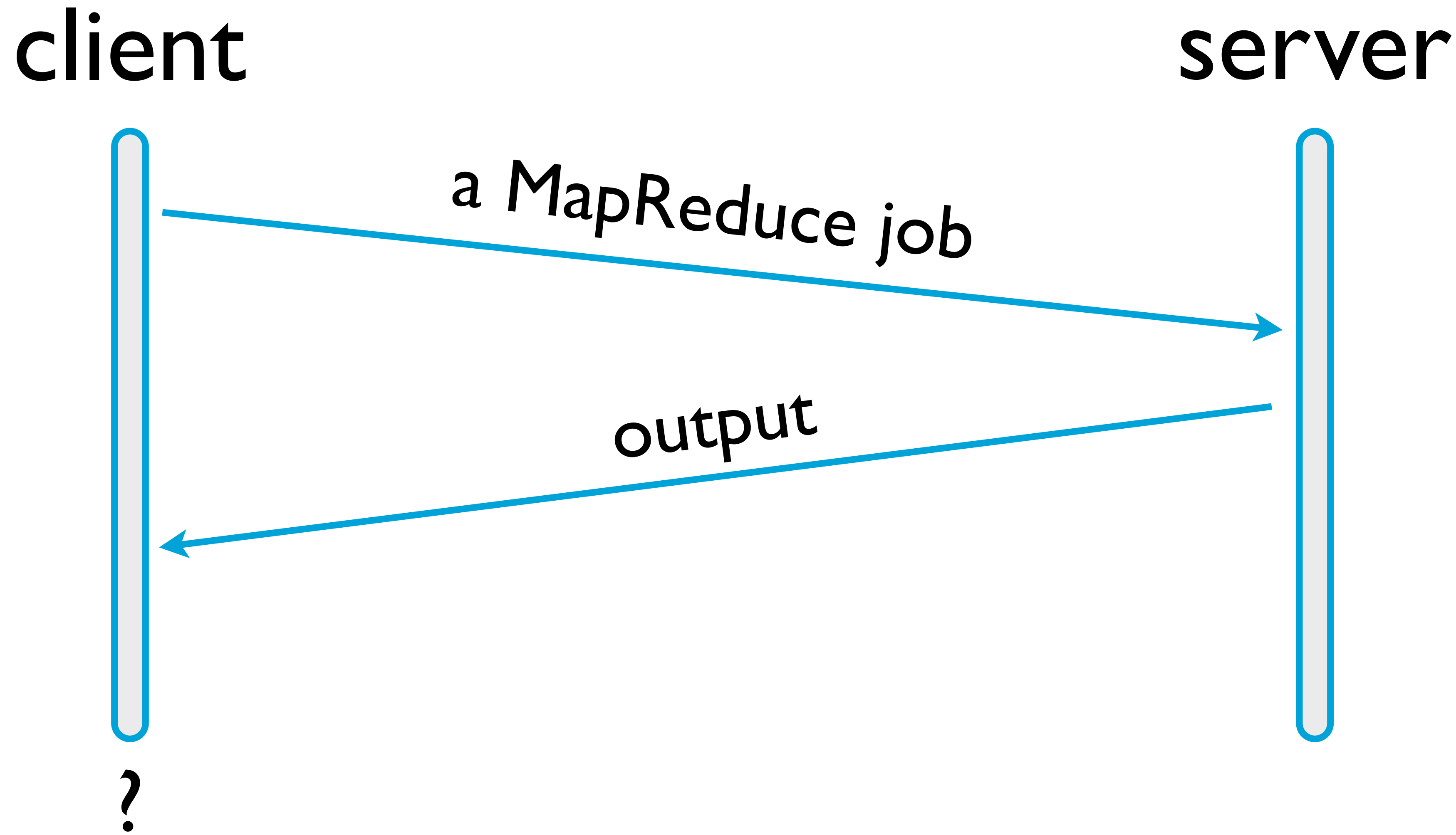
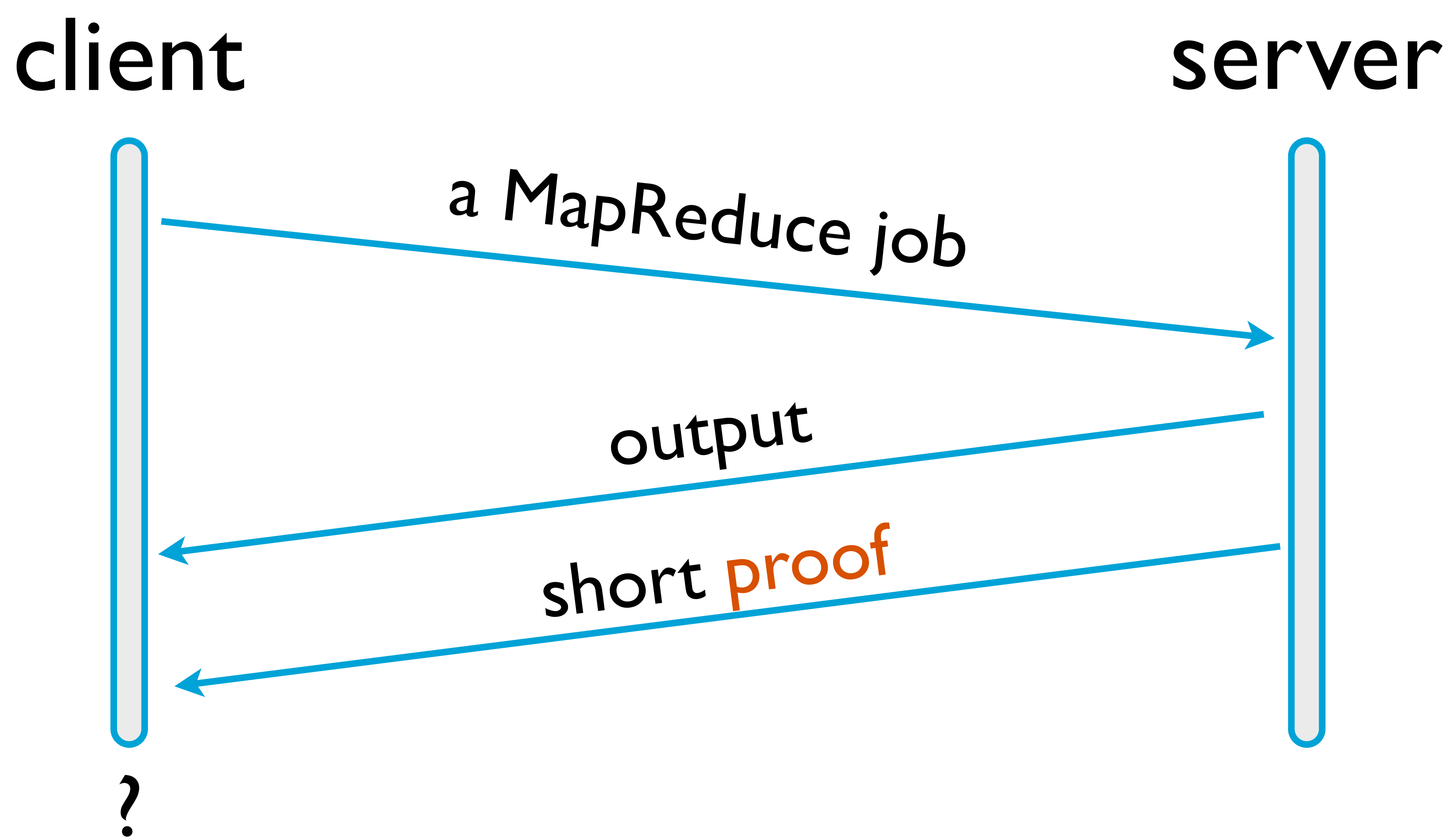
Verifying computations with state

Benjamin Braun, Ariel Feldman[†], Zuocheng Ren,
Srinath Setty, Andrew Blumberg, and Michael Walfish

The University of Texas at Austin
[†]University of Pennsylvania



the server could compute incorrectly



check the proof quickly

Theory (PCPs, arguments, etc.) offers a solution ...
but only in theory
[ALMSS92, Micali00, BCC88, Kilian92, IKO07]

Recent projects refine and implement the theory

CMT, TRMP, and Thaler [Cormode et al. ITCS12, Thaler et al. HotCloud12, Thaler CRYPTO13]

Pepper, Ginger, Zaatar, and Allspice [HotOS11, NDSS12, USENIX SECURITY12, EuroSys13, IEEE S&P13]

Pinocchio [Gennaro et al. EUROCRYPT13, Parno et al. IEEE S&P13]

BCGTV [Ben-Sasson et al. CRYPTO13]

Highlights

Compile C programs into verifiable computations

Reduce costs by over a factor of 10^{20}

Remaining roadblocks in bringing the theory to practice

- The computations have to be stateless
- The client incurs a large setup cost
- The server's overheads are large

Remaining roadblocks in bringing the theory to practice	Pantry (this talk)
• The computations have to be stateless	[Eliminate]
• The client incurs a large setup cost	[Mitigate]
• The server's overheads are large	[Retain]

Aren’t there more pragmatic alternatives?

Yes and no.

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Yes and no. Consider replication, trusted hardware, etc.:

(1) Far less expensive than Pantry ... but impose assumptions

- Long-term, we want unconditional, cost-effective guarantees
- Pantry is a step toward this goal

(2) Pantry enables new applications for which there are not pragmatic alternatives

- Computations over private server state, etc.

Rest of this talk:

- The computations have to be stateless
- The client incurs a large setup cost
- The server's overheads are large

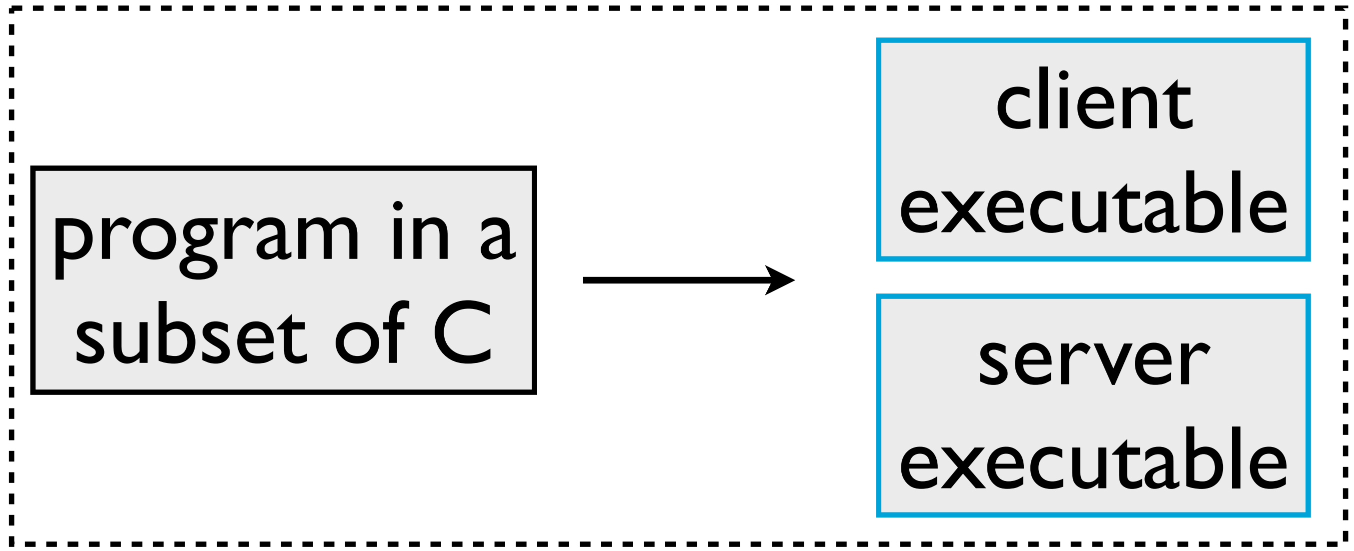
1

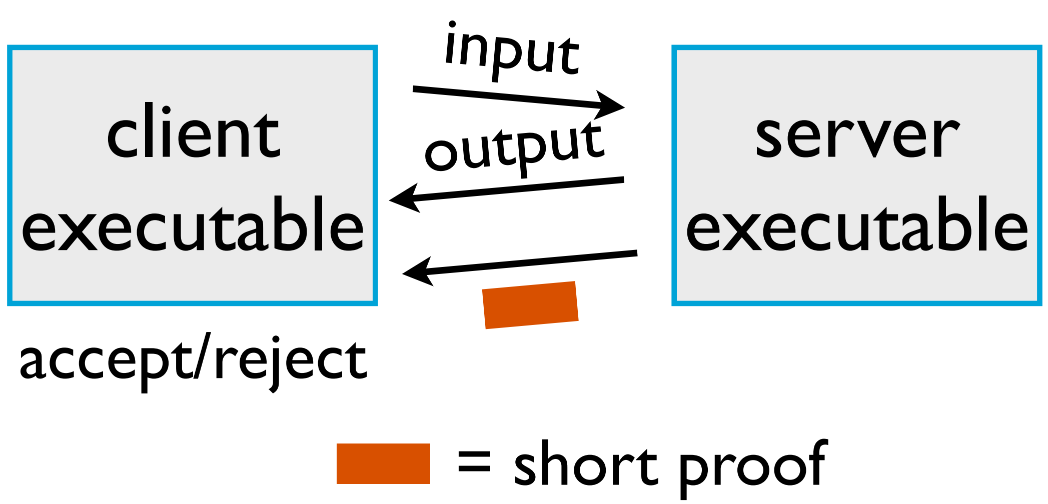
2 [Eliminate]

3 [Mitigate]

[Retain]

Pantry's base: Zaatar [EuroSys13] and Pinocchio [IEEE S&P13]





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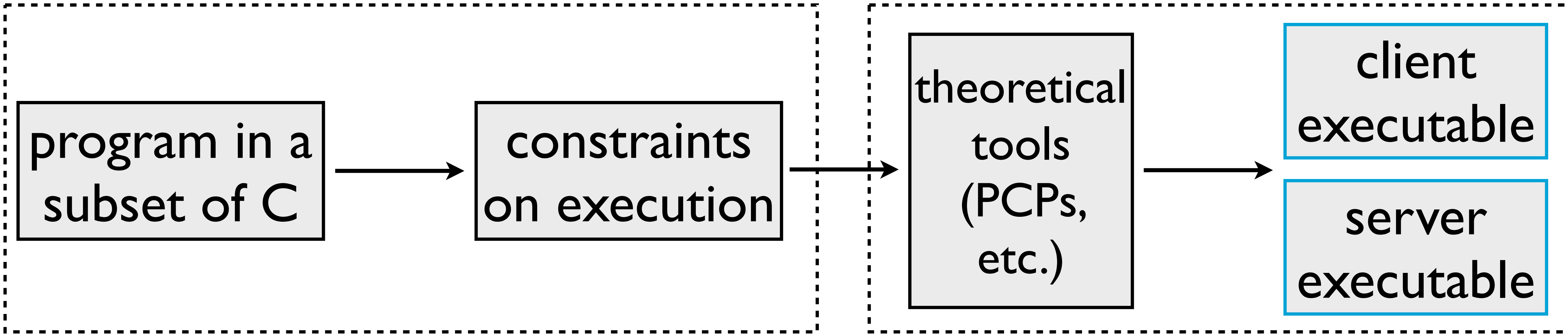

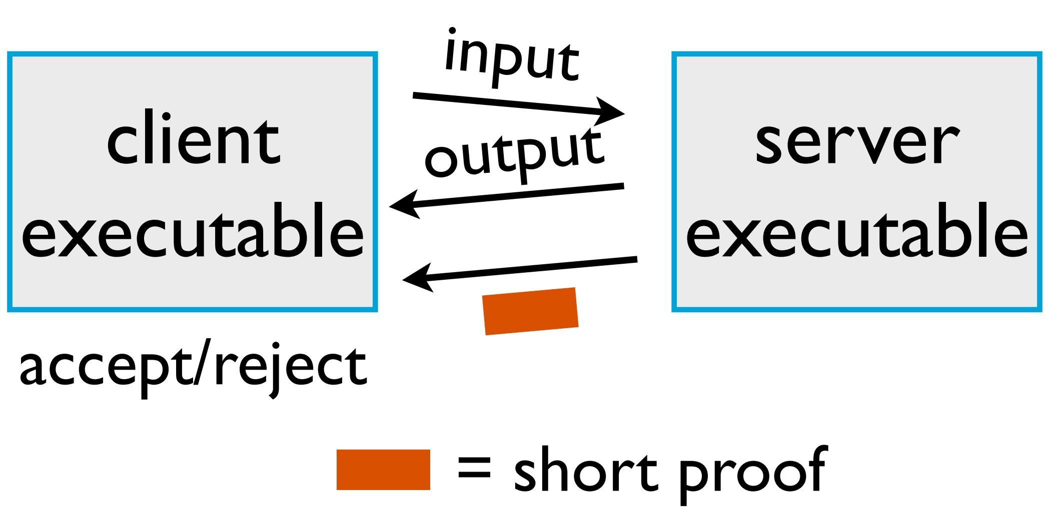

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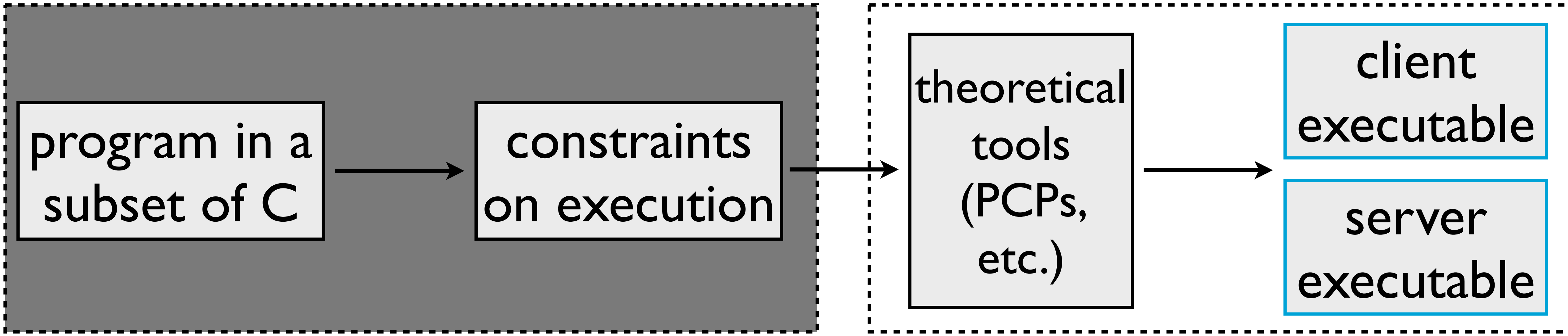

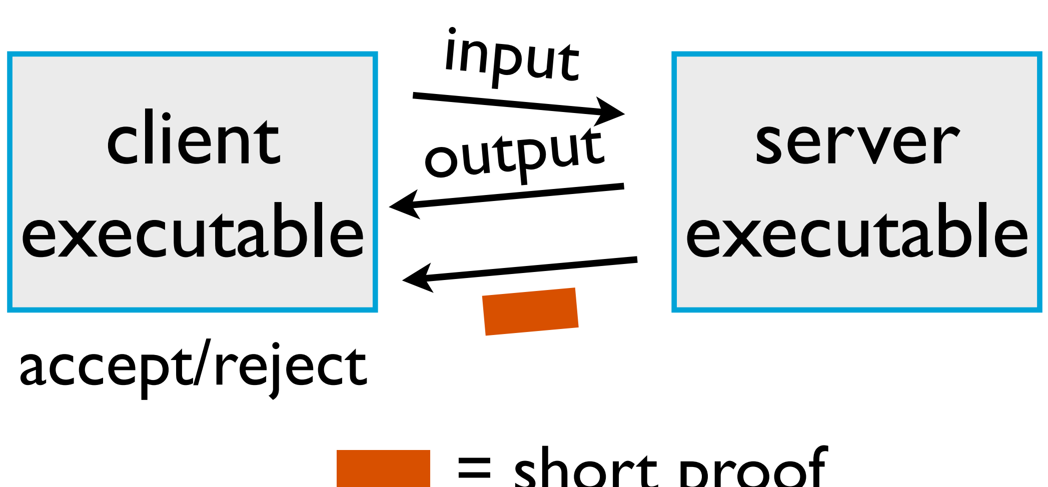

Programs compile into a set of constraints

```
int increment(int i) {
  r = i + 1;
  return r;
}
```

⟷

$0 = X - i$

$0 = Y - (X + 1)$

$0 = Y - r$

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Correct input/output pair means that the equations have a solution (i.e., constraints are satisfiable)

Suppose the input is 6

If the output is 7

$0 = X - 6$
$0 = Y - (X + 1)$
$0 = Y - 7$

There is a solution

If the output is 8

$0 = X - 6$
$0 = Y - (X + 1)$
$0 = Y - 8$

There is no solution

Constraints can represent various program structures

Example: "$Y = (X1 \neq X2)$"

$$0 = (X1 - X2) \cdot M - Y$$

$$0 = (1 - Y) \cdot (X1 - X2)$$

Observe:

if X1 == X2, then Y must be 0, to satisfy the first.

if X1 != X2, then Y must be 1, to satisfy the second.

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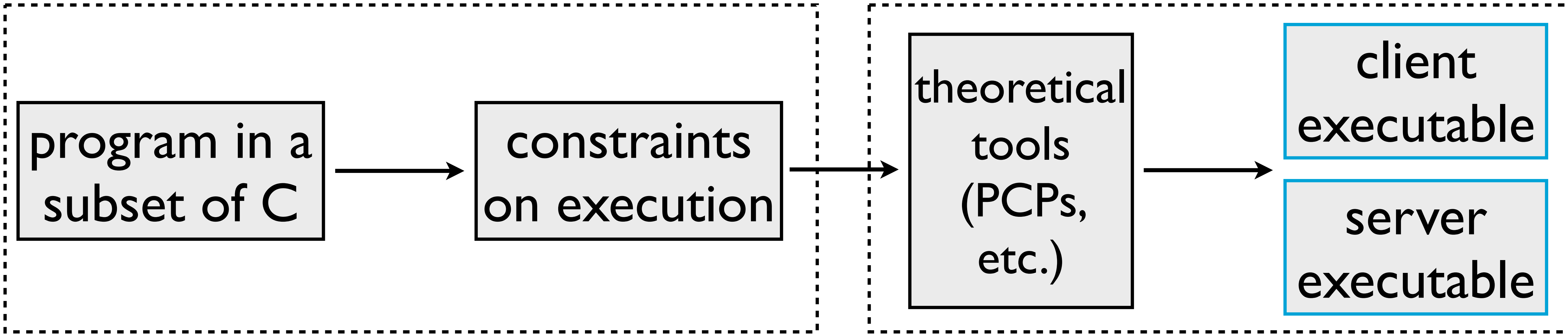
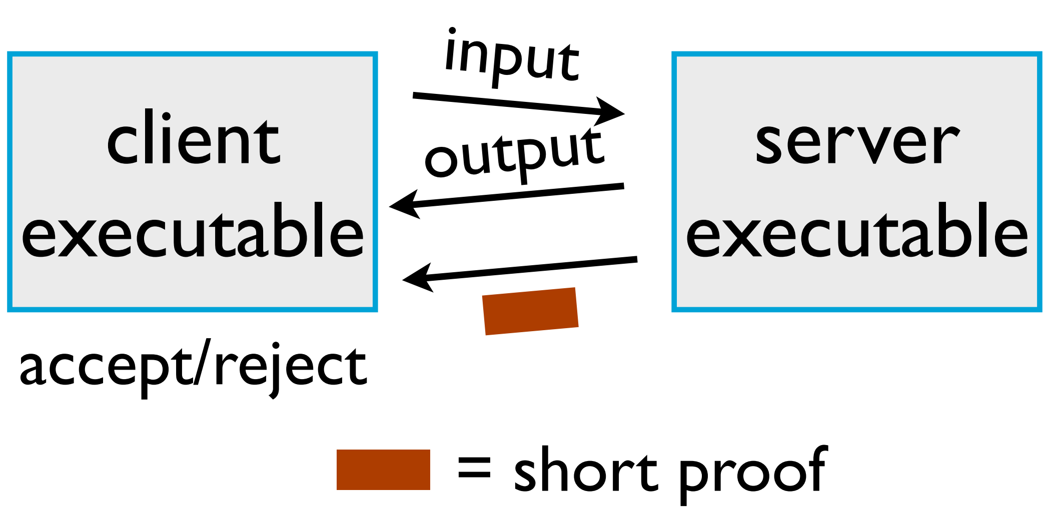


satisfiability of constraints ⇔

correct execution



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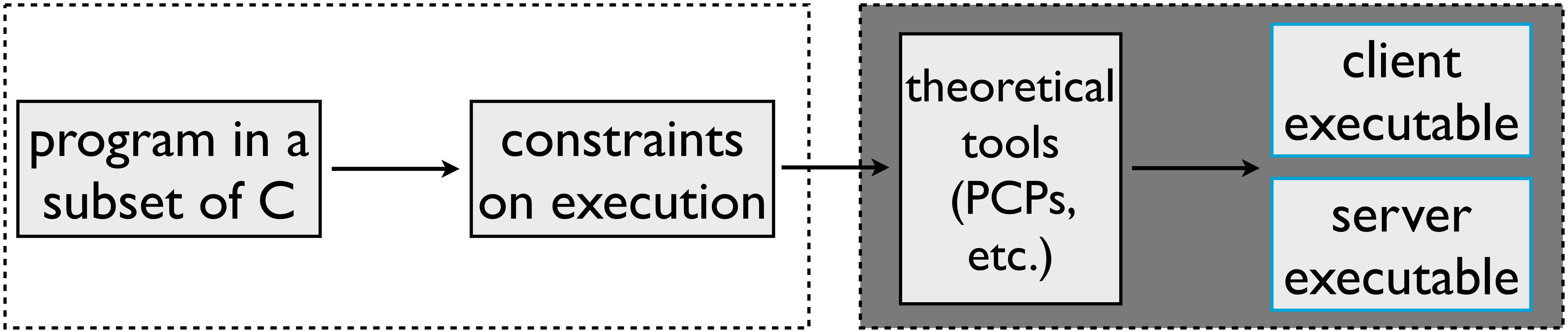

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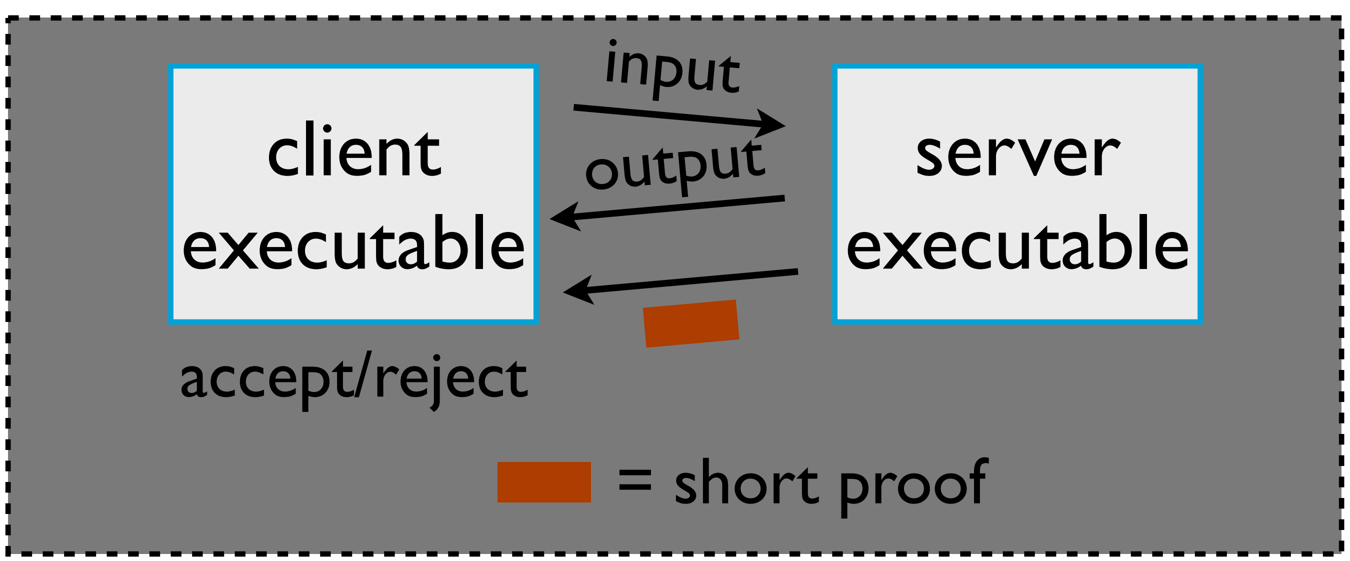
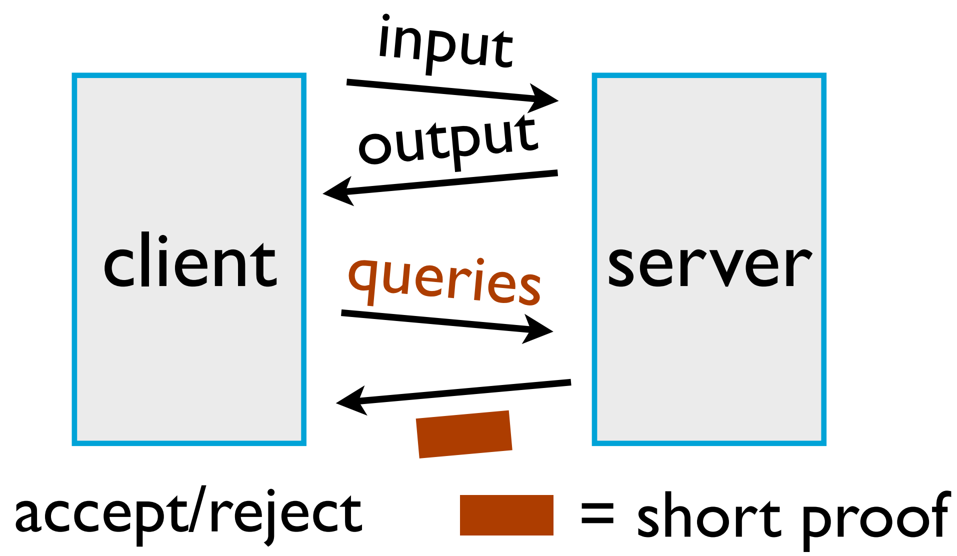
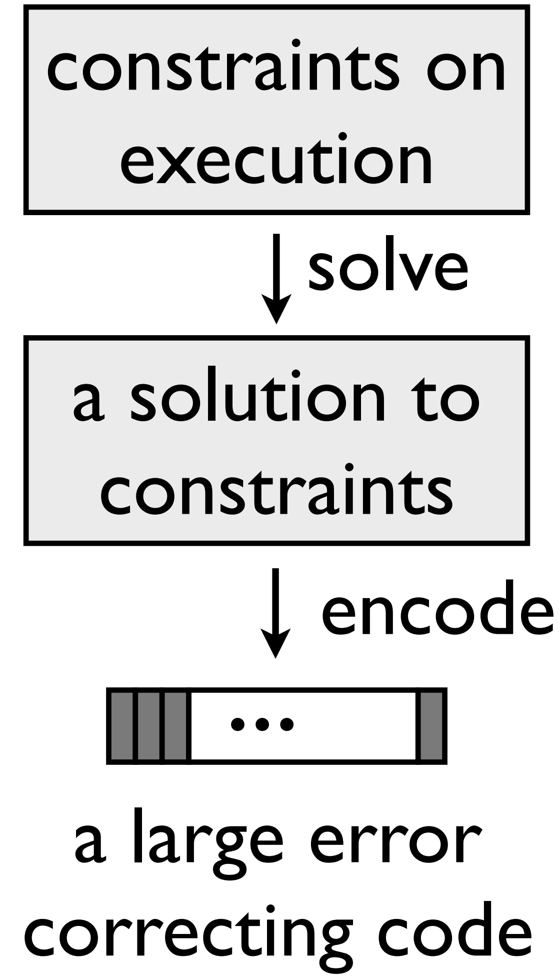


Verification protocol:





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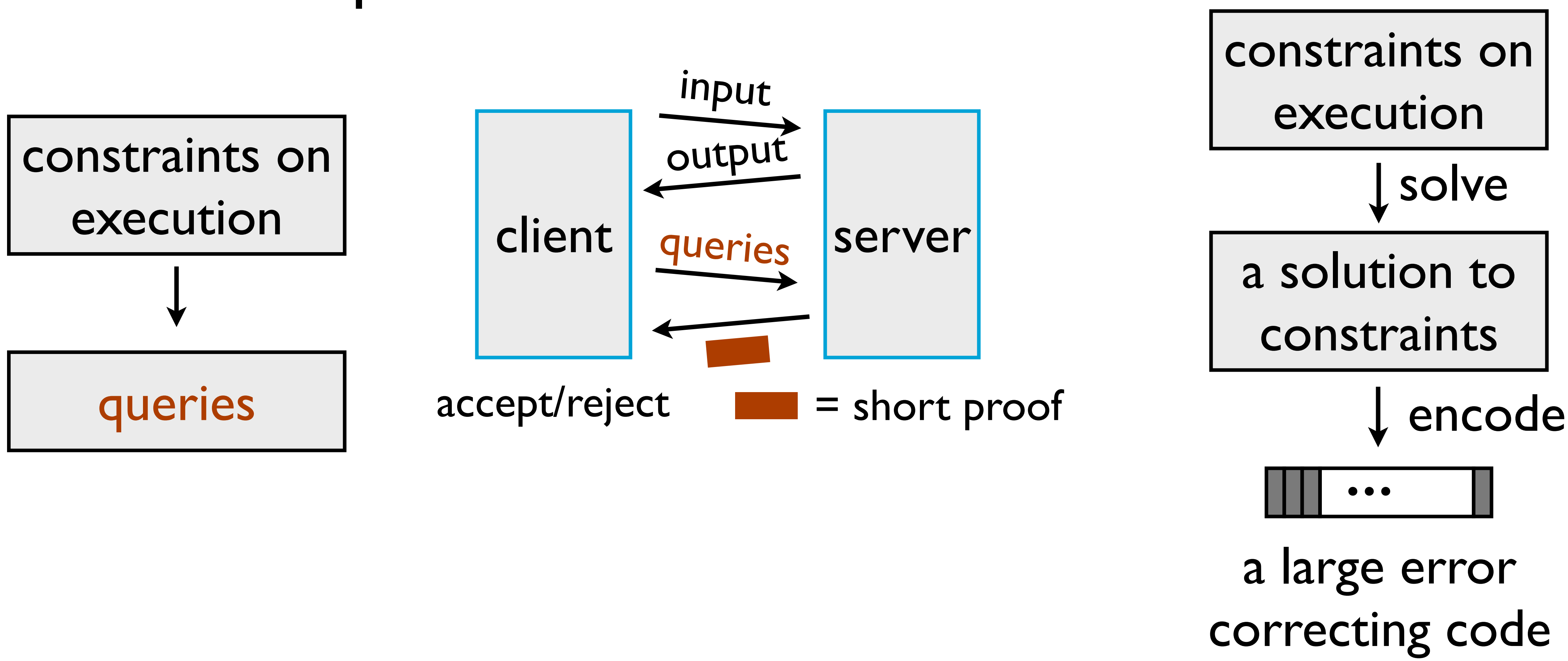

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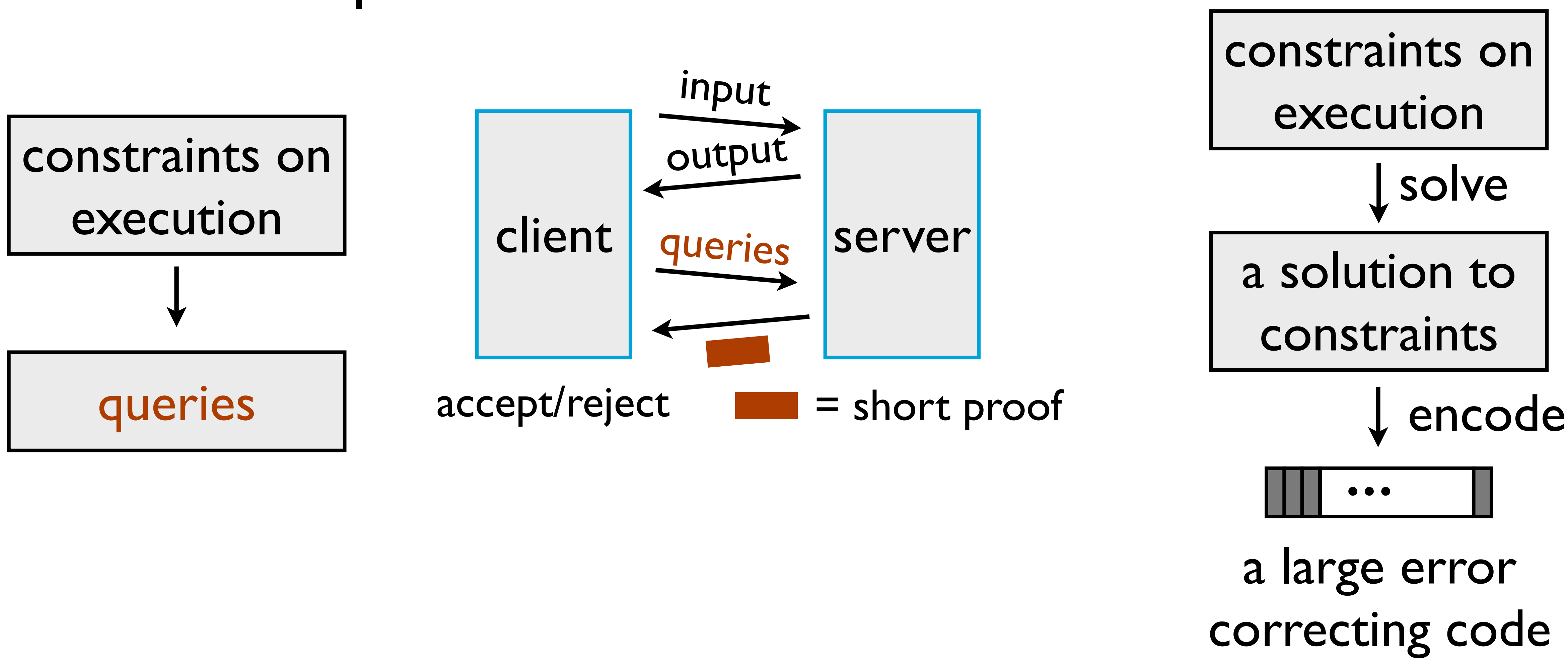

The client has to amortize its query generation costs to save resources relative to local execution

The short proof is the queried values from the large encoding

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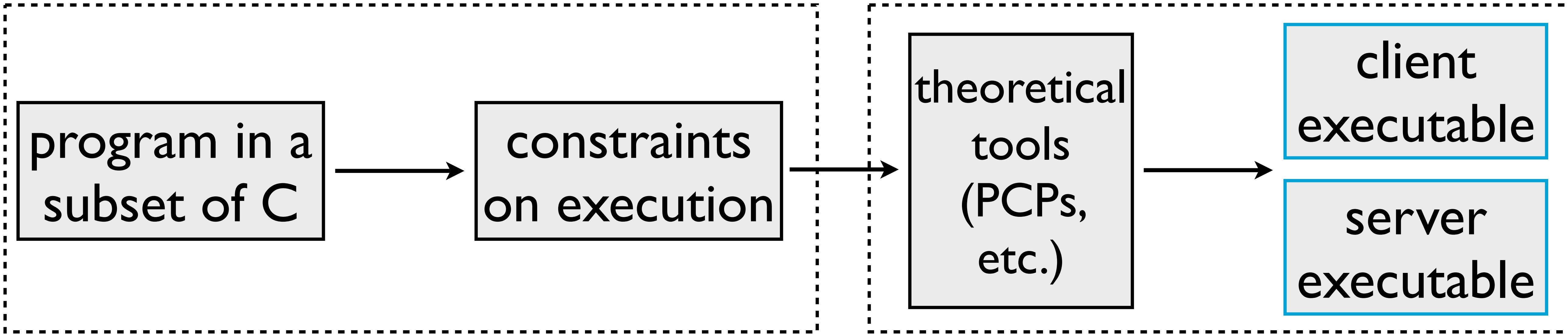
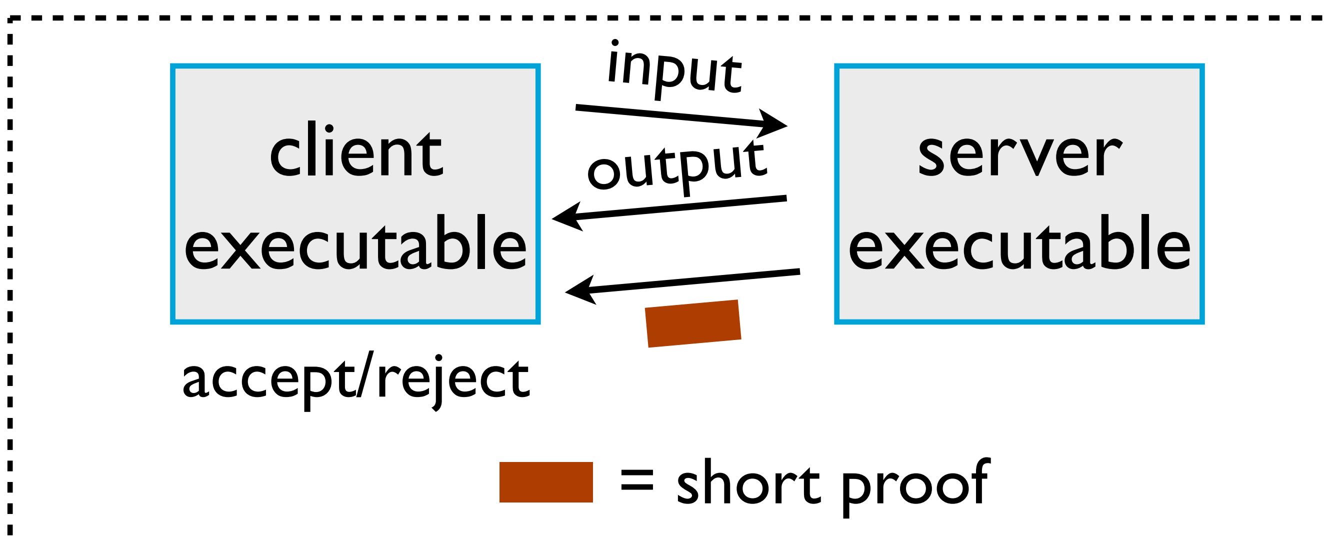


satisfiability of constraints ⇔ correct execution

a valid proof ⇔ satisfiability of constraints



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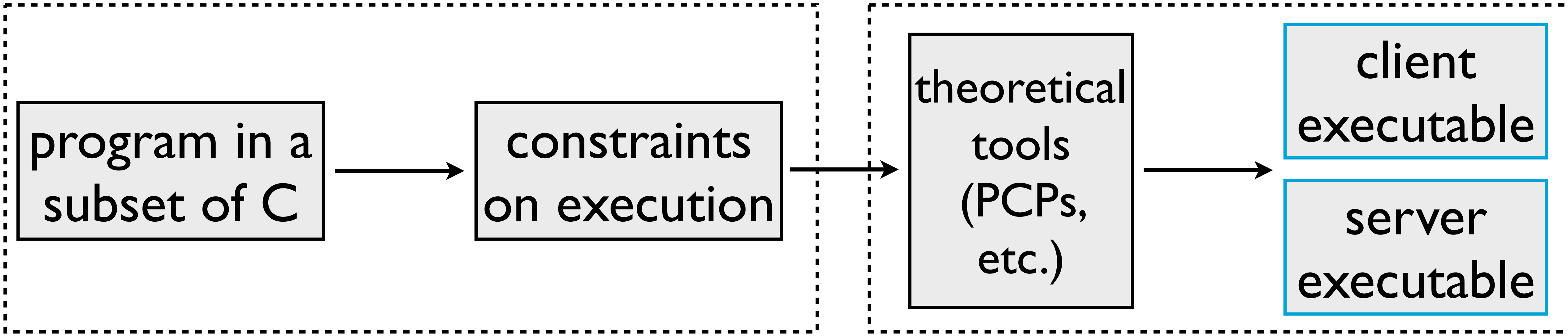

satisfiability of constraints ⇔ correct execution

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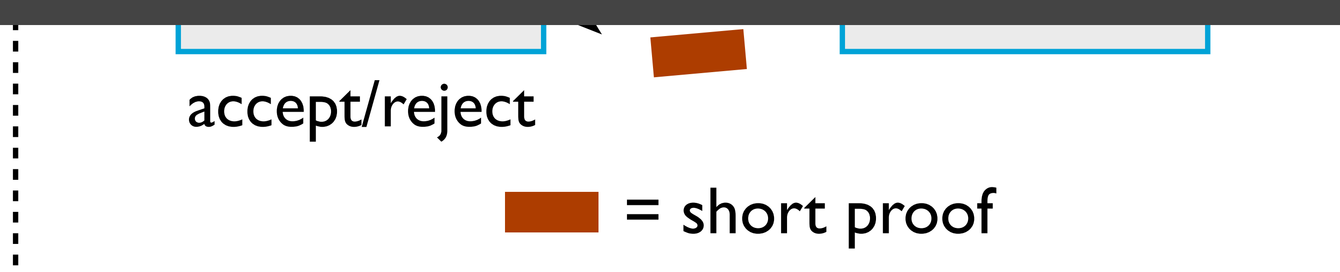
How can we design constraints such that their satisfiability is tantamount to correct storage interaction?



A naive approach

$B = read(A)$ ⟷

$B = S_0 - (A-0) \cdot C_0$

$B = S_1 - (A-1) \cdot C_1$

....

$B = S_{size} - (A-size) \cdot C_{size}$

$S_0, S_1, ..., S_{size}$ correspond to cells of storage

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switch (A) {
  case 0: B = S0; break;
  case 1: B = S1; break;
  ...
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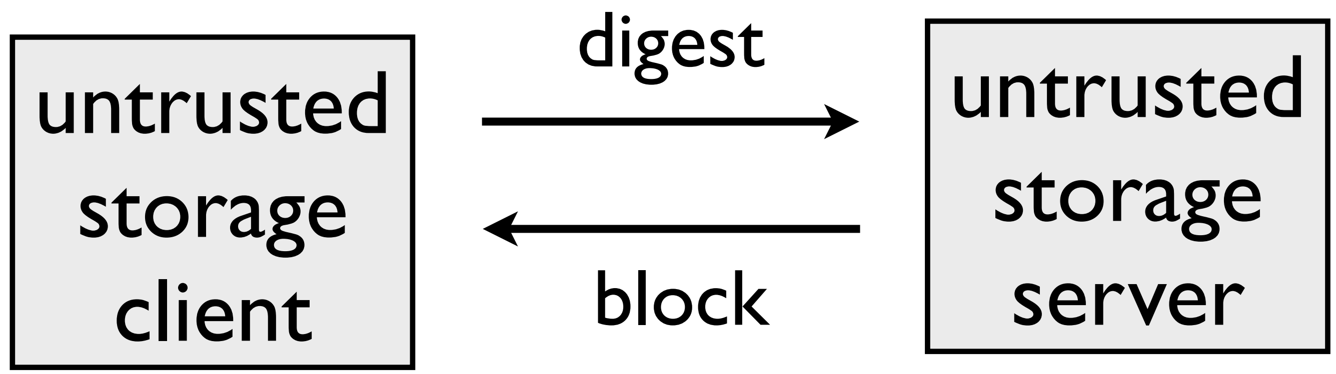
$S_0, S_1, \ldots, S_{size}$ correspond to cells of storage

- Expensive: requires one constraint for each address
- Incomplete: provides only volatile state

Consider an untrusted block store:



$H(\text{block}) \stackrel{?}{=} \text{digest}$, H is a cryptographic hash function

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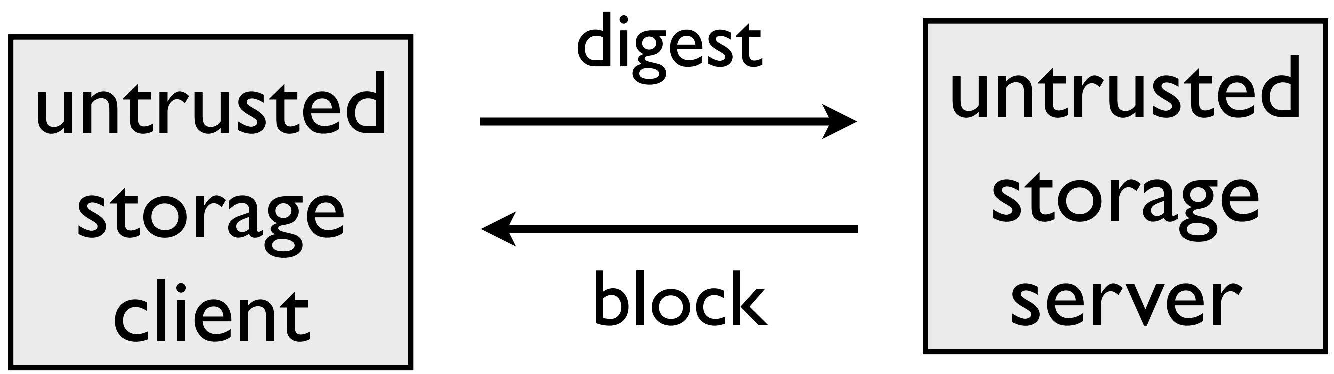

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To run a computation with remote inputs, the above client will need to:

1. Fetch blocks from the storage server
2. Check the integrity of the blocks using digests
3. Run the computation

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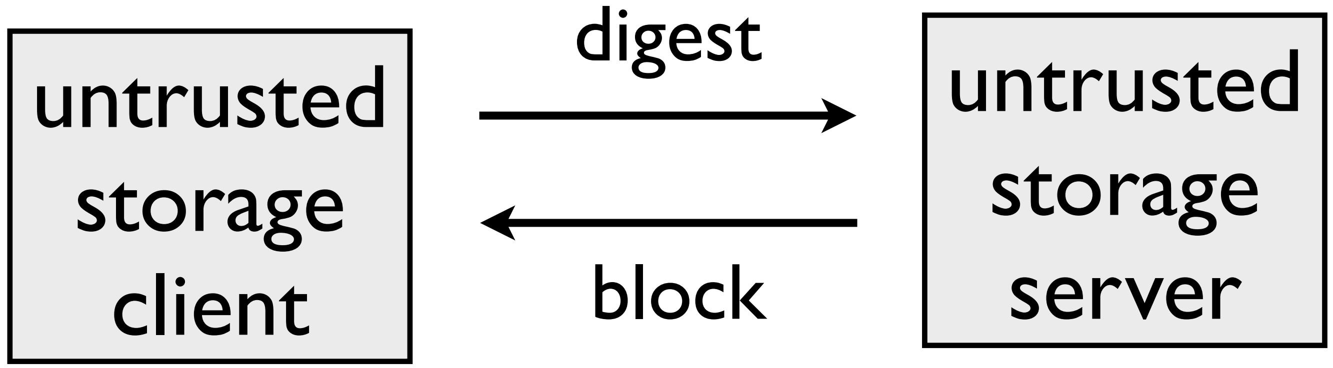

Pantry's approach to state: verifiably run the steps below on the server, by compiling these steps into constraints, without having to handle data blocks

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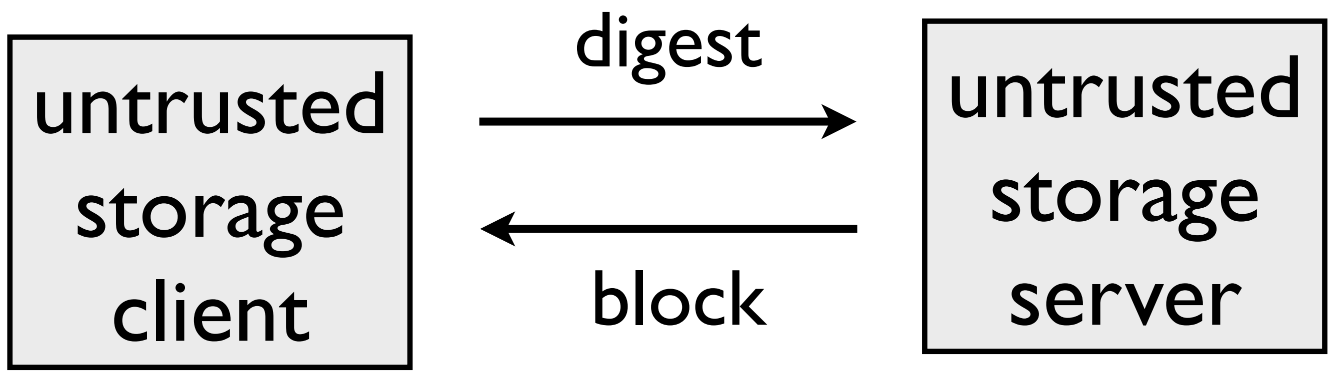

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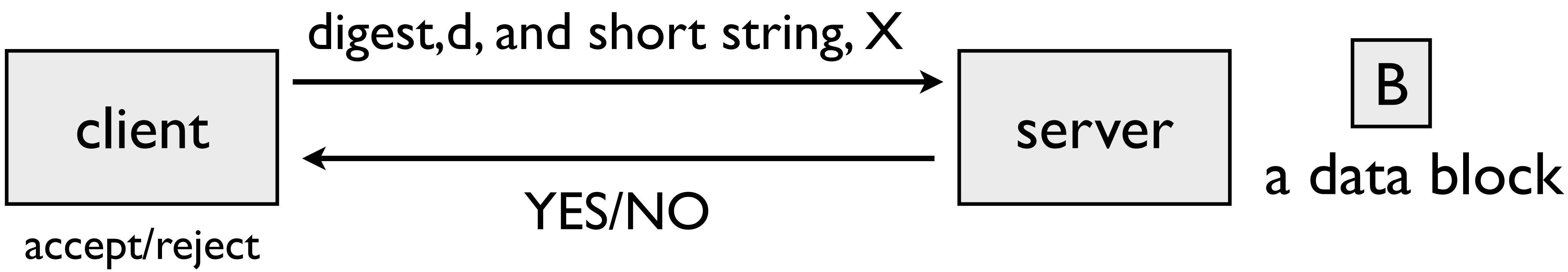
Existing work designs higher level abstractions using an untrusted block store [Merkle CRYPTO87, Blum et al. FOCS91, Fu et al. OSDI00, Li et al. OSDI04]

Pantry's approach to state, with an example

Consider a substring search with a remote data block



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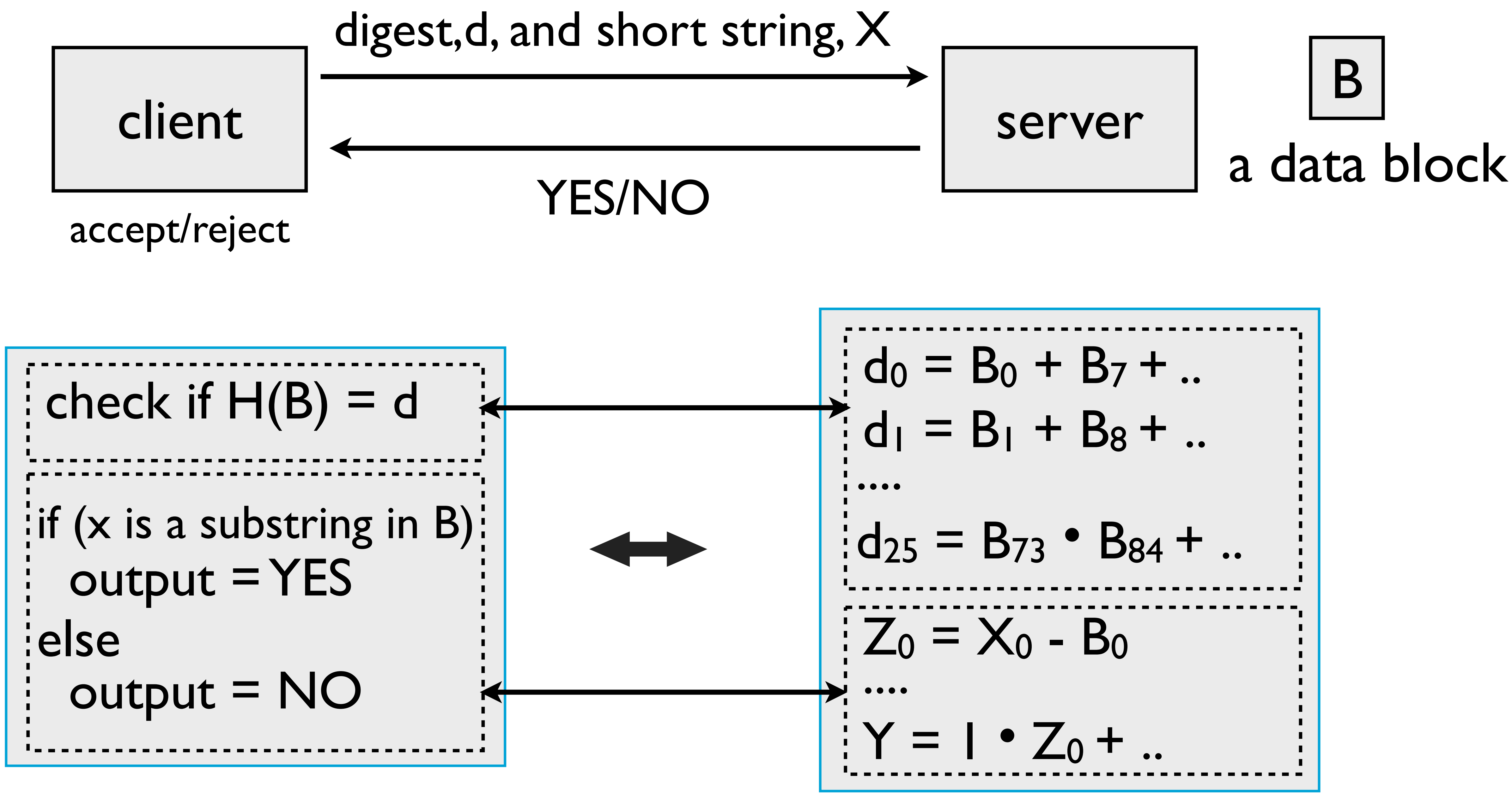

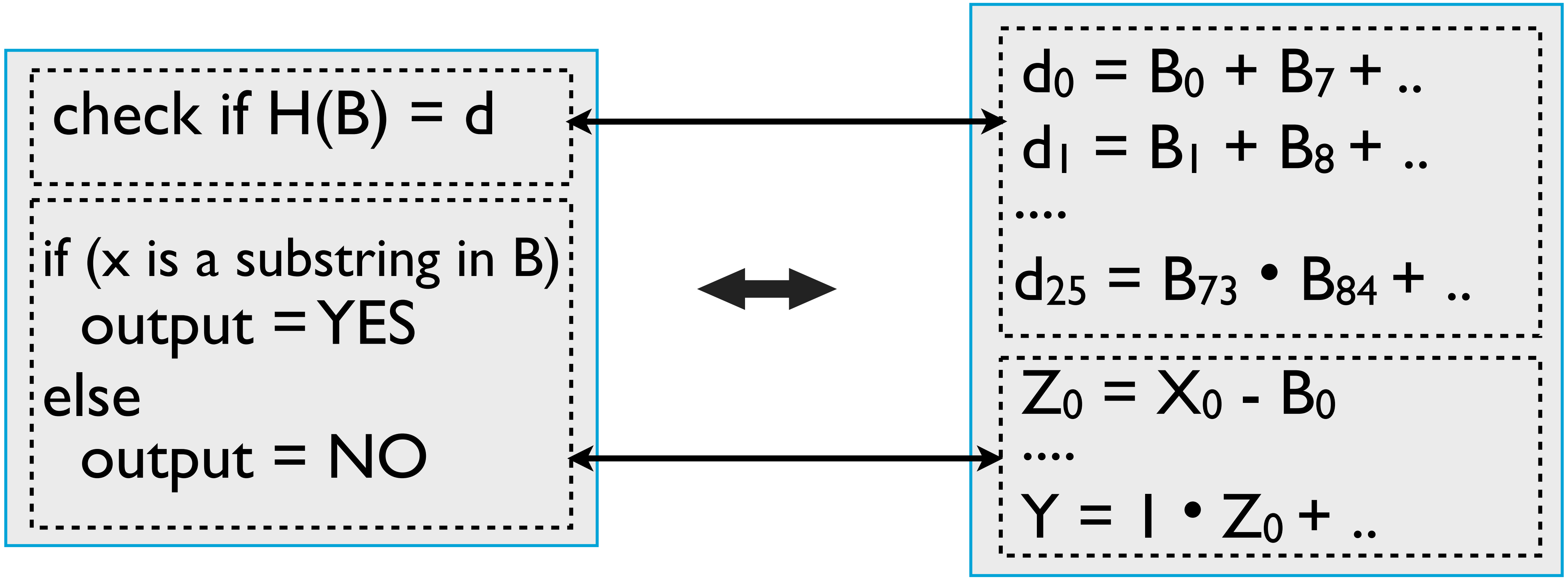

- Satisfiability of the above constraints ⇔ passing hash checks
- Passing hash checks is computationally infeasible without the right data blocks

We add two primitives to Pantry's C to expose state

- PutBlock(block): stores "block" at location H(block)
- GetBlock(digest): returns a block such that H(block) = digest

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function (digest d)
  int b = GetBlock(d)
  y = b+1
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$d_0 = B_0 + B_7 + ..$

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....

$d_{25} = B_{73} \cdot B_{84} + ..$

Representation of H in constraints

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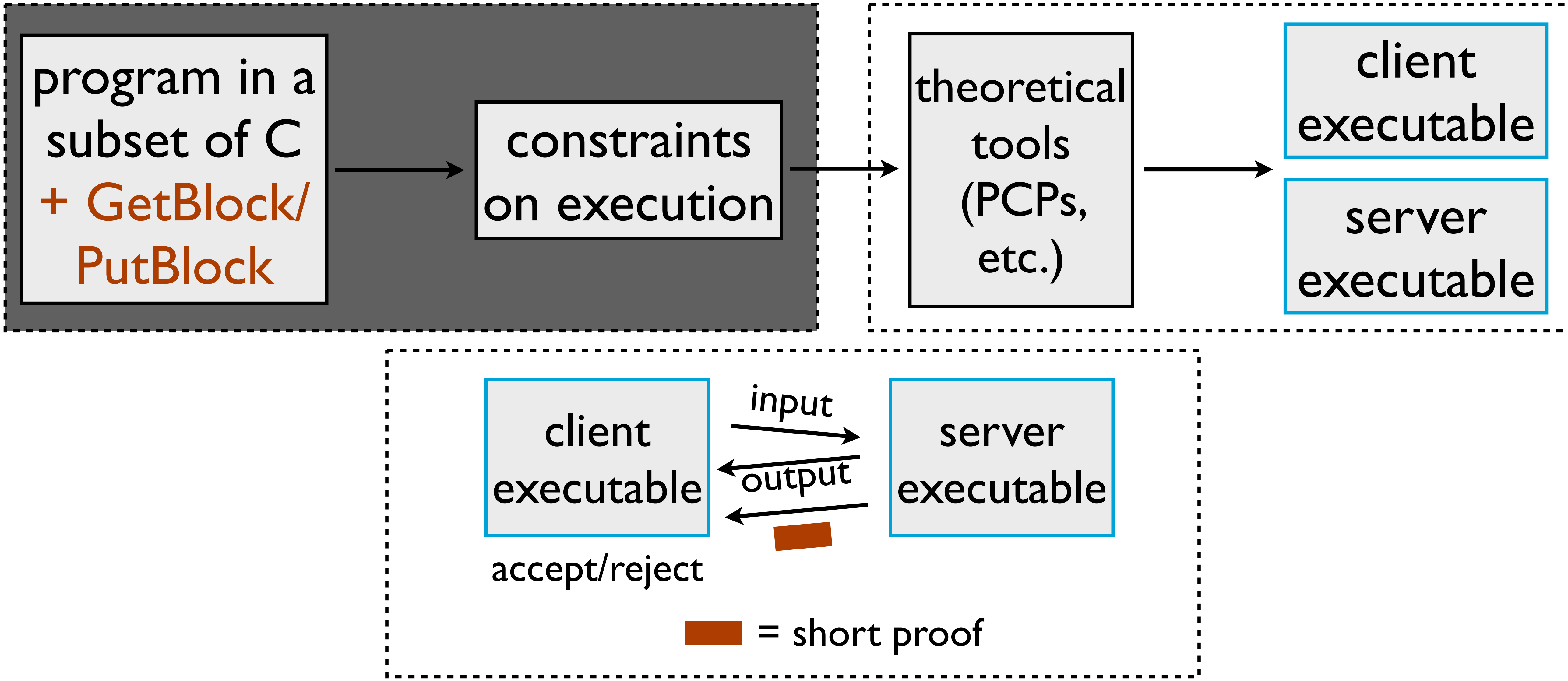
Representation of H in constraints

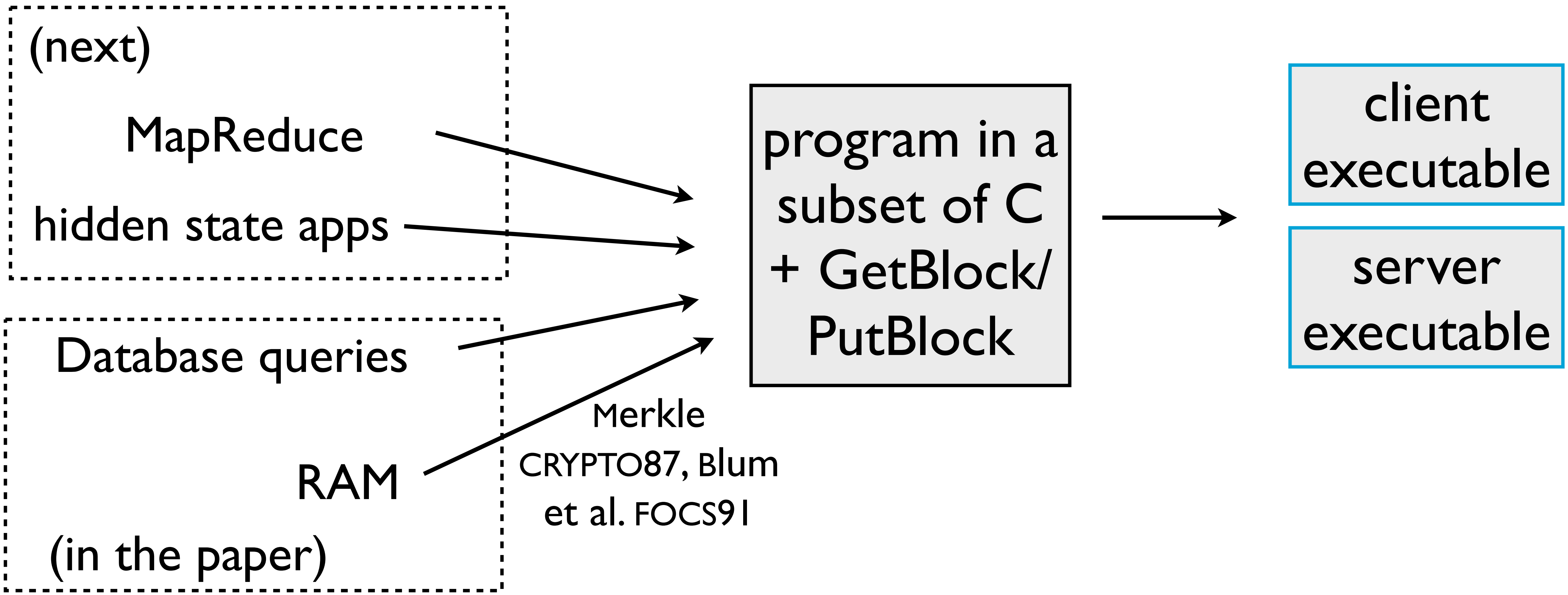
We use a hash function that has an efficient representation as a set of constraints [Ajtai STOC96]

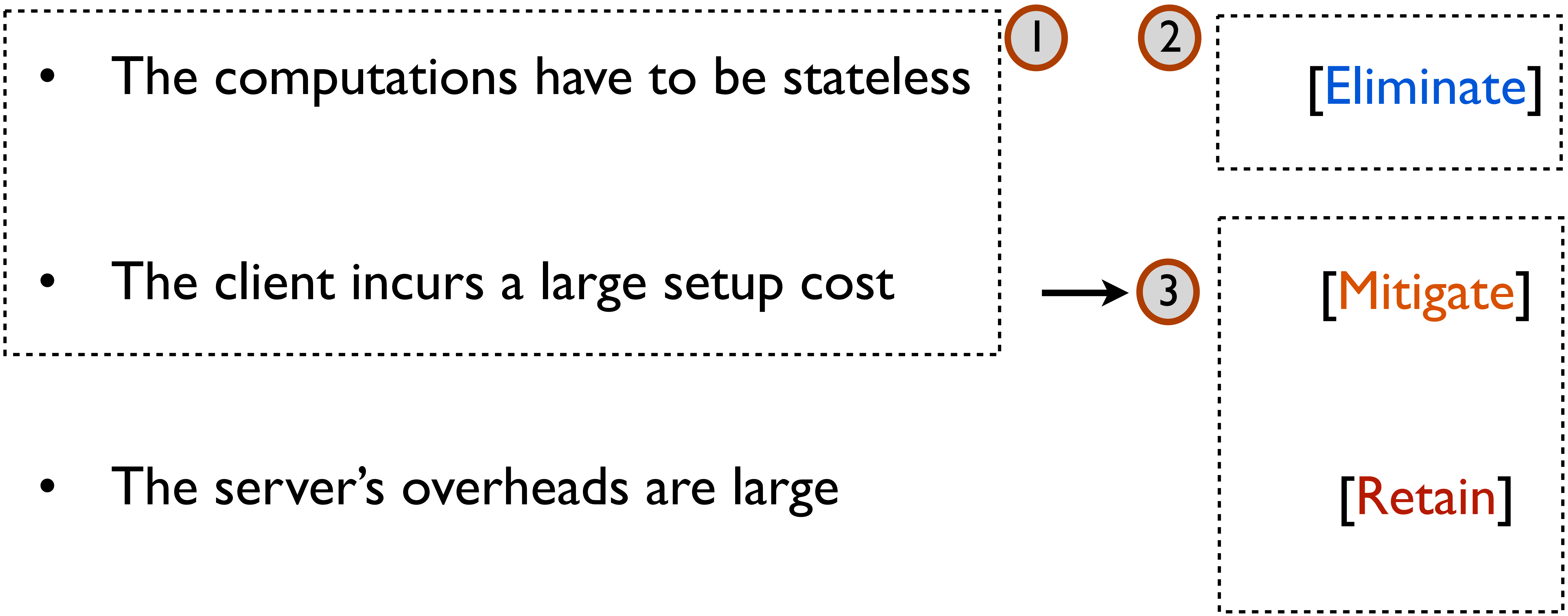
Pantry: an extension to Zaatar and Pinocchio



- a valid proof ⇔ "I know a satisfying assignment to constraints"
- satisfiability of constraints ⇔ hash checks pass
- hash checks pass ⇔ correct storage interaction

Verifiable stateful applications from C code with Pantry:

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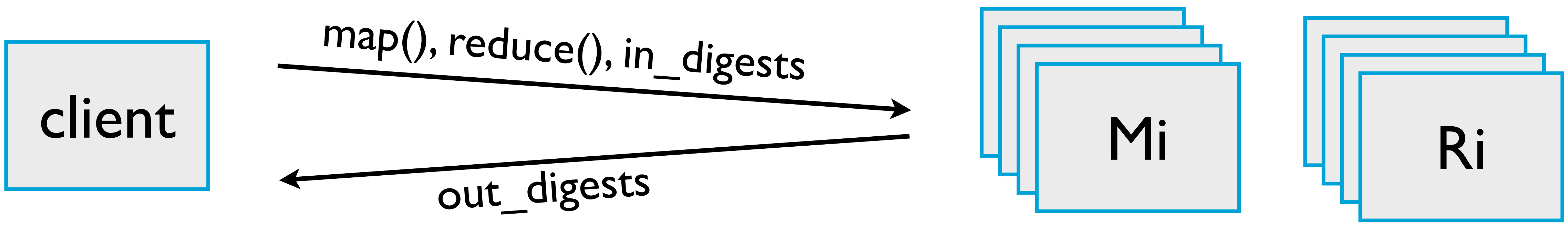
• The server's overheads are large
1
2
3
[Eliminate]
[Mitigate]
[Retain]

Pantry enables applications where the client's setup costs are tolerable:

- Data parallel computations (MapReduce, etc.) that compute over remote state
  - Have multiple identical computations
- Hidden state applications
  - The client cannot, in principle, execute on its own

The client is assured that a MapReduce job was executed correctly—without ever touching the data



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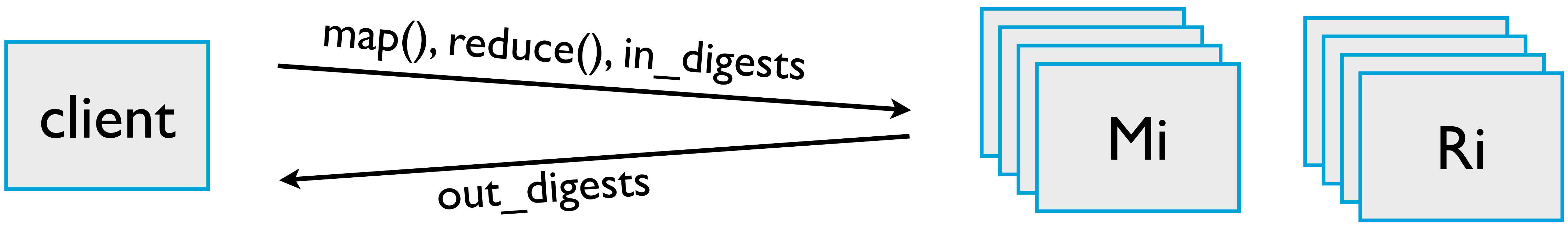

map() and reduce() are expressed in Pantry's subset of C

```
mapper(Dig in_digest, Dig *d) {
  in = GetBlock(in_digest)
  map(in, out)
  for i=1 to R
   d[i] = PutBlock(out[i])
}
```

```
reducer(Dig *d, Dig *out_digest) {
  for i=1 to M:
   in[i] = GetBlock(d[i])
  reduce(in, out)
  out_digest = PutBlock(out)
}
```

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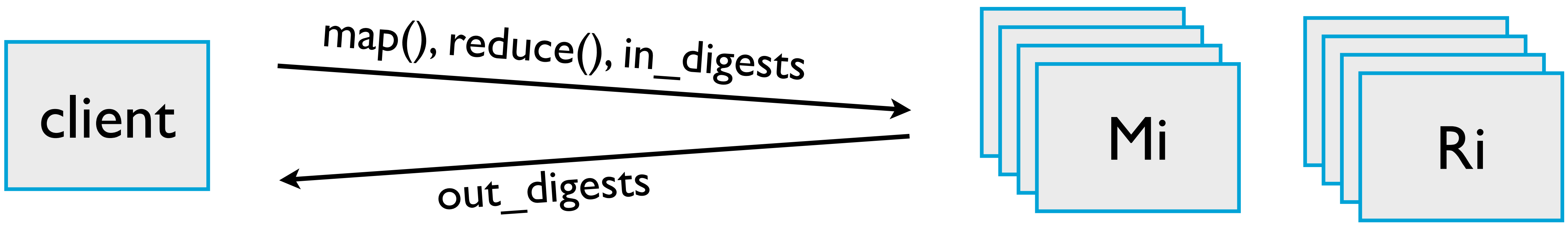
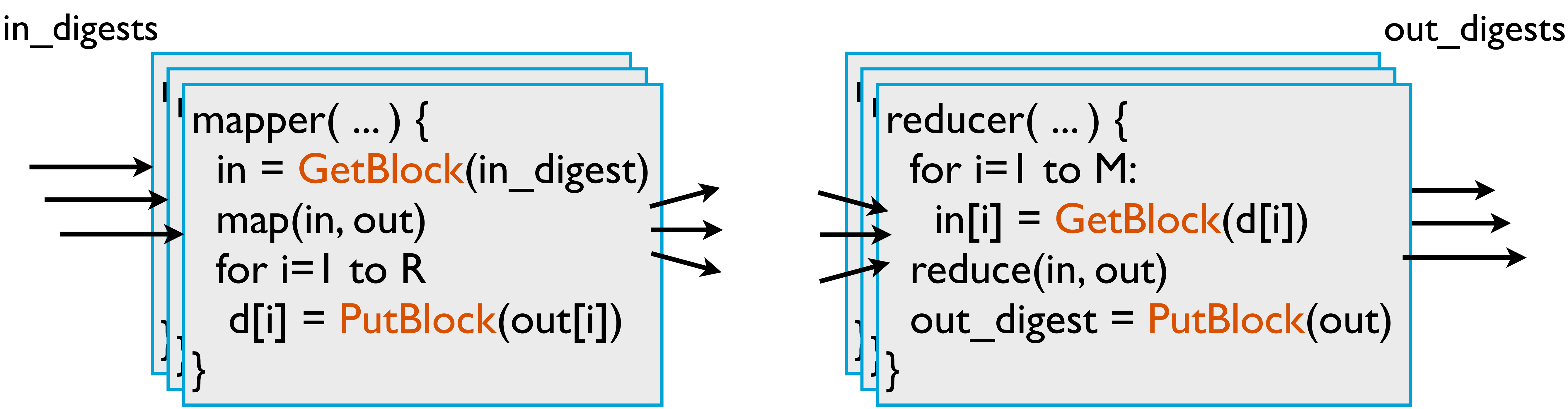


The two phases are handled separately:



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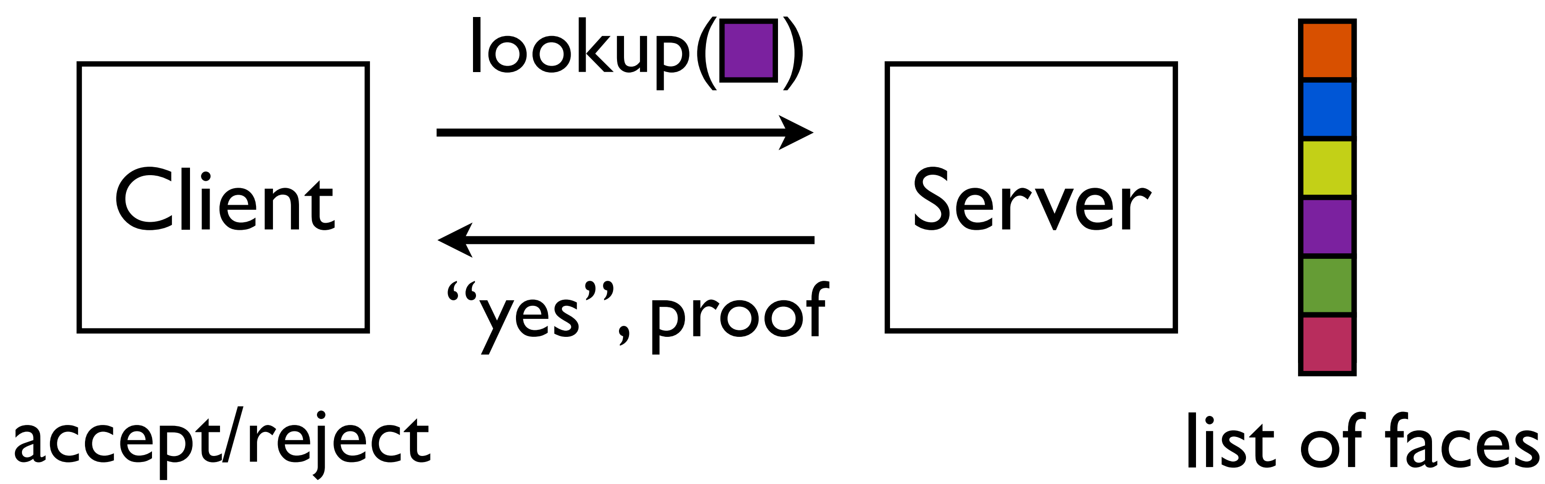
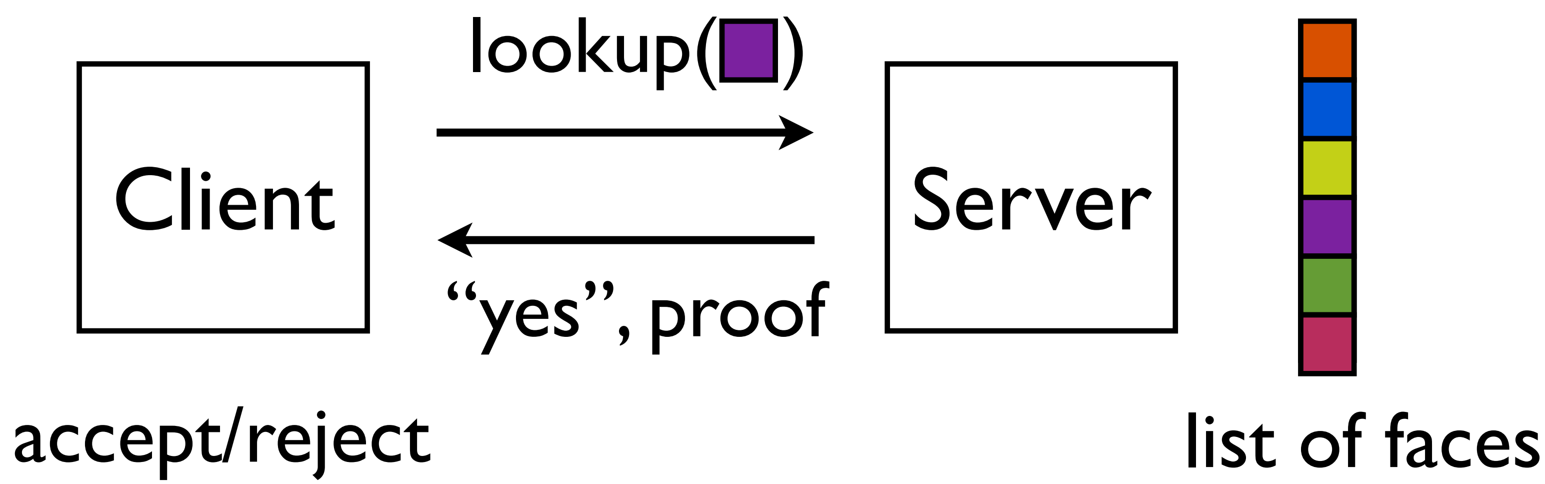


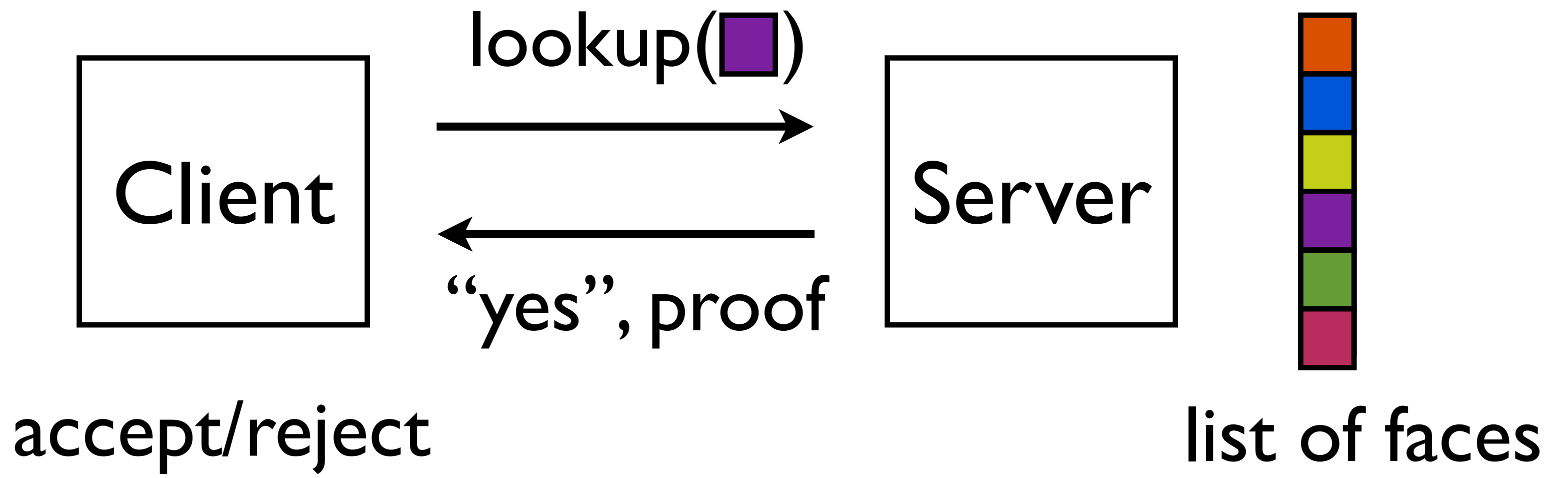
- Key idea: Pantry's storage + Pinocchio's zero-knowledge

Hidden state applications



- Key idea: Pantry’s storage + Pinocchio’s zero-knowledge
- Wrinkles:
  - Pantry’s digests aren’t information hiding (wrap digests with a cryptographic commitment scheme)
  - Standard commitment schemes are expensive (use an HMAC-based scheme that is 10X cheaper)

Hidden state applications



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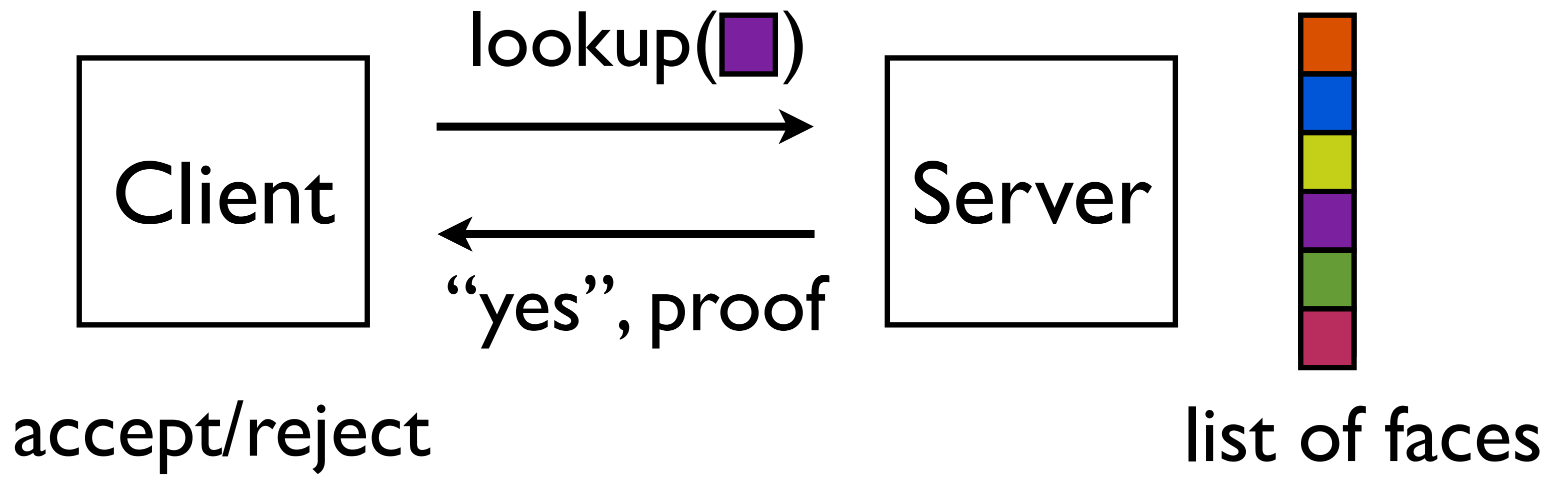

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  - Standard commitment schemes are expensive (use an HMAC-based scheme that is 10X cheaper)
- Other applications: tolling, regression analysis, etc.
- Upshot: with only C programs, one can get powerful guarantees

Benchmark applications and implementation

Benchmark applications:

- MapReduce: nucleotide substring search, dot product, nearest neighbor search, and covariance computation
- Hidden state: face matching, tolling, and regression analysis

Distributed implementation of the server

C++, Java, Go, and Python code; HTTP/Open MPI to distribute server's work

Evaluation questions

1 When does Pantry's client save resources relative to locally executing the computation?

2 What are the costs of supporting hidden state?

3 What are the costs of Pantry's server, relative to simply executing the computation?

Pantry's client saves resources at sufficiently large input sizes

MapReduce job: nucleotide substring search in which a mapper gets 600K nucleotides and outputs matching locations

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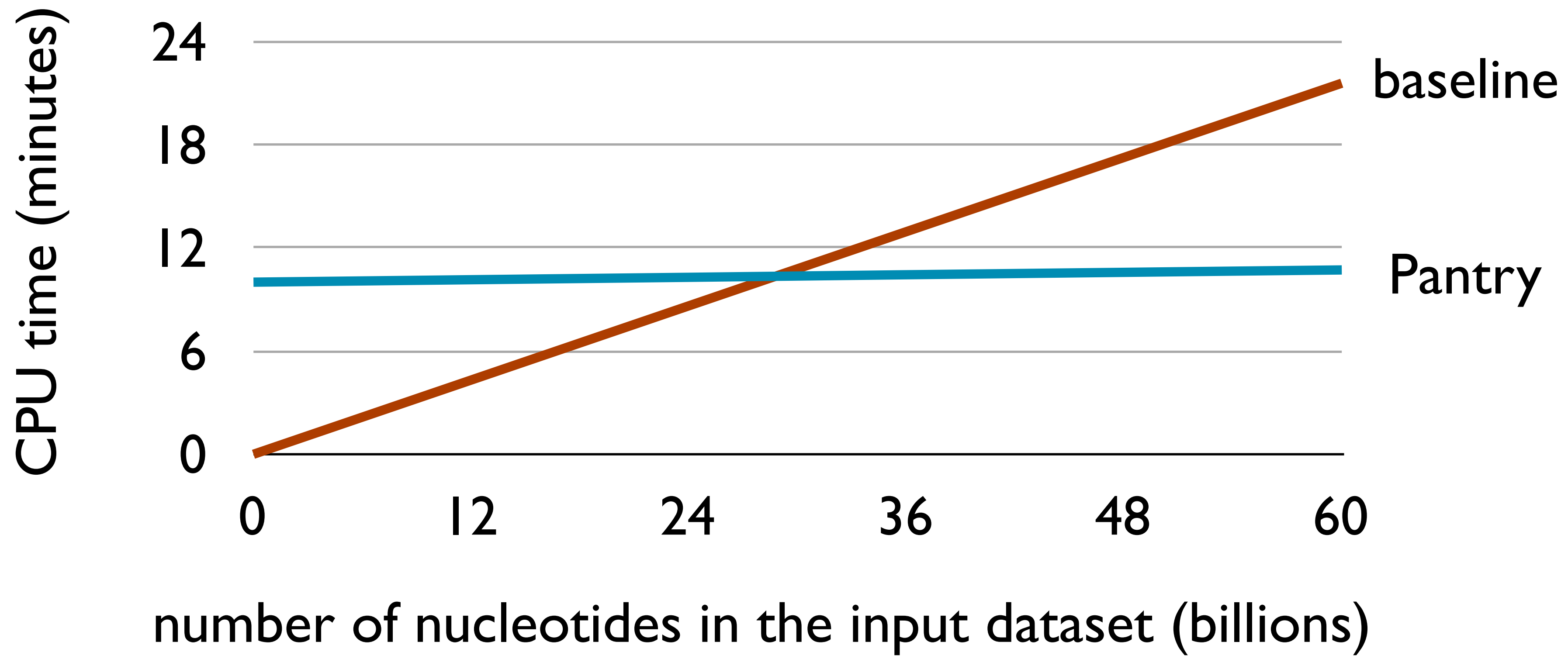

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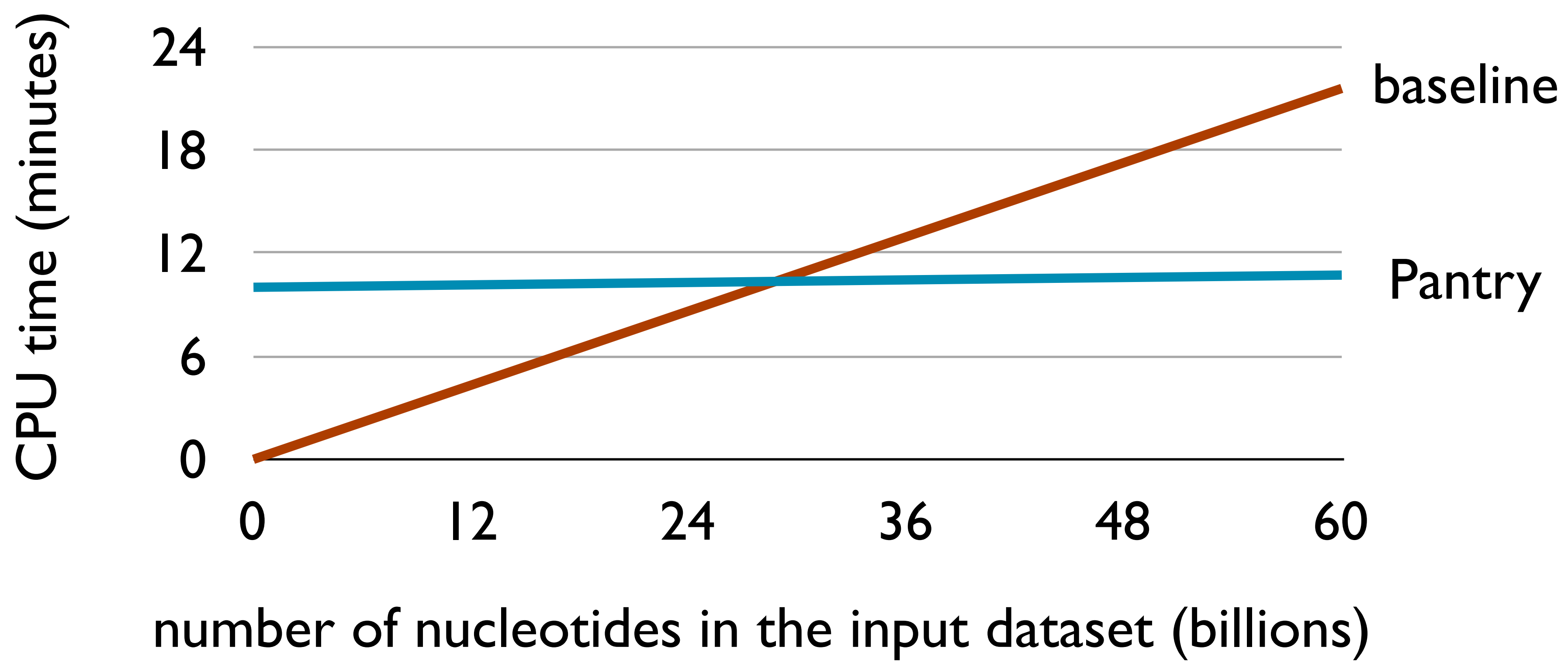


Graph is an extrapolation (slopes and y intercepts determined with experiments that use up to 250 machines and up to 1.2 billion nucleotides)

Cost of supporting hidden state applications

Server holds 128 face fingerprints (hidden state: 15 KB)

good news:

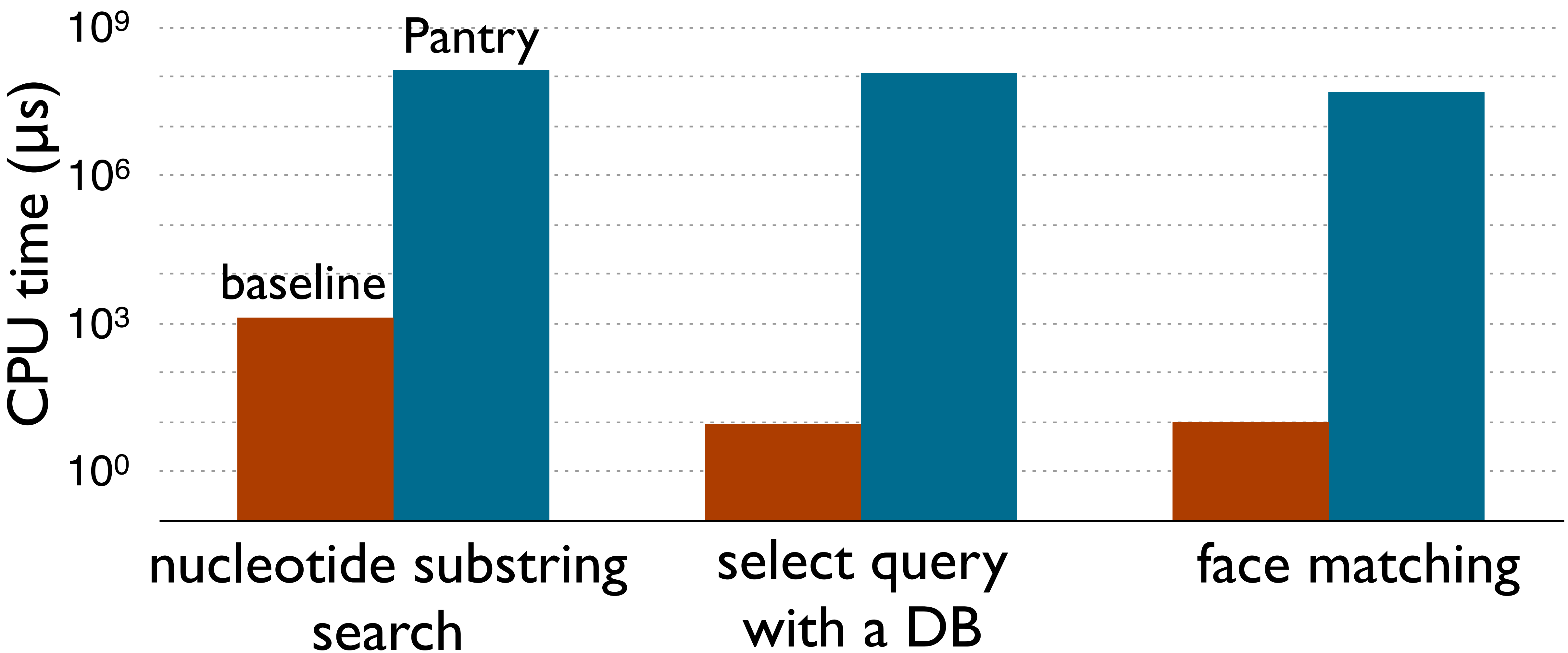
- proof size: 288 bytes
- client's CPU time: 7 ms

bad news:

- network (setup), server's storage (ongoing): 170 MB
- server's CPU time: 7.8 min

Pantry's server's cost is many orders of magnitude slower than simply executing the computation

sources of overhead: constraints + crypto ops. proportional to #constraints



Recap

- The computations have to be stateless [Eliminate]
- The client incurs a large setup cost [Mitigate]
- The server's overheads are large [Retain]

Prior work on verifiable computation

Make assumptions about the server's failure modes or give up generality:

- 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]

Unconditional guarantees and general but not geared to practice:

- Use fully homomorphic encryption [GGP, Chung et al.CRYPTO10]
- Theory of PCPs, IPs, arguments [GMR85, Ben-Or et al. STOC88, Babai et al. STOC91, Kilian STOC92, ALMSS92, AS92, Goldwasser et al. STOC 2008, Bitansky et al. ITCS12]

Four projects have produced implementations

Pepper, Ginger, Zaatar, Allspice

HotOS11
NDSS12
USENIX SECURITY12
EuroSys13
IEEE S&P13

CMT, Thaler

Cormode et al. ITCS12
Thaler et al. HotCloud12
Thaler CRYPTO13

Pinocchio, GGPR

Gennaro et al. EUROCRYPT13
Parno et al. IEEE S&P13

BCGTV

Ben-Sasson et al. CRYPTO13
Ben-Sasson et al. ITCS13
Bitansky et al. TCC13

Next steps for the area of verifiable computing

- Reducing the server's overhead (currently 3-6 orders of magnitude more than native execution)

- Avoiding the client's setup costs efficiently

- Enhancing the computational model (currently loops are unrolled, storage operations need a lot of constraints, etc.)

Takeaways

- Pantry takes another step in bringing powerful theory behind verifiable computation into practice
  - Pantry enables realistic, stateful computations: MapReduce, database queries, hidden state applications, etc.
- We think: the machinery underlying Pantry or its variant will be a key tool in building future secure systems