Practical Cryptographic Secure Computation

DHOSA MURI
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TRANSFORMATION
- SVA
- Binary translation and emulation
- Formal methods

→ e.g., Enforce properties on a malicious OS

HARDWARE
- Hardware support for isolation
- Dealing with malicious hardware

→ e.g., Prevent data exfiltration

SYSTEM ARCHITECTURES
- **Cryptographic secure computation**
- Data-centric security
- WEB-BASED ARCHITECTURES
  - Secure browser appliance
  - Secure servers

→ e.g., Enable complex distributed systems, with resilience to hostile OS's

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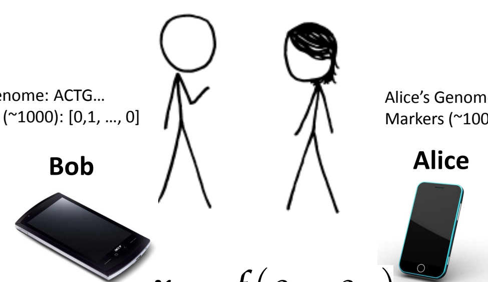
Secure Two-Party Computation

Bob's Genome: ACTG…
Markers (~1000): [0,1, …, 0]

Alice's Genome: ACTG…
Markers (~1000): [0, 0, …, 1]

Bob **Alice**



$$x = f(g_A, g_B)$$

Can Alice and Bob compute a function of their private data, without exposing anything about their data besides the result?

Secure Function Evaluation

Alice (circuit generator) **Bob (circuit evaluator)**

Picks $a \in \{0,1\}^s$ Agree on $f(a,b) \rightarrow x$ Picks $b \in \{0,1\}^t$

Garbled Circuit Protocol

Outputs $x = f(a,b)$ without revealing a to Bob or b to Alice.

Andrew Yao, 1982/1986

Yao's Garbled Circuits

Inputs		Output
a	b	x
0	0	0
0	1	0
1	0	0
1	1	1

a, b → **AND** → x

Computing with Meaningless Values?

Inputs		Output
a	b	x
a_0	b_0	x_0
a_0	b_1	x_0
a_1	b_0	x_0
a_1	b_1	x_1

a_i, b_i, x_i are **random** values, chosen by the **circuit generator** but **meaningless** to the **circuit evaluator**.

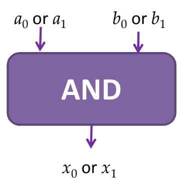
a_0 or a_1, b_0 or b_1 → **AND** → x_0 or x_1

Computing with Garbled Tables

Inputs		Output
a	b	x
a_0	b_0	$Enc_{a0,b0}(x_0)$
a_0	b_1	$Enc_{a0,b1}(x_0)$
a_1	b_0	$Enc_{a1,b0}(x_0)$
a_1	b_1	$Enc_{a1,b1}(x_1)$

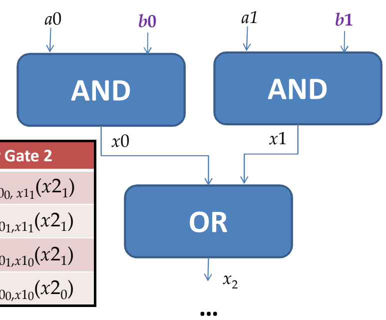
Bob can only decrypt **one** of these!

a_i, b_i, x_i are **random** values, chosen by the **circuit generator** but **meaningless** to the **circuit evaluator**.



Garbled And Gate
$Enc_{a0,\,b1}(x_0)$
$Enc_{a1,b1}(x_1)$
$Enc_{a1,b0}(x_0)$
$Enc_{a0,b0}(x_0)$

Chaining Garbled Circuits

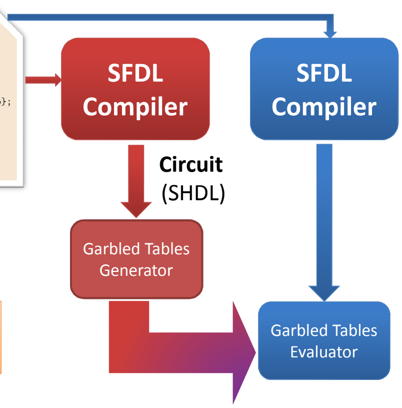


And Gate 1
$Enc_{a10,\,b11}(x1_0)$
$Enc_{a11,b11}(x1_1)$
$Enc_{a11,b10}(x1_0)$
$Enc_{a10,b10}(x1_0)$

Or Gate 2
$Enc_{x00,\,x11}(x2_1)$
$Enc_{x01,x11}(x2_1)$
$Enc_{x01,x10}(x2_1)$
$Enc_{x00,x10}(x2_0)$

We can do ***any*** computation privately this way!

Fairplay



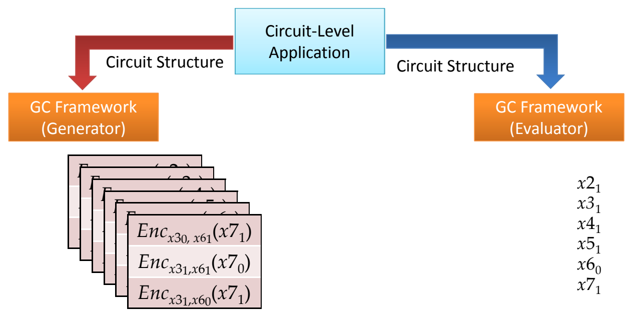

```
program Millionaires {
  type int = Int<4>;  // 4-bit integer
  type AliceInput = int;
  type BobInput = int;
  type AliceOutput = Boolean;
  type BobOutput = Boolean;
  type Output = struct {
      AliceOutput alice, BobOutput bob};
  type Input = struct {
      AliceInput alice, BobInput bob};

  function Output out(Input inp) {
    out.alice = inp.alice > inp.bob;
    out.bob = inp.bob > inp.alice;
```

SFDL Program

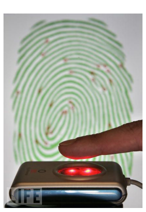
Dahlia Malkhi, Noam Nisan, Benny Pinkas and Yaron Sella [USENIX Sec 2004]

Our Approach: Faster Garbled Circuits



Gates can be evaluated as they are generated: **pipelining**
Gates can be evaluated in any topological sort order: **parallelizing**
Garbled evaluation can be **combined with normal execution**

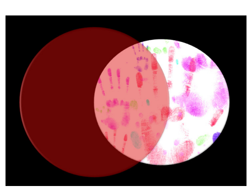
Applications



Privacy-Preserving Biometric Matching

Private Personal Genomics

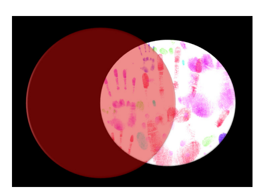
Private AES Encryption



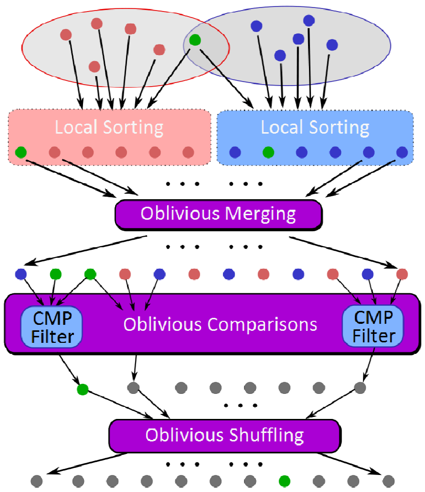
Private Set Intersection

Private Set Intersection

- Do Alice and Bob have any contacts in common?
- Two countries want to compare their miscreant lists
- Identify common medical records across hospitals
- Two companies want to do joint marketing to common customers



Sort-Compare-Shuffle

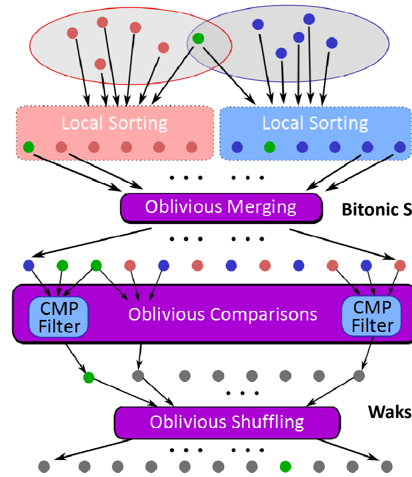


Sort: Take advantage of total order of elements

Compare adjacent elements

Shuffle to hide positions

Private Set Intersection Protocol



Gates to generate and evaluate

Free

Bitonic Sorting Circuit

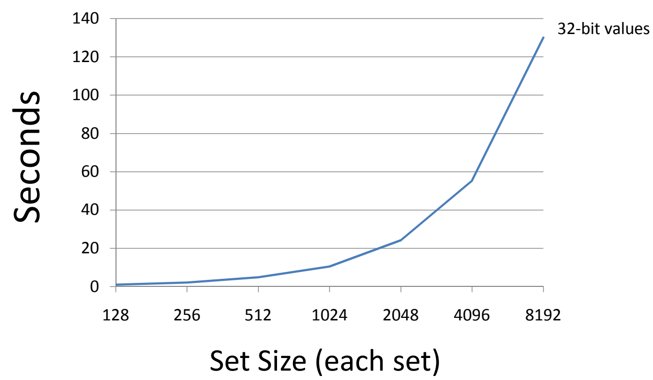
$$n\log(2n)\times 2\sigma$$

$$(3\sigma-1)(n-1)+(2\sigma-1)$$

Waksman Permutation Network

$$n\log n - n + 1$$

Private Set Intersection Results



Some Other Results

	Problem	Best Previous Result	Our Result	Speedup
USENIX Security 2011	**Hamming Distance** (Face Recognition) – 900-bit vectors	213s [SCiFI, 2010]	**0.051s**	**4176**
USENIX Security 2011	**Levenshtein Distance** (genome, text comparison) – two 200-character inputs	534s [Jha+, 2008]	**18.4s**	**29**
USENIX Security 2011	**Smith-Waterman** (genome alignment) – two 60-nucleotide sequences	[Not Implementable]	**447s**	-
USENIX Security 2011	**AES Encryption**	3.3s [Henecka, 2010]	**0.2s**	**16.5**
NDSS 2011	**Fingerprint Matching** (1024-entry database, 640x8bit vectors)	~83s [Barni, 2010]	**18s**	**4.6**

Scalable: 1 Billion gates evaluated at ~100,000 gates/second on laptop

Collaborators

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