GWP-ASan: Sampling-Based Detection of Memory-Safety Bugs in Production

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Memory Safety in Programming Languages

- Memory-unsafe languages, specifically the C and C++ programming languages, define some well-typed programs to have undefined behavior
    - Memory-safe languages: no well-typed program has undefined behavior
- Heap buffer overflows and use-after-free accesses are two major bug classes introducing undefined behavior
    - Can result in anything from program crash (denial of service), data corruption, to an attackable exploit vector 🔥

Memory-safety bugs remain the single major source of security vulnerabilities:
70% of CVEs in Android, Chrome, and iOS are due to memory safety bugs.

Dynamic Memory-Safety Bug Detection

- Numerous **pre-production** dynamic analysis tools:
  - Valgrind
  - AddressSanitizer (and its variants)
  - ... and many more
- Hardware acceleration exists, but not (yet) widely deployed:
  - Arm Memory Tagging Extension (MTE)
  - SPARC ADI (legacy architecture)

- Electric Fence Malloc Debugger, introduced in 1987, one of the first *dynamic analysis* tools to detect memory safety bugs (more details later)

Electric Fence Malloc Debugger

Page-protection based addressability checks:

- Free object pages are protected, and unprotected after an allocation
  - Use-after-free results in page fault
- Object pages are surrounded by inaccessible "guard pages"
  - Buffer overflow results in page fault

Makes use of hardware feature available in all modern CPUs' Memory Management Units (MMUs): paged virtual memory and the ability to set memory pages inaccessible.

GWP-ASan: Memory-Safety Detection in Production

- *GWP-ASan adds an “if” statement to the* ***Electric Fence*** *algorithm*
- Finds heap-use-after-free and buffer-overflow errors
- Near zero performance overhead due to sampling:
  - very low probability of detecting a particular bug
  - needs to be deployed across a large fleet of machines
  - not a replacement for AddressSanitizer or other deterministic pre-production program analysis
- Better diagnostics compared to regular memory corruption
  - Accurate fault trace
  - Allocation and deallocation stack traces

The Name “GWP-ASan” is derived from Google-Wide Profiling (GWP), and AddressSanitizer (ASan). GWP-ASan is neither GWP nor ASan.

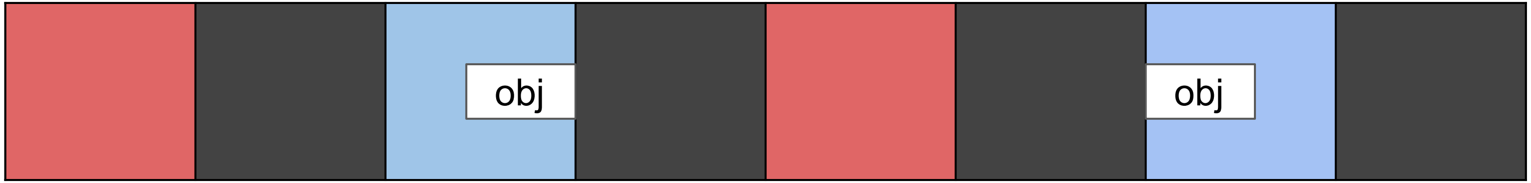
Implementation

Default Malloc + Sampling Electric Fence ⇒ GWP-ASan

```
void *malloc(size_t size) {


  return Allocate(size);
}

void free(void *ptr) {




  Deallocate(ptr);
}
```

```
  void *malloc(size_t size) {
+   if (WantToSample(size))
+     return GuardAlloc(size);
    return Allocate(size);
  }

  void free(void *ptr) {
+   if (IsGuarded(ptr)) {
+     GuardDealloc(ptr));
+     return;
+   }
    Deallocate(ptr);
  }
```

GWP-ASan Pool Layout



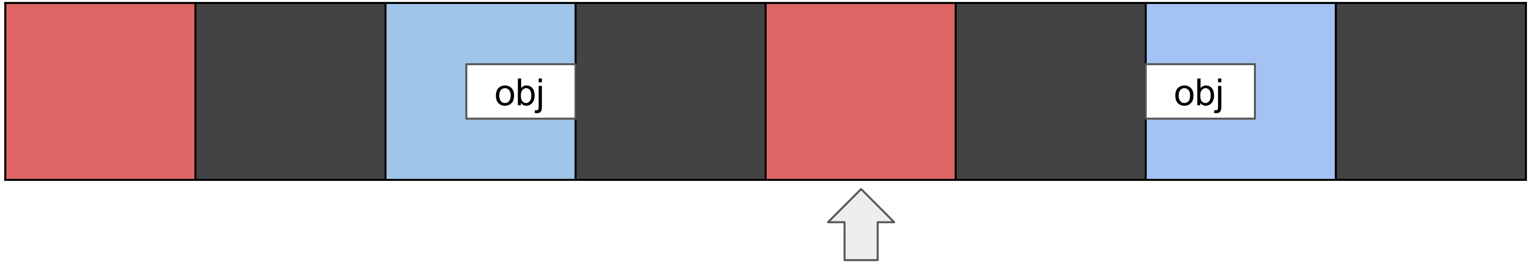
⬛ – Guard pages (`PROT_NONE`) ⇒ detect out-of-bounds accesses

🟦 – Active objects in unprotected pages (`PROT_READ|PROT_WRITE`)

🟥 – Free objects in protected page (`PROT_NONE`) ⇒ detect use-after-free

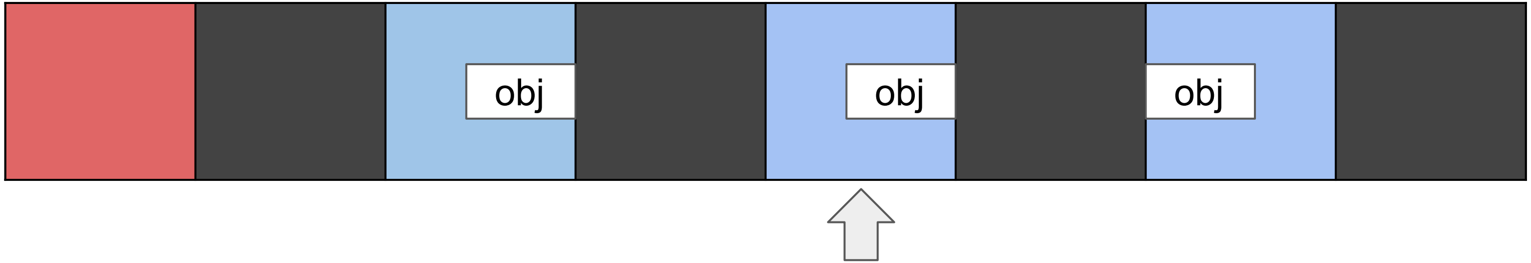
GWP-ASan: GuardAlloc()

Pick unused page…



GWP-ASan: GuardAlloc()

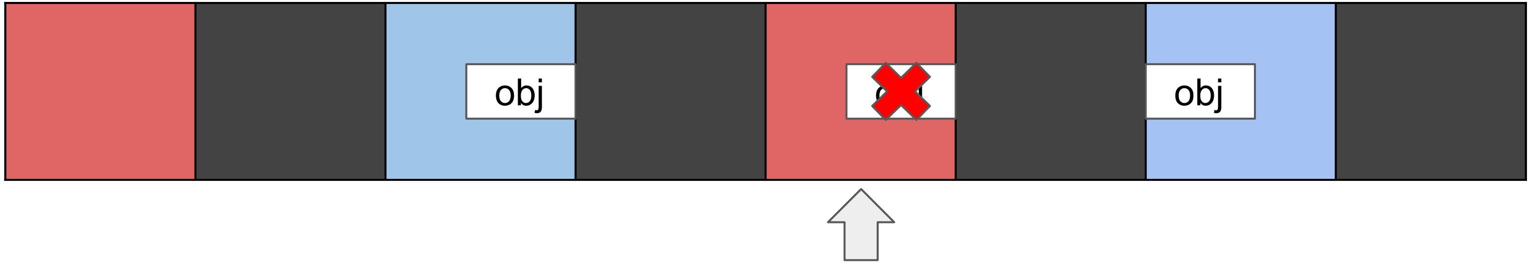
… unprotect it, and place the requested object at either end of the page:



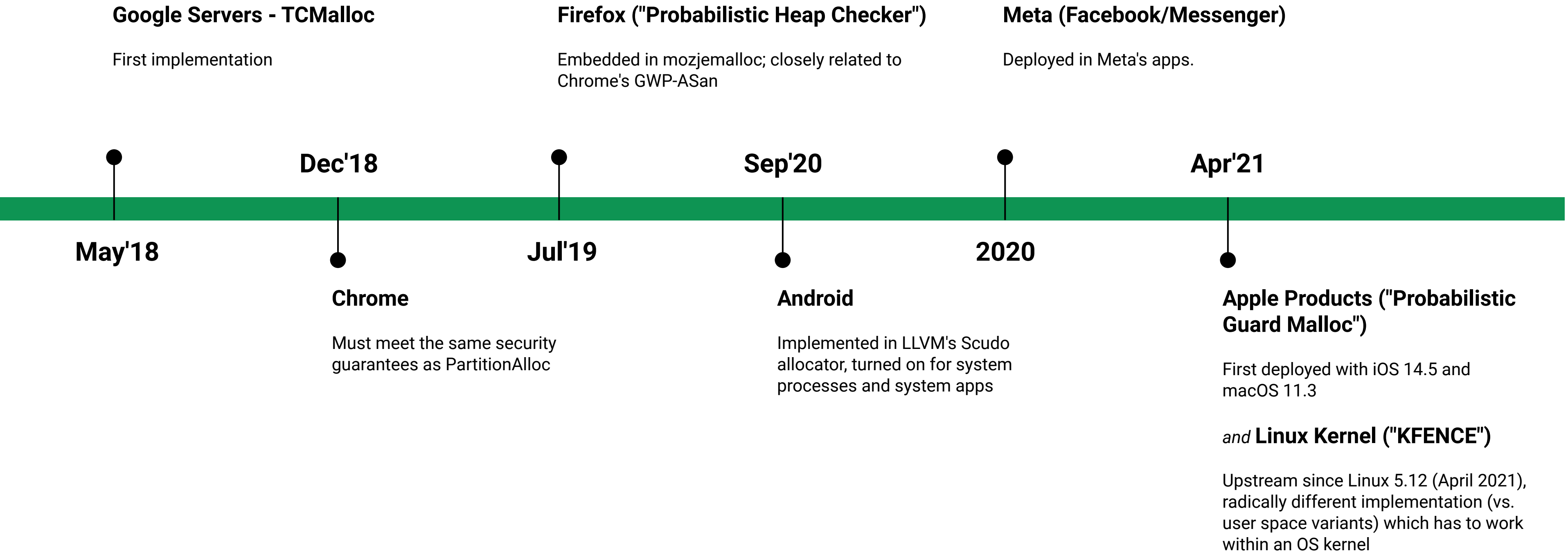
Depending on object placement (left or right), either overflow or underflow accesses will result in page faults. GuardAlloc() may randomly choose left or right placement.

GWP-ASan: GuardDealloc()

Protect the object page:



GWP-ASan Variants



May'18

Google Servers - TCMalloc

First implementation

Dec'18

Chrome

Must meet the same security guarantees as PartitionAlloc

Jul'19

Firefox ("Probabilistic Heap Checker")

Embedded in mozjemalloc; closely related to Chrome's GWP-ASan

Sep'20

Android

Implemented in LLVM's Scudo allocator, turned on for system processes and system apps

2020

Meta (Facebook/Messenger)

Deployed in Meta's apps.

Apr'21

Apple Products ("Probabilistic Guard Malloc")

First deployed with iOS 14.5 and macOS 11.3

and **Linux Kernel ("KFENCE")**

Upstream since Linux 5.12 (April 2021), radically different implementation (vs. user space variants) which has to work within an OS kernel

Results

Results: Google Server Software (TCMalloc)

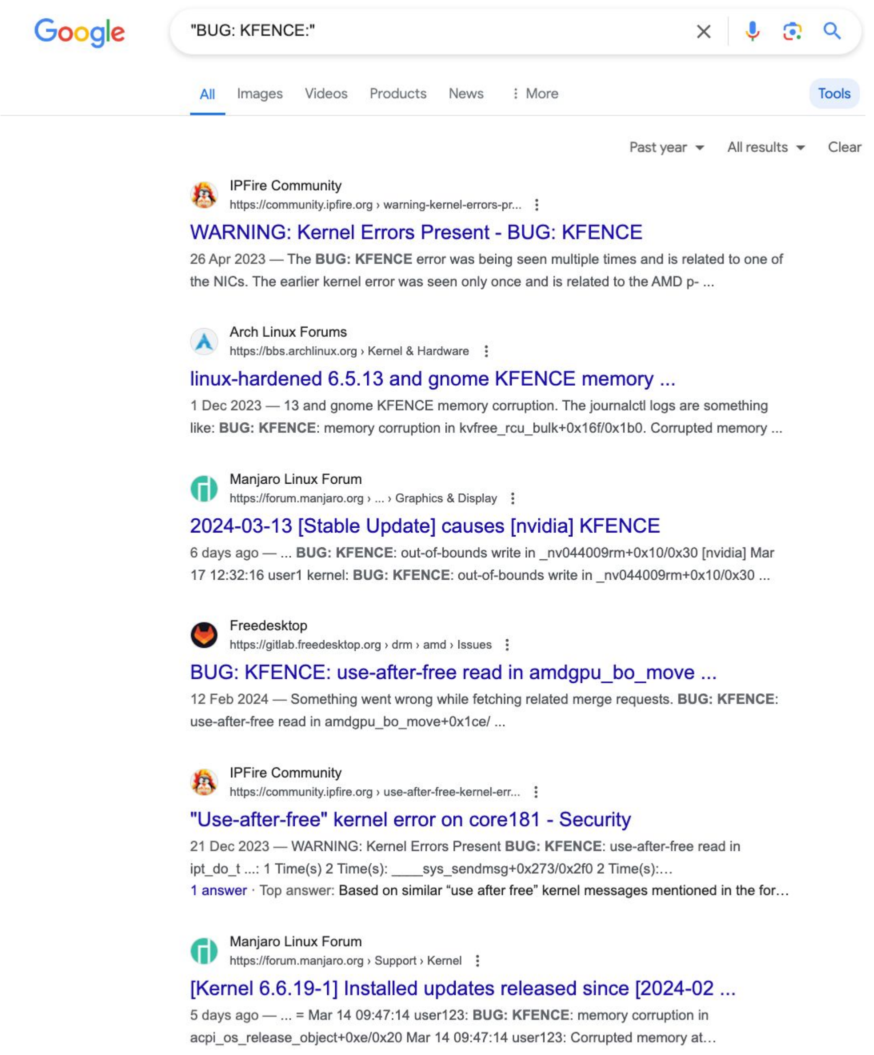
- Since 2019, more than 2300 bugs have been fixed due to GWP-ASan reports
- 80% heap use-after-free, 20% buffer overflow
- Several cases where GWP-ASan detected root cause of an ongoing issue
- Monitoring + benchmarks confirm no significant performance impact

Results: Google Chrome

- 271 bugs filed, with 65% to be possibly exploitable
- 243 bugs resolved, with 69% fix rate
- 80.4% of bugs filed were found and reported by GWP-ASan before any other crash bug was filed for the same crash

Results: KFENCE (Linux kernel)

- KFENCE has reported 60+ bugs in Google's downstream Linux kernels
- Upstream kernel up to version 6.3 has 12 fix commits mentioning KFENCE
- Enabled in various common Linux distributions and Linux CI systems



"BUG: KFENCE:"

IPFire Community
https://community.ipfire.org › warning-kernel-errors-pr... ⋮
WARNING: Kernel Errors Present - BUG: KFENCE
26 Apr 2023 — The **BUG: KFENCE** error was being seen multiple times and is related to one of the NICs. The earlier kernel error was seen only once and is related to the AMD p- ...

Arch Linux Forums
https://bbs.archlinux.org › Kernel & Hardware ⋮
linux-hardened 6.5.13 and gnome KFENCE memory ...
1 Dec 2023 — 13 and gnome KFENCE memory corruption. The journalctl logs are something like: **BUG: KFENCE**: memory corruption in kvfree_rcu_bulk+0x16f/0x1b0. Corrupted memory ...

Manjaro Linux Forum
https://forum.manjaro.org › ... › Graphics & Display ⋮
2024-03-13 [Stable Update] causes [nvidia] KFENCE
6 days ago — ... **BUG: KFENCE**: out-of-bounds write in _nv044009rm+0x10/0x30 [nvidia] Mar 17 12:32:16 user1 kernel: **BUG: KFENCE**: out-of-bounds write in _nv044009rm+0x10/0x30 ...

Freedesktop
https://gitlab.freedesktop.org › drm › amd › Issues ⋮
BUG: KFENCE: use-after-free read in amdgpu_bo_move ...
12 Feb 2024 — Something went wrong while fetching related merge requests. **BUG: KFENCE**: use-after-free read in amdgpu_bo_move+0x1ce/ ...

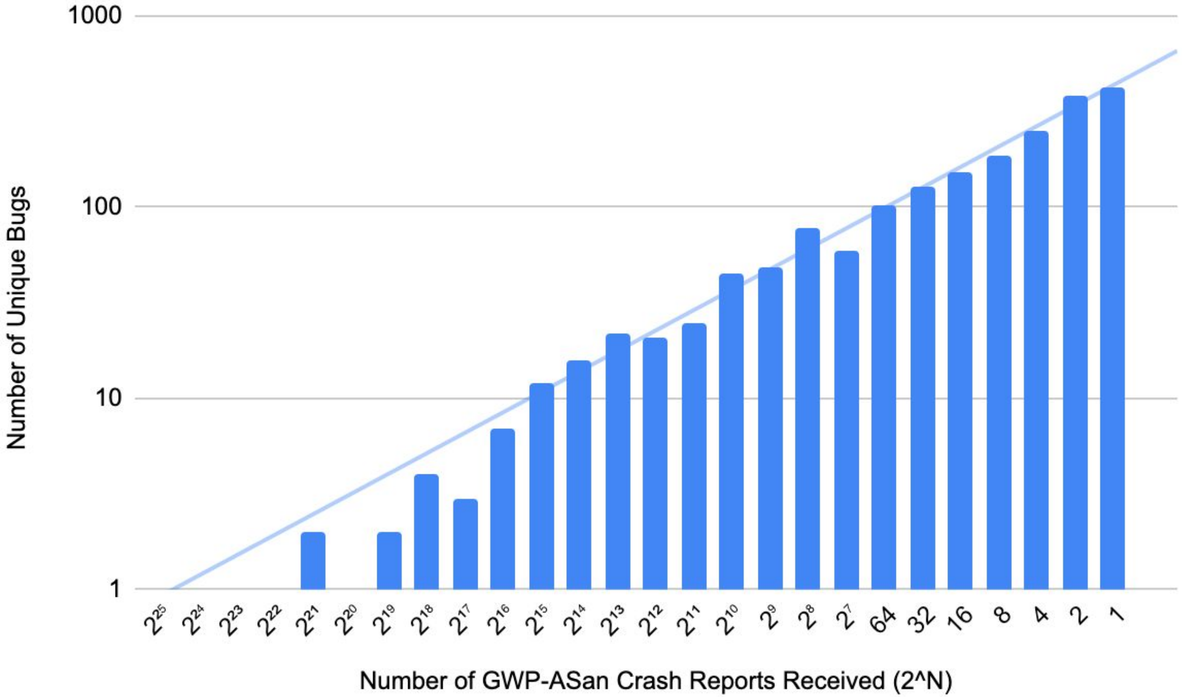
IPFire Community
https://community.ipfire.org › use-after-free-kernel-err... ⋮
"Use-after-free" kernel error on core181 - Security
21 Dec 2023 — WARNING: Kernel Errors Present **BUG: KFENCE**: use-after-free read in ipt_do_t ...: 1 Time(s) 2 Time(s): ____sys_sendmsg+0x273/0x2f0 2 Time(s):...
1 answer · Top answer: Based on similar "use after free" kernel messages mentioned in the for...

Manjaro Linux Forum
https://forum.manjaro.org › Support › Kernel ⋮
[Kernel 6.6.19-1] Installed updates released since [2024-02 ...
5 days ago — ... = Mar 14 09:47:14 user123: **BUG: KFENCE**: memory corruption in acpi_os_release_object+0xe/0x20 Mar 14 09:47:14 user123: Corrupted memory at...

Results: Android

- At time of writing the paper, ~2,000 bugs.
    - We rolled out GWP-ASan for apps in Android 14, non-crashing.
    - Now, a lot more!
- 2-3x more use-after-free than buffer-overflow
- Interesting learnings:
    - Lots of app crashes caused by memory corruption from non-app driver code (GPU, etc.)..
    - ... more bugs are yet to be found

Results: Android - more bugs are yet to be found!



Results: Apple – Probabilistic Guard Malloc (March 2024)

- Since 2021, more than 1,600 bugs have been fixed due to PGM reports
- 76% heap use-after-free, 24% buffer overflow
- About a third of fixed bugs diagnosed to be concurrency issues
- High **99% fix rate** compares very favorably with standard memory crashers
- Several cases where a single PGM report made the difference for diagnosing an ongoing, high-impact bug

On average, ***2.3 new bugs*** *have been found* ***every day***
since PGM was first deployed at scale in April 2021.

Summary

- Memory safety remains a major unresolved problem: eventually migrate away from memory-unsafe code, but this will take decades
- ***GWP-ASan offers a low overhead option for bug detection in production***
- Produces actionable reports
- Not a replacement for ASan or other testing tools
- Results from 6 major variants of GWP-ASan, which are deployed across real-world applications with billions of users

GWP-ASan is not a security mitigation mechanism; when used, however, it improves overall product security by allowing developers to detect and fix many vulnerabilities.