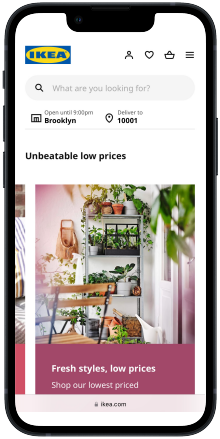
TaintMini: Detecting Flow of Sensitive Data in Mini-Programs with Static Taint Analysis

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

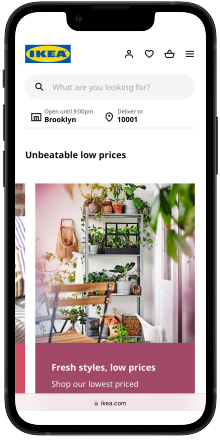
ICSE 2023

The Evolution of Mobile App Development



Web Apps

The Evolution of Mobile App Development



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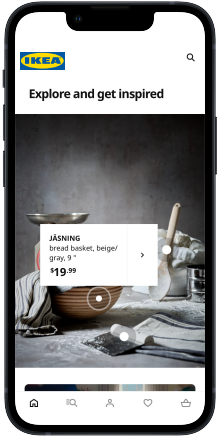
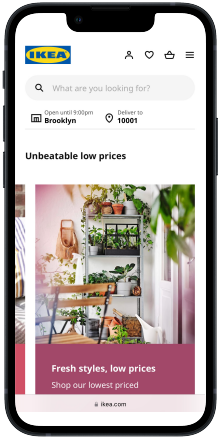


Native Apps

The Evolution of Mobile App Development



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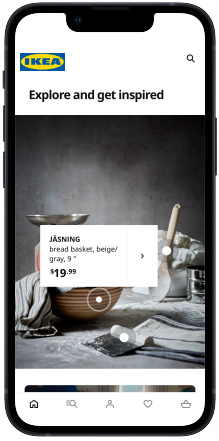

Native Apps

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

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Why WeChat?

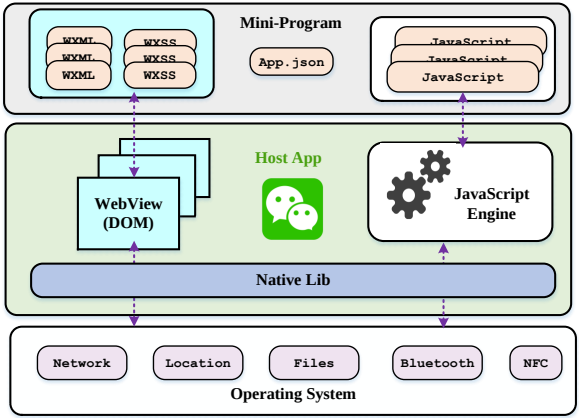
- Largest number of users (1.2 billion monthly active users)
- Pioneer of the Mini-Program paradigm
- Largest number of Mini-Programs (millions)

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.



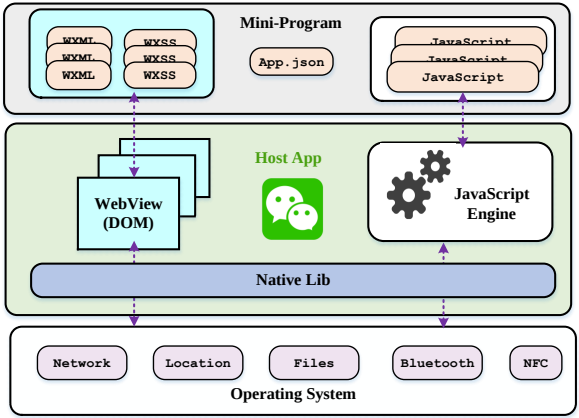
With Great Power Comes Great Responsibility

The Great Power

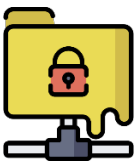
- **Resources:** Network, Files, Bluetooth, NFC, etc.
- **Data:** Users' Location, Profiles, Phone numbers, etc.

The Great Responsibility

- Protect users' sensitive data
- Prevent data leakage



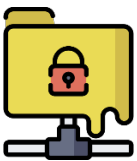
When It Fails



Data Leakage!

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

When It Fails



Data Leakage!

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

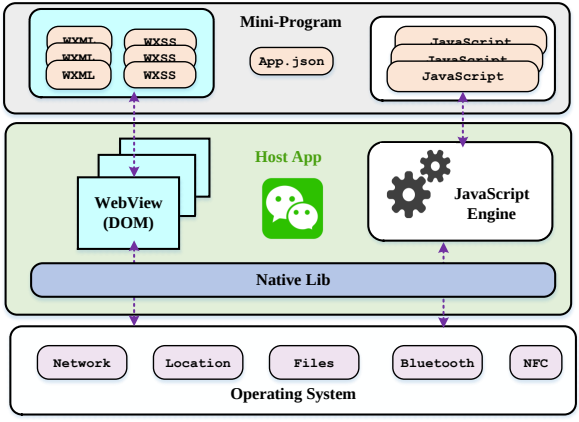
How does a Mini-Program Look Like

View - Rendering

- WXML
- WXSS

Logic - Programming

- JavaScript



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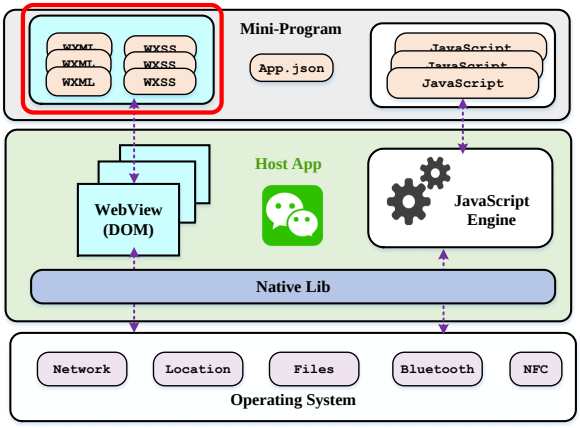

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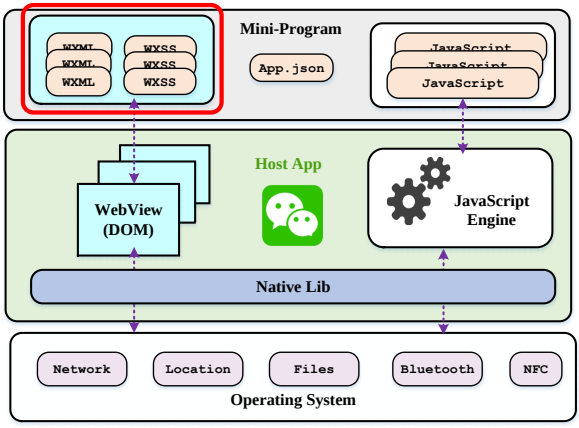

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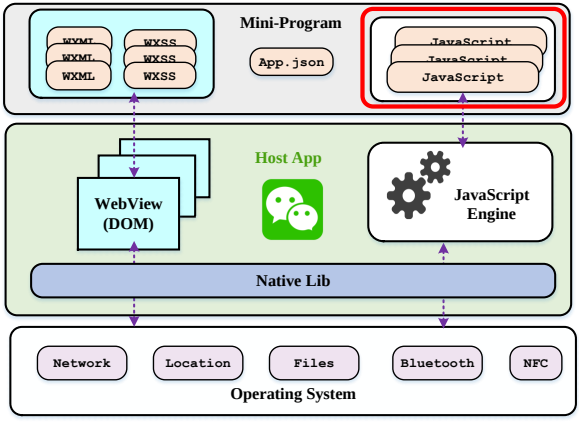
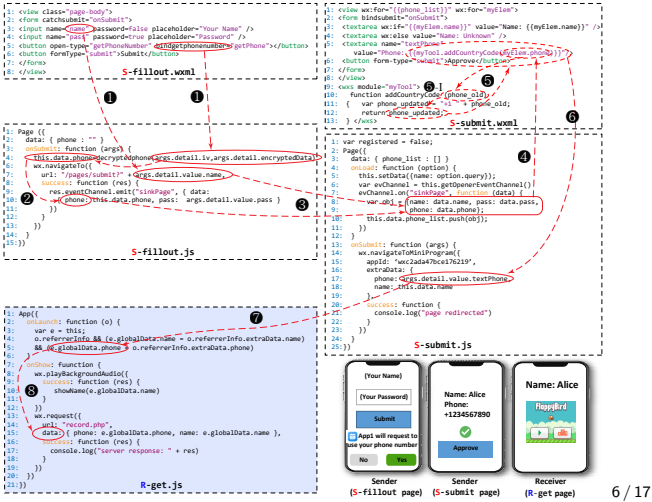


An Example to Illustrate Various Data Flows in Mini-Programs

Various Data Flows

1. JavaScript ↔ JavaScript
2. JavaScript ↔ WXML
3. WXML ↔ WXML
4. EventHandler ↔ EventHandler
5. Mini-Programs ↔ Mini-Programs



Why This is Challenging

	Web Apps	**Native Apps**	**Mini-Programs**
UI Layer Language	HTML	XML	WXML
Supports Script Execution?	✓	✗	✓
Supports In-line Tag Logic?	✗	✗	✓
Data Flows Across UIs?	✗	✗	✓
Dynamically Modifiable?	✓	✗	✗
Logic Layer Language	JavaScript	Java/Objective-C	JavaScript
OOP Script?	✓	✗	✓
Compile-free?	✓	✗	✓
Dynamically Typed?	✓	✗	✓
Information Flow Types	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. $(e_i \ggg e_j) \wedge (e_j \ggg e_k) \Longrightarrow e_i \ggg e_k$
2. $(s_p^{(i,n)} \succ e_j) \wedge (s_q^{(j,m)} \succ e_k) \Longrightarrow s_p^{(i,n)} \succ e_k$
3. $(o_a \xrightarrow{s_p^{(i,n)}} o_b) \wedge (o_b \xrightarrow{s_q^{(i,m)}} o_c) \wedge (n < m) \Longrightarrow o_a \rightarrow o_c$
4. $(e_i \ggg e_j) \wedge (o_a \xrightarrow{s_p^{(i,*)}} o_b) \wedge (o_b \xrightarrow{s_q^{(j,*)}} o_c)$
   $\Longrightarrow o_a \rightarrow o_c$
5. $(s_p^{(i,n)} \succ e_j) \wedge (o_a \xrightarrow{s_*^{(i,*)}} o_b) \wedge (o_b \xrightarrow{s_q^{(j,*)}} o_c)$
   $\Longrightarrow o_a \rightarrow o_c$
6. $(s_p^{(i,n)} \succ e_j) \wedge (o_a \xrightarrow{s_q^{(j,*)}} o_b) \wedge (o_b \xrightarrow{s_*^{(i,m)}} o_c) \wedge (n < m)$
   $\Longrightarrow o_a \rightarrow o_c$
7. $(e_i \ggg e_j) \wedge (e_j \ggg e_i) \wedge (\forall p\ s_p^{(i,*)} \not\succ e_j) \wedge$
   $(\forall q\ s_q^{(j,*)} \not\succ e_i) \wedge (o_a \xrightarrow{s_*^{(i,*)}} o_b) \wedge (o_b \xrightarrow{s_*^{(j,*)}} o_c)$
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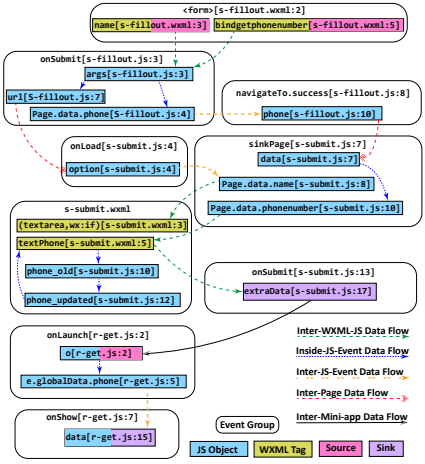

Dataset

- 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?

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- 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,
        ↪ n.globalData.userInfo = {
15       phone_number: t }, console.log("Obtained Phone Number",
         ↪ n.globalData.userInfo.phone_number), a.loginProcess(t);
16       } else n.wx_toast(e.data.message);
17       }); } },
18  wx.navigateToMiniProgram({
19      appId: e.linkAppid,
20      path: t,
21      extraData: {
22      mallId: this.data.mallId || "",
23      mallInfo: this.data.mallInfo || "",
24      memberId: this.data.memberId || "",
25      phoneNumber: this.data.phone_number || "", token:
        ↪ 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 =
   ↪  e.referrerInfo.extraData.imp_data, o =
   ↪  e.referrerInfo.extraData.src_path;
2     void 0 != a && void 0 != n && null != a && null != n
3     "" == this.data.location ? (wx.showLoading({
4     title: "Loading ..."
5      }), this.locationApp(a, n, o)) : this.data.location = "");
6      } catch (e) {}
7       t.eventReady(function() {
8       t.beginTime();
9       });
10      ...
11    wx.request({
12         url: "https://********.***.***",
13    data: location
14 });
```

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].

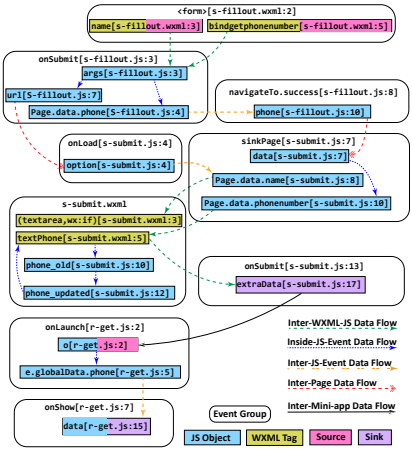
Conclusion

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

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