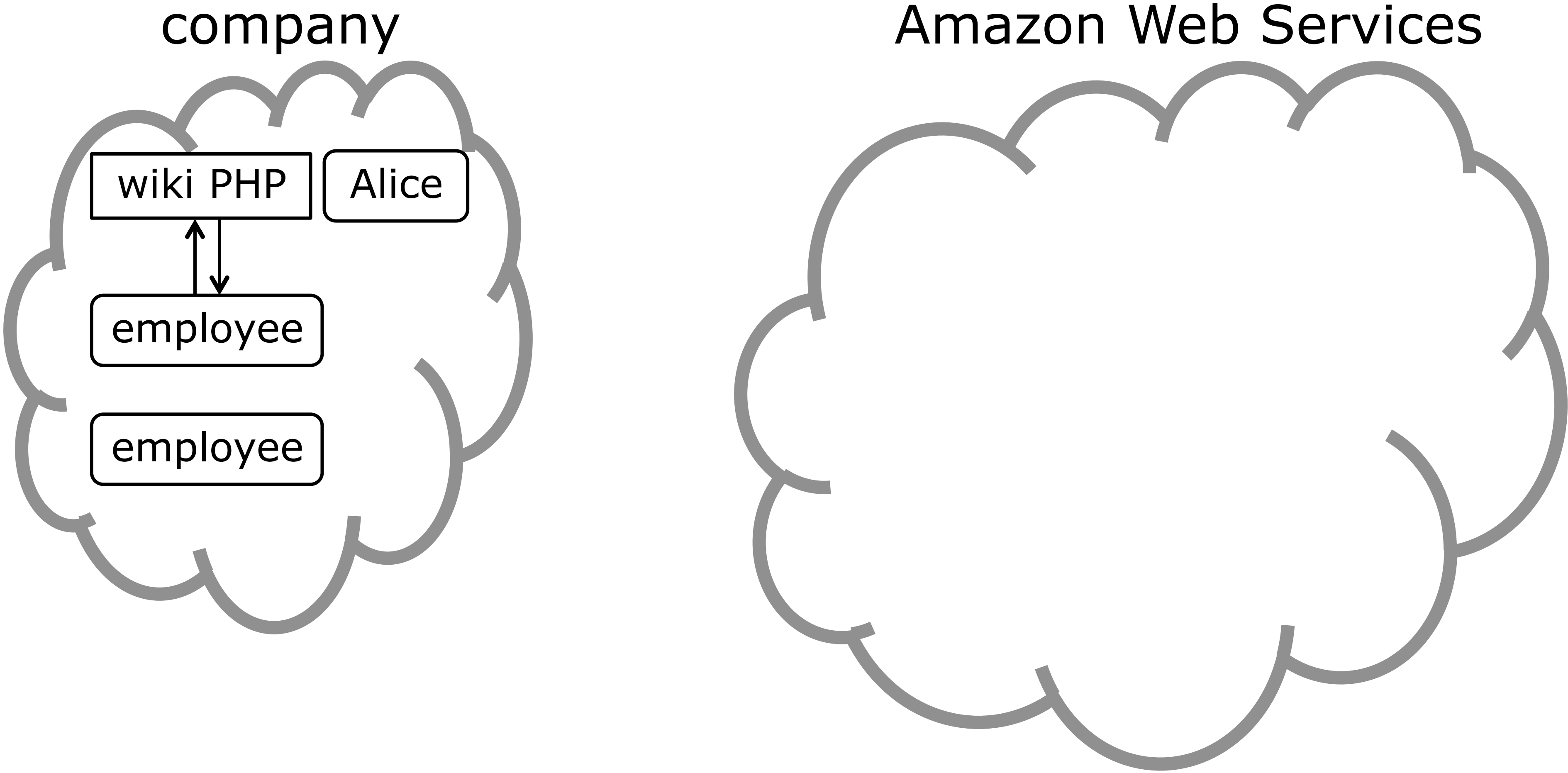
The Efficient Server Audit Problem, Deduplicated Re-execution, and the Web

Cheng Tan, Lingfan Yu,
Joshua B. Leners*, and Michael Walfish

NYU Department of Computer Science, Courant Institute
*Two Sigma Investments



company

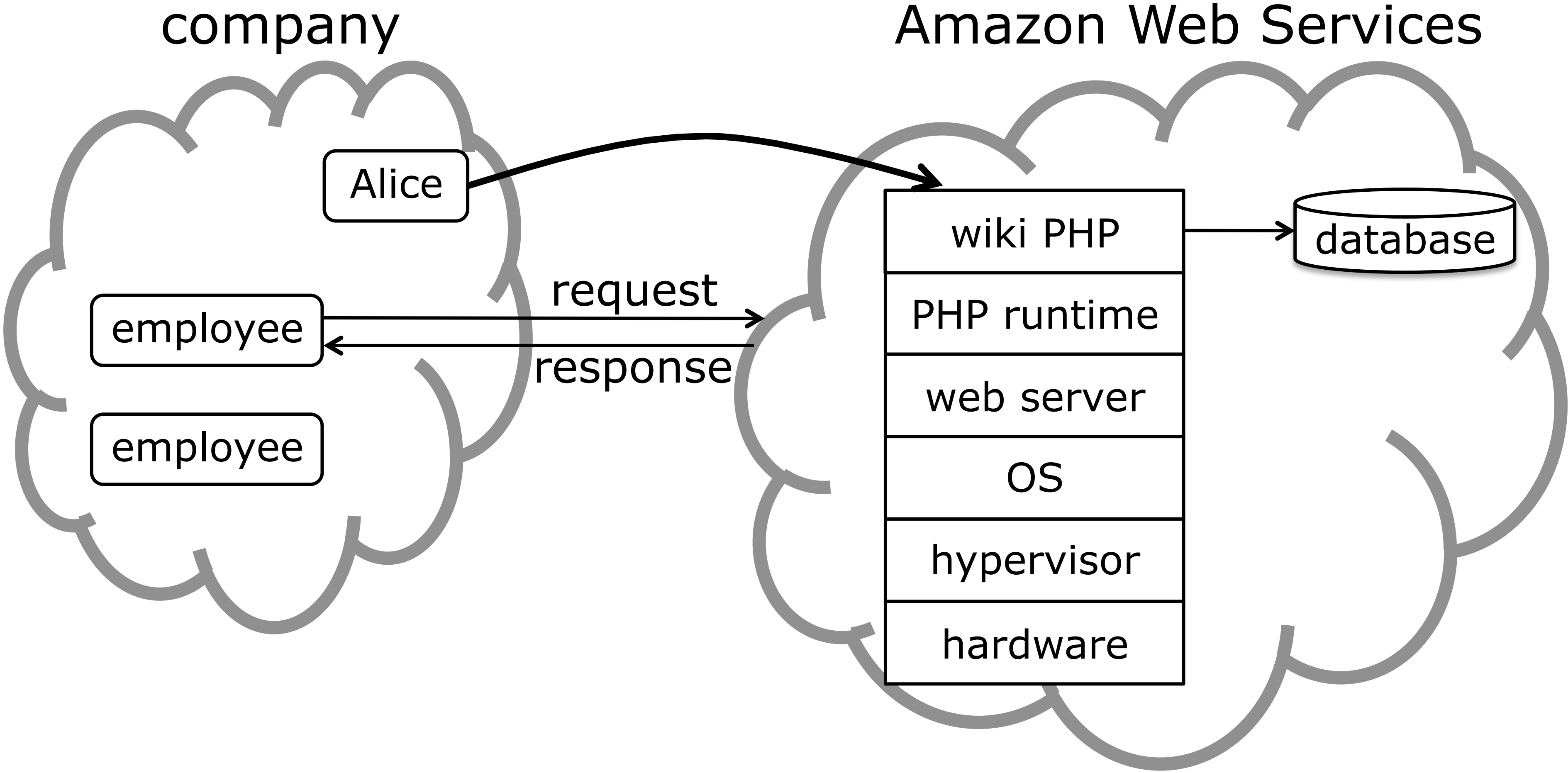
wiki PHP

Alice

employee

employee

Amazon Web Services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Alice
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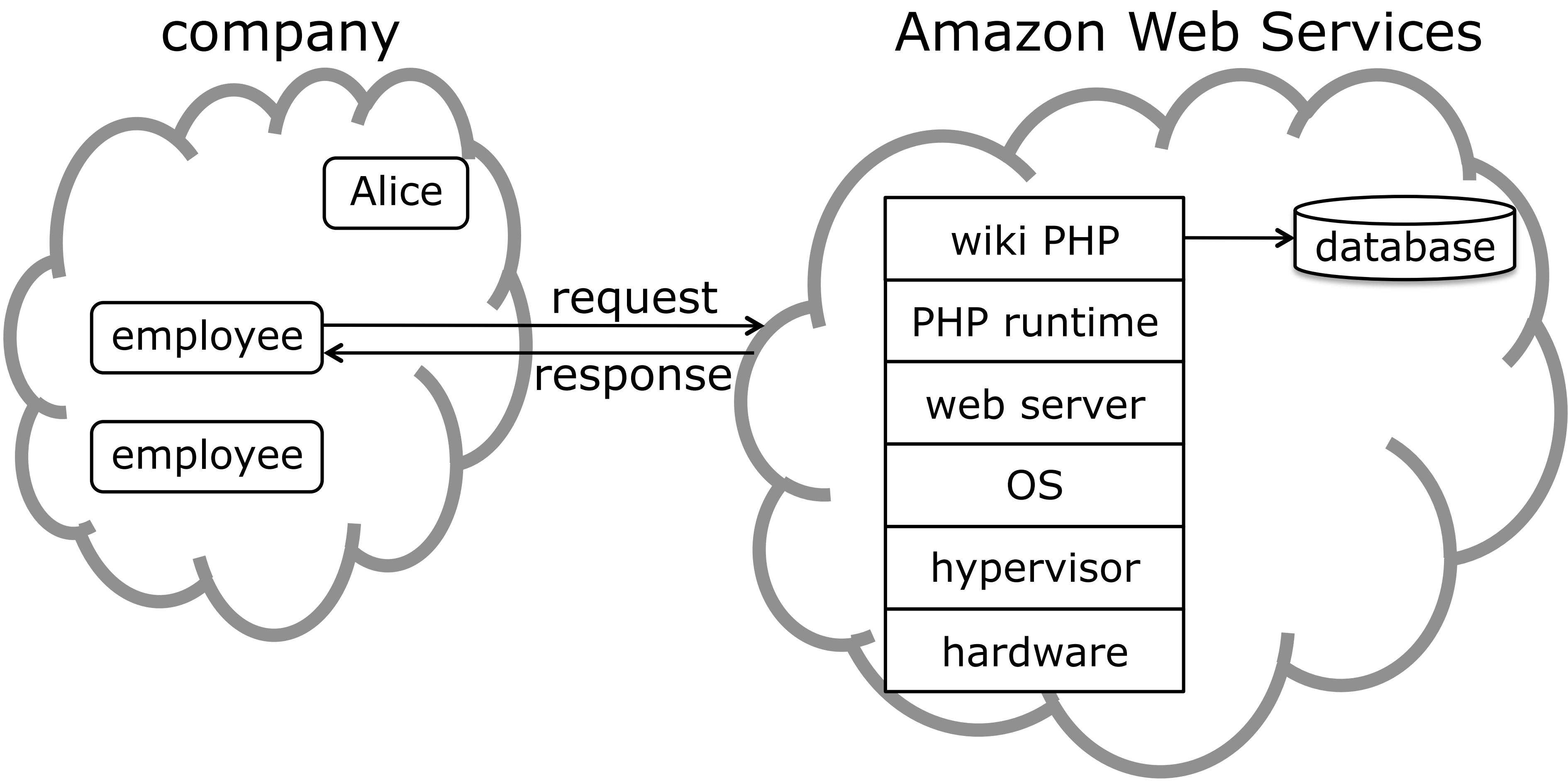
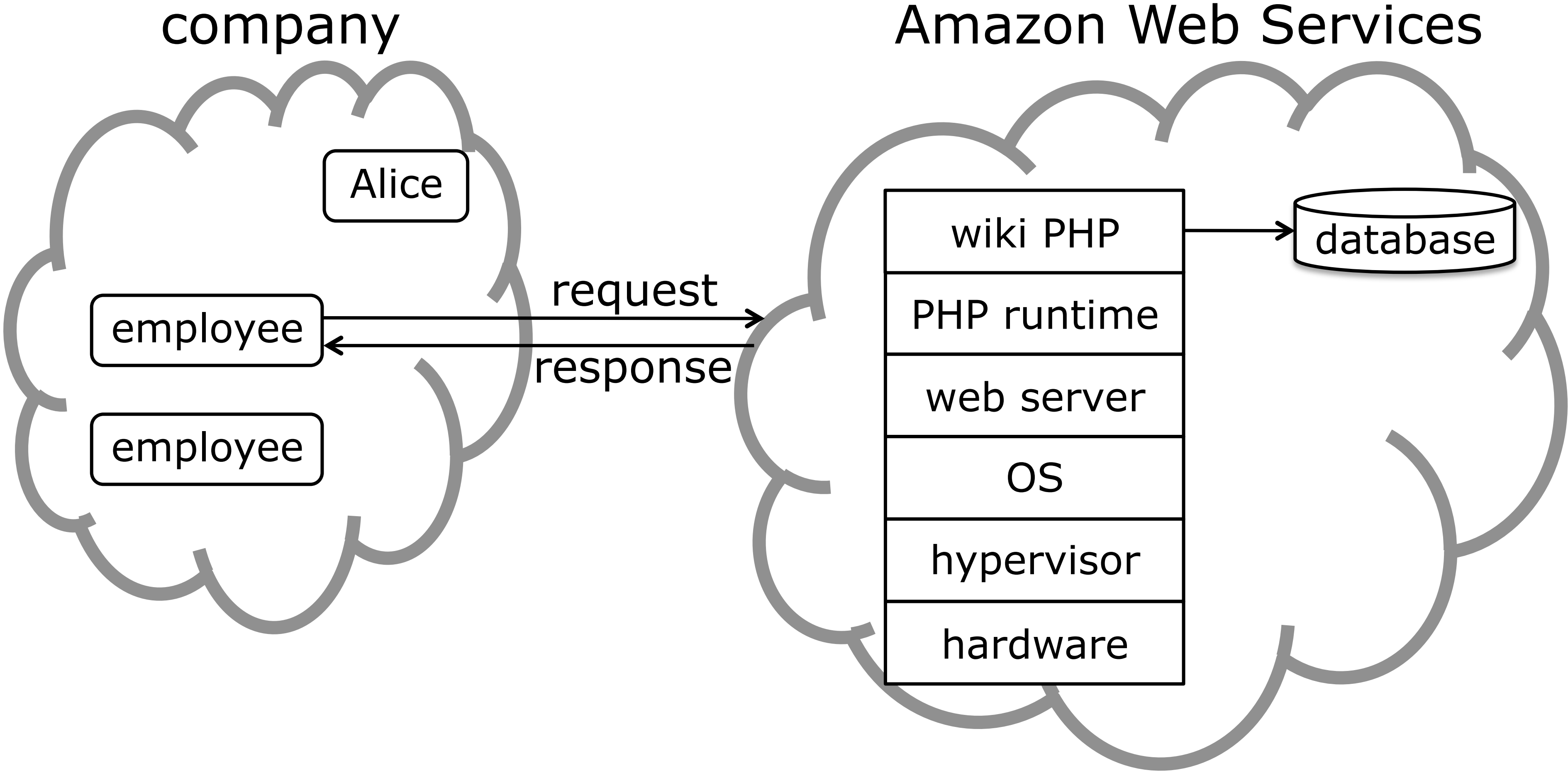
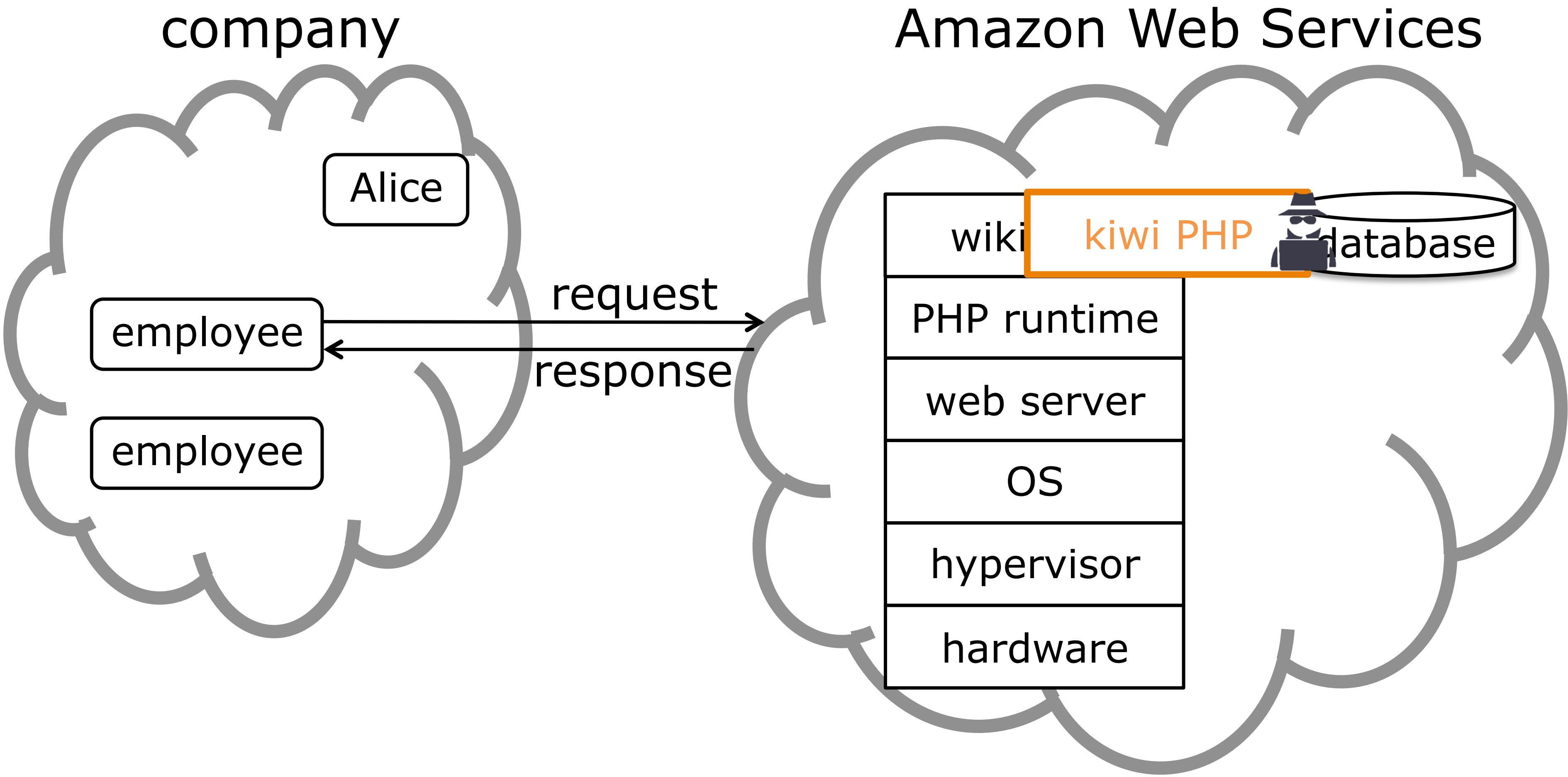
web server
OS
hypervisor
hardware
database



- Alice has confidence in the wiki's PHP code



- Alice has confidence in the wiki's PHP code
- Still, lots of things can go wrong ...



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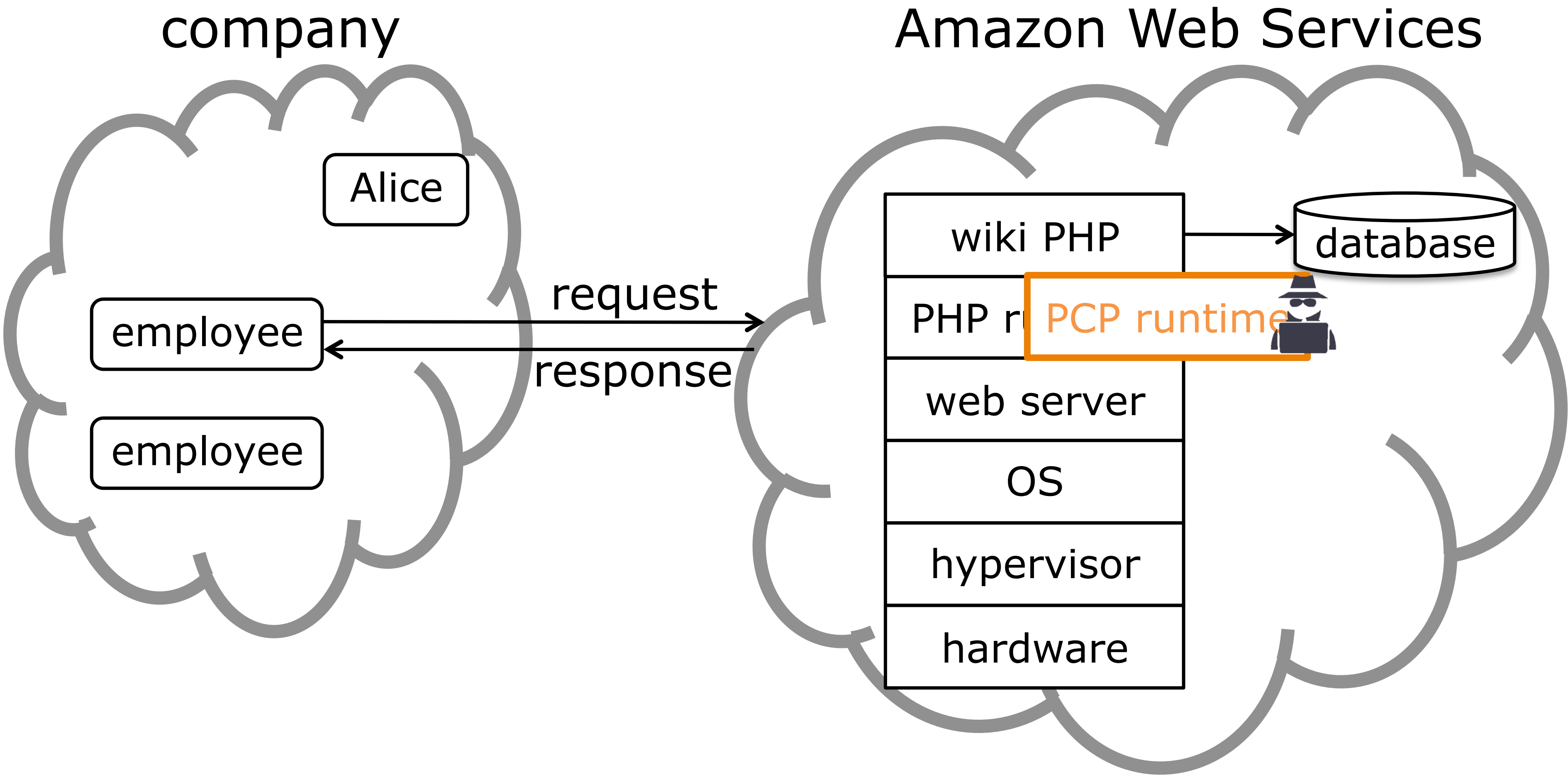

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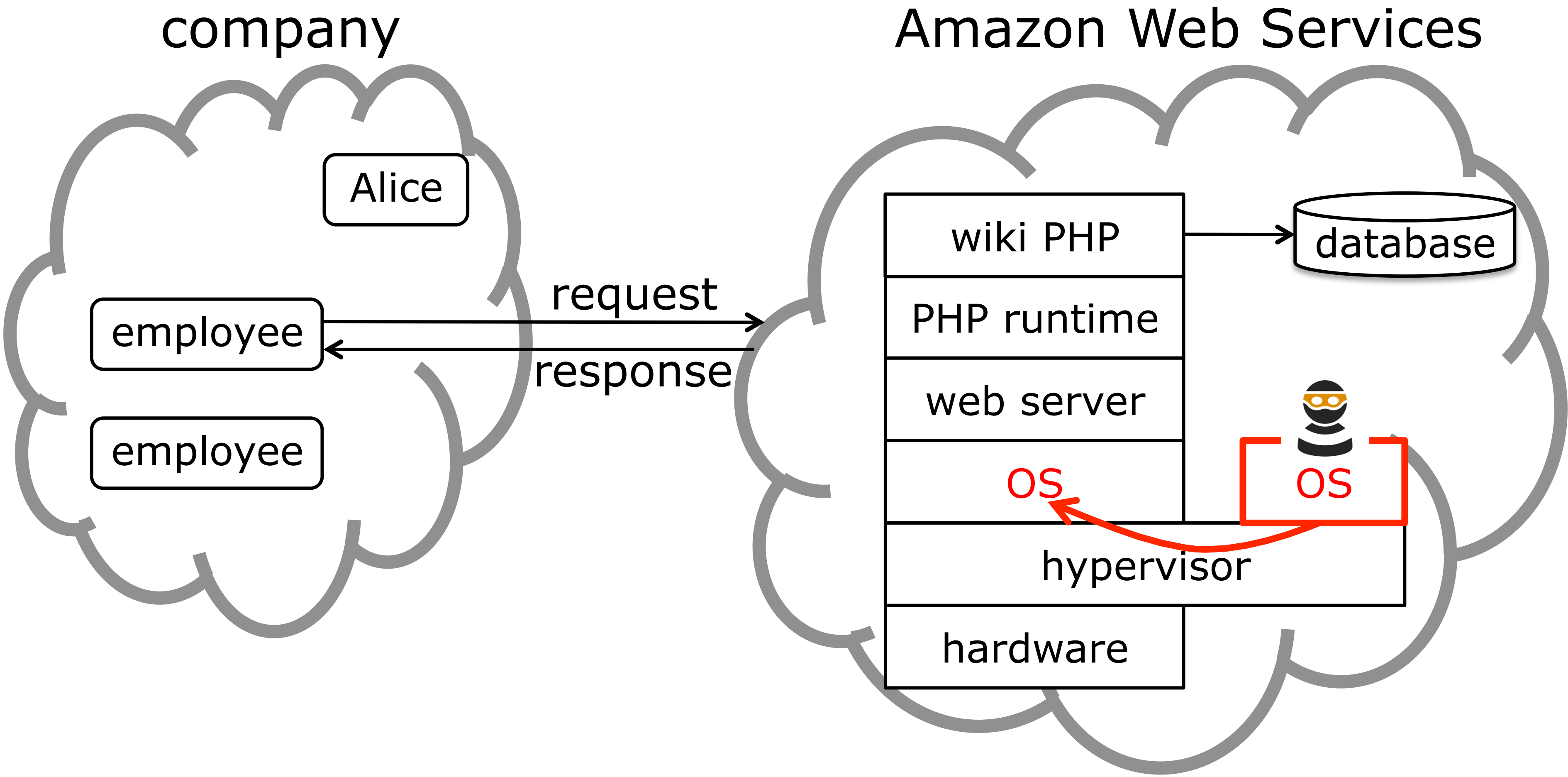

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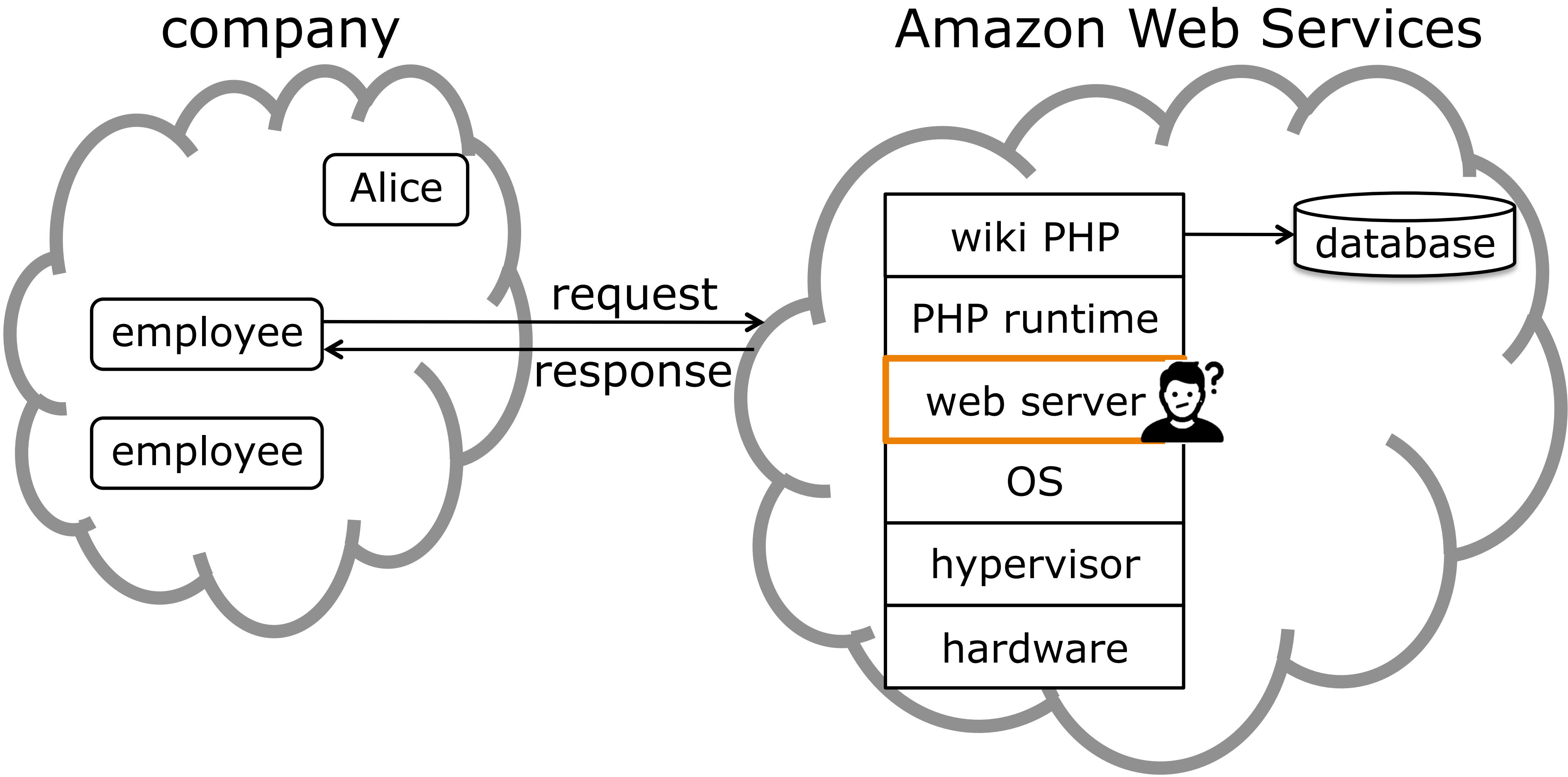

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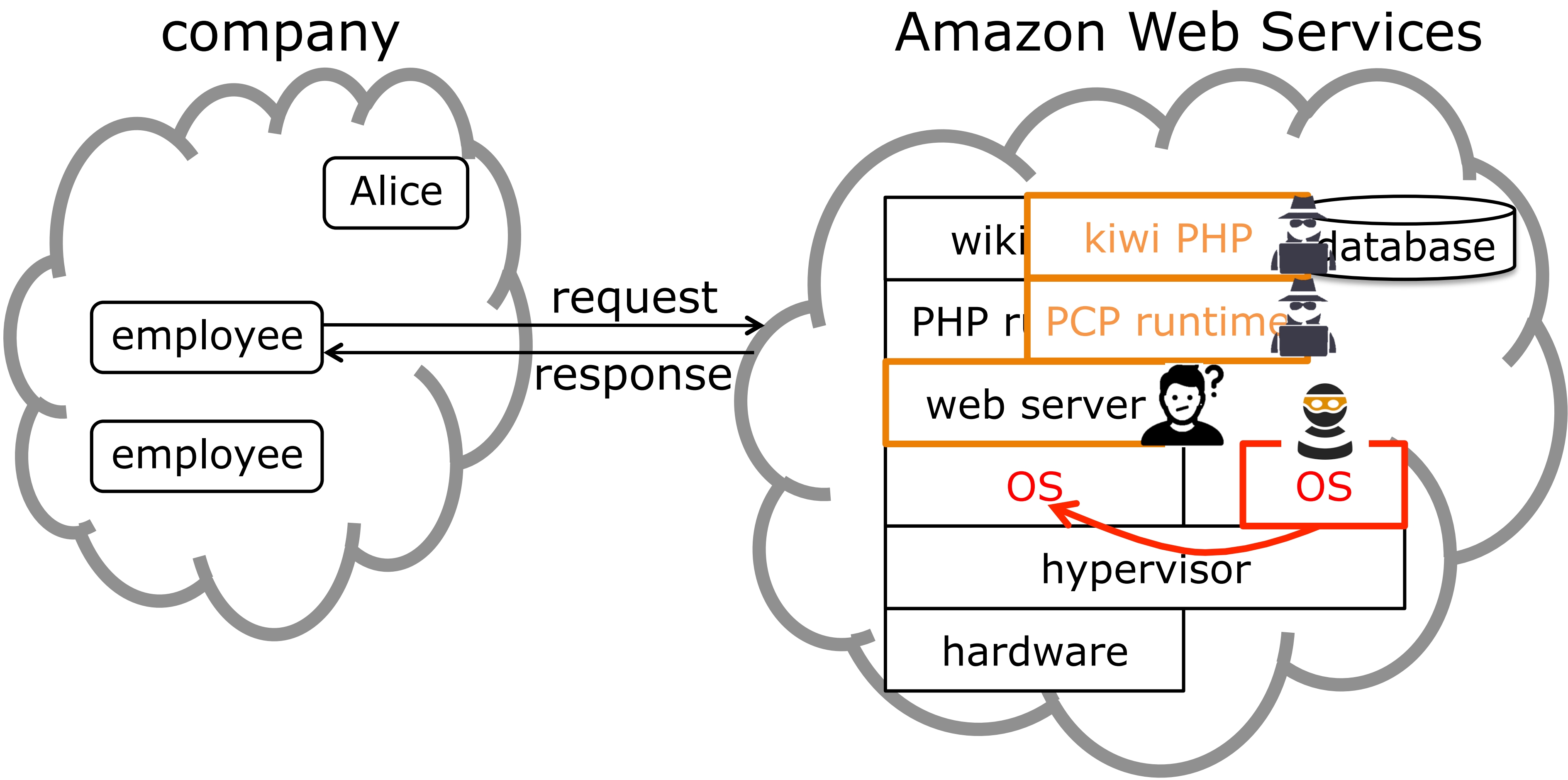

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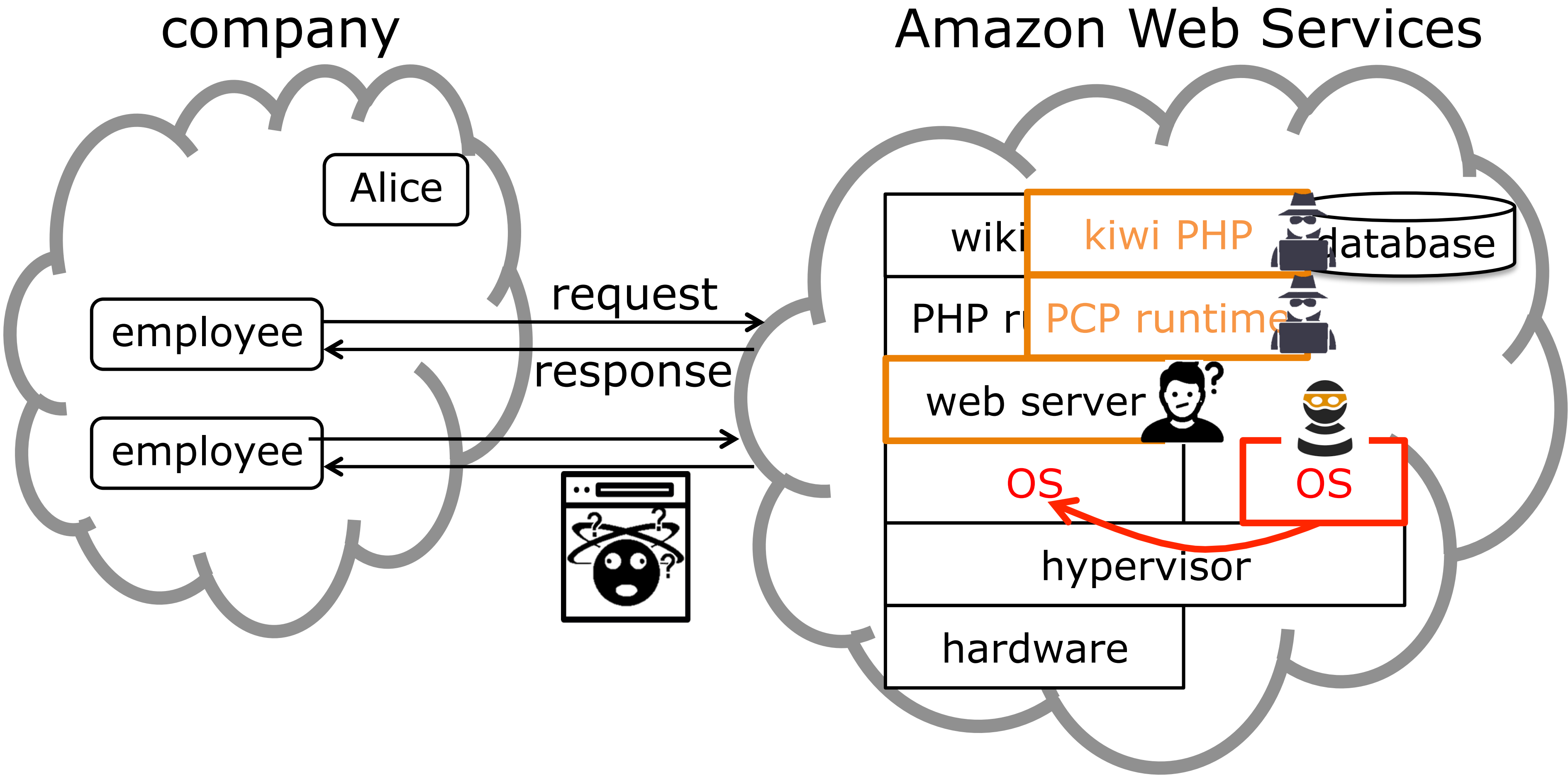

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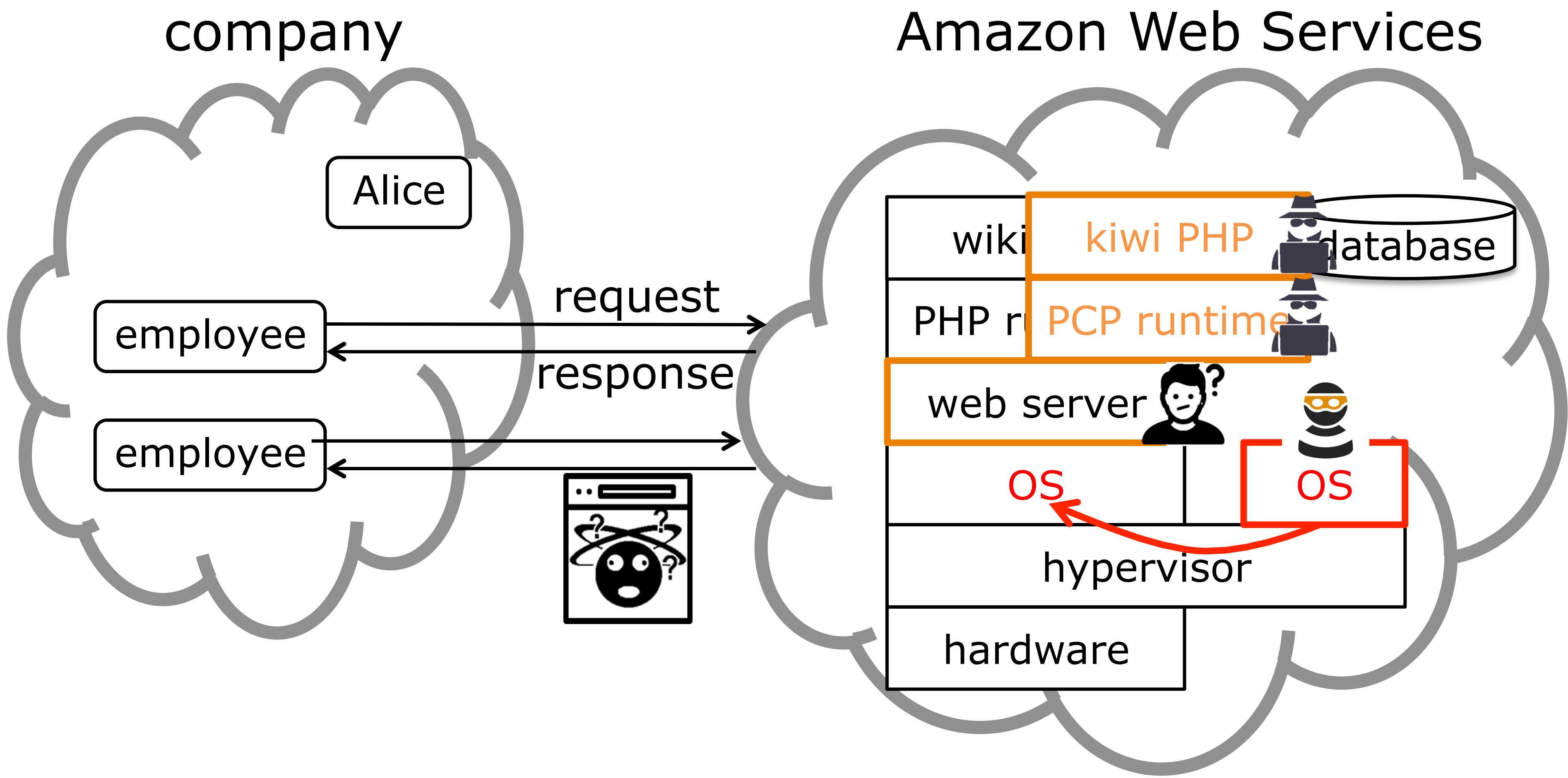
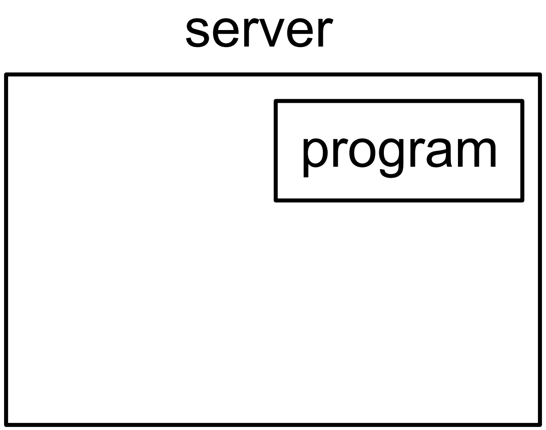


- Alice has confidence in the wiki's PHP code
- Still, lots of things can go wrong ...
- Thus, Alice wants to audit the delivered responses
  - Are they derived from executing the actual application?

The Efficient Server Audit Problem



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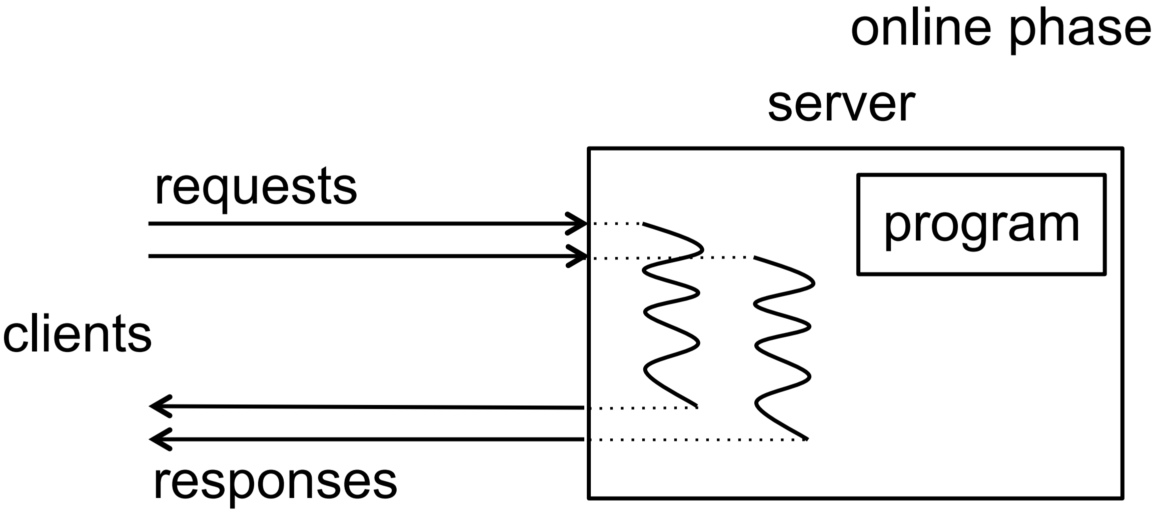
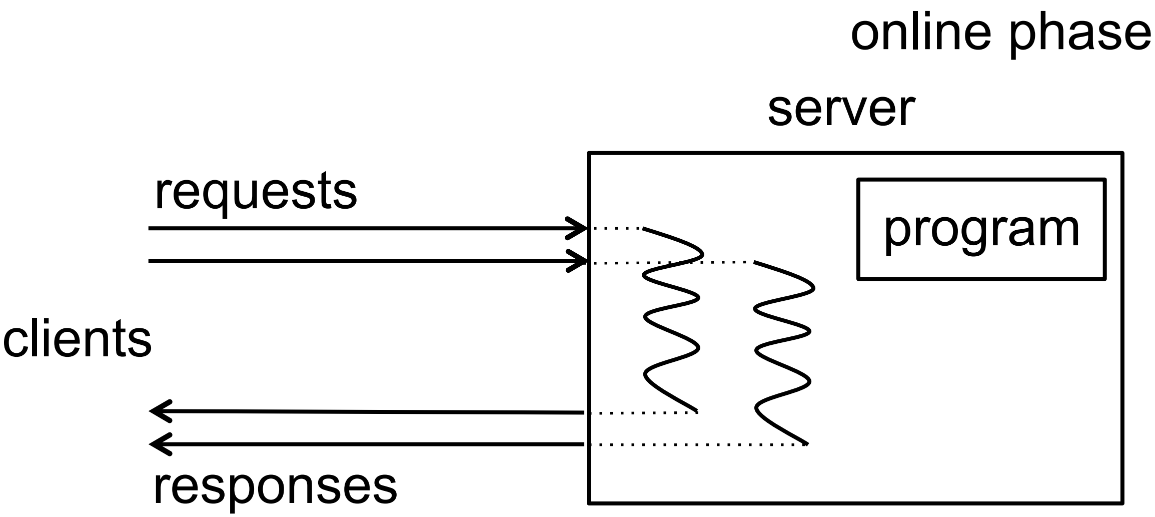
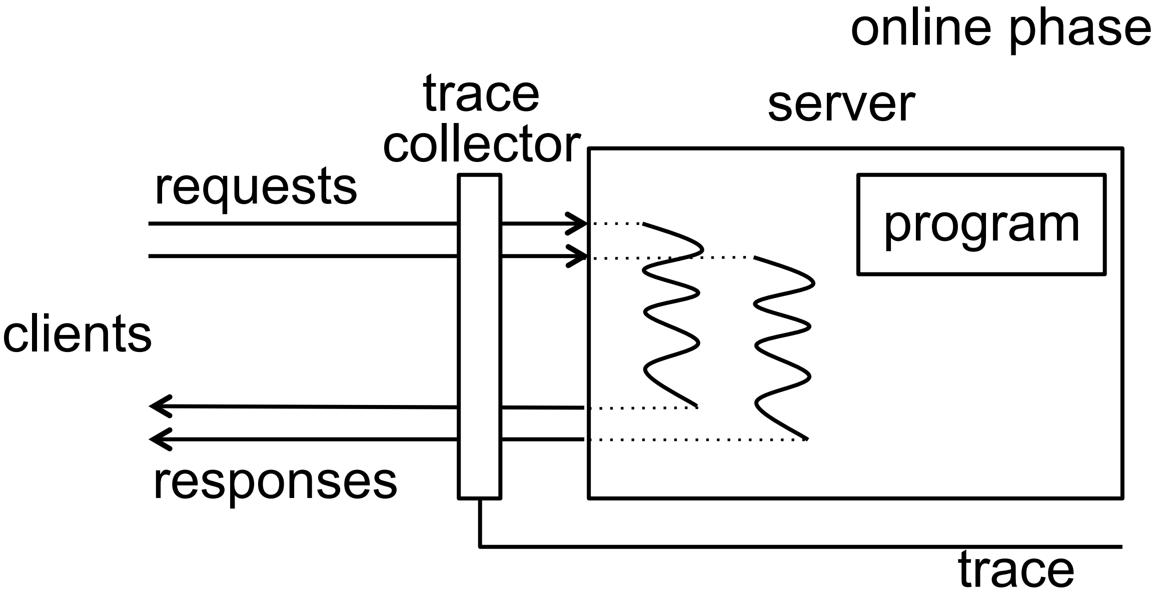


The Efficient Server Audit Problem



1. server is untrusted; can respond arbitrarily
2. server is concurrent

The Efficient Server Audit Problem



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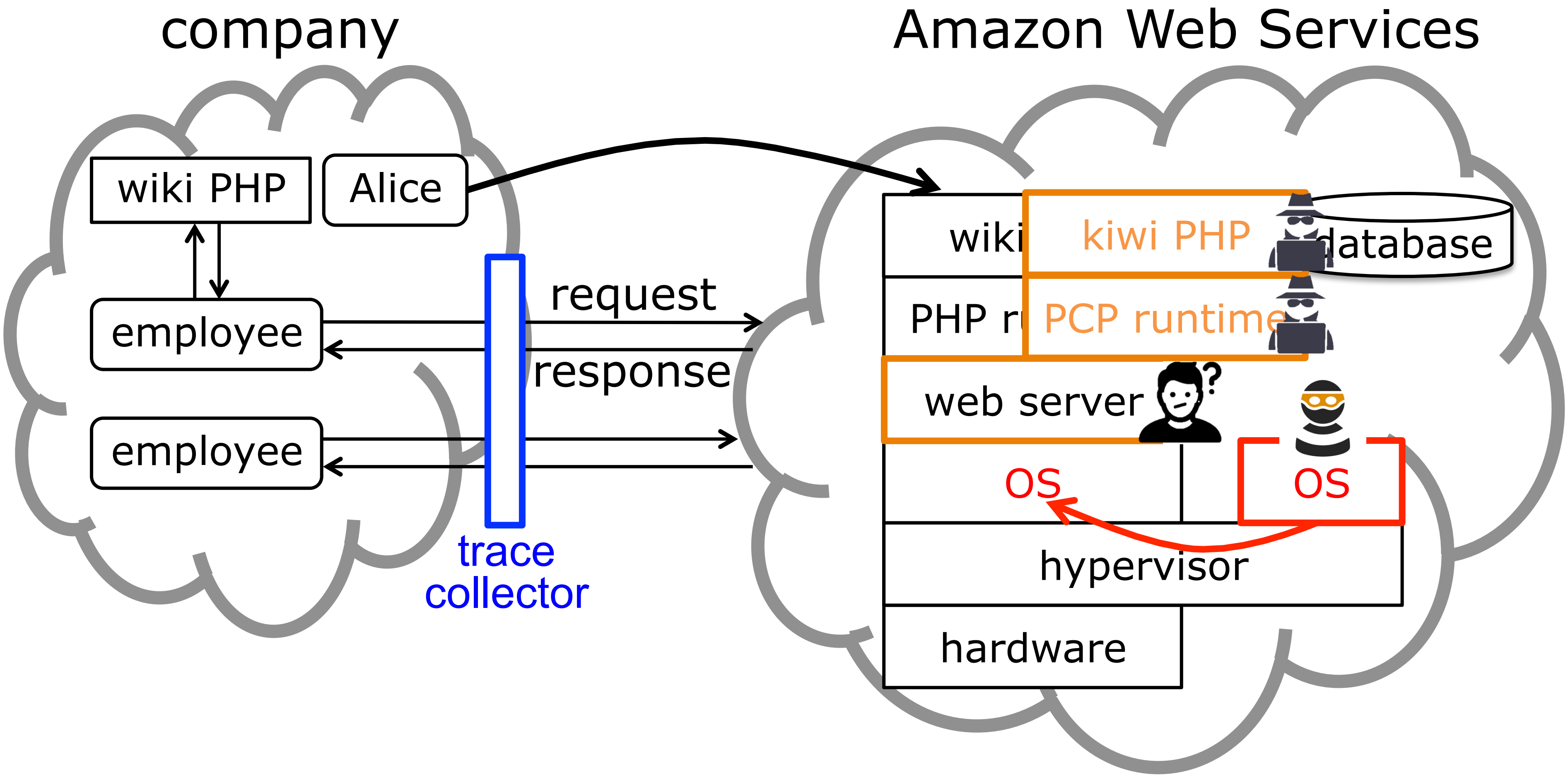


company

Amazon Web Services

wiki PHP

Alice

employee

employee

request

response

trace
collector

wiki

kiwi PHP

database

PHP r

PCP runtime

web server

?

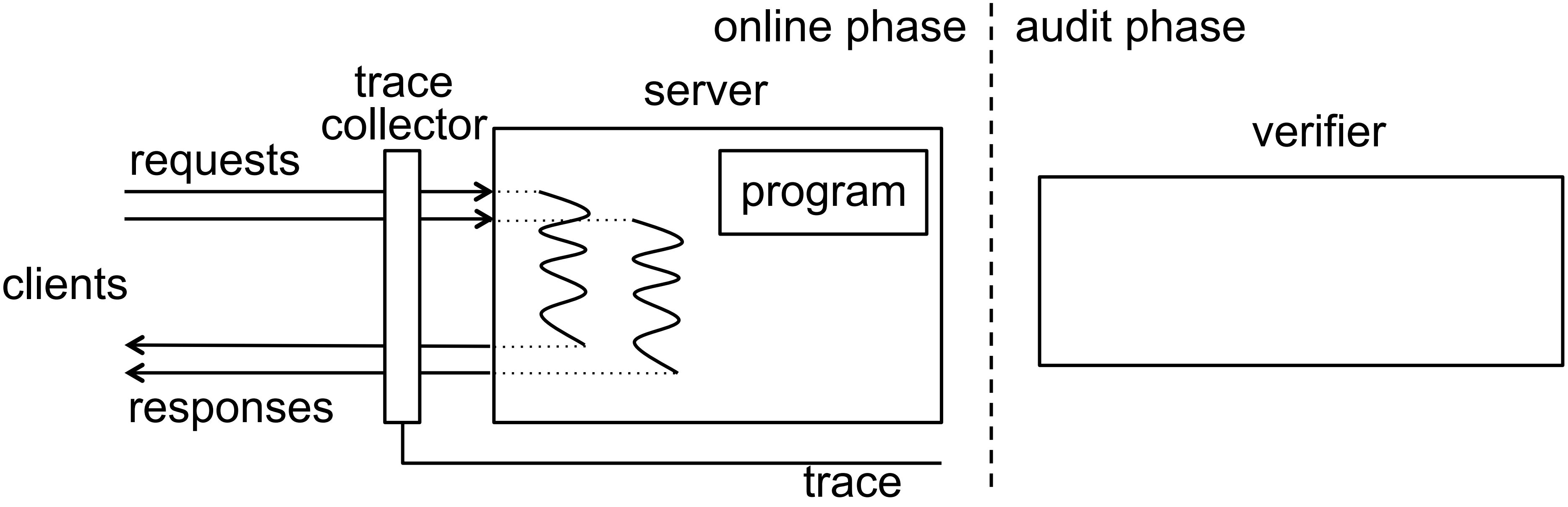
OS

OS

hypervisor

hardware

The Efficient Server Audit Problem



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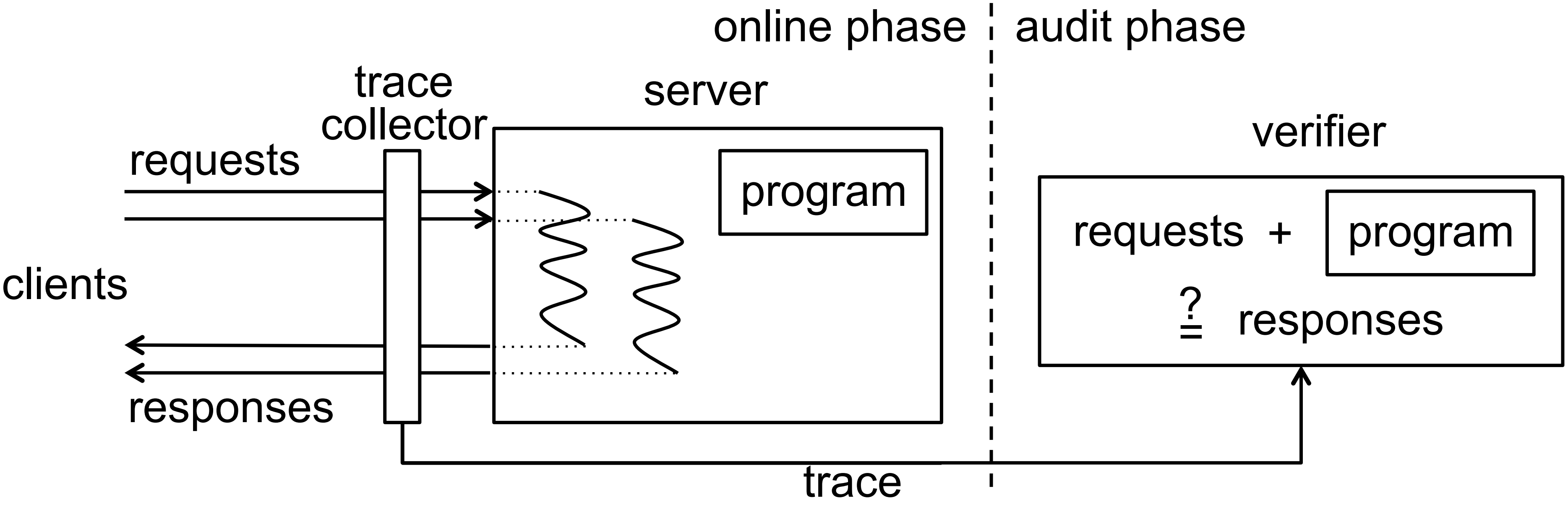

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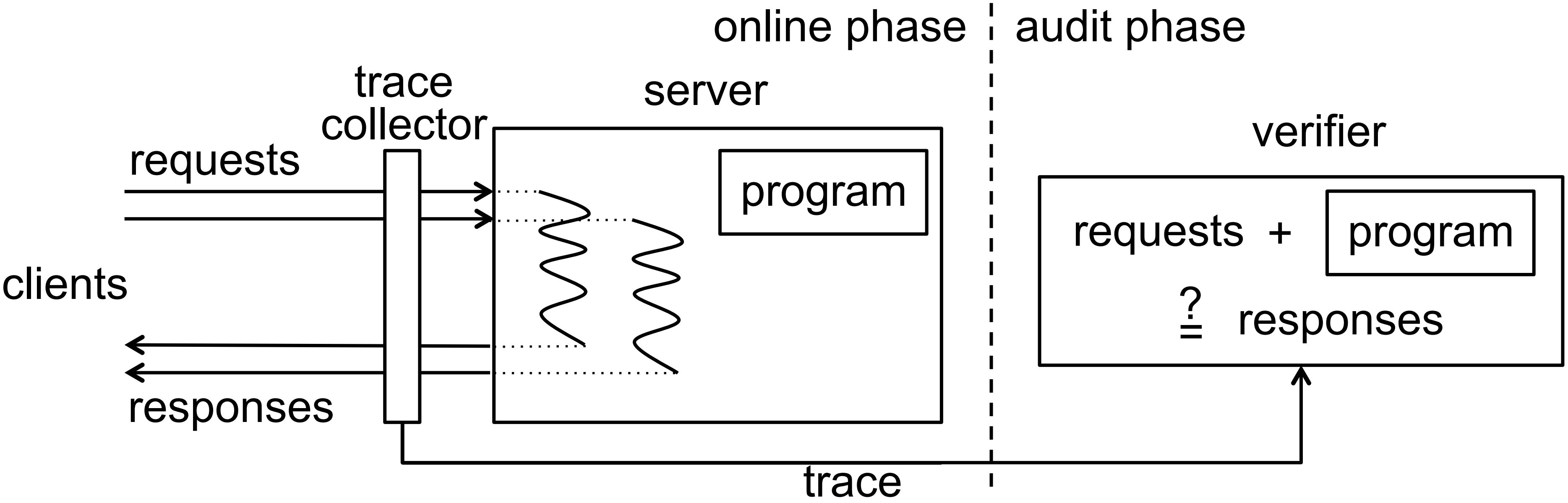
The Efficient Server Audit Problem



1. server is untrusted; can respond arbitrarily
2. server is concurrent
3. verifier is weaker than server
4. server overhead is low; legacy applications supported

The Efficient Server Audit Problem

1. server is untrusted…
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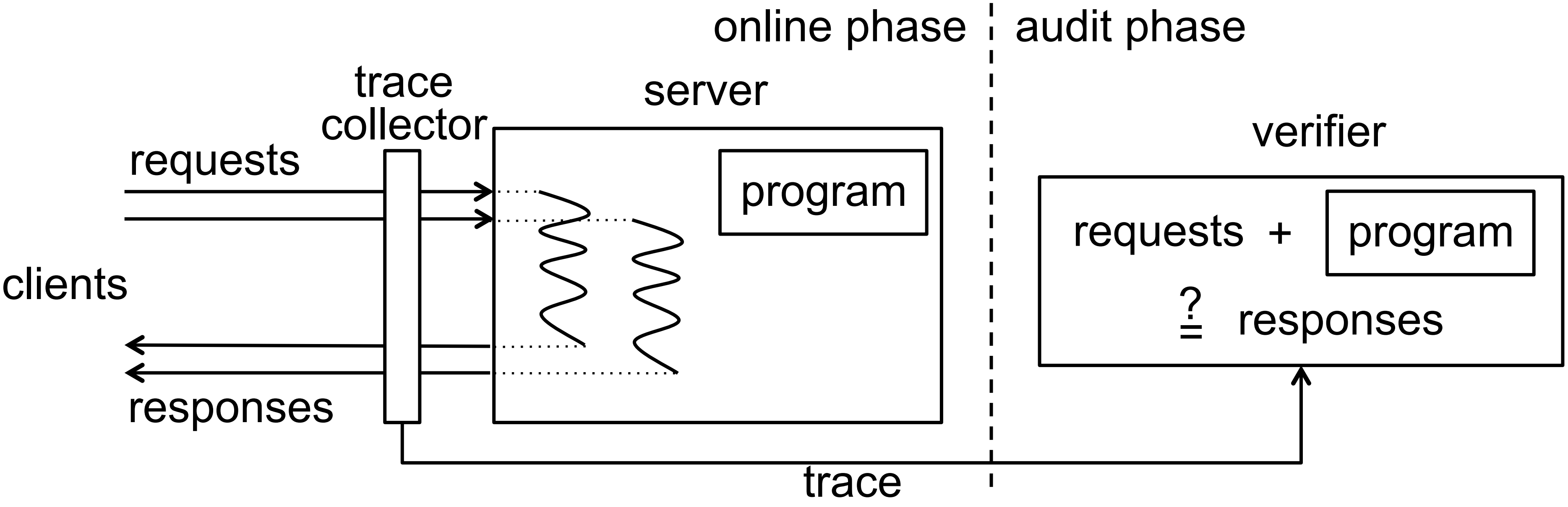

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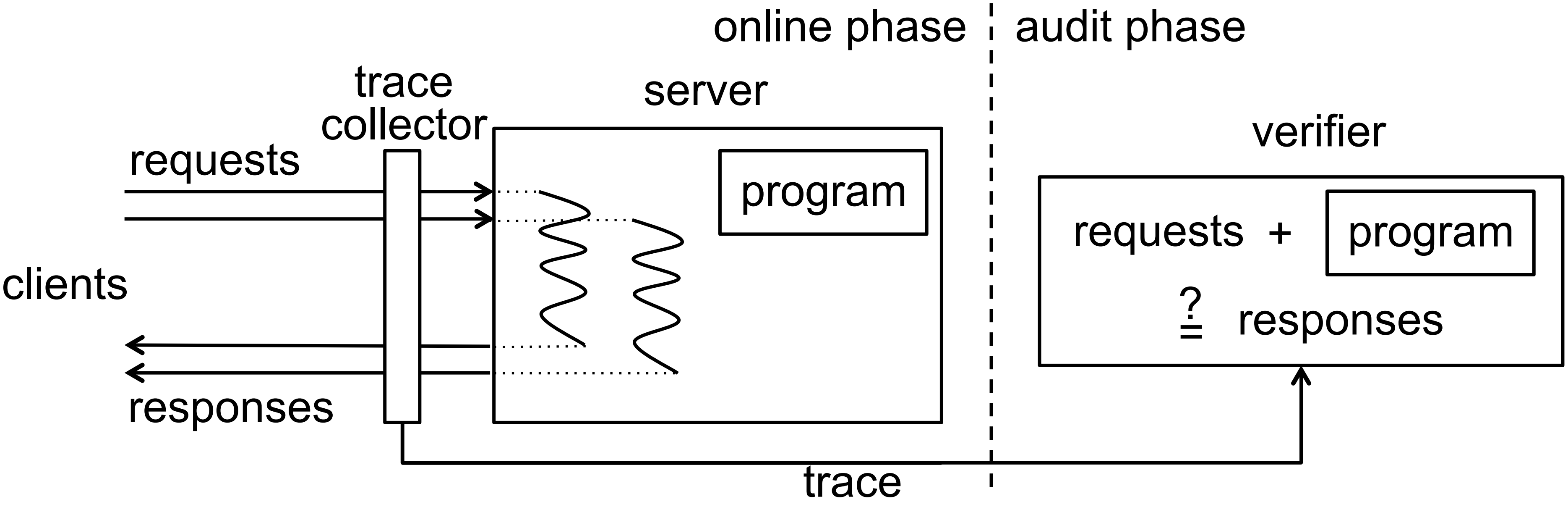
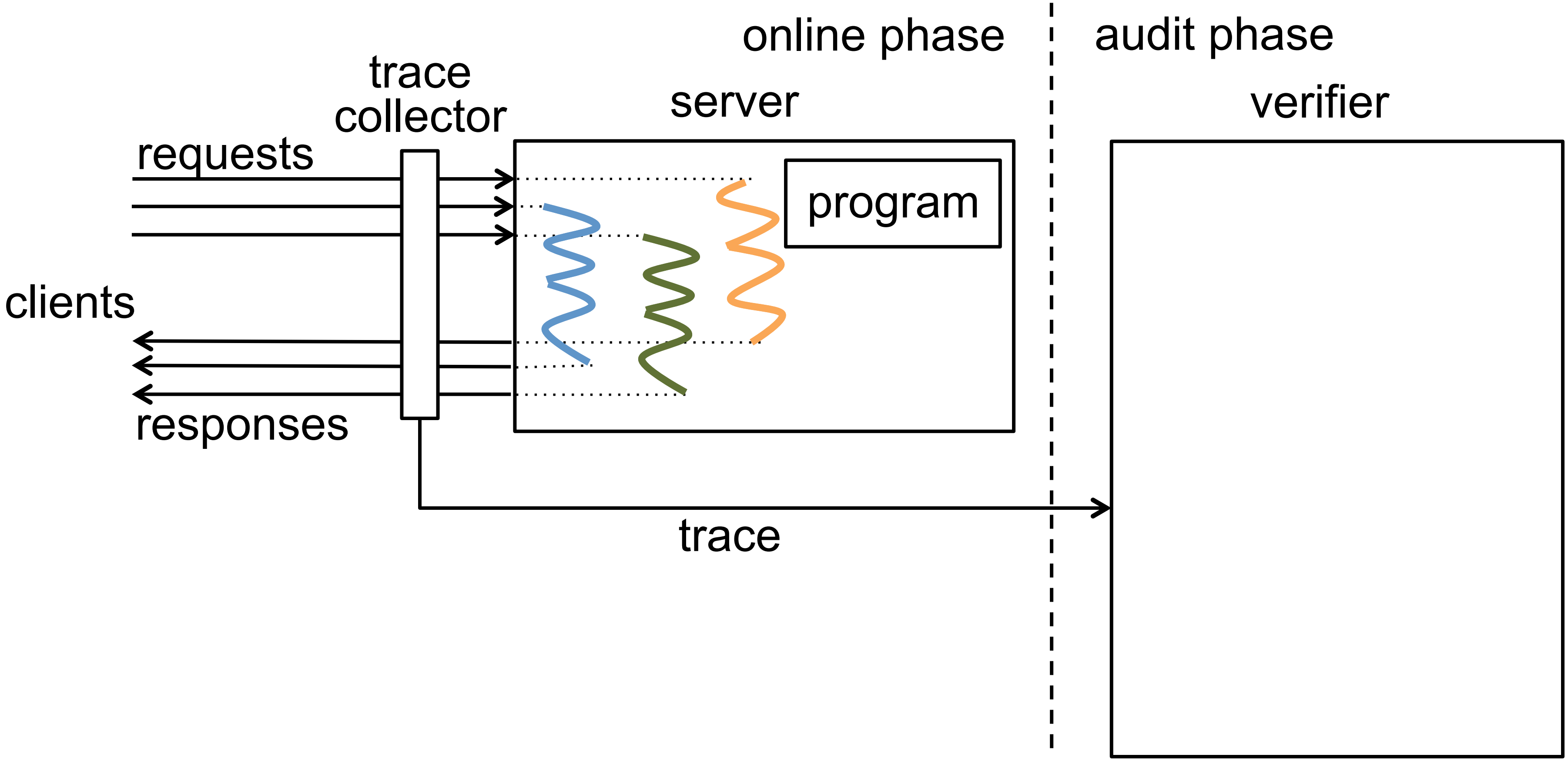


- Combination of these four is a new problem.
- Execution integrity is complementary to program verification.

What about naive re-execution?

1. server is untrusted…
2. server is concurrent
3. verifier is weaker than server
4. server overhead is low…



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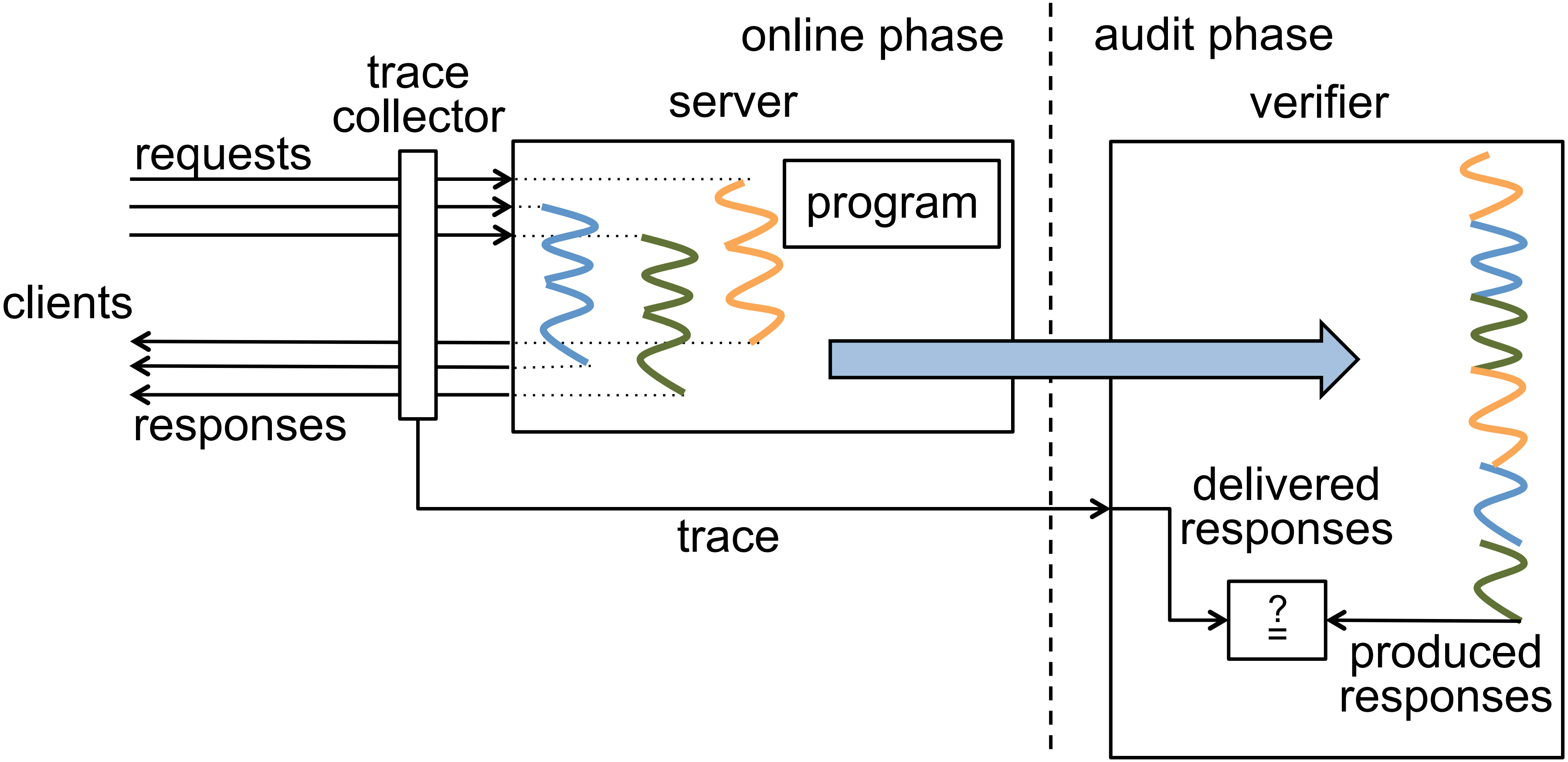
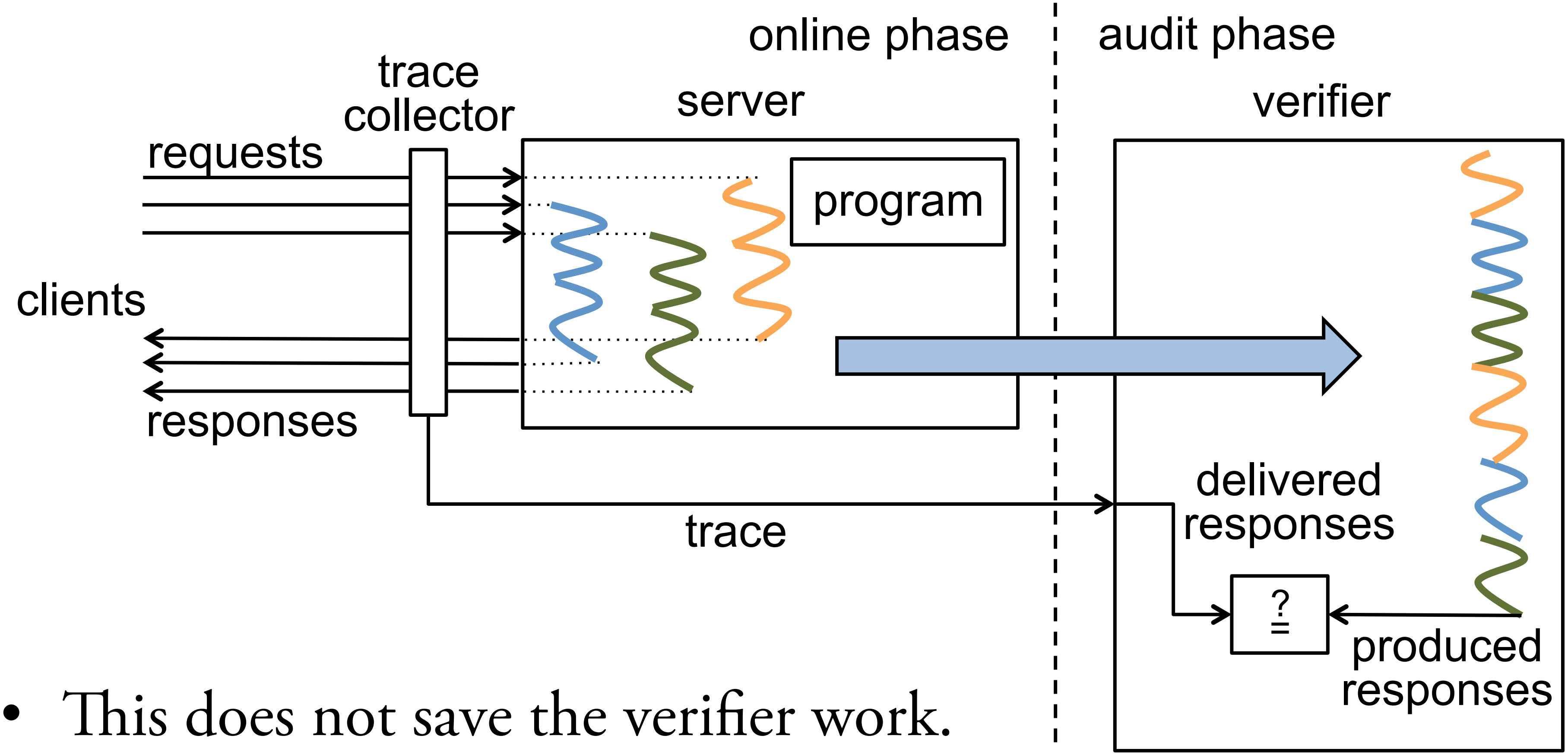


What about naive re-execution?

✓ 1. server is untrusted…
✓ 2. server is concurrent
✗ 3. verifier is weaker than server
✓ 4. server overhead is low…



- This does not save the verifier work.

What about naive re-execution?

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❓. server is concurrent
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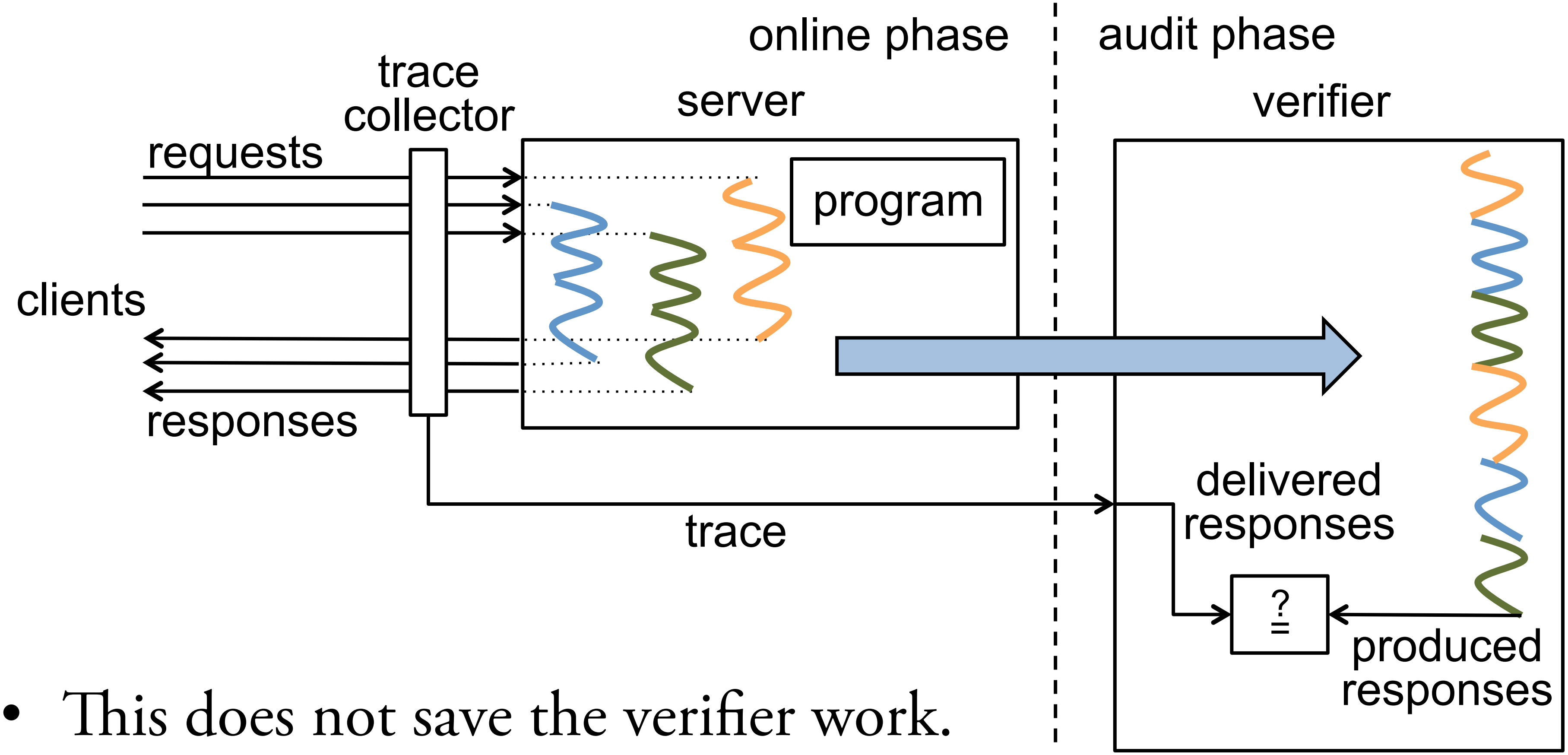
❓. server overhead is low…



- This does not save the verifier work.
- Instead, we will accelerate re-execution.

Rest of the talk

1. How does the verifier accelerate re-execution?

(these two are in tension)

2. Why are shared objects (such as DBs) challenging?

3. Does our implementation for PHP perform well?

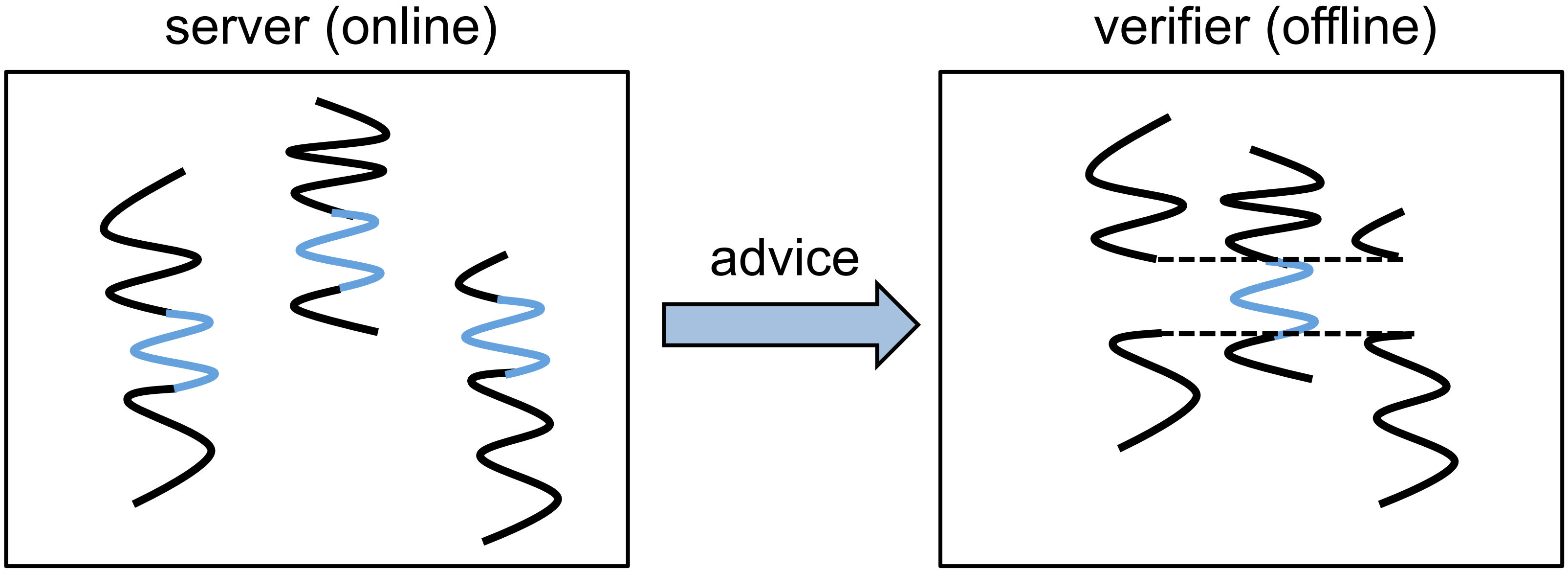
Rest of the talk

→ 1. How does the verifier accelerate re-execution?

2. Why are shared objects (such as DBs) challenging?

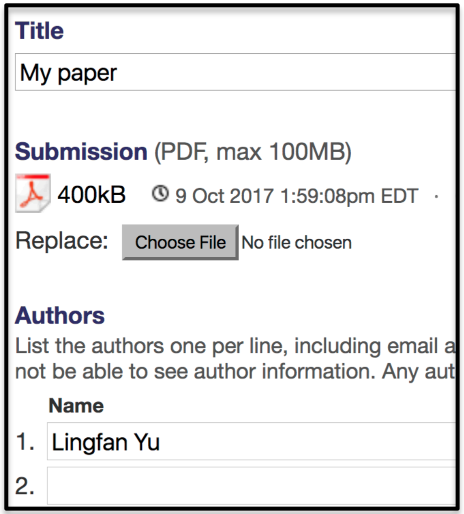
3. Does our implementation for PHP perform well?

Accelerating re-execution: a 30,000-foot view



- Deduplicate computation across requests

Poirot's observation: repeated computation



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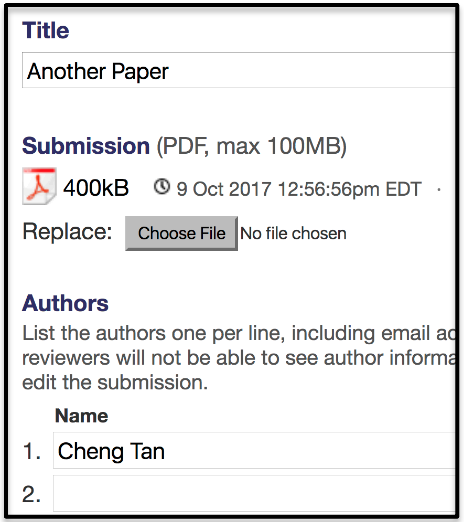

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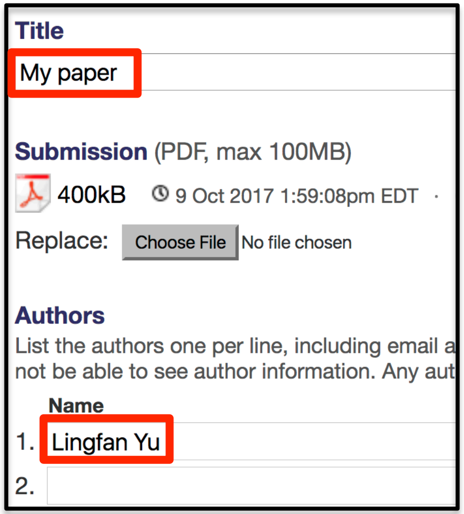

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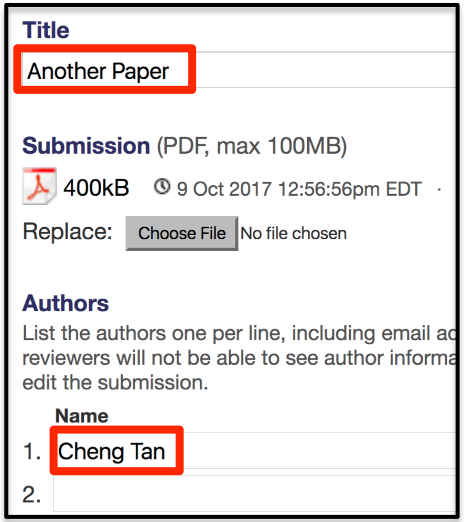

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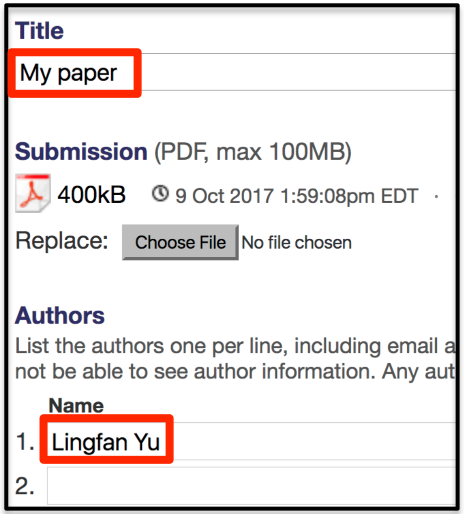

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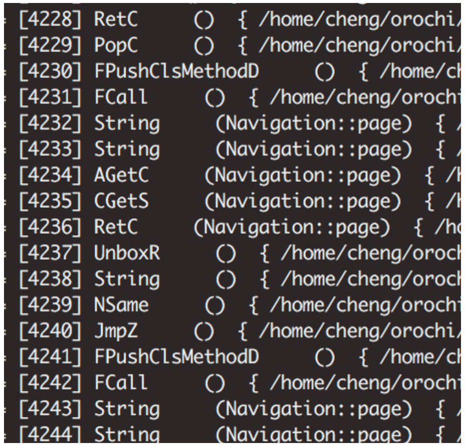

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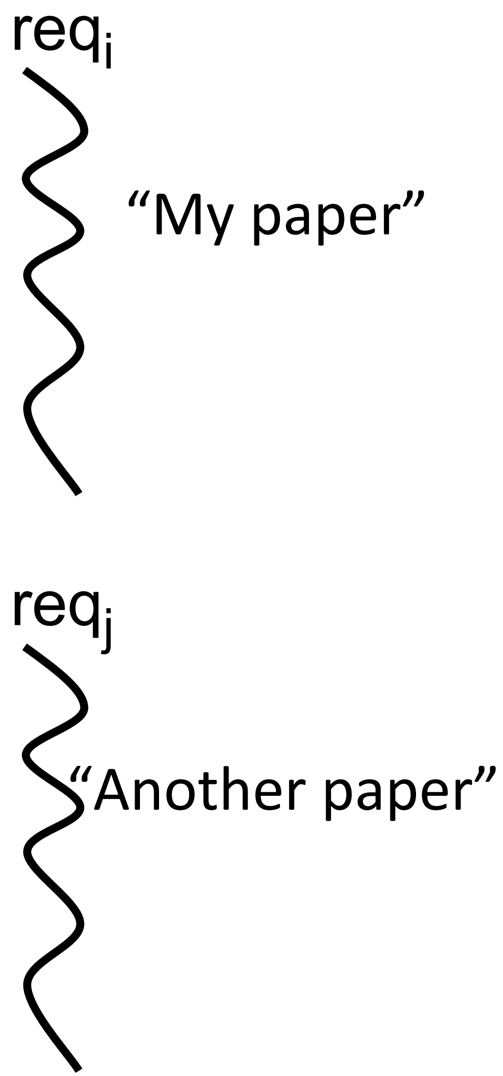

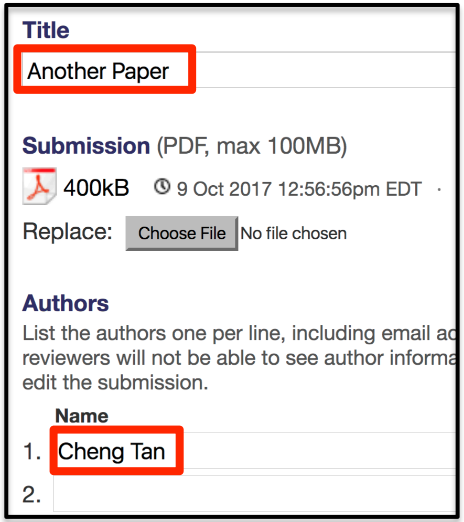

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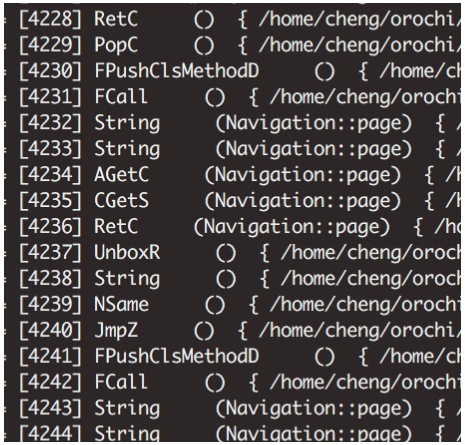

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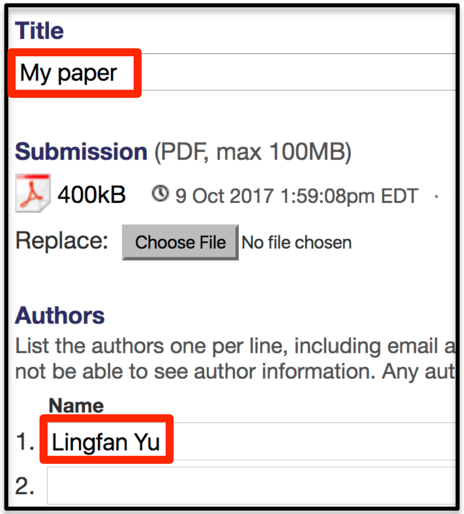

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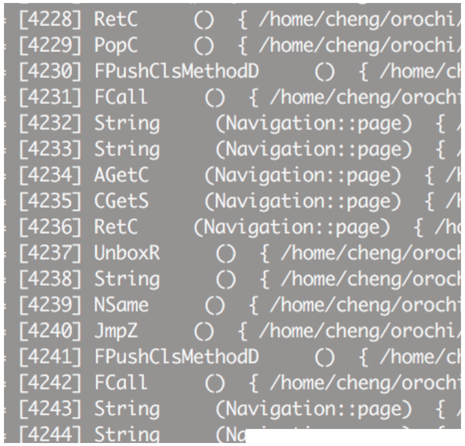

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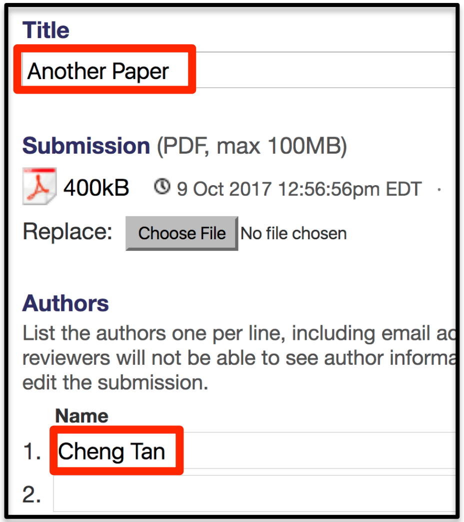
req_i

"My paper"

requires trusting the advice



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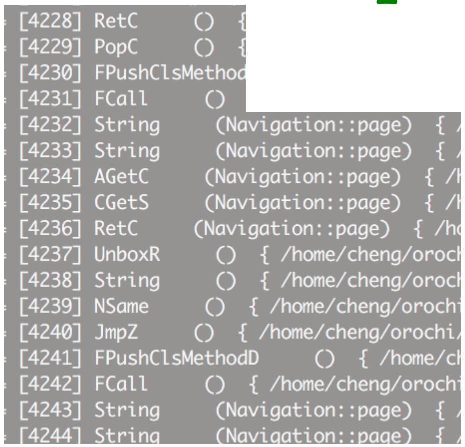

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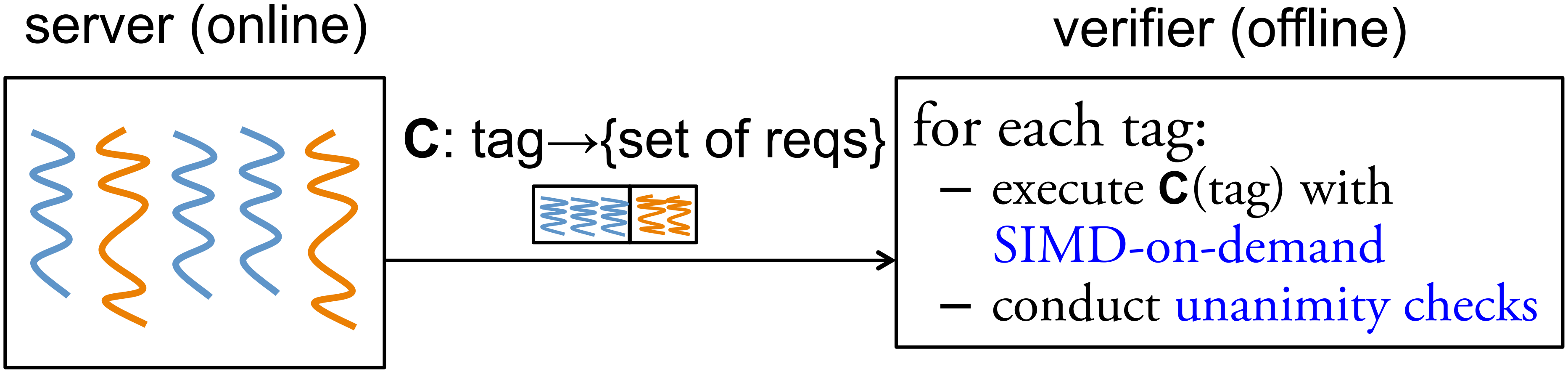
We accelerate re-execution without trusting the server



server (online)

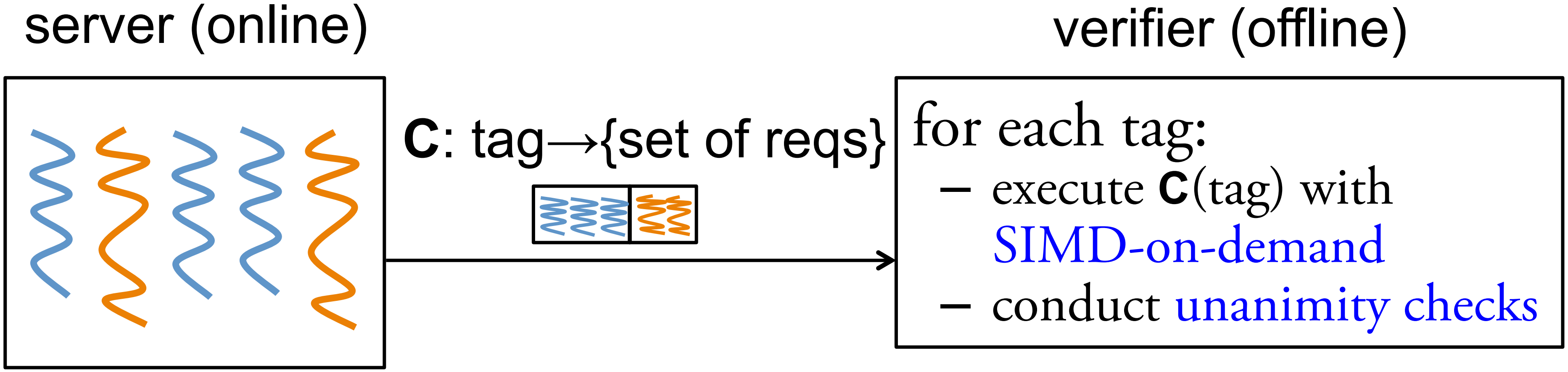
verifier (offline)

C: tag→{set of reqs}

for each tag:

- execute **C**(tag) with SIMD-on-demand
- conduct unanimity checks

We accelerate re-execution without trusting the server



server (online)

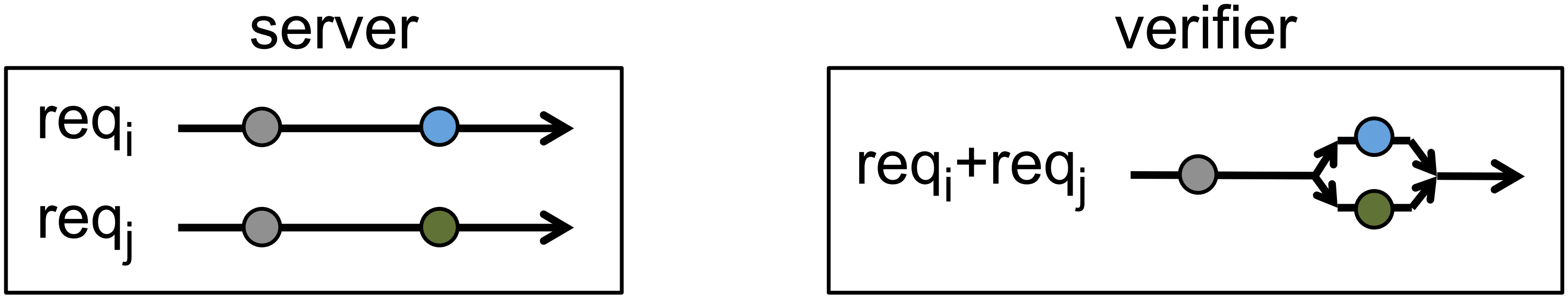
C: tag→{set of reqs}

verifier (offline)

for each tag:

- execute **C**(tag) with SIMD-on-demand
- conduct unanimity checks

SIMD-on-demand re-executes identical instructions once.



SIMD-on-demand eliminates redundant computation

```
main(a,b):
   c ← a * b
   c ← c + 1
```

req$_{i:}$ a=1;b=2

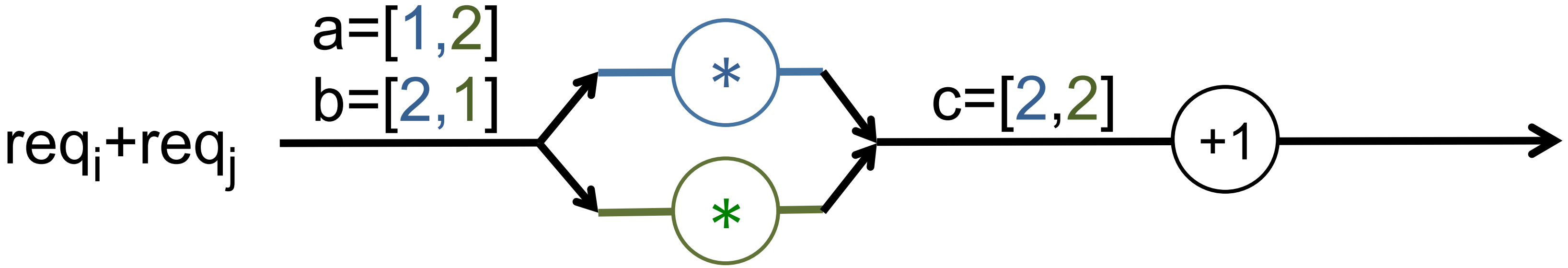
req$_{j:}$ a=2;b=1

SIMD-on-demand eliminates redundant computation

```
main(a,b):
  c ← a * b
  c ← c + 1
```

$req_{i:}$ a=1;b=2

$req_{j:}$ a=2;b=1



- Multi-value represents different values of the same variable.

SIMD-on-demand eliminates redundant computation

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main(a,b):
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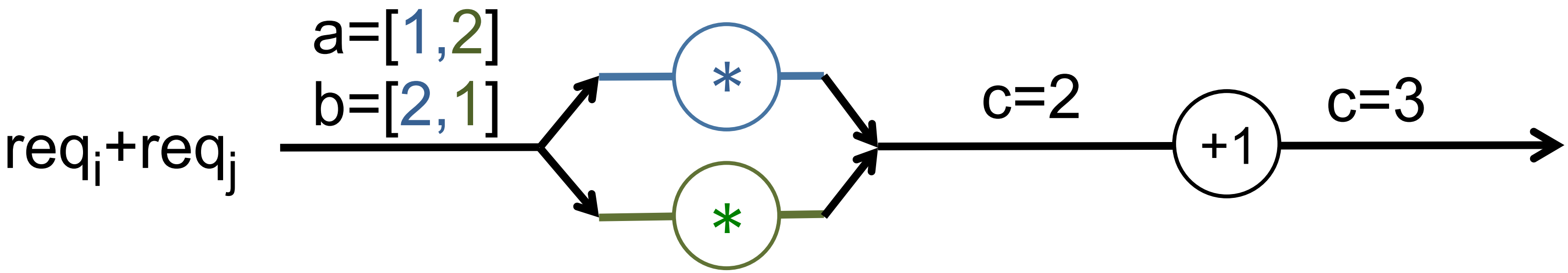
req$_{i:}$ a=1;b=2

req$_{j:}$ a=2;b=1



- Multi-value represents different values of the same variable.
- Verifier collapses multi-value to scalar if possible.

Recap

- Verifier re-executes in an accelerated way …

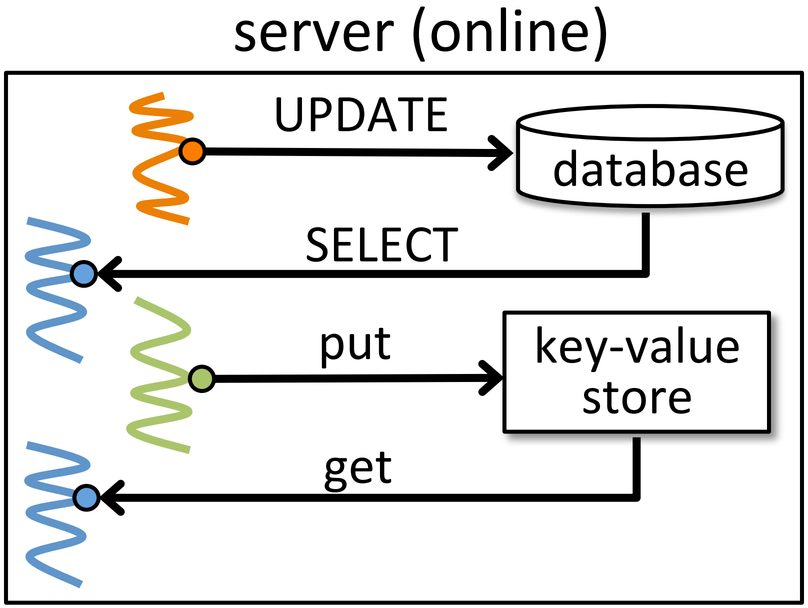
- ... by exploiting advice from the server ...

- ... without trusting that advice.

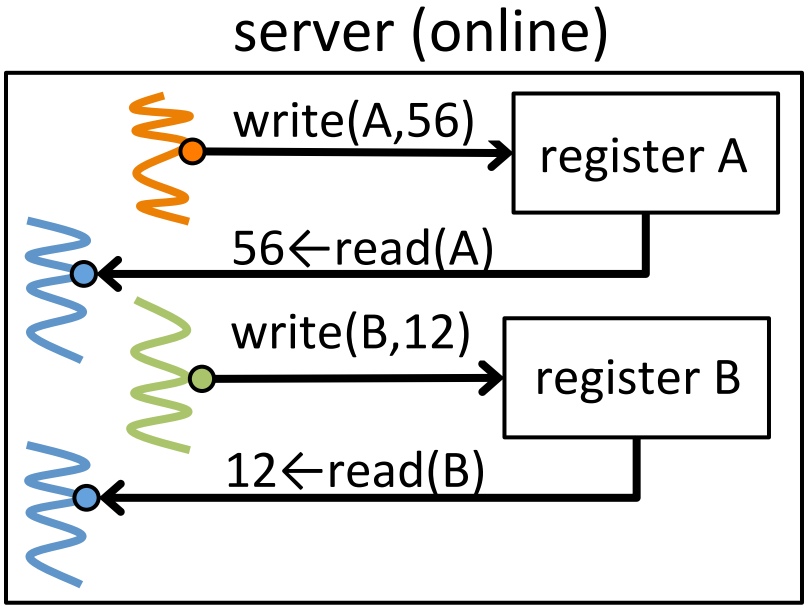
1. How does the verifier accelerate re-execution?

→ 2. Why are shared objects (such as DBs) challenging?

3. Does our implementation for PHP perform well?

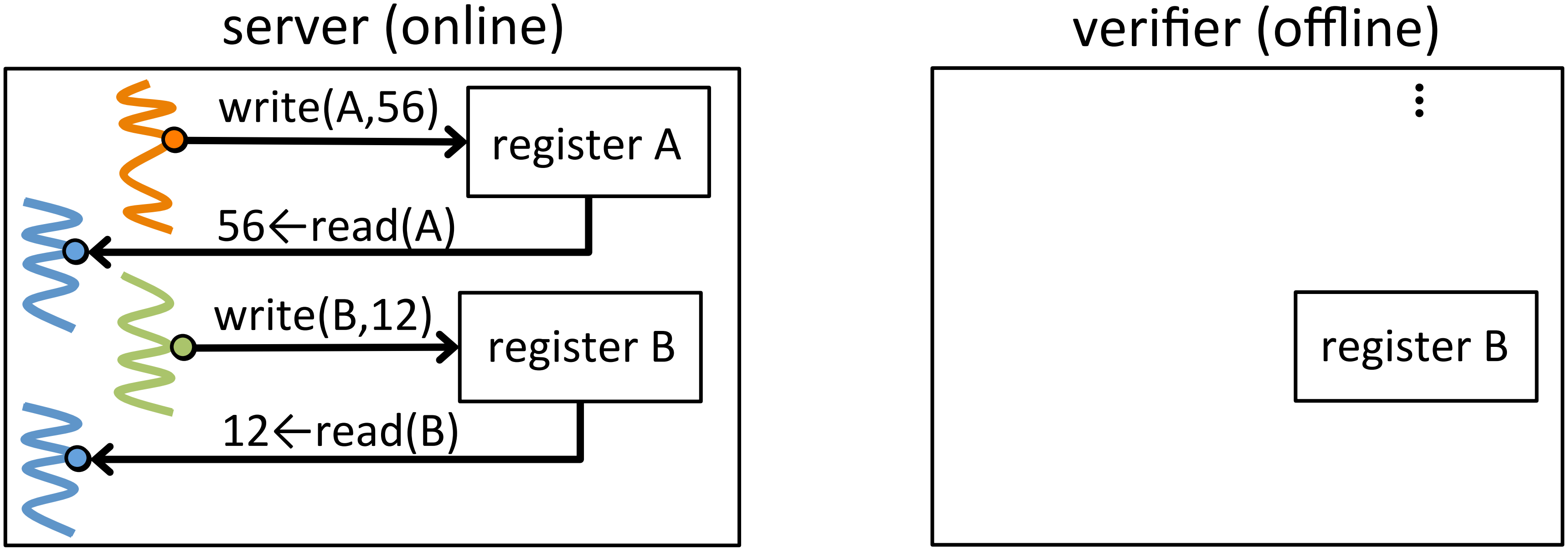


- Will try to give some intuition for the difficulties
- Solutions in the paper, rigorous proofs in tech report



- Will try to give some intuition for the difficulties
- Solutions in the paper, rigorous proofs in tech report
- For now, assume simple storage model
  - Read-write registers, named with letters

Central challenge: re-execution is out of order



server (online)

write(A,56)

register A

56←read(A)

write(B,12)

register B

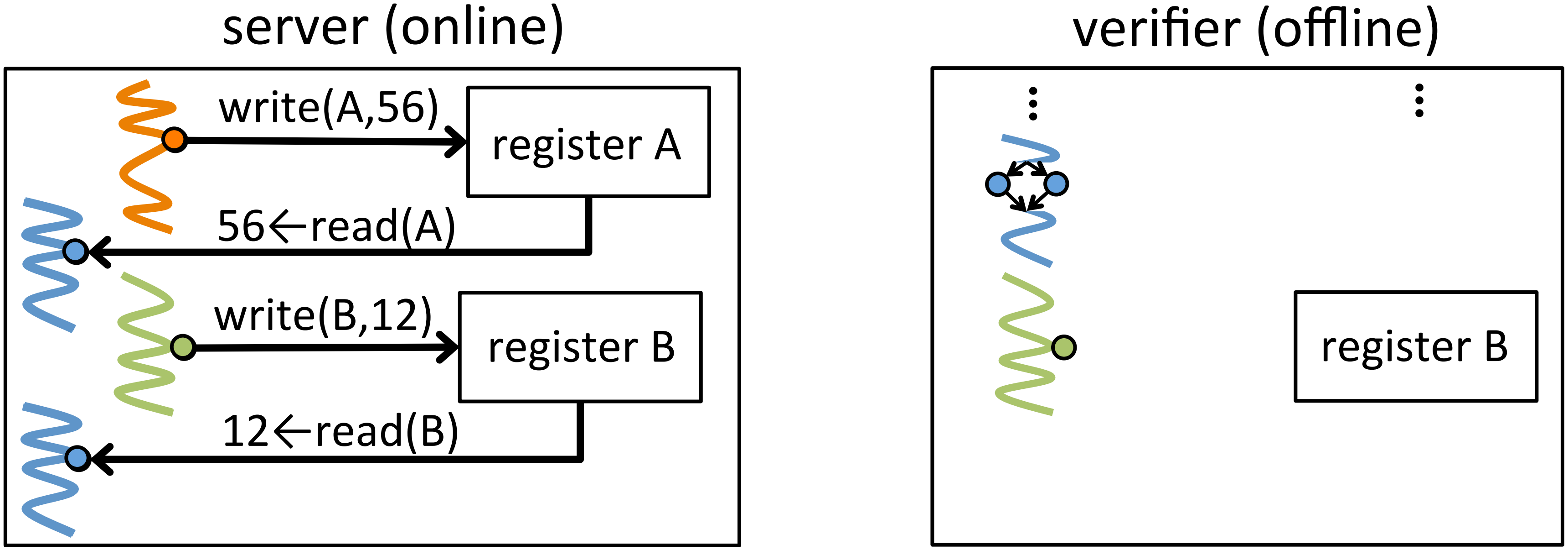
12←read(B)

verifier (offline)

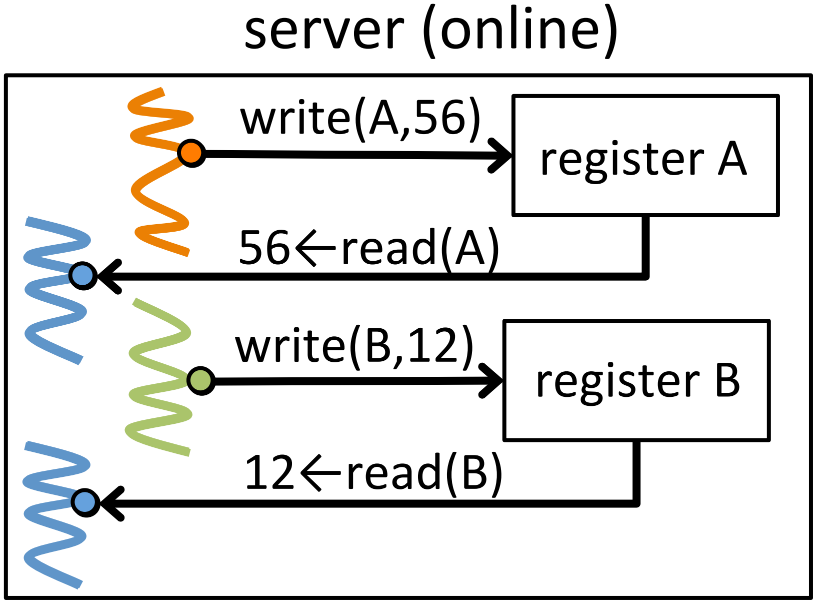
⋮

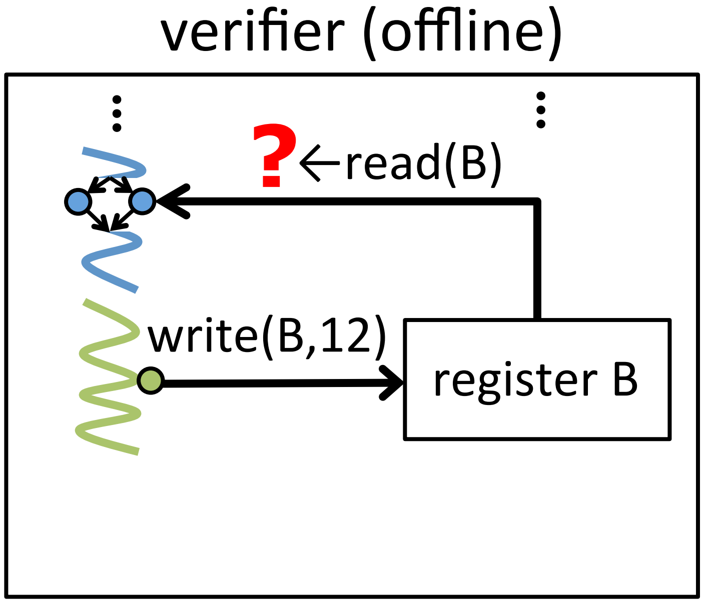
register B

Central challenge: re-execution is out of order

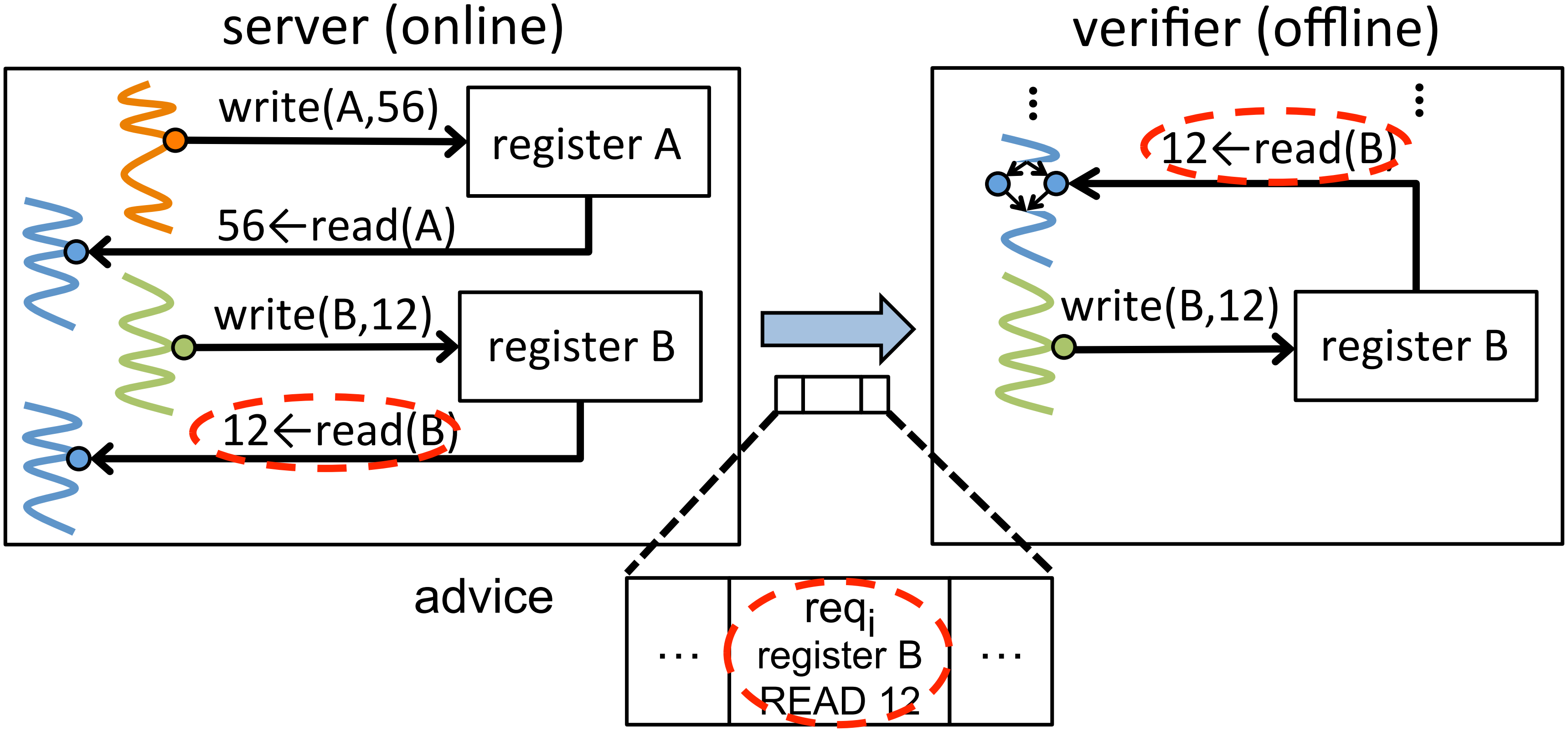


Central challenge: re-execution is out of order



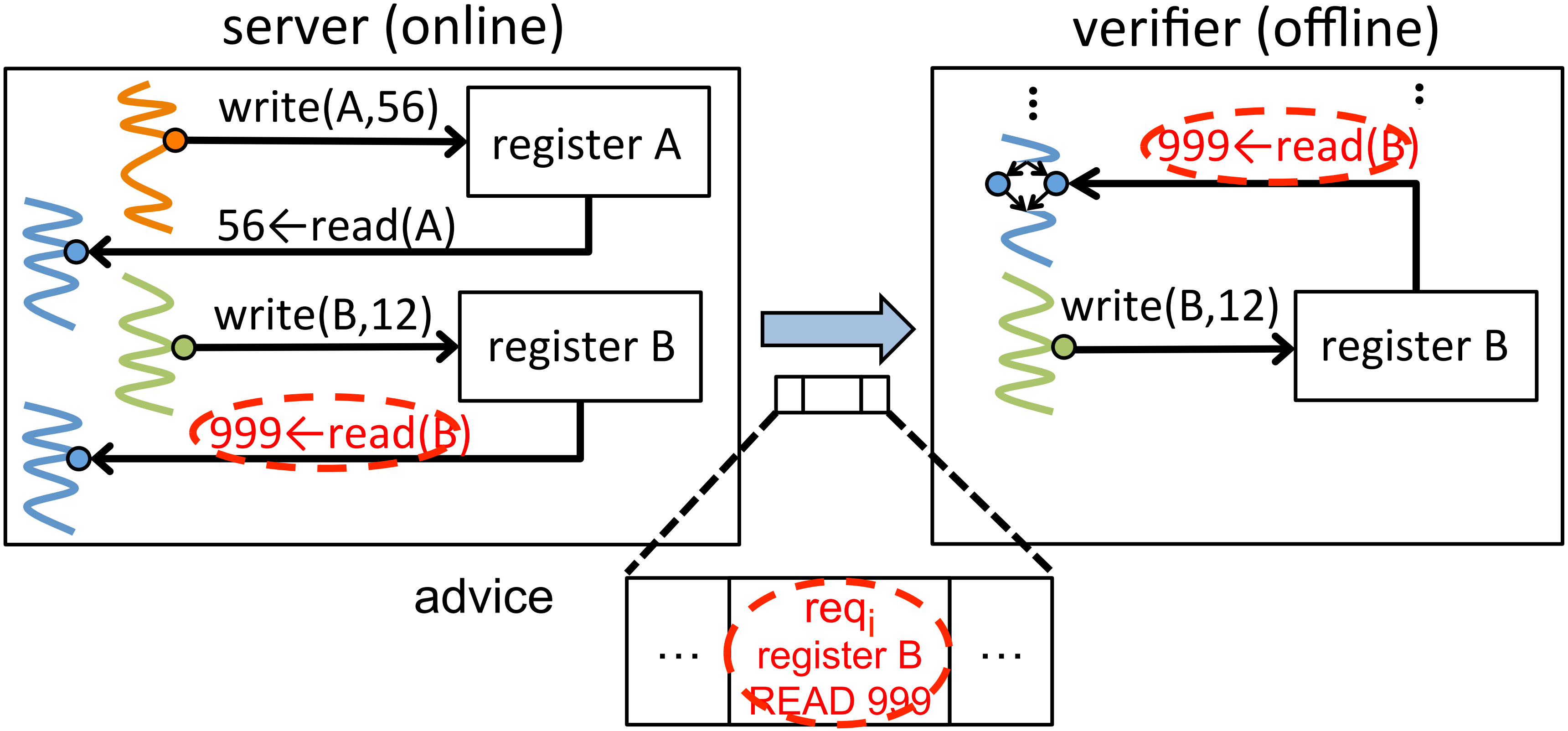


How can the verifier re-execute reads? Attempt 1:



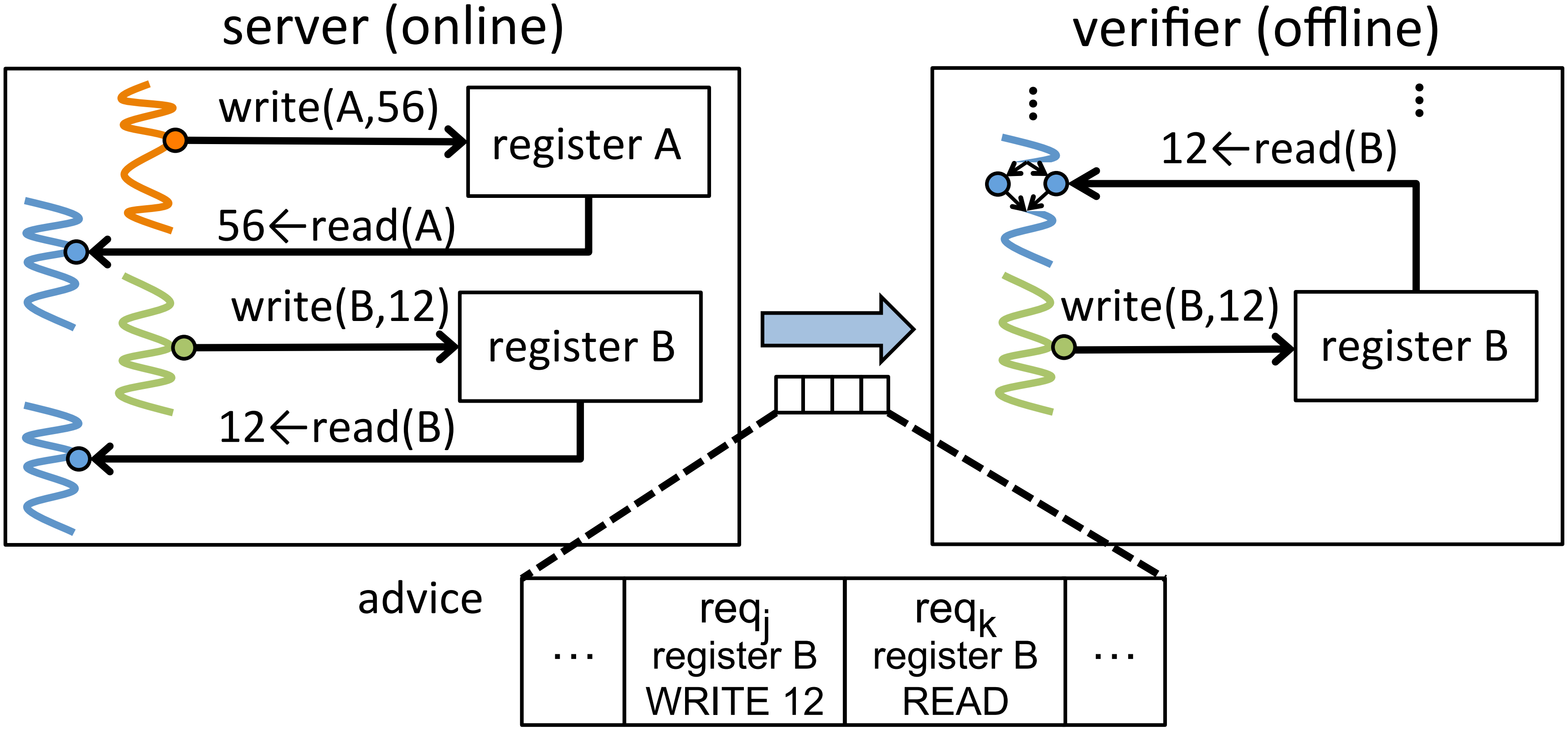
- Server logs read values; verifier supplies from log

How can the verifier re-execute reads? Attempt 1:



- Server logs read values; verifier supplies from log
- This can fool the verifier

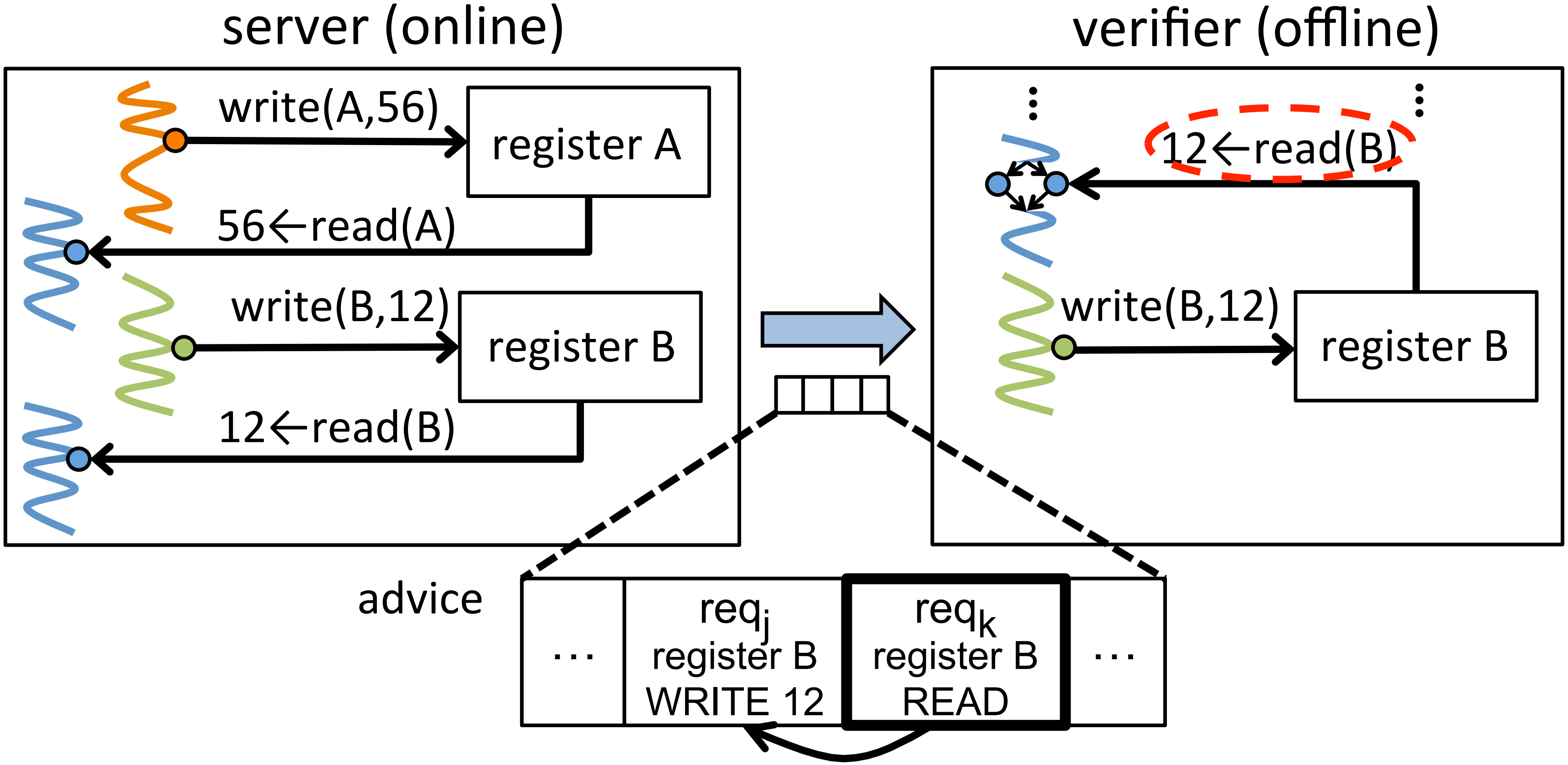
How can the verifier re-execute reads? Attempt 2:



…	req$_j$ register B WRITE 12	req$_k$ register B READ	…

- Server: logs operands
- Verifier: simulates reads using log and checks writes

How can the verifier re-execute reads? Attempt 2:



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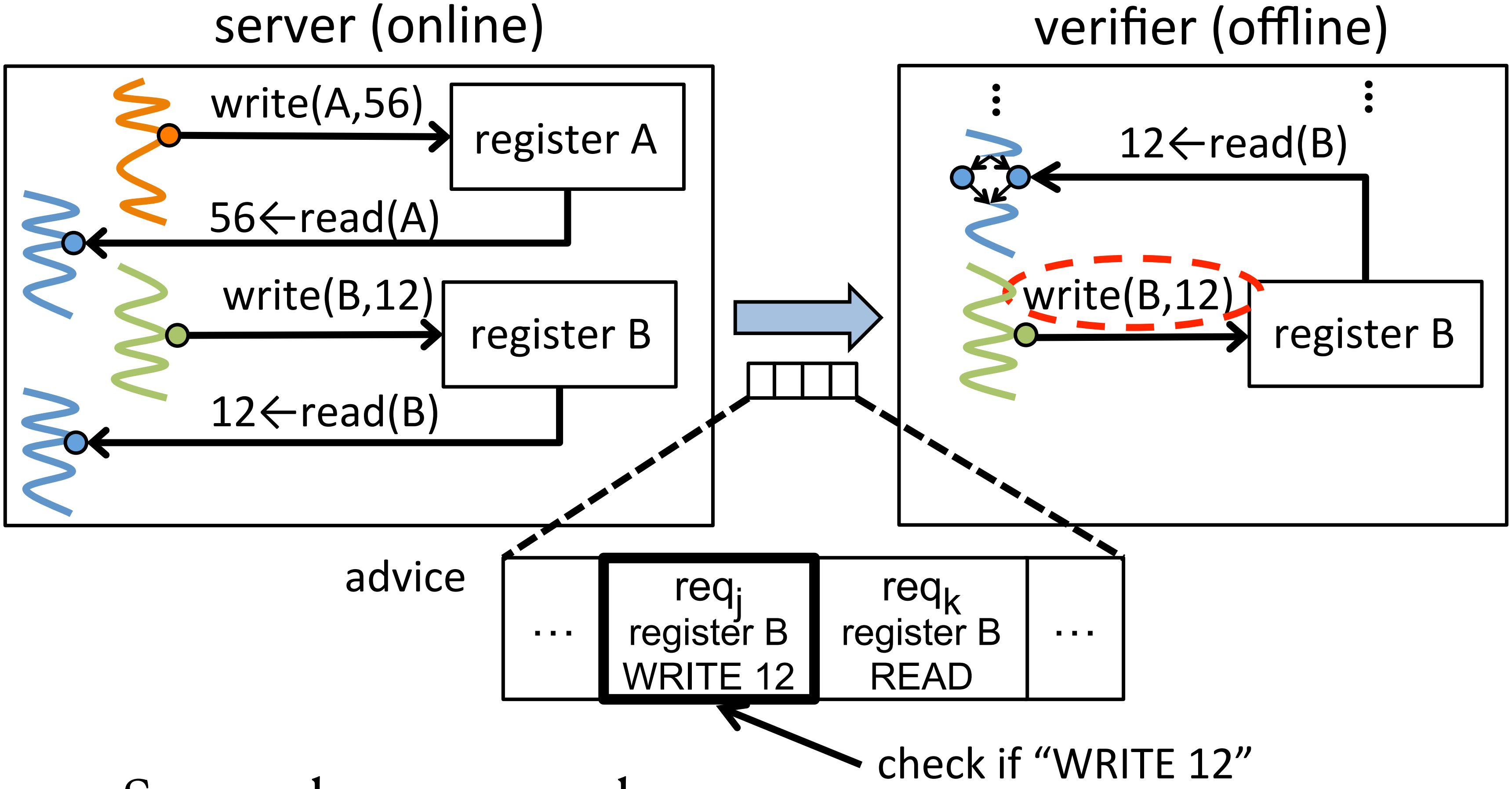
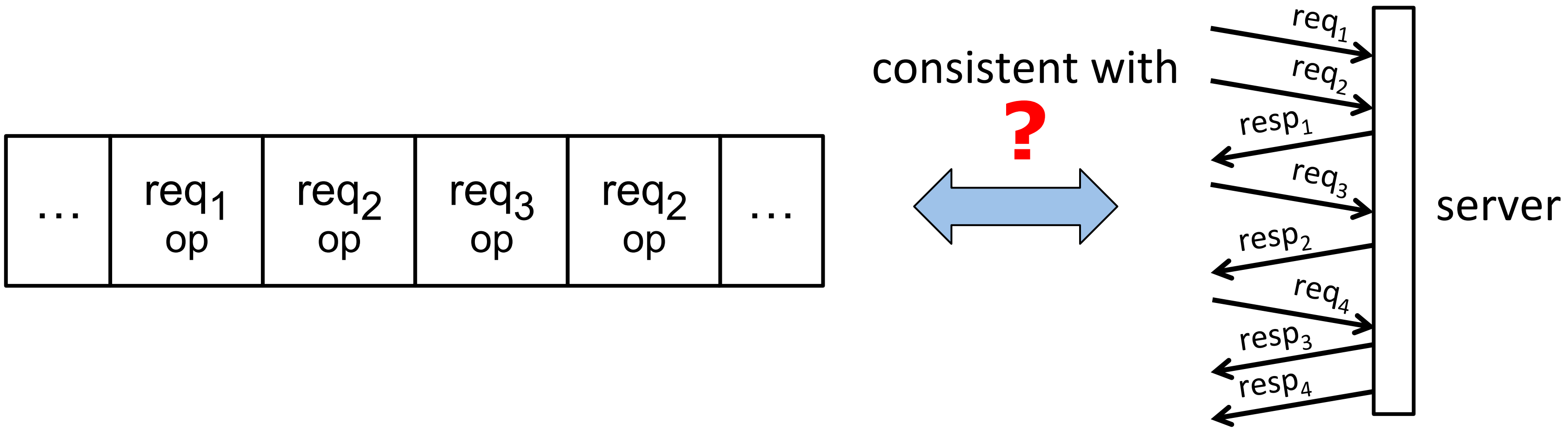


- Server: logs operands
- Verifier: simulates reads using log and checks writes

Another challenge is validating the log order

- Order in log could be nonsensical

- Verifier must check consistency of log:
  - Is log order consistent with observed request order?



…	req_1 op	req_2 op	req_3 op	req_2 op	…

consistent with

?

- This check must be efficient

1. How does the verifier accelerate re-execution?

2. Why are shared objects (such as DBs) challenging?

→ 3. Does our implementation for PHP perform well?

A built system: Orochi

- Orochi targets apps based on PHP and SQL (“LAMP”)
- Server and verifier: modified PHP runtimes
- Includes techniques for deduplicating database queries
- Details
  - Built atop HipHop VM (HHVM)
  - 20K lines of C++, PHP, Bash, Python

Evaluation questions

- Is auditing efficient for the verifier?

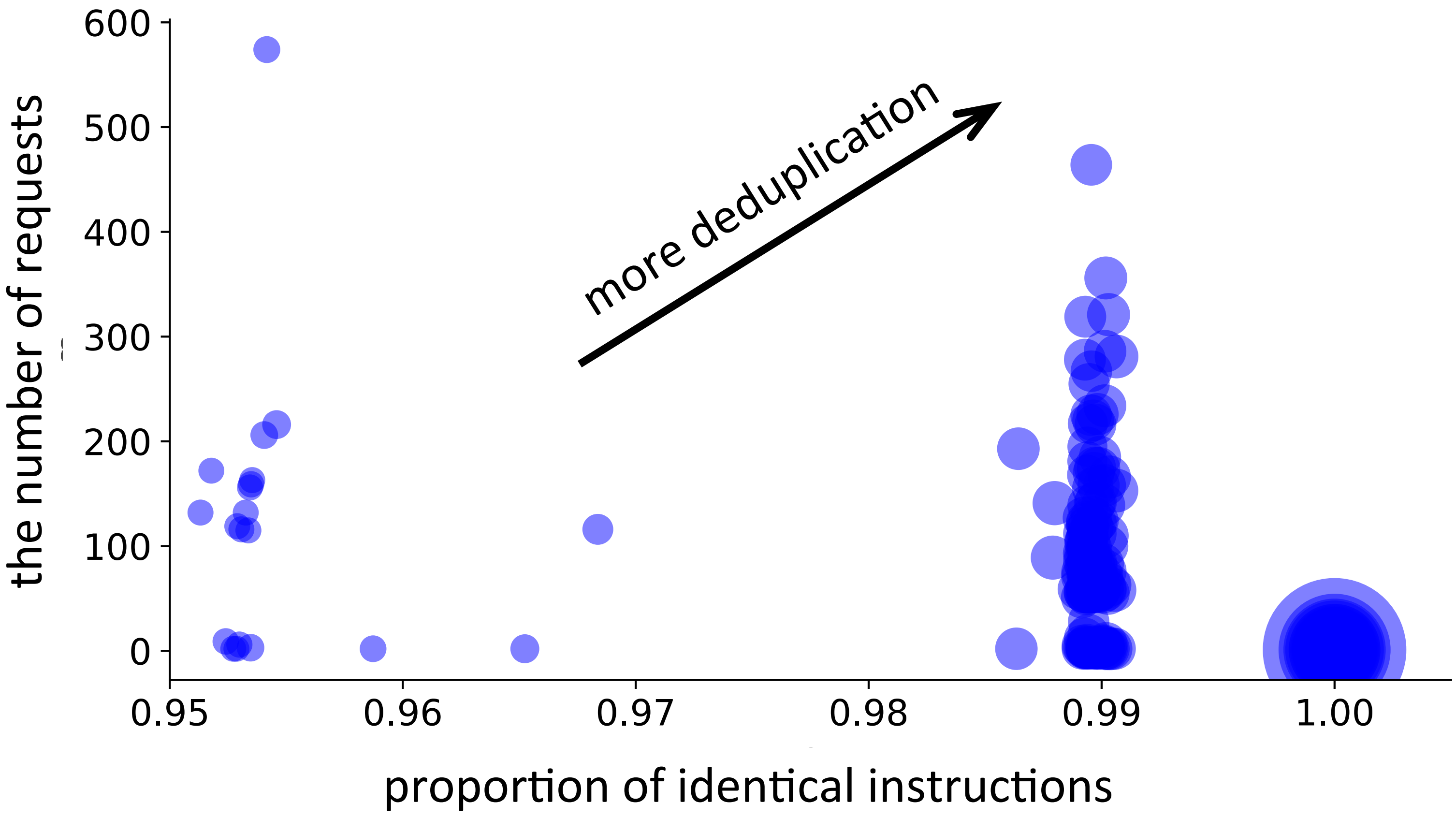
- What is the price of verifiability?

- How compatible is Orochi with legacy applications?

- Applications:
  - MediaWiki, phpBB and HotCRP

- Workloads:
  - MediaWiki: Wikipedia 2007 trace
  - phpBB: 7-day's posts from CentOS forum
  - HotCRP: Simulation of SIGCOMM'09

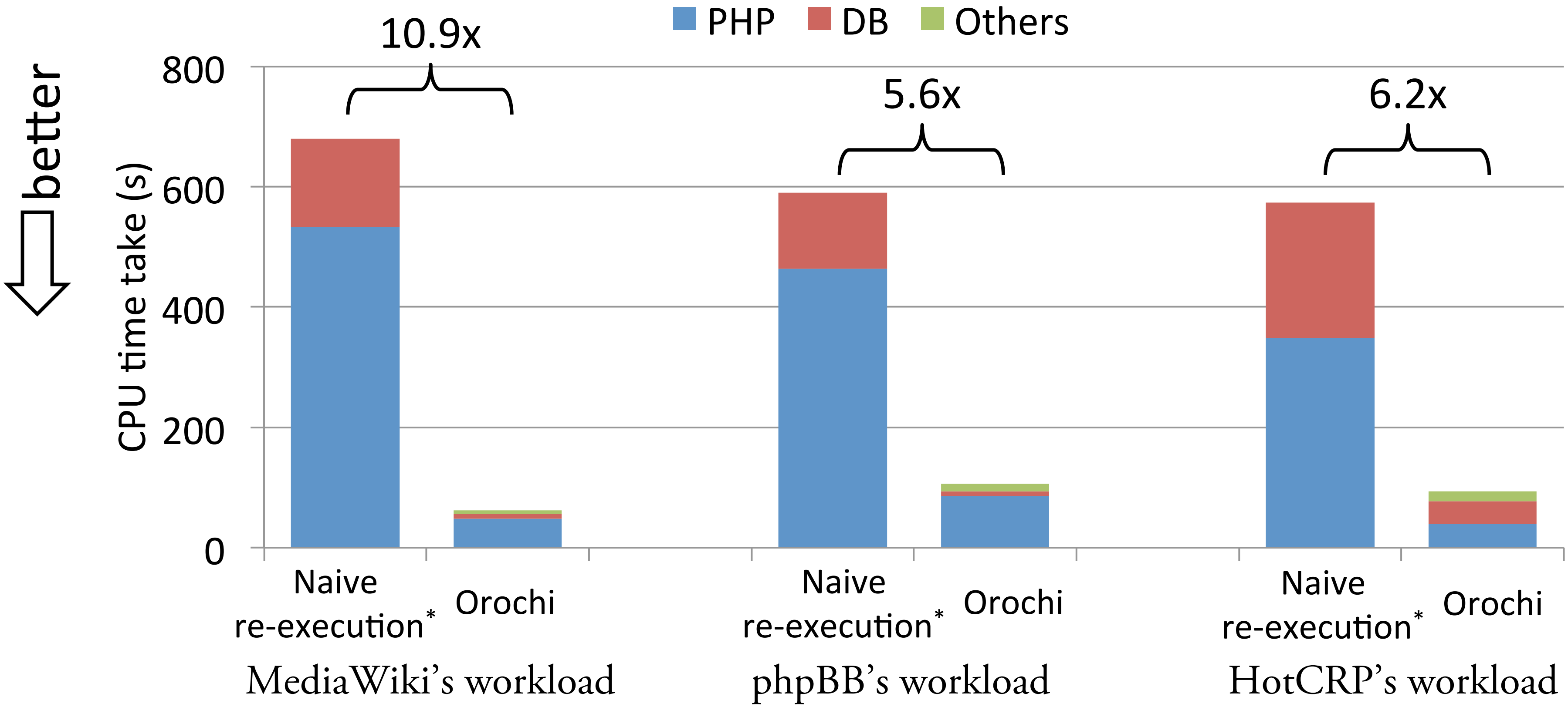
Our workloads see a lot of redundant computation



MediaWiki's workload (20K requests)

Orochi's verifier is efficient

Orochi's verifier achieves speedups compared to naive replay



* Pessimistically estimated from the original online execution

The price of verifiability is tolerable

CPU	
MediaWiki's workload	4.7%
phpBB's workload	8.6%
HotCRP's workload	5.9%

Network			
	trace (per req)	advice (per req)	Orochi's overhead
MediaWiki's workload	7.1KB	1.7KB	11.4%
phpBB's workload	5.7KB	0.3KB	2.7%
HotCRP's workload	3.2KB	0.4KB	10.9%

Storage	
MediaWiki's workload	1.0x
phpBB's workload	1.7x
HotCRP's workload	1.5x

Verifier needs to store the trace and advice for one audit epoch.

Orochi requires modest application adjustments

- Lines of code modified:
  - 346 lines of code change for MediaWiki
  - 270 lines of code change for phpBB
  - 67 lines of code change for HotCRP

- Most of the changes are due to
  - PHP features that our implementation does not support
  - Modifying the application to respect object semantics

Recap of evaluation

- Verifier: 5.6--10.9x speedup over naive re-execution

- Costs: storage at verifier, <10% overhead on server

- Compatibility: Modest application changes

Related work, future work, and wrap-up

❌ server is untrusted
2. server is concurrent
3. verifier is weaker than server
❌ server overhead is low; compatibility

Related work

- Efficient execution integrity
  - Replication: BFT
  - Attestation: TPMs, SGX
  - Probabilistic proofs: Pepper, CMT, Pinocchio, Pantry, SNARKs

- Computation deduplication (Delta execution, iThreads)

- Record-replay
  - Untrusted recorder: Accountable Virtual Machines
  - Accelerated replayer: Poirot
  - Multiprocessor: RecPlay, LEAP, DoublePlay, PRES, ODR, …

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Wrap-up and future work

- Our solution to the Efficient Server Audit Problem:
  - Includes a new accelerated re-execution technique
  - Includes new algorithms for verifying concurrent executions
  - Comes with a rigorous proof of correctness
- Our instantiation for PHP, SQL web apps:
  - 5-10x speedups over a naive replay; <10% CPU overhead on server
- Future work includes:
  - SGX integration
  - Extend to multiple interacting servers
  - Accelerate other record-replay systems