Efficient RAM and control flow in verifiable outsourced computation

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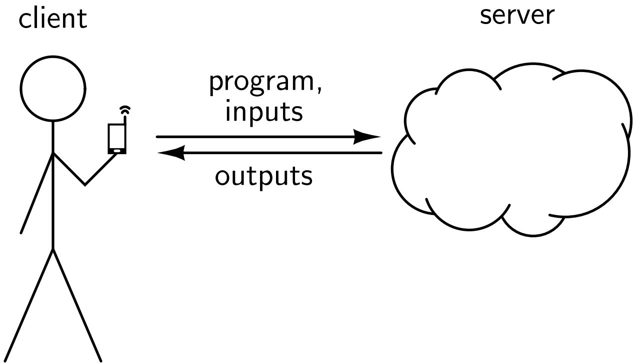
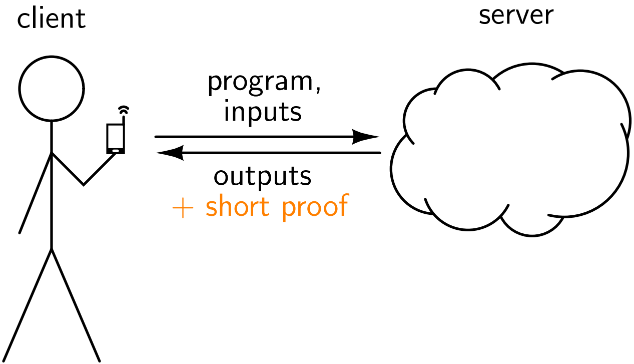
Proof-based verifiable computation enables outsourcing



Goal: A client wants to outsource a computation

- with strong correctness guarantees, and
- without assumptions about the server's hardware or how failures might occur.

Proof-based verifiable computation enables outsourcing



Approach: Server's response includes short proof of correctness.

This solution is based on powerful theoretical tools.
[GMR85, BCC88, BFLS91, ALMSS92, AS92, Kilian92, LFKN92, Shamir92, Micali00, BS05, BGHSV06, IKO07, GKR08]

Related work in proof-based verification

setup costs	applicable computations: regular structure	straight line	pure	stateful	general control flow
none	Thaler, CMT, TRMP [CRYPTO13, ITCS12, HotCloud12]				
low		Allspice [IEEE S&P13]			
med	Pepper [NDSS12]	Ginger [Security12]	Zaatar [Eurosys13], Pinocchio [IEEE S&P13]	Pantry [SOSP13]	
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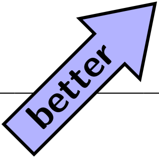

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better

Verifiable computation still faces challenges

	Buffet (this work)
Tension between expressiveness and efficiency	Substantially mitigated
Large (amortized) setup costs for the client; massive server overhead	Not addressed

The rest of this talk

1. Background: the proof-based verification framework

2. Buffet: dynamic control flow in arithmetic circuits

3. Experimental results

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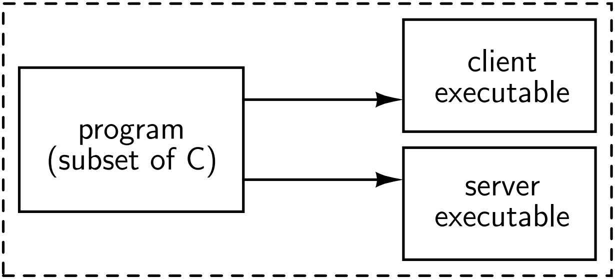
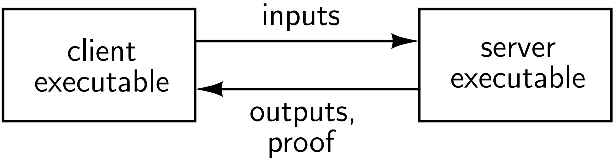
Verifiable computation overview: common machinery

Buffet and its predecessors share a common framework.





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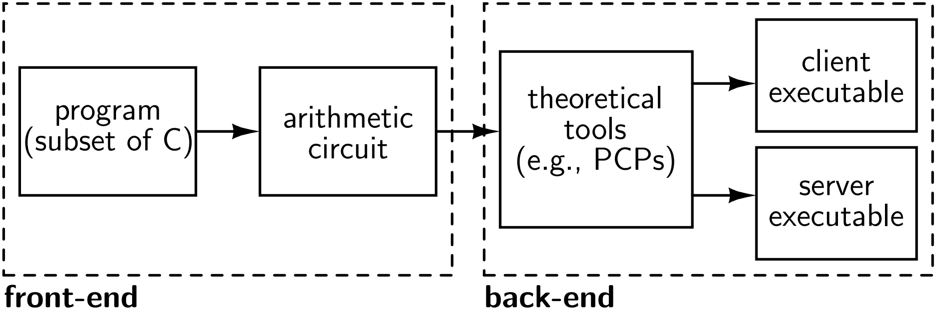

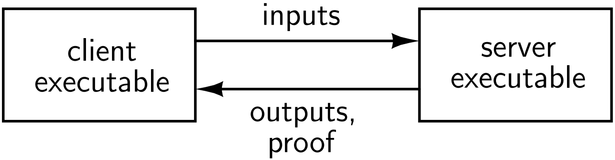

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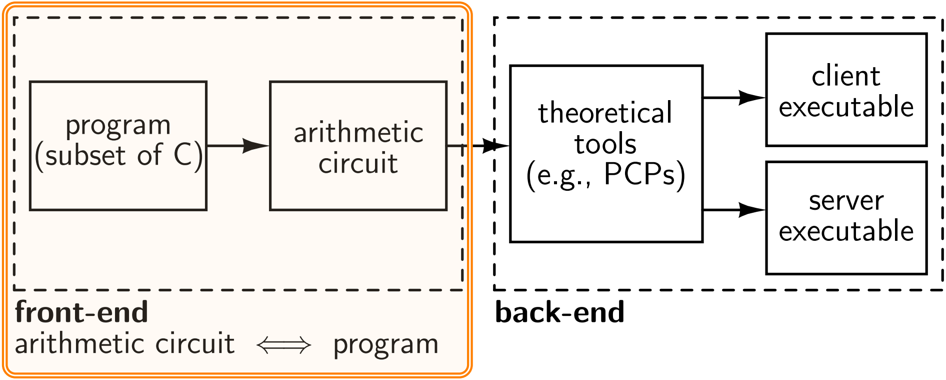

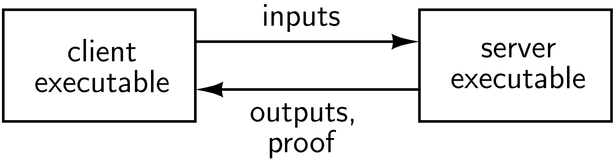

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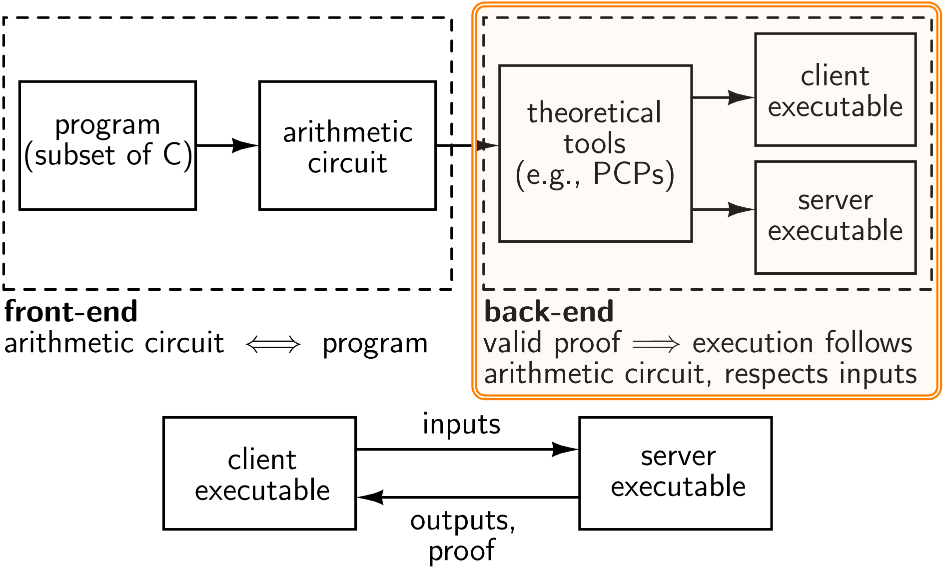

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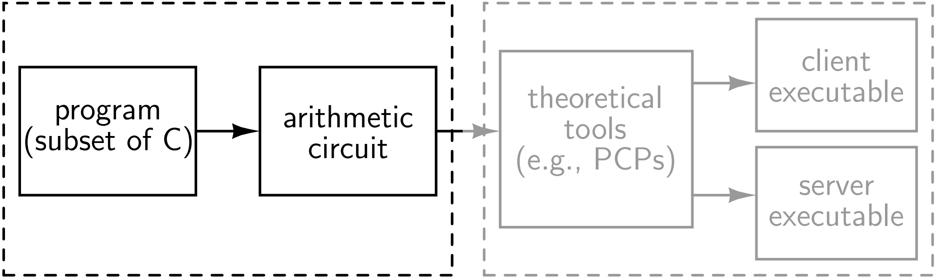

front-end
arithmetic circuit $\iff$ program

back-end
valid proof $\implies$ execution follows arithmetic circuit, respects inputs

Costs scale with arithmetic circuit size. So:

How can Buffet's front-end efficiently represent general-purpose C programs in arithmetic circuits?

Compiling programs to circuits in Pantry [SOSP13] (and Zaatar [Eurosys13] and Pinocchio [IEEE S&P13])

These compilers handle a subset of C:

1. Assignment: allocate a fresh wire for each assignment.

```
i = i + 1;
```

$\Longrightarrow$

```
i1 = i0 + 1;
```

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2. Conditionals: execute both branches and select desired result.

```
if (i > 5)
    i = i + 1;
else
    i = i * 2;
```

$\Longrightarrow$

```
i1 = i0 + 1;
i2 = i0 * 2;
i3 = (i0 > 5) ?
       i1 : i2;
```

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3. Loops: unroll at compile time. Loop bounds must be static.

```
i=0;
for (j=0; j<10; j++) {
    i++;
}
```

$\Longrightarrow$

```
i = 0;
i0=i+1;  // j == 0
i1=i0+1; // j == 1
...
i9=i8+1; // j == 9
```

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Buffet also adapts and refines a previous approach to verified RAM [BCGT12, BCGTV13, BCTV14] (see paper).

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Compiling nested loops

In a loop nest, inner loop unrolls into every iteration of outer loop.

```
i=0;
for (j=0; j<10; j++) {
  i++;
  for (k=0; k<2; k++) {
      i=i*2;
  }
}
```

⟹

```
i = 0;
i0=i+1;  // j == 0
i1=i0*2; // k == 0
i2=i1*2; // k == 1
i3=i2+1; // j == 1
i4=i3*2; // k == 0
i5=i4*2; // k == 1
...
```

Compiling nested loops with data dependent bounds

Consider a decoder for a run-length encoded string with output size `OUTLENGTH`:

"a5b2" $\Rightarrow$ "aaaaabb"

```
i = j = 0;
while (j < OUTLENGTH) {
    inchar = input[i++];
    length = input[i++];

    do {
        output[j++] = inchar;
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    } while (length > 0);
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1. Read (`inchar`,`length`) pair.

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    do {
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        length--;               (2)
    } while (length > 0);
}
```

1. Read (`inchar`,`length`) pair.
2. Emit `inchar`, `length` times.

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while (j < OUTLENGTH) {
    inchar = input[i++];
    length = input[i++];

    do {                        /* bound= ???      */
        output[j++] = inchar;
        length--;
    } while (length > 0);
}
```

At one extreme, a single character's run length could be `OUTLENGTH`. so this must be the inner bound.

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        length--;
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```

At the other extreme, every character's run length could be 1, and the outer loop would iterate `OUTLENGTH` times.

Compiling nested loops with data dependent bounds

Consider a decoder for a run-length encoded string
with output size `OUTLENGTH`:

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while (j < OUTLENGTH) {        /* bound=OUTLENGTH */
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```

But: this code executes $\texttt{OUTLENGTH}^2$ inner loop iterations,
and the resulting arithmetic circuit is quadratic in `OUTLENGTH`.

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Consider:

1. Loop nests are equivalent to finite state machines.
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Idea: transform loop nests into FSMs.

FSM Transformation: step 1

We can build a control flow graph for the RLE decoder:

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i = j = 0;
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```

FSM Transformation: step 1

We can build a control flow graph for the RLE decoder:

1

2

```
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1. Identify vertices: straight line code segments.

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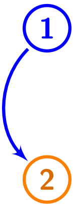


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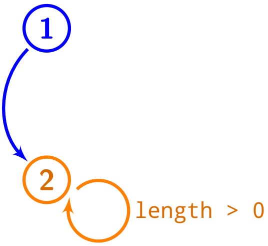


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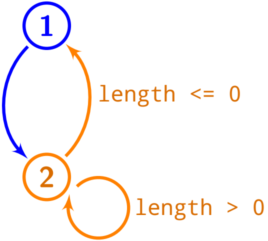


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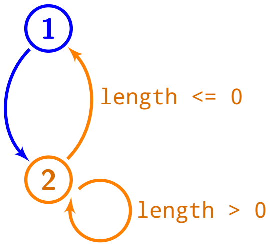
1. Identify vertices: straight line code segments.
2. Identify edges: control flow between segments.
   - 1 transitions to 2 unconditionally.
   - 2 self-transitions when `length > 0`.
   - 2 transitions to 1 when `length <= 0`.

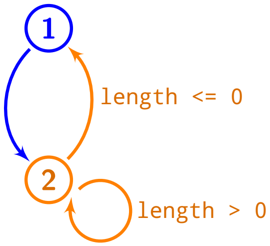
FSM Transformation: step 2

From the control flow graph



FSM Transformation: step 2

From the control flow graph, we can build a state machine.




```
i = j = 0;
state = 1;
while (j < OUTLENGTH) {
    if (state == 1) {
        inchar = input[i++];
        length = input[i++];
        state = 2;
    }
    if (state == 2) {
        output[j++] = inchar;
        length--;
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    }
    if (state == 2) {
        output[j++] = inchar;
        length--;
        if (length <= 0) {
            state = 1;
        }
    }
}
```

Buffet's FSM transformation: *loop flattening*

Buffet's transformation extends *loop flattening* [Ghuloum & Fisher, PPOPP95] with support for arbitrary loops, `break`, and `continue`.

Buffet's FSM transformation: *loop flattening*

Buffet's transformation extends *loop flattening* [Ghuloum & Fisher, PPOPP95] with support for arbitrary loops, `break`, and `continue`.

Caveats:

- Programmer must tell Buffet # of steps to unroll the FSM.
- No `goto` in Buffet's implementation (yet).
- No "program memory" ⇒ no function pointers.

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This is the approach of BCTV:
Represent a CPU transition

fetch-decode-execute

CPU state:
pc, regs, . . .

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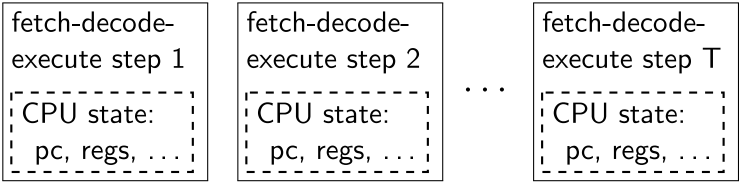

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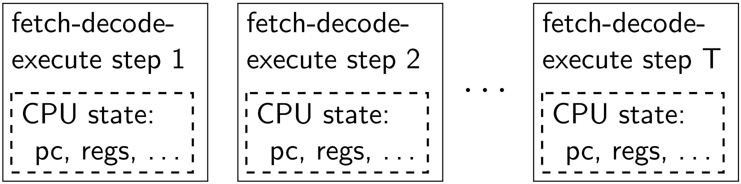

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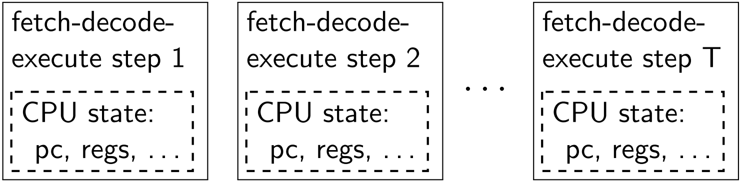

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But: BCTV pays the cost of an entire CPU for each program step.

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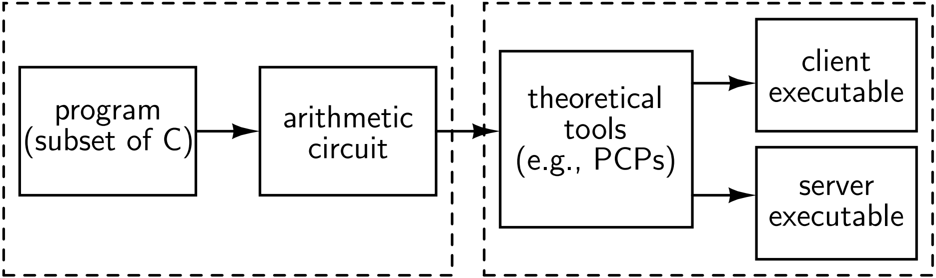
Evaluation questions



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Using the same back-end for Pantry, BCTV, and Buffet, how do the front-ends compare?

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1. For a fixed arithmetic circuit size, what is the maximum computation size each system can handle?
2. For a fixed computation size, what is the server's cost under each system?

Implementation

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Evaluation platform:

- Texas Advanced Computing Center (TACC), Stampede cluster
- Linux machines with Intel Xeon E5-2680, 32 GB of RAM

What is the maximum computation size for each system?

For an arithmetic circuit of $\approx 10^7$ gates, we have:

	Pantry	**BCTV**	**Buffet**
matrix multiplication $m \times m$	$m = 215$	$m = 7$	$m = 215$
merge sort k elements	$k = 8$	$k = 32$	$k = 512$
Knuth-Morris-Pratt search needle length $= n$ haystack length $= \ell$	$n = 4$, $\ell = 8$	$n = 16$, $\ell = 160$	$n = 256$, $\ell = 2900$

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Knuth-Morris-Pratt search needle length $= n$ haystack length $= \ell$	$n = 4$, $\ell = 8$	$n = 16$, $\ell = 160$	$n = 256$, $\ell = 2900$

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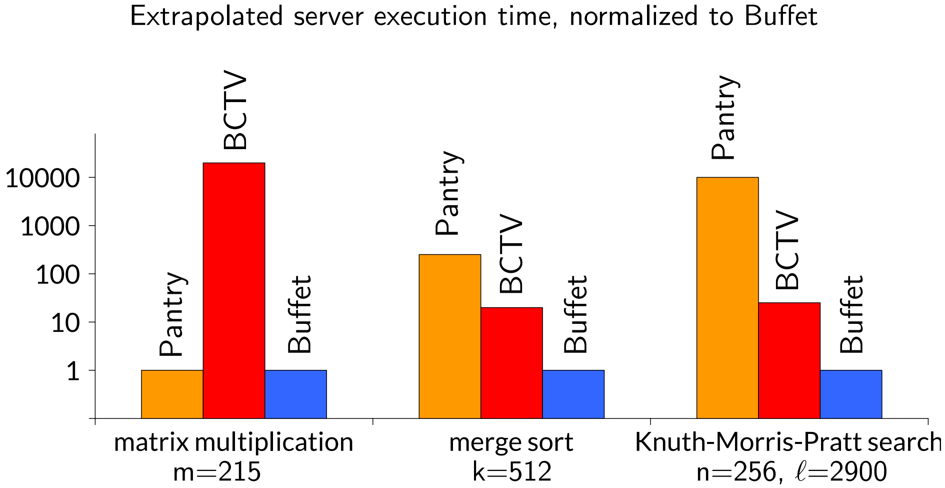
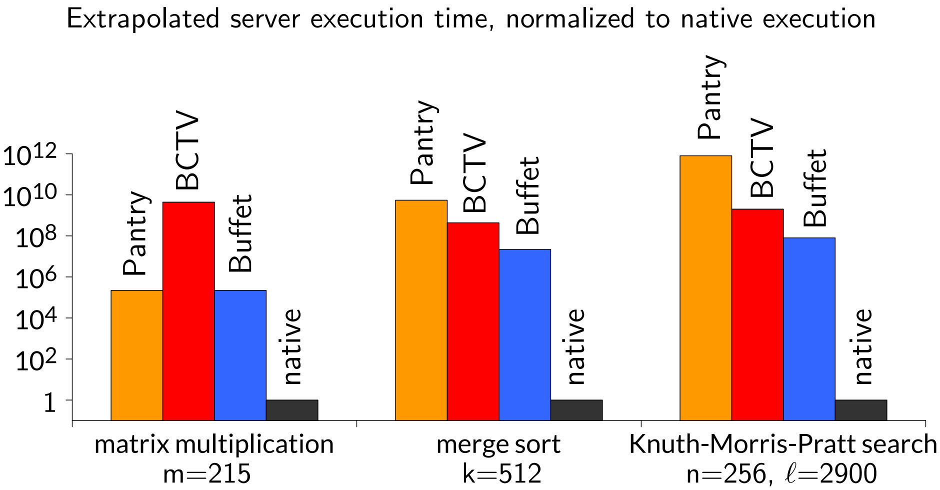
These data establish ground truth. For apples-to-apples front-end comparison, we now extrapolate to Buffet's computation sizes.

What is the server's cost for each system?



But we still have a long way to go!



Recap

Buffet combines the best aspects of Pantry and BCTV.

+ Straight line computations are very efficient.
+ Buffet charges the programmer only for what is used.
+ General looping is transformed into FSM, efficiently compiled.
+ RAM interactions are efficient (see paper).

Buffet improves on Pantry and BCTV by 1–4 orders of magnitude.

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`http://www.pepper-project.org/`