33RD USENIX SECURITY SYMPOSIUM

That Doesn’t Go There: Attacks on Shared State in Multi-User Augmented Reality Applications

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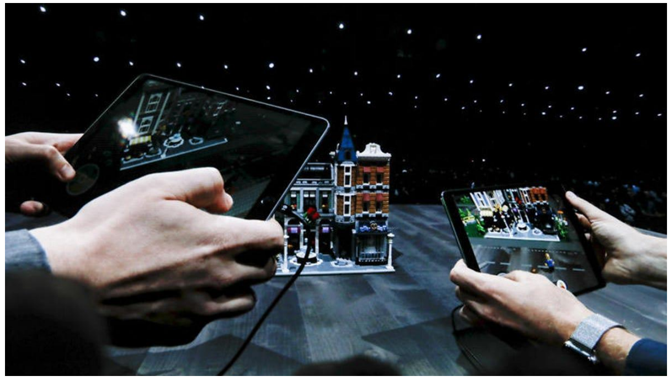
**Equal contribution*

Multi-user augmented reality apps

- A growing number of AR applications facilitate multi-user interactions with shared holograms



- These applications are supported by major industry players

ARCore by Google

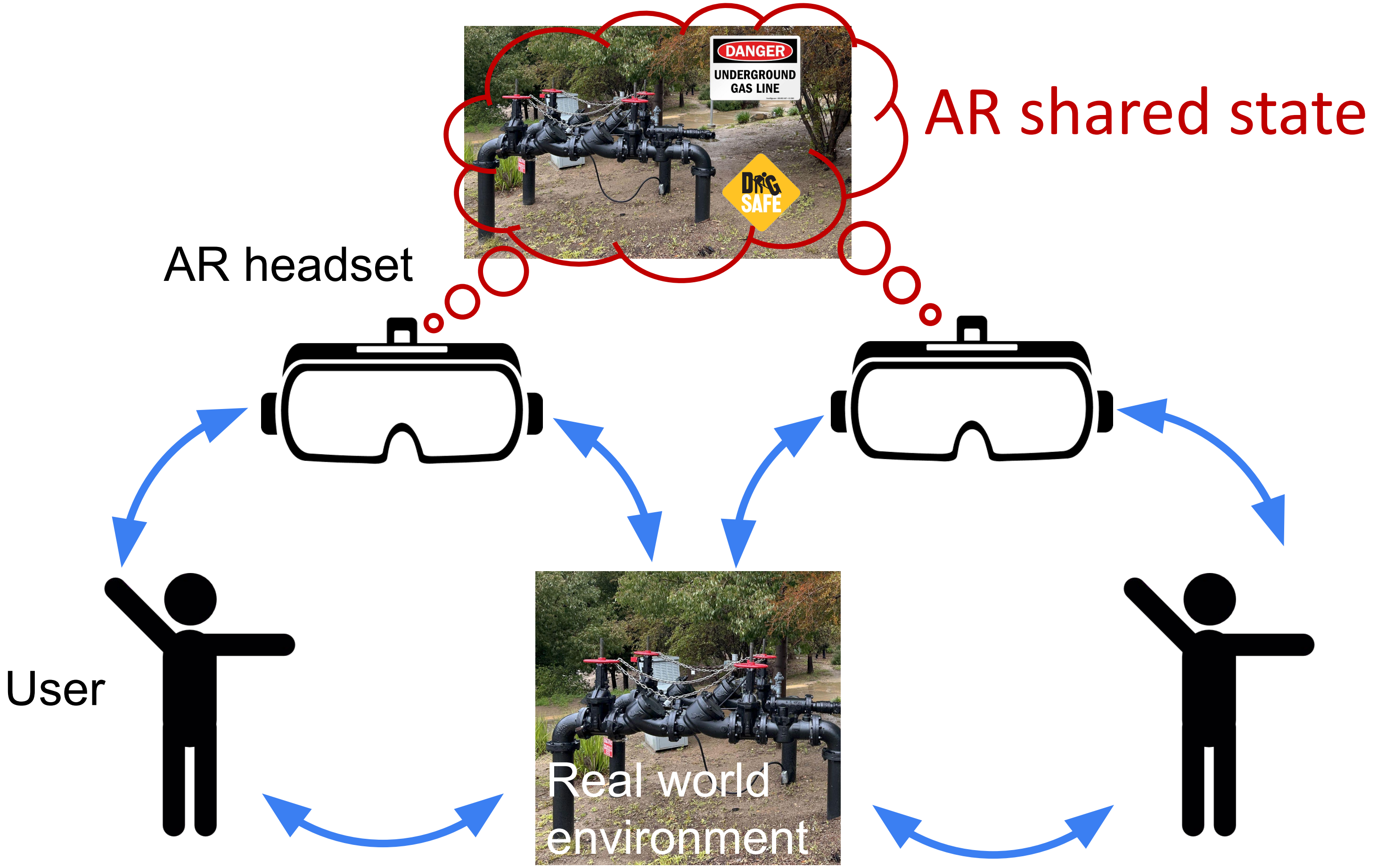
ARCore Geospatial API Challenge

Apple ARKit

What new security risks arise for multi-user AR?

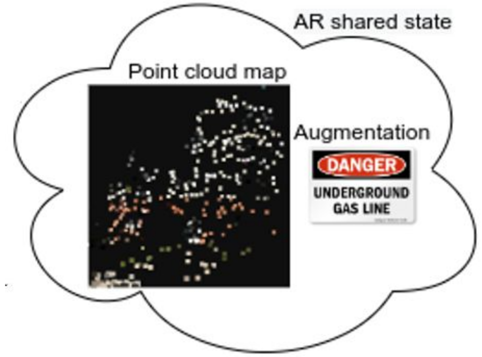
- AR devices sense the real world to create a shared AR experience

→ This exposes new attack surfaces!



Outline

- Background: “Shared State” in Augmented Reality.



- Threat Model.

- Three Scenarios of Attacks.

- Mitigation.

Background on multi-user AR

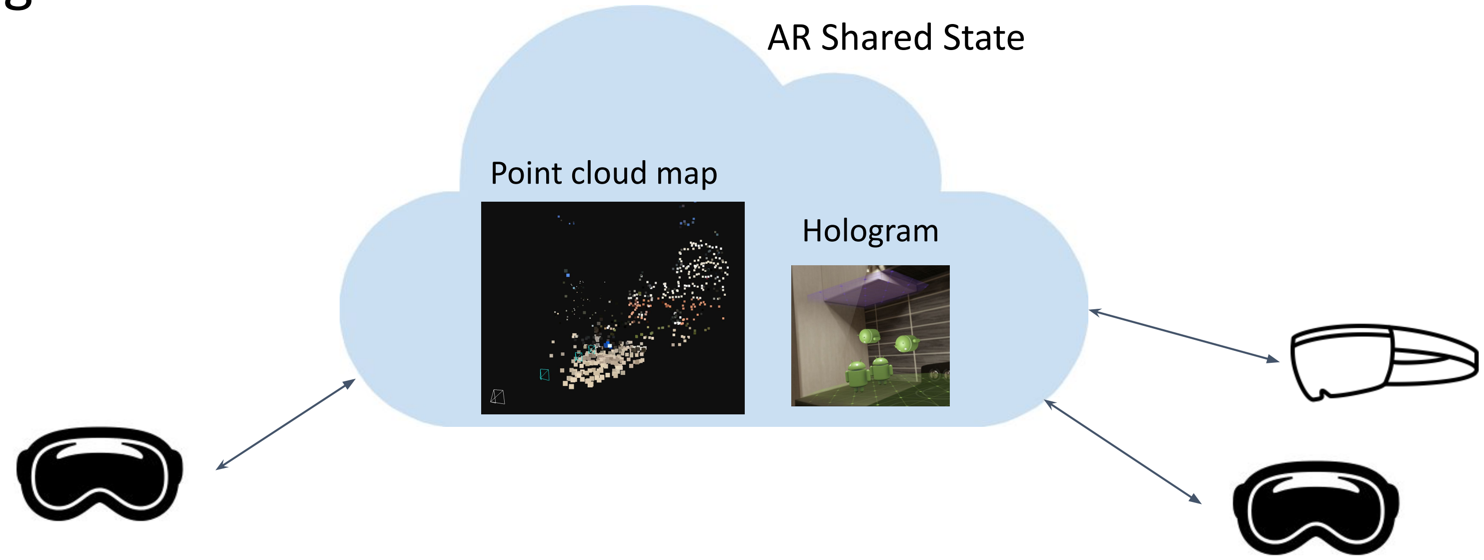
- AR devices read/write to a shared state in order to view holograms

What if an attacker poisons the shared state?

Source: https://developers.google.com/ar/develop/cloud-anchors

What is “Shared State” in augmented reality?

- Shared State: A collective set of information necessary for enabling interactive and consistent experiences among multiple users.
- Shared State contains:
  - Visual feature map of real world (point cloud map).
  - Holograms.



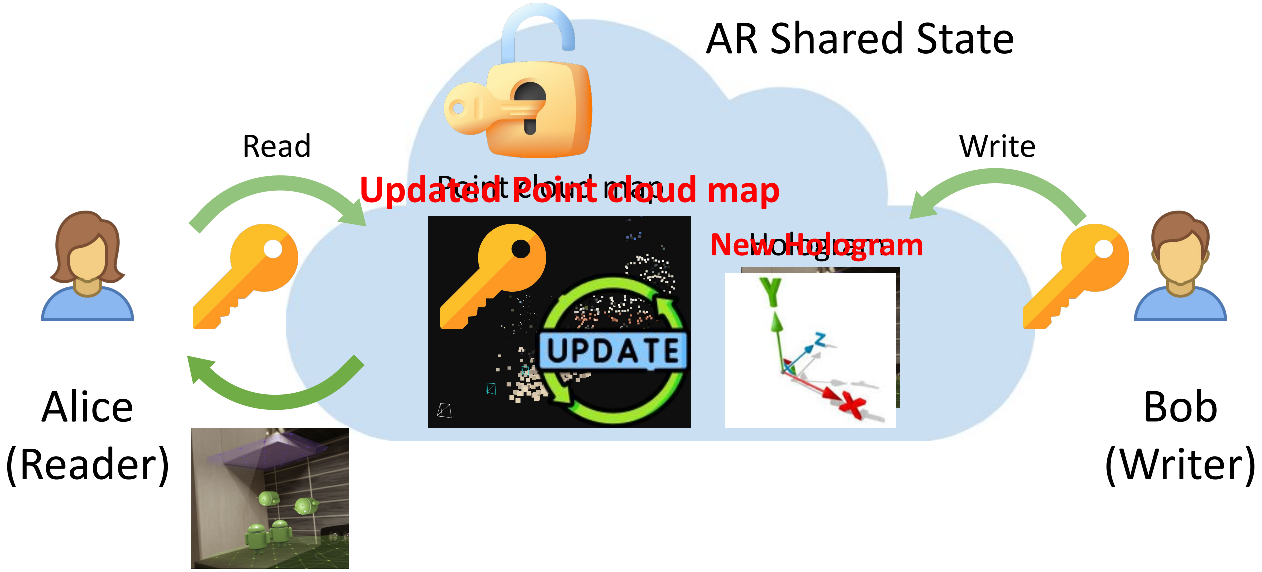
AR Shared State

Point cloud map

Hologram

How do clients communicate with the Shared State?

- Read and write operations
  - Key = real-world environment (point cloud, IMU, GPS)
  - Value = hologram
- Examples
  - Google ARCore: `hostCloudAnchor`, `resolveCloudAnchor`



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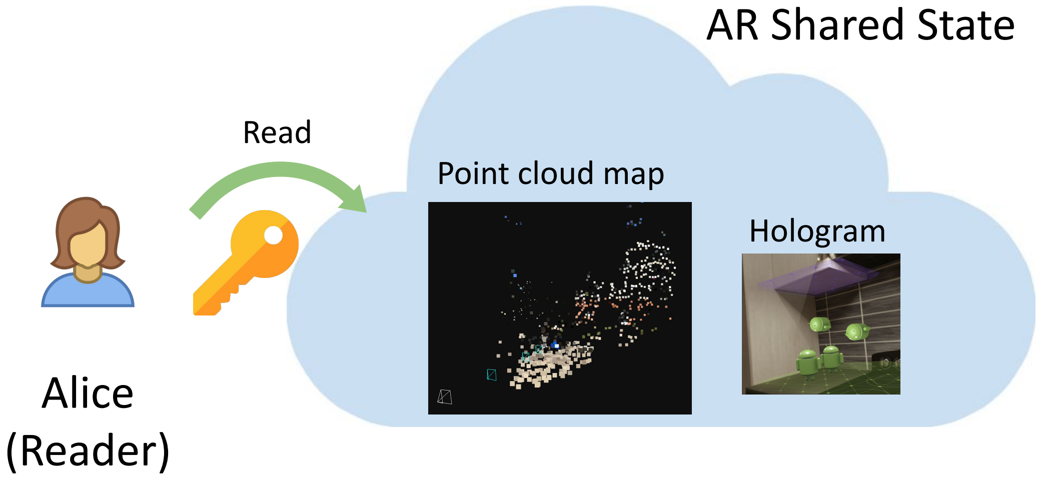

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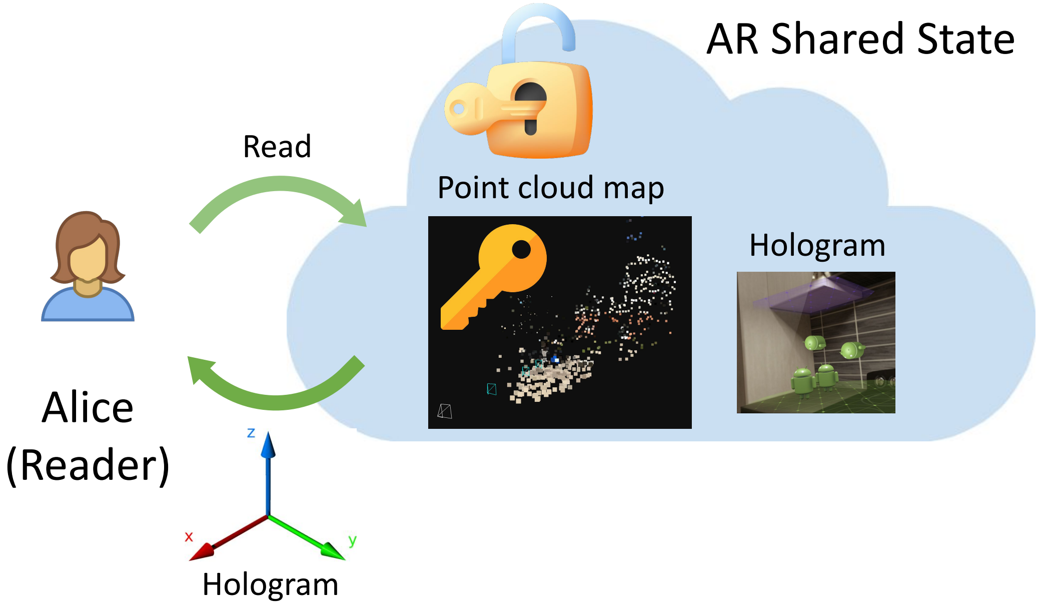

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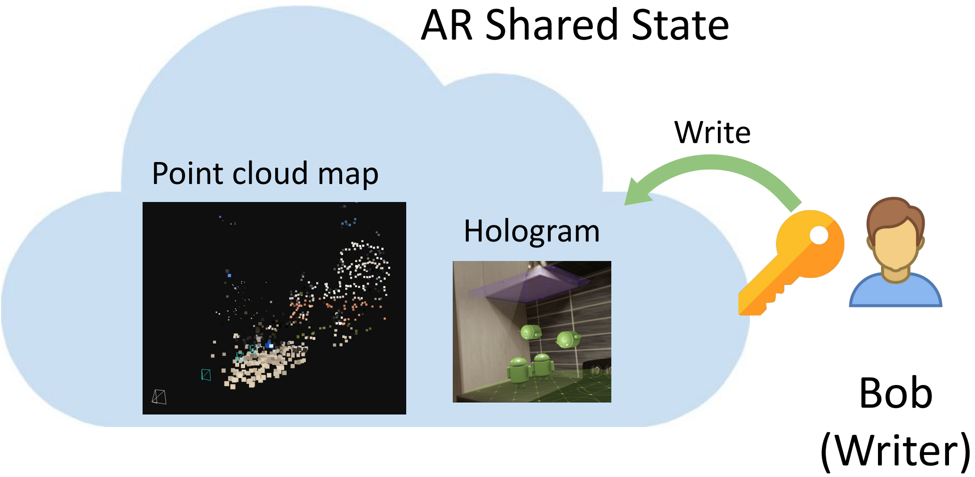

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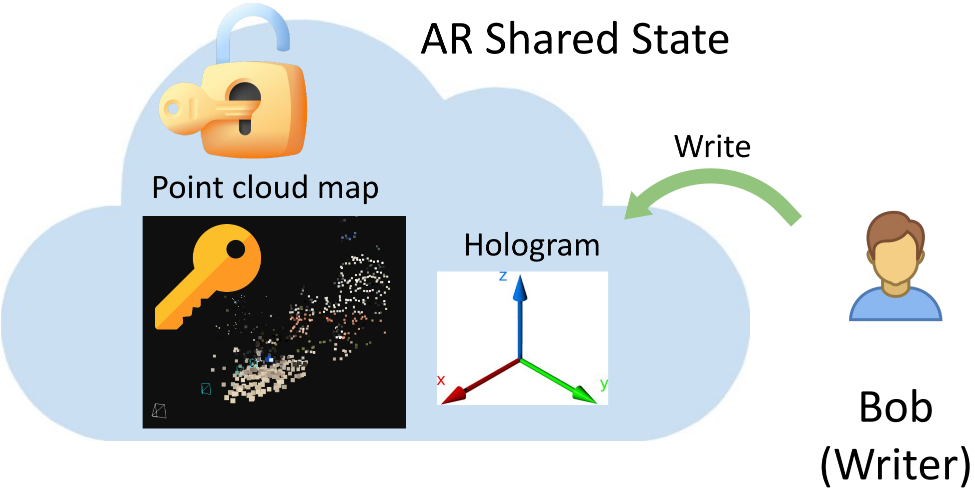

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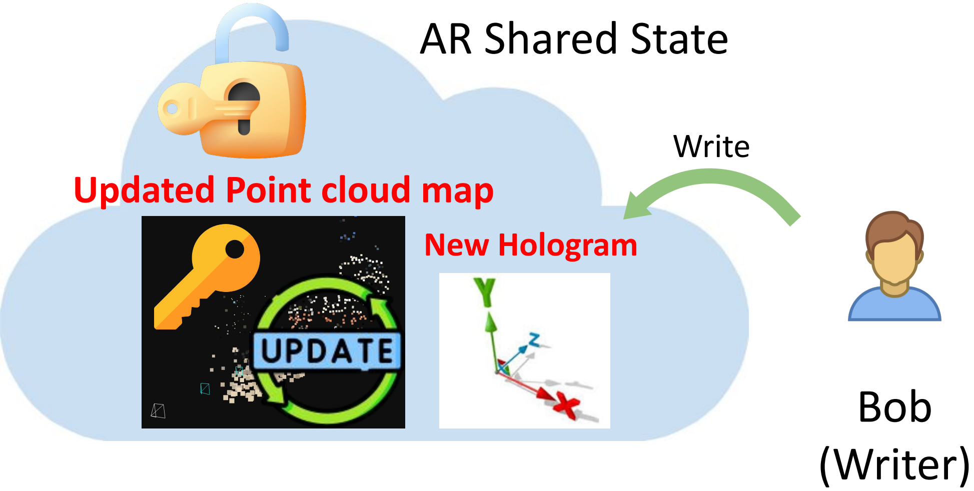
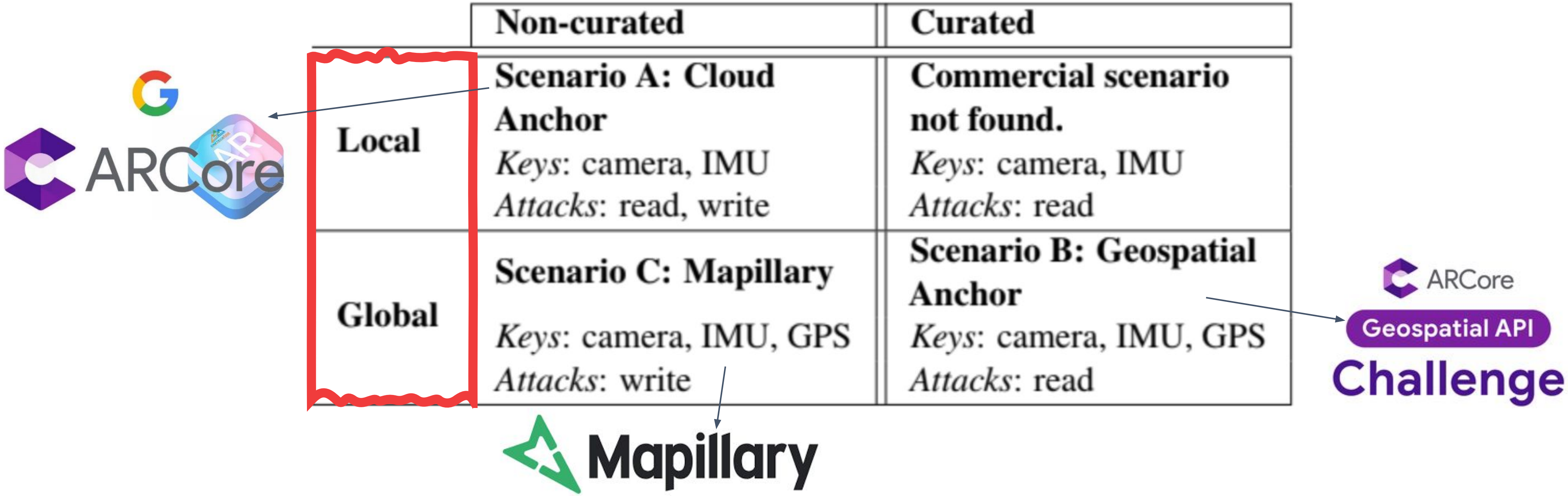


AR Shared State Taxonomy

- We examined commercial multi-user AR frameworks
- Propose the following taxonomy
  - Local: small local areas (e.g., indoor room)
  - Global: outdoor, world-scale (e.g., Pokemon Go)

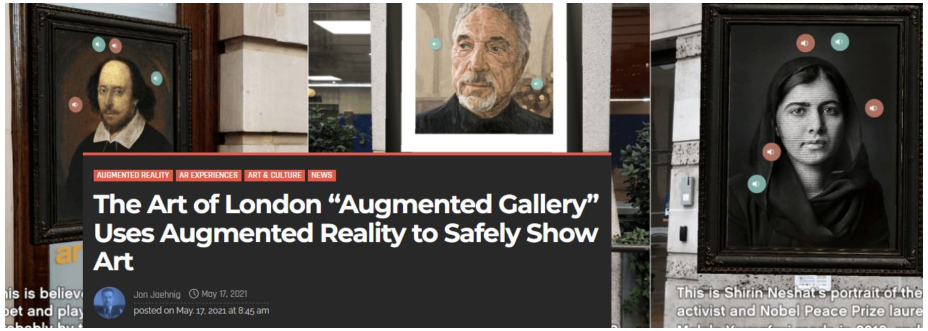


	Non-curated	Curated
Local	**Scenario A: Cloud Anchor** *Keys*: camera, IMU *Attacks*: read, write	**Commercial scenario not found.** *Keys*: camera, IMU *Attacks*: read
Global	**Scenario C: Mapillary** *Keys*: camera, IMU, GPS *Attacks*: write	**Scenario B: Geospatial Anchor** *Keys*: camera, IMU, GPS *Attacks*: read

ARCore
Mapillary
ARCore
Geospatial API
Challenge

AR Shared State Taxonomy

- Curated Shared State.
  - Curated maps are constructed by "curators".
  - <u>Only</u> curator can write in shared state.
  - But non-curator can read from shared state.



AUGMENTED REALITY AR EXPERIENCES ART & CULTURE NEWS

The Art of London "Augmented Gallery" Uses Augmented Reality to Safely Show Art

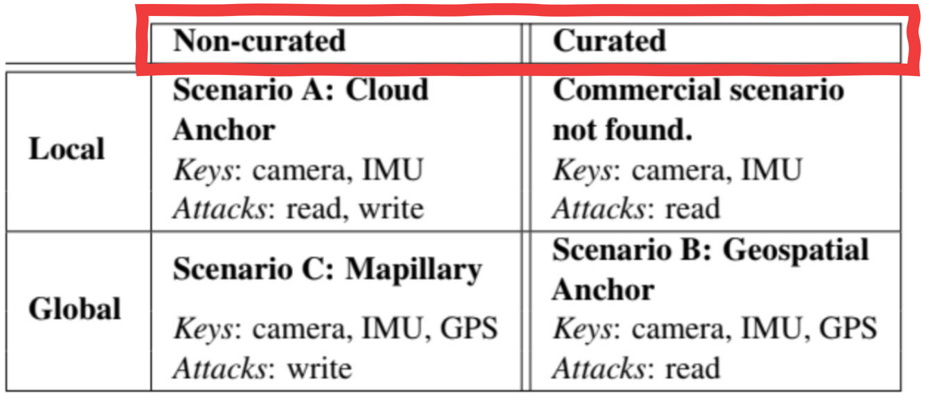
Jon Jaehnig May 17, 2021

posted on May 17, 2021 at 8:45 am

This is Shirin Neshat's portrait of the
activist and Nobel Peace Prize laure

Example of curated AR Shared State: Augmented art gallery

- Non-curated Shared State.
  - All users are allowed to Read and Write in shared state.



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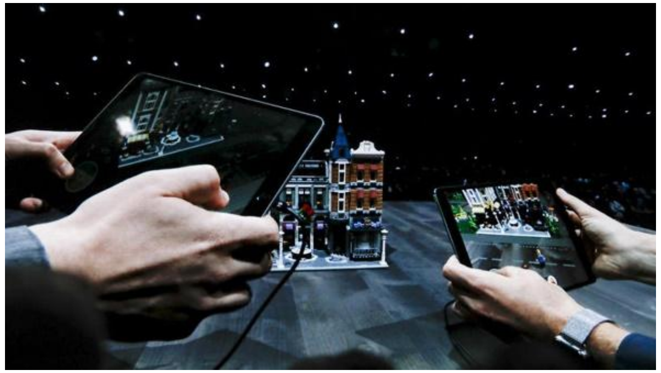
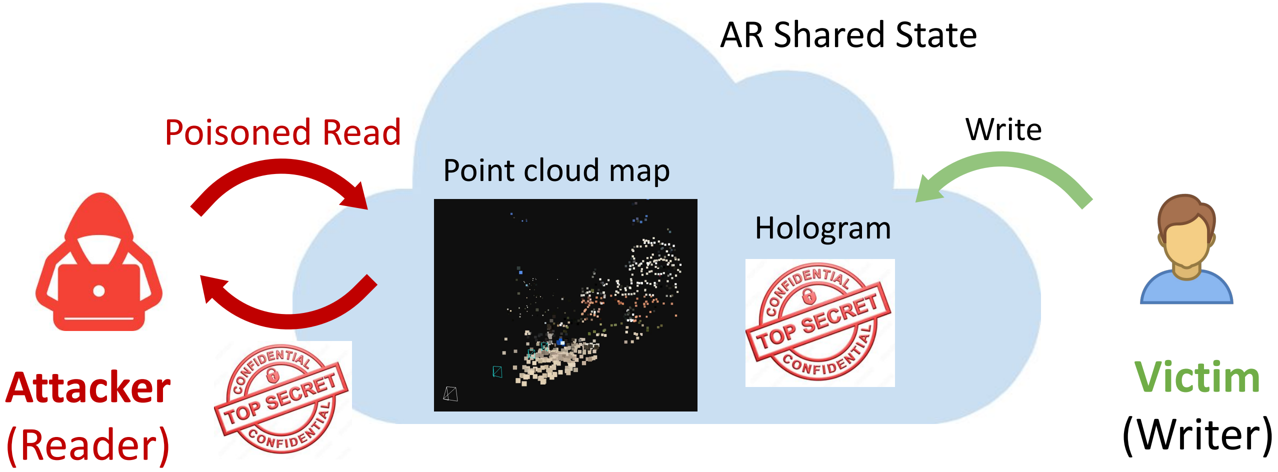


Example of non-curated AR Shared State: On-the-fly game

Threat model: Read attack

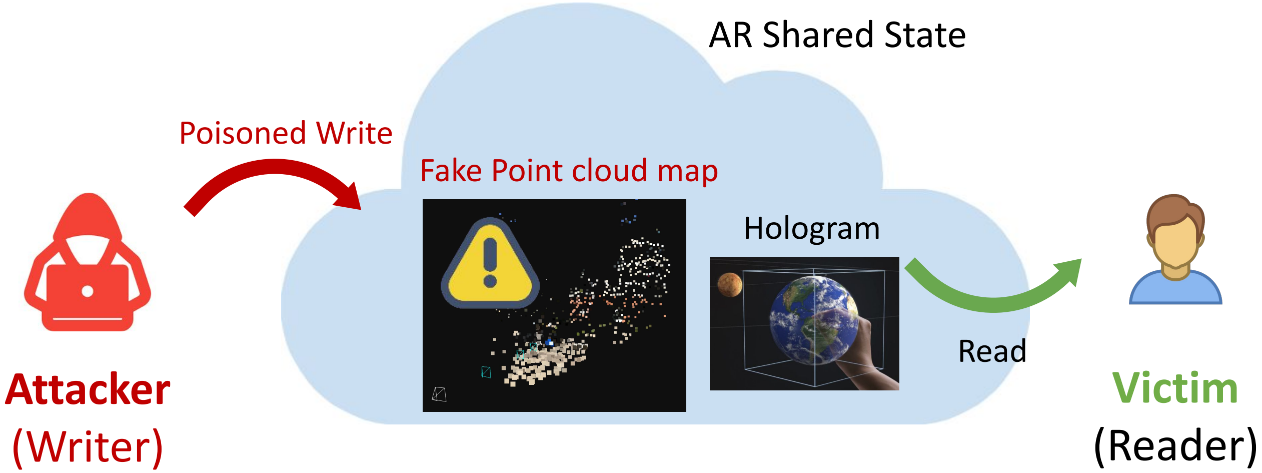
- An attacker participates in a multi-user AR application
  - Uses an unmodified AR application to access shared state
  - As a regular user, no special permissions
- Read attack:



Attacker extracts sensitive information stored within the shared state created by victim.

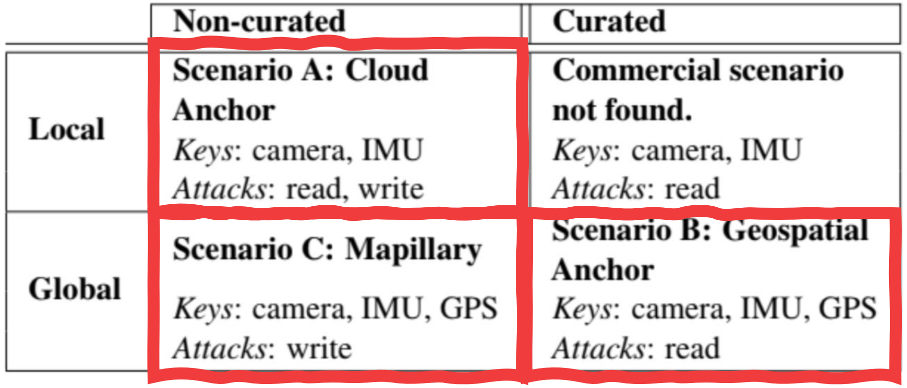
Threat model: Write attack

- Same threat model as Read attack
- Write attack:



Attacker manipulates shared state to deceive subsequent victim user!

Three Attack Scenarios



	Non-curated	Curated
Local	**Scenario A: Cloud Anchor** *Keys*: camera, IMU *Attacks*: read, write	**Commercial scenario not found.** *Keys*: camera, IMU *Attacks*: read
Global	**Scenario C: Mapillary** *Keys*: camera, IMU, GPS *Attacks*: write	**Scenario B: Geospatial Anchor** *Keys*: camera, IMU, GPS *Attacks*: read

- Scenario A: Local, Non-Curated Shared State.
  - Platform: Google’s Cloud Anchor API.
  - Attacker can read or write.

ARCore

- Scenario B: Global, Curated Shared State.
  - Platform: Google’s Geospatial API.
  - Attacker can only read.

ARCore

Geospatial API

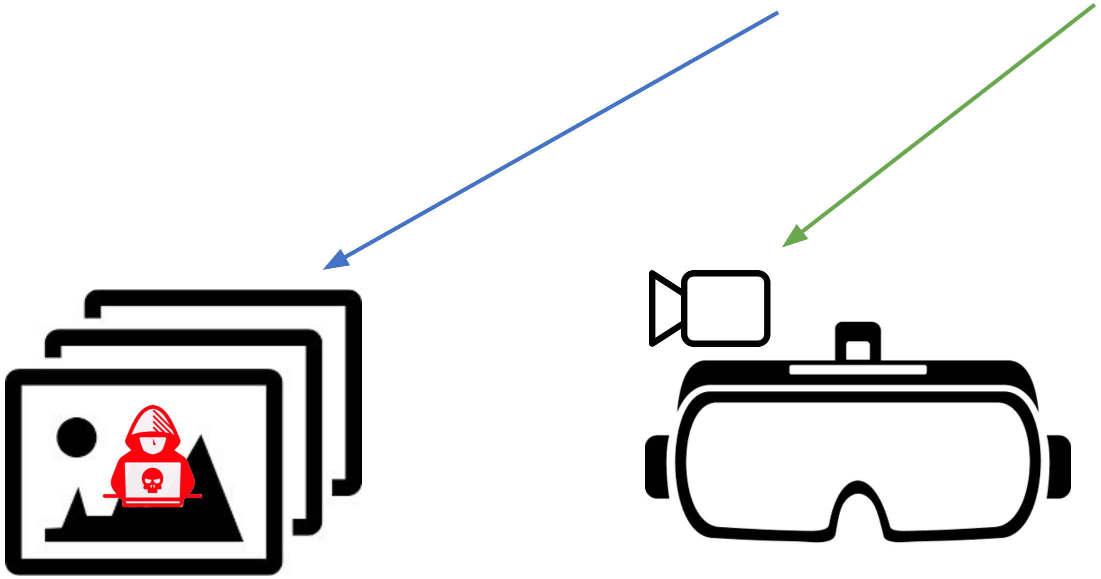
Challenge

- Scenario C: Global, Non-Curated Shared State .
  - Platform: Mapillary.
  - Attacker can read or write.

Mapillary

Scenario A: Remote read attack

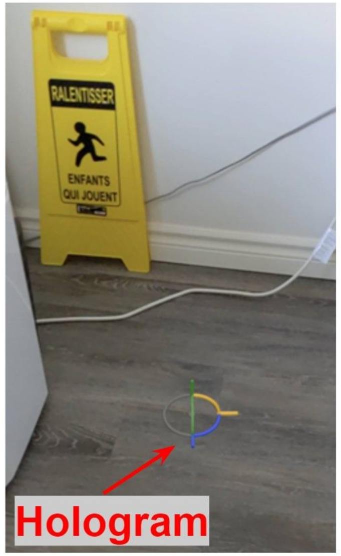
1. Attacker has control of own device
2. Show inputs to camera



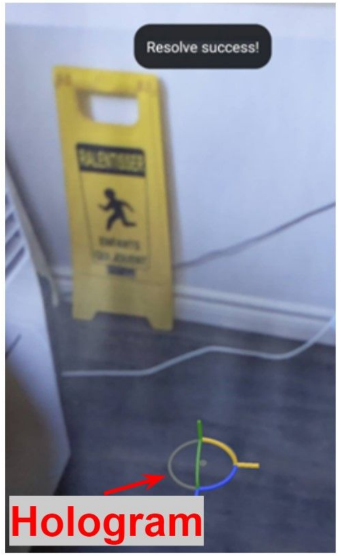
View hologram at physical location 🙂

Scenario A: Remote read attack

- Remote Read Attack: an attacker *Read* a hologram from a remote location.
- Attacker deceive Cloud Anchor API by fake camera/IMU input.



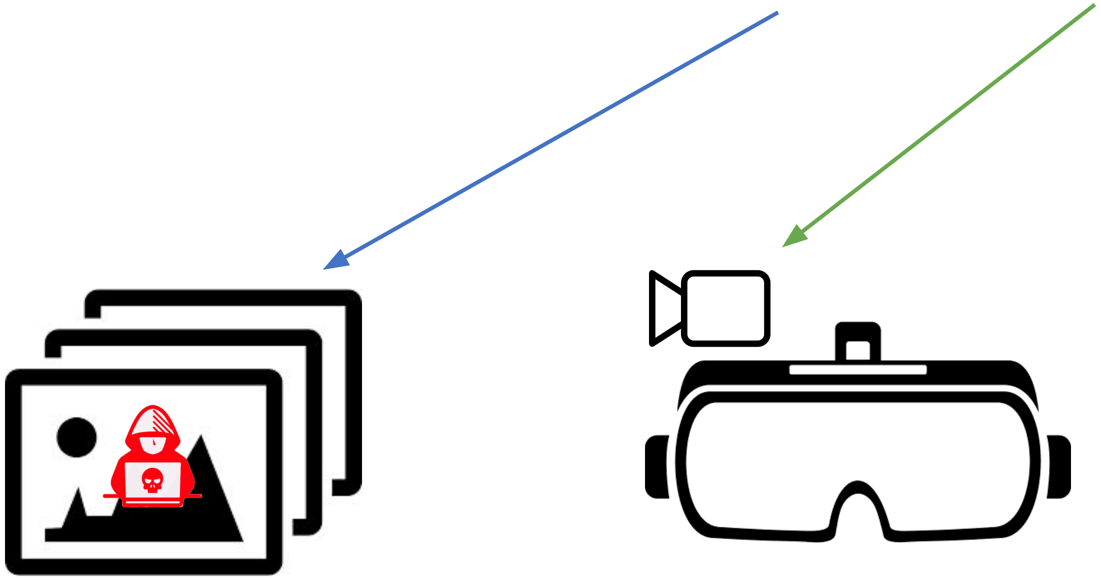
Write hologram at physical location 🙂

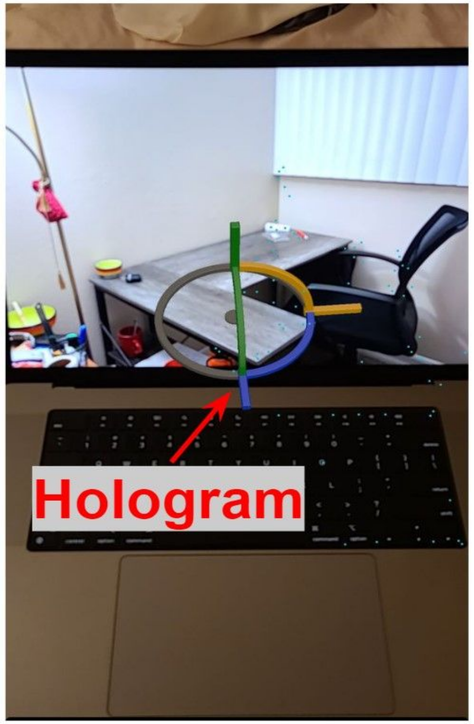


Read hologram at remote location 😈

Scenario A: Remote write attack

1. Attacker has control of own device
2. Show inputs to camera

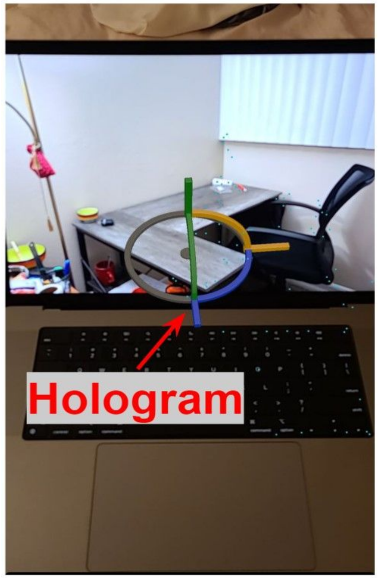




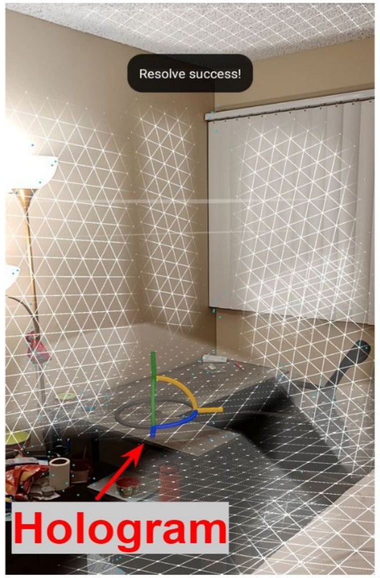
Write hologram at remote location

Scenario A: Remote write attack

- Attacker writes AR holograms in places where she is not authorized to access or contribute to
- Attacker deceives Google’s Cloud Anchor API
  - Fake camera: photograph of location



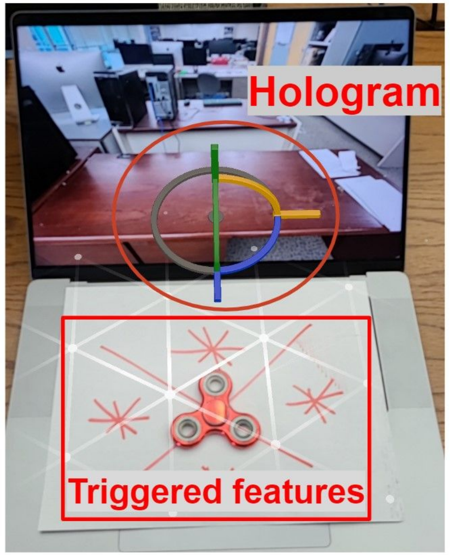
Write hologram at remote location 🦹



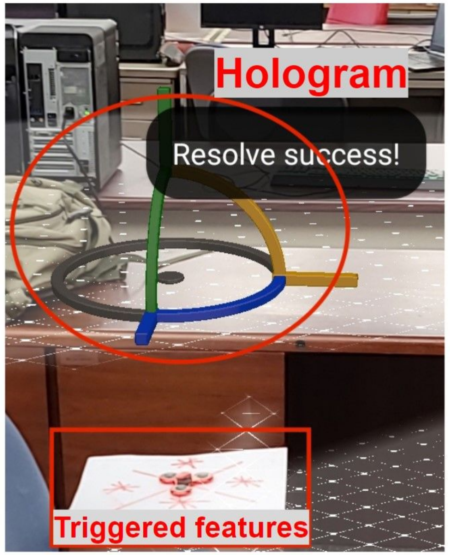
Read hologram at physical location 🙄

Scenario A: Local, Non-Curated Shared State

- Triggered Remote Write Attack:
  - Advanced Remote Write Attack.
  - Attacker can manipulate the victim's environment with pre-determined triggered features.



Write hologram at remote location with **triggered** features



Read hologram at physical location with **triggered** features

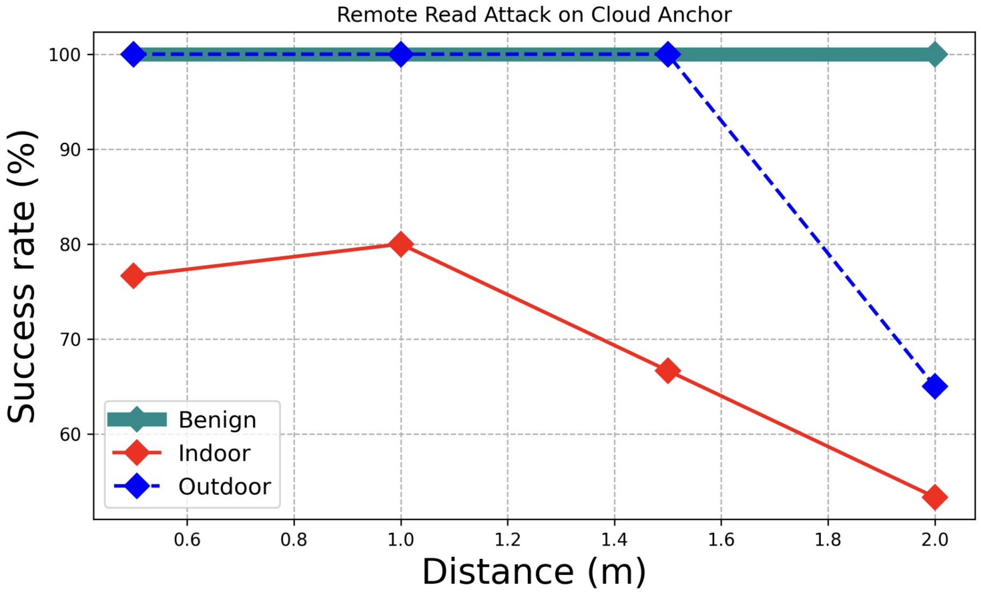
Scenario A: Evaluation

- Six different environments.

- Samsung Galaxy S20 Android phone with Google ARCore support.
- Good and robust success rate among three attacks.

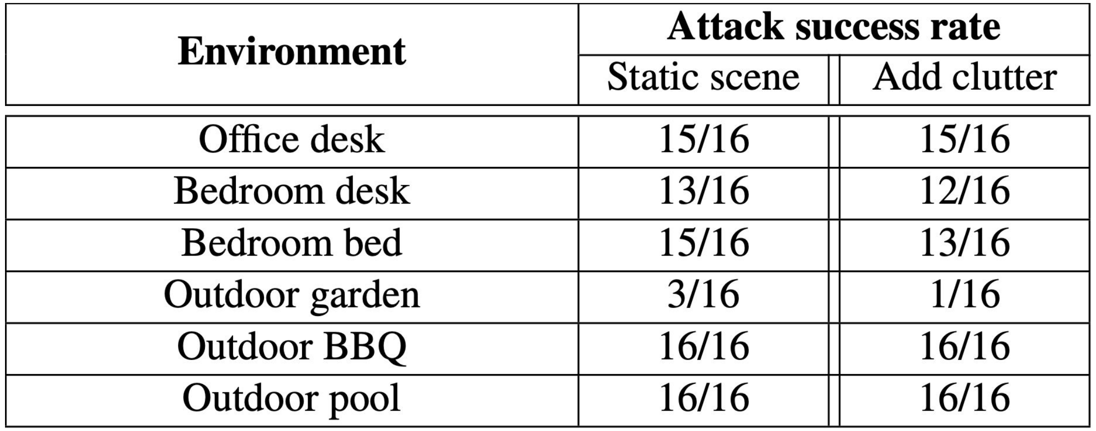
Environment	Attack success rate	
	Static scene	Add clutter
Office desk	8/16	7/16
Bedroom desk	6/16	4/16
Bedroom bed	10/16	8/16
Outdoor garden	1/16	0/16
Outdoor BBQ	16/16	15/16
Outdoor pool	15/16	14/16

Remote Write Attack Success Rates



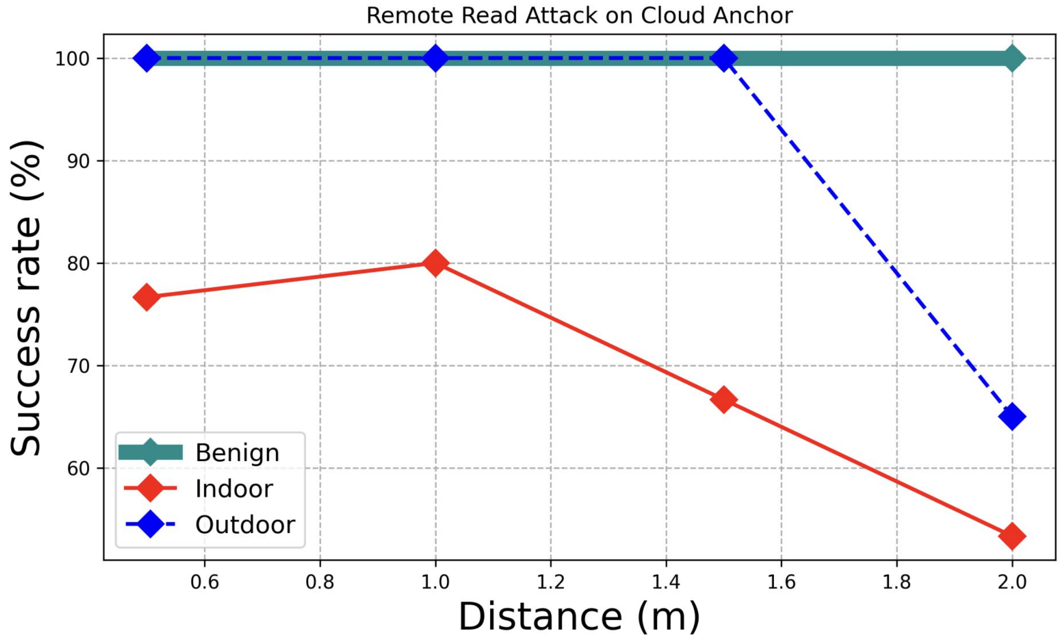
Effect of Distance on Remote Read Attack

Scenario A: Evaluation



Environment	Attack success rate	
	Static scene	Add clutter
Office desk	15/16	15/16
Bedroom desk	13/16	12/16
Bedroom bed	15/16	13/16
Outdoor garden	3/16	1/16
Outdoor BBQ	16/16	16/16
Outdoor pool	16/16	16/16

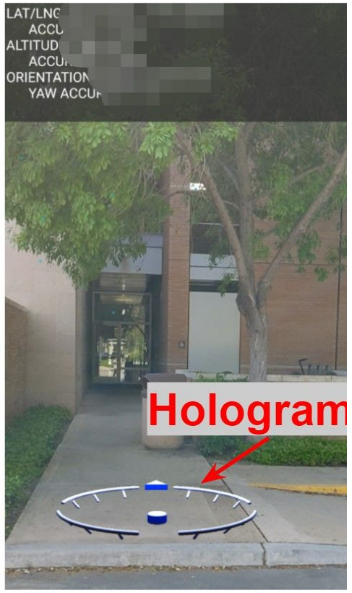
Triggered Remote Write Attack



Distance Effect on Remote Read Attack

Scenario B: Remote read attack

- Attacker reads a hologram from a remote location.
- Attacker deceives Google's Geospatial API
  - Fake camera: photograph of location
  - Fake GPS: GPS spoofing app

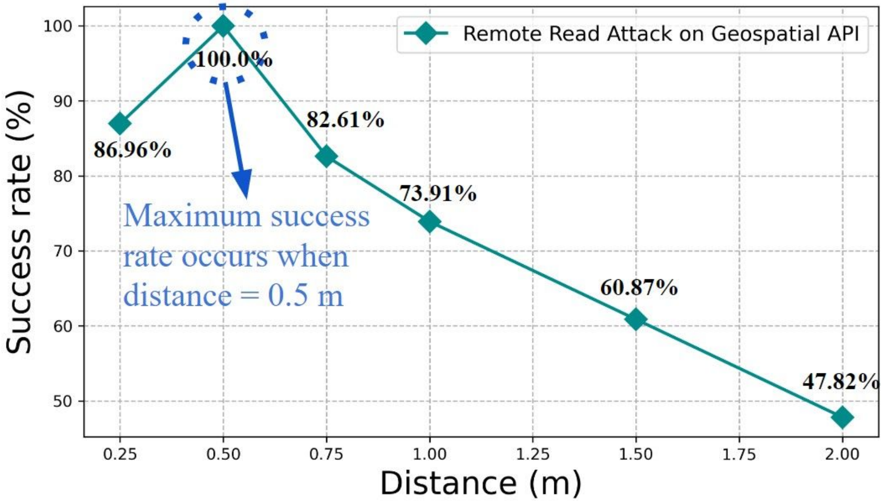


LAT/LNG
ACCU
ALTITUD
ACCU
ORIENTATION
YAW ACCU
[redacted]

Write hologram at physical location 🙂

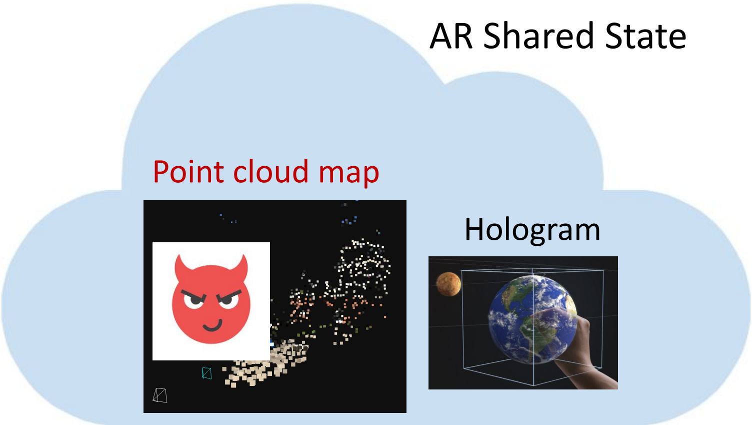
Scenario B: Evaluation

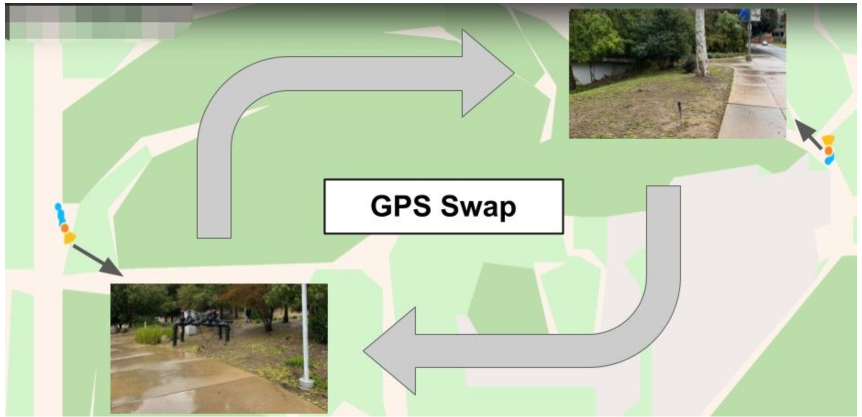
- 23 holograms at various locations within our campus.
- Samsung Galaxy S8 and the Samsung Galaxy S21 with Google Geospatial API support.
- Good and robust success rate through all locations.



Scenario C: Poisoned write

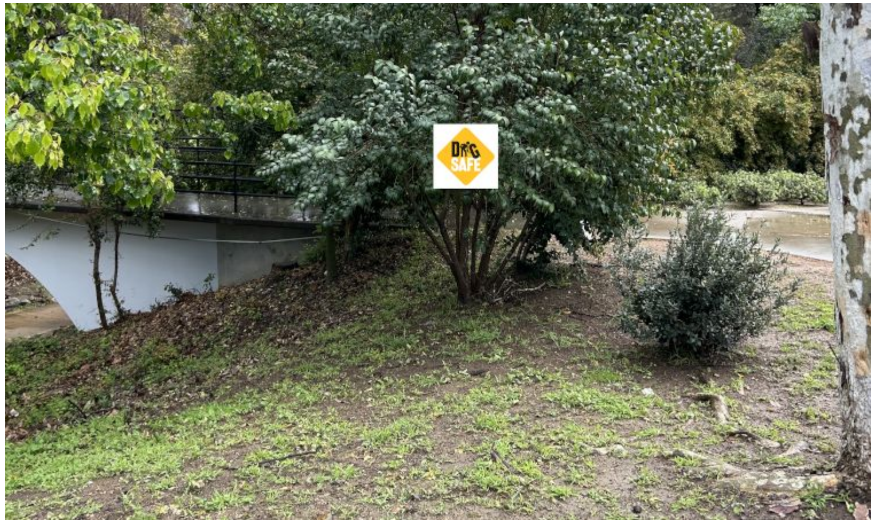
- Poisoned write to the <u>Shared State's point cloud map</u>
- Attacker deceives point cloud generation algorithms
  - Fake GPS: Swap GPS coordinates of two images sequences by editing image metadata
- Experiments done in a Mapillary sandbox with permission
  - No public users were affected

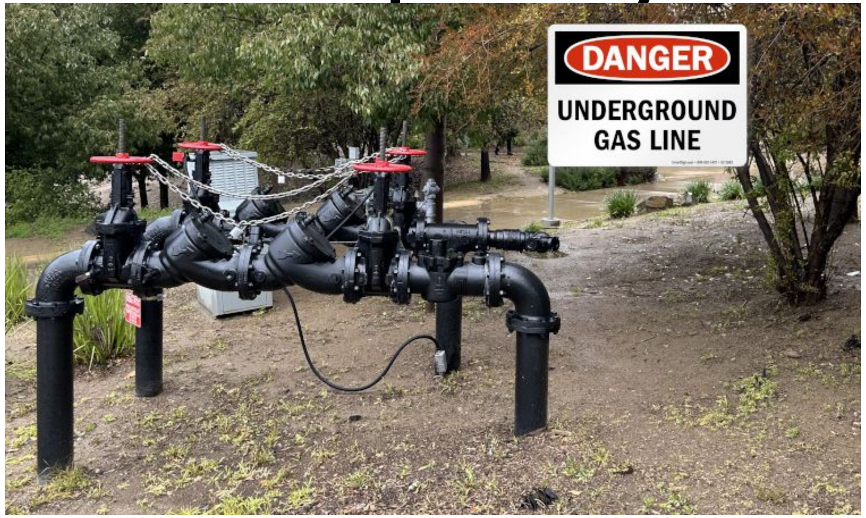




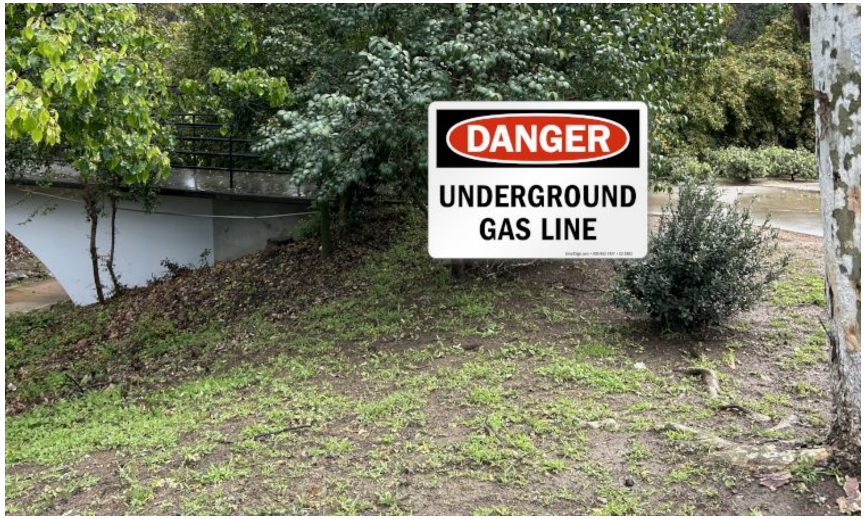
Attack 2 Preview: Example on Mapillary

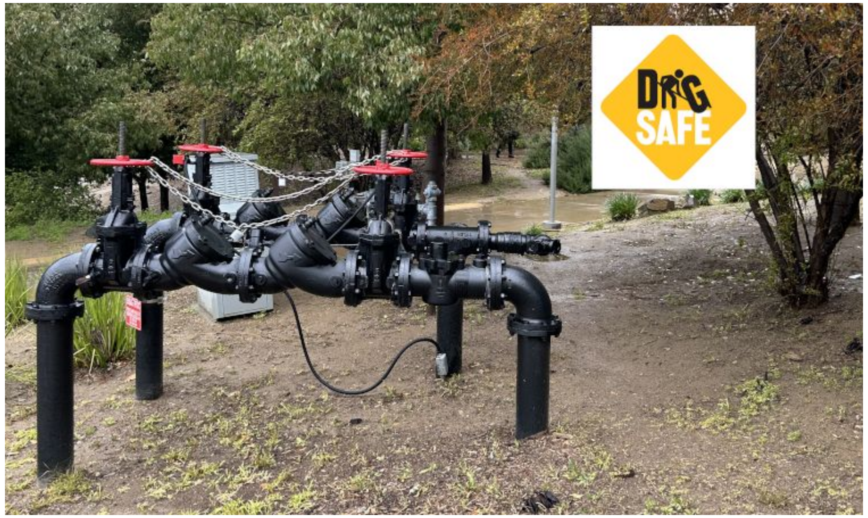
No attack:
Desired
annotations





With attack:
Annotations
swapped

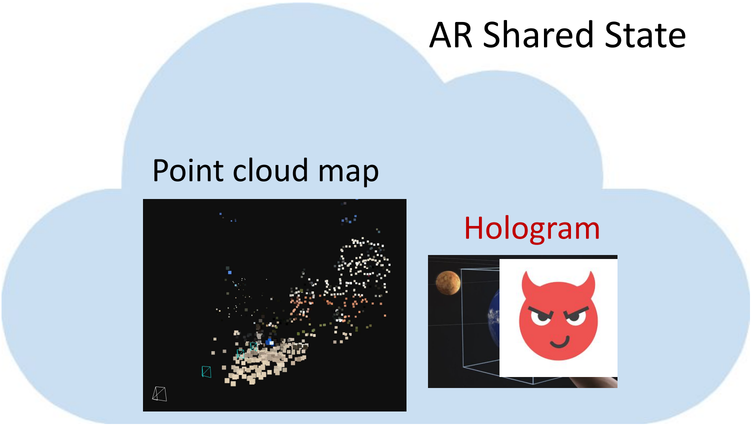




Dangerous scenario!

Scenario C: Global, Crowd-Sourced Shared

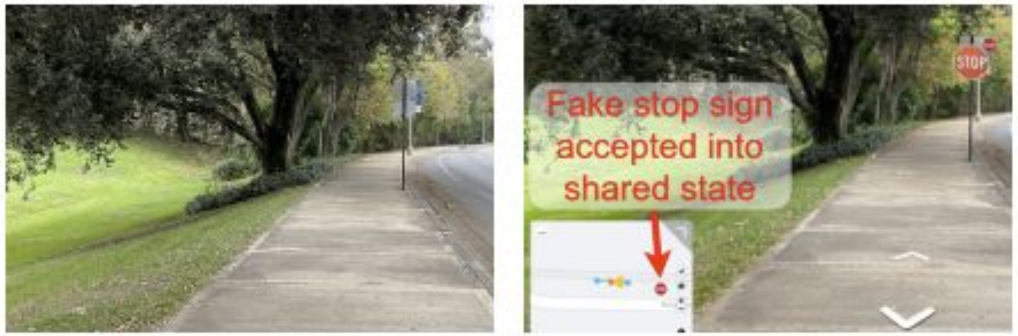
- Poisoned Write of Shared Holograms.
- Attacker deceive point cloud generation algorithms by uploading manipulated camera input to modify the holograms.



AR Shared State

Point cloud map

Hologram



(a) Real world ground truth. (b) Tampered image.

Mitigation Using Multi-Modal Sensors

- How to detect fake camera inputs?
- Idea: Use additional sensor modalities
  - AR devices equipped with depth sensor, Lidar, etc.
- How did we evaluate this defense?

CNN: ResNet-18 network to detect spoofed images

Dataset: 15 real scenes, 300 pairs of color and depth image of each scene

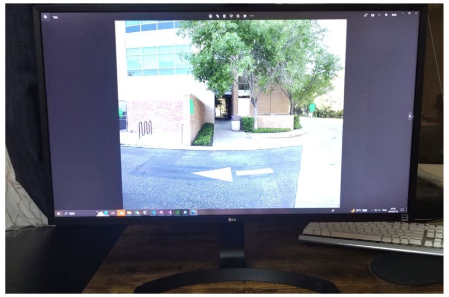
Same process to collect images in front of monitor showing spoofed image

Training: 12 scene for training; 3 scenes for test

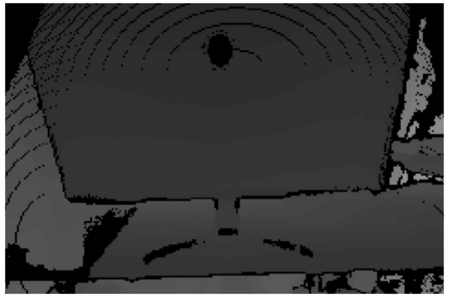
Precision: 84.22%

- Other potential mitigations
  - Clean-Slate System Design
  - Real Space Security
  - Local Moderators

RGB camera of spoofed image



Depth camera of spoofed image



Mitigation

- Clean-Slate System Design.

- Real Space Security.

- Local Moderators.

Summary

Paper

AR devices sense information about a common reality

Info shared across apps and systems

Attack opportunities!

Demo defense

- Multi-user application attacks on shared world state (**First**)
  - Read/write holograms despite not being physically present
  - Demonstrated on 3 commercial AR frameworks
- Easy mitigation strategies (e.g., multi-modal sensing) are effective
  - But require additional sensors and compute

Thank you! Questions?

Paper

Demo defense

Thank you!

Any questions?

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https://sites.google.com/view/multi-ar-defense/

Conclusion

- Common vulnerabilities regarding Read and Write operations in commercial, publicly AR frameworks with shared state.
- A unified threat model that covers these current and prospective AR applications.
- AR-specific attacks on shared state in three AR frameworks, using real AR devices in the real world (**First**).
- Detailed mitigation against attacks.