Research in Software Compartmentalization

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Memory Safety

Still the Main Security Issue in Systems Software

- Most systems software are today written in **memory-unsafe languages**
  - C/C++
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  - C/C++
  - This is for **performance** reasons
- Programming mistakes introduce bugs leading to **memory corruption/undefined behavior**
- Impact of such bugs in production goes much further than crashes: **security issues**
  - Bugs can be exploited by attackers to take over a system's execution flow, leak/tamper critical data, escalate privileges, etc.

Memory Safety

Still the Main Security Issue in Systems Software

Microsoft: 70 percent of all security bugs are memory safety issues

Percentage of memory safety issues has been hovering at 70 percent for the past 12 years.

By Catalin Cimpanu for Zero Day | February 11, 2019 | Topic: Security

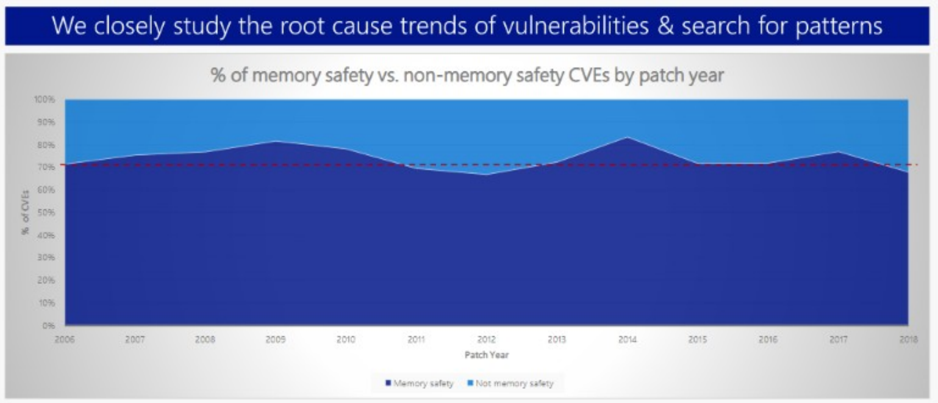

Image: Matt Miller

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Memory Safety

Still the Main Security Issue in Systems Software

Memory Safety

Possible Solutions

- **Existing solutions are not perfect**
  - Using **memory safe languages** is either too slow or too restrictive for the programmer
  - Formal **verification techniques** are either too restrictive or do not scale to the large code bases of modern systems software
  - **C/C++ hardening techniques** are not comprehensive/can be bypassed/have an unacceptable performance impact
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  - **C/C++ hardening techniques** are not comprehensive/can be bypassed/have an unacceptable performance impact
  - etc.
- **So C/C++ remain popular, and memory corruption bugs are not going away anytime soon**

Software Compartmentalization

Software Compartmentalization

Motivation & Presentation

- Software compartmentalization **decompose software into lesser-privileged components that only have access to what they need to do their job**
  - Different from previous approaches: acknowledge there will be bugs and exploits, try to limit their impact

Software Compartmentalization

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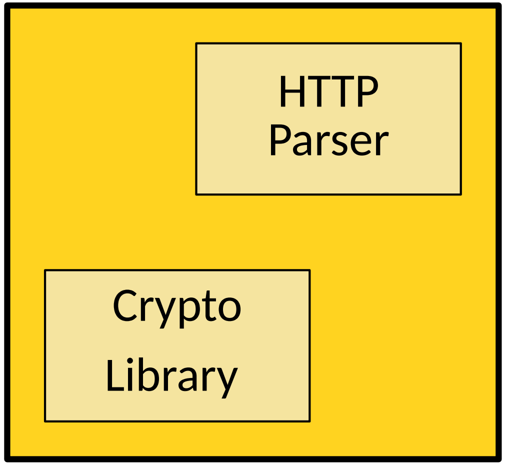

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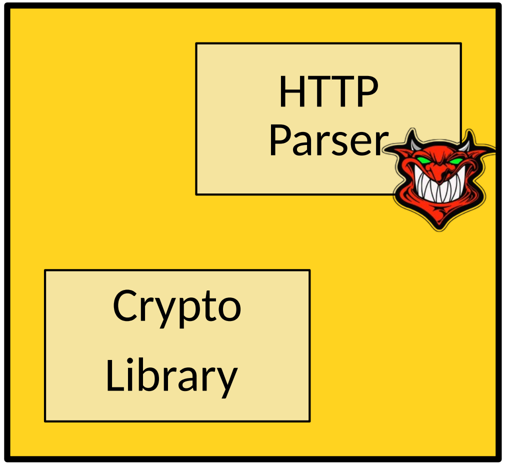

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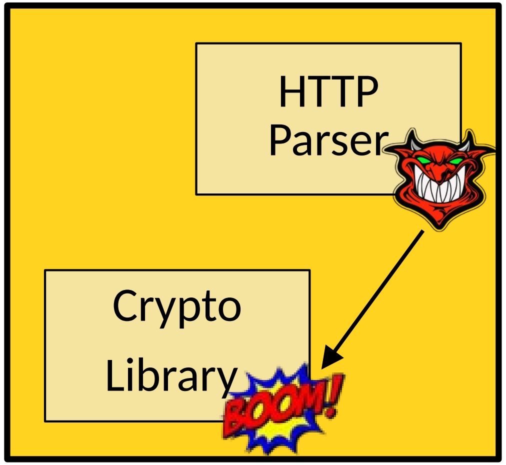

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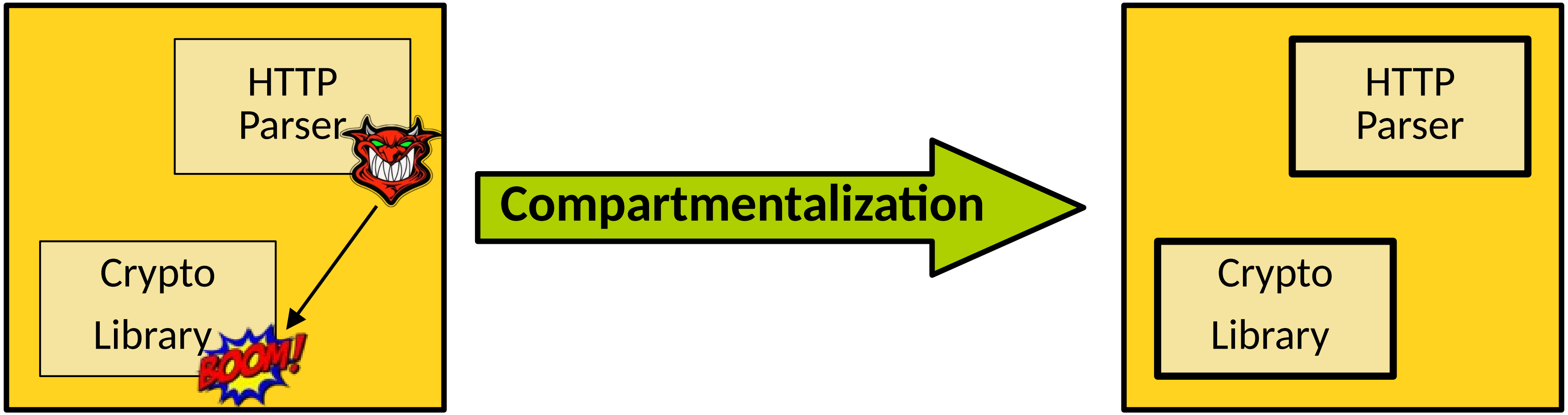

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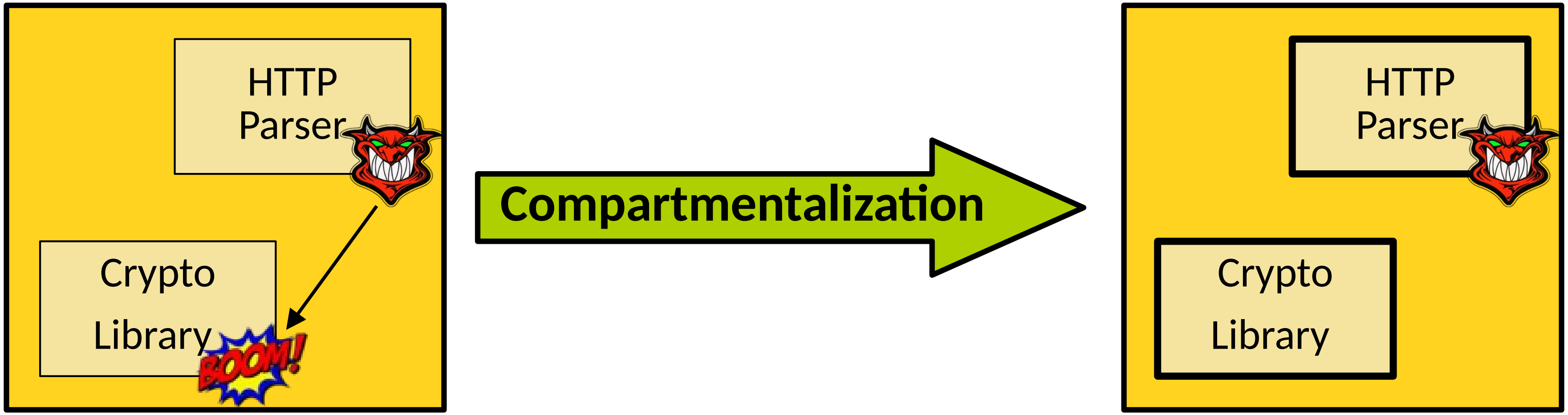

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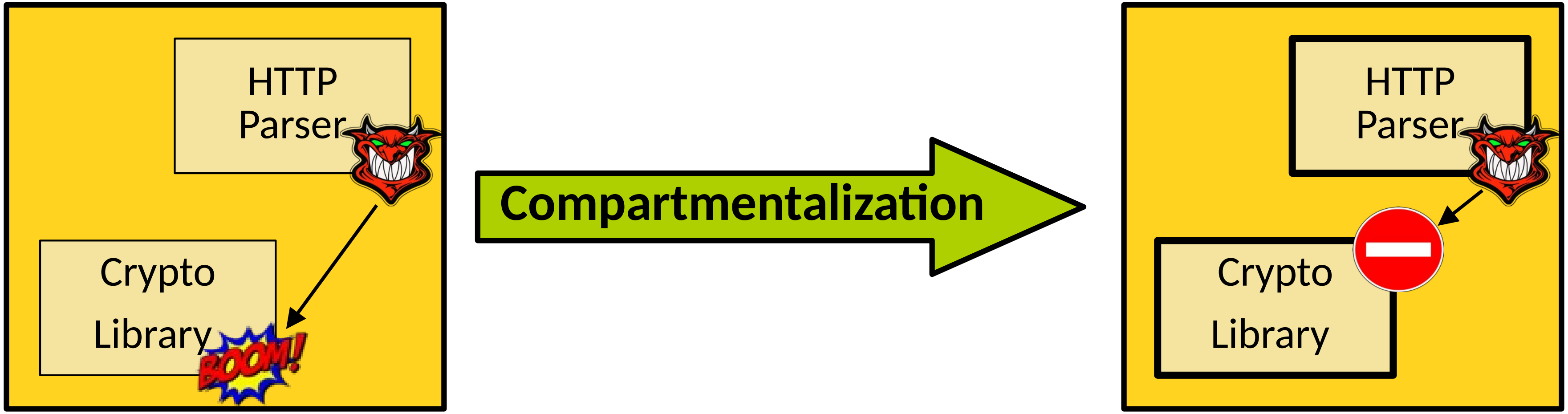

Software Compartmentalization

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- Here we'll focus on **memory compartmentalization**

Software Compartmentalization

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- Traditional examples: OS kernels, web browser, web servers, SSH software
- Here we'll focus on **memory compartmentalization**
- We'll also focus on compartmentalization **applied to existing software**

Software Compartmentalization

Illustrative Example

```
int global;

int library_function(int *parameter) {
      char *cryptokey = “private“;

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int main() {
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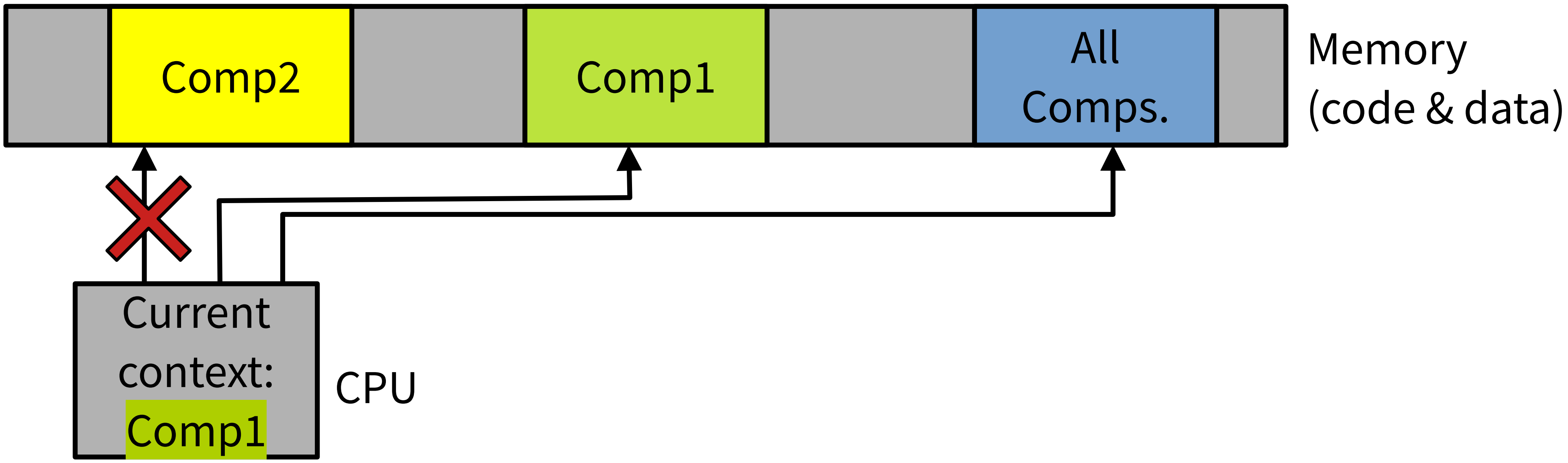
Many modern compartmentalization frameworks will help achieve that: codejail, ERIM, Hodor, Donky, Ptrsplit, memsentry, libmpk, Cali, CubicleOS, LibHermitMPK, **FlexOS**, Polytope, etc.

Software Compartmentalization

Illustrative Example

- How does it work from the hardware POV?



Software Compartmentalization

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Area of investment and support

Digital security by design

The digital security by design (DSbD) challenge funds business and researchers to update the foundation of the insecure digital computing infrastructure by creating a new, more secure hardware and software ecosystem.

Budget: £70 million

Duration: From 2020 to 2025

Partners involved: Innovate UK, Engineering and Physical Sciences Research Council (EPSRC)

Open all

DARPA

Broad Agency Announcement

Compartmentalization and Privilege Management (CPM)

INFORMATION INNOVATION OFFICE

HR001123S0028

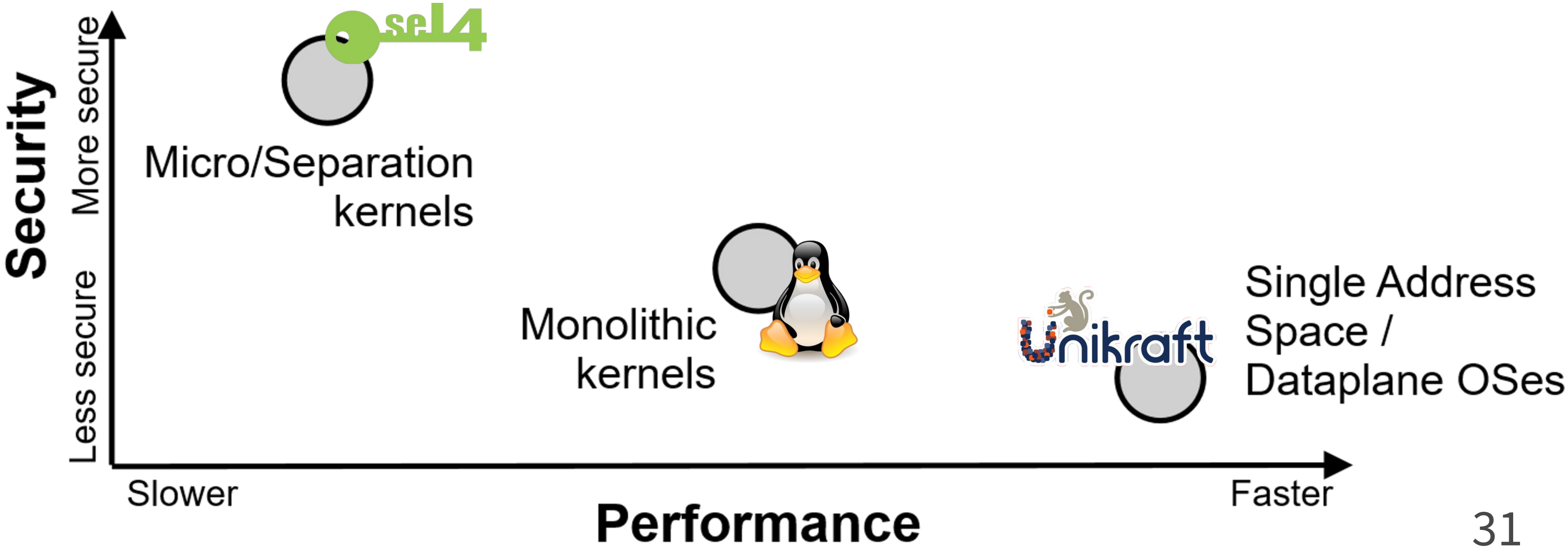
April 4, 2023

Flexible Compartmentalization

FlexOS: Flexible Compartmentalization

Motivation

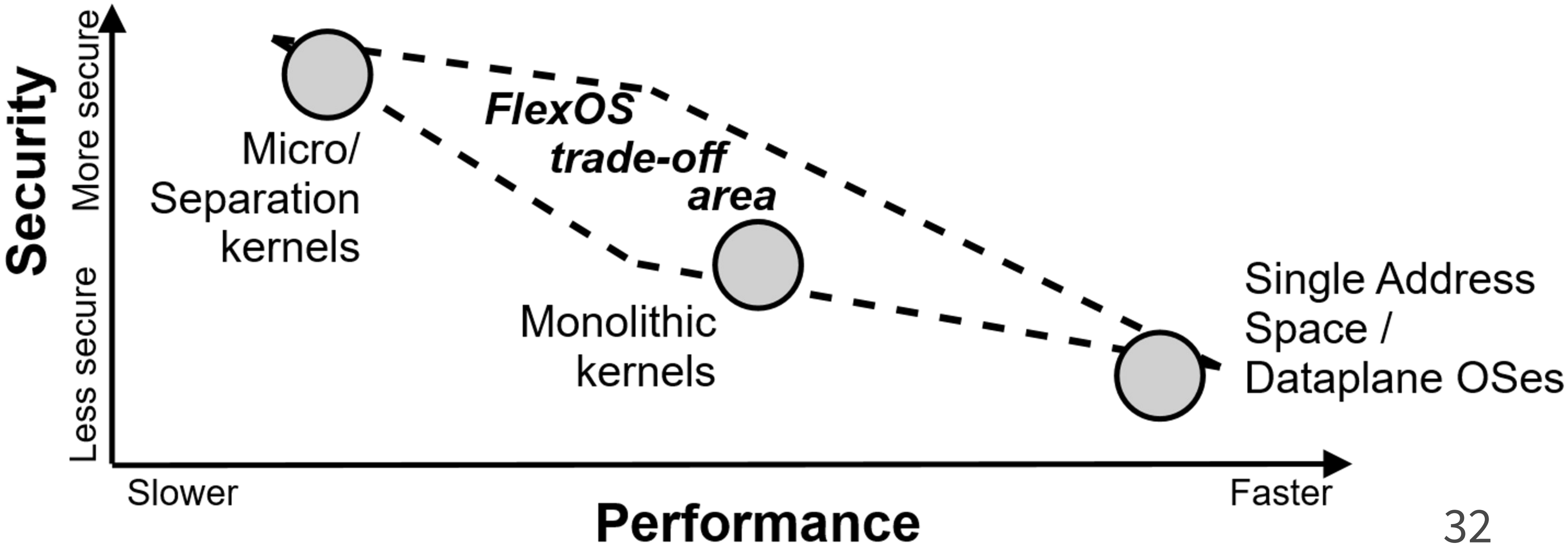
- OS security/isolation strategies are **fixed** at design time!
  - Isolation granularity, underlying mechanisms, data sharing strategies (copy/share)



FlexOS: Flexible Compartmentalization

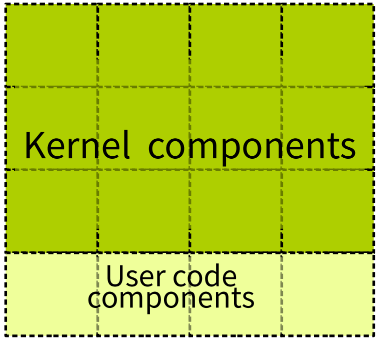
Motivation

Decouple security/isolation decisions **from the OS design**



FlexOS: Flexible Compartmentalization

Overview



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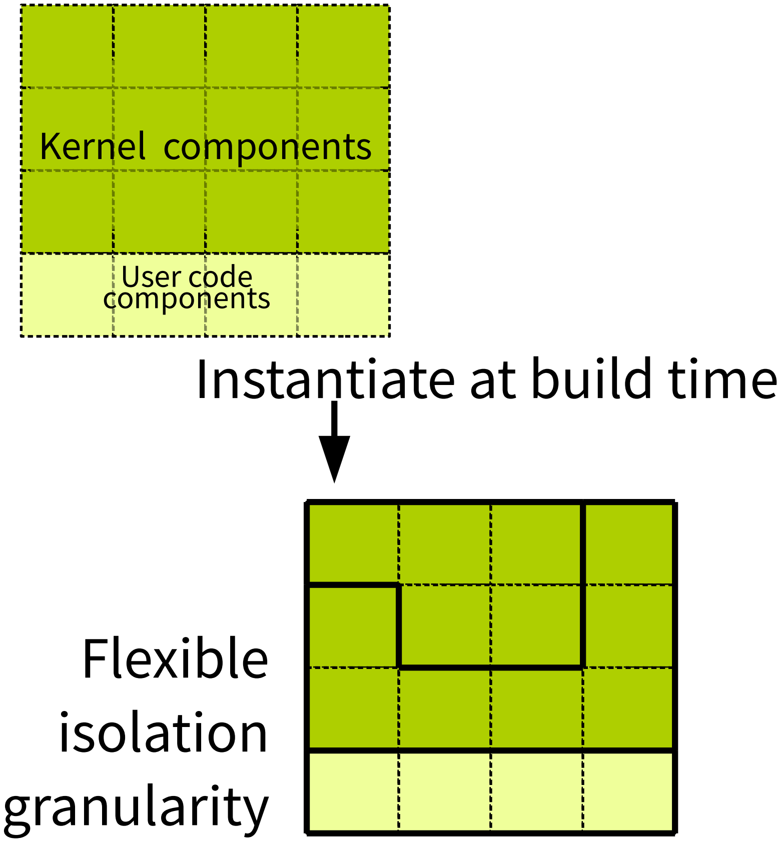

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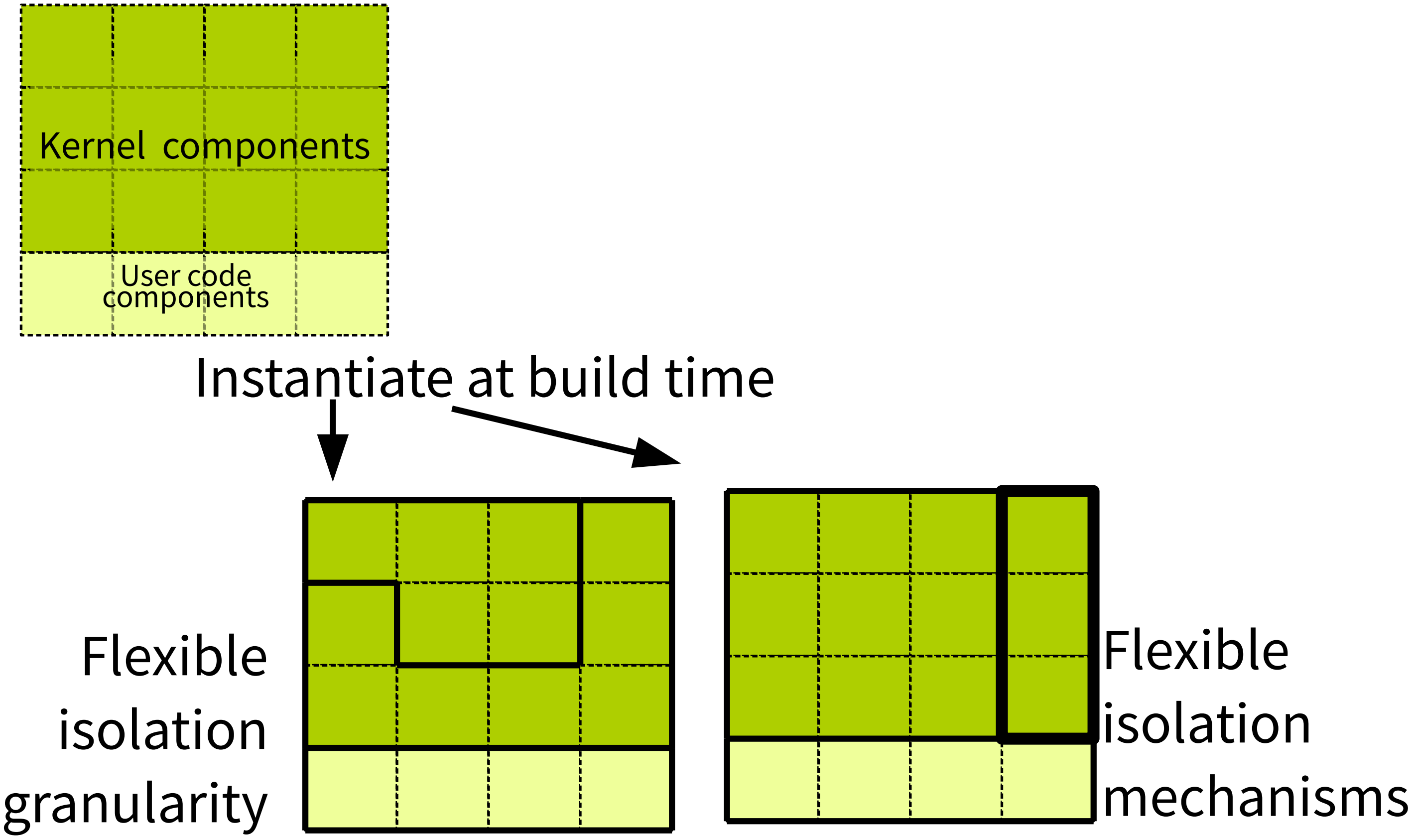

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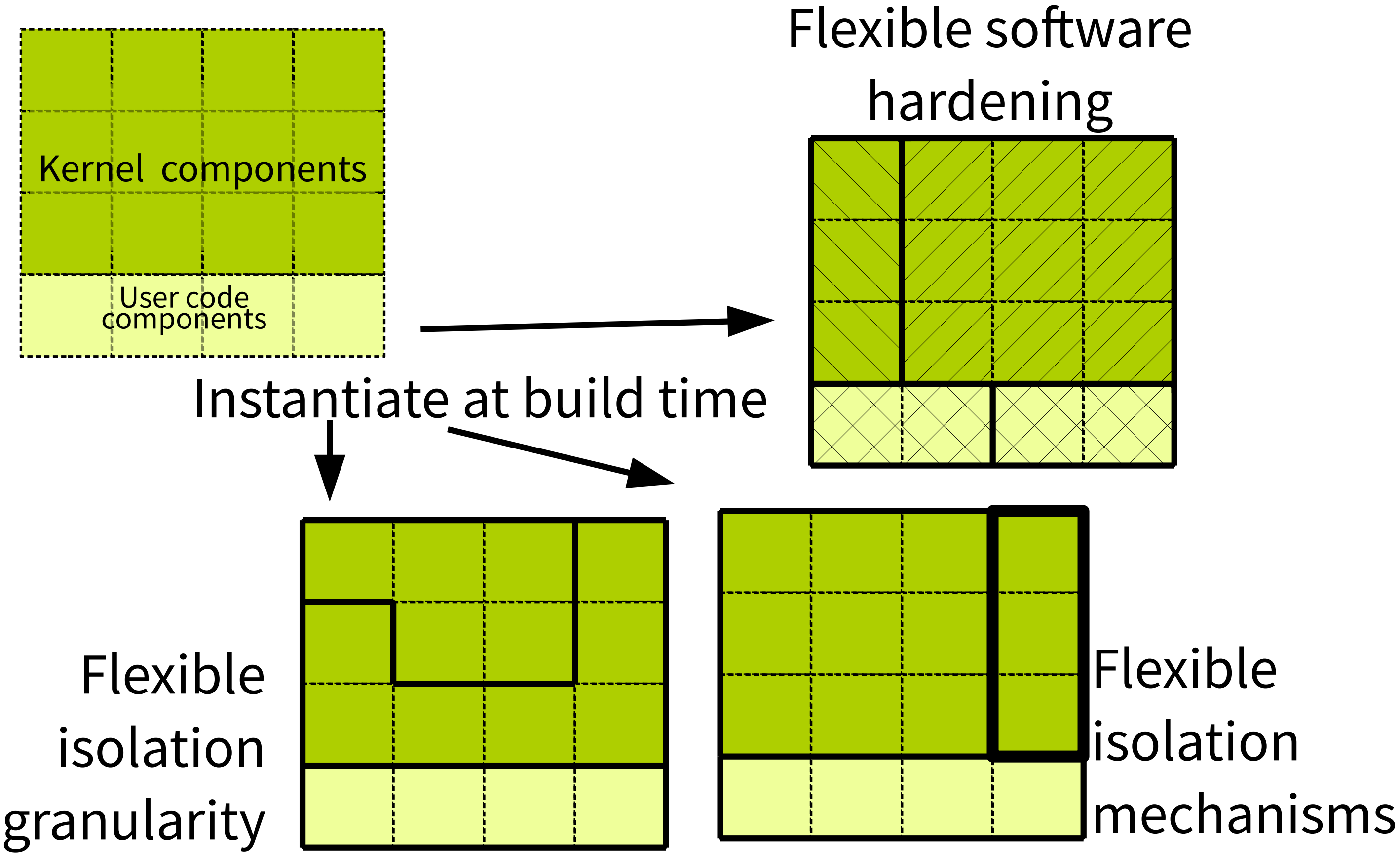

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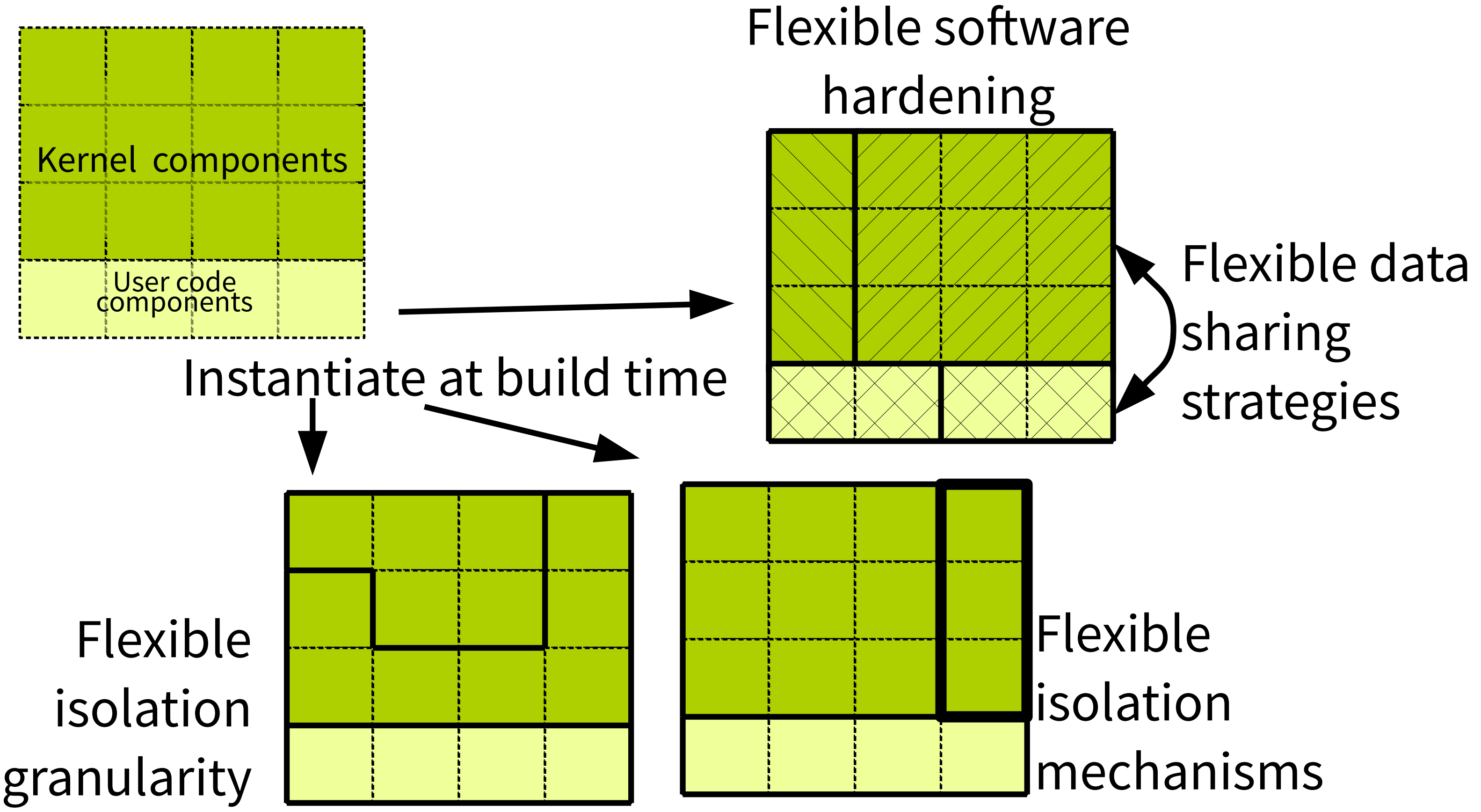

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How does it Work?

- **Software needs to be ported:**
  - Identify the finest grain components to be compartmentalized (e.g. a library, a function)
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- At build time, specify a given compartmentalization configuration
- The toolchain automatically leverages annotations and perform extensive **code generation**:
  - Instantiating gates at compartment boundaries
  - Allocating shared data in dedicated areas

FlexOS: Flexible Compartmentalization

Prototype

FlexOS: Flexible Compartmentalization

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- **Implementation on top of Unikraft**

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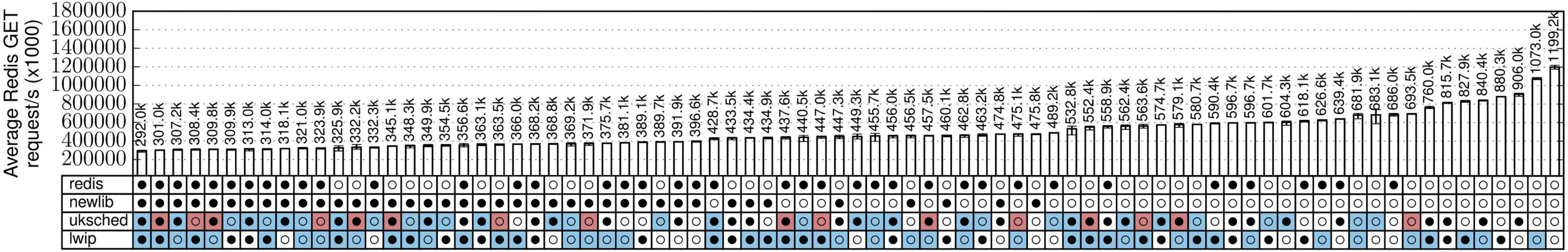
- Port of applications: Redis, Nginx, SQLite, iPerf server



Vast safety/performance design space

Interface Security

Interface Security

Recall our Illustrative Example

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Isolate `library_function` and `main` in different compartment creates a new internal trust boundary: the interface between the two compartments: here it is the call to `library_function`

Assume `main` is malicious and send corrupted values through this interface

The lack of check in `library_function` gives an untrusted caller (e.g. `main`) an arbitrary memory write primitive

Interface Security

Motivation

```c
double data[DATA_SIZE];

/* … */

int library_function(int index, double object) {
	if (index >= DATA_SIZE || index < 0)
		return -1;
	data[index] = object;

	/* … */
}

int main() {
	int index = get_index();
	double object = get_index();

	if (index < DATA_SIZE)
		library_function(index, object);

	/* … */
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```

Fix: have a check within the trusted compartment

Compartment Interface Vulnerabilities (CIVs)

Definition

- **CIVs = Vulnerabilities arising due to lack of or improper Control and Data flow validation at compartment boundaries**
- **Classes of CIVs:**

Data Leakages	***Data Corruption***	***Temporal Violations***

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Data Leakages	*Data Corruption*	*Temporal Violations*
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Interface Security

Problem Statement

- **The vast majority of modern compartmentalization framework ignore the problem of interface safety!**

Interface Security

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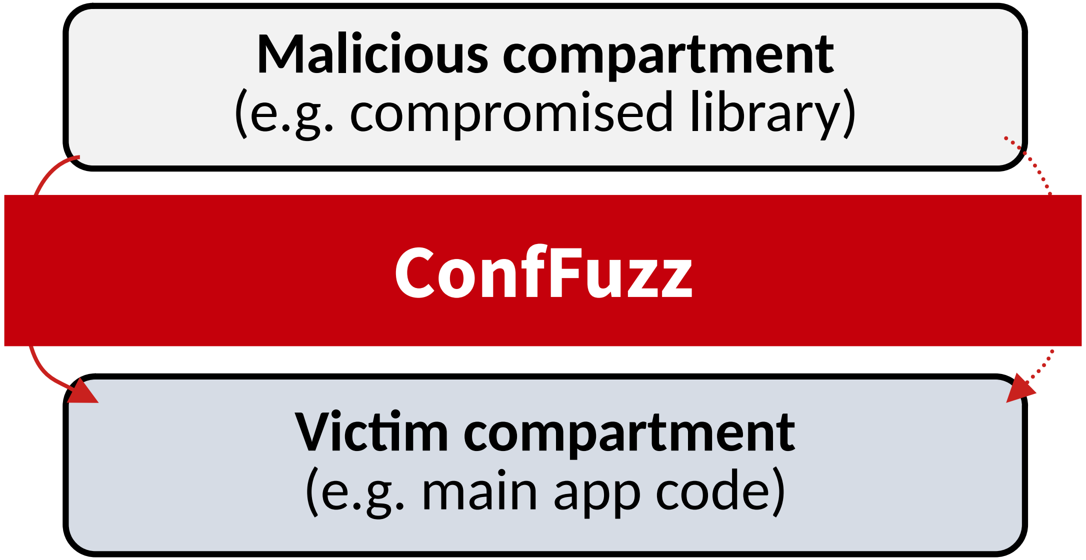
- **The vast majority of modern compartmentalization framework ignore the problem of interface safety!**
- **How bad is the problem?**
  - *How many CIVs are there at legacy, unported APIs?*
  - *Are all APIs similarly affected by CIVs? (e.g., library v.s. module APIs)*
  - *How hard are these CIVs to address when compartmentalizing?*
  - *How bad are they? i.e., if you don't fix them, what can attackers do?*

ConfFuzz: Fuzzing for CIVs



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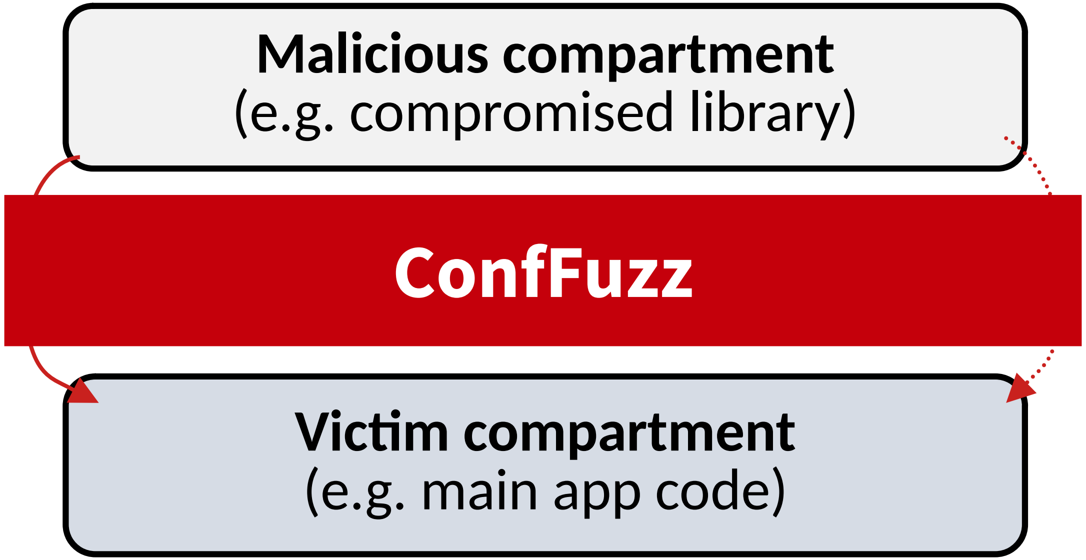

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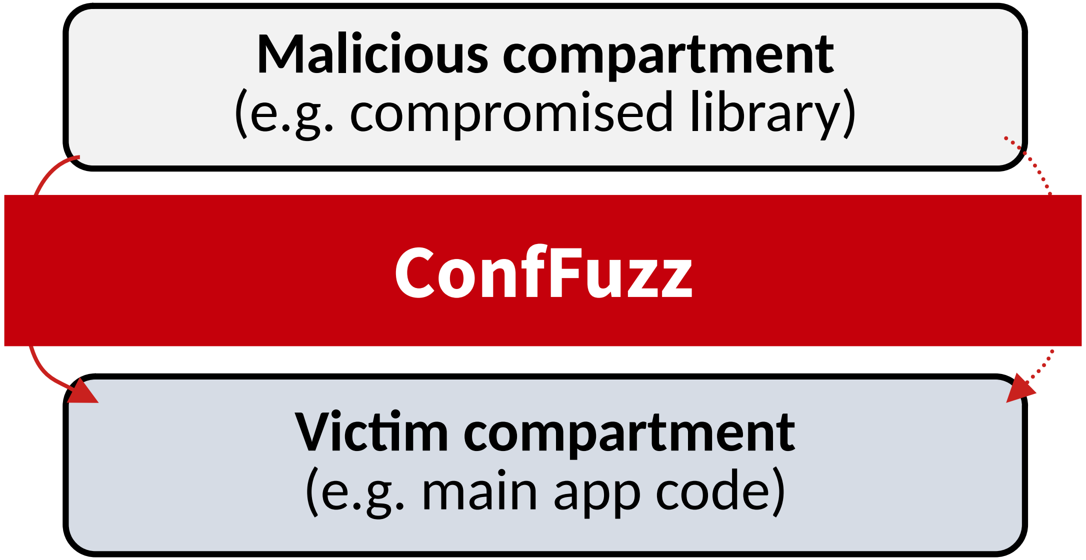

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  - E.g. library/main app. Code
- It runs on monolithic (non-compartmentalized) software to uncover a maximum of CIVs
- We apply it to many compartmentalization scenarios and **study the bugs we uncover**

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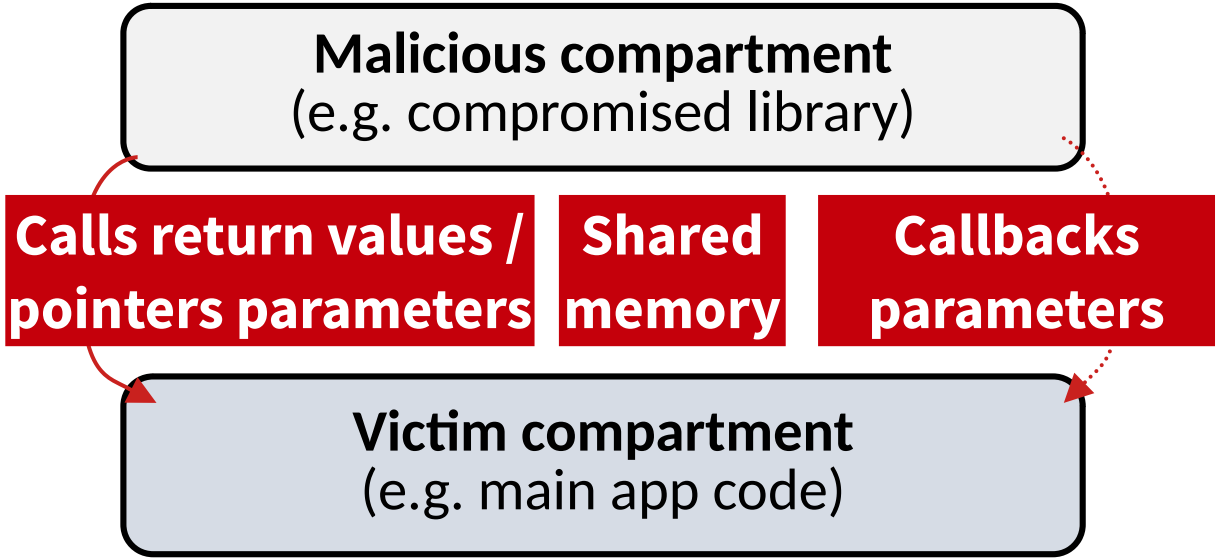

- ConfFuzz covers the entire attack surface of a victim compartment
- Can fuzz both ways:
  - **SandBox**: malicious compartment calls the victim
  - **SafeBox**: the victim calls the malicious compartment

TM	Application	Compartment API	References	Crashes		Victims	API Coverage		Impact (of which arbitrary)				
				Raw	*Dedup.*		*Callers*	*Coverage*	*Read*	*Write*	*Exec*	*Alloc*	*Null*
Sandbox	HTTPd	libmarkdown	[42]	192	13	3	1	100% (4/4)	10 (8)	7 (7)	0 (0)	1	4
		mod_markdown		381	71	5	1	100% (1/1)	62 (52)	17 (14)	2 (1)	0	30
	aspell	libaspell		278	8	1	1	34% (48/141)	7 (7)	7 (7)	2 (1)	0	3
	bind9	libxml2 (write API)		0	0	0	1	86% (13/15)	0 (0)	0 (0)	0 (0)	0	0
	bzip2	libbz2	[67], [5]	16	5	1	1	62% (5/8)	5 (2)	1 (0)	0 (0)	0	0
	cURL	libnghttp2		61	7	2	1	50% (18/36)	3 (3)	5 (5)	0 (0)	1	3
	exif	libexif		400	7	1	1	10% (13/129)	3 (3)	0 (0)	0 (0)	0	5
	FFmpeg	libavcodec		316	20	3	4	31% (19/60)	13 (12)	12 (12)	0 (0)	3	7
		libavfilter		51	1	1	2	12% (2/16)	1 (1)	0 (0)	0 (0)	0	1
		libavformat		217	9	2	3	52% (10/19)	8 (7)	1 (1)	0 (0)	0	7
	file	libmagic		150	5	1	1	63% (7/11)	5 (2)	1 (1)	0 (0)	0	4
	git	libcurl	[22]	13	4	2	1	90% (18/20)	2 (2)	2 (2)	0 (0)	1	1
		libpcre		81	2	1	1	44% (8/18)	2 (2)	0 (0)	0 (0)	2	0
	Inkscape	libpng	[67]	66	3	1	1	46% (14/30)	2 (1)	2 (2)	0 (0)	0	1
		libpoppler	[16]	81	4	2	1	100% (9/9)	4 (3)	4 (4)	0 (0)	0	2
	libxml2-tests	libxml2 (write API)		0	0	0	1	100% (47/47)	0 (0)	0 (0)	0 (0)	0	0
	lighttpd	mod_deflate		117	26	2	1	100% (6/6)	16 (11)	5 (0)	1 (1)	2	9
	Image Magick	libghostscript	[5]	67	14	2	1	100% (11/11)	4 (2)	1 (1)	0 (0)	3	9
		libpng	[67]	778	44	1	2	22% (17/77)	2 (2)	9 (9)	2 (0)	2	39
		libtiff	[67]	197	14	2	1	30% (13/43)	3 (3)	6 (6)	0 (0)	0	13
	Nginx	libpcre		144	10	1	1	93% (14/15)	8 (7)	3 (3)	0 (0)	6	2
		mod_geoip	[52]	276	25	2	1	35% (5/14)	21 (17)	4 (1)	1 (1)	1	10
	Okular	libmarkdown	[42]	64	5	3	1	100% (4/4)	3 (1)	0 (0)	0 (0)	1	2
		libpoppler	[16]	195	9	1	1	6% (24/379)	8 (6)	7 (7)	0 (0)	1	4
	Redis	mod_redisbloom		389	23	1	1	42% (8/19)	18 (13)	6 (4)	0 (0)	0	13
		mod_redisearch		381	21	1	1	54% (18/33)	15 (14)	14 (11)	0 (0)	0	12
	rsync	libpopt		167	8	1	1	90% (9/10)	4 (3)	2 (0)	0 (0)	0	5
	squid	libxml2		226	12	1	1	70% (7/10)	9 (5)	3 (3)	4 (1)	0	4
	su	libaudit		0	0	0	1	66% (2/3)	0 (0)	0 (0)	0 (0)	0	0
	Wireshark	libpcap		162	8	2	1	50% (20/40)	8 (3)	5 (5)	0 (0)	0	4
		libzlib		42	1	1	1	85% (6/7)	0 (0)	0 (0)	0 (0)	0	1
	Total:			5508	379	47	38	N/A	246 (192)	124 (105)	12 (5)	24	195
Safebox	cURL	libssl	[5]	198	27	1	1	25% (14/56)	18 (10)	5 (4)	1 (1)	0	17
	GPA	libgpgme		174	9	1	1	4% (3/72)	7 (2)	0 (0)	0 (0)	0	6
	GPG	libgcrypt	[5]	4221	105	1	1	15% (15/95)	64 (60)	4 (0)	0 (0)	77	20
	Memcached	internal_hashtable	[45]	4037	16	1	1	50% (6/12)	10 (5)	2 (0)	0 (0)	1	6
	Nginx	internal_libssl-keys	[45], [60], [15], [34]	599	46	1	1	50% (2/4)	32 (1)	28 (0)	0 (0)	0	22
		libssl	[5], [1], [22], [51]	346	39	2	1	11% (11/96)	16 (13)	19 (13)	2 (1)	0	26
	sudo	internal_auth-api		191	5	1	1	100% (5/5)	5 (4)	0 (0)	0 (0)	0	4
		libapparmor		97	3	1	1	100% (2/2)	2 (2)	2 (0)	0 (0)	0	2
	Total:			9863	250	9	8	N/A	154 (97)	60 (17)	3 (2)	78	103

25 applications

36 APIs in total

TM	Application	Compartment API	References	Crashes		Victims	API Coverage		Impact (of which arbitrary)				
				Raw	*Dedup.*		*Callers*	*Coverage*	*Read*	*Write*	*Exec*	*Alloc*	*Null*
Sandbox	HTTPd	libmarkdown	[42]	192	13	3	1	100% (4/4)	10 (8)	7 (7)	0 (0)	1	4
		mod_markdown		381	71	5	1	100% (1/1)	62 (52)	17 (14)	2 (1)	0	30
	aspell	libaspell		278	8	1	1	34% (48/141)	7 (7)	7 (7)	2 (1)	0	3
	bind9	libxml2 (write API)		0	0	0	1	86% (13/15)	0 (0)	0 (0)	0 (0)	0	0
	bzip2	libbz2	[67], [5]	16	5	1	1	62% (5/8)	5 (2)	1 (0)	0 (0)	0	0
	cURL	libnghttp2		61	7	2	1	50% (18/36)	3 (3)	5 (5)	0 (0)	1	3
	exif	libexif		400	7	1	1	10% (13/129)	3 (3)	0 (0)	0 (0)	0	5
	FFmpeg	libavcodec		316	20	3	4	31% (19/60)	13 (12)	12 (12)	0 (0)	3	7
		libavfilter		51	1	1	2	12% (2/16)	1 (1)	0 (0)	0 (0)	0	1
		libavformat		217	9	2	3	52% (10/19)	8 (7)	1 (1)	0 (0)	0	7
	file	libmagic		150	5	1	1	63% (7/11)	5 (2)	1 (1)	0 (0)	0	4
	git	libcurl	[22]	13	4	2	1	90% (18/20)	2 (2)	2 (2)	0 (0)	1	1
		libpcre		81	2	1	1	44% (8/18)	2 (2)	0 (0)	0 (0)	2	0
	Inkscape	libpng	[67]	66	3	1	1	46% (14/30)	2 (1)	2 (2)	0 (0)	0	1
		libpoppler	[16]	81	4	2	1	100% (9/9)	4 (3)	4 (4)	0 (0)	0	2
	libxml2-tests	libxml2 (write API)		0	0	0	1	100% (47/47)	0 (0)	0 (0)	0 (0)	0	0
	lighttpd	mod_deflate		117	26	2	1	100% (6/6)	16 (11)	5 (0)	1 (1)	2	9
	Image Magick	libghostscript	[5]	67	14	2	1	100% (11/11)	4 (2)	1 (1)	0 (0)	3	9
		libpng	[67]	778	44	1	2	22% (17/77)	2 (2)	9 (9)	2 (0)	2	39
		libtiff	[67]	197	14	2	1	30% (13/43)	3 (3)	6 (6)	0 (0)	0	13
	Nginx	libpcre		144	10	1	1	93% (14/15)	8 (7)	3 (3)	0 (0)	6	2
		mod_geoip	[52]	276	25	2	1	35% (5/14)	21 (17)	4 (1)	1 (1)	1	10
	Okular	libmarkdown	[42]	64	5	3	1	100% (4/4)	3 (1)	0 (0)	0 (0)	1	2
		libpoppler	[16]	195	9	1	1	6% (24/379)	8 (6)	7 (7)	0 (0)	1	4
	Redis	mod_redisbloom		389	23	1	1	42% (8/19)	18 (13)	6 (4)	0 (0)	0	13
		mod_redisearch		381	21	1	1	54% (18/33)	15 (14)	14 (11)	0 (0)	0	12
	rsync	libpopt		167	8	1	1	90% (9/10)	4 (3)	2 (0)	0 (0)	0	5
	squid	libxml2		226	12	1	1	70% (7/10)	9 (5)	3 (3)	4 (1)	0	4
	su	libaudit		0	0	0	1	66% (2/3)	0 (0)	0 (0)	0 (0)	0	0
	Wireshark	libpcap		162	8	2	1	50% (20/40)	8 (3)	5 (5)	0 (0)	0	4
		libzlib		42	1	1	1	85% (6/7)	0 (0)	0 (0)	0 (0)	0	1
	Total:			5508	379	47	38	N/A	246 (192)	124 (105)	12 (5)	24	195
Safebox	cURL	libssl	[5]	198	27	1	1	25% (14/56)	18 (10)	5 (4)	1 (1)	0	17
	GPA	libgpgme		174	9	1	1	4% (3/72)	7 (2)	0 (0)	0 (0)	0	6
	GPG	libgcrypt	[5]	4221	105	1	1	15% (15/95)	64 (60)	4 (0)	0 (0)	77	20
	Memcached	internal_hashtable	[45]	4037	16	1	1	50% (6/12)	10 (5)	2 (0)	0 (0)	1	6
	Nginx	internal_libssl-keys	[45], [60], [15], [34]	599	46	1	1	50% (2/4)	32 (1)	28 (0)	0 (0)	0	22
		libssl	[5], [1], [22], [51]	346	39	2	1	11% (11/96)	16 (13)	19 (13)	2 (1)	0	26
	sudo	internal_auth-api		191	5	1	1	100% (5/5)	5 (4)	0 (0)	0 (0)	0	4
		libapparmor		97	3	1	1	100% (2/2)	2 (2)	2 (0)	0 (0)	0	2
	Total:			9863	250	9	8	N/A	154 (97)	60 (17)	3 (2)	78	103

Library APIs

Module APIs

Internal APIs

25 applications

36 APIs in total

TM	Application	Compartment API	References	Crashes		Victims	API Coverage		Impact (of which arbitrary)				
				Raw	*Dedup.*		*Callers*	*Coverage*	*Read*	*Write*	*Exec*	*Alloc*	*Null*
Sandbox	HTTPd	libmarkdown	[42]	192	13	3	1	100% (4/4)	10 (8)	7 (7)	0 (0)	1	4
		mod_markdown		381	71	5	1	100% (1/1)	62 (52)	17 (14)	2 (1)	0	30
	aspell	libaspell		278	8	1	1	34% (48/141)	7 (7)	7 (7)	2 (1)	0	3
	bind9	libxml2 (write API)		0	0	0	1	86% (13/15)	0 (0)	0 (0)	0 (0)	0	0
	bzip2	libbz2	[67], [5]	16	5	1	1	62% (5/8)	5 (2)	1 (0)	0 (0)	0	0
	cURL	libnghttp2		61	7	2	1	50% (18/36)	3 (3)	5 (5)	0 (0)	1	3
	exif	libexif		400	7	1	1	10% (13/129)	3 (3)	0 (0)	0 (0)	0	5
	FFmpeg	libavcodec		316	20	3	4	31% (19/60)	13 (12)	12 (12)	0 (0)	3	7
		libavfilter		51	1	1	2	12% (2/16)	1 (1)	0 (0)	0 (0)	0	1
		libavformat		217	9	2	3	52% (10/19)	8 (7)	1 (1)	0 (0)	0	7
	file	libmagic		150	5	1	1	63% (7/11)	5 (2)	1 (1)	0 (0)	0	4
	git	libcurl	[22]	13	4	2	1	90% (18/20)	2 (2)	2 (2)	0 (0)	1	1
		libpcre		81	2	1	1	44% (8/18)	2 (2)	0 (0)	0 (0)	2	0
	Inkscape	libpng	[67]	66	3	1	1	46% (14/30)	2 (1)	2 (2)	0 (0)	0	1
		libpoppler	[16]	81	4	2	1	100% (9/9)	4 (3)	4 (4)	0 (0)	0	2
	libxml2-tests	libxml2 (write API)		0	0	0	1	100% (47/47)	0 (0)	0 (0)	0 (0)	0	0
	lighttpd	mod_deflate		117	26	2	1	100% (6/6)	16 (11)	5 (0)	1 (1)	2	9
	Image Magick	libghostscript	[5]	67	14	2	1	100% (11/11)	4 (2)	1 (1)	0 (0)	3	9
		libpng	[67]	778	44	1	2	22% (17/77)	2 (2)	9 (9)	2 (0)	2	39
		libtiff	[67]	197	14	2	1	30% (13/43)	3 (3)	6 (6)	0 (0)	0	13
	Nginx	libpcre		144	10	1	1	93% (14/15)	8 (7)	3 (3)	0 (0)	6	2
		mod_geoip	[52]	276	25	2	1	35% (5/14)	21 (17)	4 (1)	1 (1)	1	10
	Okular	libmarkdown	[42]	64	5	3	1	100% (4/4)	3 (1)	0 (0)	0 (0)	1	2
		libpoppler	[16]	195	9	1	1	6% (24/379)	8 (6)	7 (7)	0 (0)	1	4
	Redis	mod_redisbloom		389	23	1	1	42% (8/19)	18 (13)	6 (4)	0 (0)	0	13
		mod_redisearch		381	21	1	1	54% (18/33)	15 (14)	14 (11)	0 (0)	0	12
	rsync	libpopt		167	8	1	1	90% (9/10)	4 (3)	2 (0)	0 (0)	0	5
	squid	libxml2		226	12	1	1	70% (7/10)	9 (5)	3 (3)	4 (1)	0	4
	su	libaudit		0	0	0	1	66% (2/3)	0 (0)	0 (0)	0 (0)	0	0
	Wireshark	libpcap		162	8	2	1	50% (20/40)	8 (3)	5 (5)	0 (0)	0	4
		libzlib		42	1	1	1	85% (6/7)	0 (0)	0 (0)	0 (0)	0	1
	Total:			5508	379	47	38	N/A	246 (192)	124 (105)	12 (5)	24	195
Safebox	cURL	libssl	[5]	198	27	1	1	25% (14/56)	18 (10)	5 (4)	1 (1)	0	17
	GPA	libgpgme		174	9	1	1	4% (3/72)	7 (2)	0 (0)	0 (0)	0	6
	GPG	libgcrypt	[5]	4221	105	1	1	15% (15/95)	64 (60)	4 (0)	0 (0)	77	20
	Memcached	internal_hashtable	[45]	4037	16	1	1	50% (6/12)	10 (5)	2 (0)	0 (0)	1	6
	Nginx	internal_libssl-keys	[45], [60], [15], [34]	599	46	1	1	50% (2/4)	32 (1)	28 (0)	0 (0)	0	22
		libssl	[5], [1], [22], [51]	346	39	2	1	11% (11/96)	16 (13)	19 (13)	2 (1)	0	26
	sudo	internal_auth-api		191	5	1	1	100% (5/5)	5 (4)	0 (0)	0 (0)	0	4
		libapparmor		97	3	1	1	100% (2/2)	2 (2)	2 (0)	0 (0)	0	2
	Total:			9863	250	9	8	N/A	154 (97)	60 (17)	3 (2)	78	103

Library APIs

Module APIs

Internal APIs

25 applications

36 APIs in total

16 of which taken from the literature

TM	Application	Compartment API	References	Crashes Raw	Crashes Dedup.	Victims	API Coverage Callers	API Coverage Coverage	Impact (of which arbitrary) Read	Write	Exec	Alloc	Null
Sandbox	HTTPd	libmarkdown	[42]	192	13	3	1	100% (4/4)	10 (8)	7 (7)	0 (0)	1	4
		mod_markdown		381	71	5	1	100% (1/1)	62 (52)	17 (14)	2 (1)	0	30
	aspell	libaspell		278	8	1	1	34% (48/141)	7 (7)	7 (7)	2 (1)	0	3
	bind9	libxml2 (write API)		0	0	0	1	86% (13/15)	0 (0)	0 (0)	0 (0)	0	0
	bzip2	libbz2	[67], [5]	16	5	1	1	62% (5/8)	5 (2)	1 (0)	0 (0)	0	0
	cURL	libnghttp2		61	7	2	1	50% (18/36)	3 (3)	5 (5)	0 (0)	1	3
	exif	libexif		400	7	1	1	10% (13/129)	3 (3)	0 (0)	0 (0)	0	5
	FFmpeg	libavcodec		316	20	3	4	31% (19/60)	13 (12)	12 (12)	0 (0)	3	7
		libavfilter		51	1	1	2	12% (2/16)	1 (1)	0 (0)	0 (0)	0	1
		libavformat		217	9	2	3	52% (10/19)	8 (7)	1 (1)	0 (0)	0	7
	file	libmagic		150	5	1	1	63% (7/11)	5 (2)	1 (1)	0 (0)	0	4
	git	libcurl	[22]	13	4	2	1	90% (18/20)	2 (2)	2 (2)	0 (0)	1	1
		libpcre		81	2	1	1	44% (8/18)	2 (2)	0 (0)	0 (0)	2	0
	Inkscape	libpng	[67]	66	3	1	1	46% (14/30)	2 (1)	2 (2)	0 (0)	0	1
		libpoppler	[16]	81	4	2	1	100% (9/9)	4 (3)	4 (4)	0 (0)	0	2
	libxml2-tests	libxml2 (write API)		0	0	0	1	100% (47/47)	0 (0)	0 (0)	0 (0)	0	0
	lighttpd	mod_deflate		117	26	2	1	100% (6/6)	16 (11)	5 (0)	1 (1)	2	9
	Image Magick	libghostscript	[5]	67	14	2	1	100% (11/11)	4 (2)	1 (1)	0 (0)	3	9
		libpng	[67]	778	44	1	2	22% (17/77)	2 (2)	9 (9)	2 (0)	2	39
		libtiff	[67]	197	14	2	1	30% (13/43)	3 (3)	6 (6)	0 (0)	0	13
	Nginx	libpcre		144	10	1	1	93% (14/15)	8 (7)	3 (3)	0 (0)	6	2
		mod_geoip	[52]	276	25	2	1	35% (5/14)	21 (17)	4 (1)	1 (1)	1	10
	Okular	libmarkdown	[42]	64	5	3	1	100% (4/4)	3 (1)	0 (0)	0 (0)	1	2
		libpoppler	[16]	195	9	1	1	6% (24/379)	8 (6)	7 (7)	0 (0)	1	4
	Redis	mod_redisbloom		389	23	1	1	42% (8/19)	18 (13)	6 (4)	0 (0)	0	13
		mod_redisearch		381	21	1	1	54% (18/33)	15 (14)	14 (11)	0 (0)	0	12
	rsync	libpopt		167	8	1	1	90% (9/10)	4 (3)	2 (0)	0 (0)	0	5
	squid	libxml2		226	12	1	1	70% (7/10)	9 (5)	3 (3)	4 (1)	0	4
	su	libaudit		0	0	0	1	66% (2/3)	0 (0)	0 (0)	0 (0)	0	0
	Wireshark	libpcap		162	8	2	1	50% (20/40)	8 (3)	5 (5)	0 (0)	0	4
		libzlib		42	1	1	1	85% (6/7)	0 (0)	0 (0)	0 (0)	0	1
	Total:			5508	379	47	38	N/A	246 (192)	124 (105)	12 (5)	24	195
Safebox	cURL	libssl	[5]	198	27	1	1	25% (14/56)	18 (10)	5 (4)	1 (1)	0	17
	GPA	libgpgme		174	9	1	1	4% (3/72)	7 (2)	0 (0)	0 (0)	0	6
	GPG	libgcrypt	[5]	4221	105	1	1	15% (15/95)	64 (60)	4 (0)	0 (0)	77	20
	Memcached	internal_hashtable	[45]	4037	16	1	1	50% (6/12)	10 (5)	2 (0)	0 (0)	1	6
	Nginx	internal_libssl-keys	[45], [60], [15], [34]	599	46	1	1	50% (2/4)	32 (1)	28 (0)	0 (0)	0	22
		libssl	[5], [1], [22], [51]	346	39	2	1	11% (11/96)	16 (13)	19 (13)	2 (1)	0	26
	sudo	internal_auth-api		191	5	1	1	100% (5/5)	5 (4)	0 (0)	0 (0)	0	4
		libapparmor		97	3	1	1	100% (2/2)	2 (2)	2 (0)	0 (0)	0	2
	Total:			9863	250	9	8	N/A	154 (97)	60 (17)	3 (2)	78	102

Library APIs

Module APIs

Internal APIs

25 applications

36 APIs in total

16 of which taken from the literature

Found 629 unique CIVs

TM	Application	Compartment API	References	Crashes Raw	Crashes Dedup.	Victims	API Coverage Callers	API Coverage Coverage	Impact (of which arbitrary) Read	Write	Exec	Alloc	Null
Sandbox	HTTPd	libmarkdown	[42]	192	13	3	1	100% (4/4)	10 (8)	7 (7)	0 (0)	1	4
		mod_markdown		381	71	5	1	100% (1/1)	62 (52)	17 (14)	2 (1)	0	30
	aspell	libaspell		278	8	1	1	34% (48/141)	7 (7)	7 (7)	2 (1)	0	3
	bind9	libxml2 (write API)		0	0	0	1	86% (13/15)	0 (0)	0 (0)	0 (0)	0	0
	bzip2	libbz2	[67], [5]	16	5	1	1	62% (5/8)	5 (2)	1 (0)	0 (0)	0	0
	cURL	libnghttp2		61	7	2	1	50% (18/36)	3 (3)	5 (5)	0 (0)	1	3
	exif	libexif		400	7	1	1	10% (13/129)	3 (3)	0 (0)	0 (0)	0	5
	FFmpeg	libavcodec		316	20	3	4	31% (19/60)	13 (12)	12 (12)	0 (0)	3	7
		libavfilter		51	1	1	2	12% (2/16)	1 (1)	0 (0)	0 (0)	0	1
		libavformat		217	9	2	3	52% (10/19)	8 (7)	1 (1)	0 (0)	0	7
	file	libmagic		150	5	1	1	63% (7/11)	5 (2)	1 (1)	0 (0)	0	4
	git	libcurl	[22]	13	4	2	1	90% (18/20)	2 (2)	2 (2)	0 (0)	1	1
		libpcre		81	2	1	1	44% (8/18)	2 (2)	0 (0)	0 (0)	2	0
	Inkscape	libpng	[67]	66	3	1	1	46% (14/30)	2 (1)	2 (2)	0 (0)	0	1
		libpoppler	[16]	81	4	2	1	100% (9/9)	4 (3)	4 (4)	0 (0)	0	2
	libxml2-tests	libxml2 (write API)		0	0	0	1	100% (47/47)	0 (0)	0 (0)	0 (0)	0	0
	lighttpd	mod_deflate		117	26	2	1	100% (6/6)	16 (11)	5 (0)	1 (1)	2	9
	Image Magick	libghostscript	[5]	67	14	2	1	100% (11/11)	4 (2)	1 (1)	0 (0)	3	9
		libpng	[67]	778	44	1	2	22% (17/77)	2 (2)	9 (9)	2 (0)	2	39
		libtiff	[67]	197	14	2	1	30% (13/43)	3 (3)	6 (6)	0 (0)	0	13
	Nginx	libpcre		144	10	1	1	93% (14/15)	8 (7)	3 (3)	0 (0)	6	2
		mod_geoip	[52]	276	25	2	1	35% (5/14)	21 (17)	4 (1)	1 (1)	1	10
	Okular	libmarkdown	[42]	64	5	3	1	100% (4/4)	3 (1)	0 (0)	0 (0)	1	2
		libpoppler	[16]	195	9	1	1	6% (24/379)	8 (6)	7 (7)	0 (0)	1	4
	Redis	mod_redisbloom		389	23	1	1	42% (8/19)	18 (13)	6 (4)	0 (0)	0	13
		mod_redisearch		381	21	1	1	54% (18/33)	15 (14)	14 (11)	0 (0)	0	12
	rsync	libpopt		167	8	1	1	90% (9/10)	4 (3)	2 (0)	0 (0)	0	5
	squid	libxml2		226	12	1	1	70% (7/10)	9 (5)	3 (3)	4 (1)	0	4
	su	libaudit		0	0	0	1	66% (2/3)	0 (0)	0 (0)	0 (0)	0	0
	Wireshark	libpcap		162	8	2	1	50% (20/40)	8 (3)	5 (5)	0 (0)	0	4
		libzlib		42	1	1	1	85% (6/7)	0 (0)	0 (0)	0 (0)	0	1
	Total:			5508	379	47	38	N/A	246 (192)	124 (105)	12 (5)	24	195
Safebox	cURL	libssl	[5]	198	27	1	1	25% (14/56)	18 (10)	5 (4)	1 (1)	0	17
	GPA	libgpgme		174	9	1	1	4% (3/72)	7 (2)	0 (0)	0 (0)	0	6
	GPG	libgcrypt	[5]	4221	105	1	1	15% (15/95)	64 (60)	4 (0)	0 (0)	77	20
	Memcached	internal_hashtable	[45]	4037	16	1	1	50% (6/12)	10 (5)	2 (0)	0 (0)	1	6
	Nginx	internal_libssl-keys	[45], [60], [15], [34]	599	46	1	1	50% (2/4)	32 (1)	28 (0)	0 (0)	0	22
		libssl	[5], [1], [22], [51]	346	39	2	1	11% (11/96)	16 (13)	19 (13)	2 (1)	0	26
	sudo	internal_auth-api		191	5	1	1	100% (5/5)	5 (4)	0 (0)	0 (0)	0	4
		libapparmor		97	3	1	1	100% (2/2)	2 (2)	2 (0)	0 (0)	0	2
	Total:			9863	250	9	8	N/A	154 (97)	60 (17)	3 (2)	78	103

Library APIs

Module APIs

Internal APIs

5 security impact types

25 applications

36 APIs in total

16 of which taken from the literature

Found 629 unique CIVs

TM	Application	Compartment API	References	Crashes Raw	Crashes Dedup.	Victims	API Coverage Callers	API Coverage Coverage	Impact (of which arbitrary) Read	Write	Exec	Alloc	Null
Sandbox	HTTPd	libmarkdown	[42]	192	13	3	1	100% (4/4)	10 (8)	7 (7)	0 (0)	1	4
		mod_markdown		381	71	5	1	100% (1/1)	62 (52)	17 (14)	2 (1)	0	30
	aspell	libaspell		278	8	1	1	34% (48/141)	7 (7)	7 (7)	2 (1)	0	3
	bind9	libxml2 (write API)		0	0	0	1	86% (13/15)	0 (0)	0 (0)	0 (0)	0	0
	bzip2	libbz2	[67], [5]	16	5	1	1	62% (5/8)	5 (2)	1 (0)	0 (0)	0	0
	cURL	libnghttp2		61	7	2	1	50% (18/36)	3 (3)	5 (5)	0 (0)	1	3
	exif	libexif		400	7	1	1	10% (13/129)	3 (3)	0 (0)	0 (0)	0	5
	FFmpeg	libavcodec		316	20	3	4	31% (19/60)	13 (12)	12 (12)	0 (0)	3	7
		libavfilter		51	1	1	2	12% (2/16)	1 (1)	0 (0)	0 (0)	0	1
		libavformat		217	9	2	3	52% (10/19)	8 (7)	1 (1)	0 (0)	0	7
	file	libmagic		150	5	1	1	63% (7/11)	5 (2)	1 (1)	0 (0)	0	4
	git	libcurl	[22]	13	4	2	1	90% (18/20)	2 (2)	2 (2)	0 (0)	1	1
		libpcre		81	2	1	1	44% (8/18)	2 (2)	0 (0)	0 (0)	2	0
	Inkscape	libpng	[67]	66	3	1	1	46% (14/30)	2 (1)	2 (2)	0 (0)	0	1
		libpoppler	[16]	81	4	2	1	100% (9/9)	4 (3)	4 (4)	0 (0)	0	2
	libxml2-tests	libxml2 (write API)		0	0	0	1	100% (47/47)	0 (0)	0 (0)	0 (0)	0	0
	lighttpd	mod_deflate		117	26	2	1	100% (6/6)	16 (11)	5 (0)	1 (1)	2	9
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		libtiff	[67]	197	14	2	1	30% (13/43)	3 (3)	6 (6)	0 (0)	0	13
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		mod_geoip	[52]	276	25	2	1	35% (5/14)	21 (17)	4 (1)	1 (1)	1	10
	Okular	libmarkdown	[42]	64	5	3	1	100% (4/4)	3 (1)	0 (0)	0 (0)	1	2
		libpoppler	[16]	195	9	1	1	6% (24/379)	8 (6)	7 (7)	0 (0)	1	4
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	su	libaudit		0	0	0	1	66% (2/3)	0 (0)	0 (0)	0 (0)	0	0
	Wireshark	libpcap		162	8	2	1	50% (20/40)	8 (3)	5 (5)	0 (0)	0	4
		libzlib		42	1	1	1	85% (6/7)	0 (0)	0 (0)	0 (0)	0	1
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		libapparmor		97	3	1	1	100% (2/2)	2 (2)	2 (0)	0 (0)	0	2
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  - 75% of scenarios have at least 1 write vulnerability
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- **Fixing CIVs goes beyond writing simple checks**
  - Requires API redesign in many cases, hard to automate

Availability

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Everything is Open!

- **FlexOS: Flexible compartmentalization**
  - ASPLOS'22 Paper: https://arxiv.org/pdf/2112.06566.pdf
  - Project website: https://project-flexos.github.io
- **ConfFuzz: Fuzzing compartmentalized API vulnerabilities**
  - NDSS'23 Paper: https://arxiv.org/pdf/2212.12904.pdf
  - Project website: https://conffuzz.github.io
- The main author of FlexOS and ConfFuzz is **Hugo Lefeuvre**: https://research.manchester.ac.uk/en/persons/hugo.lefeuvre

FlexOS: Towards Flexible OS Isolation

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ABSTRACT

At design time, modern operating systems are locked in a specific safety and isolation strategy that mixes one or more hardware/software protection mechanisms (e.g. user/kernel separation); revisiting these choices after deployment requires a major refactoring effort. This rigid approach shows its limits given the wide variety of modern applications' safety/performance requirements, when new hardware isolation mechanisms are rolled out, or when existing ones break.

We present FlexOS, a novel OS allowing users to easily specialize the safety and isolation strategy of an OS at compilation/deployment time instead of design time. This modular LibOS is composed of fine-grained components that can be isolated via a range of hardware protection mechanisms with various data sharing strategies and additional software hardening. The OS ships with an exploration technique helping the user navigate the vast safety/performance design space it unlocks. We implement a prototype of the system and demonstrate, for several applications (Redis/Nginx/SQLite), FlexOS' vast configuration space as well as the efficiency of the exploration technique: we evaluate 80 FlexOS configurations for Redis and show how that space can be probabilistically subset to the 5 safest ones under a given performance budget. We also show that, under equivalent configurations, FlexOS performs similarly or better than existing solutions which use fixed safety configurations.

CCS CONCEPTS

• **Software and its engineering → Operating systems**; • **Security and privacy → Operating systems security**.

KEYWORDS

Operating Systems, Security, Isolation

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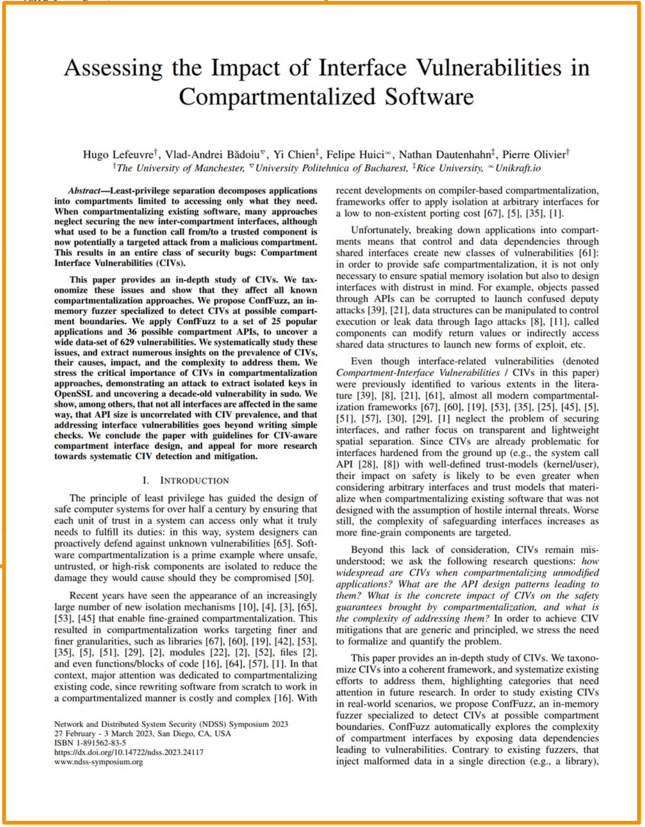
ASPLOS '22, February 28 – March 4, 2022, Lausanne, Switzerland

ACM ISBN 978-1-4503-9205-1/22/02…$15.00
https://doi.org/10.1145/3503222.3507759



Assessing the Impact of Interface Vulnerabilities in Compartmentalized Software

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***Abstract*—Least-privilege separation decomposes applications into compartments limited to accessing only what they need. When compartmentalizing existing software, many approaches neglect securing the new inter-compartment interfaces, although what used to be a function call from/to a trusted component is now potentially a targeted attack from a malicious compartment. This results in an entire class of security bugs: Compartment Interface Vulnerabilities (CIVs).**

This paper provides an in-depth study of CIVs. We taxonomize these issues and show that they affect all known compartmentalization approaches. We propose ConfFuzz, an in-memory fuzzer specialized to detect CIVs at possible compartment boundaries. We apply ConfFuzz to a set of 25 popular applications and 36 possible compartment APIs, to uncover a wide data-set of 629 vulnerabilities. We systematically study these issues, and extract numerous insights on the prevalence of CIVs, their causes, impact, and the complexity to address them. We stress the critical importance of CIVs in compartmentalization approaches, demonstrating an attack to extract isolated keys in OpenSSL and uncovering a decade-old vulnerability in sudo. We show, among others, that not all interfaces are affected in the same way, that API size is uncorrelated with CIV prevalence, and that addressing interface vulnerabilities goes beyond writing simple checks. We conclude the paper with guidelines for CIV-aware compartment interface design, and appeal for more research towards systematic CIV detection and mitigation.

I. INTRODUCTION

The principle of least privilege has guided the design of safe computer systems for over half a century by ensuring that each unit of trust in a system can access only what it truly needs to fulfill its duties: in this way, system designers can proactively defend against unknown vulnerabilities [65]. Software compartmentalization is a prime example where unsafe, untrusted, or high-risk components are isolated to reduce the damage they would cause should they be compromised [50].

Recent years have seen the appearance of an increasingly large number of new isolation mechanisms [10], [4], [3], [65], [53], [45] that enable fine-grained compartmentalization. This resulted in compartmentalization works targeting finer and finer granularities, such as libraries [67], [60], [19], [42], [53], [35], [5], [51], [29], [2], modules [22], [2], [52], files [2], and even functions/blocks of code [16], [64], [57], [1]. In that context, major attention was dedicated to compartmentalizing existing code, since rewriting software from scratch to work in a compartmentalized manner is costly and complex [16]. With recent developments on compiler-based compartmentalization, frameworks offer to apply isolation at arbitrary interfaces for a low to non-existent porting cost [67], [5], [35], [1].

Unfortunately, breaking down applications into compartments means that control and data dependencies through shared interfaces create new classes of vulnerabilities [61]: in order to provide safe compartmentalization, it is not only necessary to ensure spatial memory isolation but also to design interfaces with distrust in mind. For example, objects passed through APIs can be corrupted to launch confused deputy attacks [39], [21], data structures can be manipulated to control execution or leak data through Iago attacks [8], [11], called components can modify return values or indirectly access shared data structures to launch new forms of exploit, etc.

Even though interface-related vulnerabilities (denoted *Compartment-Interface Vulnerabilities* / CIVs in this paper) were previously identified to various extents in the literature [39], [8], [21], [61], almost all modern compartmentalization frameworks [67], [60], [19], [53], [35], [25], [45], [5], [51], [57], [30], [29], [1] neglect the problem of securing interfaces, and rather focus on transparent and lightweight spatial separation. Since CIVs are already problematic for interfaces hardened from the ground up (e.g., the system call API [28], [8]) with well-defined trust-models (kernel/user), their impact on safety is likely to be even greater when considering arbitrary interfaces and trust models that materialize when compartmentalizing existing software that was not designed with the assumption of hostile internal threats. Worse still, the complexity of safeguarding interfaces increases as more fine-grain components are targeted.

Beyond this lack of consideration, CIVs remain misunderstood; we ask the following research questions: *how widespread are CIVs when compartmentalizing unmodified applications? What are the API design patterns leading to them? What is the concrete impact of CIVs on the safety guarantees brought by compartmentalization, and what is the complexity of addressing them?* In order to achieve CIV mitigations that are generic and principled, we stress the need to formalize and quantify the problem.

This paper provides an in-depth study of CIVs. We taxonomize CIVs into a coherent framework, and systematize existing efforts to address them, highlighting categories that need attention in future research. In order to study existing CIVs in real-world scenarios, we propose ConfFuzz, an in-memory fuzzer specialized to detect CIVs at possible compartment boundaries. ConfFuzz automatically explores the complexity of compartment interfaces by exposing data dependencies leading to vulnerabilities. Contrary to existing fuzzers, that inject malformed data in a single direction (e.g., a library),

Network and Distributed System Security (NDSS) Symposium 2023
27 February - 3 March 2023, San Diego, CA, USA
ISBN 1-891562-83-5
https://dx.doi.org/10.14722/ndss.2023.24117
www.ndss-symposium.org