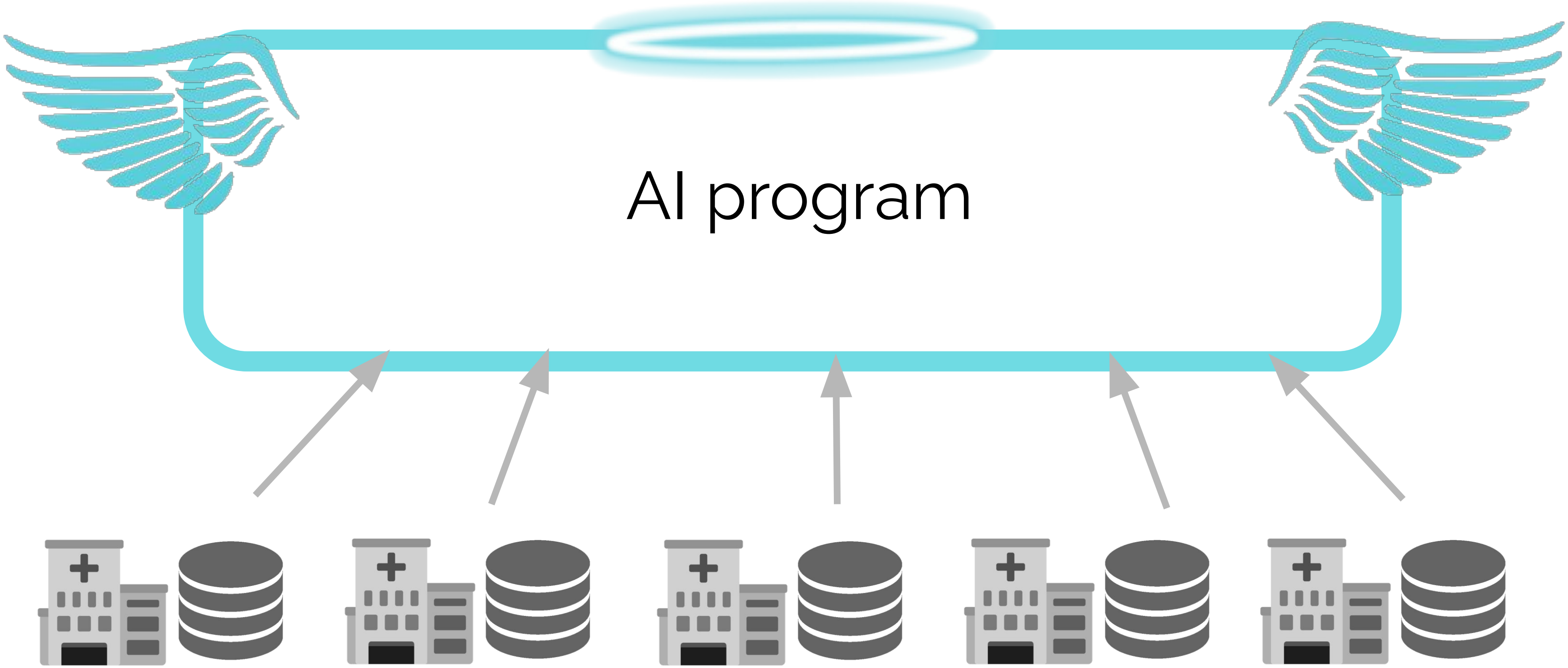
Joint work with Chang Liu,
Michael Hicks, and others

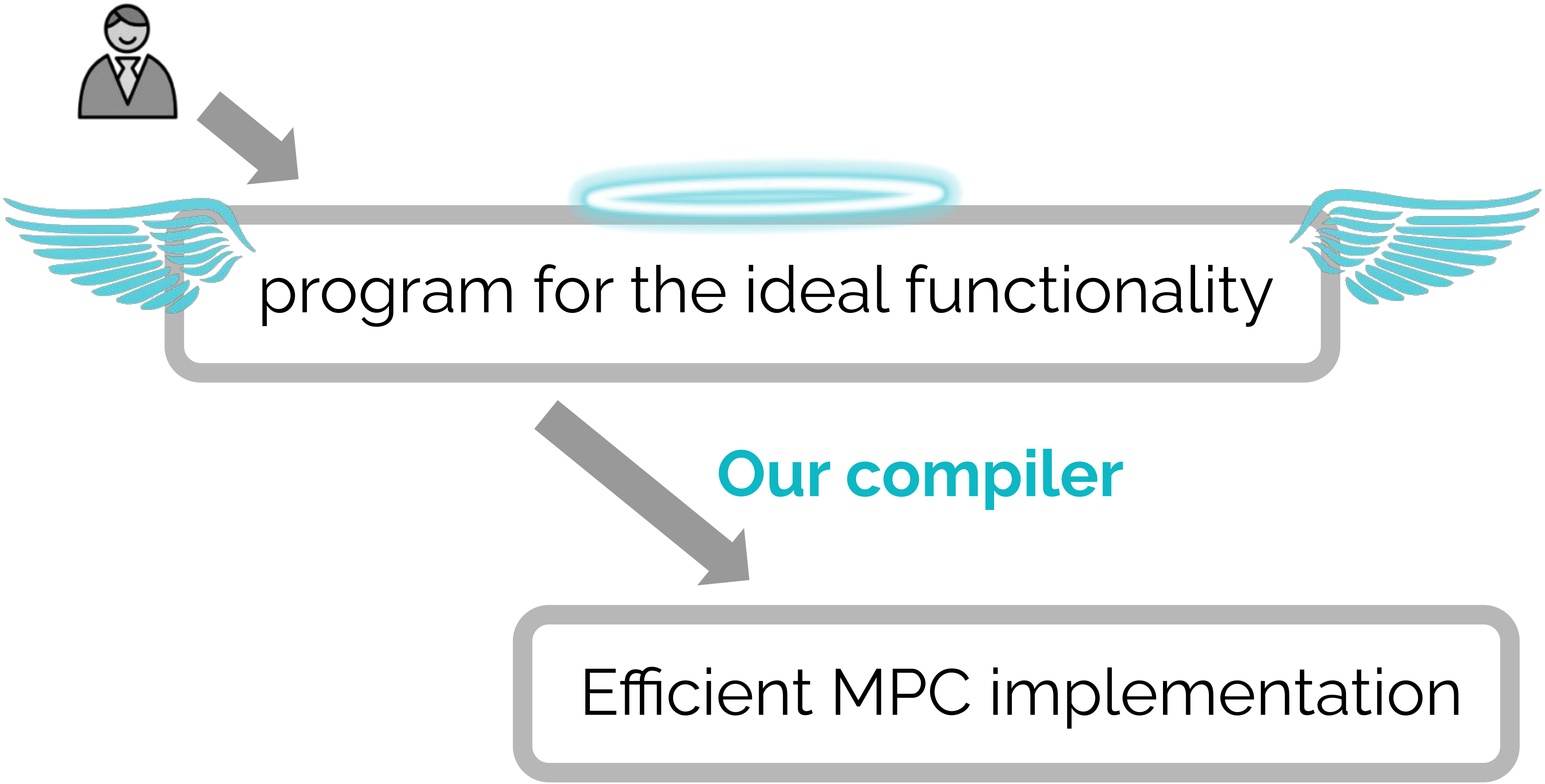
Example: Joint Clinical Study

MPC: learn only the outcome and nothing else

MPC: learn only the outcome and nothing else

Security: as secure as using an **ideal functionality**





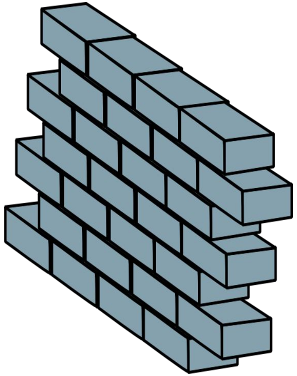
program for the ideal functionality

Our compiler

Efficient MPC implementation

Programs

Dynamic memory accesses



Circuits

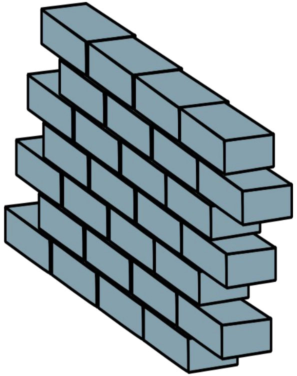
Static wiring

Binary search: access patterns depend on query

```
func search(val, s, t)
    mid = (s + t)/2
    if val < mem[mid]
            search (val, 0, mid)
    else search (val, mid+ 1, t)
```

Programs

Dynamic memory accesses

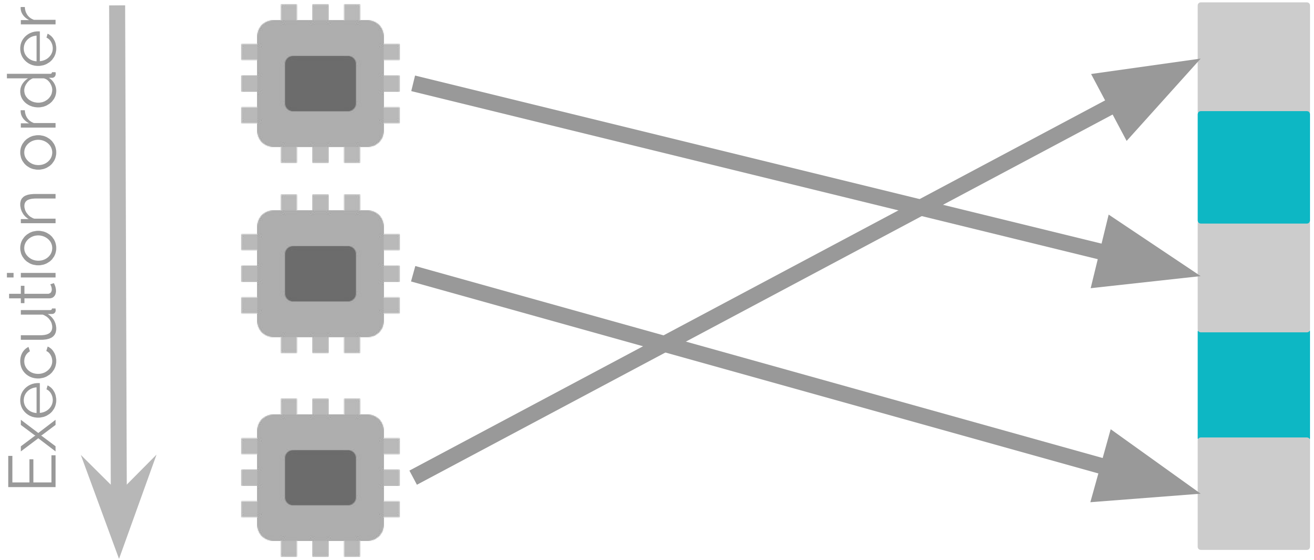


Circuits

Static wiring

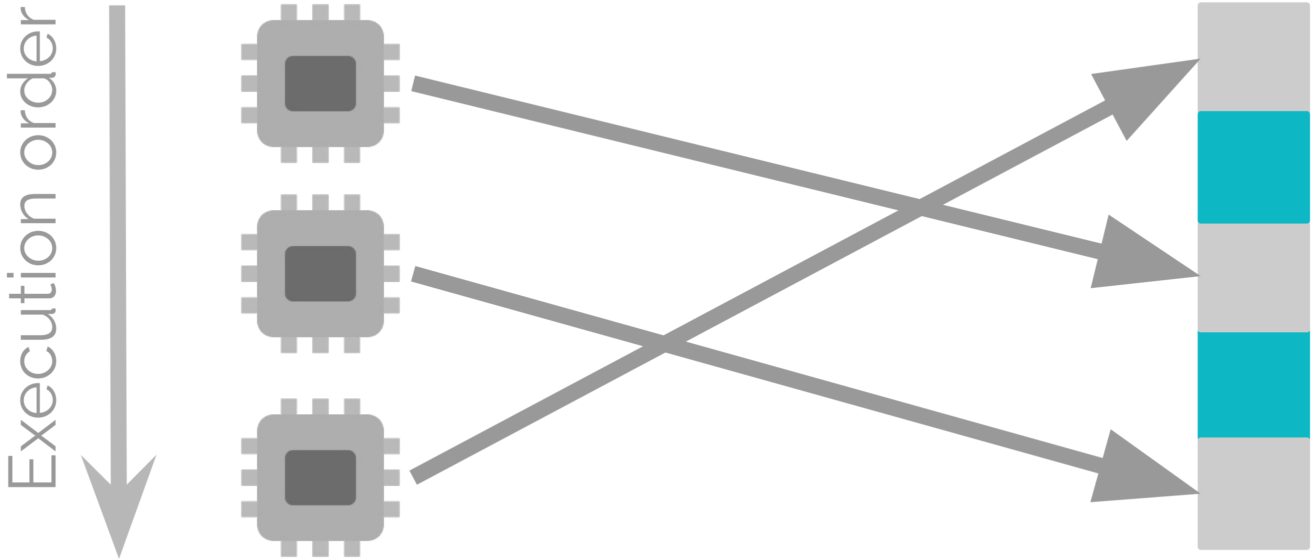
Naive idea 1 (secure but inefficient)

Use a **linear-scan circuit** to implement every memory access



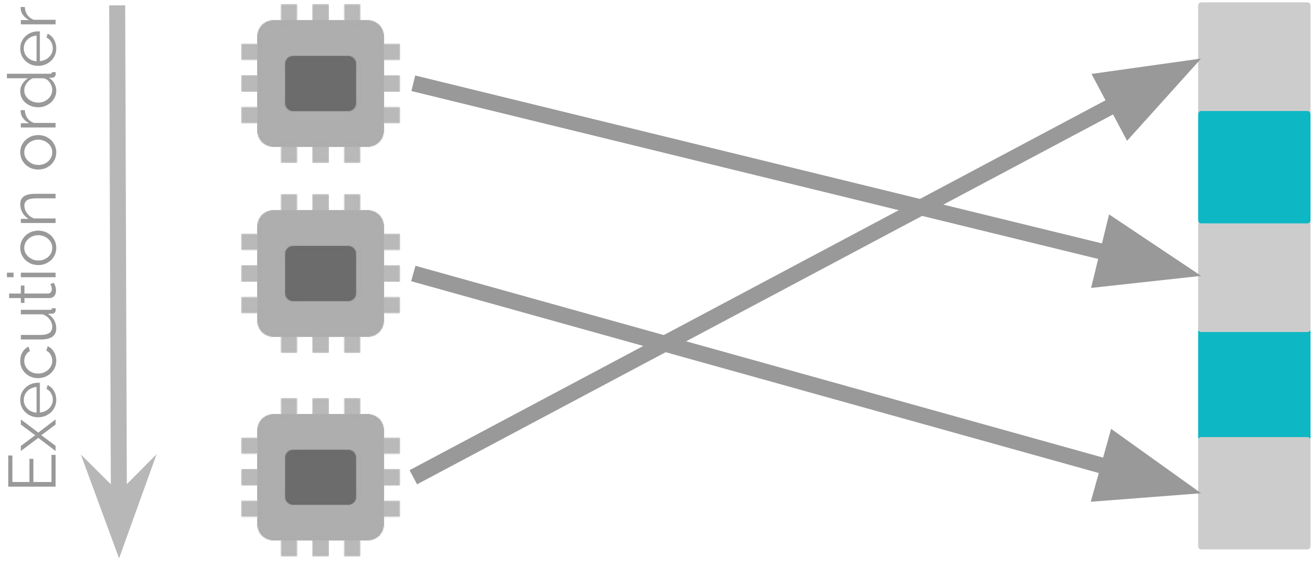
Naive idea 2 (efficient but insecure)

Each step of the computation is a circuit, each circuit reads and writes memory



Oblivious RAM

- Memory accesses do NOT leak information



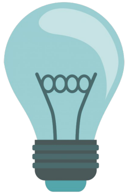
Oblivious RAM

- Memory accesses do NOT leak information
- Each step ⇒ poly log circuits

Signal, a private messaging app with >40 million monthly active users,

runs the **Path ORAM** algorithm!

Naive idea: Put everything in ORAM



In practice, not all data must be placed in ORAM

Accesses that do not depend on secret inputs need not be hidden

Example: FindMax

```
int max(public int n, secret int h[]) {
        public int i = 0;
        secret int m = 0;
        while (i < n) {
                if (h[i] > m) then m = h[i];
                i++;
        }
        return m;
}
```

Example: FindMax

```
int max(public int n, secret int h[]) {
    public int i = 0;
    secret int m = 0;
    while (i < n) {
        if (h[i] > m) then m = h[i];
        i++;
    }
    return m;
}
```

h[i] need not be in ORAM.
Encryption suffices.

Example: Main loop in Dijkstra

```
for(int i=1; i<n; ++i) {
   int bestj = -1;
   for(int j=0; j<n; ++j)
     if(!vis[j] && (bestdis < 0 || dis[j] < bestdis))
            bestdis = dis[j];

   vis[bestj] = 1;
   for(int j=0; j<n; ++j)
     if(!vis[j] && (bestdis + e[bestj][j] < dis[j]))
       dis[j] = bestdis + e[bestj][j];
}
```

dis[]: not in ORAM

vis[], e[][]: in ORAM

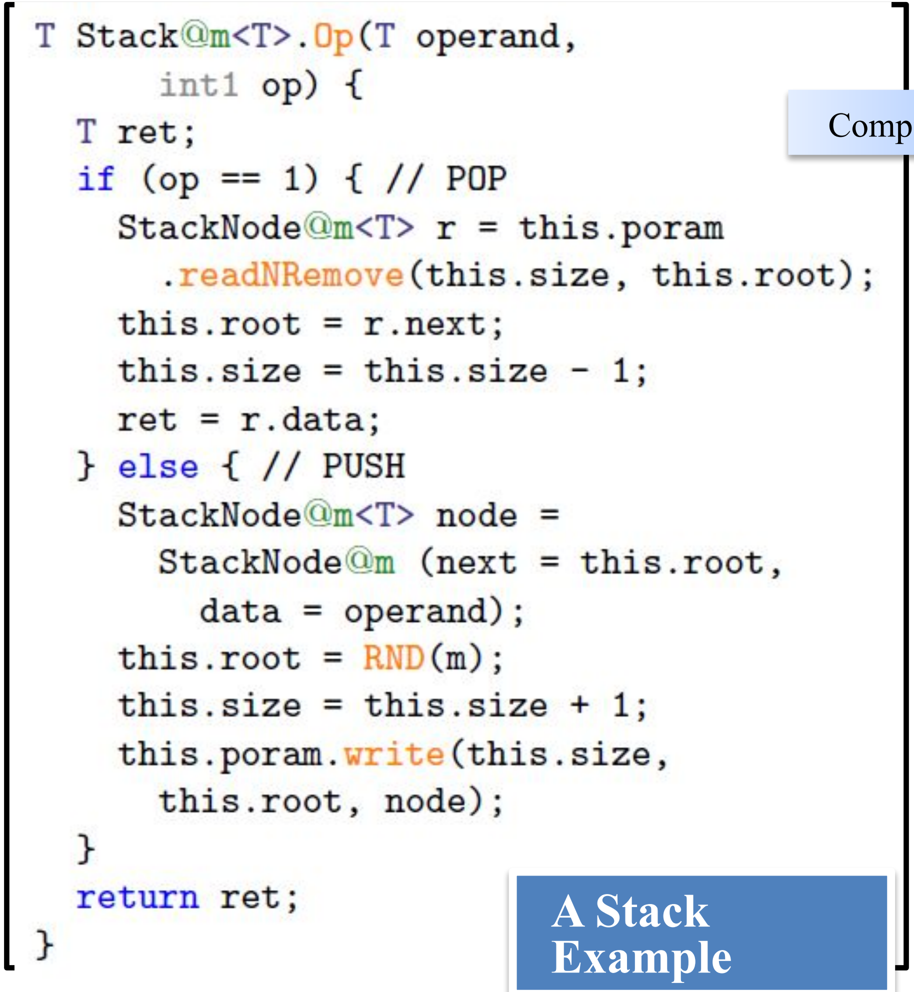
We built a compiler to automate this analysis

```
for(int i=1; i<n; ++i) {
   int bestj = -1;
   for(int j=0; j<n; ++j)
      if(!vis[j] && (bestdis < 0 || dis[j] < bestdis))
               bestdis = dis[j];

   vis[bestj] = 1;
   for(int j=0; j<n; ++j)
      if(!vis[j] && (bestdis + e[bestj][j] < dis[j]))
         dis[j] = bestdis + e[bestj][j];
}
```

dis[]: not in ORAM

vis[], e[][]: **in ORAM**

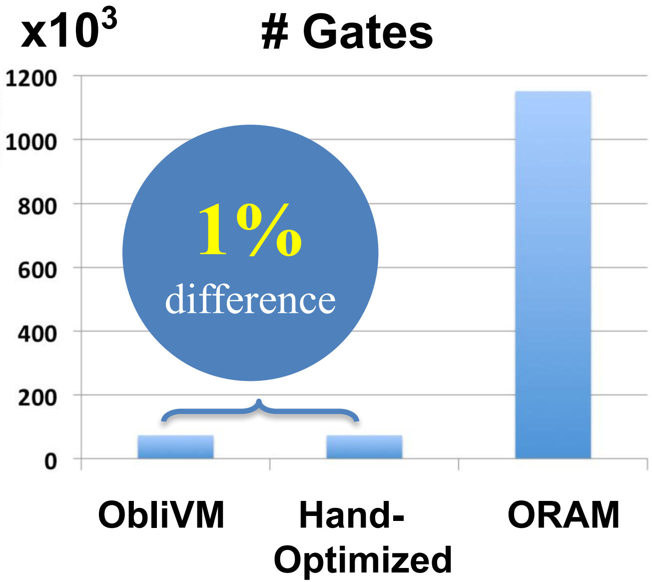


```
T Stack@m<T>.Op(T operand,
      int1 op) {
  T ret;
  if (op == 1) { // POP
    StackNode@m<T> r = this.poram
      .readNRemove(this.size, this.root);
    this.root = r.next;
    this.size = this.size - 1;
    ret = r.data;
  } else { // PUSH
    StackNode@m<T> node =
      StackNode@m (next = this.root,
        data = operand);
    this.root = RND(m);
    this.size = this.size + 1;
    this.poram.write(this.size,
      this.root, node);
  }
  return ret;
}
```

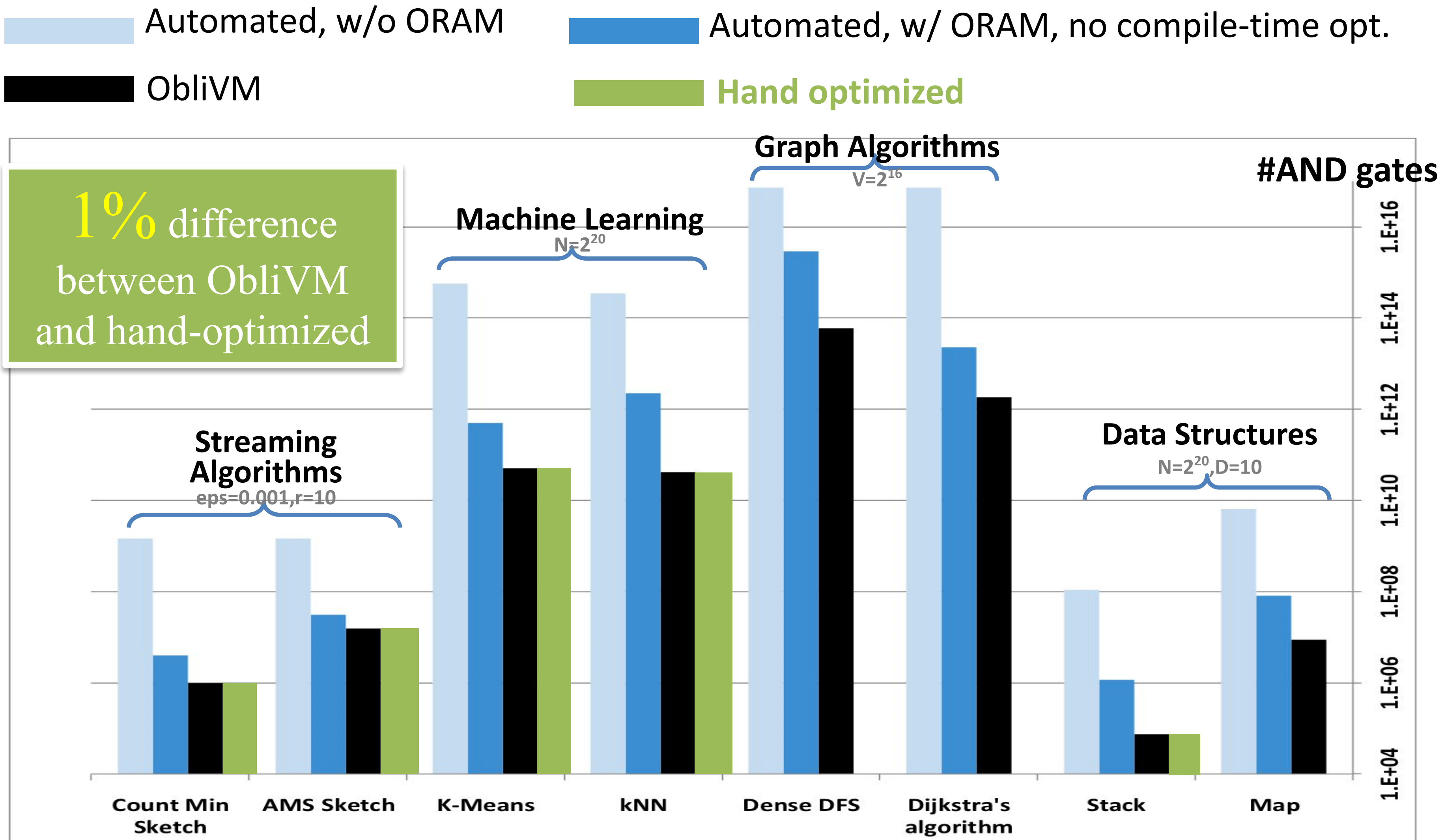
A Stack Example

Compile

Efficient Oblivious Stack



1% difference



1% difference between ObliVM and hand-optimized

Memory-trace oblivious type system

Memory-trace oblivious type system

Information flow type system

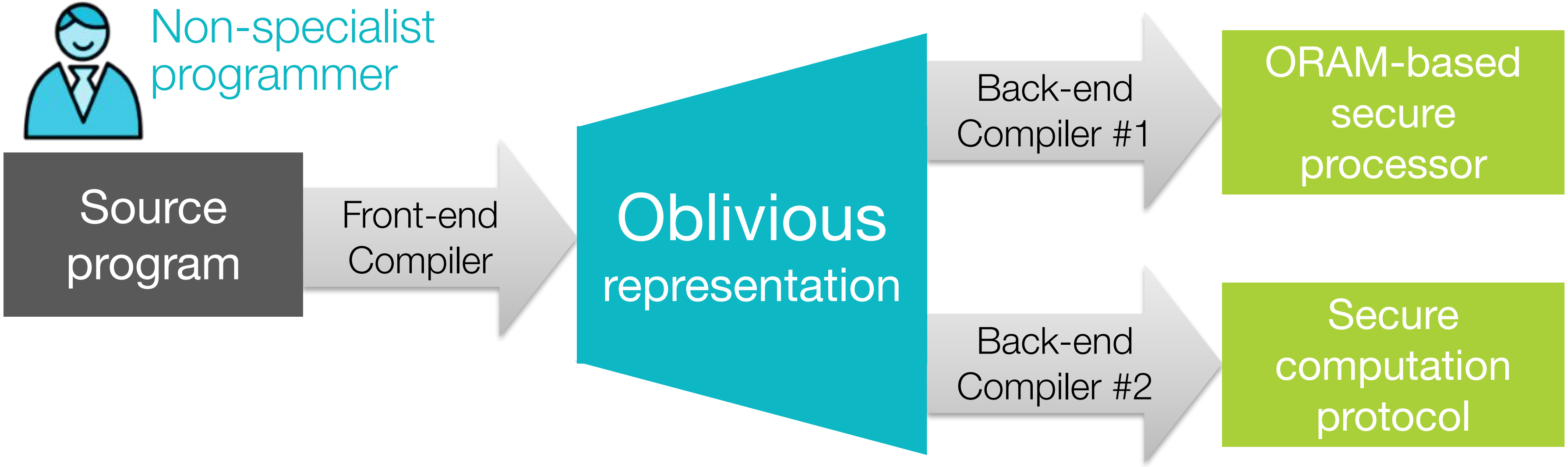
Data sent to “**low outputs**” does not depend on **secret inputs**.

Memory trace oblivious type system

Type system captures traces

A program’s **memory traces** do not depend on **secret inputs**.

ObliVM: a programming framework for oblivious computation



Non-specialist programmer

Source program

Front-end Compiler

Oblivious representation

Back-end Compiler #1

ORAM-based secure processor

Back-end Compiler #2

Secure computation protocol

More details in our papers

- Memory Trace Oblivious Program Execution. Joint with Chang Liu and Mike Hicks.
- ObliVM: A Programming Framework for Secure Computation. Joint with Chang Liu, Xiao Shaun Wang, Kartik Nayak, and Yan Huang.
- GhostRider: A Hardware-Software System for Memory Trace Oblivious Computation. Joint with Chang Liu, Michael Hicks, Austin Harris, Mohit Tiwari, Martin Maas.

Our related works

xjSNARK: Optimizing compiler for ZKP

Cool subsequent work by others

A Language for Probabilistically Oblivious Computation, POPL’20

By David Darais, Ian Sweet, Chang Liu, and Michael Hicks

Two Challenges

- Cryptography speaks the circuits, not programs

- Choosing the right and most efficient cryptographic primitive

Viaduct:
automatically synthesizing cryptographic protocols

Joint work with Coşku Acay, Rolph Recto, Joshua Gancher, and Andrew C. Myers

What if the programmer doesn’t know which cryptographic primitive to use?

Implementing Shell with FLAM annotations

```
host alice: {A}
host bob   : {B}

val n: {B ∧ A←} =
  endorse (input int bob) from {B}
var tries: {A ⊓ B} = 5
var win: {A ⊓ B} = false
while (0 < tries ∧ !win) {
  val guess =
    declassify (input int alice) to {A ⊓ B→}
  val tguess: {A ⊓ B} =
    endorse guess from {A ⊓ B→}
  win = declassify (n == tguess) to {A ⊓ B}
  tries -= 1
}
output win to alice, bob
```

“Endorse” raises the integrity label

Prevent dealer from changing shell

```
host Alice    // dealer
host Bob      // player

let shell = endorse (input Alice) to Bob
let valid = declassify (0 ≤ shell ≤ 2) to Bob
if valid:
  let guess = endorse (input Bob) to Alice
  let win = declassify (guess == shell) to Alice ∨ Bob
  output win to Alice, Bob
```

“Endorse” raises the integrity label

$A \land B^{\leftarrow}$: private to A, trusted by A and B

A: private and trusted to A

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host Alice    // dealer
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“Declassify” downgrades the privacy label

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```

Allow player to read valid

“Declassify” downgrades the privacy label

$(A^{\rightarrow} \wedge B^{\rightarrow}) \wedge (A^{\leftarrow} \wedge B^{\leftarrow})$:

A and B can see,
trusted by A and B

$A \wedge B^{\leftarrow}$:

private to A, trusted by A and B

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Reveal the result

Synthesis: partitioning the program

Who should execute this?

```
host Alice    // dealer
host Bob      // player

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Who should execute this?

~~Alice~~ ?

Synthesis: partitioning the program

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Who should execute this?

~~Alice ?~~

~~Bob ?~~

Synthesis: partitioning the program

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Who should execute this?

Synthesis: partitioning the program

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```


MPC

Naive synthesis: execute entire program in MPC!

- 👍 Secure
- 👎 Inefficient

Avoid using crypto

e.g. local execution or replicated execution

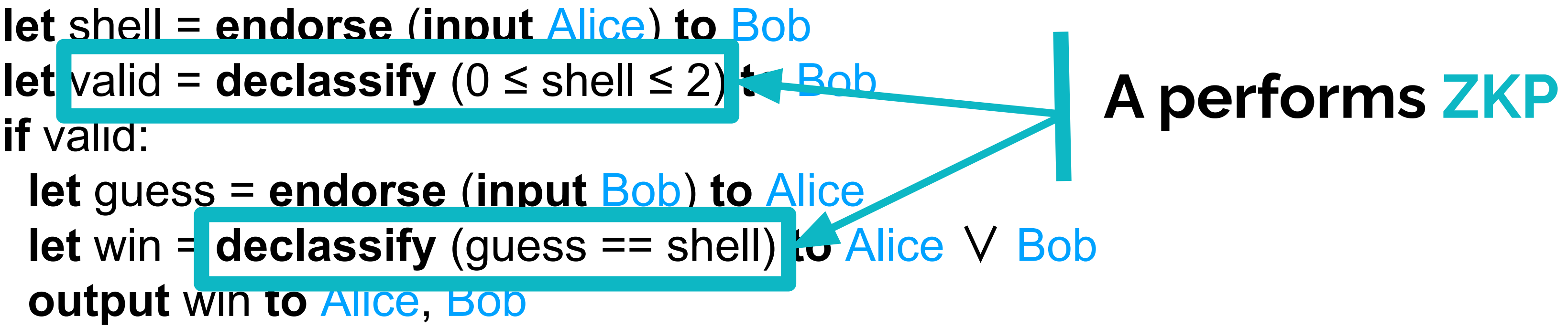
Use cheaper crypto

e.g. commitment < ZKP < MPC

… while respecting security

A more efficient synthesis

```
host Alice    // dealer
host Bob      // player
```



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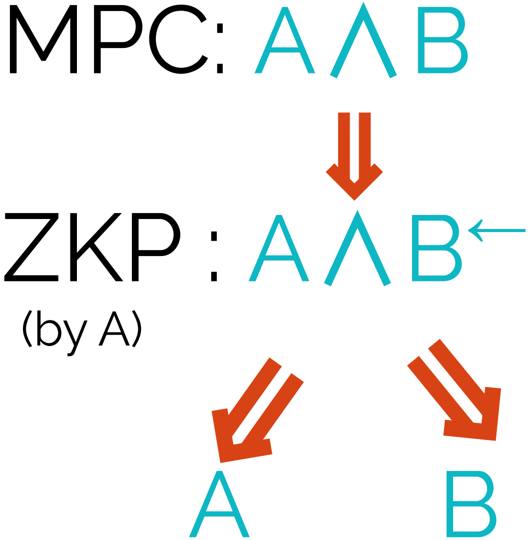
A performs ZKP

Think of crypto as "principals"

MPC: $A \wedge B$	neither can see, trusted by A and B
ZKP : $A \wedge B^{\leftarrow}$ (by A)	private to A, trusted by A and B
commit: $A \wedge B^{\leftarrow}$ (by A)	private to A, trusted by A and B

Lattice defines an ordering among principals ⇒ **"acts for"**



MPC: $A \wedge B$ neither can see, trusted by A and B

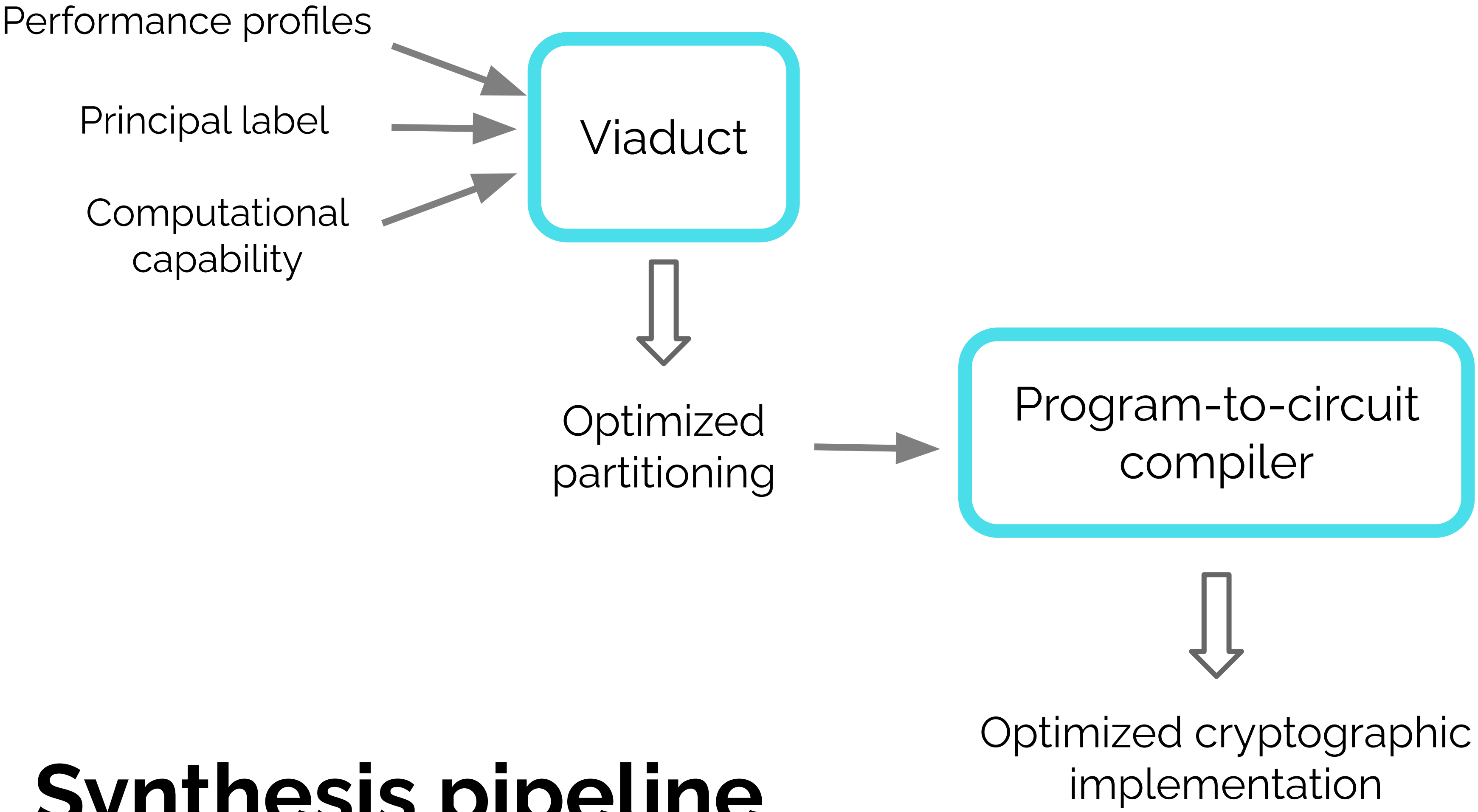
⇓

ZKP : $A \wedge B$ ← private to A, trusted by A and B

(by A)

⇙ ⇘

A B



Performance profiles

Principal label

Computational capability

Viaduct

Optimized partitioning

Program-to-circuit compiler

Optimized cryptographic implementation

Synthesis pipeline

Check out our open-source implementation

https://viaduct-lang.org

Open questions

- Compiler correctness

Open questions

- Compiler correctness
- More expressive performance profiles

  e.g., bandwidth vs compute
  boolean vs numeric computation
  prover vs verifier time

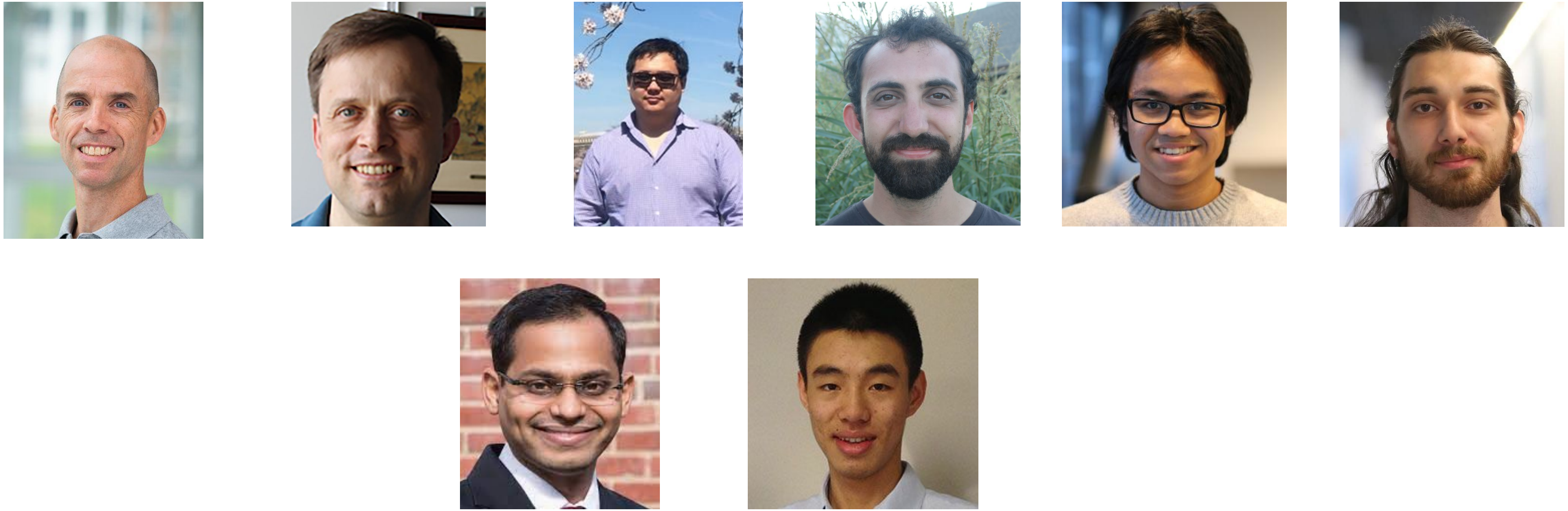
Open questions

- Compiler correctness
- More expressive performance profiles
- Utilize “hand-optimized” capabilities
  - e.g., private set intersection

Open questions

- Compiler correctness
- More expressive performance profiles
- Utilize “hand-optimized” capabilities
- Reason about other security properties

  e.g., fairness



Thank you!

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