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Toward Online Verification of Client Behavior in Distributed Applications

Robby Cochran
Mike Reiter

University of North Carolina at Chapel Hill

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CLIENT
Is this message from an unmodified client?
SERVER
+
VERIFIER

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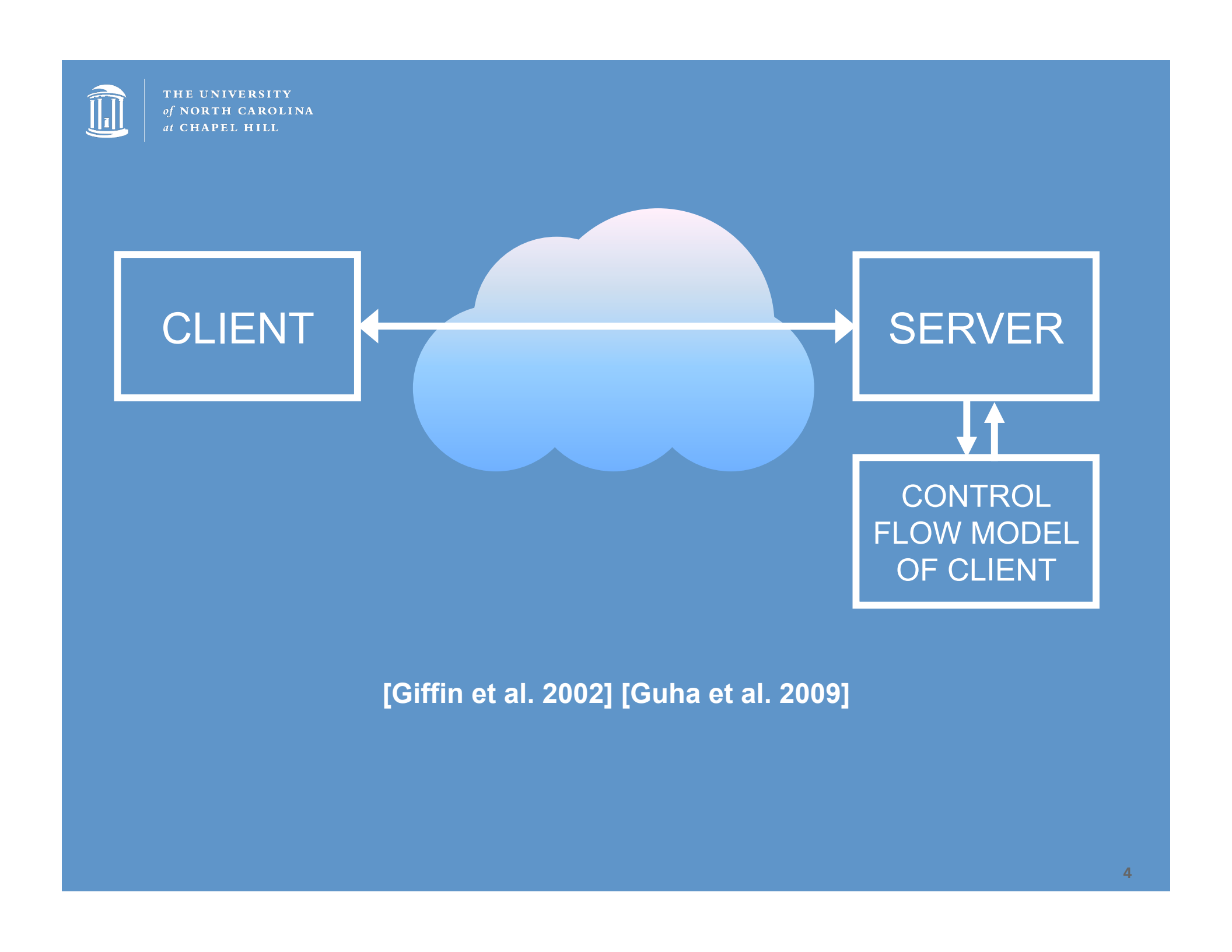
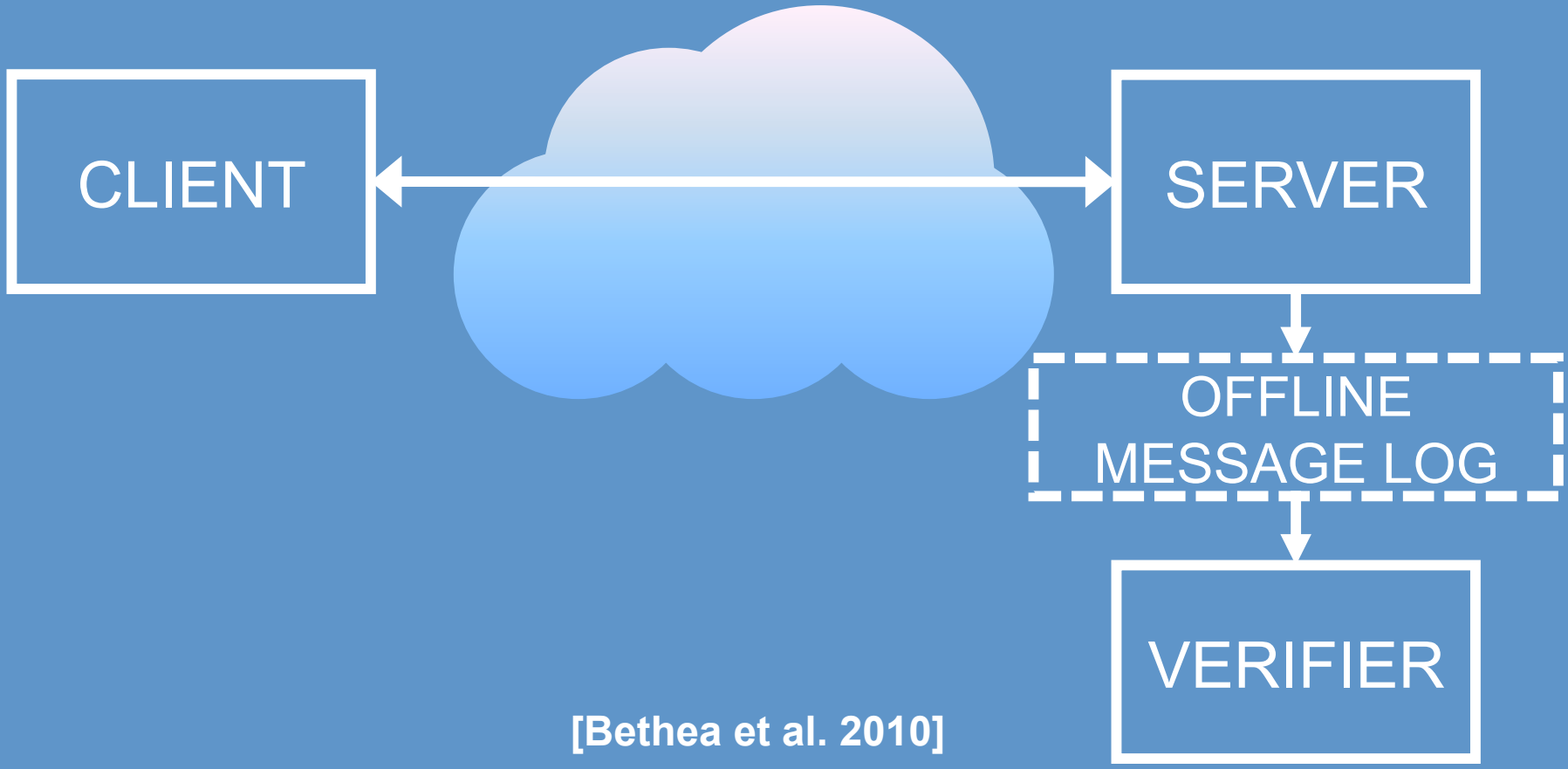
Goals

- Detect if client messages are consistent with the sanctioned client software …
  - Adversary might modify binary/memory
  - or rewrite message on the wire
- … Much more quickly than previous work
- Ideally we would do so online…

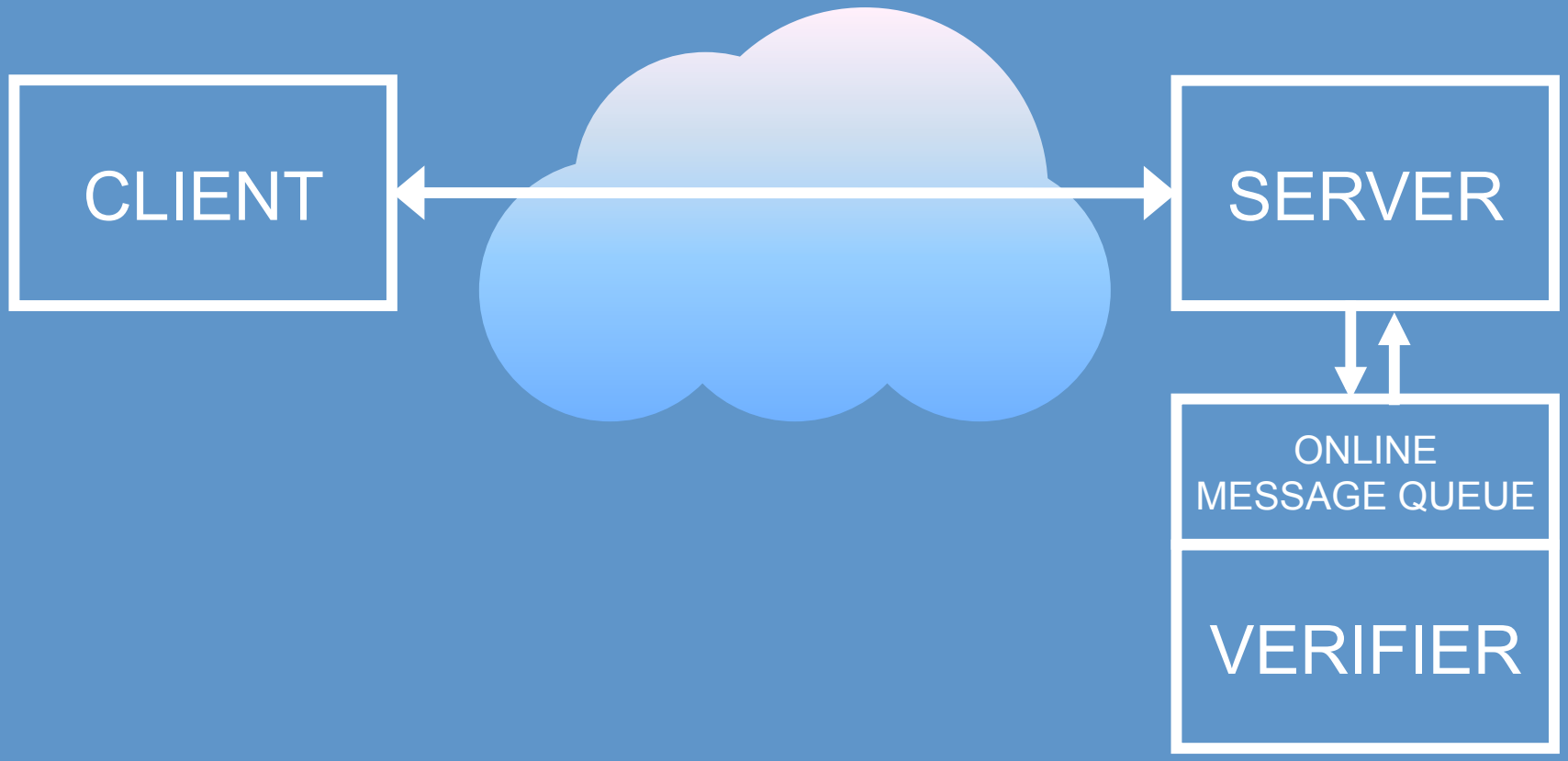


[Giffin et al. 2002] [Guha et al. 2009]

[Vikram et al. 2009]



[Bethea et al. 2010]


CLIENT
SERVER
ONLINE
MESSAGE QUEUE
VERIFIER

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Introduction

- **Existing techniques to verify client behavior**
  - Imprecise
  - Increase bandwidth usage
  - Computationally expensive
- **Our method**
  - Precise: no false negatives and no false positives
  - No additional bandwidth *required*
  - Validates most legitimate behavior faster than previous techniques

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Overview

- *Introduction*
- ***Symbolic Execution***
- ***Key Insight #1: Common Case Optimization***
- ***Key Insight #2: Guided Search with History***
- ***Case Studies***
- ***Conclusion***

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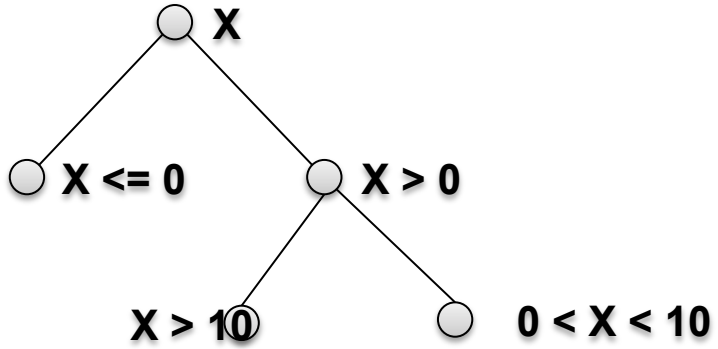
Symbolic Execution
[Boyer 1975]

- A way of deriving the effects of a given program on a given system
  - Constraints on input are constructed based on each execution path
- Built on top of KLEE [Cadar et al. 2008]



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Symbolic Environment

How can we use symbolic execution to verify a message?

```
1  loc = 0
2  while true do
3    key = symbolicReadKey()
4    if key == ESC then
5      sendQuitMsg()
6    else if key == UP then
7      loc = loc + 1
8    else if key == DN then
9      loc = loc – 1
10   end if
11     sendMsg(loc)
12 end while
```

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Symbolic State	Execution Prefix
loc == 0 ∧ key == ESC	1,2,3,4,5

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Symbolic State	Execution Prefix
loc == 0 ∧ key == ESC	1,2,3,4,5
loc == 1 ∧ key != ESC ∧ key == UP	1,2,3,4,6, 7,11

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Symbolic Environment

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loc == 0 ∧ key == ESC	1,2,3,4,5
loc == 1 ∧ key != ESC ∧ key == UP	1,2,3,4,6, 7,11
loc == -1 ∧ key != ESC ∧key != UP ∧ key == DN	1,2,3,4,6, 8,9,11

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Checking a Client Message

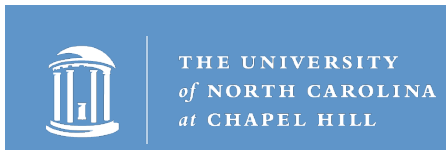
Client Message: msg_0

```
<location>1</location>
```

STP **Satisfiability Modulo Theory Solver** [Ganesh et al. 2007]

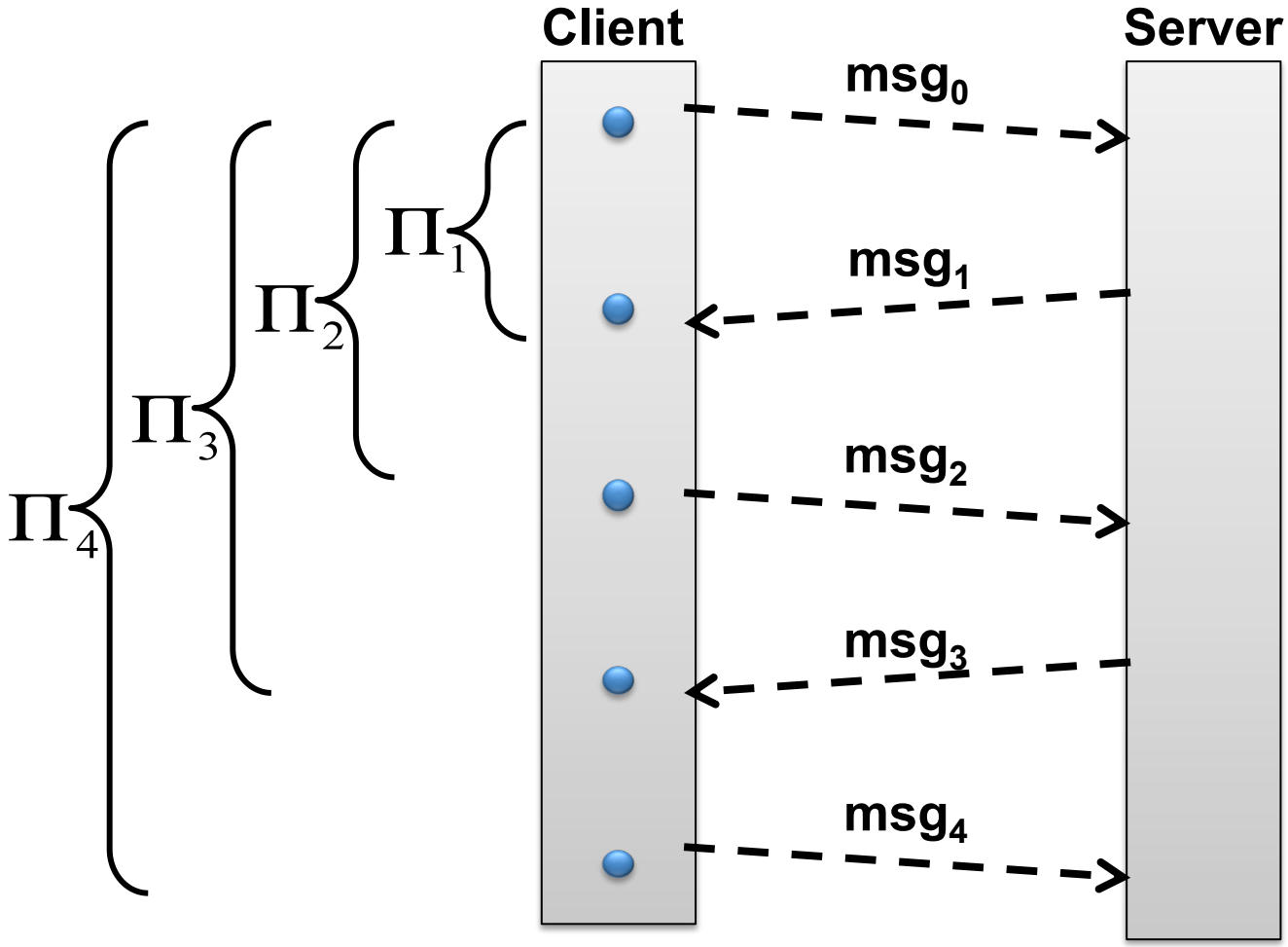
Check consistency of message with formulas generated via symbolic execution.

	Symbolic State	Execution Prefix
	loc == 0 ∧ key == ESC	1,2,3,4,5
	loc == 1 ∧ key != ESC ∧ key == UP	1,2,3,4,6, 7,11
	loc == -1 ∧ key != ESC ∧key != UP ∧ key == DN	1,2,3,4,6, 8,9,11



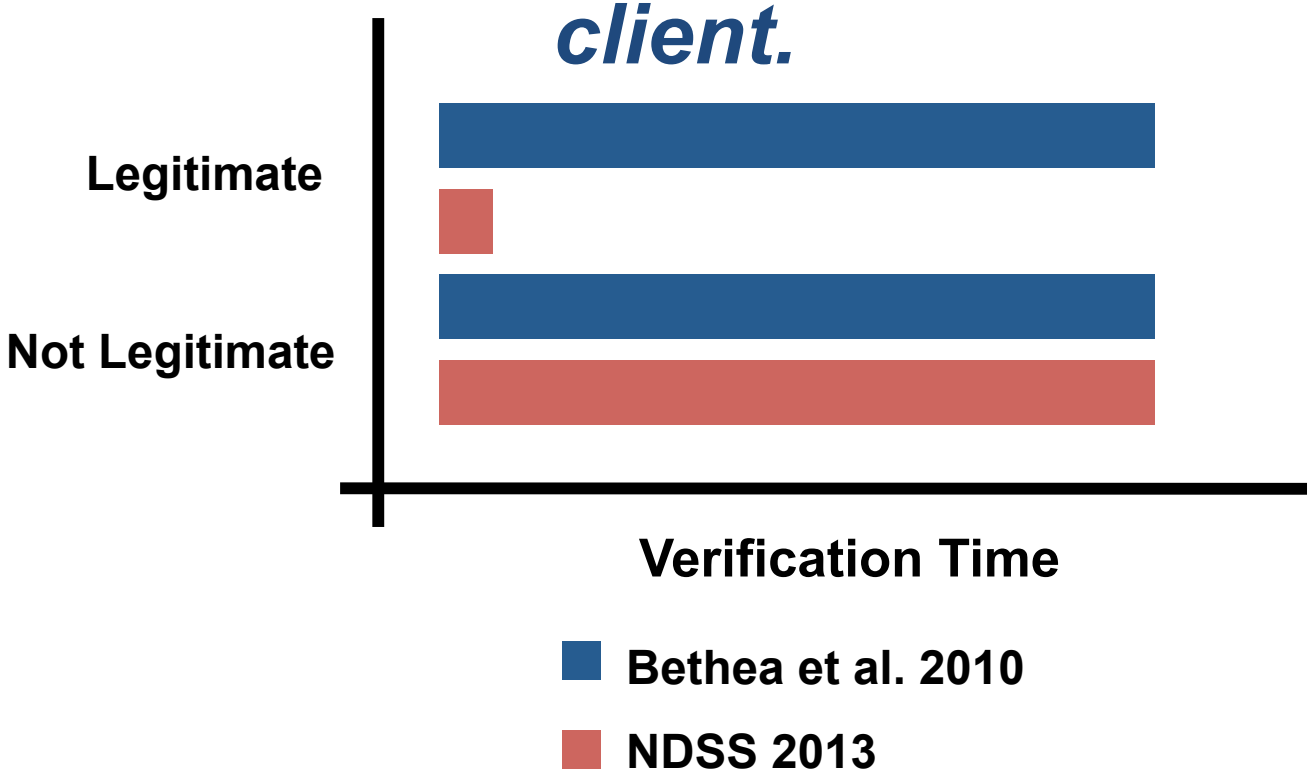
Verifying Client Messages

Iteratively find *execution prefix* $\prod$ consistent with msg_0, msg_1, …, msg_n



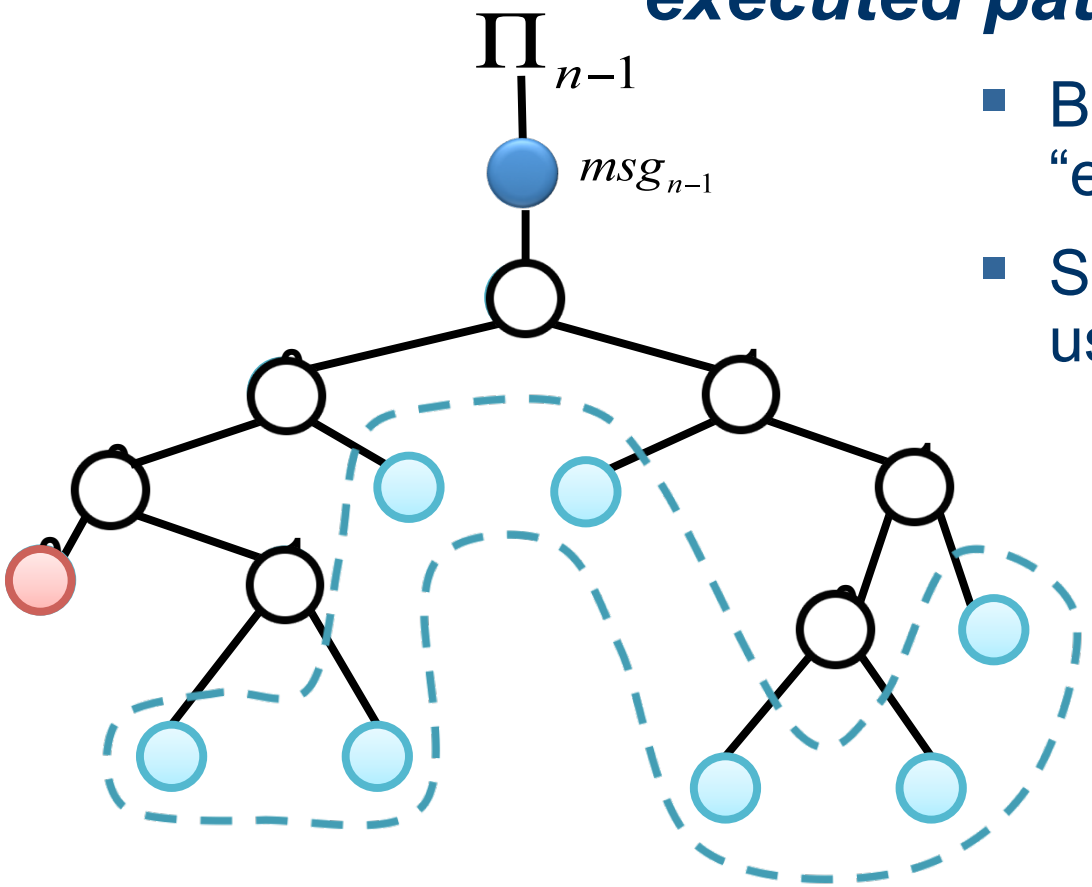
Verifying Client Messages

Key Insight #1: Optimize for the common case of a legitimate client.



Verification: Node Selection

Key Insight #2:
Correlate message contents with previously executed paths



- Build training corpus of "execution fragments"
- Select next node to explore using training data

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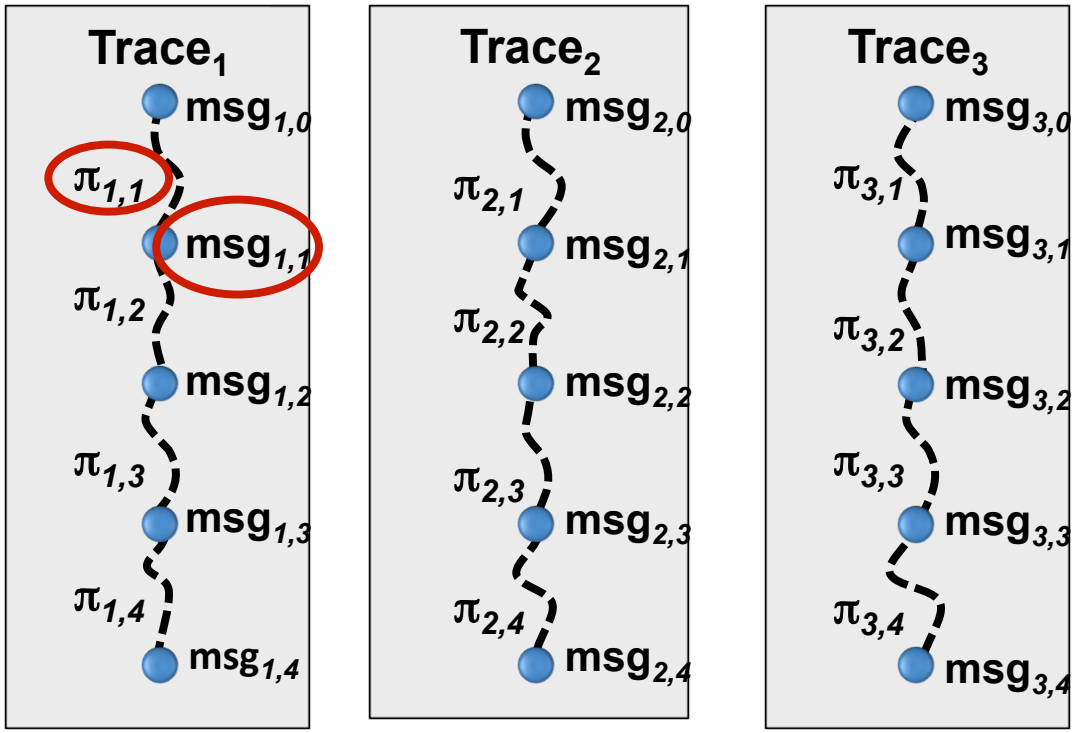
Building Training Corpus

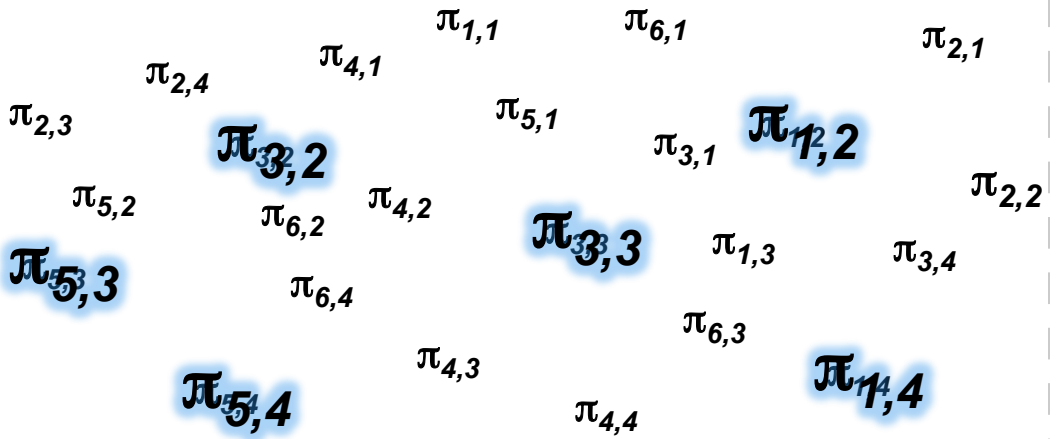


Execute client software to generate a set of message traces.

Split each trace into a set of execution fragments $\pi_{i,j}$

Associate each $\pi_{i,j}$ with the set of messages it is consistent with.

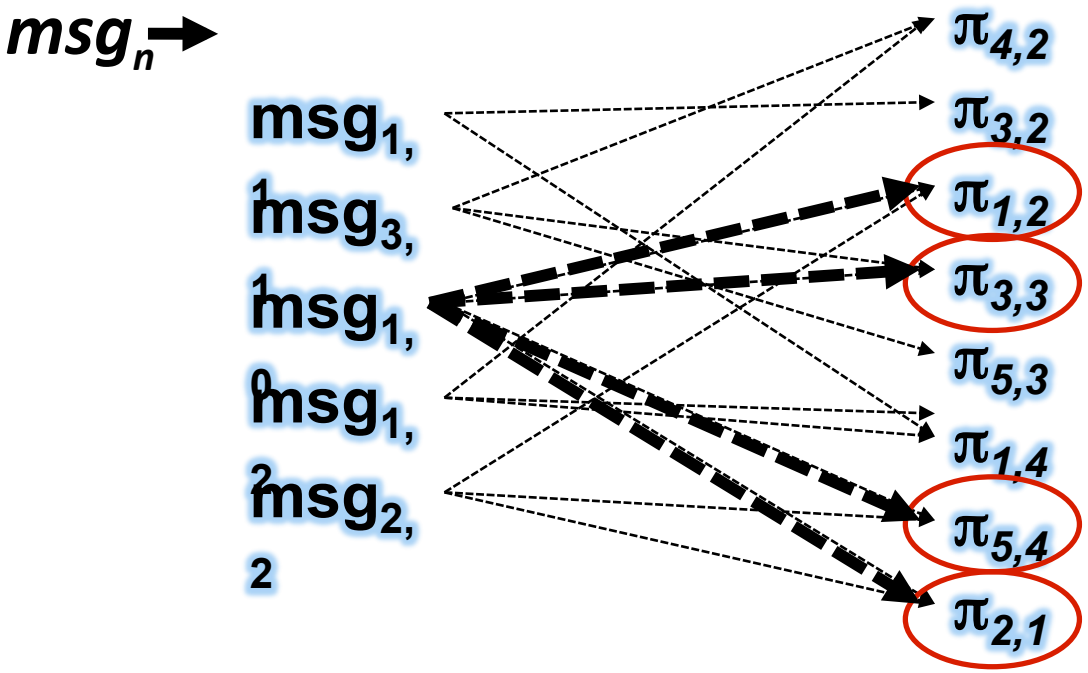
Clustering Training Data



Cluster execution fragments π by edit distance using k-medoids clustering.

Cluster messages by edit distance using k-medoids clustering.

Using the Clusters



Map message medoids to execution fragment medoids.

Find message medoid closest to msg_n via edit distance.

Use associated execution fragment medoids to guide search.

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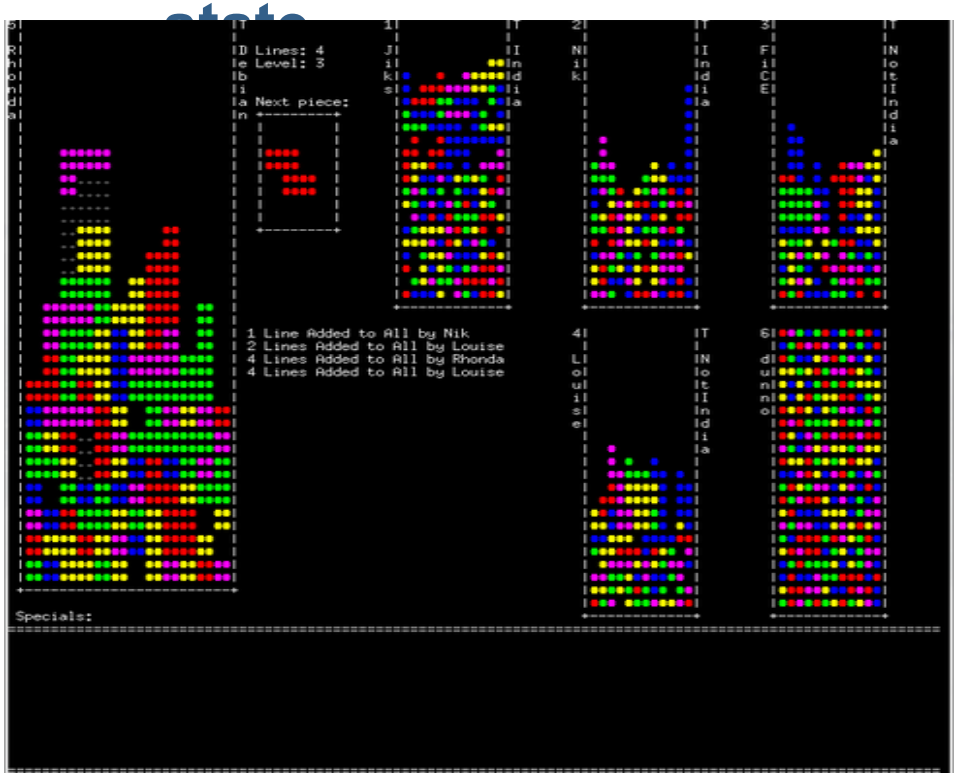
Case Studies

- **Networked games are popular!**
  - Some > 10 million subscribers
  - Gaming industry revenues of $67 billion (2012)
- **Cheaters reduce the quality of the game for honest players**
  - Our technique detects any cheat that requires a modification to the client binary or memory

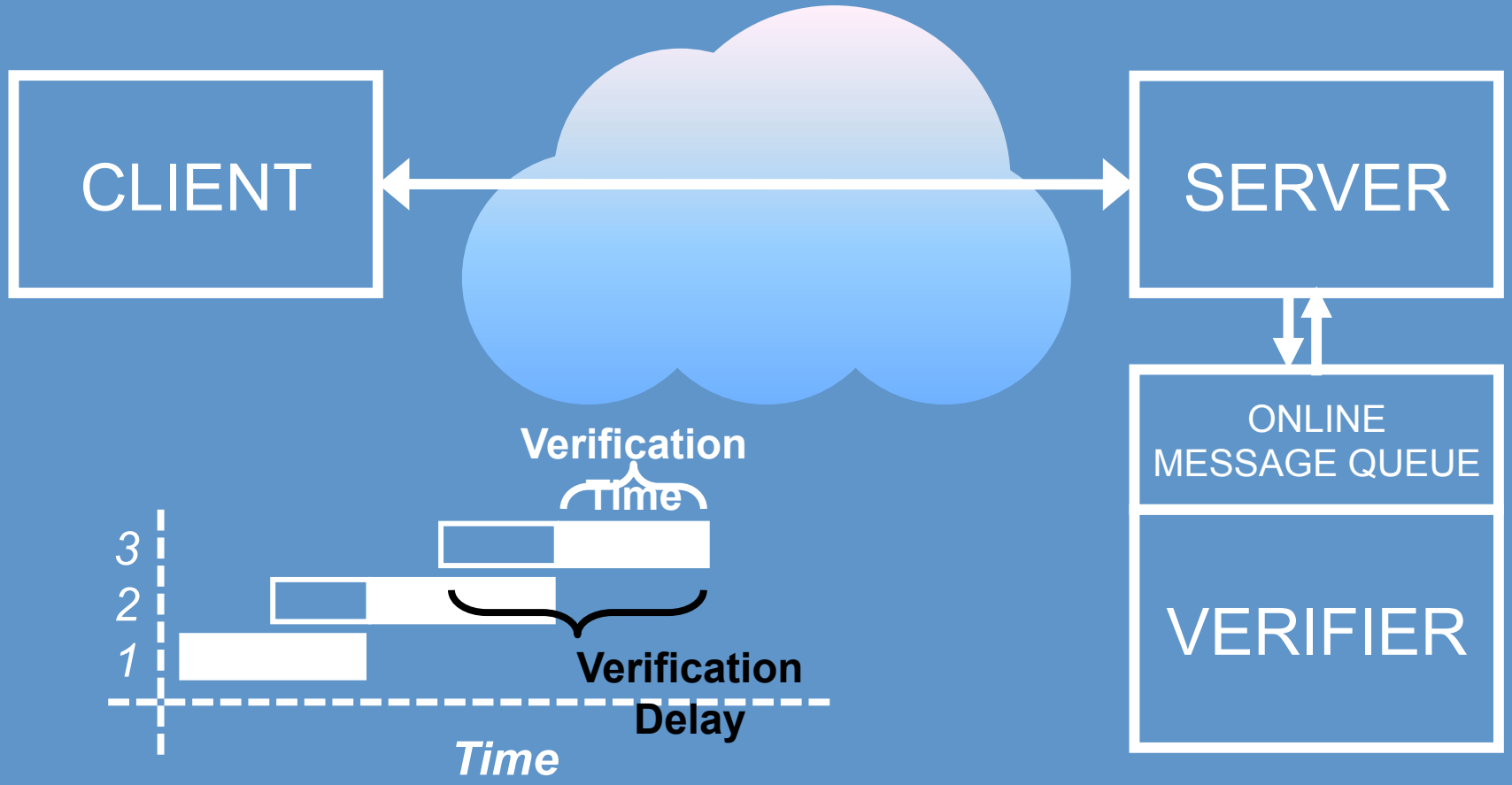
Case Studies

- **XPilot**
  - Open-source multiplayer 2D shooter
  - 150000 lines of C
  - Little client-side state

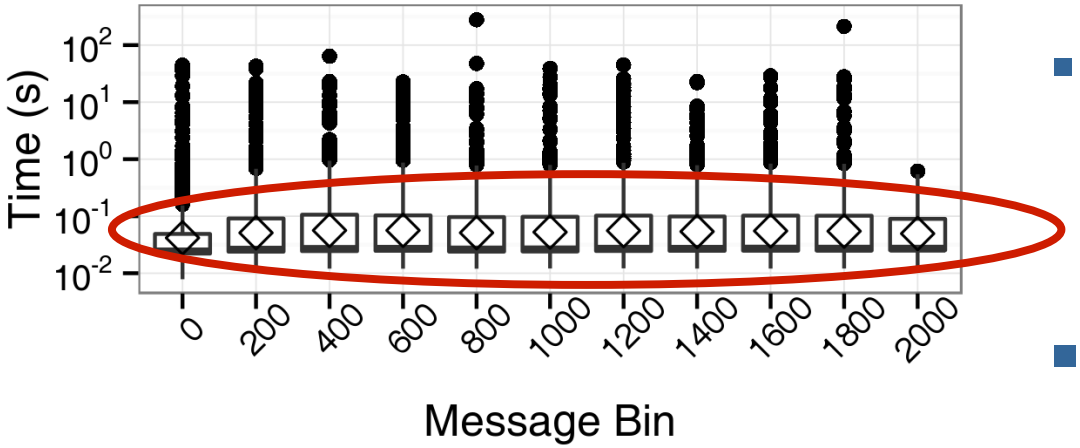
- **TetriNET**
  - Text-based multiplayer Tetris game
  - 5000 lines of C
  - More ambiguity at server about client

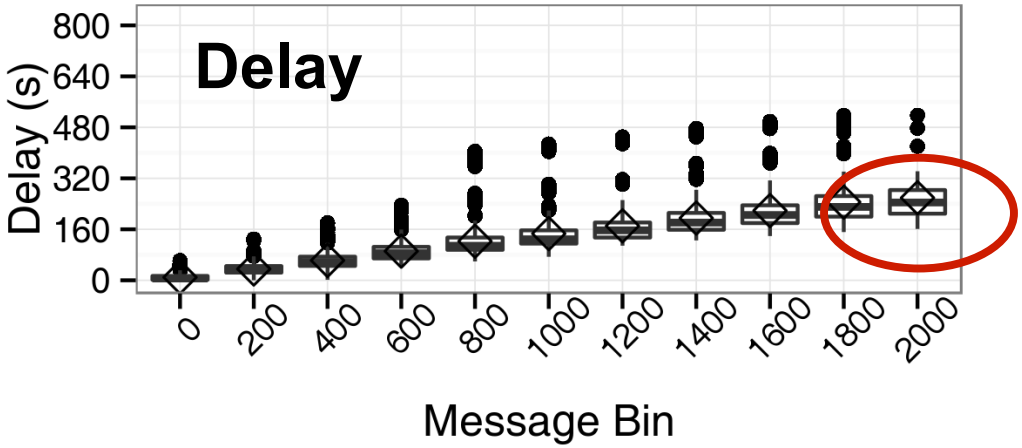


Measuring Performance



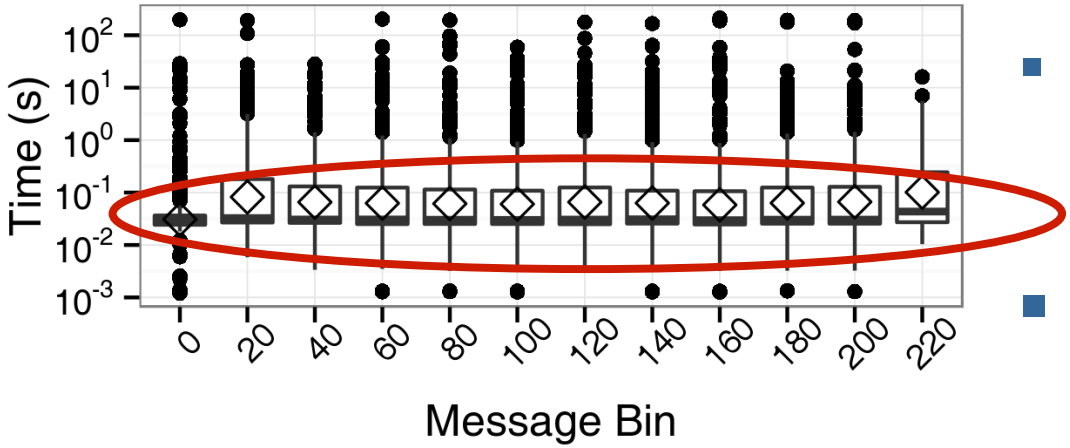
XPilot Results

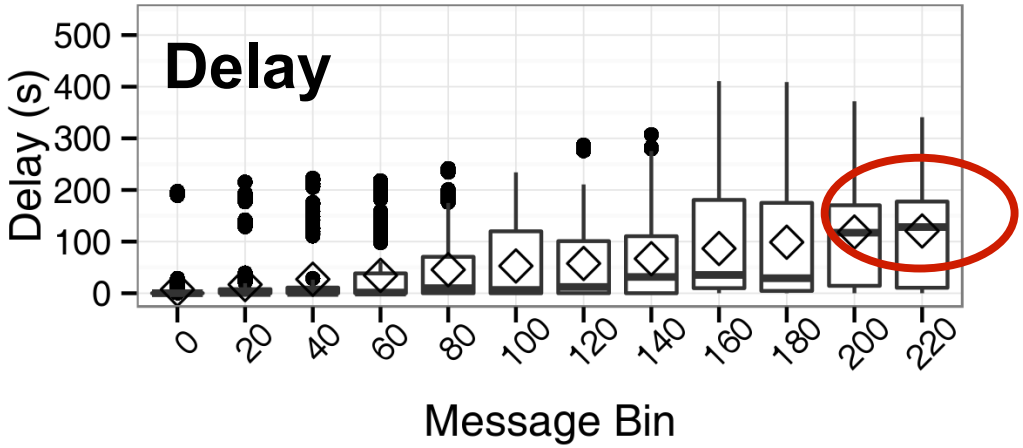




- 40-fold cross validation
  - 4000 points per bin
  - Average: 32 messages/ second
- **Average verification time < 100ms**
- **Average delay at end of queue is less than 5 min**
- **100x faster than previous work**

TetriNET Results





- 20-fold cross validation
  - Average game 6.5 minutes
  - 20x20 = 400 points per bin
- **Average verification time < 100ms**
- **Average Delay at end of queue is less than 2 min**
- **See paper for a variation that often keeps up with gameplay with a small increase in bandwidth**

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Conclusion

- **Key Insights**
  - Optimize for the common case legitimate client
  - Use a search heuristic that correlates message contents with previously executed paths
  - Optimize symbolic execution components for our specific needs (see paper)
- **Contribution: Precise client checking algorithm**
  - Dramatically improves performance over previous work with similar design goals
  - In some cases, verification comes very close to keeping pace with the application (see paper)

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Questions?