Taking proof-based verified computation a few steps closer to practicality

Srinath Setty, Victor Vu, Nikhil Panpalia, Benjamin Braun, Andrew J. Blumberg, and Michael Walfish

The University of Texas at Austin
use auxiliary information to quickly verify

client

process_image (input)

output, auxiliary information

server
Probabilistically checkable proofs (PCPs) can help

- Fast verification: client saves work (asymptotically)
- General-purpose: can outsource any computation
- Unconditional: no assumptions about the server
The theory provides strong security properties, but the costs are outrageous

- Verifying multiplication of $500 \times 500$ matrices would take more than 500 trillion CPU years (seriously)

There is a lot of renewed interest in reducing costs with built systems

- Two efforts: PEPPER [HotOS11, NDSS12], Thaler et al. [ITCS12, HotCloud12]
- In some cases, PEPPER reduces costs by a factor of $10^{20}$ over a naive implementation of the theory
But all of these recent works have notable limitations

1. The client has to outsource large computations to offset verification costs

2. Their model of computation is arithmetic circuits

Example:

Arithmetic circuits cannot concisely express conditional control flow or comparisons
GINGER addresses some of these limitations

Reduces the client’s checking work and network costs by several orders of magnitude

Includes a massively parallel GPU-based implementation

Supports a general-purpose programming model

Concise conditionals, comparisons, efficient floating-point representation, etc.

A compiler to go from high-level code to executables
The main takeaway

**GINGER** and its predecessor (**PEPPER**) together reduce costs by a factor of $10^{20}$ using theory and systems techniques.

We still need a factor of $\approx 10^3$ on the server for true practicality.

We think that proof-based verified computation could be practical in the near future.
Rest of this talk

→ Design of GINGER

Experimental results
Theory that GINGER builds on

client

server

circuit, input

output

queries to the proof

responses: 9, 1, ...

accept/reject

client’s tests

proof
The server creates a proof by redundantly encoding the circuit’s wire values.

**Diagram:**
- **Circuit for the computation:**
  - Two X-gates with inputs 2 and 4, and 5 and 3, respectively.
  - An addition gate with inputs 10 and 12, resulting in an output of 22.

- **Values on wires of the circuit:**
  - Row 1: 2, 5, 10, 4, 3, 12, 22

- **Proof:**
  - 2, 1, 0, 4, 9, 22, 44, ...
  - (Note: The proof is not fully shown in the diagram.)

**Redundant encoding:**
- The values are encoded redundantly to create a proof.
A diagram illustrates the interaction between a client and a server. The client sends a circuit and input to the server, which processes them and returns an output. The client then queries the proof related to the circuit. The responses from the server include accept/reject decisions. The diagram shows the flow of information between the client and server, with arrows indicating the direction of data exchange.
The client queries the server’s proof and runs a set of tests

tests at the client
1. consistency test
2. linearity test
3. quadratic corr. test
4. circuit test

accept/reject

proof at the server

queries to the proof
responses: 9, 0, ...

2
1
0
4
9
22
44
•

4
There is some probability that the client accepts an incorrect proof.

The costs depend on the size of the circuit.
GINGER’s contributions include:

→ Reducing the costs by revisiting the client’s tests

Broadening the space of computations

Incorporating primitive floating-point numbers (in the paper)
Reducing the costs by revisiting the client’s tests

client’s tests
1. consistency test
2. linearity test
3. quadratic corr. test
4. circuit test

Modifications:

Trade off more queries that are cheap for fewer of a more expensive type

Reuse queries across tests, and compress queries

Benefit: savings in client’s checking costs and network costs
GINGER’s contributions include:

✓ Reducing the costs by revisiting the client’s tests

→ Broadening the space of computations

Incorporating primitive floating-point numbers (in the paper)
We change the model of computation from arithmetic circuits to systems of equations.

The new model can represent general-purpose programming constructs concisely.

End-to-end costs decrease by many orders of magnitude.
An example

\[
\text{increment}(X) \quad \Rightarrow \quad Y = X + 1
\]

\[\begin{align*}
0 &= X - \text{<input>} \\
0 &= Y - (X + 1) \\
0 &= Y - \text{<output>}
\end{align*}\]

Once the inputs are fixed, an incorrect output will result in an inconsistent system of equations.

Suppose the input is 6

\[
\begin{align*}
0 &= X - 6 \\
0 &= Y - (X + 1) \\
0 &= Y - 7
\end{align*}\]

If the output is 7

There is a solution

If the output is 8

\[
\begin{align*}
0 &= X - 6 \\
0 &= Y - (X + 1) \\
0 &= Y - 8
\end{align*}\]

There is no solution
We can encode many program constructs

For example, consider “X != Y”:

Our equation is \(1 = (X - Y) \times M\)

Observe: no solution if \(X = = Y\)
Another example with conditional control flow

```plaintext
function(bool X)
    if (X)
        Y = 3
    else
        Y = 4

0 = X - M
Y = M * 3 + (1-M) * 4
```
Compiling code into a system of equations

\[
\text{function(bool } X) \\
\text{ if (X)} \\
\text{ Y = 3} \\
\text{ else} \\
\text{ Y = 4}
\]

\[
0 = X - M \\
Y = M \times 3 + (1-M) \times 4
\]
The server creates a proof by redundantly encoding a solution to the system of equations.

\[
\begin{align*}
0 &= X_1 - 2 \\
0 &= X_2 - 5 \\
0 &= X_3 - (X_1 \times X_2) \\
0 &= Y - 22
\end{align*}
\]
GINGER’s contributions include:

✓ Reducing the costs by revisiting the client’s tests

✓ Broadening the space of computations

Incorporating primitive floating-point numbers (in the paper)
Implementation and experimental testbed

Massively parallel implementation

- C++ code with OpenMP threads; HTTP/Open MPI to distribute server’s work
- CUDA to offload work to GPUs

Evaluation testbed

- A cluster at Texas Advanced Computing Center (TACC)
- Each machine runs Linux on an Intel Xeon 2.53 GHz with 48GB of RAM.
- For GPU experiments, we use NVIDIA Tesla M2070 GPUs (448 CUDA cores and 6GB of memory)
Evaluation questions

1. What are the break-even points under GINGER?

2. What is the result of parallelizing the server?

3. What are the savings from using systems of equations as opposed to circuits?
The break-even points decrease significantly

Consider outsourcing many instances of $400 \times 400$ matrix multiplication

<table>
<thead>
<tr>
<th></th>
<th>CPU</th>
<th>GPU for crypto</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>break-even # instances</strong></td>
<td><strong>PEPPER</strong></td>
<td><strong>GINGER</strong></td>
</tr>
<tr>
<td>CPU</td>
<td>4500</td>
<td>3600</td>
</tr>
<tr>
<td><strong>client verification time</strong></td>
<td><strong>PEPPER</strong></td>
<td><strong>GINGER</strong></td>
</tr>
<tr>
<td>CPU</td>
<td>5.3 hours</td>
<td>4.3 hours</td>
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<tr>
<td>GPU for crypto</td>
<td>2.1 hours</td>
<td>1.5 hours</td>
</tr>
<tr>
<td>GPU for crypto</td>
<td>1300</td>
<td>1800</td>
</tr>
</tbody>
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Evaluation questions

1. What are the break-even points under GINGER?

2. What is the result of parallelizing the server?

3. What are the savings from using systems of equations as opposed to circuits?
Parallelizing the server results in a near-linear speedup in most cases.
Evaluation questions

1. What are the break-even points under GINGER?

2. What is the result of parallelizing the server?

3. What are the savings from using systems of equations as opposed to circuits?
GINGER’s representation is many orders of magnitude shorter compared to Boolean circuits.

<table>
<thead>
<tr>
<th>Benchmark</th>
<th># gates in Boolean circuit</th>
<th># variables in GINGER’s representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>root finding via bisection</td>
<td>$3 \times 10^8$</td>
<td>$2 \times 10^3$</td>
</tr>
<tr>
<td>Hamming distance</td>
<td>$10^6$</td>
<td>$2 \times 10^4$</td>
</tr>
</tbody>
</table>
Rest of this talk

✓ Design of GINGER

✓ Experimental results

→ Limitations, related work, and outlook
Limitations of GINGER

The client needs to outsource many instances to gain

The server’s resource costs are still high

Also, the efficiency of the server sometimes relies on reducing the redundancy in the proof’s encoding

The number of iterations in a loop should be known at compile time
Prior work on verifying computations

Make strong trust assumptions or give up being general-purpose:

Replication [Castro & Liskov TOCS02], trusted hardware [Chiesa & Tromer ICS10, Sadeghi et al. TRUST10], and auditing [Monrose et al. NDSS99, Haeberlen et al. SOSP07]

Special-purpose [Freivalds MFCS79, Golle & Mironov RSA01, Sion VLDB05, Benabbas et al. CRYPTO11, Boneh & Freeman EUROCRYPT11]

Use fully homomorphic encryption [Gennaro et al. CRYPTO10, Chung et al. CRYPTO10]

Proof-based verified computation [Ben-Or STOC88, Babai STOC91, Kilian STOC92, Blum et al. JACM95, Arora et al. JACM98, Ben-Sasson et al. 12, Gennaro et al. 12]

Built systems:

Toward practical interactive proofs [Cormode ITCS12, Thaler et al. HotCloud12] based on [Goldwasser et al. STOC08]

Our prior work: PEPPER [HotOS11, NDSS12] based on [Ishai et al. CCC07]
Summary of GINGER

Reduces the client’s checking work and network costs by several orders of magnitude

Includes a massively parallel GPU-based implementation

Supports a general-purpose programming model
Looking back

About two years ago, we set out to build a system for proof-based verified computation

Then, the estimated costs were on the order of trillions of CPU years

Main takeaway

We combined theory and systems techniques to reduce costs by a factor of $10^{20}$

We still need a factor of $\approx 10^{3}$ on the server for true practicality

But we think that proof-based verified computation could be practical for real in the near future