Accountable Virtual Machines

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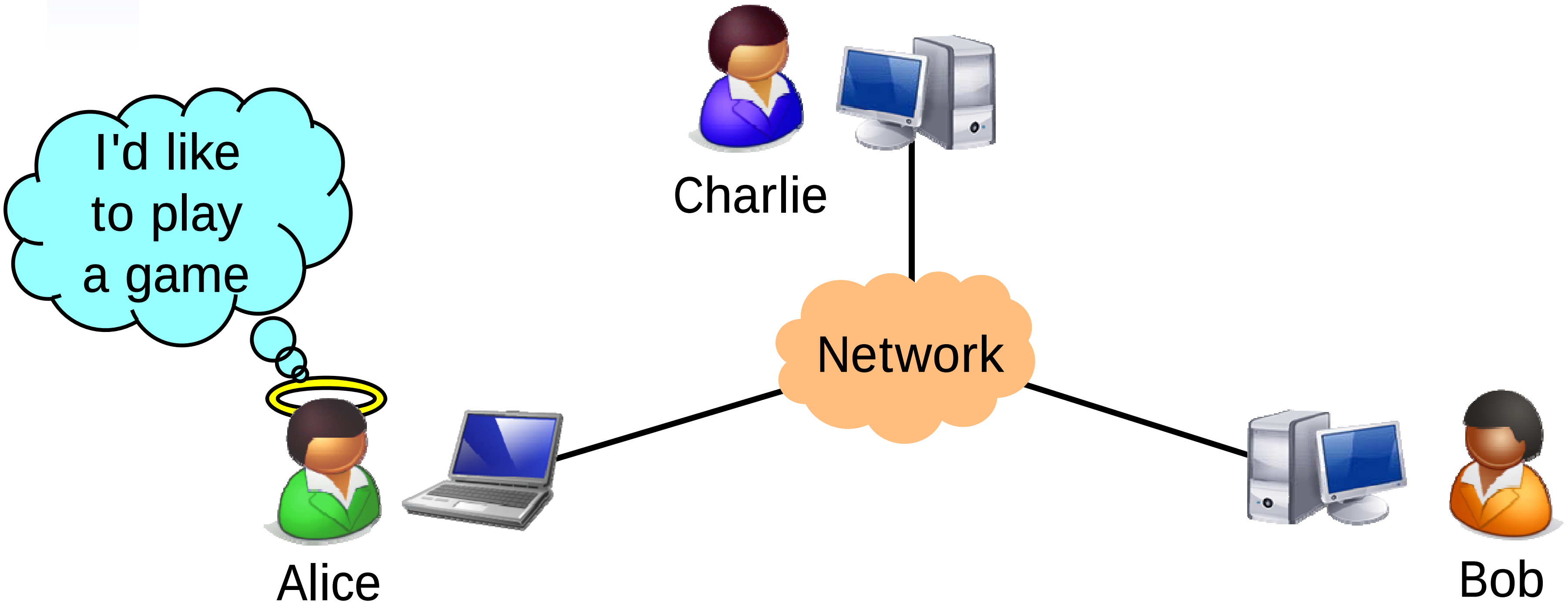
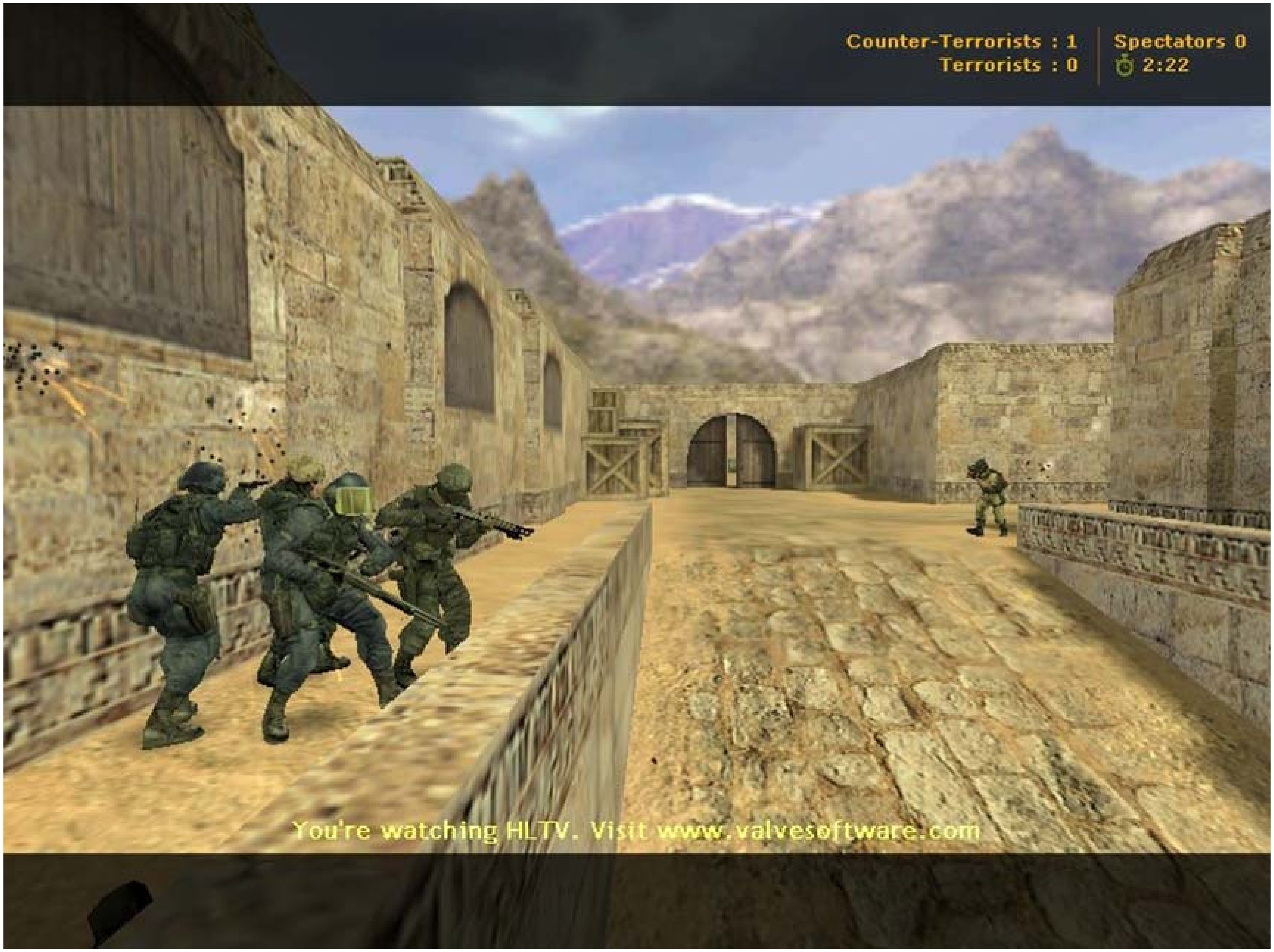
Scenario: Multiplayer game



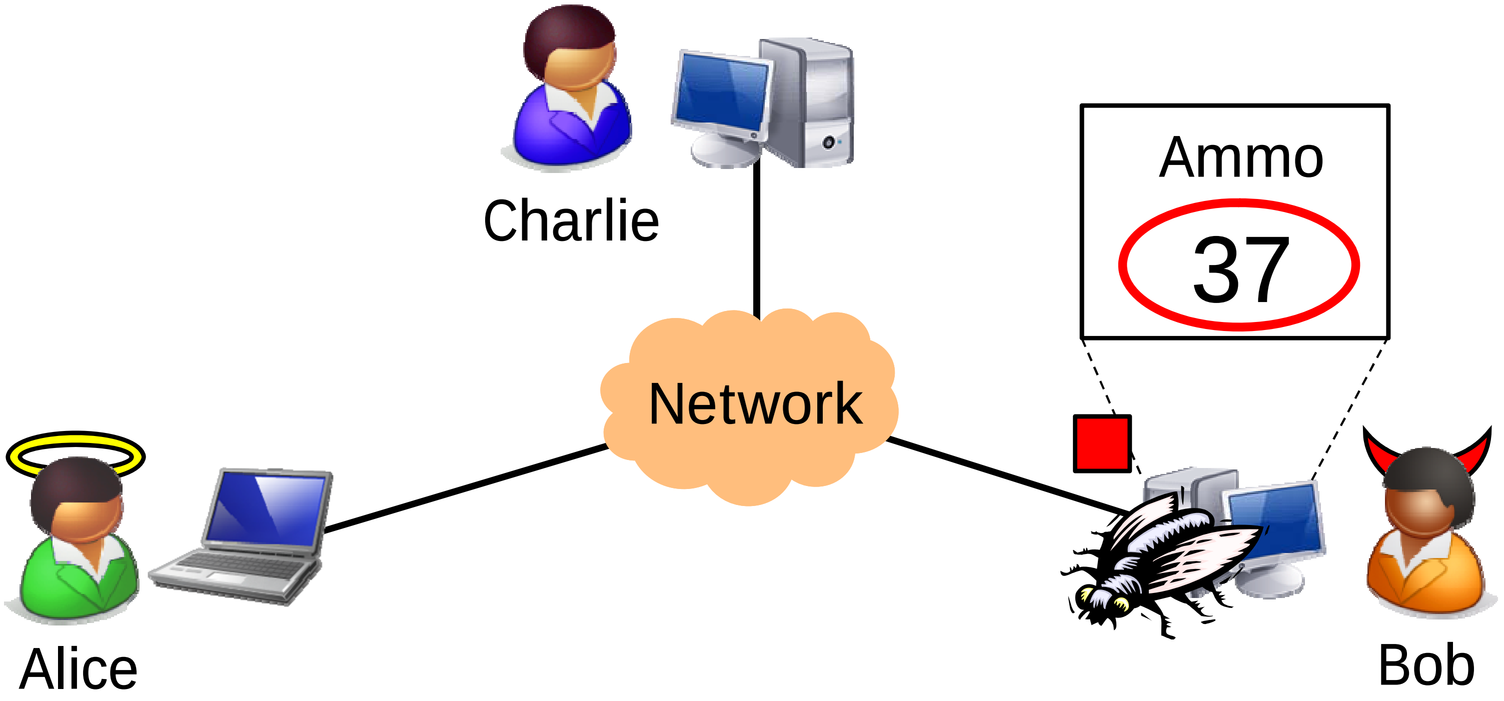
- Alice decides to play a game of Counterstrike with Bob and Charlie

What Alice sees



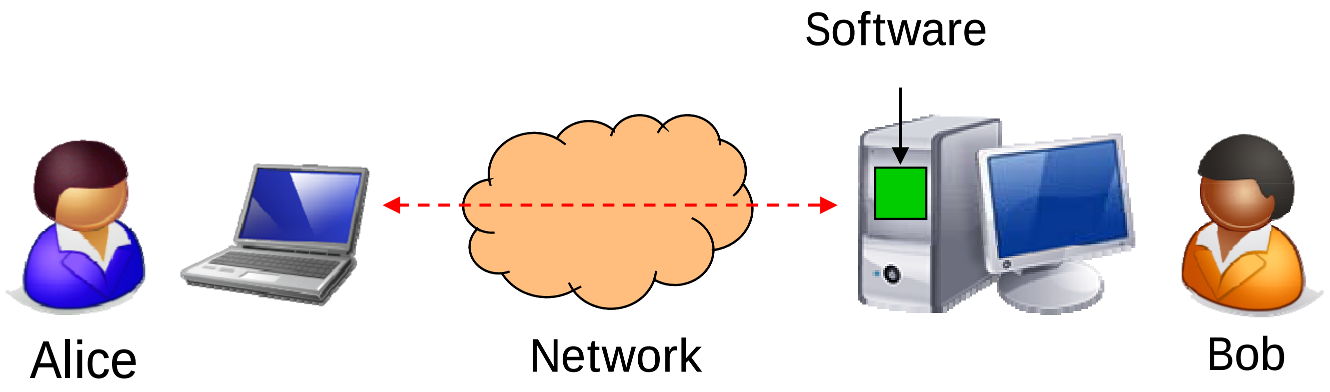
Alice

Could Bob be cheating?



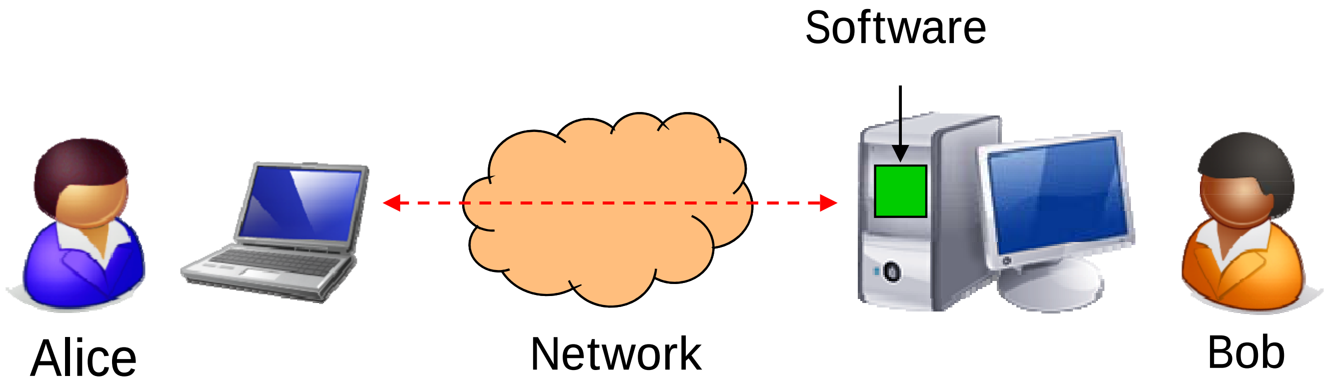
- In Counterstrike, ammunition is local state
  - Bob can manipulate counter and prevent it from decrementing
  - Such cheats (and many others) do exist, and are being used

This talk is not (just) about cheating!



- Cheating is a serious problem in itself
  - Multi-billion-dollar industry
- But we address a more general problem:
  - Alice relies on software that runs on a third-party machine
  - Examples: Competitive system (auction), federated system...
  - How does Alice know if the software running as intended?

Goal: Accountability



- We want Alice to be able to
  - Detect when the remote machine is faulty
  - Obtain evidence of the fault that would convince a third party
- Challenges:
  - Alice and Bob may not trust each other
    - Possibility of intentional misbehavior (example: cheating)
  - Neither Alice nor Bob may understand how the software works
    - Binary only - no specification of the correct behavior

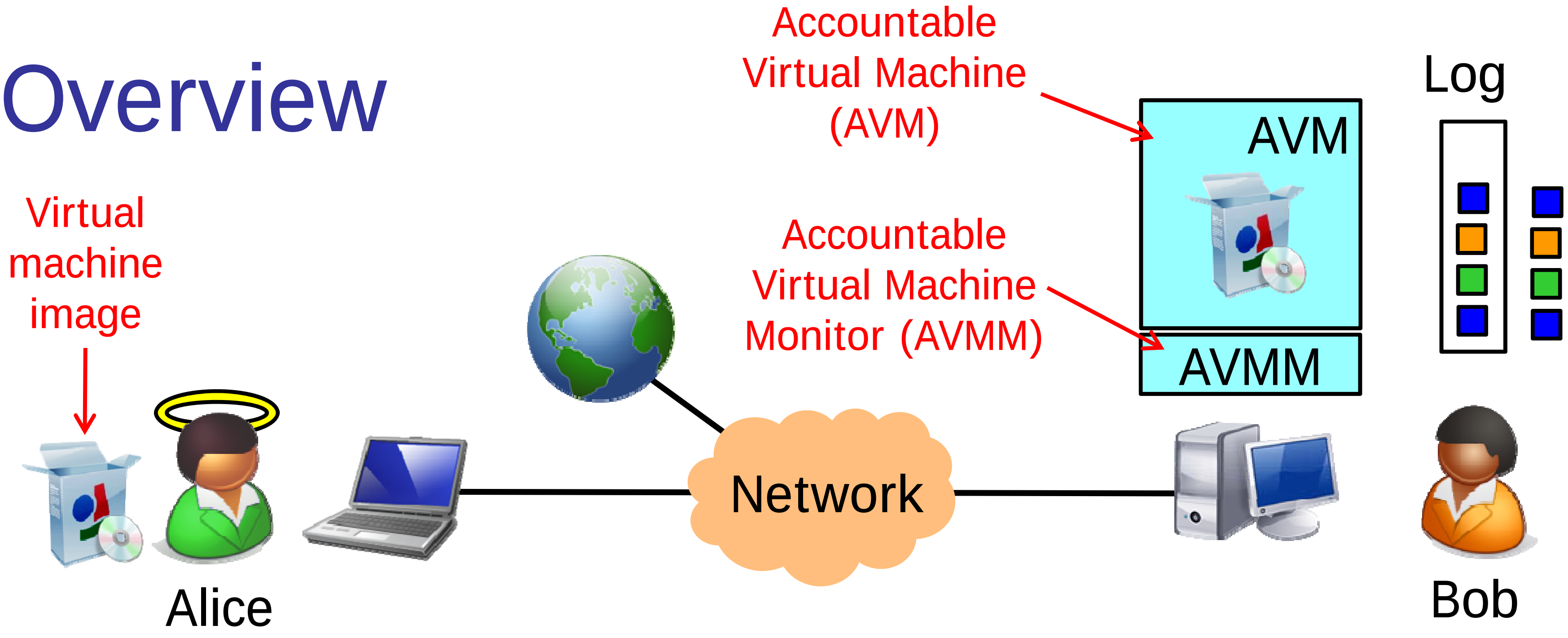
Outline

- Problem: Detecting faults on remote machines
  - Example: Cheating in multiplayer games
- Solution: Accountable Virtual Machines

NEXT

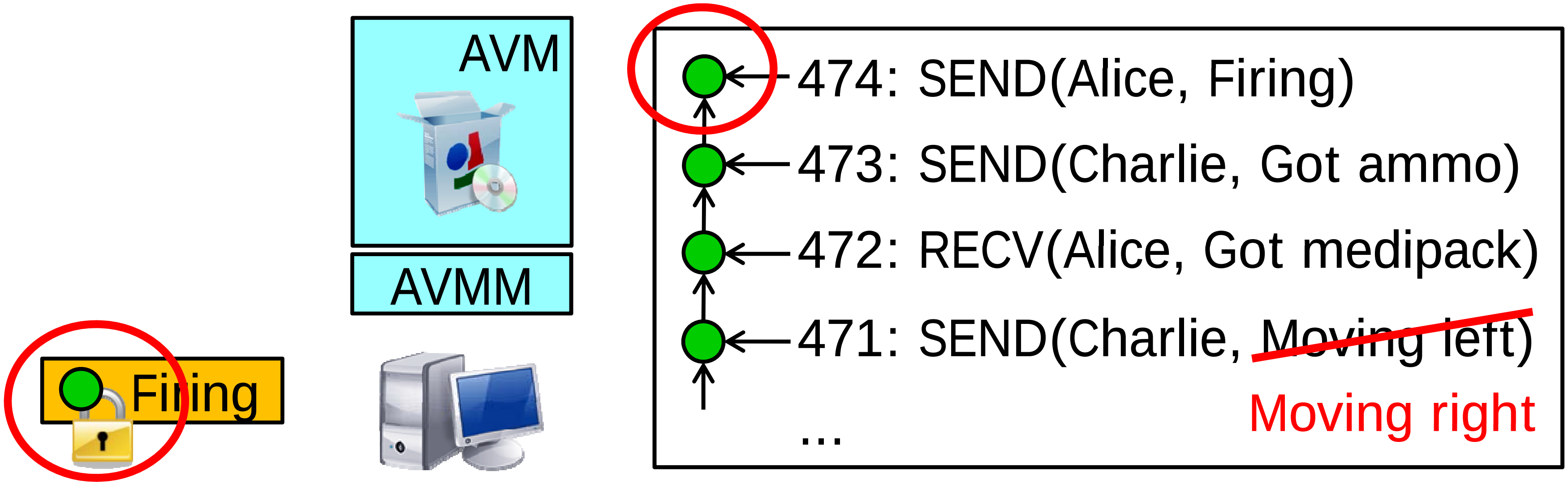
- Evaluation
  - Using earlier example (cheating in Counterstrike)
- Summary

Overview


Virtual machine image
Alice
Network
Accountable Virtual Machine (AVM)
Accountable Virtual Machine Monitor (AVMM)
AVM
AVMM
Log
Bob

- Bob runs Alice's software image in an AVM
  - AVM maintains a log of network in-/outputs
- Alice can check this log with a reference image
  - AVM correct: Reference image can produce same network outputs when started in same state and given same inputs
  - AVM faulty: Otherwise

Tamper-evident logging



AVM

AVMM

Firing

474: SEND(Alice, Firing)

473: SEND(Charlie, Got ammo)

472: RECV(Alice, Got medipack)

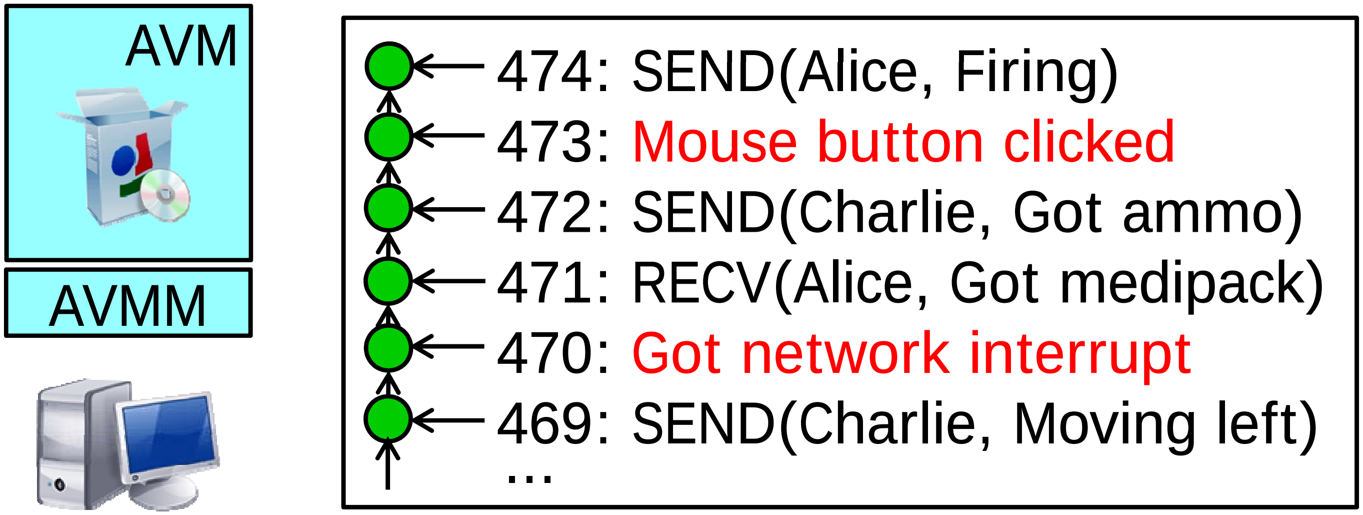
471: SEND(Charlie, ~~Moving left~~)

Moving right

...

- Message log is tamper-evident [SOSP'07]
  - Log is structured as a hash chain
  - Messages contain signed authenticators
- Result: Alice can either...
  - ... detect that the log has been tampered with, or
  - ... get a complete log with all the observable messages

Execution logging



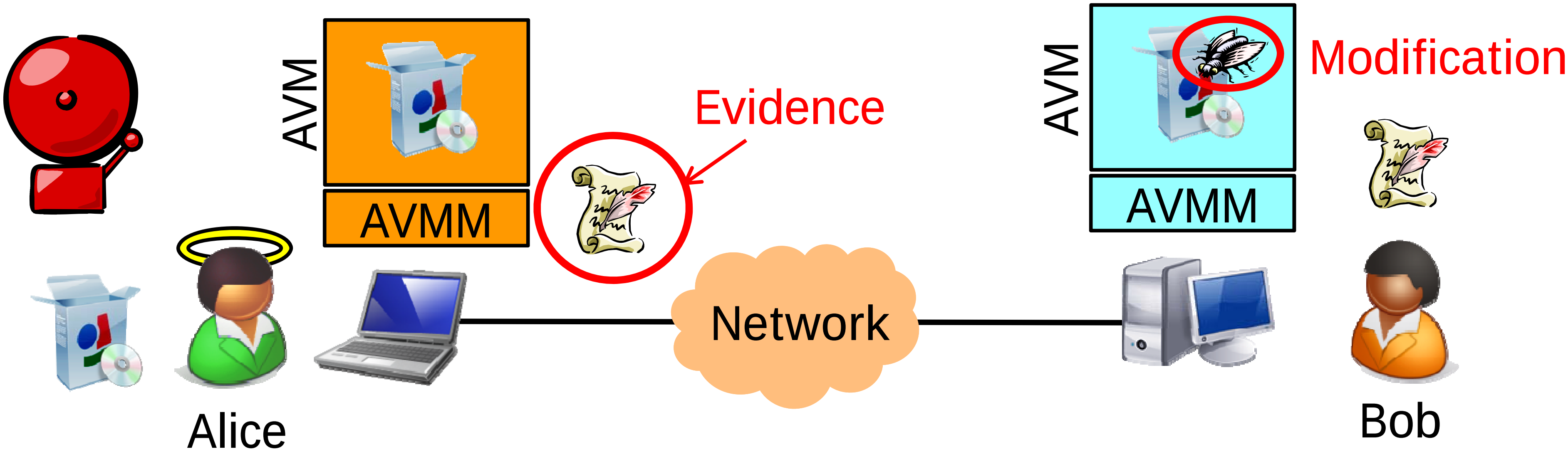
```
474: SEND(Alice, Firing)
473: Mouse button clicked
472: SEND(Charlie, Got ammo)
471: RECV(Alice, Got medipack)
470: Got network interrupt
469: SEND(Charlie, Moving left)
…
```

- How does Alice know whether the log matches a correct execution of her software image?
- Idea: AVMM can specify an execution
  - AVMM additionally logs all nondeterministic inputs
  - AVM correct: Can replay inputs to get execution
  - AVM faulty: Replay inevitably (!) fails

Auditing and replay

371: SEND(Alice, Firing)
370: SEND(Alice, Firing)
369: SEND(Alice, Firing)
368: Mouse button clicked
367: SEND(Alice, Got medipack)
366: Mouse moved left

373: SEND(Alice, Firing)
372: SEND(Alice, Firing)
371: SEND(Alice, Firing)
370: SEND(Alice, Firing)
369: SEND(Alice, Firing)
368: Mouse button clicked
367: SEND(Alice, Got medipack)
366: Mouse moved left
...



AVM properties

- Strong accountability
  - Detects faults
  - Produces evidence
  - No false positives

If it runs in a VM, it will work

- Works for arbitrary, unmodified binaries
  - Nondeterministic events can be captured by AVM Monitor

- Alice does not have to trust Bob, the AVMM, or any software that runs on Bob's machine
  - If Bob tampers with the log, Alice can detect this
  - If Bob's AVM is faulty, ANY log Bob could produce would inevitably cause a divergence during replay

Outline

- Problem: Detecting faults on remote machines
  - Example: Cheating in multiplayer games
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- Evaluation ⇦ NEXT
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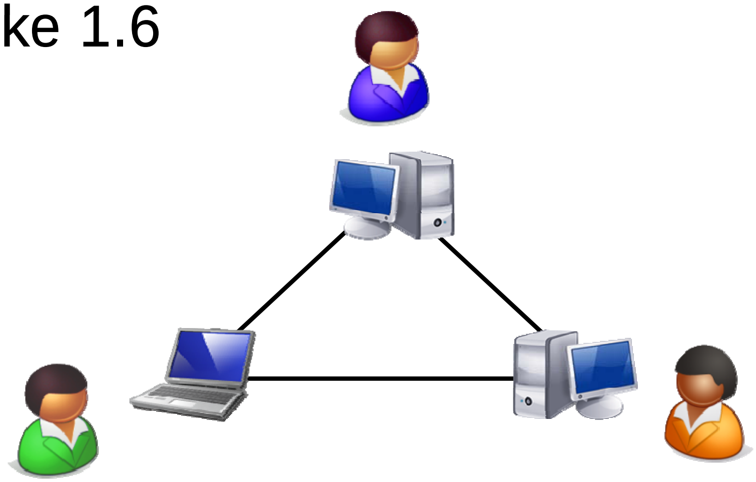
Methodology

- We built a prototype AVMM
  - Based on logging/replay engine in VMware Workstation 6.5.1
  - Extended with tamper-evident logging and auditing
- Evaluation: Cheat detection in games
  - Setup models competition / LAN party
  - Three players playing Counterstrike 1.6
  - Nehalem machines (i7 860)
  - Windows XP SP3

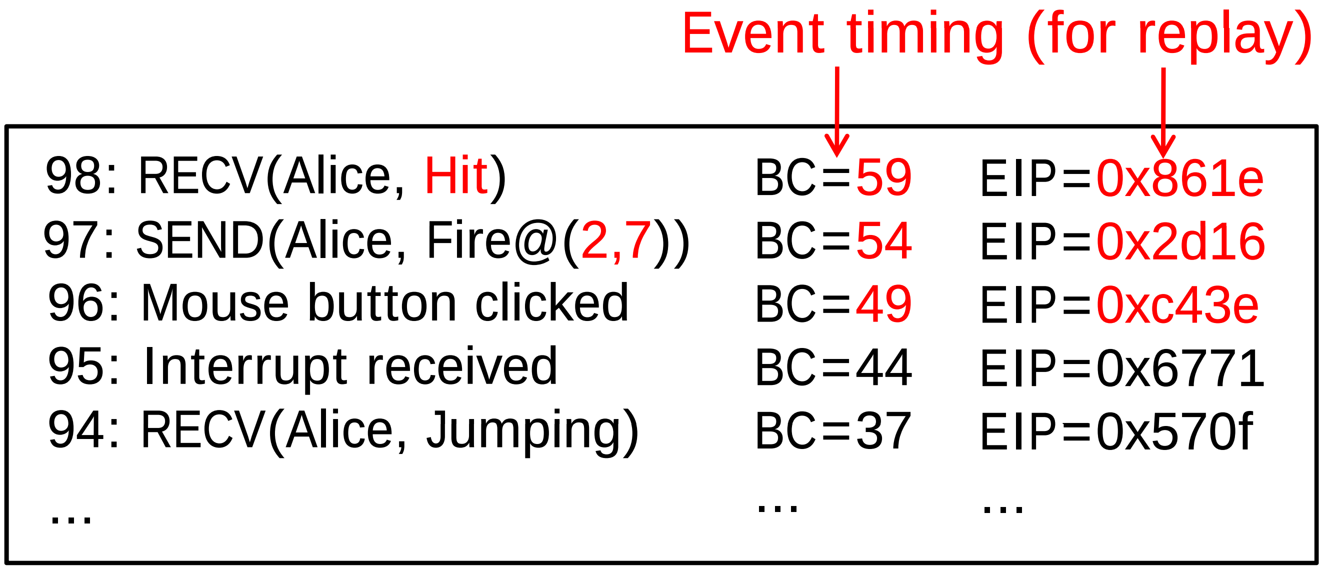


Evaluation topics

- Effectiveness against real cheats
- Overhead
  - Disk space (for the log)
  - Time (auditing, replay)
  - Network bandwidth (for authenticators)
  - Computation (signatures)
  - Latency (signatures)
- Impact on game performance
- Online auditing
- Spot checking tradeoffs
  - Using a different application: MySQL on Linux

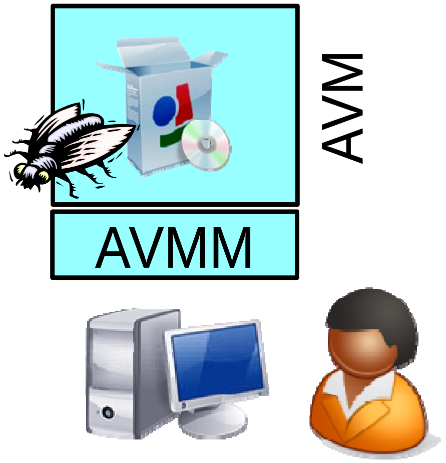
Please refer to the paper for additional results!

AVMs can detect real cheats


Event timing (for replay)

```
98: RECV(Alice, Hit)              BC=59   EIP=0x861e
97: SEND(Alice, Fire@(2,7))       BC=54   EIP=0x2d16
96: Mouse button clicked          BC=49   EIP=0xc43e
95: Interrupt received            BC=44   EIP=0x6771
94: RECV(Alice, Jumping)          BC=37   EIP=0x570f
...                               ...     ...
```

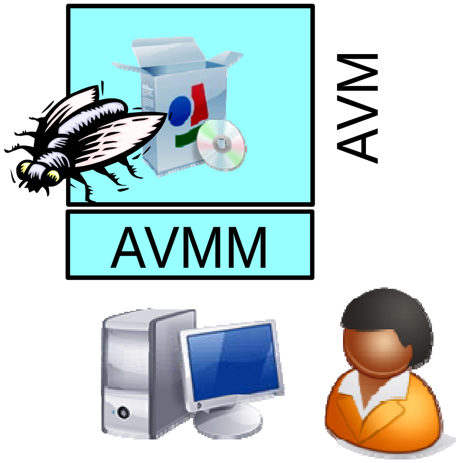
Bob's log



- If the cheat needs to be installed in the AVM to be effective, AVM can trivially detect it
  - Reason: Event timing + control flow change
  - Examined real 26 cheats from the Internet; all detectable

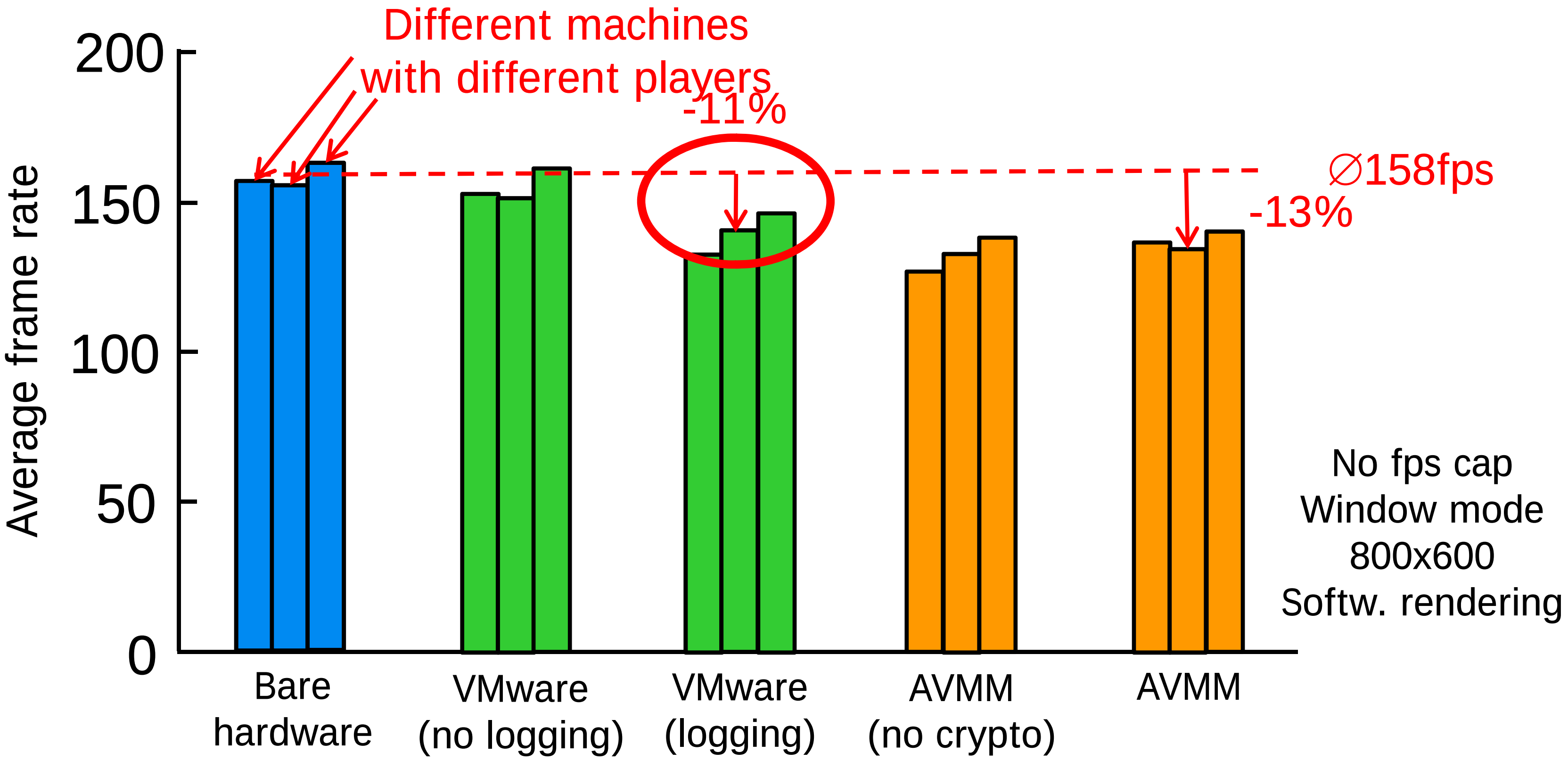
AVMs can detect real cheats

```
99: RECV(Alice, Hit)             BC=      EIP=
98: SEND(Alice, Fire@(2,7))      BC=      EIP=
97: Mouse button clicked         BC=      EIP=
96: Mouse move right  1 inch     BC=      EIP=

94: Mouse move up 1 inch         BC=      EIP=

92: RECV(Alice, Jumping)         BC=      EIP=
...                              ...      ...
```



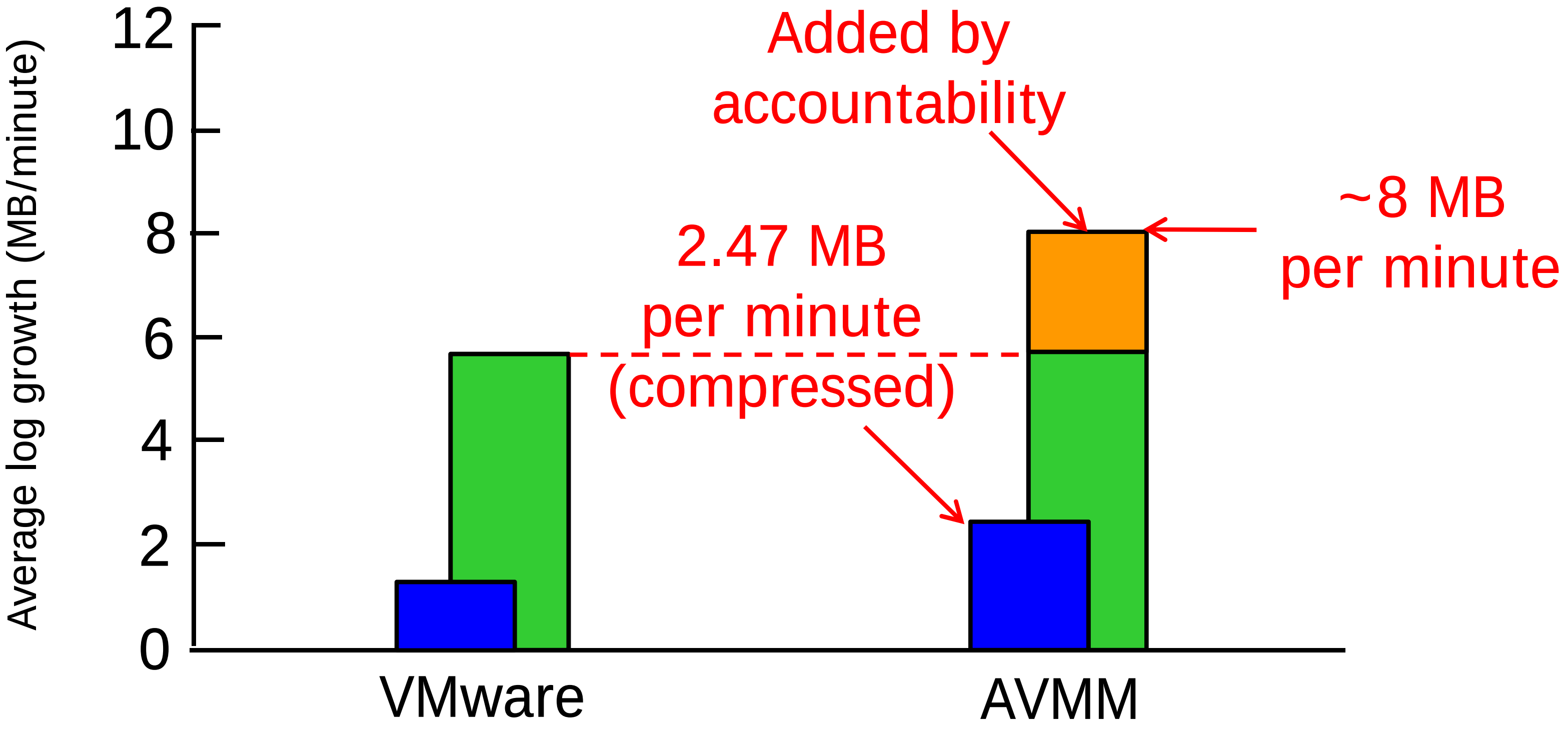
- Couldn't cheaters adapt their cheats?
- There are three types of cheats:
  1. Detection impossible (Example: Collusion)
  2. Detection not guaranteed, but evasion technically difficult
  3. Detection guaranteed (≥15% of the cheats in our sample)

Impact on frame rate



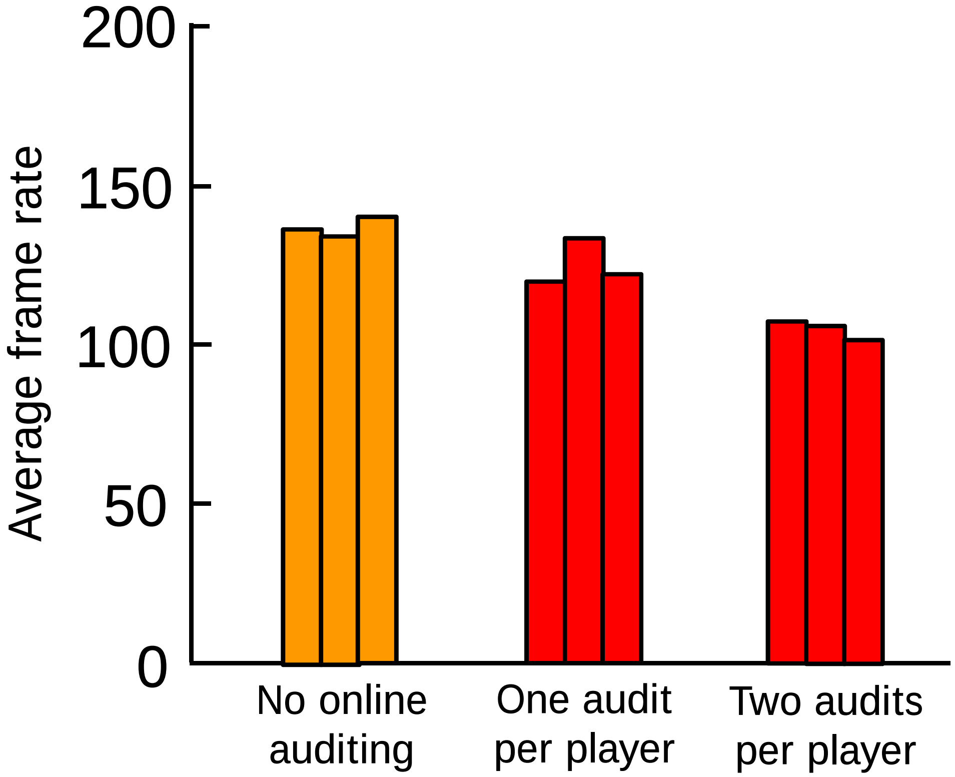
- Frame rate is ~13% lower than on bare hw
  - 137fps is still a lot! 60--80fps generally recommended
  - 11% due to logging; additional cost for accountability is small

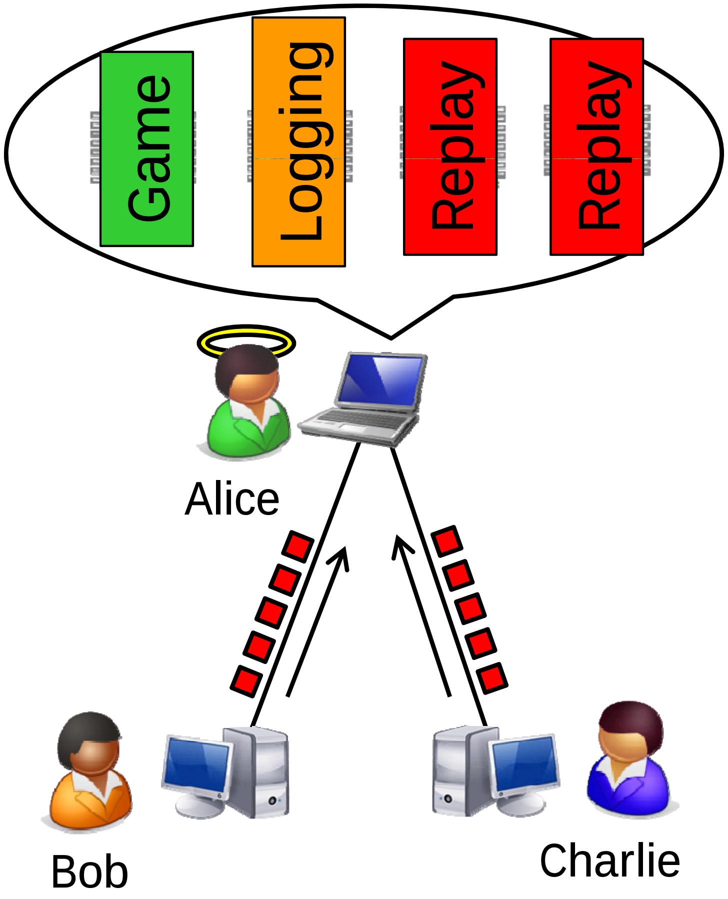
Cost of auditing



- When auditing a player after a one-hour game,
  - How big is the log we have to download? 148 MB
  - How much time is needed for replay? ~ 1 hour

Online auditing





- Idea: Stream logs to auditors during the game
  - Result: Detection within seconds after fault occurs
  - Replay can utilize unused cores; frame rate penalty is low

Summary

- Accountable Virtual Machines (AVMs) offer strong accountability for unmodified binaries
  - Useful when relying on software executing on remote machines: Federated system, multiplayer games, ...
  - No trusted components required
- AVMs are practical
  - Prototype implementation based on VMware Workstation
  - Evaluation: Cheat detection in Counterstrike

Questions?

Thank you!

Our enthusiastic Counterstrike volunteers