

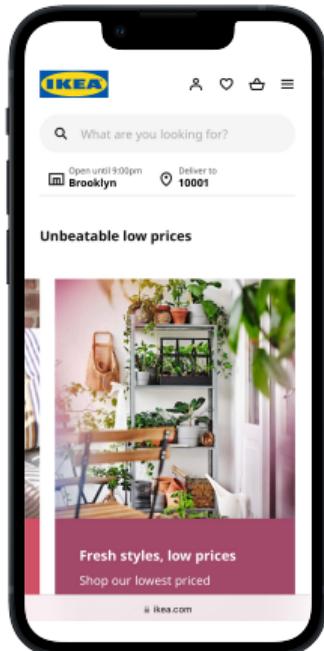


TaintMini: Detecting Flow of Sensitive Data in Mini-Programs with Static Taint Analysis

Chao Wang, Ronny Ko, Yue Zhang
Yuqing Yang, and Zhiqiang Lin

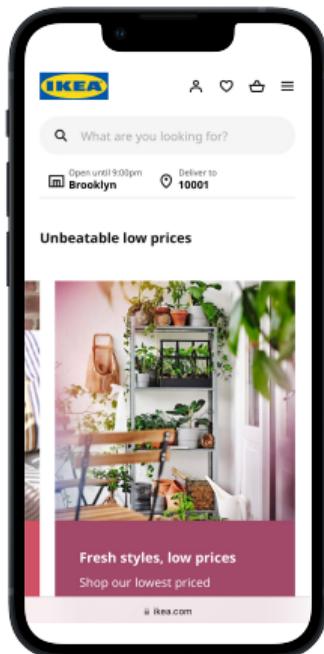
ICSE 2023

The Evolution of Mobile App Development

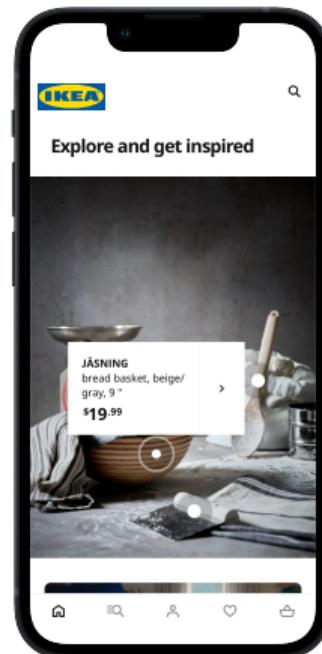


Web Apps

The Evolution of Mobile App Development

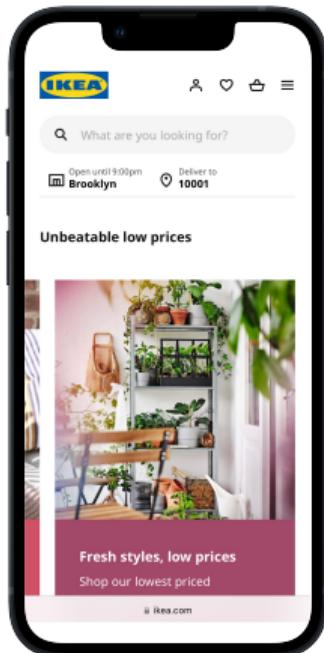


Web Apps

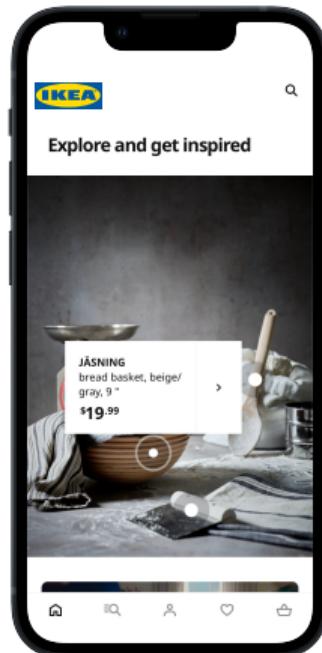


Native Apps

The Evolution of Mobile App Development



Web Apps



Native Apps



Mini-Programs

The Evolution of Mobile App Development



Apps	Web Apps	Native Apps	Mini-Programs
End Users			
Install-less?	✓	✗	✓
Developers			
Native APIs Access?	✗	✓	✓
Cross-platforms?	✓	✗	✓
Lightweight?	✗	✗	✓

Our Focus: the Mini-Programs in WeChat Super App

There are many other super apps

- ① Alipay
- ② SnapChat
- ③ TikTok
- ④ ...



WeChat Mini-Program

Our Focus: the Mini-Programs in WeChat Super App

There are many other super apps

- ① Alipay
- ② SnapChat
- ③ TikTok
- ④ ...

Why WeChat?

- ▶ Largest number of users (1.2 billion monthly active users)
- ▶ Pioneer of the Mini-Program paradigm
- ▶ Largest number of Mini-Programs (**millions**)

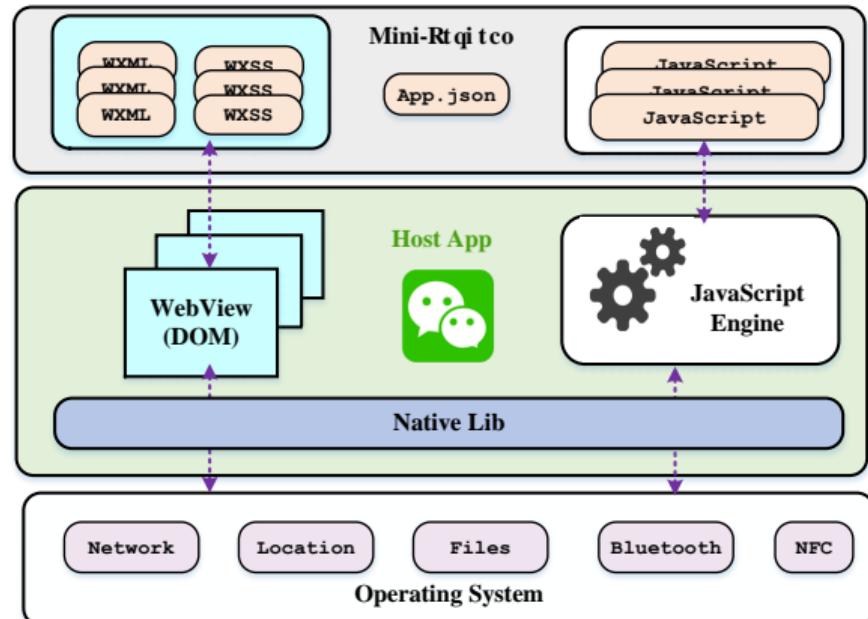


WeChat Mini-Program

With Great Power Comes Great Responsibility

The Great Power

- ▶ **Resources:** Network, Files, Bluetooth, NFC, etc.
- ▶ **Data:** Users' Location, Profiles, Phone numbers, etc.



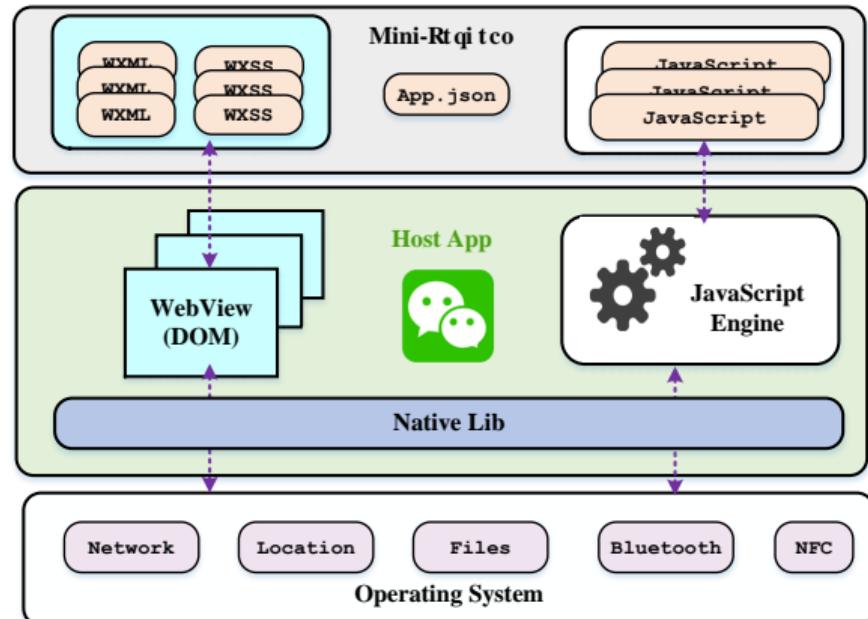
With Great Power Comes Great Responsibility

The Great Power

- ▶ **Resources:** Network, Files, Bluetooth, NFC, etc.
- ▶ **Data:** Users' Location, Profiles, Phone numbers, etc.

The Great Responsibility

- ▶ Protect users' sensitive data
- ▶ Prevent data leakage



When It Fails



Data Leakage!

- ▶ Mini-Programs can now directly access **private and sensitive data** via APIs provided by the host app
- ▶ **Accidentally** leaked by careless programmers
- ▶ **Intentionally** leaked by malicious Mini-Programs

When It Fails



Data Leakage!

- ▶ Mini-Programs can now directly access **private and sensitive data** via APIs provided by the host app
- ▶ **Accidentally** leaked by careless programmers
- ▶ **Intentionally** leaked by malicious Mini-Programs

Then we must detect such data leakage in Mini-Programs?

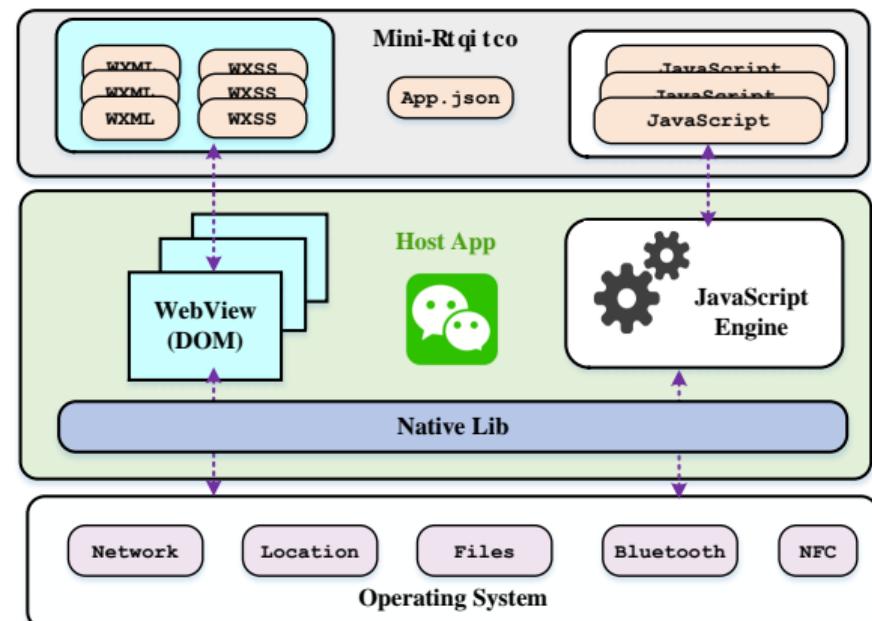
How does a Mini-Program Look Like

View - Rendering

- ▶ WXML
- ▶ WXSS

Logic - Programming

- ▶ JavaScript



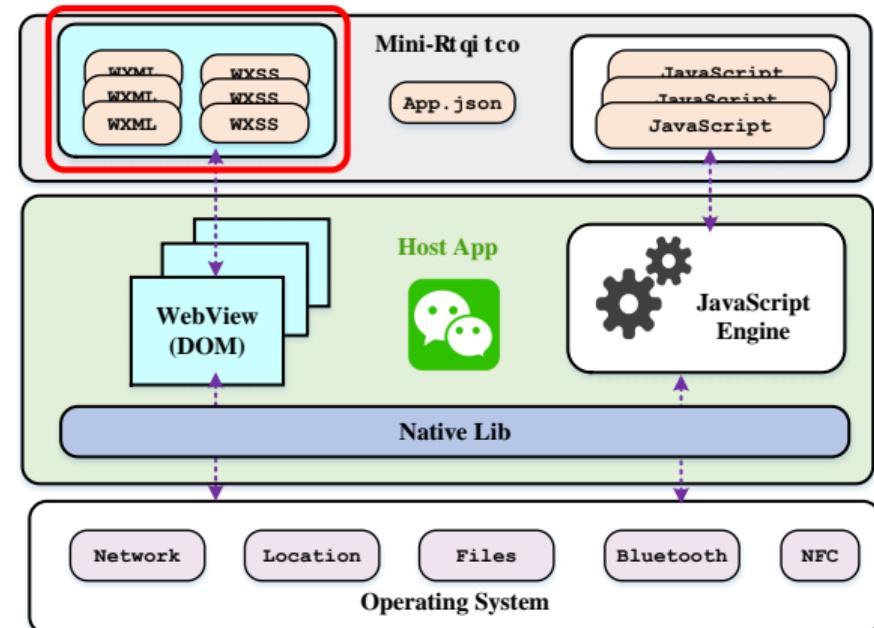
How does a Mini-Program Look Like

View - Rendering

- ▶ WXML
- ▶ WXSS

Logic - Programming

- ▶ JavaScript



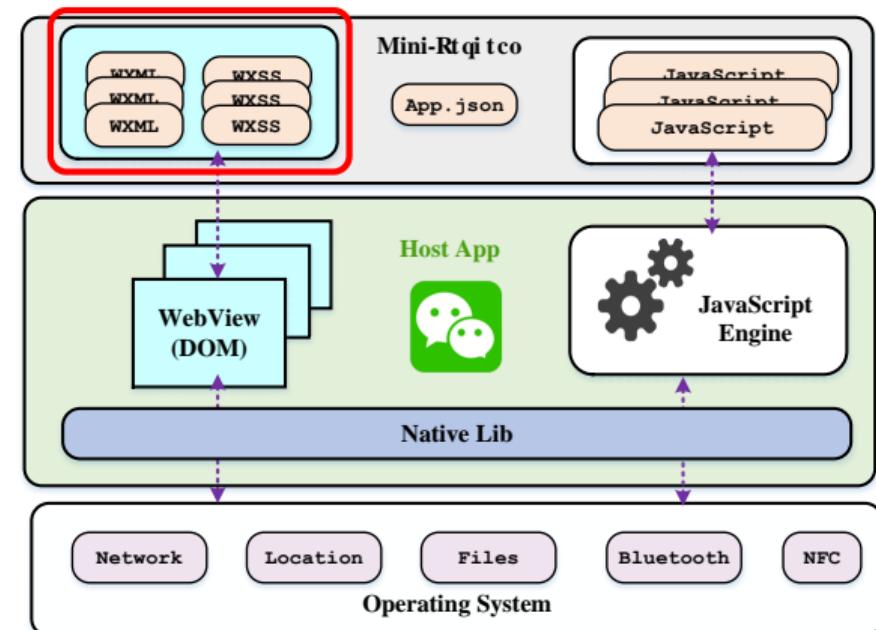
How does a Mini-Program Look Like

View - Rendering

- ▶ WXML
- ▶ WXSS

Logic - Programming

- ▶ JavaScript



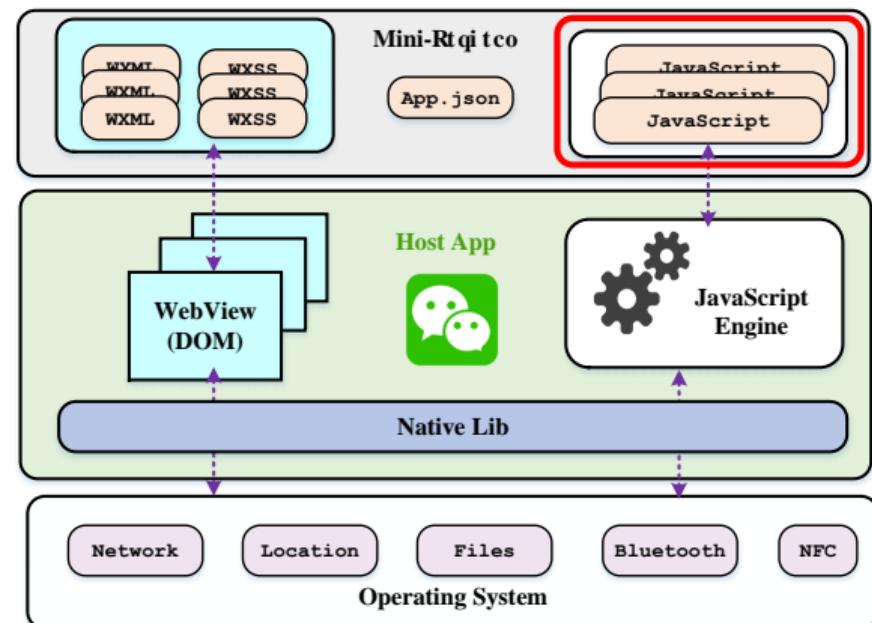
How does a Mini-Program Look Like

View - Rendering

- ▶ WXML
- ▶ WXSS

Logic - Programming

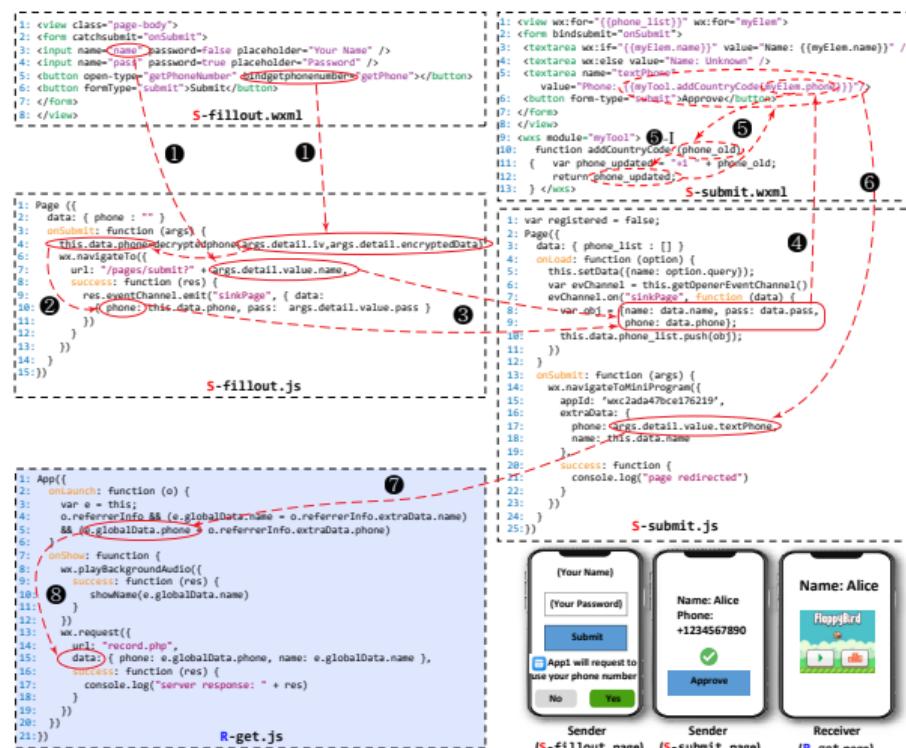
- ▶ JavaScript



An Example to Illustrate Various Data Flows in Mini-Programs

Various Data Flows

- ➊ JavaScript ↔ JavaScript
- ➋ JavaScript ↔ WXML
- ➌ WXML ↔ WXML
- ➍ EventHandler ↔ EventHandler
- ➎ Mini-Programs ↔ Mini-Programs



Why This is Challenging

	Web Apps	Native Apps	Mini-Programs
UI Layer Language	HTML	XML	WXML
<i>Supports Script Execution?</i>	✓	✗	✓
<i>Supports In-line Tag Logic?</i>	✗	✗	✓
<i>Data Flows Across UIs?</i>	✗	✗	✓
<i>Dynamically Modifiable?</i>	✓	✗	✗
Logic Layer Language	JavaScript	Java/Objective-C	JavaScript
<i>OOP Script?</i>	✓	✗	✓
<i>Compile-free?</i>	✓	✗	✓
<i>Dynamically Typed?</i>	✓	✗	✓
<i>Information Flow Types</i>	JS↔JS JS↔HTML App↔App EH↔EH	Java↔Java Java↔XML App↔App EH↔ EH	JS↔JS JS↔WXML App↔App EH↔ EH WXML↔WXML

Our Solution

- ① Track data flows between WXML tags and JavaScript

Universal Data-Flow Graph (UDFG) Generation

- ② Track data flows between asynchronous JavaScript callback functions

Data-Flow Propagation

- ③ Track data flows between Mini-Program pages & Mini-Programs

Data-Flow Resolution

Notations

$o_a \in \mathbb{O}$: Data object o_a (in the data object universe \mathbb{O})
$e_i \in \mathbb{E}$: Event group e_i (in the event group universe \mathbb{E})
$s_p^{(i,n)}$: Event group e_i 's p -th code statement, where n is the order of statement execution within e_i
$o_a \xrightarrow{s_p^{(i,n)}} o_b$: $s_p^{(i,n)}$ creates the data flow from o_a to o_b
$e_i \ggg e_j$: The application framework defines by design that e_j synchronously executes after e_i completes
$s_p^{(i,n)} \succ e_j$: The application code's $s_p^{(i,n)}$ calls e_j

Rules

1. $(e_i \ggg e_j) \wedge (e_j \ggg e_k) \implies e_i \ggg e_k$
2. $(s_p^{(i,n)} \succ e_j) \wedge (s_q^{(j,m)} \succ e_k) \implies s_p^{(i,n)} \succ e_k$
3. $(o_a \xrightarrow{s_p^{(i,n)}} o_b) \wedge (o_b \xrightarrow{s_q^{(i,m)}} o_c) \wedge (n < m) \implies o_a \rightarrow o_c$
4. $(e_i \ggg e_j) \wedge (o_a \xrightarrow{s_p^{(i,*)}} o_b) \wedge (o_b \xrightarrow{s_q^{(j,*)}} o_c)$
 $\implies o_a \rightarrow o_c$
5. $(s_p^{(i,n)} \succ e_j) \wedge (o_a \xrightarrow{s_r^{(i,*)}} o_b) \wedge (o_b \xrightarrow{s_q^{(j,*)}} o_c)$
 $\implies o_a \rightarrow o_c$
6. $(s_p^{(i,n)} \succ e_j) \wedge (o_a \xrightarrow{s_q^{(j,*)}} o_b) \wedge (o_b \xrightarrow{s_r^{(i,m)}} o_c) \wedge (n < m)$
 $\implies o_a \rightarrow o_c$
7. $(e_i \ggg e_j) \wedge (e_j \ggg e_i) \wedge (\forall p s_p^{(i,*)} \not\succ e_j) \wedge$
 $(\forall q s_q^{(j,*)} \not\succ e_i) \wedge (o_a \xrightarrow{s_r^{(i,*)}} o_b) \wedge (o_b \xrightarrow{s_t^{(j,*)}} o_c)$
 $\implies o_a \rightarrow o_c$

Our Solution

- ① Track data flows between WXML tags and JavaScript

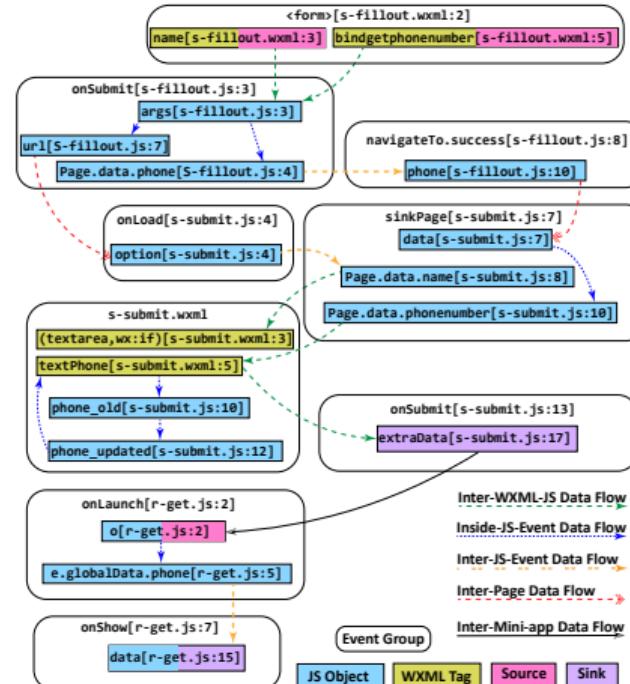
Universal Data-Flow Graph (UDFG) Generation

- ② Track data flows between asynchronous JavaScript callback functions

Data-Flow Propagation

- ③ Track data flows between Mini-Program pages & Mini-Programs

Data-Flow Resolution



Dataset

- ▶ Downloaded by open source MiniCrawler [ZTY⁺21]
- ▶ **238,866** distinct Mini-Programs out of 3.3 million Mini-Programs
- ▶ **25.83** pages per Mini-Program on average
- ▶ **144.83 KiB** of JavaScript per Mini-Program on average

Research Questions

RQ1

Does TaintMini have any FPs and FNs?

RQ2

How long does TaintMini take to analyze a Mini-Program on average?

RQ3

What are those Mini-Programs that contain flow-sensitive data?

RQ4

What is the data that may be leaked through those Mini-Programs that contain sensitive data flow?

Research Questions

RQ1: Does TaintMini have any FPs and FNs?

- ▶ Sampled **100** Mini-Programs in each set (FP and FN)
- ▶ Manually inspected by experts
- ▶ **0** FPs
- ▶ **5** FNs (5.00%): using non-standard APIs to get sensitive data

Research Questions

RQ1: Does TaintMini have any FPs and FNs?

- ▶ Sampled **100** Mini-Programs in each set (FP and FN)
- ▶ Manually inspected by experts
- ▶ **0** FPs
- ▶ **5** FNs (5.00%): using non-standard APIs to get sensitive data

RQ2: How long does TaintMini take to analyze a mini-program on average?

- ▶ Recorded execution time of analysis for each Mini-Program
- ▶ **3.73** seconds on average to analyze one Mini-Program

RQ3: What are those Mini-Programs that contain flow-sensitive data?

► **27,184 (11.38%)** Mini-Programs out of **238,866** contain sensitive data flows.

Category	Unrated Mini-apps				Rated Mini-apps							
					0.0 - 3.0			3.0 - 4.0			4.0 - 5.0	
Business	1,290	12,547	10.3	2	9	22.2	10	62	16.1	73	645	11.3
E-Learning	131	1,625	8.1	4	9	44.4	8	56	14.3	20	185	10.8
Education	3,531	31,057	11.4	17	105	16.2	79	590	13.4	497	3,661	13.6
Entertainment	338	3,661	9.2	14	74	18.9	29	289	10.0	50	671	7.5
Finance	58	951	6.1	0	4	0.0	4	35	11.4	40	313	12.8
Food	633	4,775	13.3	0	3	0.0	4	31	12.9	75	453	16.6
Games	288	3,438	8.4	25	204	12.3	45	422	10.7	25	265	9.4
Government	793	6,525	12.2	0	10	0.0	9	76	11.8	64	542	11.8
Health	543	5,320	10.2	1	6	16.7	8	57	14.0	81	598	13.5
Job	445	3,375	13.2	7	21	33.3	24	119	20.2	56	431	13.0
Lifestyle	3,358	27,670	12.1	12	63	19.0	99	520	19.0	443	2,916	15.2
Photo	99	1,444	6.9	5	30	16.7	15	109	13.8	14	209	6.7
Shopping	4,082	36,696	11.1	6	38	15.8	44	397	11.1	484	3,895	12.4
Social	509	4,004	12.7	2	19	10.5	31	193	16.1	93	769	12.1
Sports	375	2,531	14.8	1	3	33.3	8	50	16.0	82	489	16.8
Tool	6,159	58,636	10.5	52	380	13.7	128	1,176	10.9	684	5,623	12.2
Traffic	629	4,634	13.6	11	34	32.4	26	177	14.7	144	911	15.8
Travelling	236	1,755	13.4	0	1	0.0	4	20	20.0	21	195	10.8
Ungrouped	7	58	12.1	0	1	0.0	0	0	-	0	0	-
Total	23,504	210,702	11.2	159	1,014	15.7	575	4,379	13.1	2,946	22,771	12.9

RQ4: What is the data that may be leaked through those Mini-Programs?

- ▶ **Storage, profile, and location** are the top categories that may be leaked
- ▶ **Network** is the top channel that data may be leaked through

Category	APIs (Example)	Total	Network Channel		Cross-App Channel	
			L	%	L	%
Storage	wx.getStorageSync	205,109	20,719	10.10	420	0.20
Profile	wx.getUserInfo	156,891	7,552	4.81	20	0.01
Location	wx.getLocation	145,205	3,737	2.57	4	0.00
Address	wx.chooseAddress	24,249	627	2.59	0	0.00
Open-API	wx.getWeRunData	5,273	295	5.59	0	0.00
Device	wx.getNetworkType	85,358	112	0.13	11	0.01
Media	wx.chooseVideo	89,351	39	0.04	0	0.00

Applications: Automatic Detection of Collusion Attacks

Leaking phone number

- ▶ The sender Mini-Program collects users' phone numbers
- ▶ The sender Mini-Program transfers them to another mini-program

```
1  getPhoneNumber: function(e) {
2    ...
3    n.globalData.btnCanClick = !0, wx.hideLoading(); else {
4      var o = {
5        iv: e.detail.iv,
6        encryptedData: e.detail.encryptedData,
7        type: n.globalData.appType
8      };
9      var l = n.getUrl("info");
10     t.default.post(l, o).then(function(e) {
11       if (200 == e.data.status) {
12         wx.hideLoading();
13         var t = e.data.data.phoneNumber;
14         this.data.phone_number = e.data.data.phoneNumber,
15         ↪ n.globalData.userInfo = {
16           phone_number: t }, console.log("Obtained Phone Number",
17           ↪ n.globalData.userInfo.phone_number), a.loginProcess(t);
18       } else n.wx_toast(e.data.message);
19     });
20   },
21   wx.navigateToMiniProgram({
22     appId: e.linkAppid,
23     path: t,
24     extraData: {
25       mallId: this.data.mallId || "",
26       mallInfo: this.data.mallInfo || "",
27       memberId: this.data.memberId || "",
28       phoneNumber: this.data.phone_number || "", token:
29         ↪ this.data.token || "" })
```

Applications: Automatic Detection of Collusion Attacks

Leaking location data

- The receiver Mini-Program does not have permission to retrieve users' location
- The receiver Mini-Program receives location data from other Mini-Programs

```
1  var a = e.referrerInfo.extraData.location, n =
2    ↪ e.referrerInfo.extraData.imp_data, o =
3    ↪ e.referrerInfo.extraData.src_path;
4    void 0 != a && void 0 != n && null != a && null != n
5    "" == this.data.location ? (wx.showLoading({
6      title: "Loading ..."
7    }), this.locationApp(a, n, o)) : this.data.location = "";
8    } catch (e) {}
9    t.eventReady(function() {
10      t.beginTime();
11    });
12    ...
13    wx.request({
14      url: "https://*****.***.***",
15      data: location
16    });
17  
```

Future Works

- ① Implicit data flows resolution
- ② Dynamic analysis
- ③ Extend to other mobile super apps (e.g., Alipay, Baidu, Tiktok, etc.)

Related Works

- ▶ **Taint Analysis.** Widely used program analysis technique for numerous applications, such as exploit detection [NS05, CLZ21], privacy leakage detection [EKKV11, EGH⁺14], and cryptographic key misuse detection [ZCD⁺19, RY17]. In the past decades, numerous taint analysis systems have been proposed and applied to analyze different languages (e.g., Java [TPF⁺09, HDM14, HCF05, TPF⁺09] and C [MWX⁺15, FC20]) and frameworks (Android [DAL⁺17, EGH⁺14, ZTD19, YY12], iOS [EKKV11] and Microservices [ZLW⁺22]).

Related Works

- ▶ **Mini-Program Security.** Lu *et al.* [LXX⁺20] have studied the resource management in mini-programs, and identified a few flaws that enable the attackers to steal sensitive user information. Zhang *et al.* [ZTY⁺21] developed MiniCrawler and studied the security practice of the mini-programs. Zhang *et al.* [ZZL⁺22] discovered identity confusion vulnerabilities against mini-programs, allowing the attacker to invoke high privileged capabilities. Most recently, Yang *et al.* also recently investigated the vulnerability of cross-mini-program redirection among mini-programs in WeChat and Baidu [YZL22].

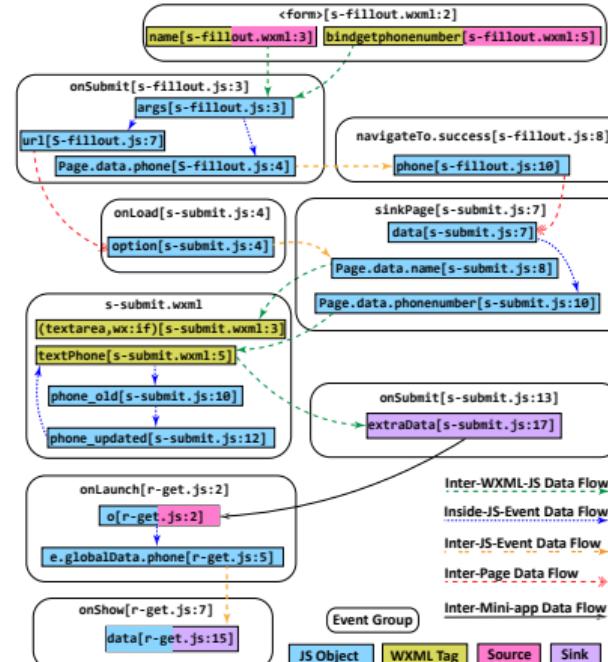
Conclusion

TaintMini

- First **open source**, static taint analysis framework for Mini-Programs

Evaluated w/ 238K Mini-Programs

- **Empirical Results.** Identified 27,184 (11.38%) Mini-Programs contain sensitive data flows
- **Security Application.** Identified 455 colluding apps



Source code of TaintMini has been made available at: github.com/OSUSecLab/TaintMini

References I

-  Sanchuan Chen, Zhiqiang Lin, and Yinqian Zhang, *SelectiveTaint: Efficient data flow tracking with static binary rewriting*, 30th USENIX Security Symposium (USENIX Security 21), USENIX Association, August 2021, pp. 1665–1682.
-  Lisa Nguyen Quang Do, Karim Ali, Benjamin Livshits, Eric Bodden, Justin Smith, and Emerson R. Murphy-Hill, *Cheetah: just-in-time taint analysis for android apps*, Proceedings of the 39th International Conference on Software Engineering, ICSE 2017, Buenos Aires, Argentina, May 20-28, 2017 - Companion Volume (Sebastián Uchitel, Alessandro Orso, and Martin P. Robillard, eds.), IEEE Computer Society, 2017, pp. 39–42.
-  William Enck, Peter Gilbert, Seungyeop Han, Vasant Tendulkar, Byung-Gon Chun, Landon P Cox, Jaeyeon Jung, Patrick McDaniel, and Anmol N Sheth, *Taintdroid: an information-flow tracking system for realtime privacy monitoring on smartphones*, ACM Transactions on Computer Systems (TOCS) 32 (2014), no. 2, 1–29.
-  Manuel Egele, Christopher Kruegel, Engin Kirda, and Giovanni Vigna, *Pios: Detecting privacy leaks in ios applications.*, NDSS, 2011, pp. 177–183.
-  Xiaoqin Fu and Haipeng Cai, *Scaling application-level dynamic taint analysis to enterprise-scale distributed systems*, ICSE '20: 42nd International Conference on Software Engineering, Companion Volume, Seoul, South Korea, 27 June – 19 July, 2020 (Gregg Rothermel and Doo-Hwan Bae, eds.), ACM, 2020, pp. 270–271.
-  Vivek Haldar, Deepak Chandra, and Michael Franz, *Dynamic taint propagation for java*, 21st Annual Computer Security Applications Conference (ACSAC'05), IEEE, 2005, pp. 9–pp.
-  Wei Huang, Yao Dong, and Ana Milanova, *Type-based taint analysis for java web applications*, International Conference on Fundamental Approaches to Software Engineering, Springer, 2014, pp. 140–154.

References II

-  Haoran Lu, Luyi Xing, Yue Xiao, Yifan Zhang, Xiaojing Liao, XiaoFeng Wang, and Xueqiang Wang, *Demystifying resource management risks in emerging mobile app-in-app ecosystems*, Proceedings of the 2020 ACM SIGSAC Conference on Computer and Communications Security, 2020, pp. 569–585.
-  Jiang Ming, Dinghao Wu, Gaoyao Xiao, Jun Wang, and Peng Liu, {*TaintPipe*}: *Pipelined symbolic taint analysis*, 24th USENIX Security Symposium (USENIX Security 15), 2015, pp. 65–80.
-  James Newsome and Dawn Xiaodong Song, *Dynamic taint analysis for automatic detection, analysis, and signaturegeneration of exploits on commodity software.*, NDSS, vol. 5, Citeseer, 2005, pp. 3–4.
-  Sazzadur Rahaman and Danfeng Yao, *Program analysis of cryptographic implementations for security*, 2017 IEEE Cybersecurity Development (SecDev), IEEE, 2017, pp. 61–68.
-  Omer Tripp, Marco Pistoia, Stephen J Fink, Manu Sridharan, and Omri Weisman, *Taj: effective taint analysis of web applications*, ACM Sigplan Notices **44** (2009), no. 6, 87–97.
-  Zhemin Yang and Min Yang, *Leakminer: Detect information leakage on android with static taint analysis*, 2012 Third World Congress on Software Engineering, IEEE, 2012, pp. 101–104.
-  Yuqing Yang, Yue Zhang, and Zhiqiang Lin, *Cross miniapp request forgery: Root causes, attacks, and vulnerability detection*, Proceedings of the 29th ACM Conference on Computer and Communications Security, 2022.
-  Li Zhang, Jiongyi Chen, Wenrui Diao, Shangqin Guo, Jian Weng, and Kehuan Zhang, {*CryptoREX*}: *Large-scale analysis of cryptographic misuse in {IoT} devices*, 22nd International Symposium on Research in Attacks, Intrusions and Defenses (RAID 2019), 2019, pp. 151–164.

References III

-  Zexin Zhong, Jiangchao Liu, Diyu Wu, Peng Di, Yulei Sui, and Alex X. Liu, *Field-based static taint analysis for industrial microservices*, 44th IEEE/ACM International Conference on Software Engineering: Software Engineering in Practice, ICSE (SEIP) 2022, Pittsburgh, PA, USA, May 22-24, 2022, IEEE, 2022, pp. 149–150.
-  Jie Zhang, Cong Tian, and Zhenhua Duan, *Fastdroid: efficient taint analysis for android applications*, Proceedings of the 41st International Conference on Software Engineering: Companion Proceedings, ICSE 2019, Montreal, QC, Canada, May 25-31, 2019 (Joanne M. Atlee, Tevfik Bultan, and Jon Whittle, eds.), IEEE / ACM, 2019, pp. 236–237.
-  Yue Zhang, Bayan Turkistani, Allen Yuqing Yang, Chaoshun Zuo, and Zhiqiang Lin, *A measurement study of wechat mini-apps*, Proceedings of the ACM on Measurement and Analysis of Computing Systems 5 (2021), no. 2, 1–25.
-  Lei Zhang, Zhibo Zhang, Ancong Liu, Yinzhi Cao, Xiaohan Zhang, Yanjun Chen, Yuan Zhang, Guangliang Yang, and Min Yang, *Identity confusion in webview-based mobile app-in-app ecosystems*, 31st USENIX Security Symposium (USENIX Security'22), 2022.