Shadow: The Case for Determinism on the Edge

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Concerns for the Edge

Edge Concern	Effect	Problem

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Provisioning	More jitter	

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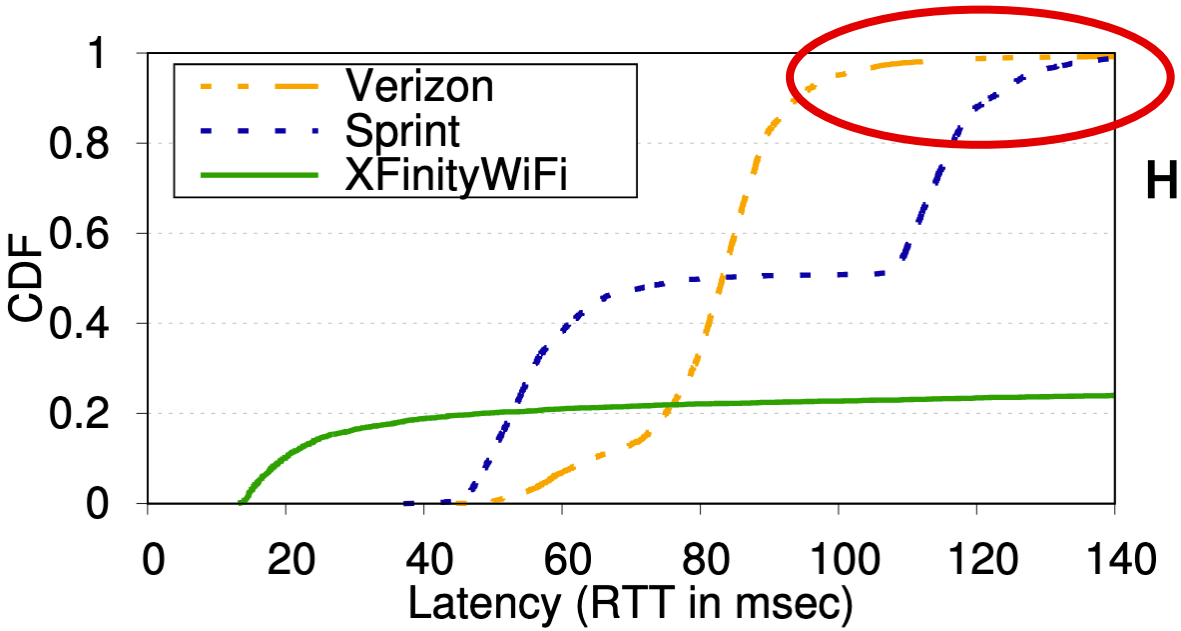

High tail latency!

[1] Lee, H., Flinn, J., And Tonshal, B. Raven: Improving interactive latency for the connected car.

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Moving From the Cloud to Edge

- Applications are typically latency-sensitive or require high bandwidth

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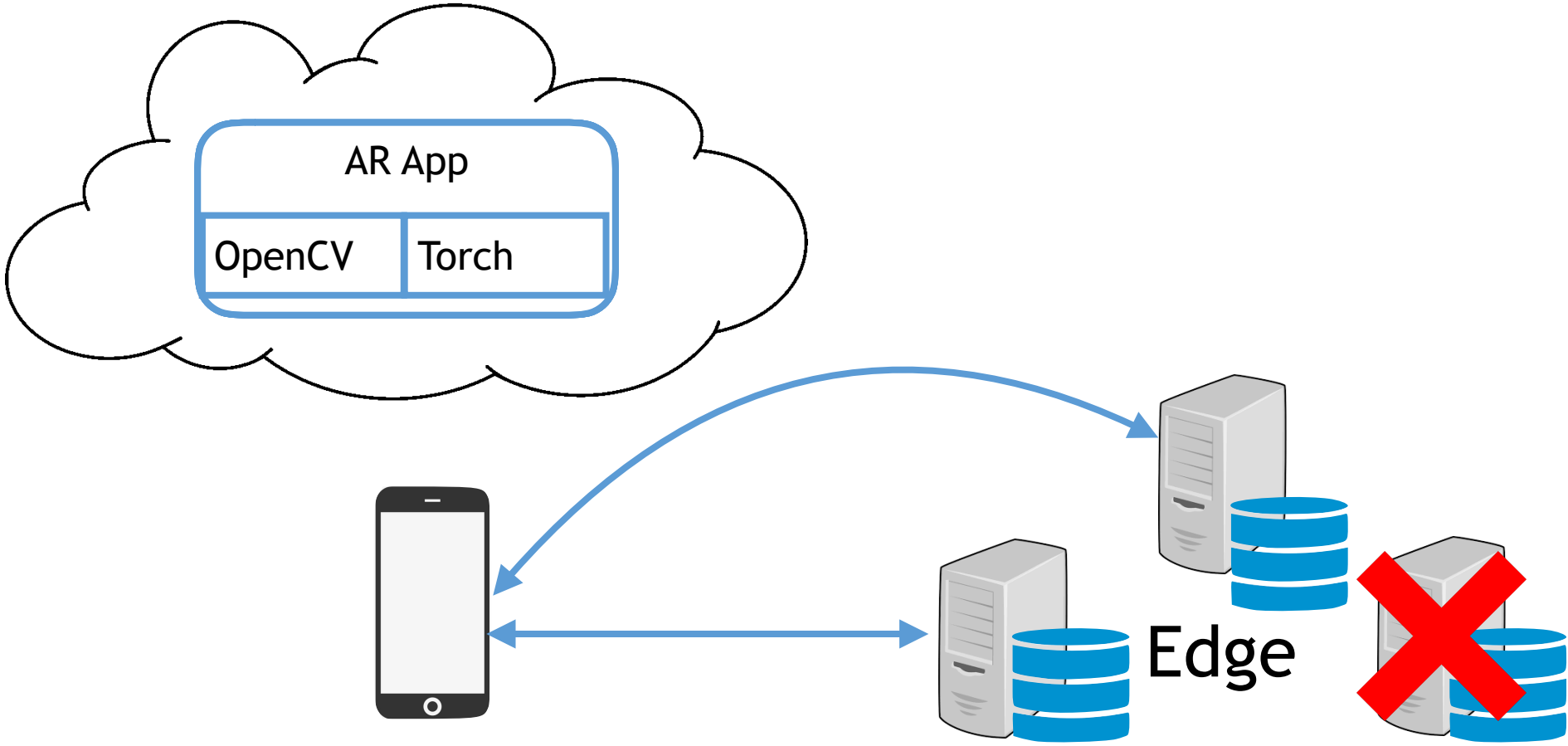
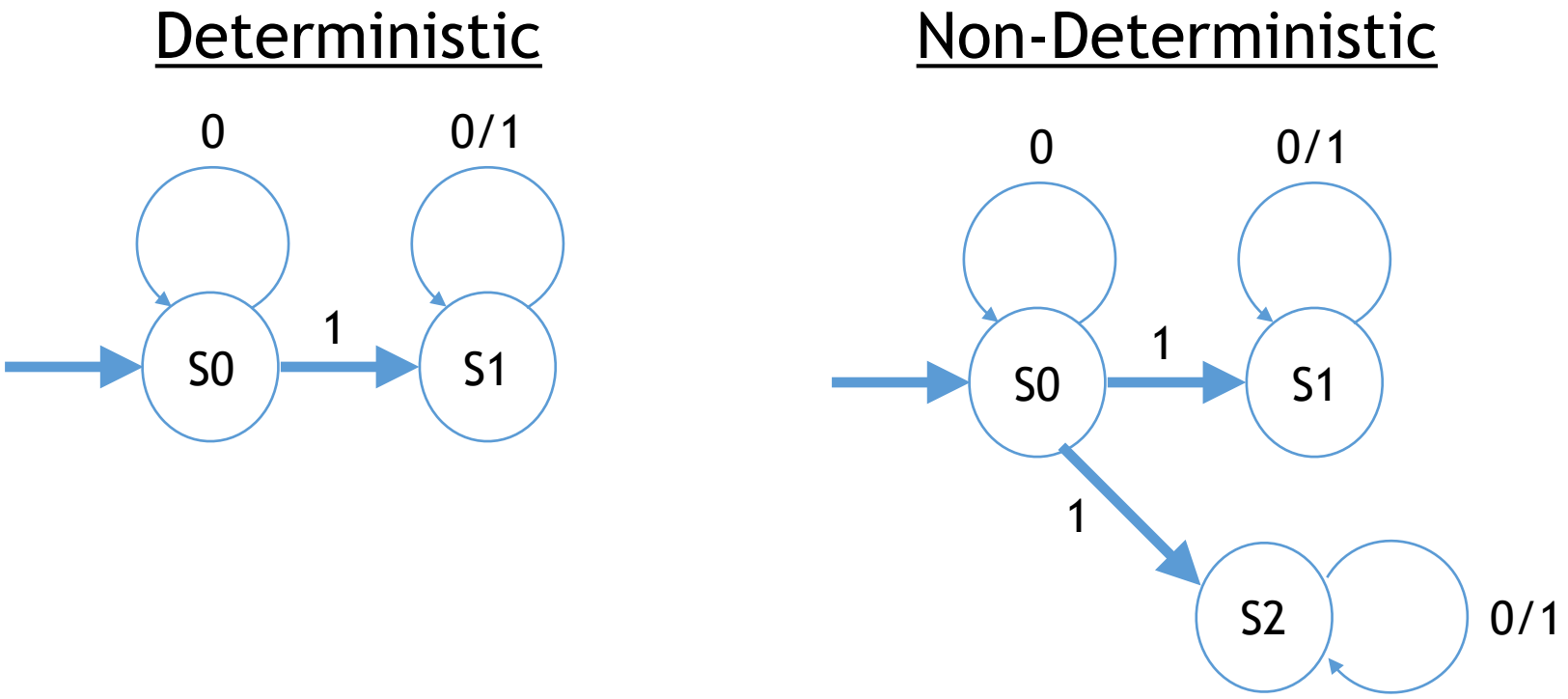


Outline

- Motivation
- Determinism to the rescue
- Shadow: Deterministic containers
- Evaluation

Determinism to the Rescue

- A deterministic execution of an application provides the necessary support for edge systems



Determinism to the Rescue

- Determinism allows applications to be replicated across multiple servers

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- Determinism allows applications to be replicated across multiple servers
- Determinism enables migration with minimal downtime

Migration

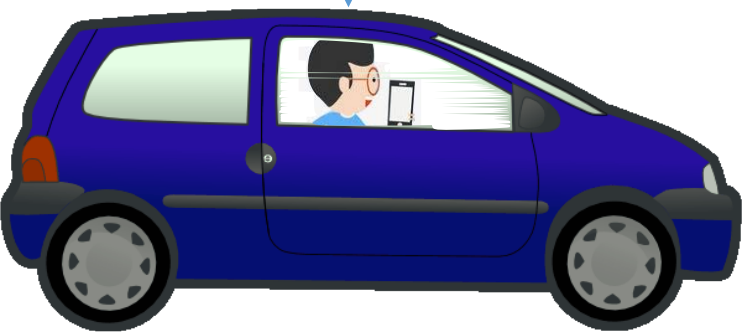
Server inputs: a







Low-latency connection



Server Responses: 1

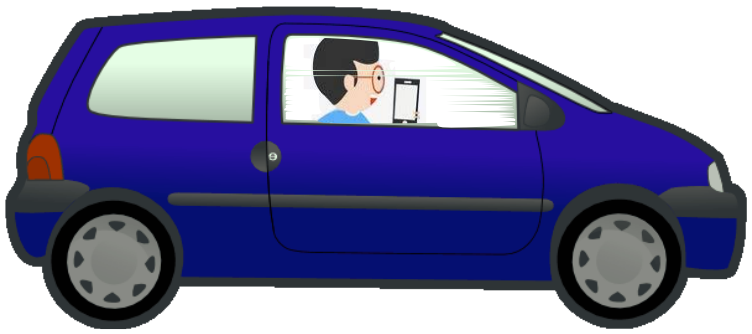
Migration

Server inputs: a





Better connection discovered



Server Responses: 1

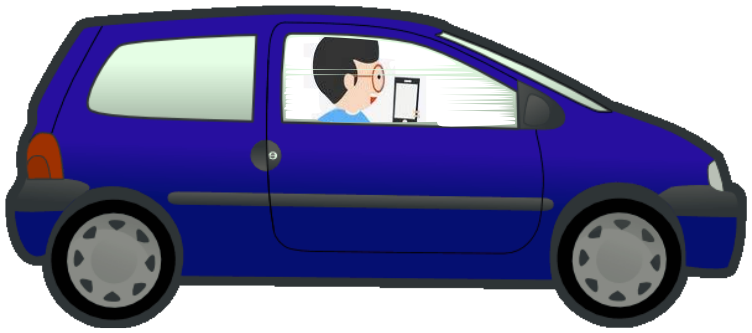
Migration

Server inputs: a



Initiate migration!





Server Responses: 1

Migration

Server inputs: a b

Server inputs: a

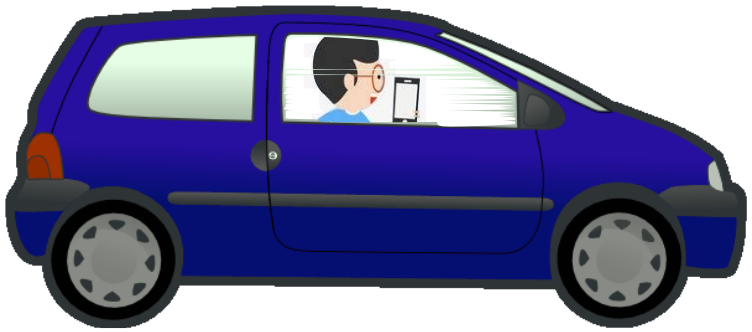


Checkpoint Application



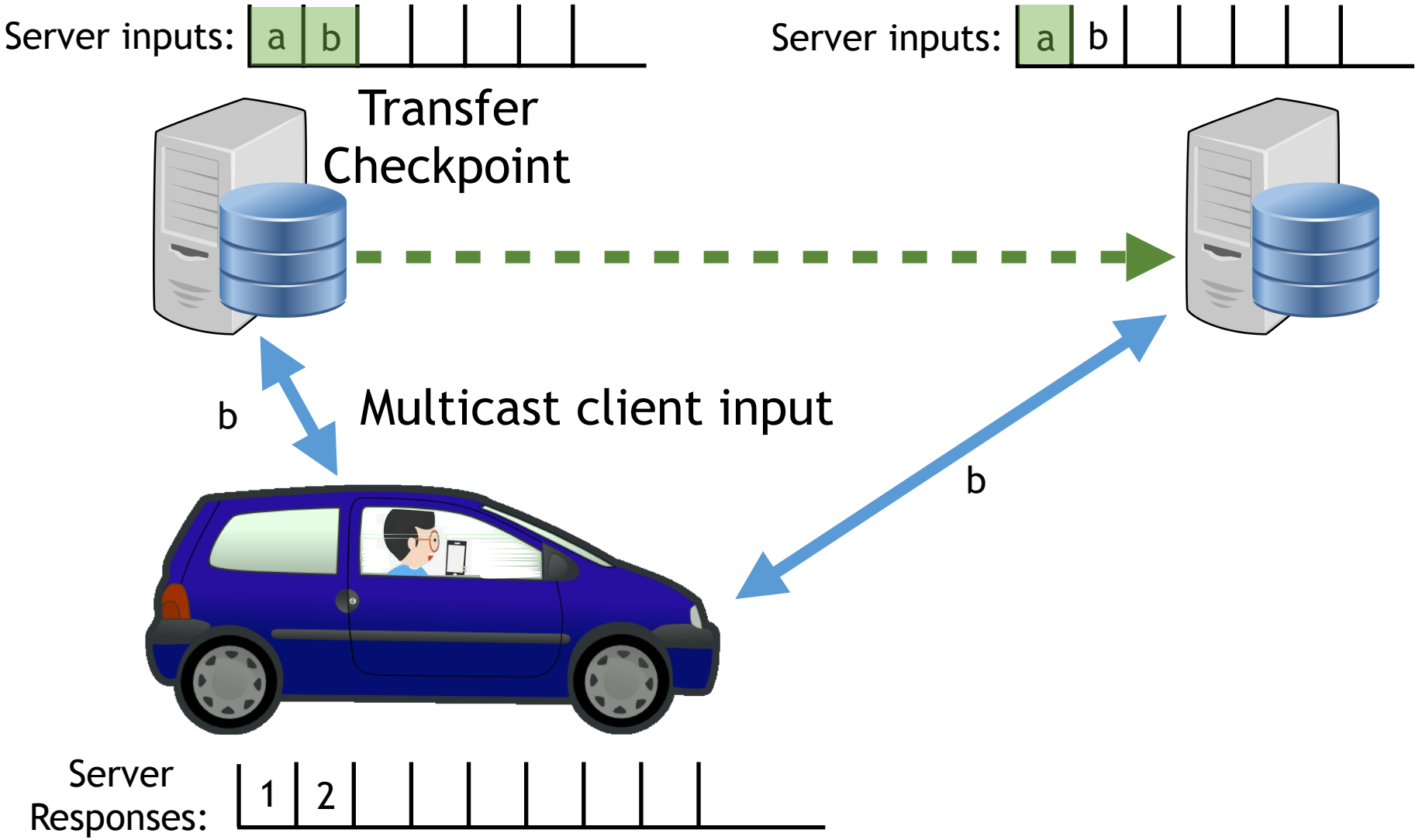


b

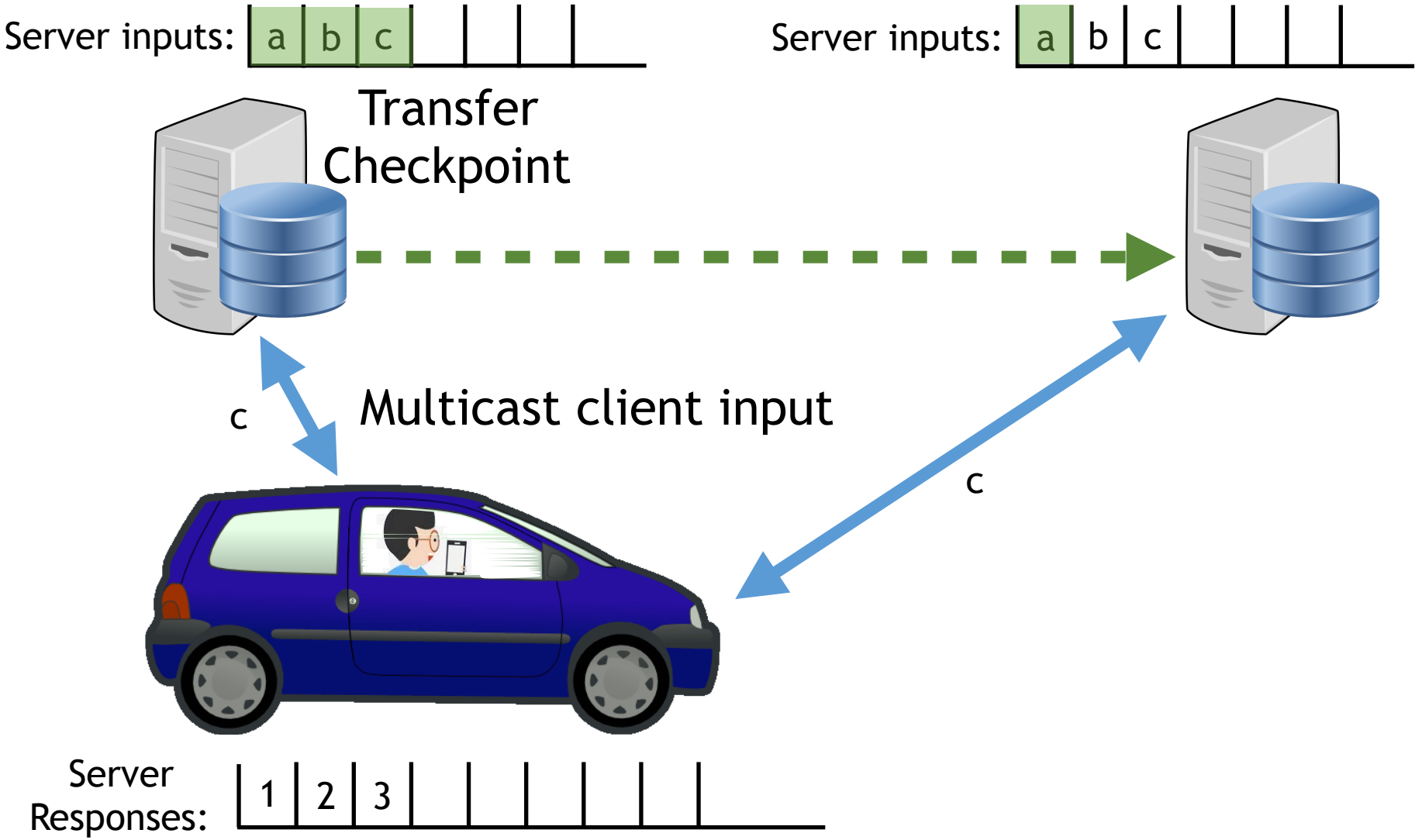


Server Responses: 1 ?

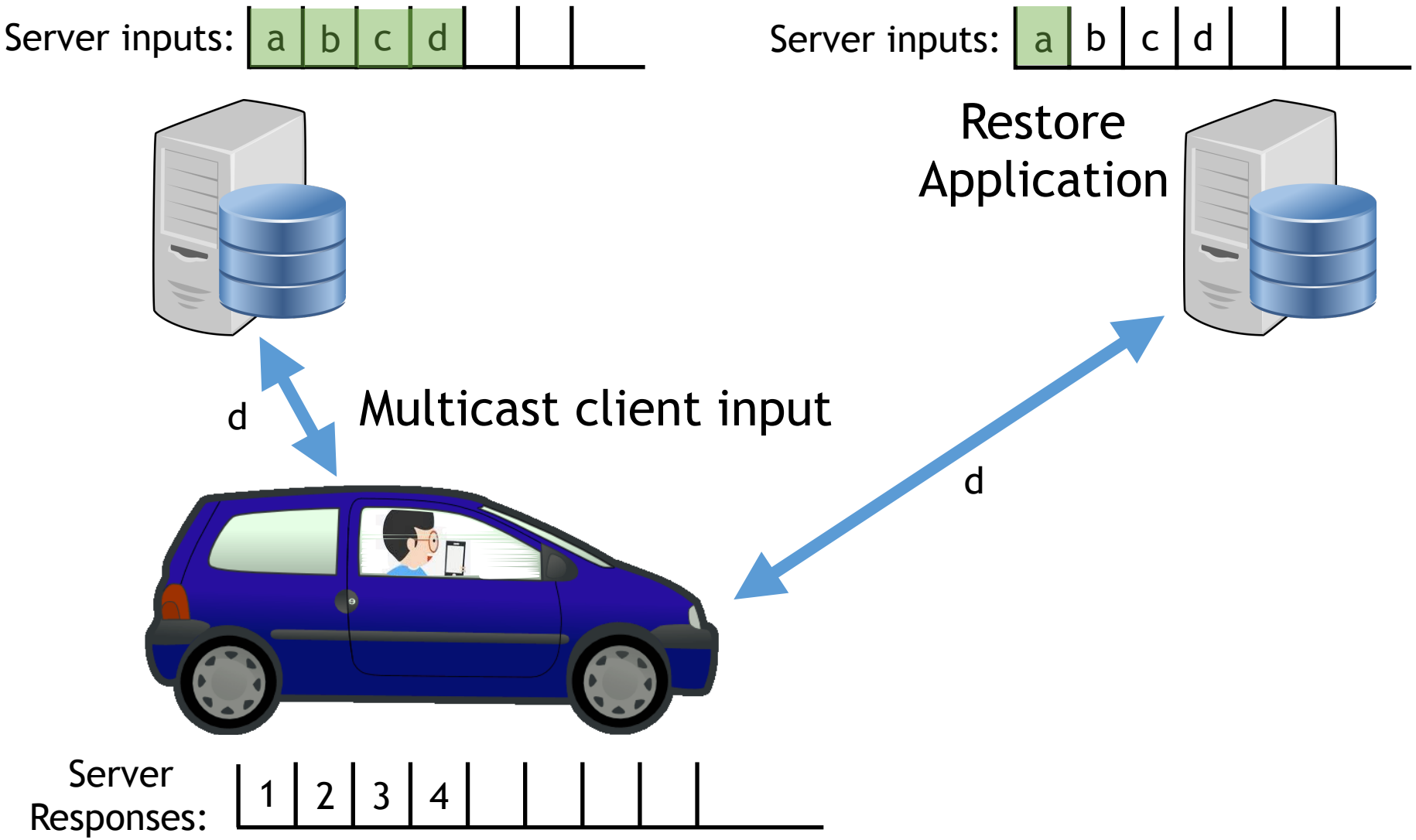
Migration


Server inputs:
a
b
Server inputs:
a
b
Transfer
Checkpoint
b
Multicast client input
b
Server
Responses:
1
2

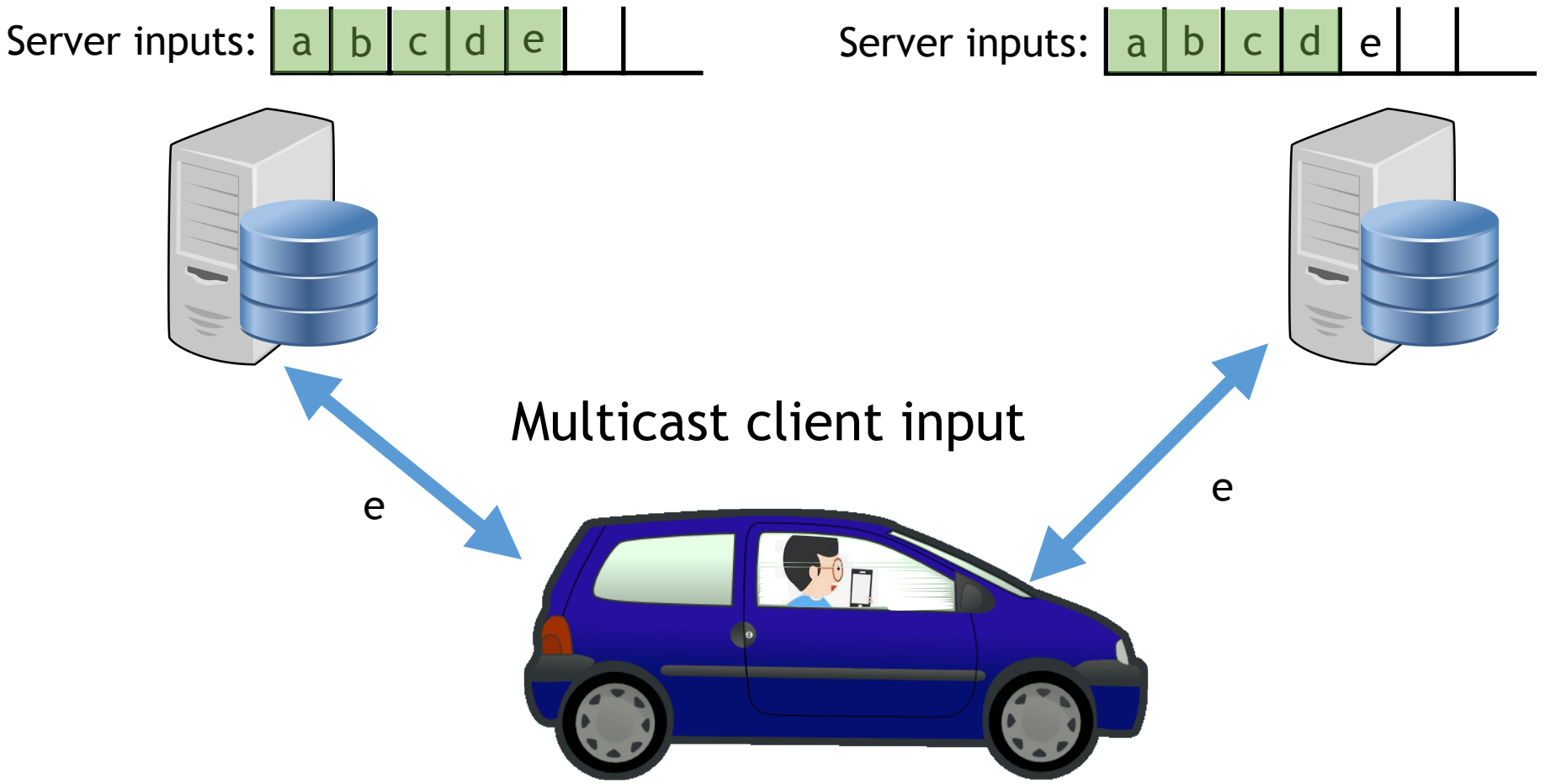
Migration


Server inputs:
a
b
c
Server inputs:
a
b
c
Transfer
Checkpoint
c
Multicast client input
c
Server
Responses:
1
2
3

Migration


Server inputs:
a
b
c
d
Server inputs:
a
b
c
d
Restore Application
d
Multicast client input
d
Server Responses:
1
2
3
4

Migration


Server inputs: a b c d e
Server inputs: a b c d e
Multicast client input
e
e
Server Responses: 1 2 3 4 5

Migration

Server inputs: a b c d e f

Server inputs: a b c d e f

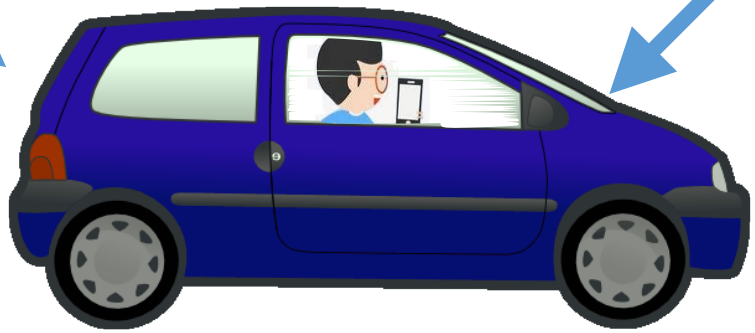




Multicast client input

f

f



Server Responses: 1 2 3 4 5 6

Migration

Server inputs: a b c d e f

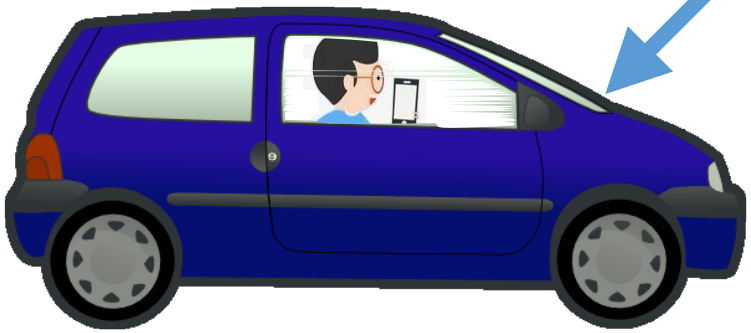


Server inputs: a b c d e f



Migration complete!

g



Client inputs: 1 2 3 4 5 6

Determinism to the Rescue

Edge Concern	Problem	Solution
Provisioning	• Limited edge resources • Mobile network variability	**Determinism**
Mobility	• Low-latency connections are lost	**Determinism**
Reliability	• Numerous providers • Distributed	**Determinism**
More data sources	• More IoT devices = more sensitive user data	**Determinism**

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Challenge: Applications are inherently non-deterministic!

Determinism to the Rescue

- Non-determinism in applications
  - Randomness
  - Time
  - Multi-threading
  - Network communication
  - Inter-process communication (IPC)

Determinism to the Rescue

- Non-determinism in applications
  - Randomness
  - Time
  - Multi-threading
  - Network communication
  - Inter-process communication (IPC)
- Challenge: How can we make non-deterministic applications behave deterministically??

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Shadow

- Goal: Eliminate sources of non-determinism

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  - Minimize application modifications
  - Maintain similar performance to non-deterministic executions

Deterministic Containers

- Shadow removes non-determinism from applications deployed within containers
  - Multi-threading
  - OS Events
  - Client inputs
  - External Sources of Non-Determinism

Deterministic Thread Scheduler

- Shadow uses a deterministic thread scheduler based on *weak* determinism[1]

[1] Olseweski, M., Ansel, J., And Amarsinghe, S. Kendo: Efficient deterministic multithreading in software.

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- Shadow uses a deterministic thread scheduler based on *weak* determinism[1]
- Weak determinism globally orders all synchronization operations

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Operating System Events

- System Calls
  - getrandom()
  - gettimeofday()
  - getpid()
  - …

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Client Inputs

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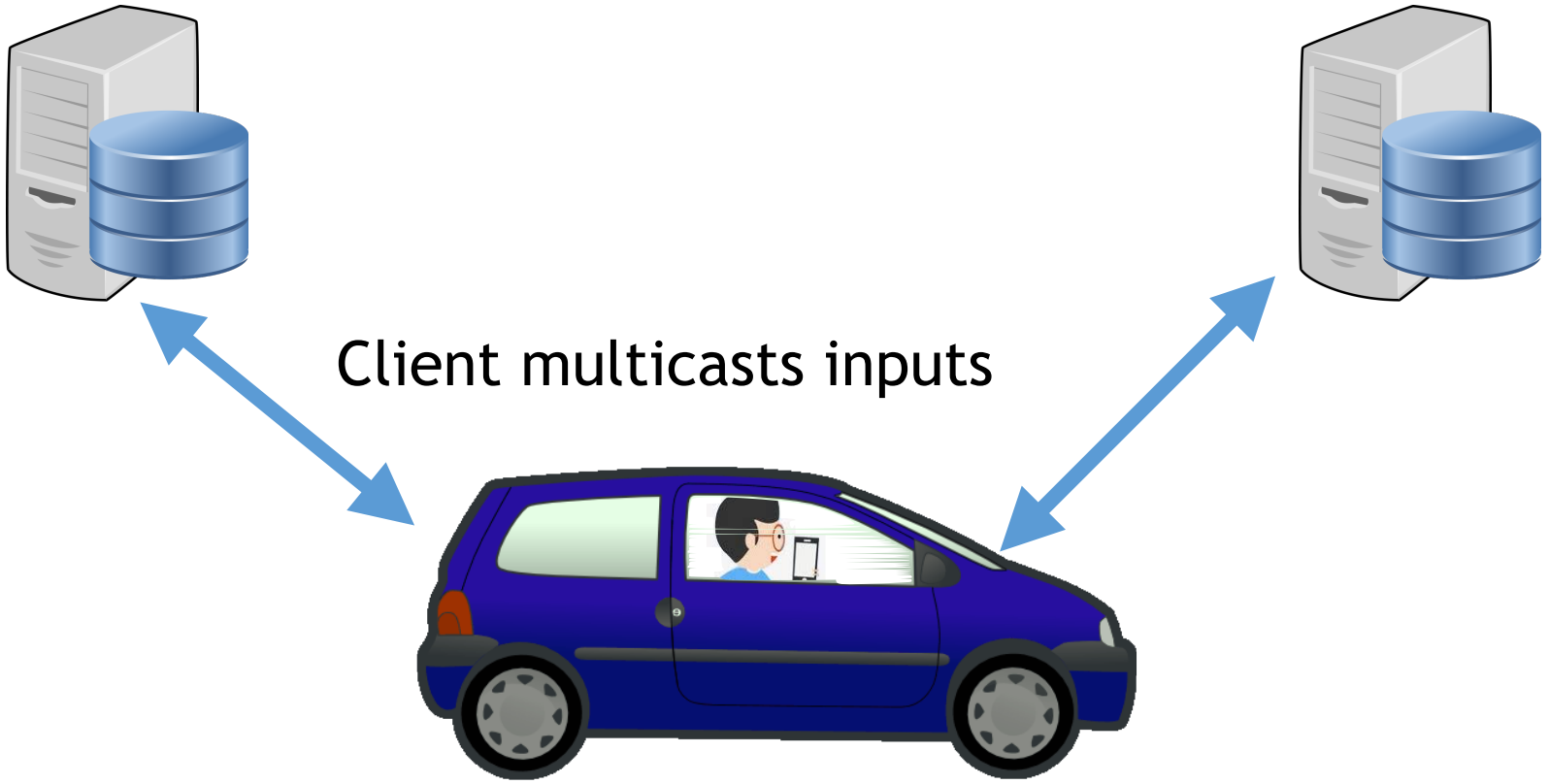

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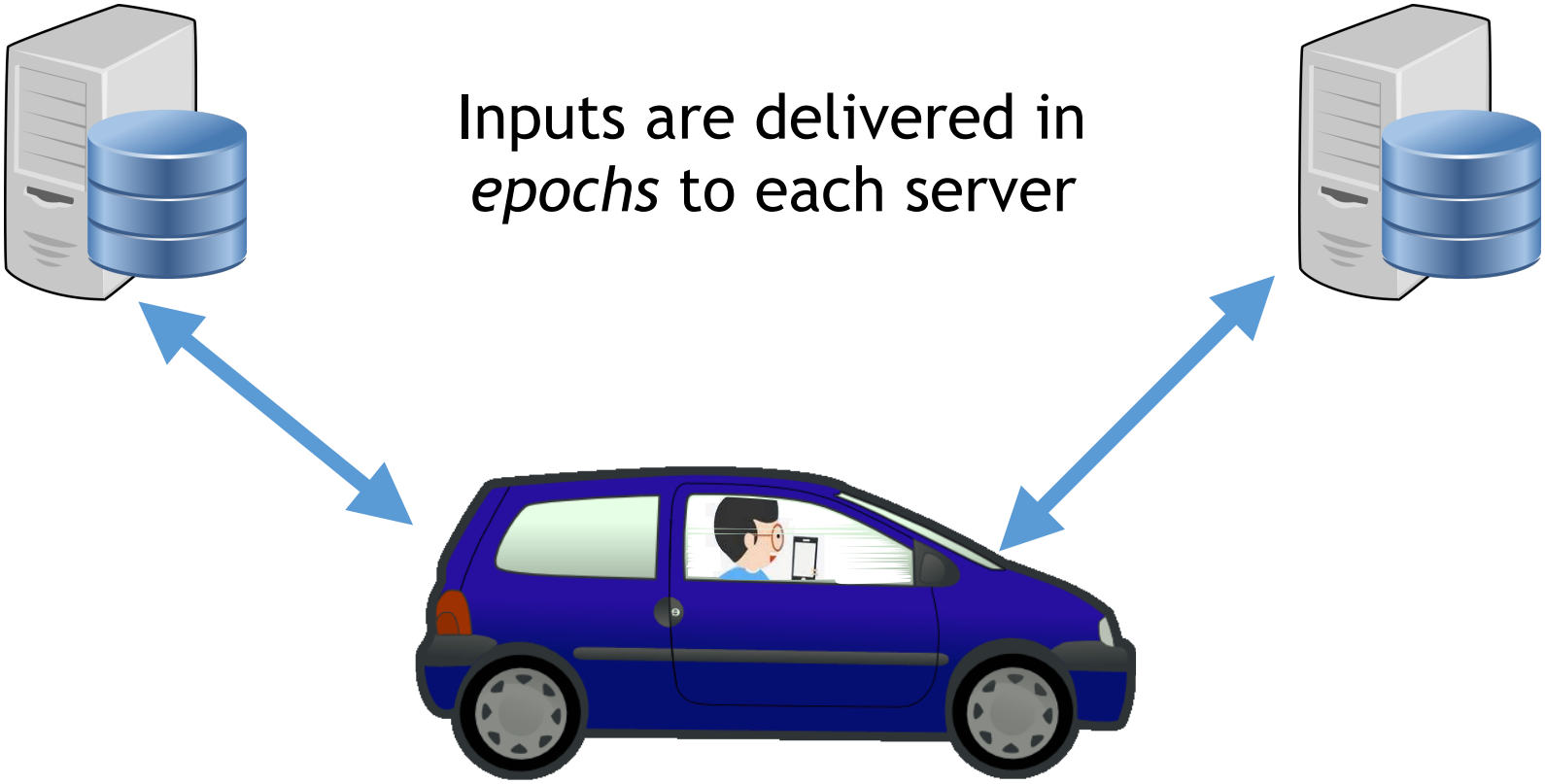

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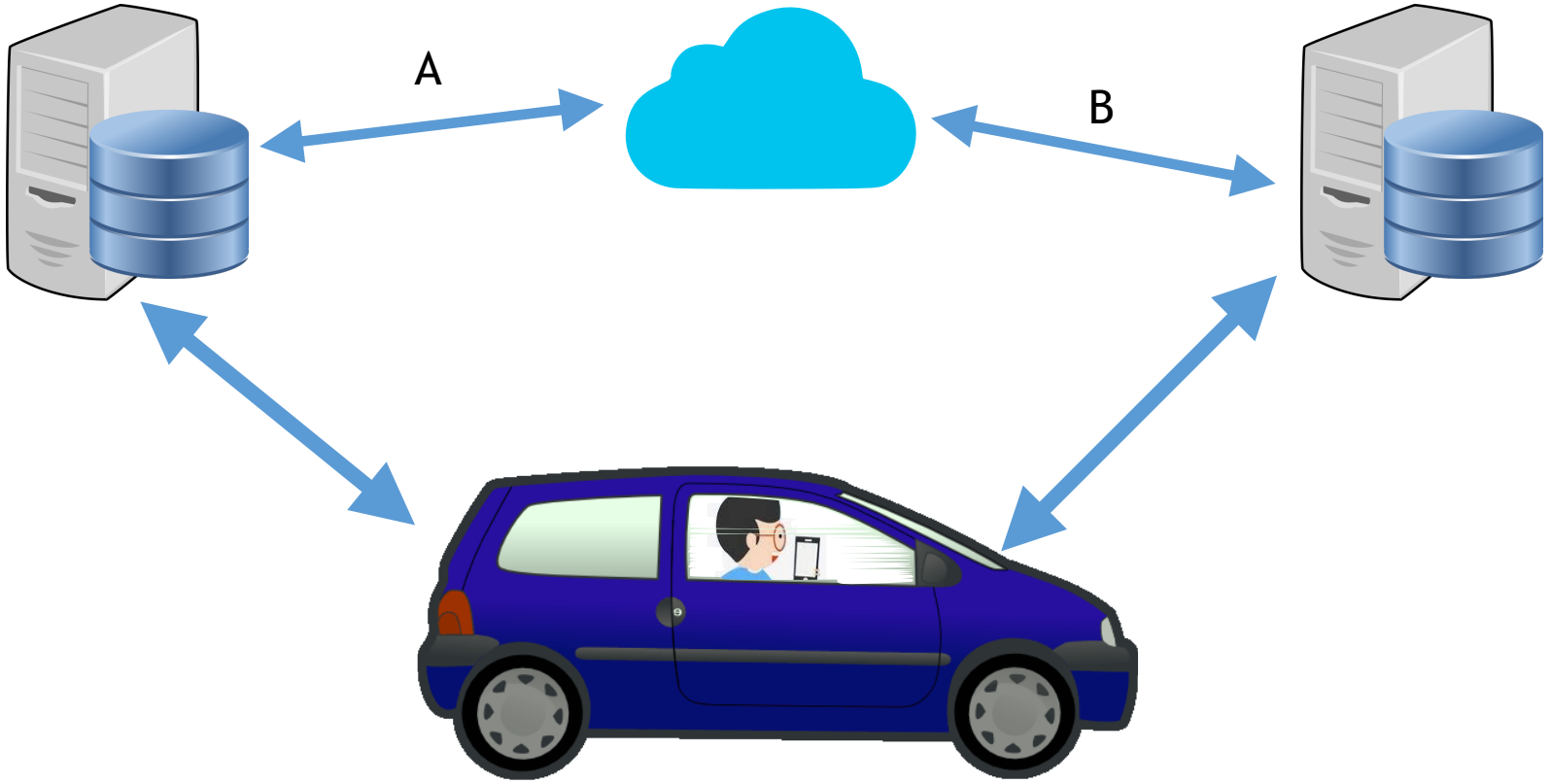

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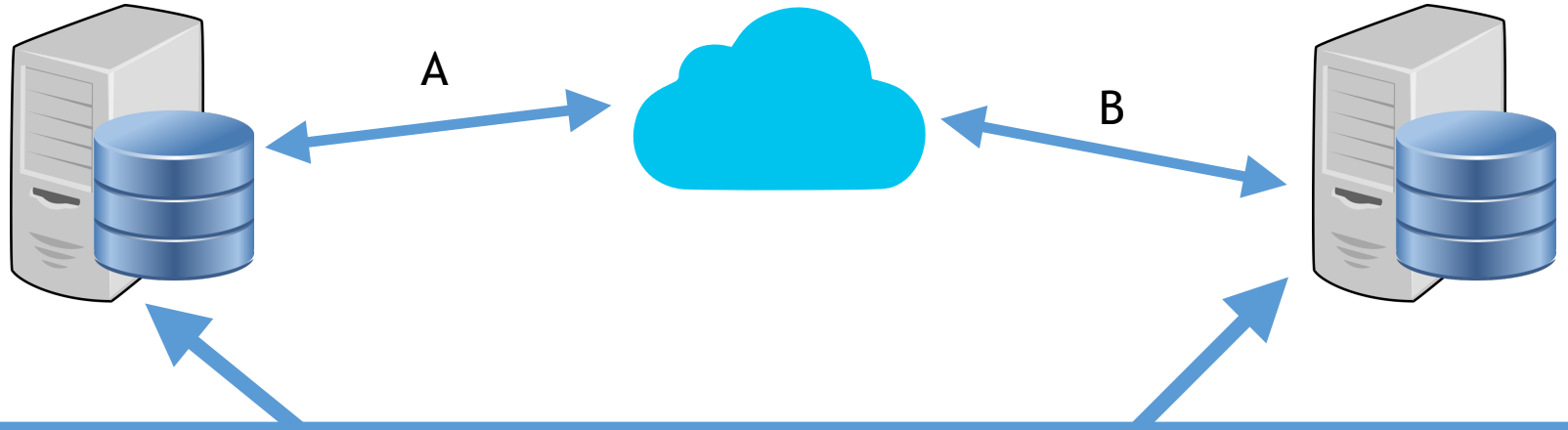

3rd party service responses are not identical

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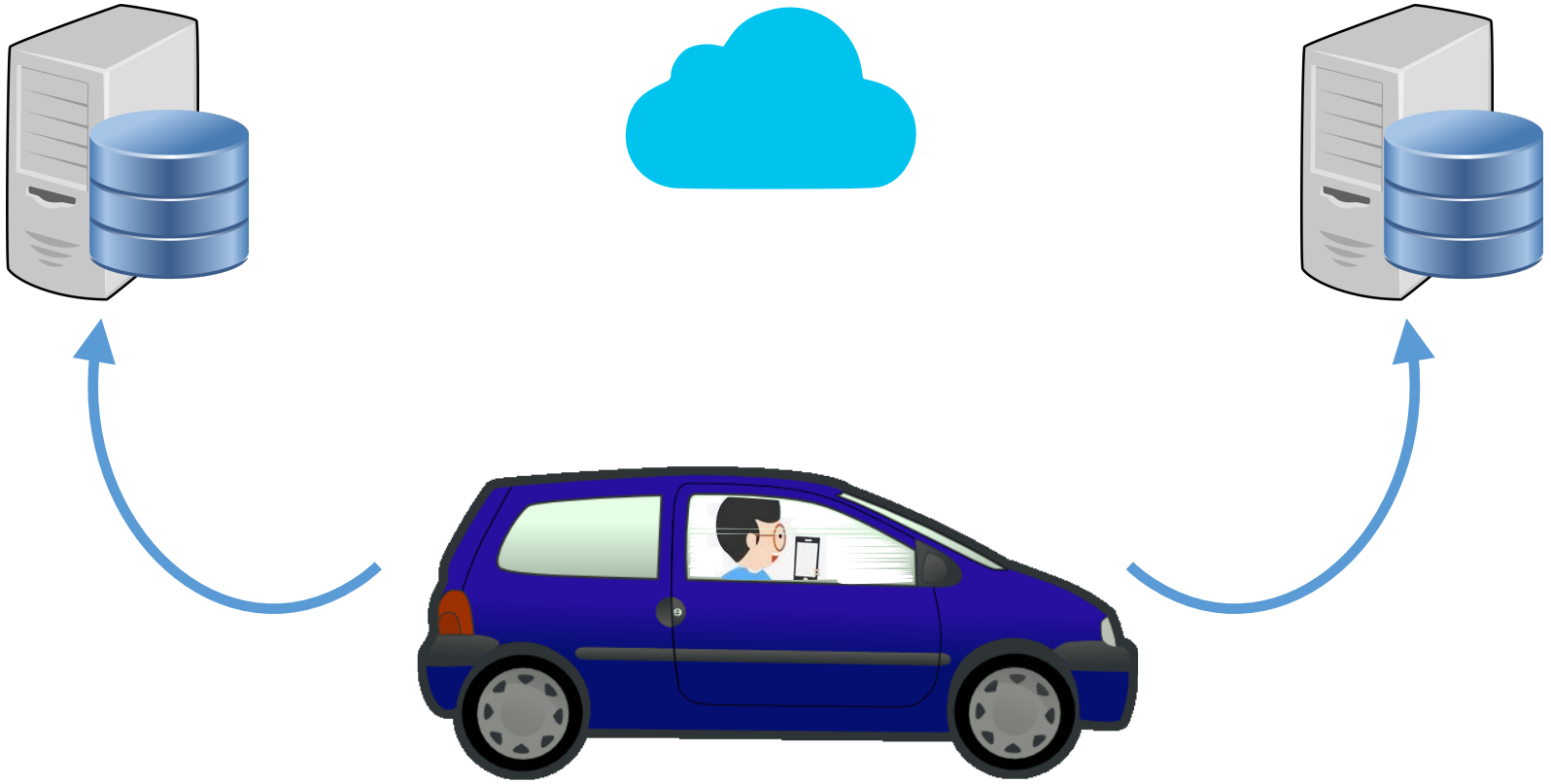

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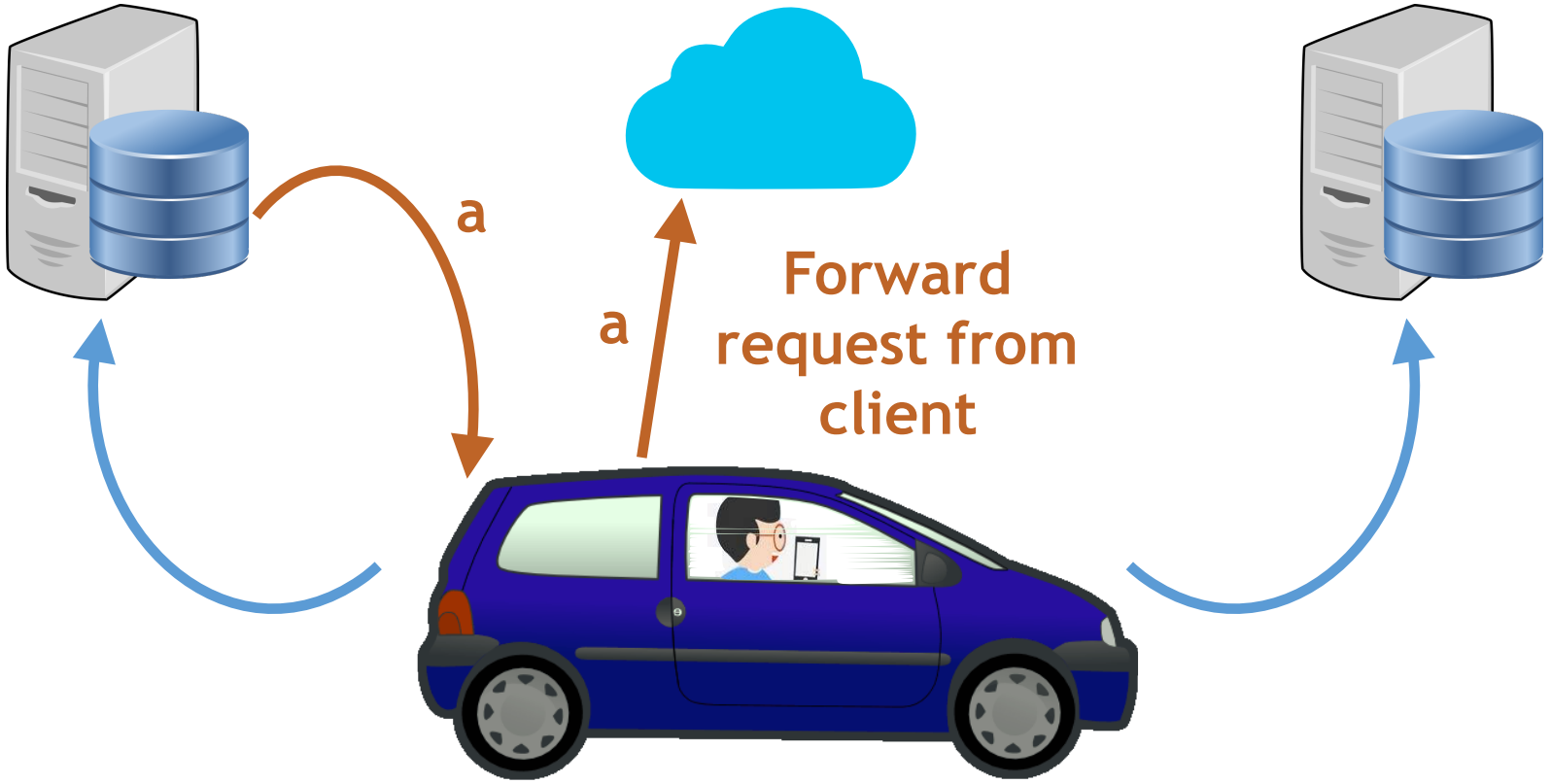

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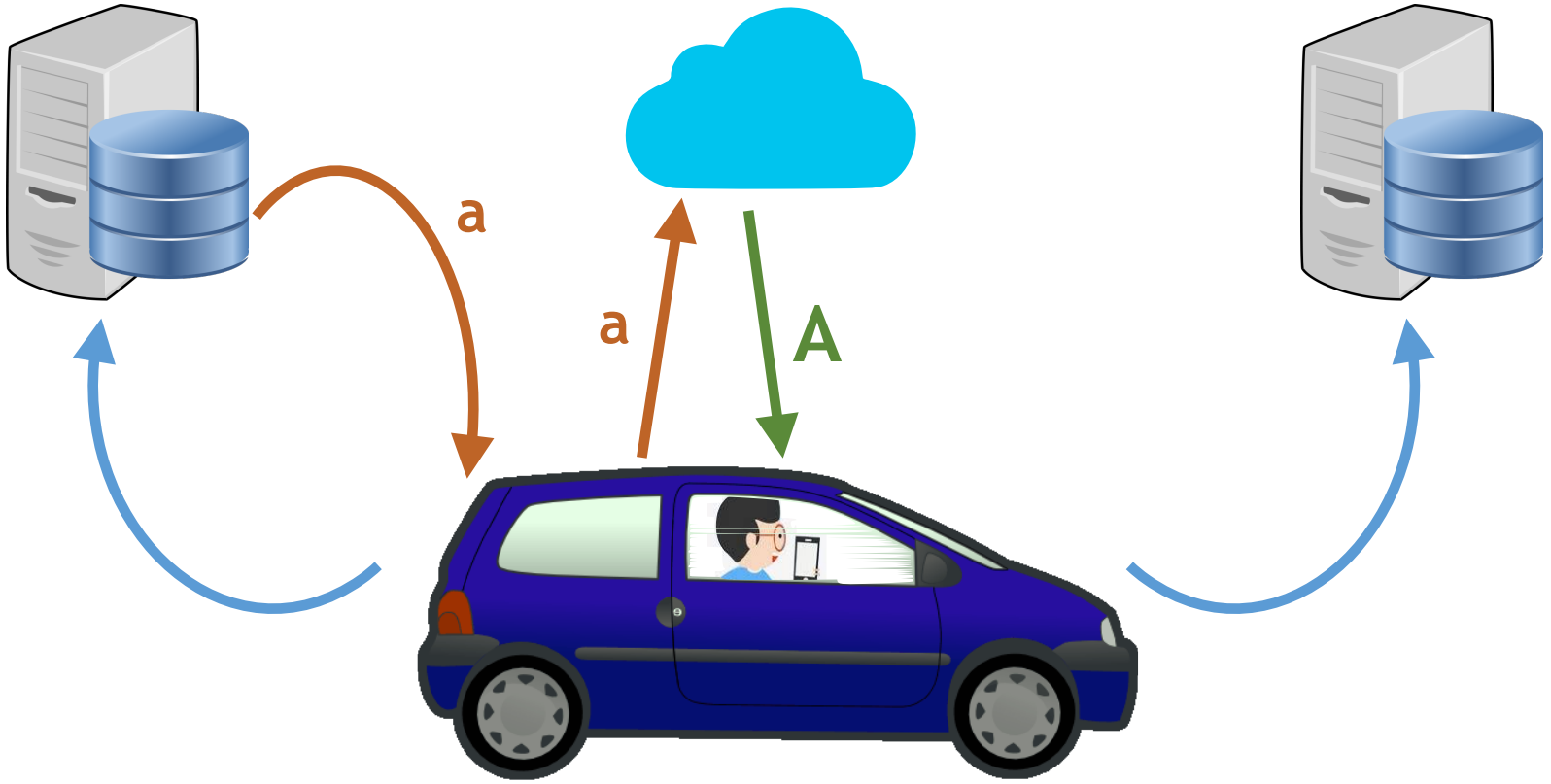

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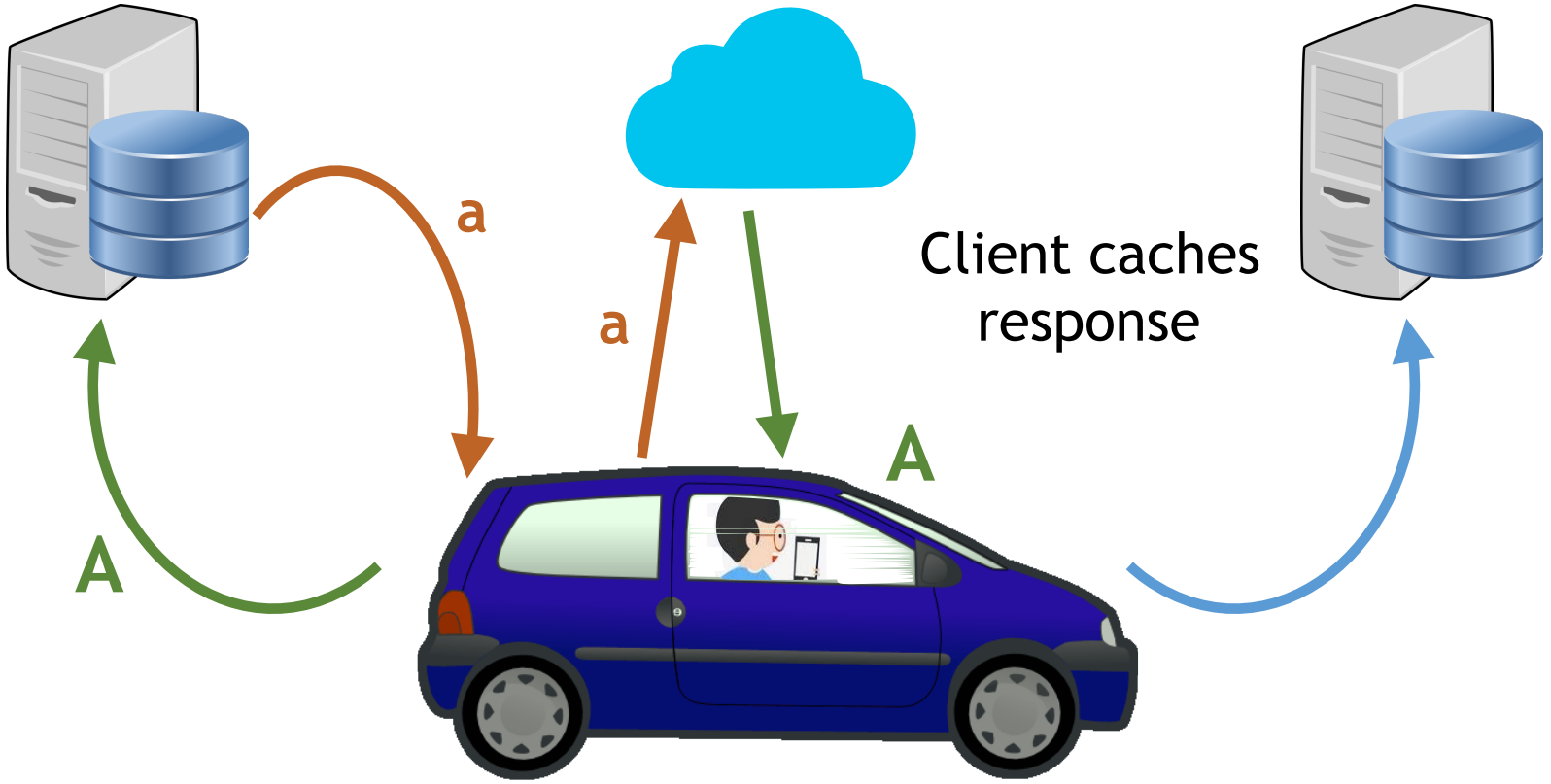

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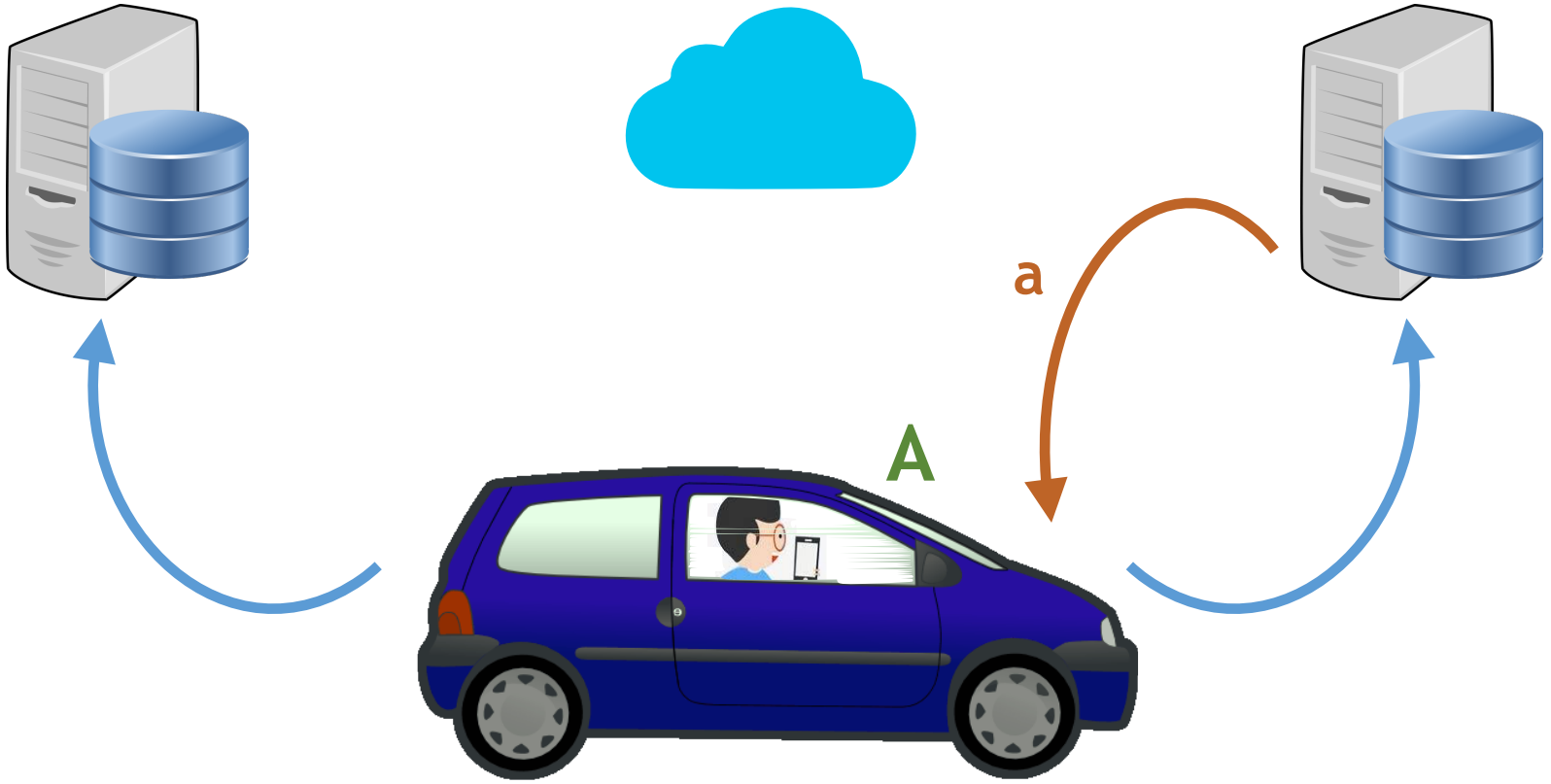

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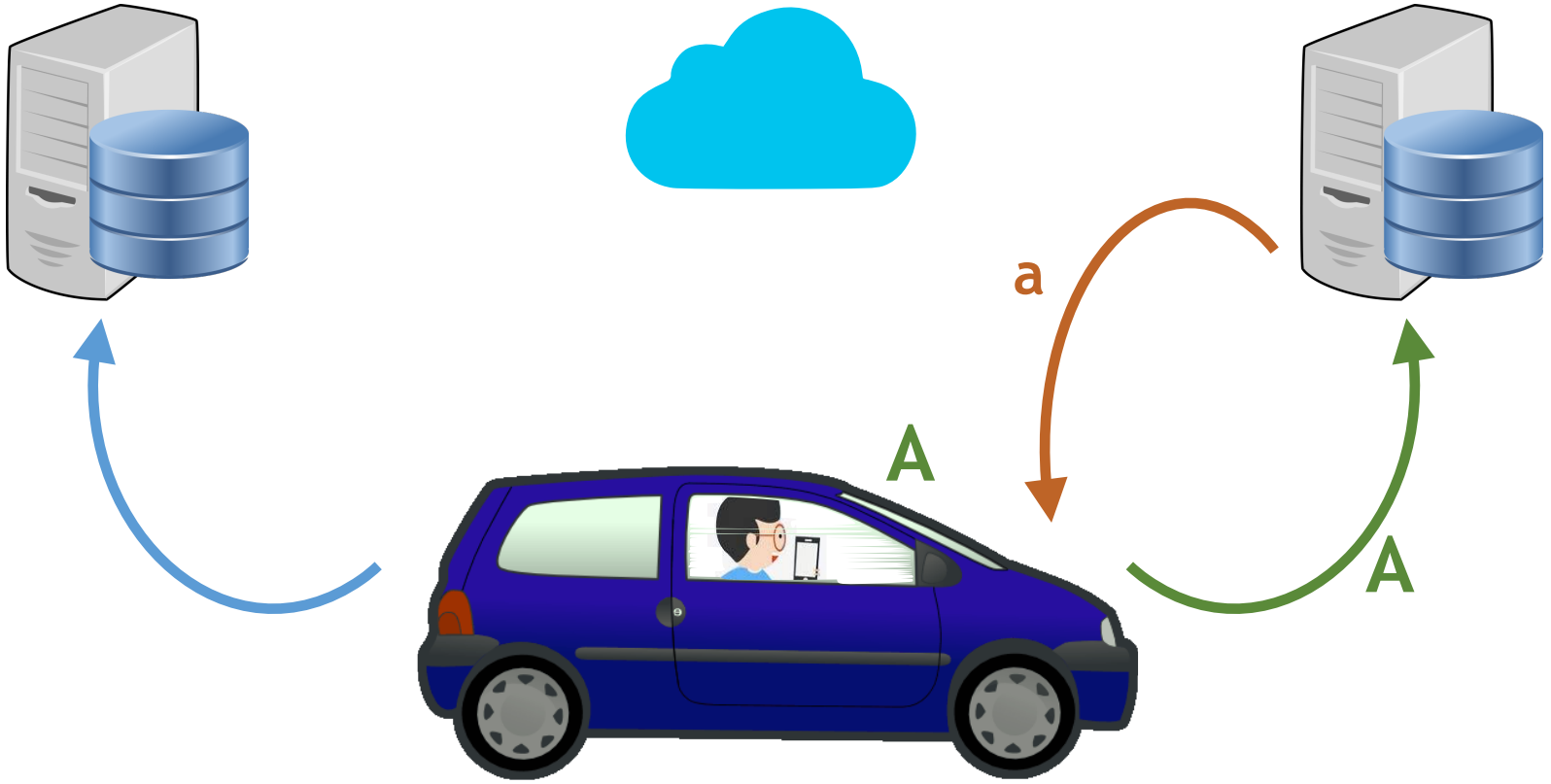

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3rd party services can produce non-deterministic results and still work with Shadow!

Determinism Summary

Non-Determinisim	Solution	Application Limitations
Multi-threading	Weak determinism	No data races
OS Events	Deterministic syscalls	Time skew No IPC or kernel devices
Client Inputs	Use client as primary	None
External Sources	Use client as primary	None

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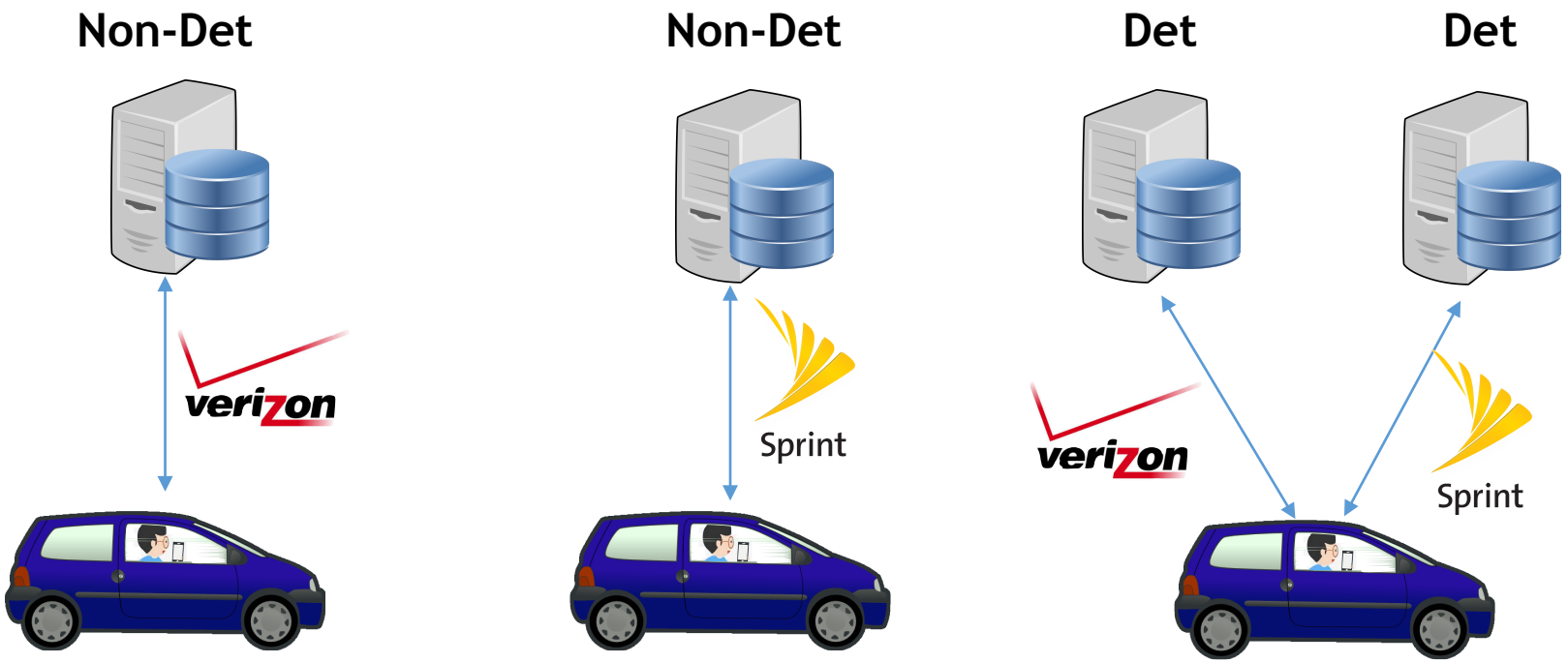
Evaluation

- Test Application
  - Vehicle Caravan



Jitter Results

- Emulate suburban network traces from VNperf[1]
- Evaluate quality of experience for the client using response time from server



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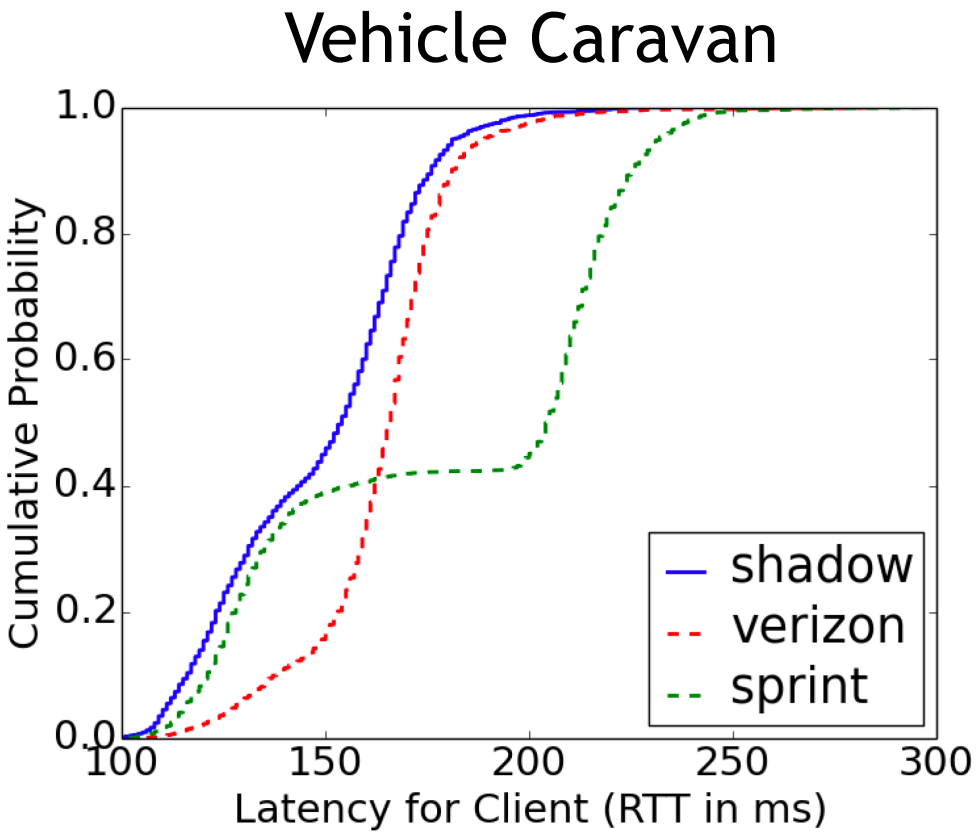

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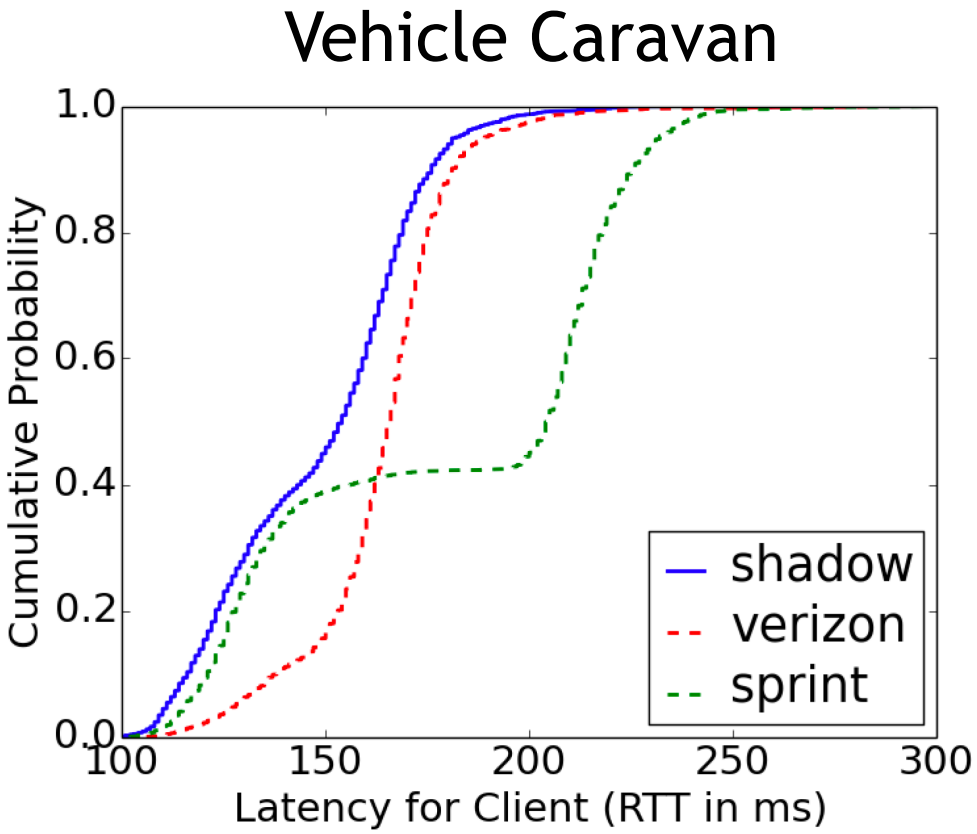

Shadow reduces the median response by up to 25 percent

Discussion

- Feedback
  - Are Shadow's limitations reasonable to place on applications?
  - How prevalent does the community think single-client applications will be in edge deployments?
  - What other applications could benefit from a deterministic environment?
- Controversial points
  - Applications must fit into Shadow's restrictions (e.g. no IPC, clock skew, race-free)
- Everything falls apart…
  - Performance overhead of determinism outweighs the benefits
  - If the majority of applications cannot be modified to fit into Shadow's restrictions