Regulating Smart Devices in Restricted Spaces

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My group’s research

Computer Security and Software Engineering

• **Cloud platform security:**
  - “How can I entrust the cloud with my code and data?”
  - “Can I manage the security of my code and data?”

• **Web browsers and apps:**
  - “How do I ensure the privacy of my browsing activity?”
  - “Can I trust the new browser app I just downloaded?”

• **Smart devices and apps:**
  - “How do I know that my phone is secure?”
  - “How do I create apps that work across diverse platforms like the iPhone, Android, Windows, etc.”
Devices are everywhere!
Number of devices is increasing

- Predicted 1.2 billion new smart phones by 2018
- Predicted 50% device use increase year over year in enterprise sector until 2018 [Gartner 2014]
## Devices are increasingly capable

<table>
<thead>
<tr>
<th>Model</th>
<th>CPU (GHz)</th>
<th>Screen (1000x)</th>
<th>Rear camera</th>
<th>Front camera</th>
<th>Battery (mAh)</th>
<th>Sensors other than Camera/Microphone</th>
</tr>
</thead>
<tbody>
<tr>
<td>iPhone</td>
<td>0.4</td>
<td>153</td>
<td>2MP</td>
<td>-</td>
<td>1,400</td>
<td>3 (light, accelerometer, proximity)</td>
</tr>
<tr>
<td>iPhone3</td>
<td>0.6</td>
<td>153</td>
<td>3MP</td>
<td>-</td>
<td>1,150</td>
<td>4 (+= compass)</td>
</tr>
<tr>
<td>iPhone4</td>
<td>0.8</td>
<td>614</td>
<td>5MP</td>
<td>0.3MP</td>
<td>1,420</td>
<td>6 (+= gyroscope, infrared)</td>
</tr>
<tr>
<td>iPhone5</td>
<td>1.3 (2 core)</td>
<td>727</td>
<td>8MP</td>
<td>1.2MP</td>
<td>1,560</td>
<td>7 (+=fingerprint)</td>
</tr>
<tr>
<td>iPhone6</td>
<td>2.0 (2 core)</td>
<td>1000</td>
<td>12MP</td>
<td>5.0MP</td>
<td>1,715</td>
<td>8 (+= barometer)</td>
</tr>
</tbody>
</table>
And we are hungry for more
With great power …

… comes great responsibility
How can devices be misused?

1. **Malicious end-users** can leverage sensors to exfiltrate or infiltrate unauthorized data.

2. **Malicious apps** on devices can achieve similar goals even if end-user is benign.
Government or corporate office

• **Problem**: Sensitive documents and meetings can be ex-filtrated using the camera, microphone and storage media

• **Current solution**: Physical security scans, device isolation

Faraday cages
Challenge: Bring your own device

Growing BYOD Trends

2013:
- SMBs supporting BYOD will increase by 14%
  - 2012 - 59%
  - 2013 - 73%

2014:
- Number of connected devices: 3.3/employee

Gartner predicts 90% of companies will allow BYOD

Employee tablet use will see a year-to-year increase of 50%

1.2 billion smartphones will enter the market in the next 5 years
Classroom and exam setting
Classroom and exam setting

• **Problem**: Personal devices can be used to infiltrate unauthorized information

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[NY Times July 2012]
At Top School, Cheating Voids 70 Pupils’ Tests

Seventy students were involved in a pattern of smartphone-enabled cheating last month at Stuyvesant High School, New York City officials said Monday, describing an episode that has blighted one of the country’s most prestigious public schools.

[Financial Crypto 2014]
Outsmarting Proctors with Smartwatches: A Case Study on Wearable Computing Security

Alex Migicovsky, Zakir Durumeric, Jeff Ringenberg, and J. Alex Halderman

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Scanners catch JEE cheats

ROVING BUREAU

Roving invigilators armed with signal scanners to detect mobile data and call traffic inside examination halls caught five JEE candidates using a smartphone or a smartwatch to cheat on the first day of the test.
Classroom and exam setting

• **Current solution**: Deterrence via rules and threats. Invigilation to ensure compliance

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**NO MOBILE PHONES, iPods, MP3/4 PLAYERS.**

**NO PRODUCTS WITH AN ELECTRONIC COMMUNICATION/STORAGE DEVICE OR DIGITAL FACILITY.**

Possession of unauthorised items is an infringement of the regulations and could result in **DISQUALIFICATION** from the current examination and the overall qualification. Candidates are advised that mobile phones in particular must not be in their possession whether switched on or not.

This poster must be displayed in a prominent place both inside and outside each examination room.
Challenge: Assistive devices

- Students may wish to use devices for legitimate reasons:
  - Smart glass or contacts for vision correction
  - Bluetooth-enabled hearing aids
  - Smart watches to monitor time
Other social settings

• Restaurants, conferences, gym locker rooms, private homes, ...

• **Problems:**
  – Recording private conversations
  – Pictures of individuals taken and posted to social networks without their consent
  – Pictures and videos of otherwise private locations, e.g., private homes
Other social settings

• **Current solutions**: Informal enforcement

• **Challenge**: Social isolation 😊

“For the first time ever this place, Feast, in NYC just asked that I remove Google Glass because customers have complained of privacy concerns […] I left”

![Notice sign]

“NOTICE
No wearable cameras permitted in locker room.”
**Malicious apps exploiting sensors**

**Sensory malware**

Early example of sensory malware [CCS 2011]

- Use accelerometer and record keystroke press vibrations
- Up to 80% accuracy in word recovery

Figure 1: Our experimental placement of a mobile phone running a malicious application attempting to recover text entered using the nearby keyboard.
Malicious apps exploiting sensors

Sensory malware

• Attacks have now been demonstrated using every imaginable sensor
• Attack accuracy will *improve* with each generation of devices and sensors
Claim
Smart devices will become integrated with daily lives $\rightarrow$ \textit{Ad hoc} solutions, e.g., banning device use, will no longer be acceptable

Vision
Need systematic methods to regulate devices and ensure responsible use

\textbf{Discussion}: Only considering \textit{overt} device use. Covert use detection still requires traditional physical security measures.
What solutions exist today?

Mobile device management (MDM) solutions

Samsung KNOX Workspace provides advance security and usability features. Our MDM partners support many KNOX features and offer comprehensive policy levels. Select the MDMs of your choice and click **Show features** to find the MDM solution that matches your enterprise's needs.
Mobile device management

• Solution for enterprises that offer Bring your own device (BYOD) models
• Employees are given a mobile device outfitted with a secure software stack
• Enterprise policies “pushed” to device when employee changes device persona
Mobile device management

Main shortcoming of current MDM solutions

- Enterprise must trust software stack on guest device to enforce policies correctly
- But guest devices under control of possibly malicious end-users

• Solution for enterprises that offer *Bring your own device* (BYOD) models

• Employees are given a mobile device outfitted with a secure software stack

• Enterprise policies “pushed” to device when employee changes device persona
Contributions of our work

• **Restricted space**: Location owned by a **host**, where **guest devices** must follow the host’s usage policies

• Enable guest devices to **prove** policy compliance to restricted space hosts

• Use a simple, low-level API that **reduces size of trusted computing base** on guest devices
Key technical challenges

1. Guest devices are under the control of possibly malicious end-user
   - **Solution**: Use trusted hardware on guest device

2. What constitutes proof of compliance?
   - **Solution**: Send guest device configuration, showing policy compliance, to host

3. Doesn’t that compromise guest device privacy?
   - **Solution**: Allow guest to vet all communication to and from the host
Threat model

• **Trusted hardware on guest devices:**
  – Guest devices equipped with ARM TrustZone

• **Hosts and guests are mutually-distrusting:**
  – Hosts do not trust end-user of guest device or its end-user software stack
  – Guests do not trust host’s *reconfiguration requests* to ensure policy compliance

• **Guest devices are used overtly:**
  – Host must still use traditional physical methods to detect covert device use
Guest device check-in

Public space

Restricted space
Guest device check-in

Public space

Restricted space
Mutual authentication

Host’s policy server

Mutual authentication

Restricted space
Host requests guest analysis

Host's policy server

Request device memory

Addr1, Addr2, Addr3, ...

Restricted space
Guest vets host’s request

Forward host’s request
Addr1, Addr2, Addr3, …

Guest’s vetting service

Host’s policy server

Request device memory
Addr1, Addr2, Addr3, …

Restricted space
Guest vets host’s request

- Guest’s vetting service
- Host’s policy server

Options:
- Guest’s vetting service
- Restricted space
Host analyzes guest device

Guest’s vetting service

Host’s policy server

Send device memory

Addr1, Addr2, Addr3, …

Restricted space
Host pushes policy to guest

Host’s policy server

Send memory updates

Restricted space

Guest’s vetting service
3 Guest vets host’s updates

Guest’s vetting service

Restricted space

Forward host’s requested updates

Send memory updates

Host’s policy server
3

Guest applies host’s updates

Guest’s vetting service

Host’s policy server

Apply memory updates

Restricted space
Host requests proof

Host’s policy server

Request proof of policy compliance

Restricted space

Guest’s vetting service

4
4

Guest sends proof

Guest’s vetting service

Host’s policy server

Verification token

Restricted space

Proof
Guest device check-out

Revert changes

Public space

Restricted space
Operational details

1. How can host trust guest to apply policy?
   ➢ **Answer**: Leverage ARM TrustZone

2. Why memory snapshots and updates?
   ➢ **Answer**: Powerful low-level API. Reduces TCB

3. How does vetting service ensure safety?
   ➢ **Answer**: Simple, conservative program analysis

4. Can’t guest device simply reboot to undo?
   ➢ **Answer**: REM-suspend protocol
The ARM TrustZone

Guest device

Normal world (Untrusted)

Secure world (Protected by H/W)

Normal-world memory

Secure-world memory

ARM TrustZone
Secure boot protects secure world

Normal world (Untrusted)

Secure world

Secure boot

Normal-world memory

Secure-world memory

ARM TrustZone
Secure world stores keys

Normal world (Untrusted)

Secure world

Secure boot

PubKeyG, PrivKeyG

Normal-world memory

Secure-world memory

ARM TrustZone
Memory is partitioned

Normal world (Untrusted)

Secure world

- Secure boot
- PubKeyG, PrivKeyG

Secure-world memory

Normal-world memory

ARM TrustZone
Memory is partitioned

Normal world (Untrusted)

Secure world

- Secure boot
- PubKeyG, PrivKeyG

Normal-world memory

Secure-world memory

ARM TrustZone
We enhance the secure world

Normal world (Untrusted)

Secure world (booted securely)

1. Authentication
2. NW analysis
3. NW updates
4. Verif. tokens

Normal-world memory

Secure-world memory

ARM TrustZone
Goal

Establish shared session key $k_s$ between host and guest
Establishing session key

Simplified TLS/SSL handshake

• Host’s keypair: PubKeyH, PrivKeyH
• Guest’s keypair: PubKeyG, PrivKeyG

1. Guest ↔ Host: Exchange/verify public keys
2. Host → Guest: $Enc_{PubKeyG}(k_s) + Signature_{PrivKeyH}$
3. Guest (secure world): Verify host signature, decrypt message and obtain $k_s$
Guest device analysis

- **Request device memory**
  - Addr1, Addr2, Addr3, …

- **Send device memory**
  - Addr1, Addr2, Addr3, …

- **Host’s policy server**
  - $k_s$

- **Restricted space**
  - $k_s$
SW reads NW memory

Normal world (Untrusted)

Secure world

Normal-world memory

Secure-world memory

ARM TrustZone

Notes
Utilities
iTunes
App Store
Settings
Grocery list
Phone
Mail
Safari
iPod

$k_s$
Analysis of NW memory snapshot

- Infer what peripherals are installed, and where in memory their drivers are installed
- Detect guest device for malware infection, including kernel-level rootkits

[Baliga, Ganapathy, Iftode, ACSAC’08, TDSC’11]
Why look for NW rootkits?

Secure world

Normal world (Untrusted)

Secure world memory

ARM TrustZone

Normal world OS

Rootkit

Secure world applies updates

$k_s$
Why look for NW rootkits?

Normal world (Untrusted)

Secure world

Rootkit

Rootkit undoes host’s changes

Normal world OS

Secure-world memory

ARM TrustZone
Analysis of NW memory snapshot

Recursive traversal of memory data structures

- Root symbols & kernel entry points
- Code whitelist
- Data structs
- Code pages
- Data invariants

Host’s policy server
Vetting host’s requests

- Vetting server ensures that host’s requests do not compromise guest privacy
- **Vetting policy**: Host only allowed to request guest device’s kernel memory
Guest device update

Host’s policy server

Memory updates

Restricted space
SW updates NW memory

Normal world
(Untrusted)

Secure world

Secure-world memory

ARM TrustZone

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$k_s$
Updating peripheral drivers

- Device drivers in normal world control execution of device peripherals
Introduce dummy driver to control peripheral (e.g., disable it). Update kernel driver hooks.
Are driver updates effective?

<table>
<thead>
<tr>
<th>Peripheral considered</th>
<th>Update size (bytes)</th>
<th>Guest device</th>
<th>Peripheral disabled?</th>
</tr>
</thead>
<tbody>
<tr>
<td>USB webcam</td>
<td>302</td>
<td>i.MX53</td>
<td>✔️</td>
</tr>
<tr>
<td>Camera</td>
<td>212</td>
<td>Nexus phone</td>
<td>✔️</td>
</tr>
<tr>
<td>WiFi</td>
<td>338</td>
<td>Nexus phone</td>
<td>✔️</td>
</tr>
<tr>
<td>3G (Data)</td>
<td>252</td>
<td>Nexus phone</td>
<td>✔️</td>
</tr>
<tr>
<td>3G (Voice)</td>
<td>224</td>
<td>Nexus phone</td>
<td>✔️</td>
</tr>
<tr>
<td>Microphone</td>
<td>184</td>
<td>Nexus phone</td>
<td>✔️</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>132</td>
<td>Nexus phone</td>
<td>✔️</td>
</tr>
</tbody>
</table>
Vetting host’s updates

- An untrusted host can introduce new code into guest devices
- **Vetting policy**: Ensure that dummy drivers are a *subset* of the original drivers
  - Via ARM-binary analysis on

3

Guest device

Guest’s vetting service
Proof of compliance

Host's policy server

Request proof of policy compliance

Verification token

Restricted space
4

Verification tokens

• Host requests proof of compliance
• Secure world computes a fresh snapshot of all NW memory locations updated by host
• Verification token:

\[ \text{HMAC}(\text{red, green, blue, yellow, purple}, k_s) \]

• Verification token matches if and only if normal world memory still in compliance with the host’s usage policy
Memory updates are ephemeral

- Guest device can violate host’s usage policies by simply rebooting to undo host’s memory updates!

- Once device checked in, secure world must:
  - Mediate all low-battery and power-off interrupts
  - Checkpoint device memory to disk
  - Upon power up, must restore device memory from checkpoint
Device checkpoint

• **Problem**: Checkpoint stored on disk
  – Readable by untrusted end-user
  – But session key $k_s$ must not be stored in clear
  – Otherwise, malicious end-user can use it to impersonate guest’s trusted secure world!

• **Solution**: REM-suspend protocol
• ARM TrustZone equips each device with a device-specific key $K_{DEV}$

• The key $K_{DEV}$ is only accessible from the secure world

• We use $K_{DEV}$ to encrypt $k_s$ in device checkpoint

• When device is powered again, secure world uses $K_{DEV}$ to decrypt and restore $k_s$
REM-suspend

Guest device storage

Secure world

$K_{DEV}$

$K_s$

$K_s$

ARM TrustZone
REM-suspend

Guest device storage

Secure world

$k_s$, $K_{DEV}$

ARM TrustZone
Are memory updates the right API?

- Powerful, low-level API for device control
- Simplifies design of secure world (TCB) and keeps it device-independent

<table>
<thead>
<tr>
<th>TCB component</th>
<th>SLOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory manager</td>
<td>1381</td>
</tr>
<tr>
<td>Authentication</td>
<td>1285</td>
</tr>
<tr>
<td>Memory ops., verification tokens</td>
<td>305</td>
</tr>
<tr>
<td>REM-suspend</td>
<td>609</td>
</tr>
<tr>
<td>SHA1 + HMAC</td>
<td>861</td>
</tr>
<tr>
<td>X509</td>
<td>877</td>
</tr>
<tr>
<td>RSA</td>
<td>2307</td>
</tr>
</tbody>
</table>
Do memory updates affect app stability?

- **Passive updates**: Update memory and start the app

<table>
<thead>
<tr>
<th>USB</th>
<th>MobileWebCam</th>
<th>ZOOM FX</th>
<th>Retrica</th>
<th>Candy Cam</th>
<th>HD Cam Ultra</th>
</tr>
</thead>
<tbody>
<tr>
<td>App Error</td>
<td>Android Error</td>
<td>App Error</td>
<td>App Error</td>
<td>Android Error</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Camera</th>
<th>Android Cam</th>
<th>Camera MX</th>
<th>ZOOM FX</th>
<th>Droid HD Cam</th>
<th>HD Cam Ultra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Android Error</td>
<td>App Error</td>
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<table>
<thead>
<tr>
<th>WiFi</th>
<th>Spotify</th>
<th>Play Store</th>
<th>YouTube</th>
<th>Chrome</th>
<th>Facebook</th>
</tr>
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<tbody>
<tr>
<td>No Connection</td>
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<table>
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<th>3G (Data)</th>
<th>Spotify</th>
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<table>
<thead>
<tr>
<th>3G (Voice)</th>
<th>Default call application</th>
<th></th>
<th></th>
<th></th>
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<tr>
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<td>Microphone</td>
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Do memory updates affect app stability?

- **Active updates**: Update memory with “live” app

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<tr>
<td>Blank Screen</td>
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<td></td>
<td>Unable to place call</td>
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Related approaches

- **Device virtualization:**
  - Heavyweight; probably not for all devices
  - Still requires host to trust hypervisor on guest

- **Mobile device management solutions:**
  - No proofs to host
  - Device-dependent TCB on guest

- **Context-based access control:**
  - Same shortcomings as MDM solutions above
Conclusion

A systematic method to regulate devices and ensure responsible use

- Low-level API allows hosts to analyze and control guests
  - Simplifies design and size of TCB
- Hosts can obtain proofs of guest compliance
  - Relies on ARM TrustZone hardware
- Vetting service balances guest privacy with host’s usage policies
Other research projects…

Generic theme: Computer Security and Software Engineering

- Improving cloud platform security
  \[\text{[ACSAC’08a, RAID’10, CCS’12a, SOCC’14]}\]
- Operating system reliability and security
  \[\text{[ASPLOS’08, ACSAC’08b, ACSAC’09a, MobiSys’11, TDSC’11, TIFS’13]}\]
- Hardware support for software and system security
  \[\text{[CCS’08, ECOOP’12a, TIFS’13, MobiSys’16-sub]}\]
- Web application and Web browser security
  \[\text{[ACSAC’09b, ECOOP’12a, ECOOP’12b, ECOOP’14, FSE’14]}\]
- Tools for cross-platform mobile app development
  \[\text{[ICSE’13, ASE’15]}\]
- Retrofitting legacy software for security
  \[\text{[CCS’05, Oakland’06, ASPLOS’06, ICSE’07, CCS’08, CCS’12b]}\]
- Reverse-engineering x86 and ARM binary software
  \[\text{[ICSE’16-sub]}\]
Collaborators

Senior colleagues

Rutgers
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- Prof. Santosh Nagarakatte

Penn State
- Prof. Trent Jaeger

Univ. of Wisconsin
- Prof. Somesh Jha
- Prof. Thomas Reps

TU-Darmstadt
- Prof. Ahmad Reza-Sadeghi

Google
- Dr. Ulfar Erlingsson
- Dr. Andres Lagar-Cavilla

Microsoft Research India
- Dr. Sriram Rajamani

Students

😊 Graduated PhDs
1. Dr. Mohan Dhawan (IBM Research)
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3. Dr. Shakeel Butt (Nvidia → Google)
4. Dr. Liu Yang (HP Labs → Baidu)
5. Dr. Rezwana Karim (Samsung Research)
6. Dr. Amruta Gokhale (Teradata)

😊 Former Postdocs
1. Dr. Arati Baliga (AT&T Security Labs)

😊 Graduated MS students
1. Jeffrey Bickford (AT&T Research)
2. Yogesh Padmanaban (Microsoft)

😊 Current PhD students
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That's all Folks!