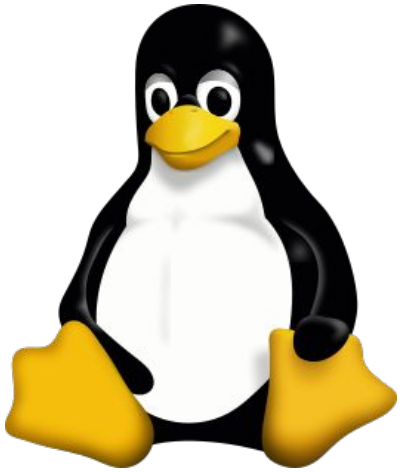
A Decade of Low-hanging Fruit in the Linux Kernel



Kees ("Case") Cook
https://fosstodon.org/@kees
kees@kernel.org

https://outflux.net/slides/2024/bsidespdx/decade.pdf

Hello Neighbors!

Fred Rogers

with apologies to

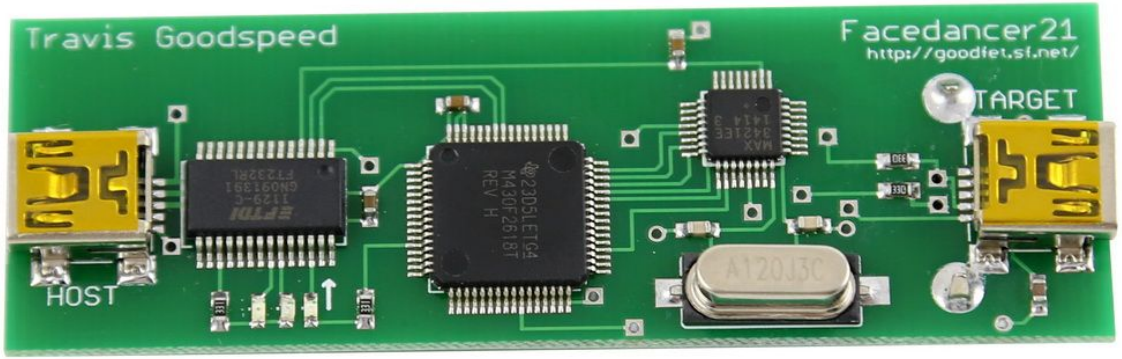
&

Travis Goodspeed

Hello Neighbors!

Fred Rogers

with apologies to



About me

Professionally:

2003 .. 2006: Open Source Development Lab (became the Linux Foundation)

2006 .. 2011: Canonical, Ubuntu Security Team Lead

2011+: Google, Upstream Linux Kernel Security Hardening Lead

chromeOS

Personally:

2002+: Portlander

∞: Free Software Hacker

2006, 2007: DefCon CTF Black Badge winner


BUT YOU DON'T
HAVE TO TAKE
MY WORD FOR IT...

"Seriously, Kees. You are just making security people look bad. Stop it."

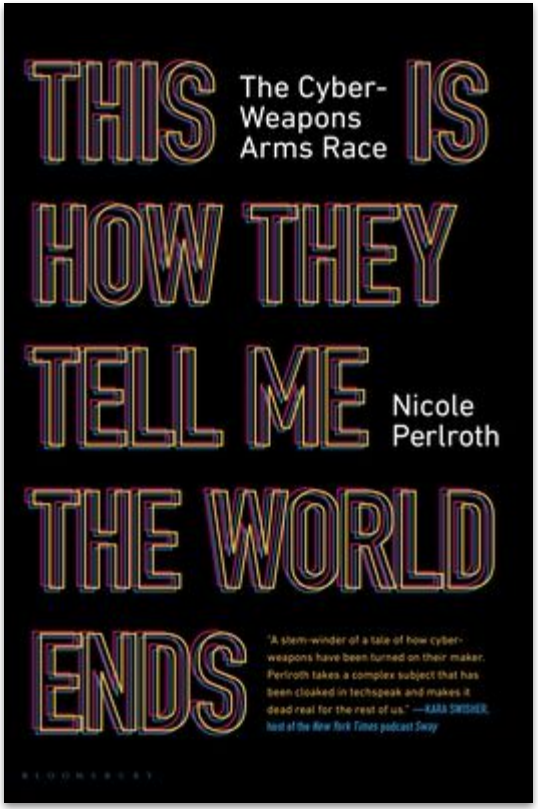
– Linus Torvalds, circa 2017

"Seriously, Kees. You are just making security people look bad. Stop it."

– Linus Torvalds, circa 2017

<Narrator> He did not, in fact, stop it </Narrator>

"The most likely way for the world to be destroyed, most experts agree, is by accident.



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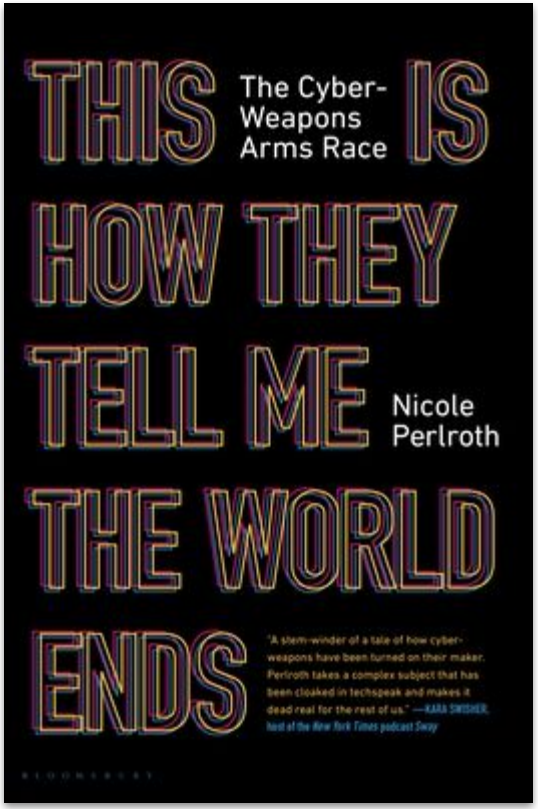

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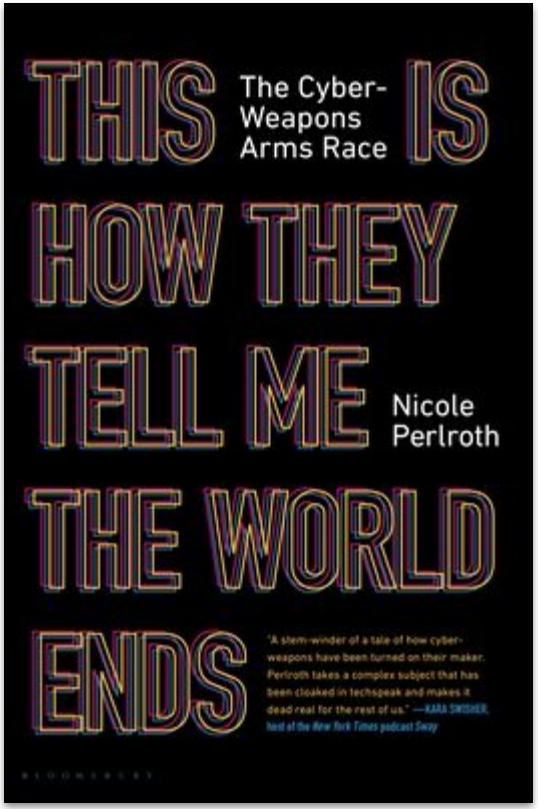

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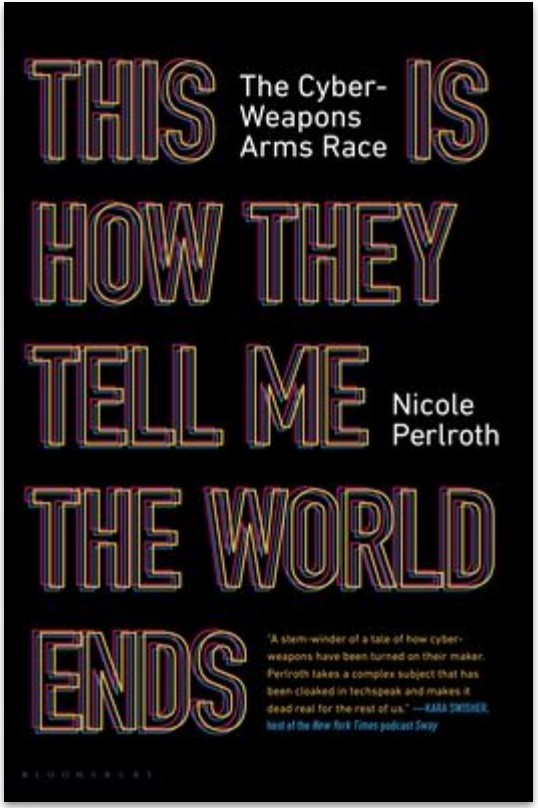
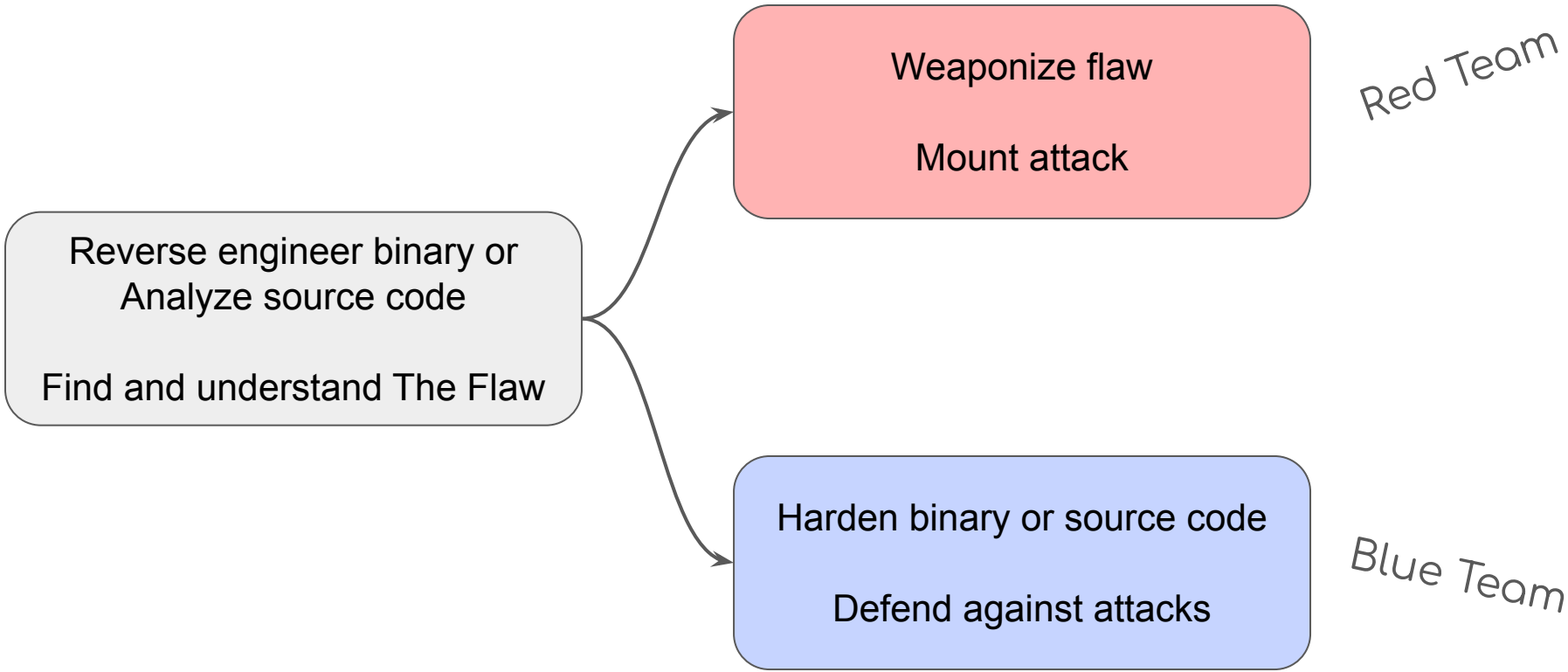
– Nathaniel Borenstein, of MIME fame (as attributed by Nicole Perlroth)



Practicing Accidents: Capture the Flag



Practicing Accidents: Capture the Flag

Reverse engineer binary or
Analyze source code

Find and understand The Flaw

Weaponize flaw

Mount attack

Harden binary or source code

Defend against attacks

Body Armor: Linux Kernel Self-Protection Project

I announced the project in November 2015 (as an upstream Linux focus area)

Our two specific goals:

- Remove entire bug classes (stop the whack-a-mole of fixing individual bugs)
- Eliminate exploitation methods (don't make things easy for attackers)

It's been almost 10 years of cat herding!

Have things improved?

Let's look at vulnerability trends ...

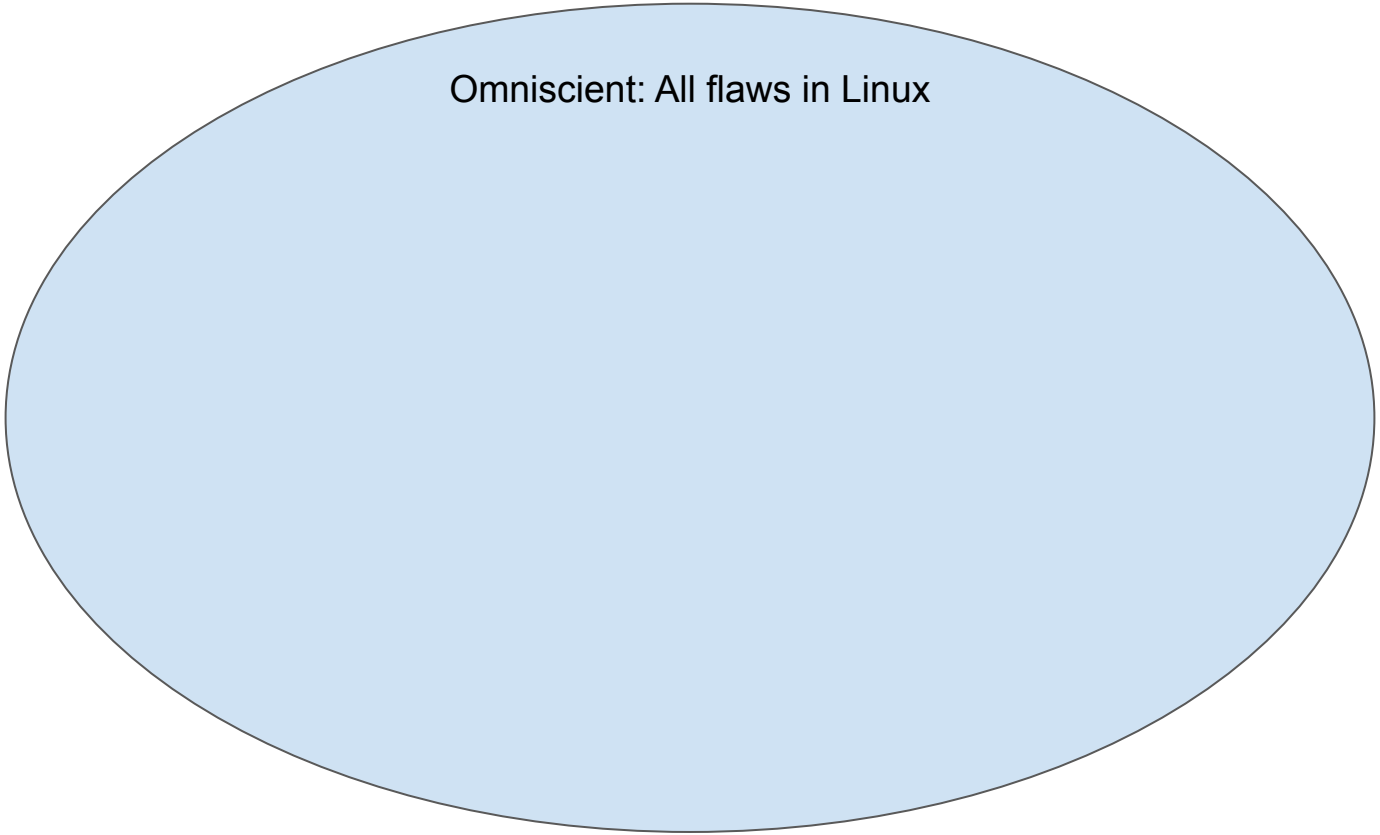
But first … Linux kernel flaws and CVEs

- Common Vulnerability Enumeration (maps vulnerabilities to CVE identifiers)

- Linux Kernel became its own CVE Naming Authority (CNA) in Feb 2024, which changed how CVEs got assigned.

- Prior to that, CVEs were most often assigned by general-purpose distros, and followed their threat models. (And dramatically under-counted flaws in the kernel.)

Linux Flaws Venn Diagram of Doom



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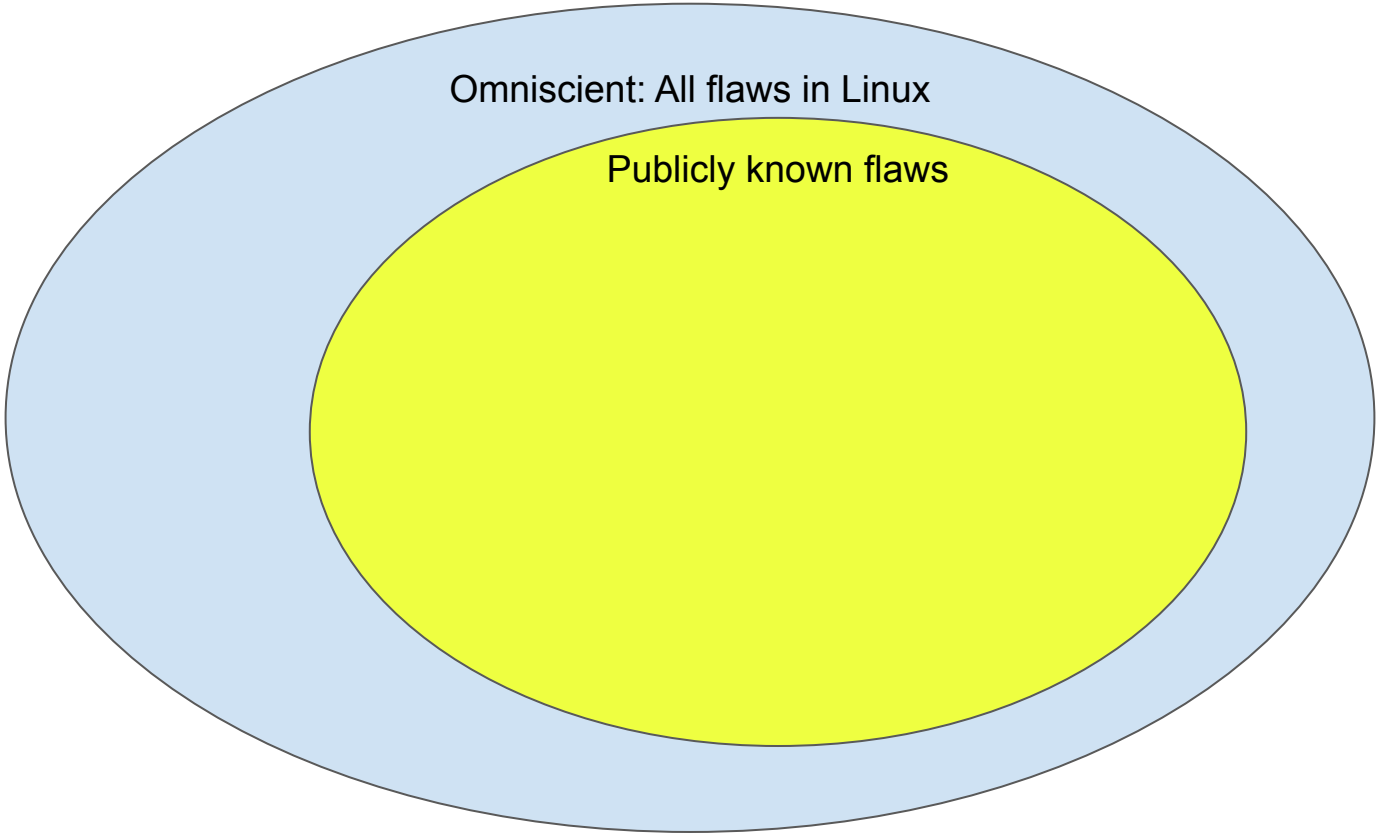

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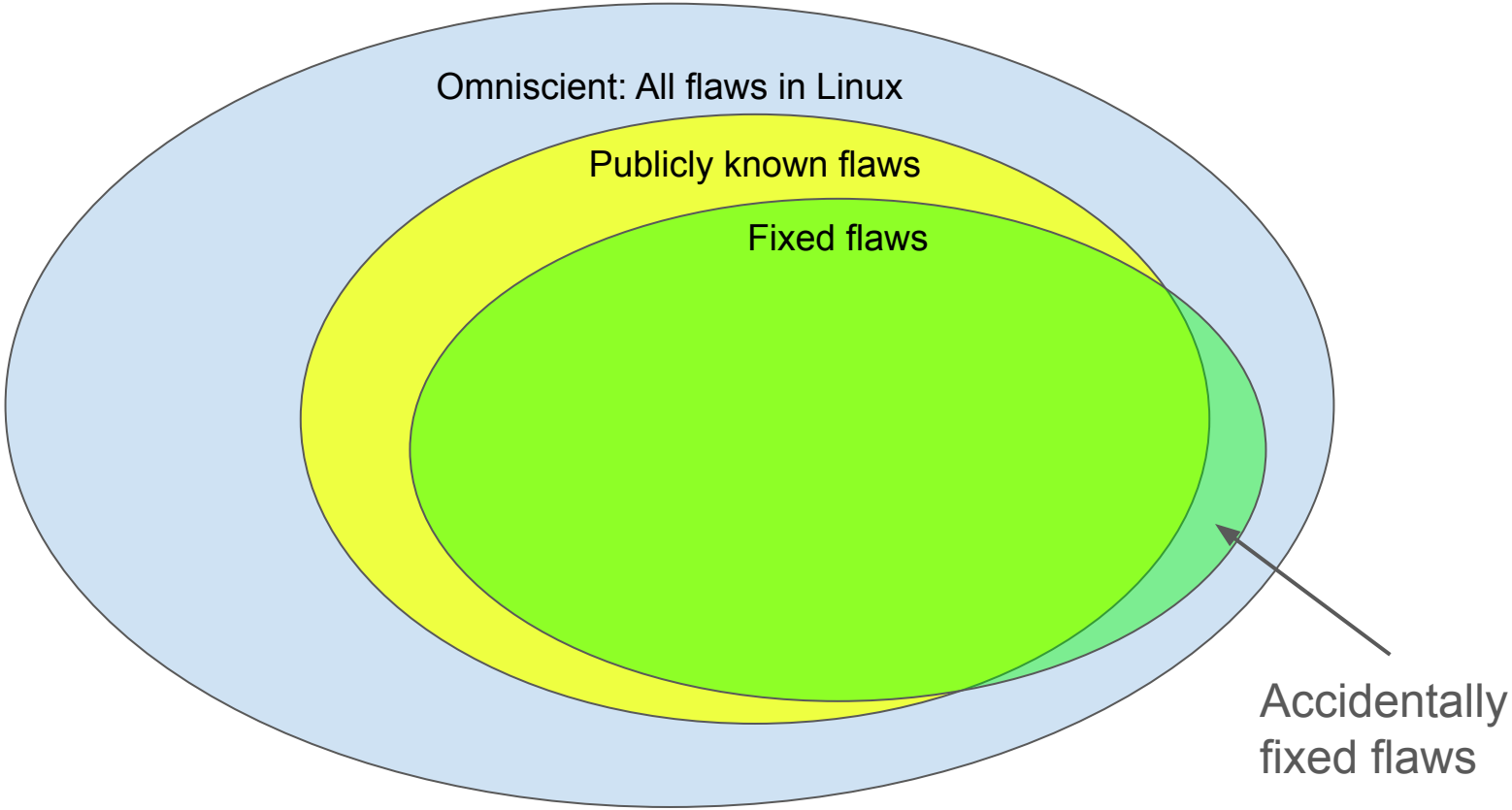

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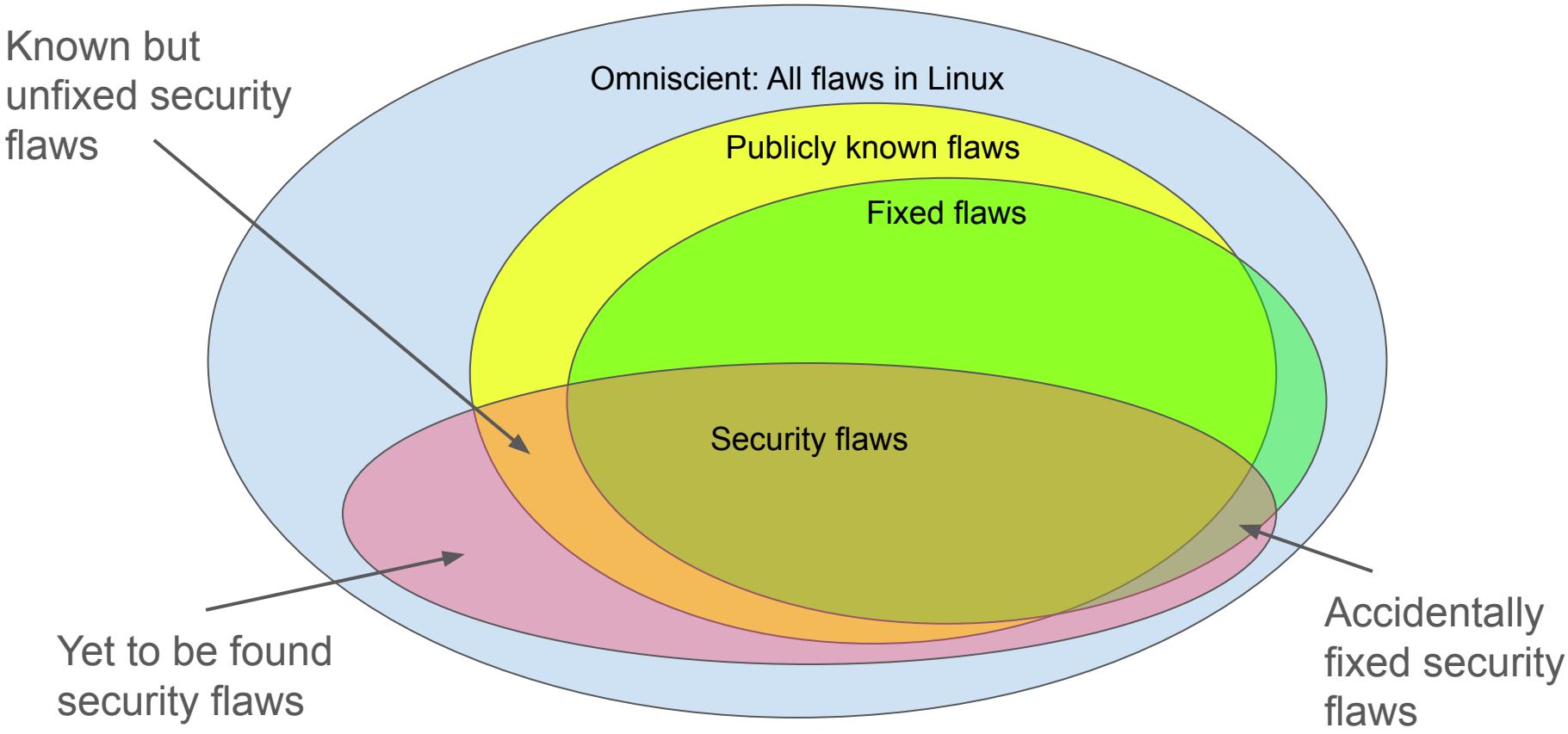

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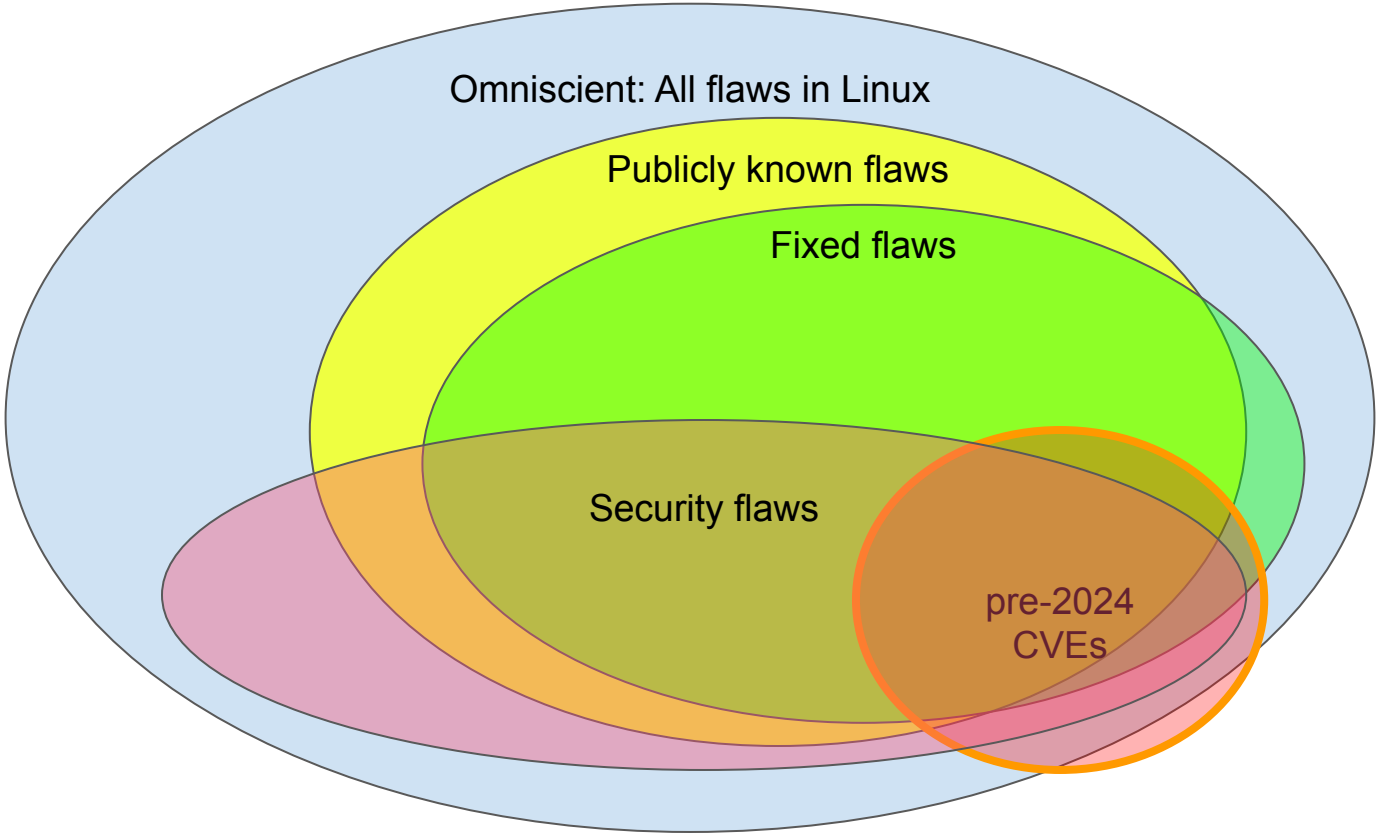
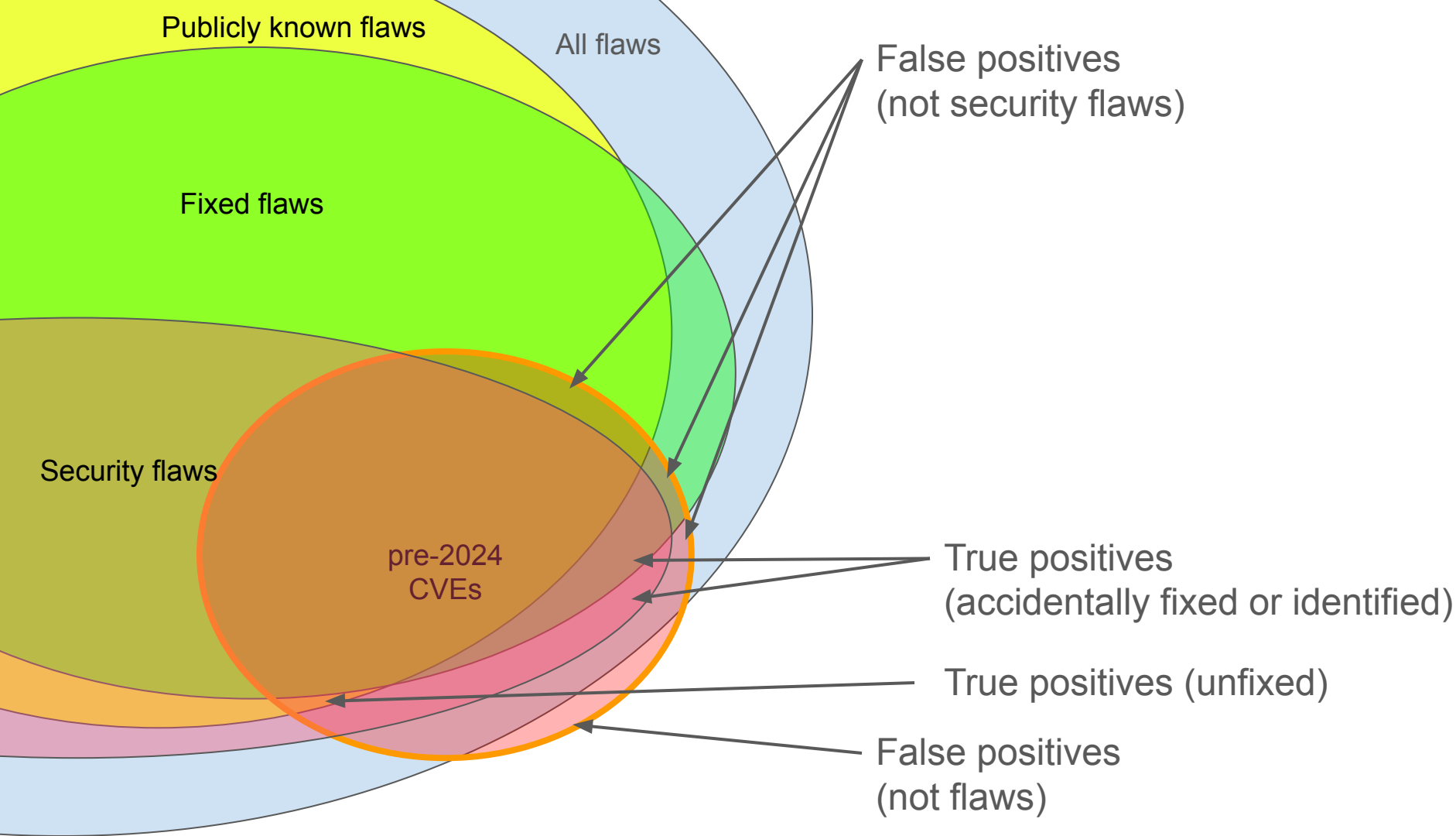
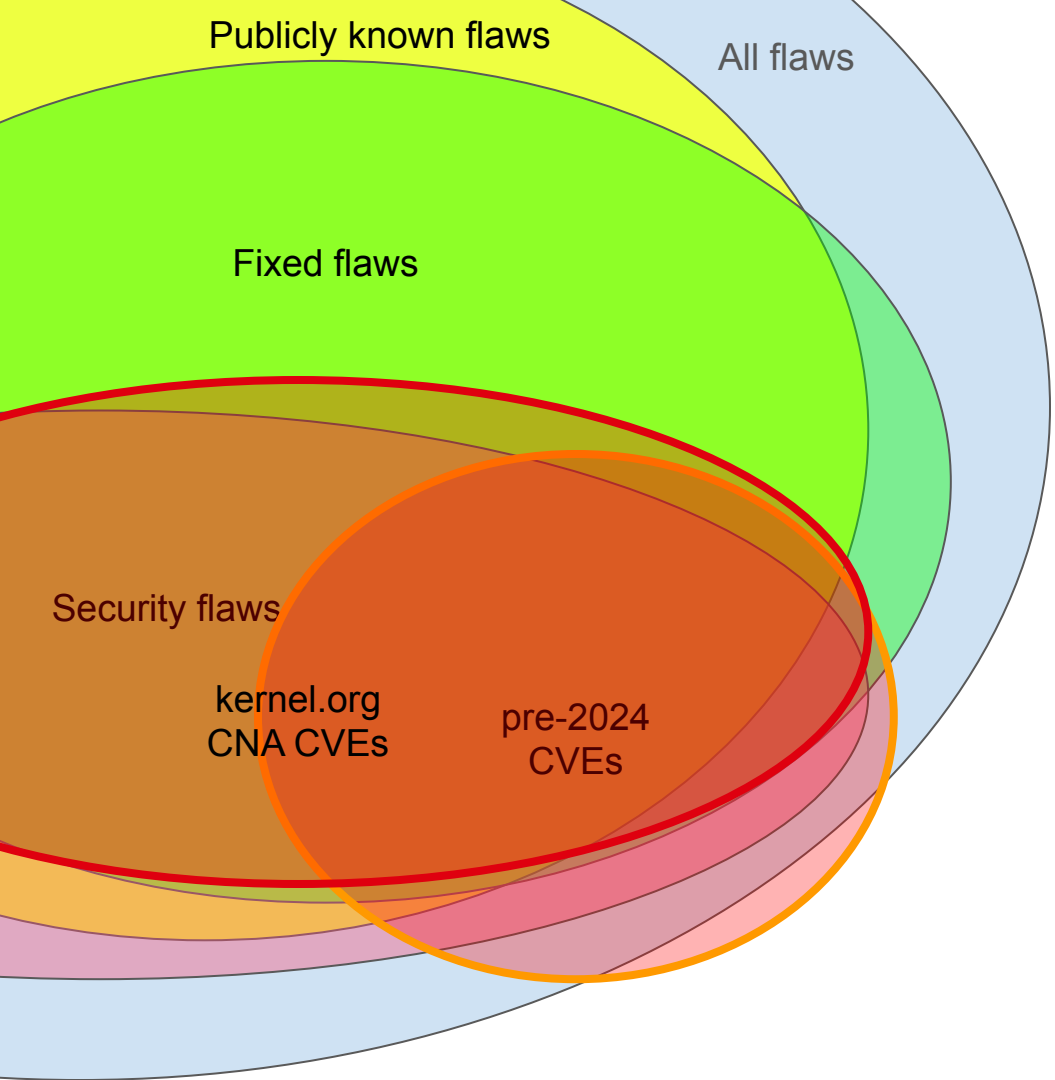



Publicly known flaws
All flaws
Fixed flaws
Security flaws
pre-2024
CVEs
False positives
(not security flaws)
True positives
(accidentally fixed or identified)
True positives (unfixed)
False positives
(not flaws)


Publicly known flaws
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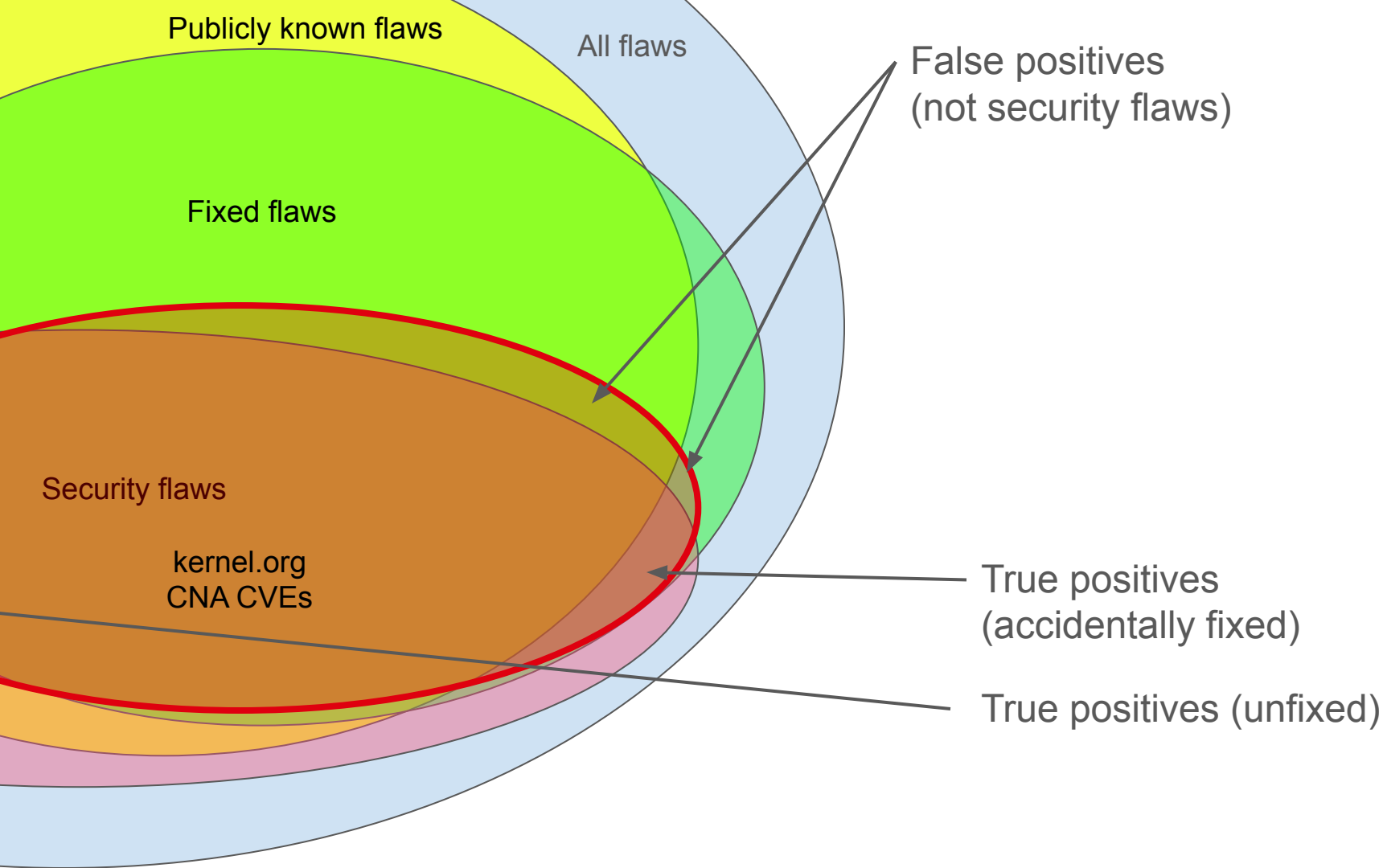
kernel.org
CNA CVEs
pre-2024
CVEs


Publicly known flaws
All flaws
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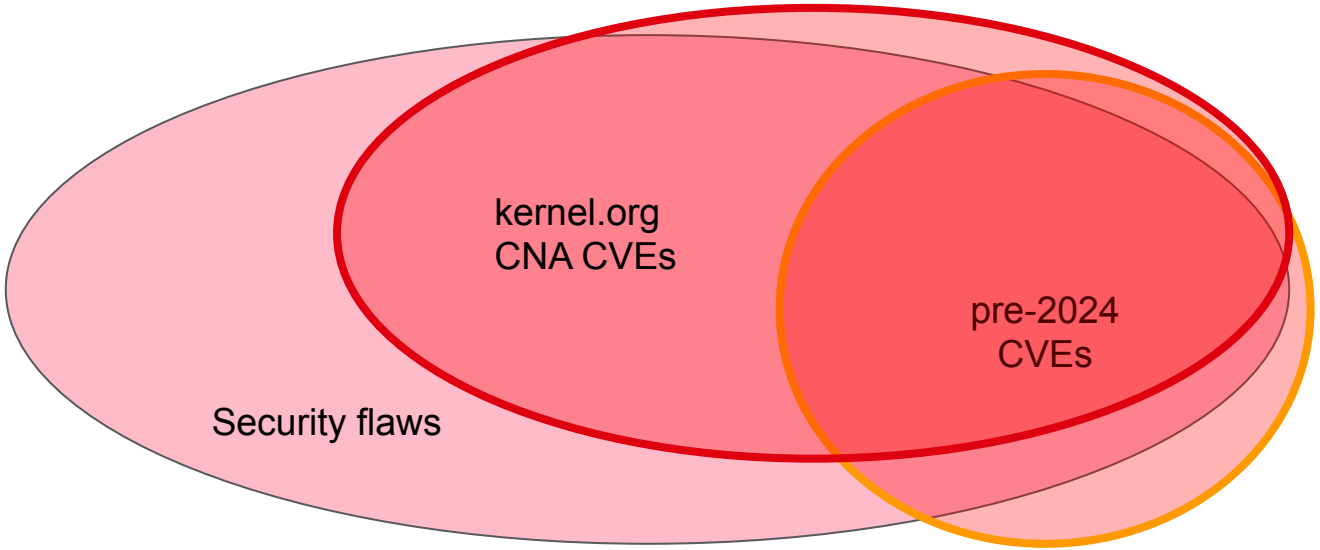
CNA CVEs
False positives
(not security flaws)
True positives
(accidentally fixed)
True positives (unfixed)

Reminder: the goal is to fix *security flaws*, not CVEs… (kernel.org CNA CVEs match reality much better)

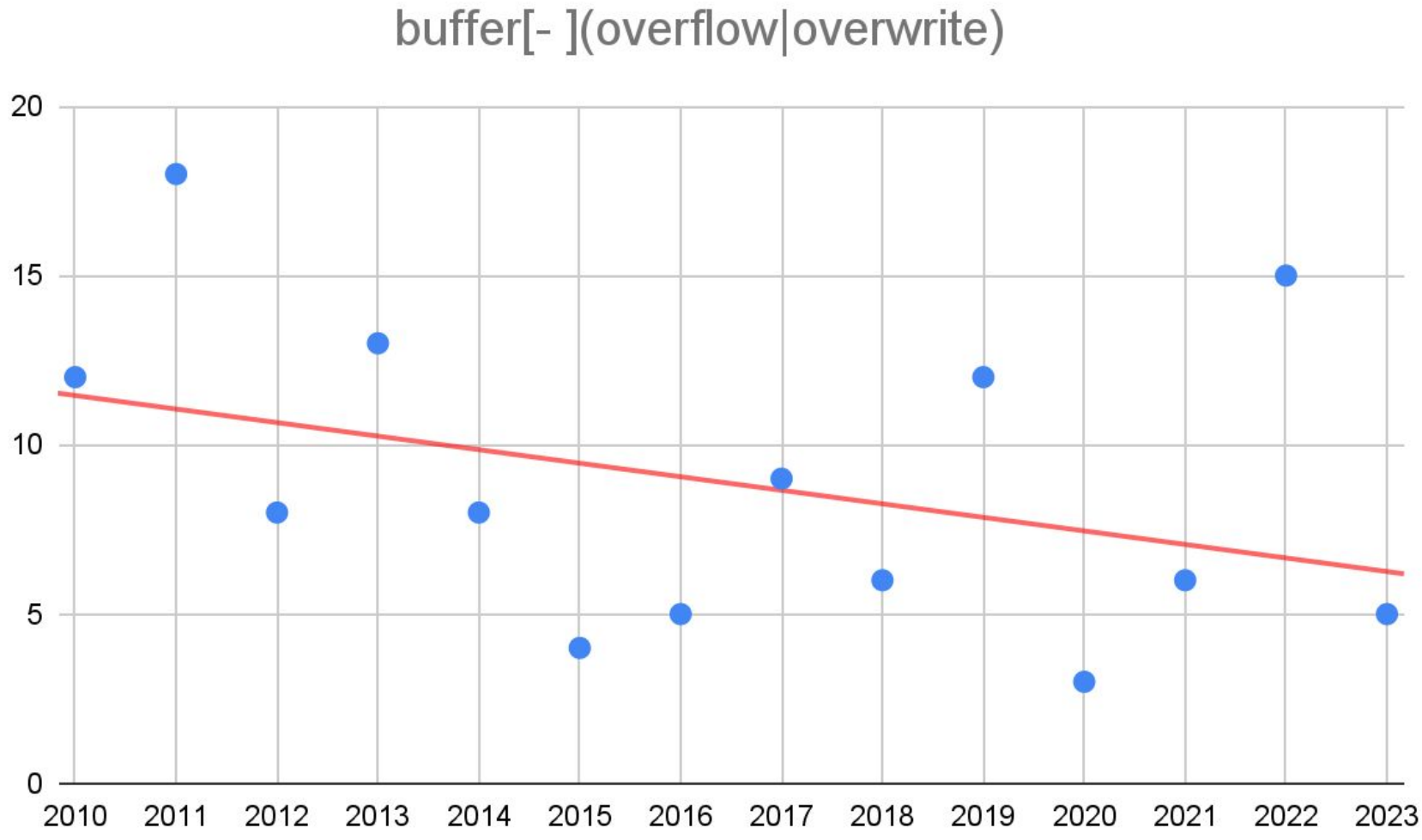


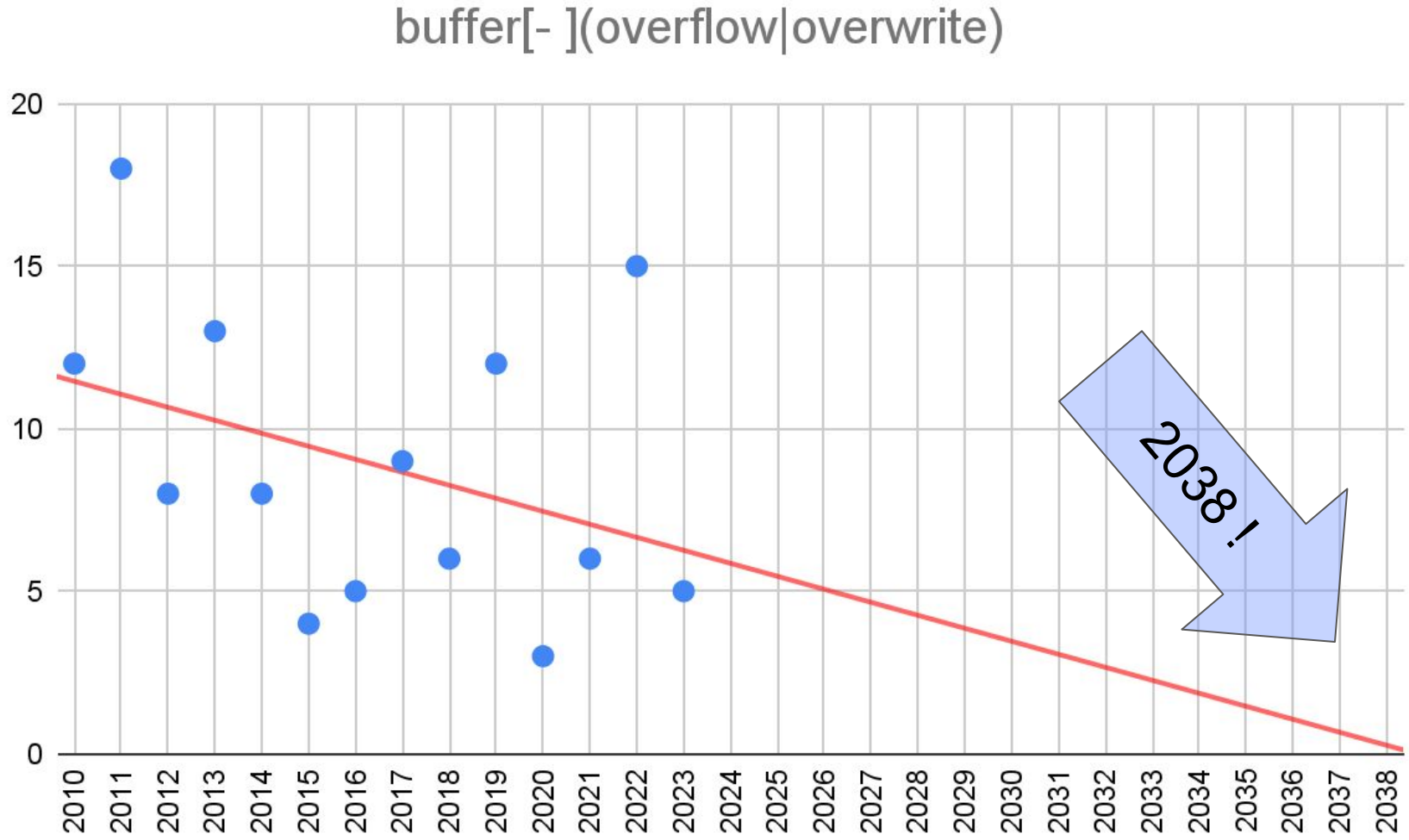
Lies, Damn Lies, and Statistics

- I use the Ubuntu CVE Tracker for my vulnerability statistics – they track the commits that introduced flaws as well as commits that fixed flaws, and they assign severity. This is everything I need to examine trends and lifetimes.

- Doing a retrospective examination of CVEs across the switch between CVE assignment methods isn't going to be easy. So I won't! To get a historical sense of vulnerability class trends, I only looked at pre-CNA CVEs.

- Now let's really look at some trends in bug classes!


buffer[-](overflow|overwrite)
20
15
10
5
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023


buffer[-](overflow|overwrite)
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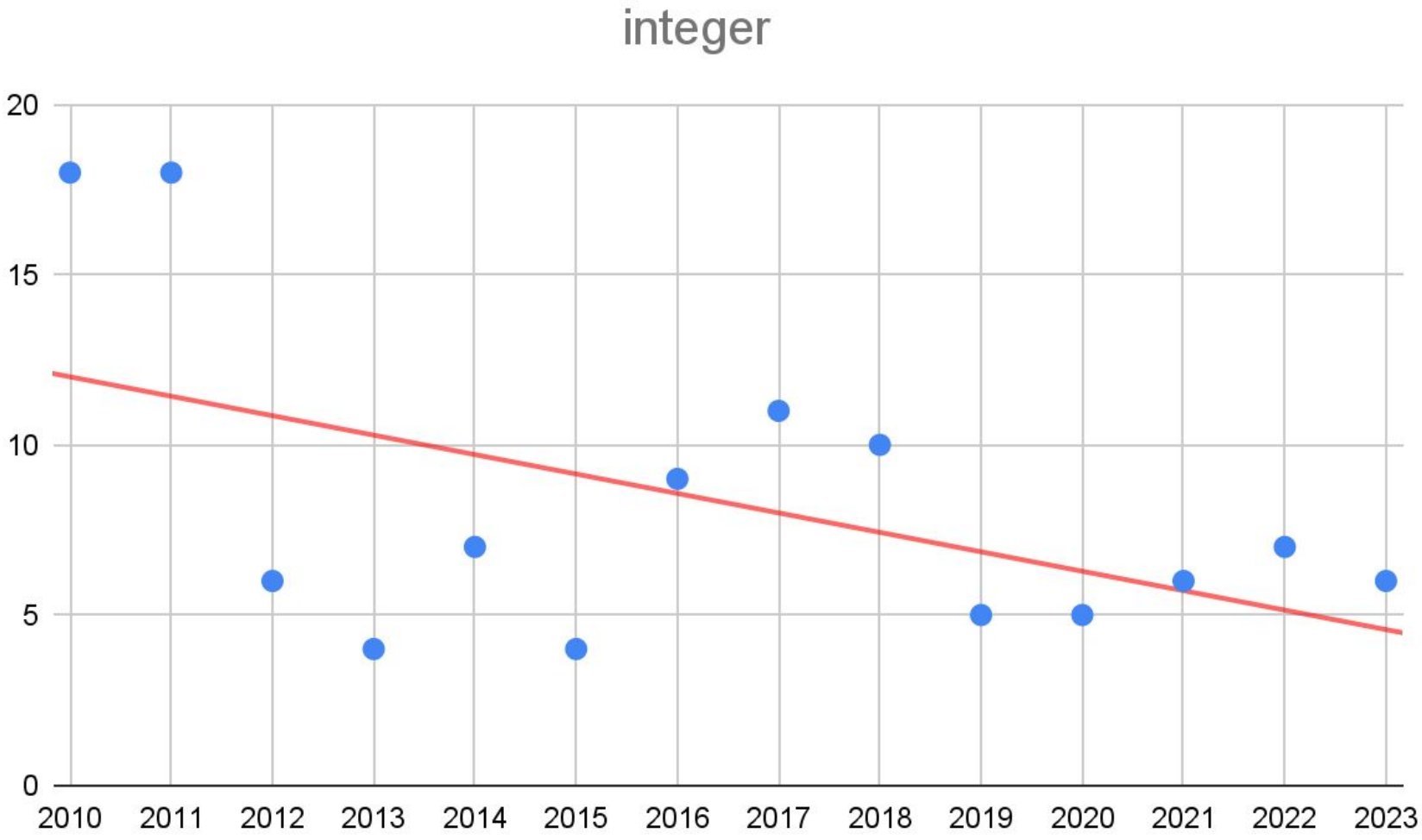
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2038.!

32-bit time_t Unix Epoch wrap!

```
11111111111111111111111111111111 03:14:07 19 Jan 2038 UTC
                                +1         *tick*
---------------------------------
00000000000000000000000000000000 00:00:00  1 Jan 1970 UTC
```

So … integer overflows …


integer
20
15
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2010
2011
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2016
2017
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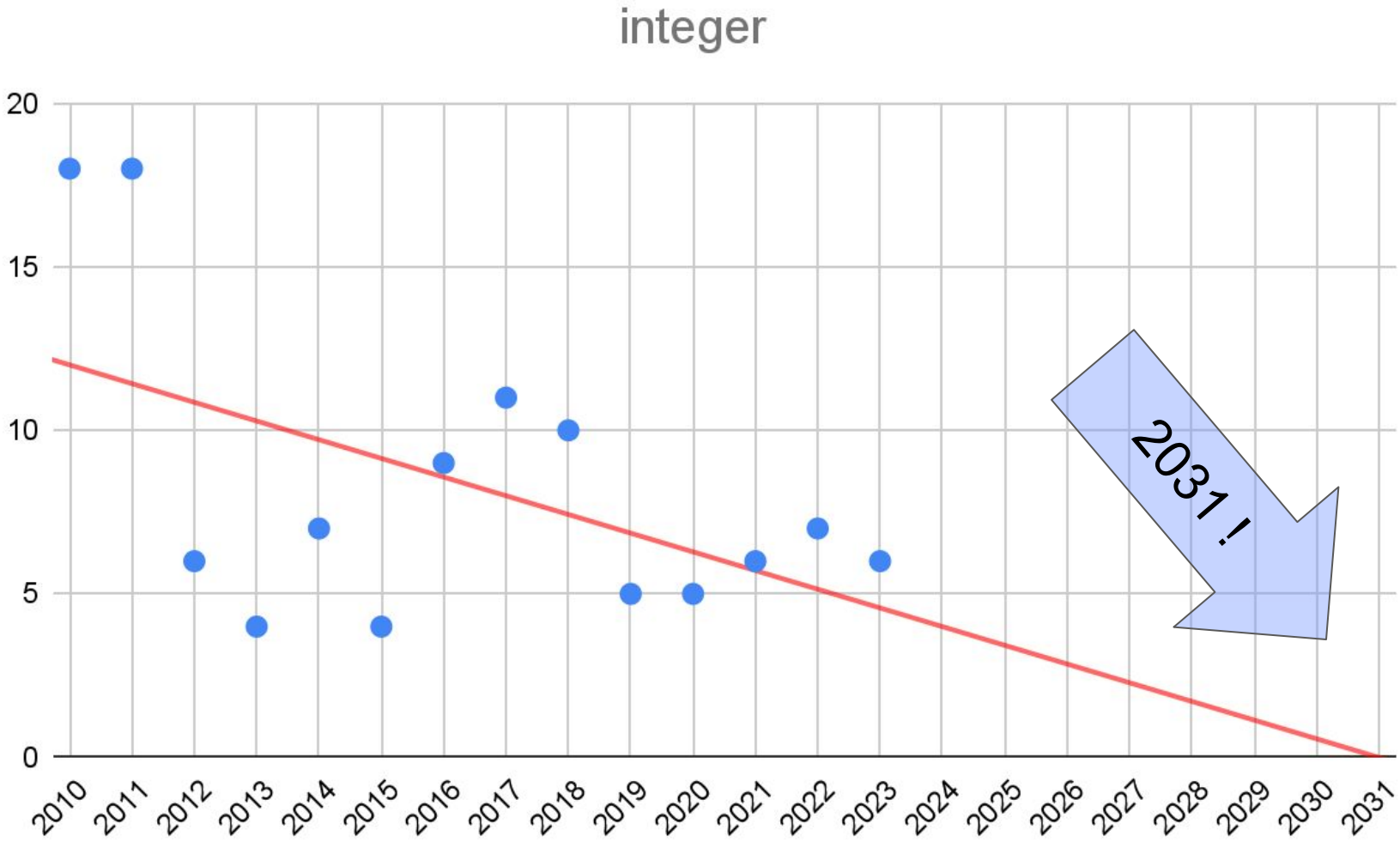
2019
2020
2021
2022
2023


integer
20
15
10
5
0
2031 !
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
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2029
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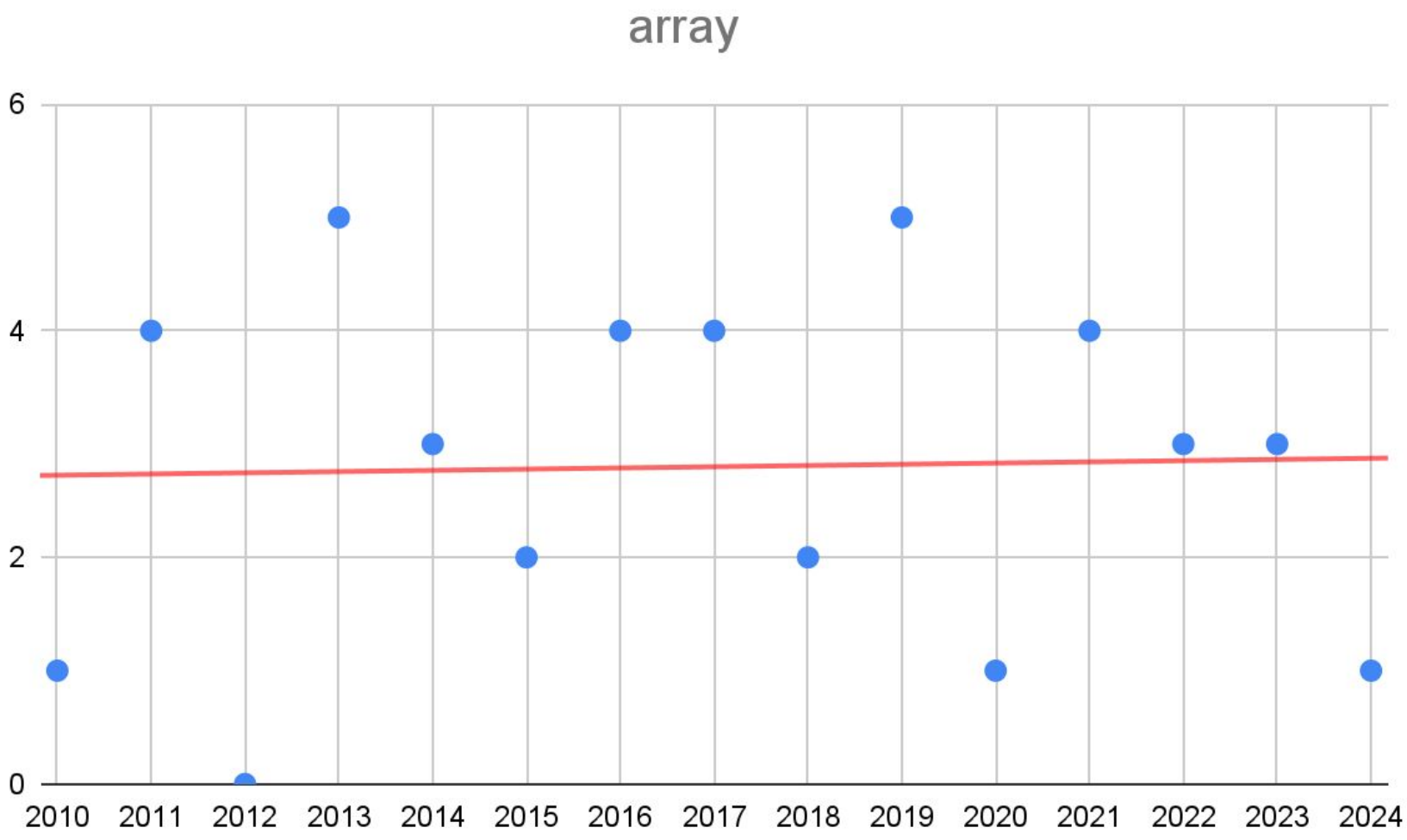
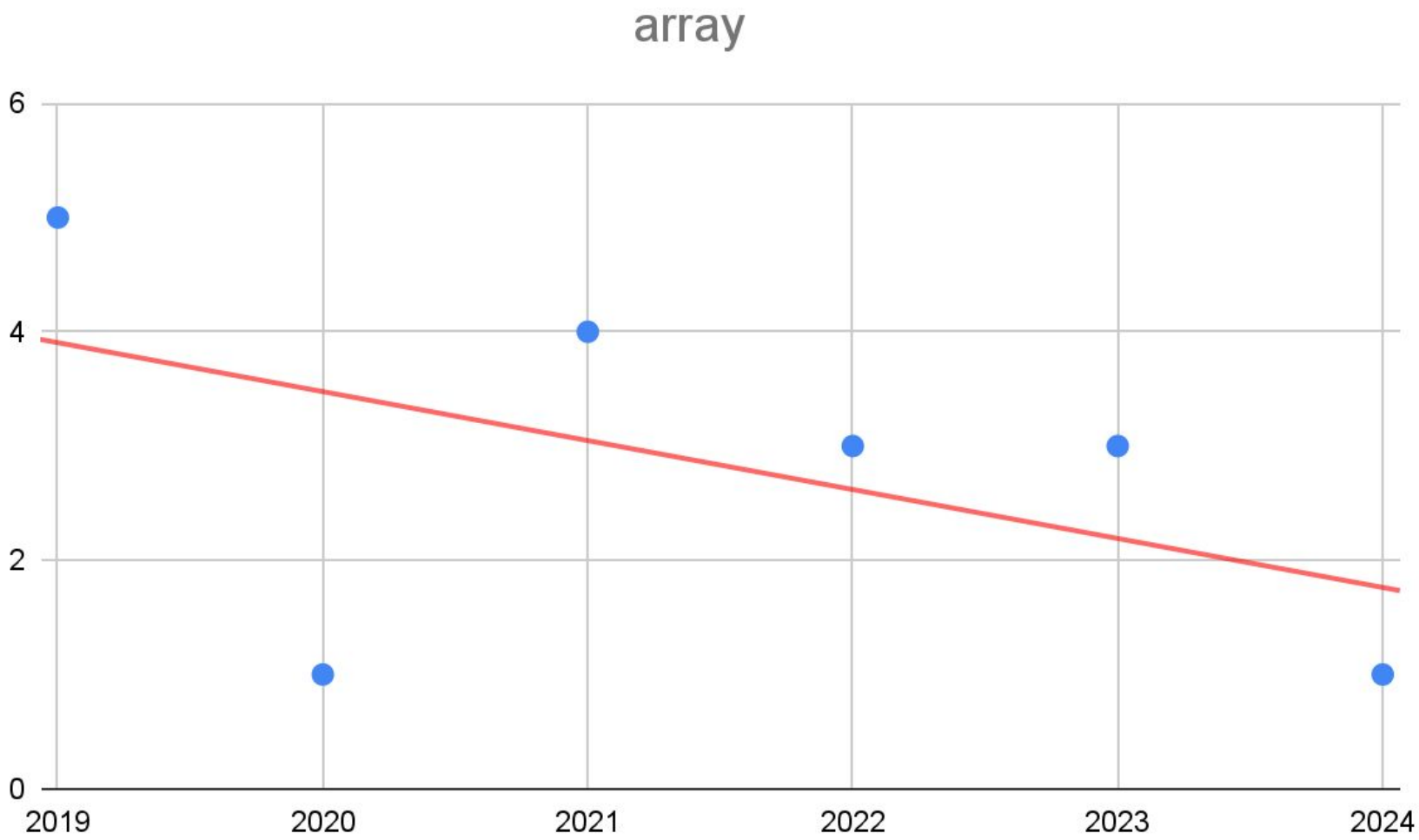

array
6
4
2
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024

2020: BleedingTooth

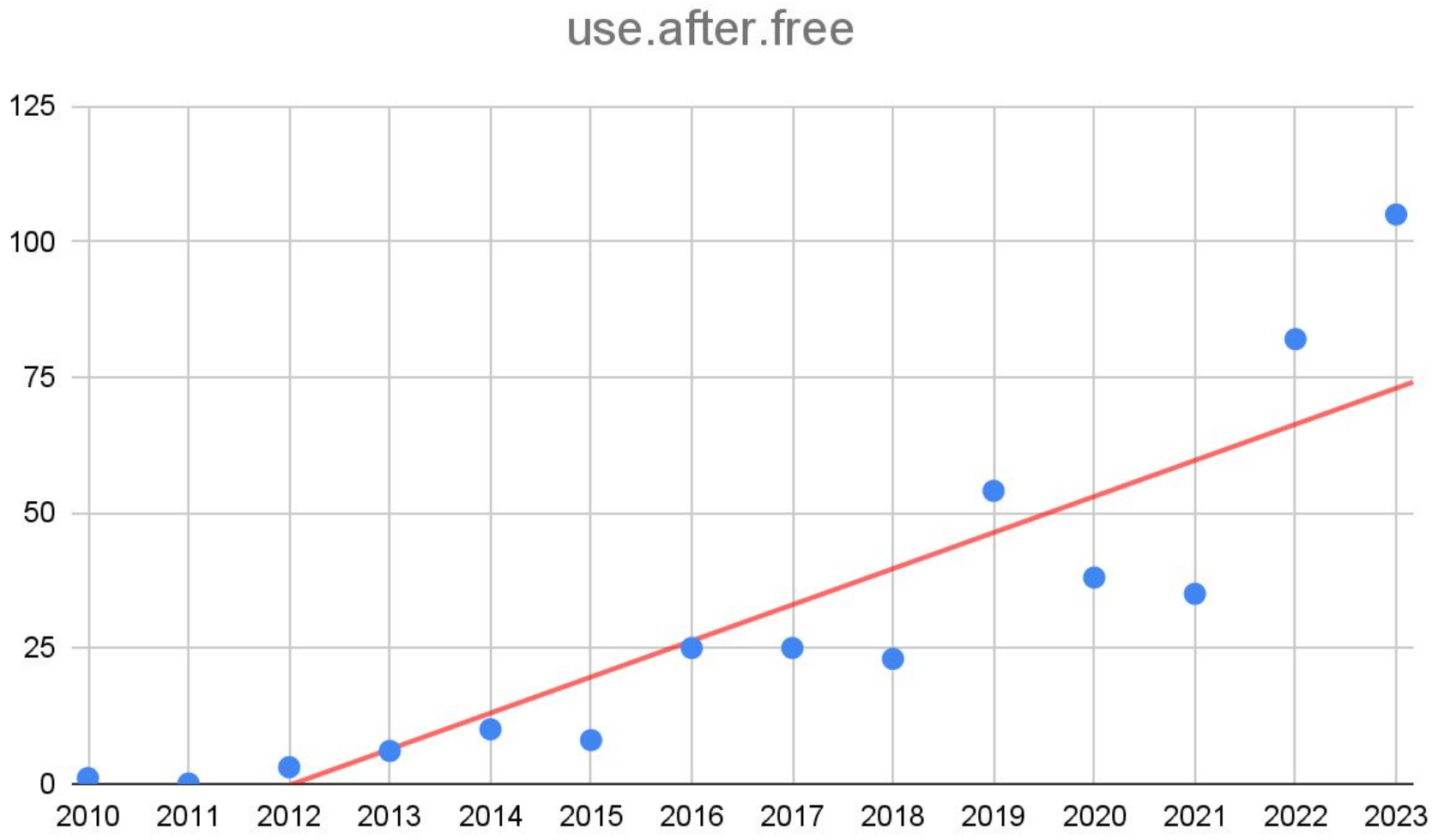
https://google.github.io/security-research/pocs/linux/bleedingtooth/writeup.html

```
struct hci_dev {
        ...
        struct discovery_state {
                ...
                u8 last_adv_data[HCI_MAX_AD_LENGTH];
                ...
        };
        ...
        struct list_head {
                struct list_head *next;
                struct list_head *prev;
        } mgmt_pending;
        ...
};

memcpy(d->last_adv_data, data, len);  /* len > HCI_MAX_AD_LENGTH ?! */
```


array
6
4
2
0
2019
2020
2021
2022
2023
2024

So where is the low hanging fruit now?


use.after.free
125
100
75
50
25
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

Where are all the Use-After-Free flaws coming from?

```
30 net/netfilter
28 net/l2tp
17 drivers/android/binder.c
16 sound/core
15 fs/ext4
14 net/sched
14 fs/io_uring.c
11 net/bluetooth
10 net/ipv4
 9 kernel/futex.c
 8 net/ax25
 7 fs/btrfs
 6 net/nfc
 6 kernel/trace
 5 net/sctp
 5 net/packet
 5 net/ipv6
 5 fs/io-wq.h
 5 drivers/tty/vt
 5 drivers/net/hamradio
 5 drivers/gpu/drm
 4 net/unix
 4 net/socket.c
 4 fs/ntfs3
 4 fs/namei.c
 4 fs/eventpoll.c
 4 fs/cifs
 4 drivers/usb/misc
 4 drivers/media/dvb-core
 4 drivers/media/cec/core
 4 drivers/gpu/drm/vmwgfx
 4 drivers/block
 3 net/xfrm
   ...
```

Use-After-Free Research and Mitigation

- Google kernelCTF Vulnerability (and Patch) Reward Program
  https://google.github.io/security-research/kernelctf/rules
  - netfilter
    https://docs.google.com/spreadsheets/d/e/2PACX-1vS…wfvYC2oF/pubhtml
  - io_uring
    https://security.googleblog.com/2023/06/learnings-from-kctf-vrps-42-linux.html

- Android Binder being rewritten in Rust:
  https://rust-for-linux.com/android-binder-driver

How did we drive down other bug classes?

- refactored to use trapping reference counters
- refactored to fault when accessing beyond the end of kernel stack
- removed Variable Length Arrays (VLAs) on the stack
- replaced open-coded allocation size arithmetic
- replaced set_fs() API to avoid user/kernel address space confusions
- improved compiler to reject implicit switch case fall-throughs
- improved compiler to zero-initialize stack variables
- improved compiler to actually check array sizes
- MOAR…

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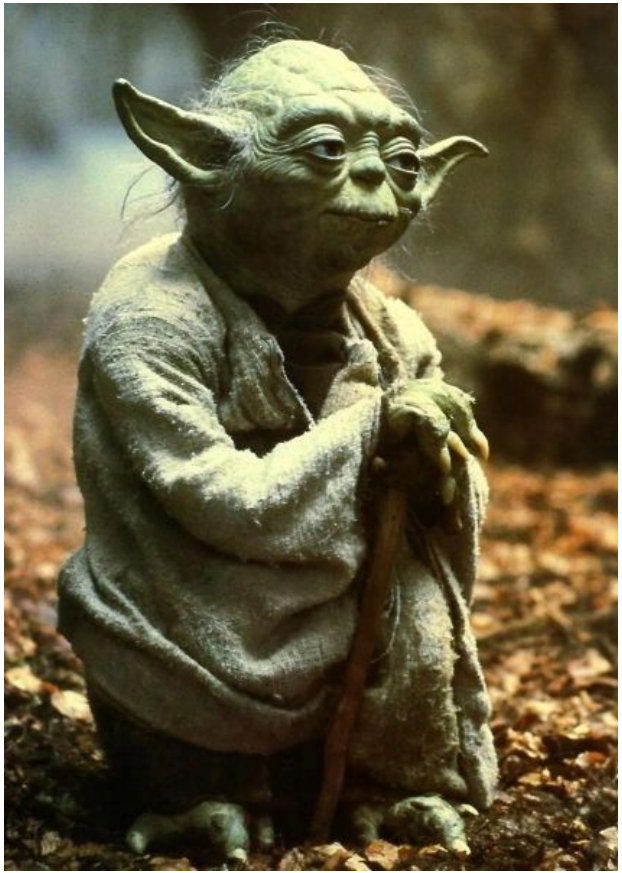
C supports ambiguity



"Ambiguity is the path to the Dark Side.

Ambiguity leads to confusion;

confusion leads to flaws;

flaws lead to suffering.

I sense much ambiguity in you."

– Yoda, about the C language

C supports ambiguity (but we can fix that)

- "Undefined Behavior" is the source of *so many* flaws, but is just one special case of "language ambiguity"
- and of course the lack of memory safety, no variable lifetime enforcement, no safe concurrency

What to do about it?

- Remove ambiguity in C
- Write new stuff in Rust

With Undefined Behavior

Anything is Possible

https://raphlinus.github.io/programming/rust/2018/08/17/undefined-behavior.html

Remove Ambiguity in C
"uninitialized" stack variables

There is no such thing as "uninitialized" !

```
int function(int input)
{
    int on_the_stack;  /* contains whatever was on stack */

    return input * on_the_stack; /* returns what??? */
}
```

Remove Ambiguity in C
"uninitialized" stack variables

Now we can build with `-ftrivial-auto-var-init=zero` ...

```
int function(int input)
{
    int on_the_stack;  /* contains 0 */

    return input * on_the_stack; /* returns 0 */
}
```

Some compiler folks worried "this will fork the language" … YES PLEASE

Remove Ambiguity in C
not all arrays can be bounds checked

```
struct foo {
    …
    …
    int fixed_size_array[16];
    int flexible_array[];
};
```

Can do bounds checking! (16 elements)

No dimension: no bounds checking :(

Remove Ambiguity in C
not all arrays can be bounds checked

Now we can use the `counted_by` attribute …

```
struct foo {
    …
    int items;
    int fixed_size_array[16];
    int flexible_array[] __attribute__((counted_by(items));
};
```

Can do bounds checking! (16 elements)

Can do bounds checking! ("items"-many elements)

Remove Ambiguity in C

The C Standard is strict, slow-moving, and prioritizes compatibility over robustness. The key to making any practical progress with GCC, Clang, and even MSVC is to use the magic phrase:

Remove Ambiguity in C*ompilers*

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I would like to add this **Language Extension** …

Then coordinate the extension between compilers, and the C Standard can catch up when they're ready.

Write New Stuff in Rust

It's a long road to in the Linux kernel, but the language bindings have been steadily landing. Entire graphics drivers have been written in Rust: Apple AGX, Nova. Also filesystems, block drivers, network PHY drivers… If the Linux kernel can get it done, so can your project!

You know it's time to ditch C/C++ when even governments have noticed the dumpster fire. National Security Agency (NSA), Cybersecurity and Infrastructure Security Agency (CISA), and Office of the National Cyber Director (ONCD):

The Case for Memory Safe Roadmap

Exploring Memory Safety in Critical Open Source Projects

https://rust-for-linux.com/

Those have been my shared struggles. How're you doing?

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Just getting started? Keep it up!

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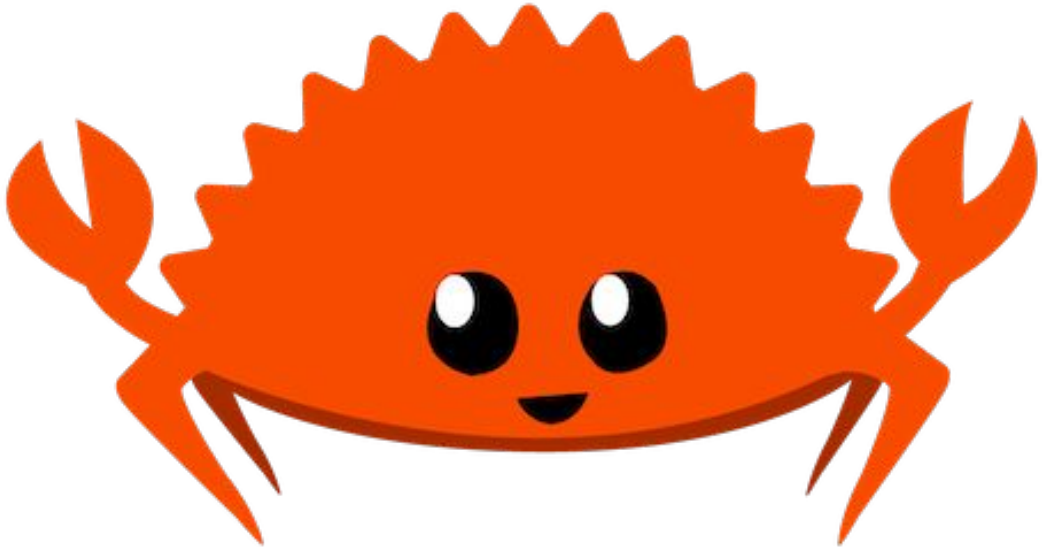

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Doing other stuff in this industry? I love it!

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All of our work can be a struggle, but it makes a difference

I don't care if this is cheesy, it's still true…

Fred Rogers again:

"… what you're planning and doing are things that can be a real help to you and your neighbor.

I'm proud of you."

Thank you!

Enjoy the rest of the day :)

Kees ("Case") Cook
https://fosstodon.org/@kees
kees@kernel.org

https://outflux.net/slides/2024/bsidespdx/decade.pdf