Paul E. McKenney, Facebook

Linux Plumbers Conference Refereed Track, September 23, 2021

So You Want To Torture RCU?

A Round For Those Torturing SW!!!

- 0day test robot
- kernelci
- -next tree
- hulk test robot
- syzkaller
- kselftest
- trinity
- coccinelle
- smatch
- Linux Test Project
- ktest
- And many many more!!!

“Shut Up And Start Torturing!!!”

“Shut Up And Start Torturing!!!”

- Given suitable system running qemu & kvm:

```
PATH=”tools/testing/selftests/rcutorture/bin:$PATH” export PATH
kvm.sh # Default 30 minutes (AKA 30m) on each of 19 scenarios.
kvm.sh --cpus 64 # Run scenarios concurrently in two batches of 30 minutes each.
kvm.sh --allcpus --duration 1d # Weekend run.
kvm.sh --cpus 128 --duration 12h --trust-make # All scenarios in one batch.
Kvm.sh --cpus 16 --configs "2*SRCU-N 2*SRCU-P 2*SRCU-t 2*SRCU-u" # 2x each SRCU scenario.
kvm-again.sh /path/to/old/run/results --duration 45s # No kernel builds.
kvm-remote.sh “sys1 sys2 … sys20” --cpus 80 --configs “TREE10 15*CFLIST”
# Replace “sys1” etc. with names of systems you can non-interactively ssh to.
```

What Does Success Look Like?

```
RUDE01 ------- 2102 GPs (7.00667/s) [tasks-rude: g0 f0x0 ]
SRCU-N ------- 42229 GPs (140.763/s) [srcu: g549860 f0x0 ]
SRCU-P ------- 11887 GPs (39.6233/s) [srcud: g110444 f0x0 ]
SRCU-t ------- 59641 GPs (198.803/s) [srcu: g1 f0x0 ]
SRCU-u ------- 59209 GPs (197.363/s) [srcud: g1 f0x0 ]
TASKS01 ------- 1029 GPs (3.43/s) [tasks: g0 f0x0 ]
TASKS02 ------- 1043 GPs (3.47667/s) [tasks: g0 f0x0 ]
TASKS03 ------- 1019 GPs (3.39667/s) [tasks: g0 f0x0 ]
TINY01 ------- 43373 GPs (144.577/s) [rcu: g0 f0x0 ] n_max_cbs: 34463
TINY02 ------- 46519 GPs (155.063/s) [rcu: g0 f0x0 ] n_max_cbs: 2197
TRACE01 ------- 756 GPs (2.52/s) [tasks-tracing: g0 f0x0 ]
TRACE02 ------- 559 GPs (1.86333/s) [tasks-tracing: g0 f0x0 ]
TREE01 ------- 8930 GPs (29.7667/s) [rcu: g64765 f0x0 ]
TREE02 ------- 17514 GPs (58.38/s) [rcu: g138645 f0x0 ] n_max_cbs: 18010
TREE03 ------- 15920 GPs (53.0667/s) [rcu: g159973 f0x0 ] n_max_cbs: 1025308
TREE04 ------- 10821 GPs (36.07/s) [rcu: g70293 f0x0 ] n_max_cbs: 81293
TREE05 ------- 16942 GPs (56.4733/s) [rcu: g123745 f0x0 ] n_max_cbs: 99796
TREE07 ------- 8248 GPs (27.4933/s) [rcu: g52933 f0x0 ] n_max_cbs: 183589
TREE09 ------- 39903 GPs (133.01/s) [rcu: g717745 f0x0 ] n_max_cbs: 83002
```


Plus exit code of zero, which can be useful when bisecting.

Other kvm.sh Parameters?

- `--kconfig`: Specify Kconfig options
- `--bootargs`: Specify kernel-boot parameters
- `--kasan`: Run under KASAN
- `--kcsan`: Run under KCSAN (big binaries!)
  - Also requires very recent compilers
- `--torture`: rcu, lock, scf, refscale, rcuscale
- `--dryrun scenarios`: Show batches for given CPUs/configs
  - Useful for working out what `--config` argument to specify

https://paulmck.livejournal.com/57769.html https://paulmck.livejournal.com/58077.html

“I Cannot Decide What to Torture!!!”

- Use the `torture.sh` script
- By default, tortures a little of everything
  - Takes about 12 hours on a heavy-duty laptop
- Many arguments to control its torturing

https://paulmck.livejournal.com/61587.html

Arguments to `torture.sh`

- `--do-all`: Everything including KCSAN (disabled by default)
- `--do-none`: Nothing
- `--do-kasan`, `--do-kcsan`: Enable debugging
- Select tests:
  - `--do-clocksourcewd`, `--do-kvfree`, `--do-locktorture`, `--do-rcuscale`, `--do-rcutorture`, `--do-refscale`, `--do-scftorture`
- Select scenarios:
  - `--configs-rcutorture`, `--configs-locktorture`, `--configs-scftorture`
- `--duration`: Nominal duration: 10m → 11h on 16 CPUs

“But I Want To Use A Debugger!!!”

“But I Want To Use A Debugger!!!”

- --gdb is your friend:

```
$ kvm.sh --allcpus --torture lock --configs LOCK05 --gdb
Waiting for you to attach a debug session, for example:
    gdb tools/testing/selftests/rcutorture/res/2020.08.27-14.51/LOCK05/vmlinux
After symbols load and the "(gdb)" prompt appears:
    target remote :1234
    continue
```

- Once you have connected, use gdb commands
  - But “hbreak” instead of “break”
  - The Linux kernel is not fond of software breakpoints

https://paulmck.livejournal.com/58616.html

“I Found a Bug!!! What Now???”

“I Found a Bug!!! What Now???”

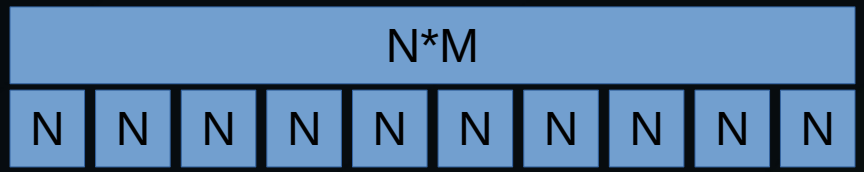
- Fix it and post the patch? ;-)
- With RCU, heisenbugs are the common case
  - So make it happen more often!

How to De-Heisenbug Bugs???

- It is not always easy, but here are a few tricks...

How to De-Heisenbug Bugs???

- Adjust CPUs to increase probability by factor of M
  - Mx fewer runs with Mx more CPUs each
    - If races are between many random kthreads
  - Mx more runs with Mx fewer CPUs each
    - If races are between a few specific kthreads
- This is theory: The real world does what it pleases

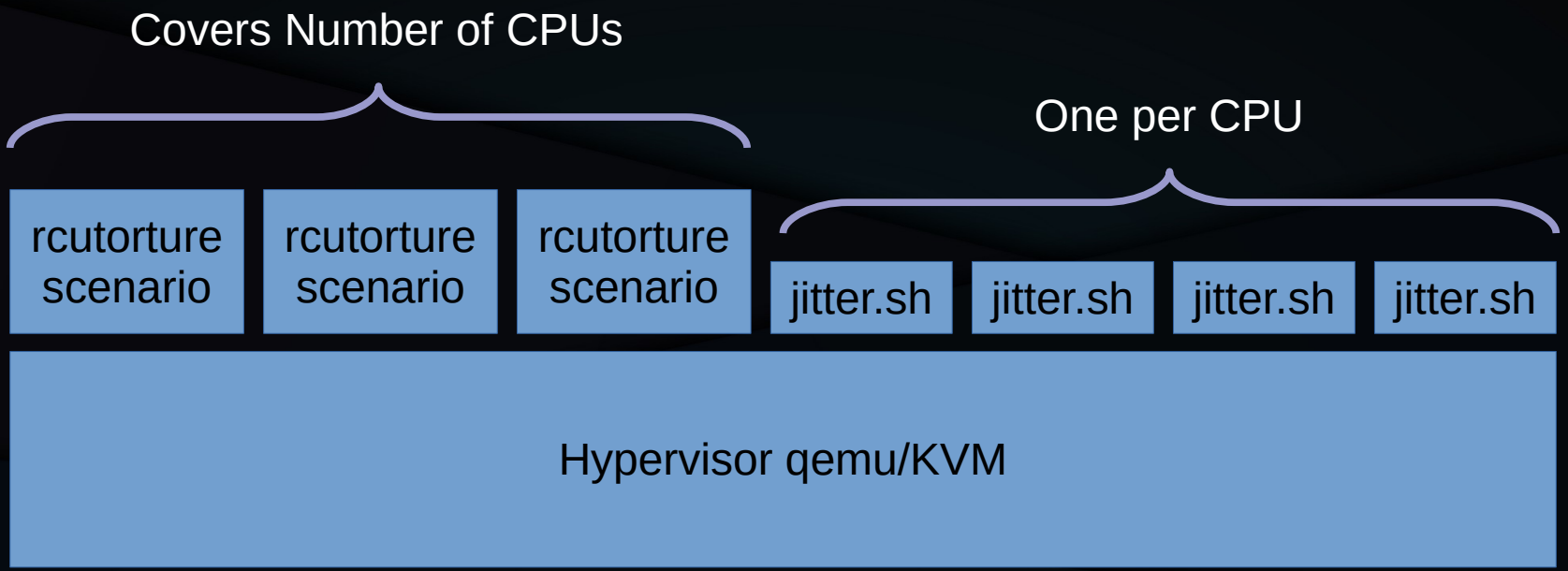


How to De-Heisenbug Bugs???

- Make risky operations happen more frequently!
  - CPU hotplug is one of the usual suspects:

    `rcutorture.onoff_interval=200`
  - Long-lived readers (automatic)
  - Full-system idle `rcutorture.stutter`
  - Callback floods `rcutorture.fwd_progress`
  - vCPU preemption `kvm.sh --jitter “N us-sleep us-spin”`
    - See next slide

Preemption Via Jitter

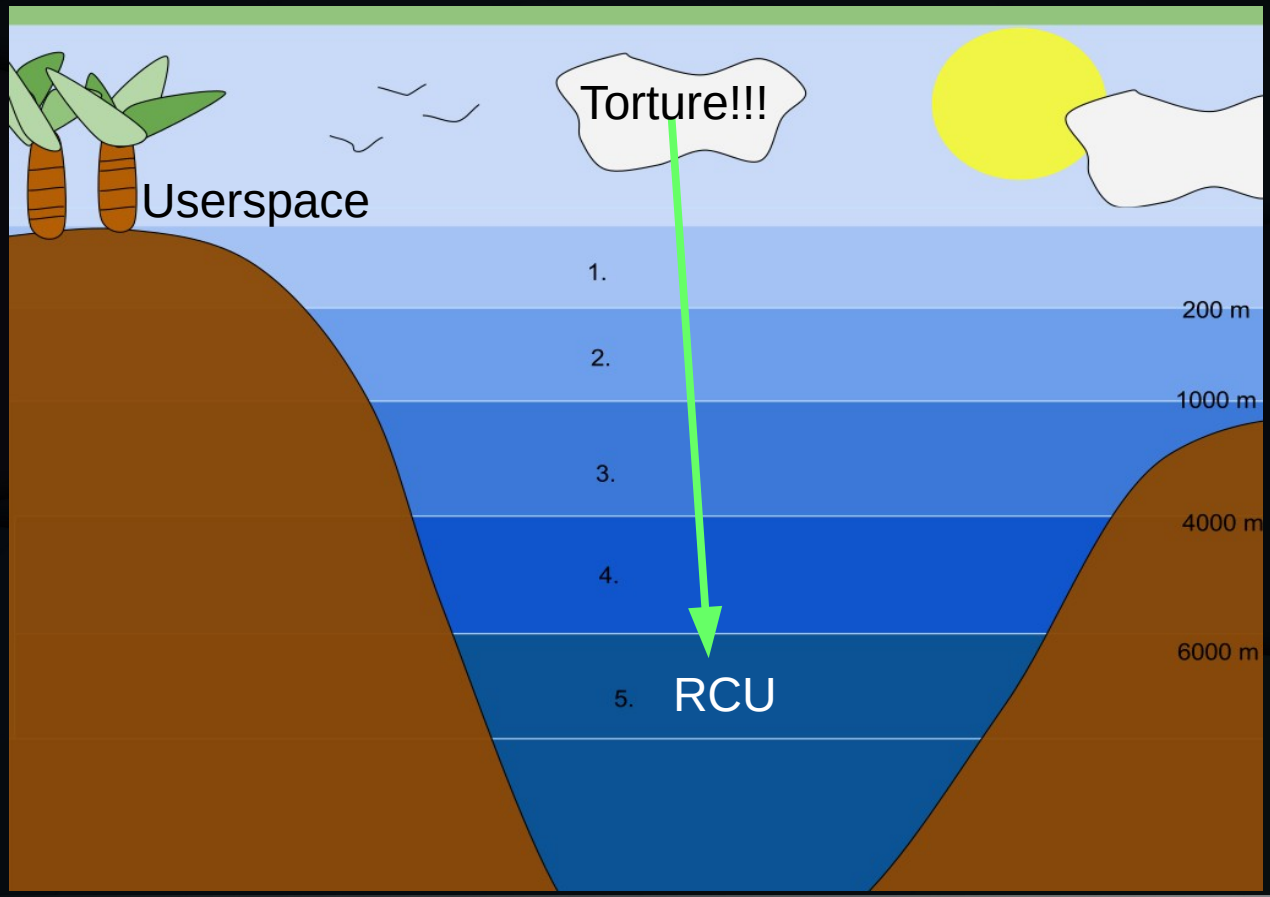


The jitter.sh script binds to randomly selected CPUs, forcing preemption, even when that vCPU thinks that it has disabled interrupts.

How to De-Heisenbug Bugs???

- Which scenarios cause the problem most frequently?
  - Use `--configs` to run those scenarios
  - Use `config2csv.sh` to compare configurations
  - Double down on suspected accelerators
    - Kconfig options and/or kernel boot parameters
    - Modify kernel or scripts in some cases

Kernel Module, Not Userspace



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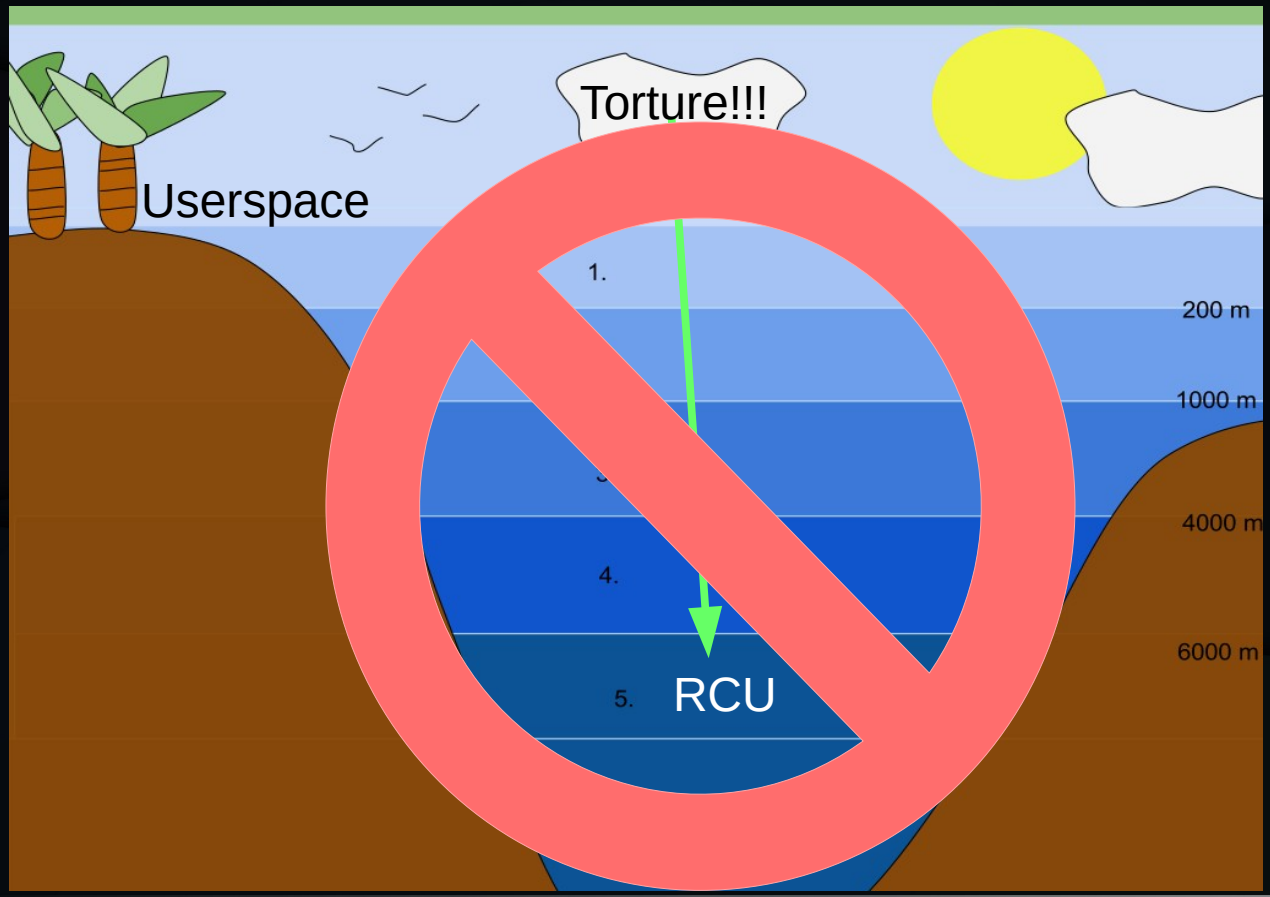

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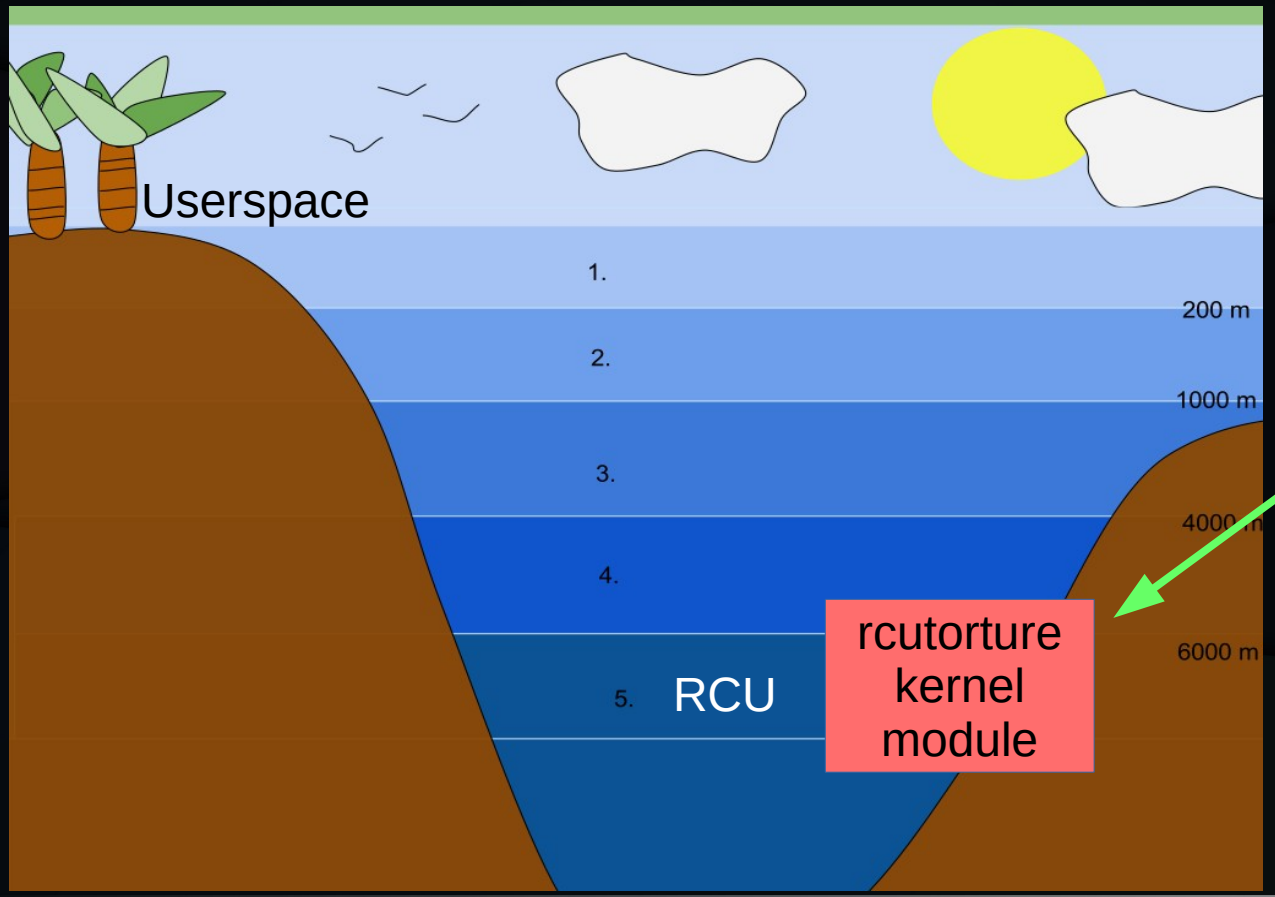


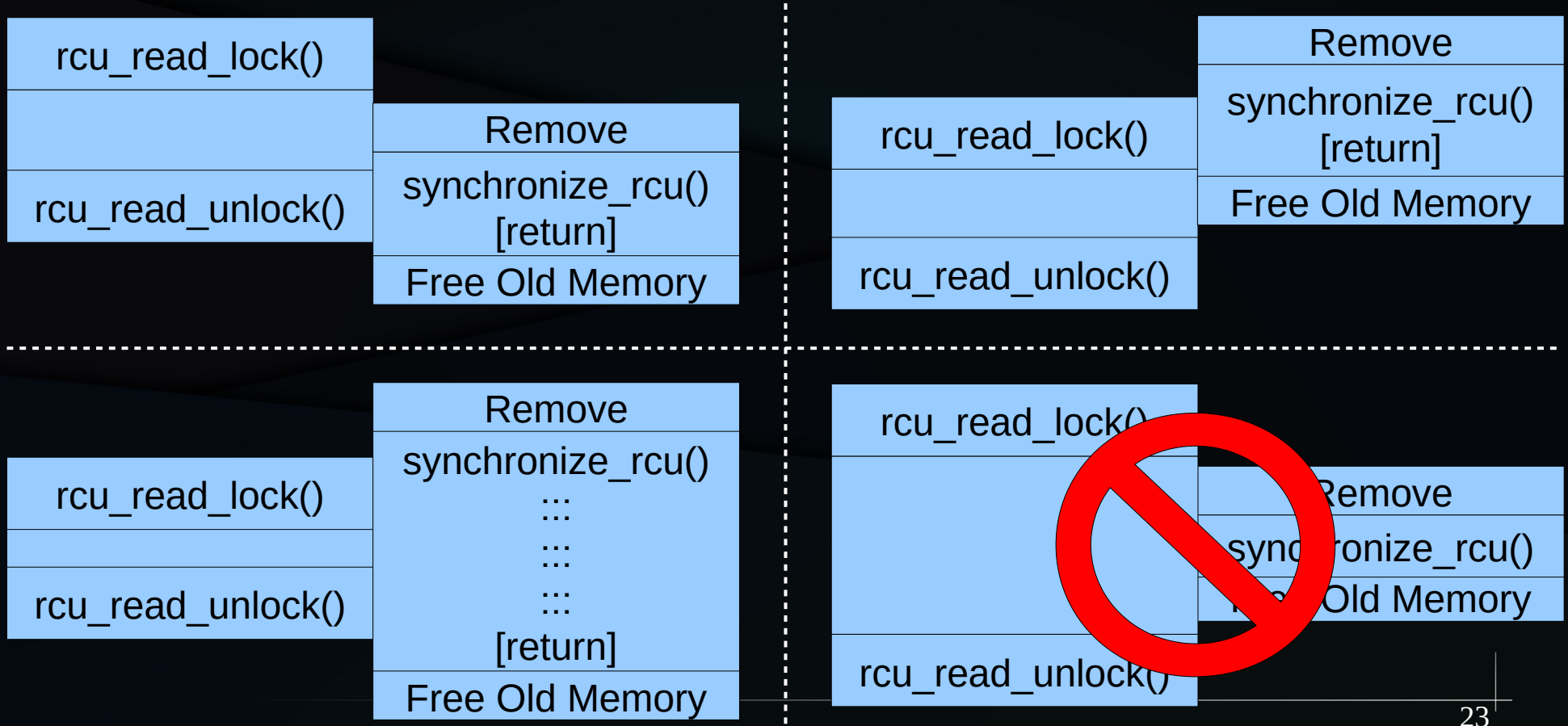
How to De-Heisenbug Bugs???

- Enlist the aid of the laws of physics!!!
- The speed of light is too slow and atoms are too big
  - Hence memory latency and NUMA effects
- For each rcutorture guest OS:
  - Place two CPUs in one hyperthreaded core
  - Place two other CPUs in another core
    - Preferably on some other socket
- Greatly increases probability of some types of period races
  - Accesses take longer only sometimes, raise collision cross section

The effects were not subtle: `https://paulmck.livejournal.com/62071.html`

Semantics

RCU Semantics (Graphical)



RCU Semantics (API)

- RCU has simple semantics:
  - RCU grace period must wait for all pre-existing RCU readers
- Trivial textbook RCU implementation:

```
#define rcu_read_lock() __asm__ __volatile__("": : :"memory")
#define rcu_read_unlock() __asm__ __volatile__("": : :"memory")
#define rcu_dereference(p) \
({ \
        typeof(*p) *__p1 = READ_ONCE(p); \
        __p1; \
})
#define rcu_assign_pointer(p, v) smp_store_release((p), (v))
void synchronize_rcu(void)
{
        int cpu;

        for_each_online_cpu(cpu)
                sched_setaffinity(current->pid, cpumask_of(cpu));
}
```

Just a Few Linux-Kernel Issues...

- Systems with 1000s of CPUs
- Sub-20-microsecond real-time response requirements
- CPUs can come and go (“CPU hotplug”)
- If you disturb idle CPUs. you enrage low-power embedded folks
- Forward progress requirements: callbacks, network DoS attacks
- RCU grace periods must provide extremely strong ordering
- RCU uses the scheduler, and the scheduler uses RCU
- Firmware sometimes lies about the number and age of CPUs
- RCU must work during early boot, even before RCU initialization
- Preemption can happen, even when interrupts are disabled (vCPUs!)
- RCU should avoid exploitable ease-of-use issues

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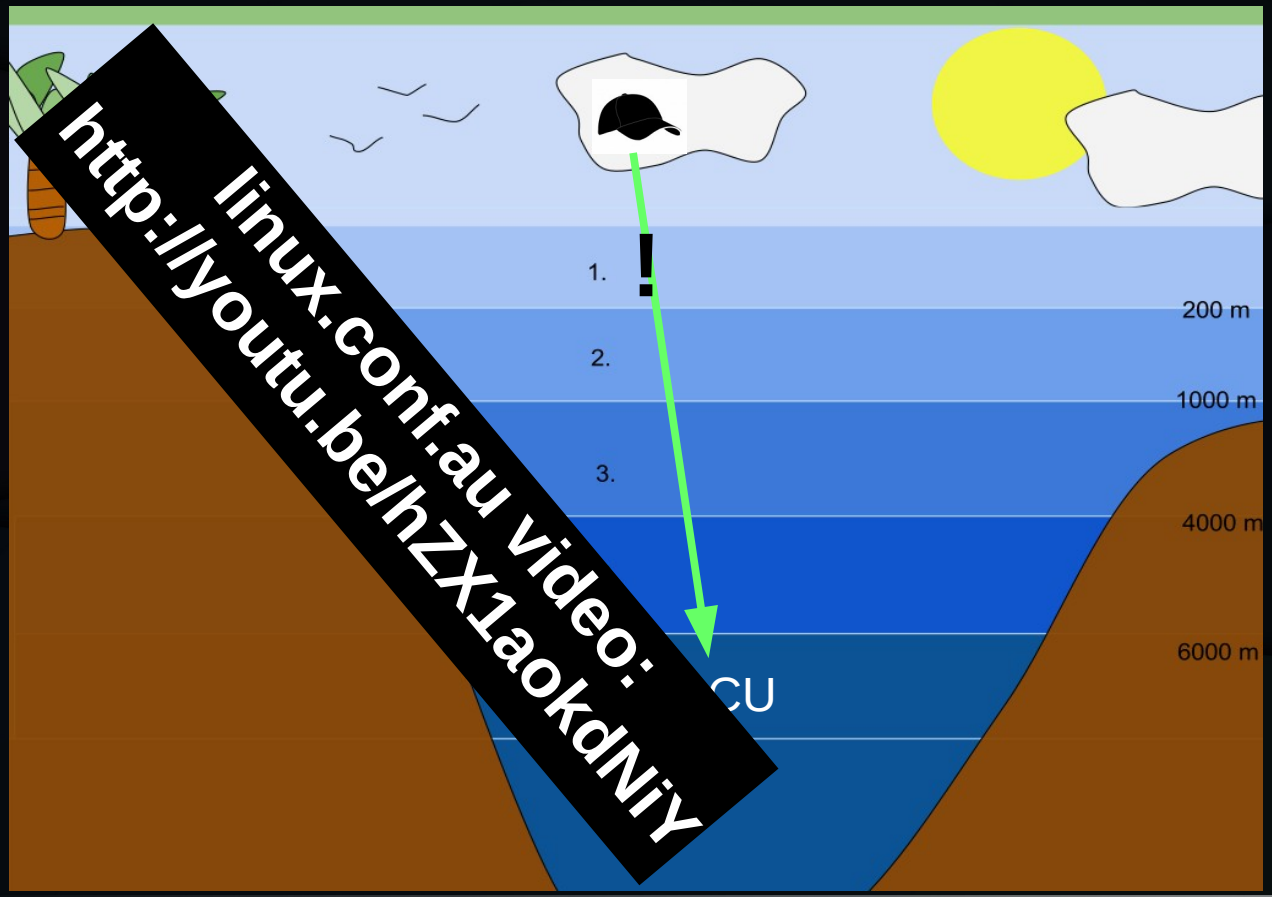
Not Just a Theoretical Possibility...



Many Types of RCU Readers (Old)

```
rcu_read_lock();
do_something_1();
preempt_disable();
do_something_2();
rcu_read_unlock();
do_something_3();
preempt_enable();
```

```
local_bh_disable();
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rcu_read_lock();
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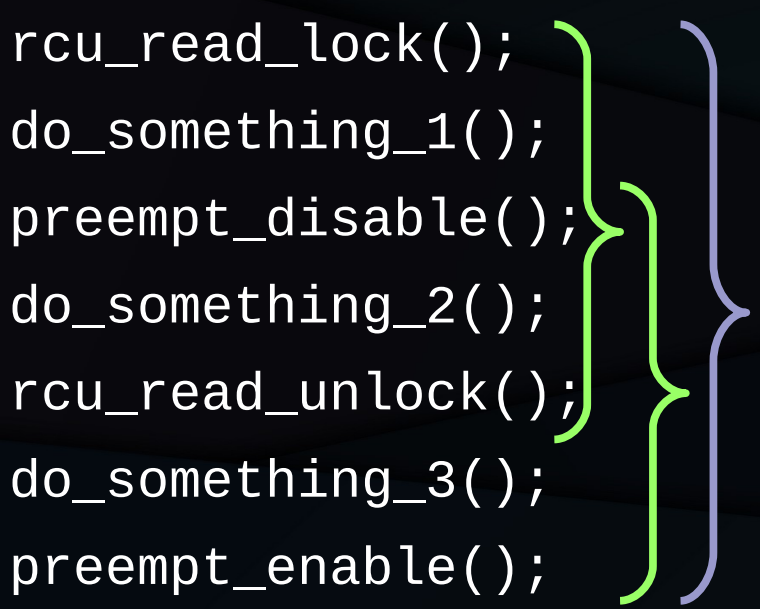
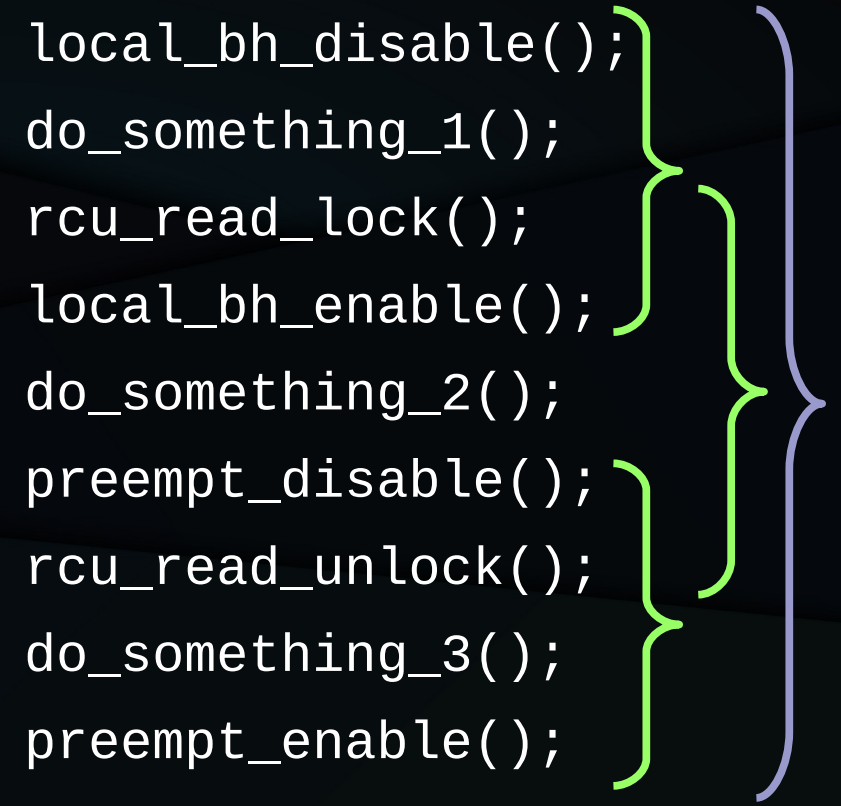
```

Many Types of RCU Readers (New)





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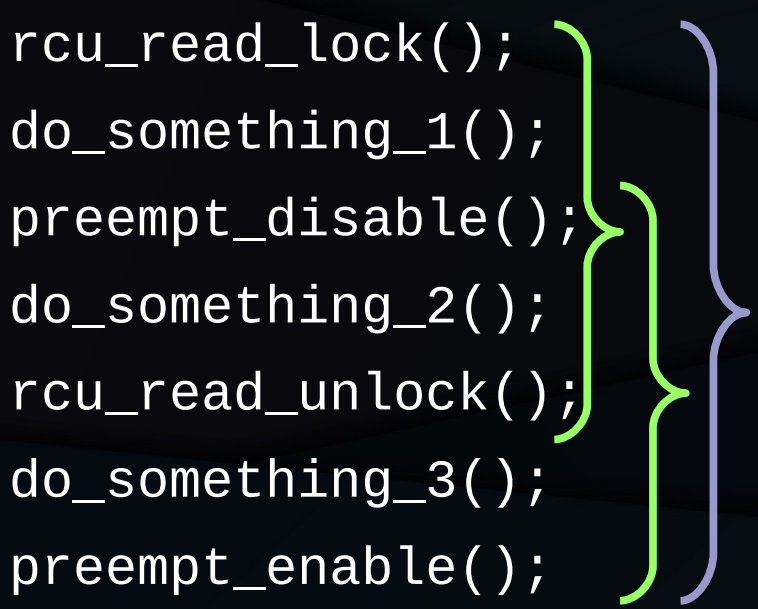

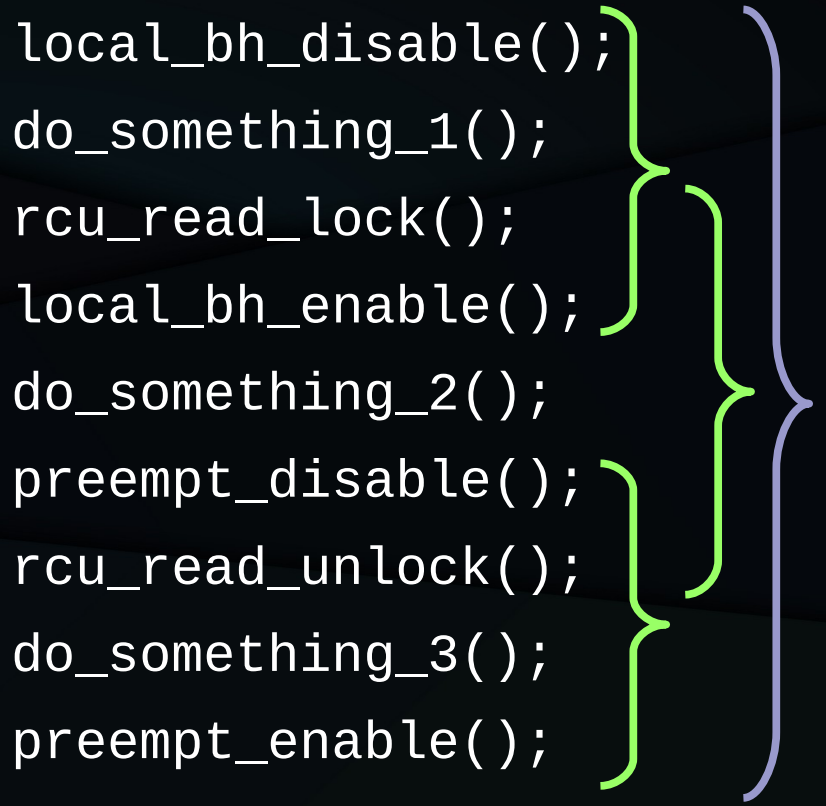

Therefore, rcutorture must randomly generate overlapping readers.

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```

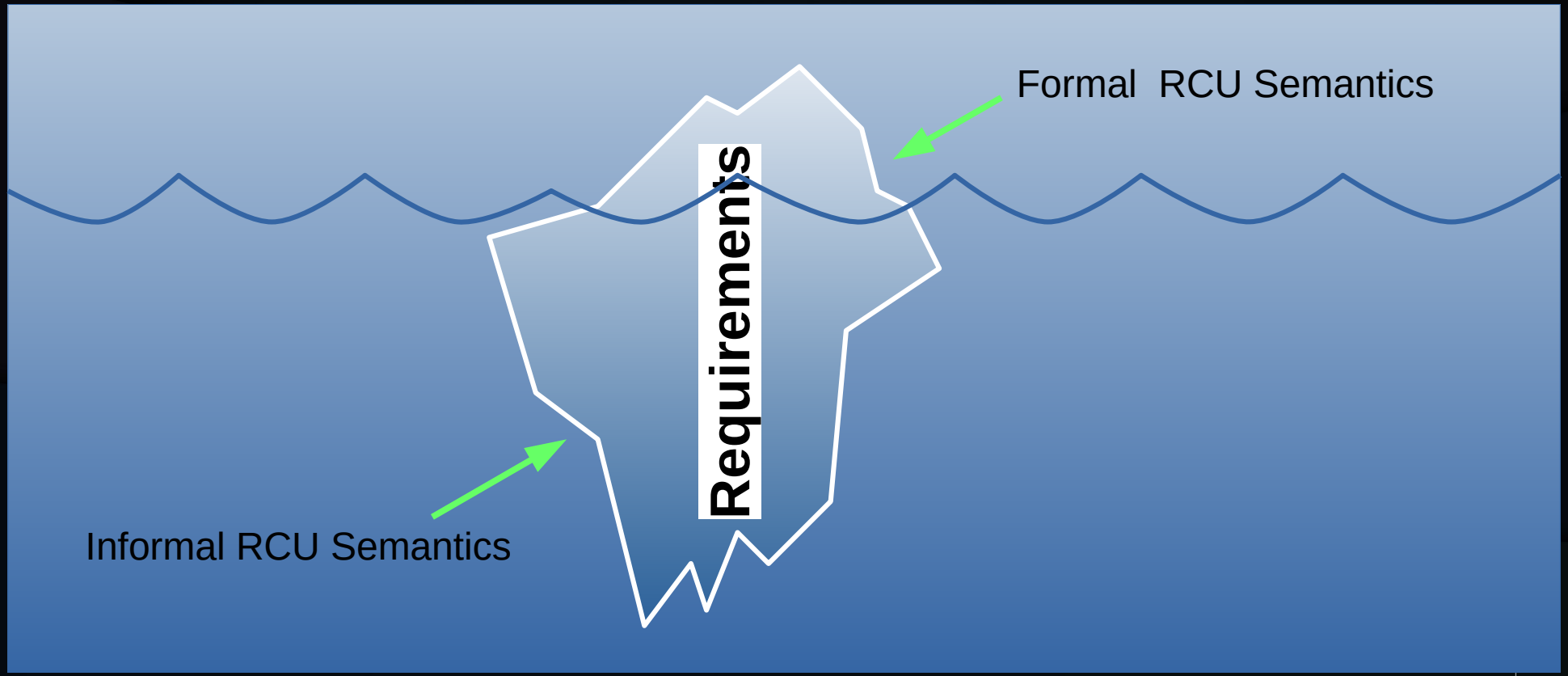
Therefore, rcutorture must randomly generate overlapping readers. **But including nested readers!!!**

Here is Your Elegant Synchronization Mechanism:

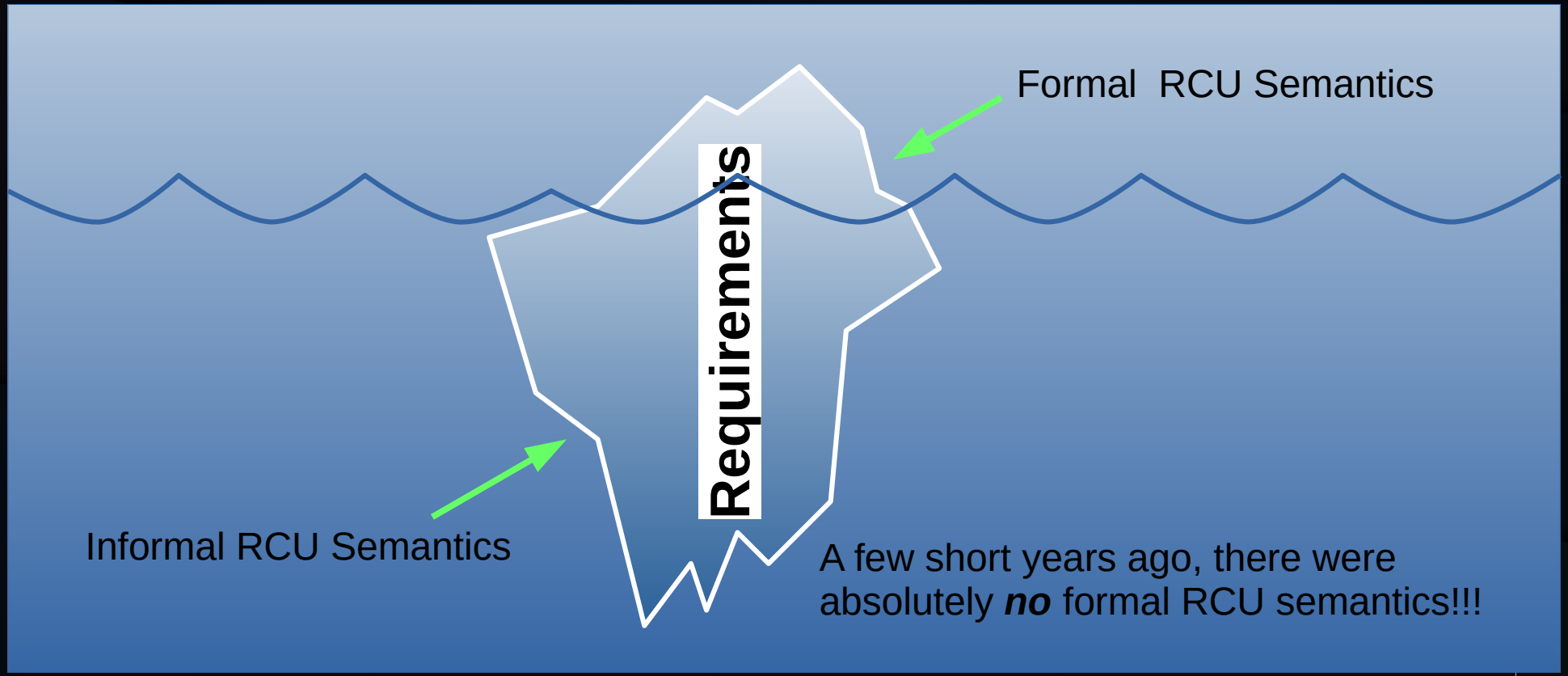
Photo by "Golden Trvs Gol twister", CC by SA 3.0

Here is Your Elegant Synchronization Mechanism Equipped to Survive in The Linux Kernel:

Semantics are the Tip of the Iceberg



Semantics are the Tip of the Iceberg



Software Engineering

Software Engineering

- RCU contains 17,682 LoC (including comments, etc.)
- 1-3 bugs/KLoC for production-quality code: ***18-53 bugs***
  - Best case I have seen: 0.04 bugs/KLoC for safety-critical code
    - Extreme code-style restrictions, single-threaded, formal methods, …
    - And still way more than zero bugs!!! :-)
- Median age of an RCU LoC is less than four years
  - And young code tends to be buggier than old code!
- We should therefore expect a few tens more bugs!!!

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- **An rcutorture run that “succeeds” has failed to find them!!!**

Installed Base

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Million-Year Bug? Once In a Million Years!!!

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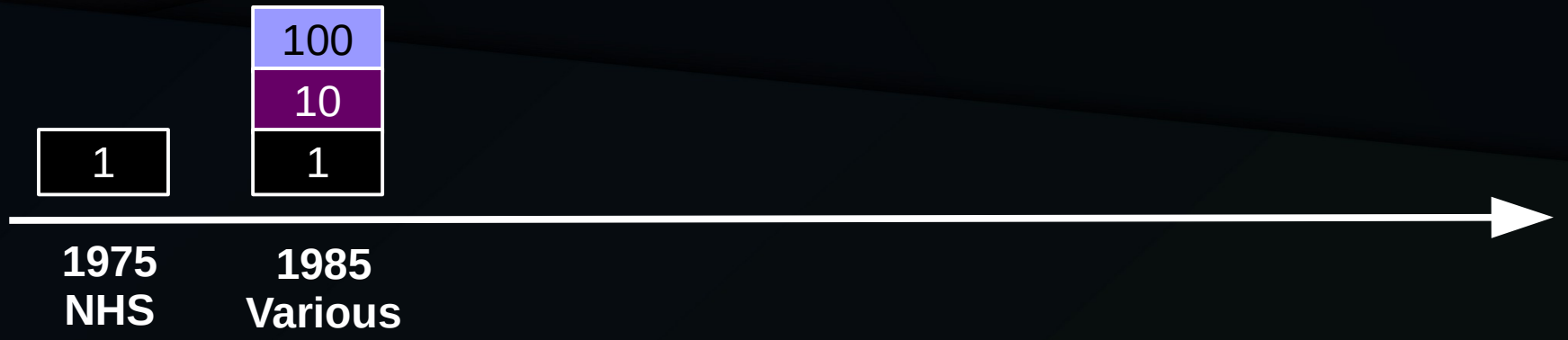
Murphy is a nice guy: Everything that can happen, will...

Installed Base

Million-Year Bug? Once In a Million Years!!!
Murphy is a nice guy: Everything that can happen, will...
...maybe in geologic time

Installed Base

Million-Year Bug? Once in Ten Millennia

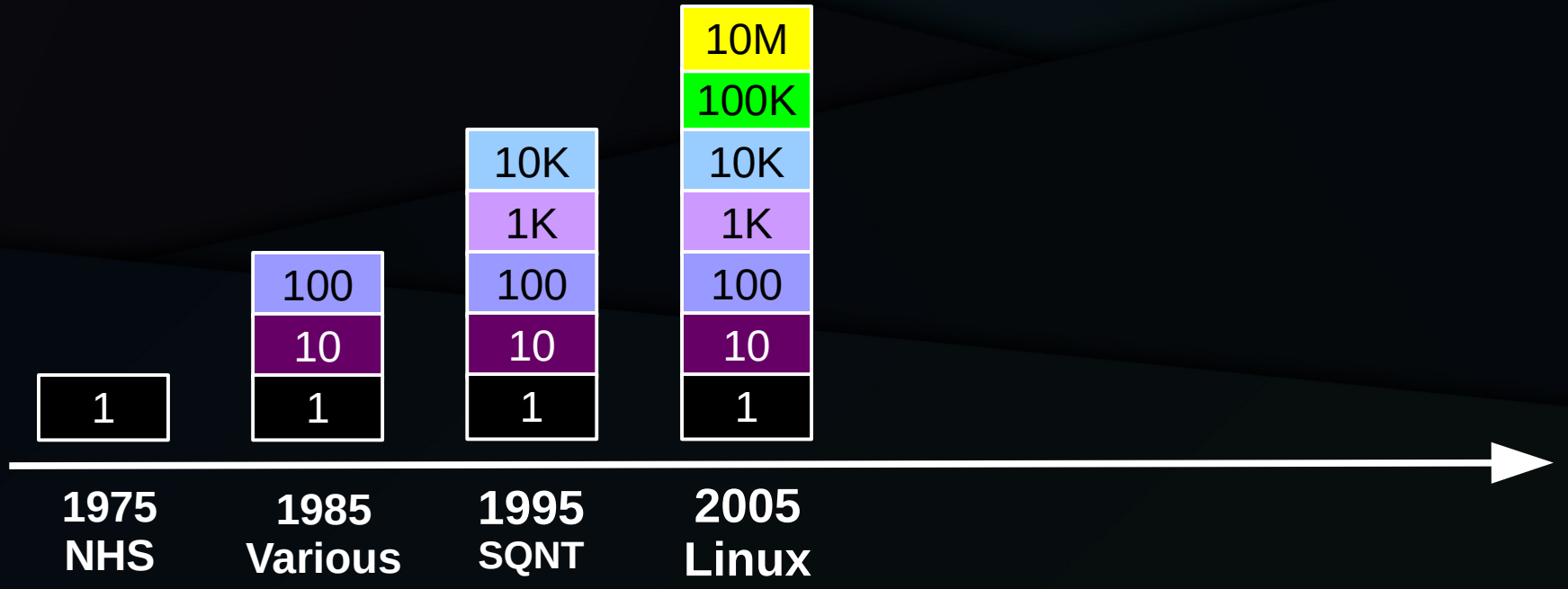


Installed Base

Million-Year Bug? Once per Century

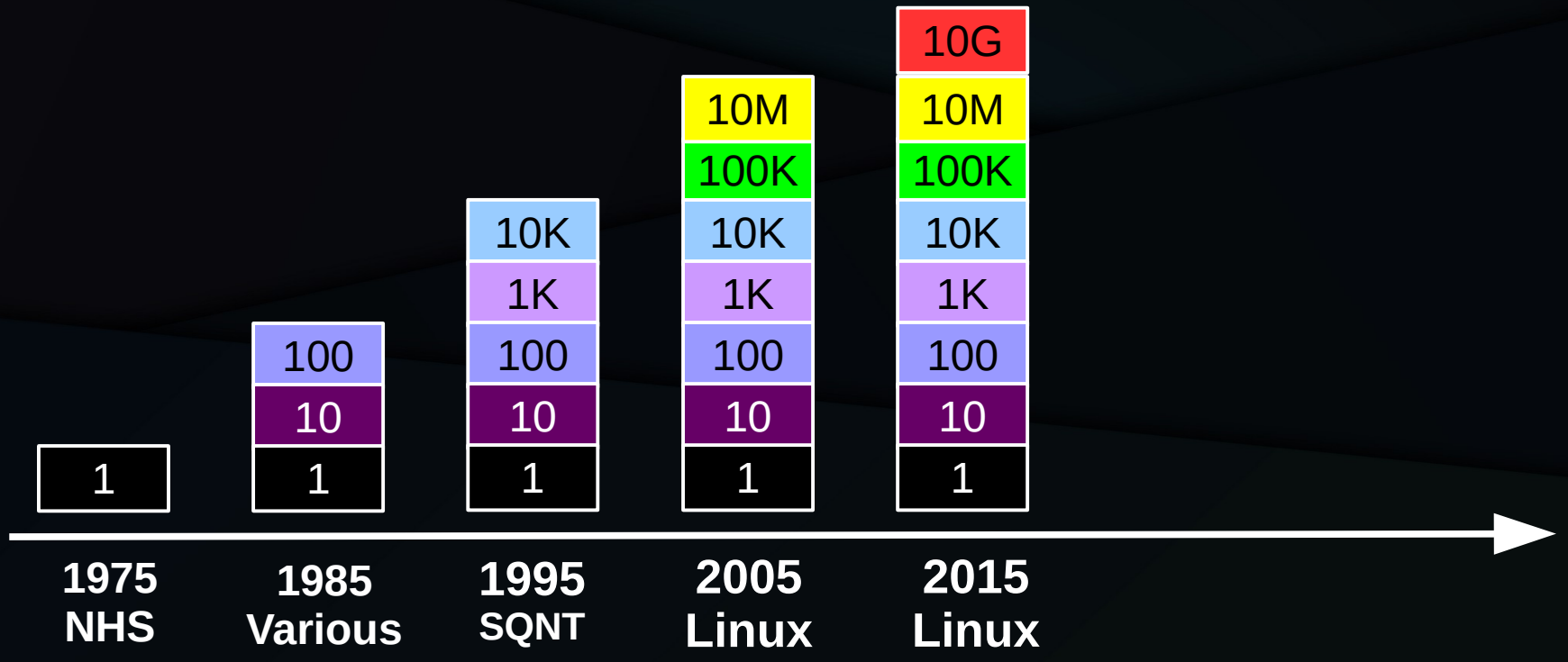
Installed Base

Million-Year Bug? Once a Month



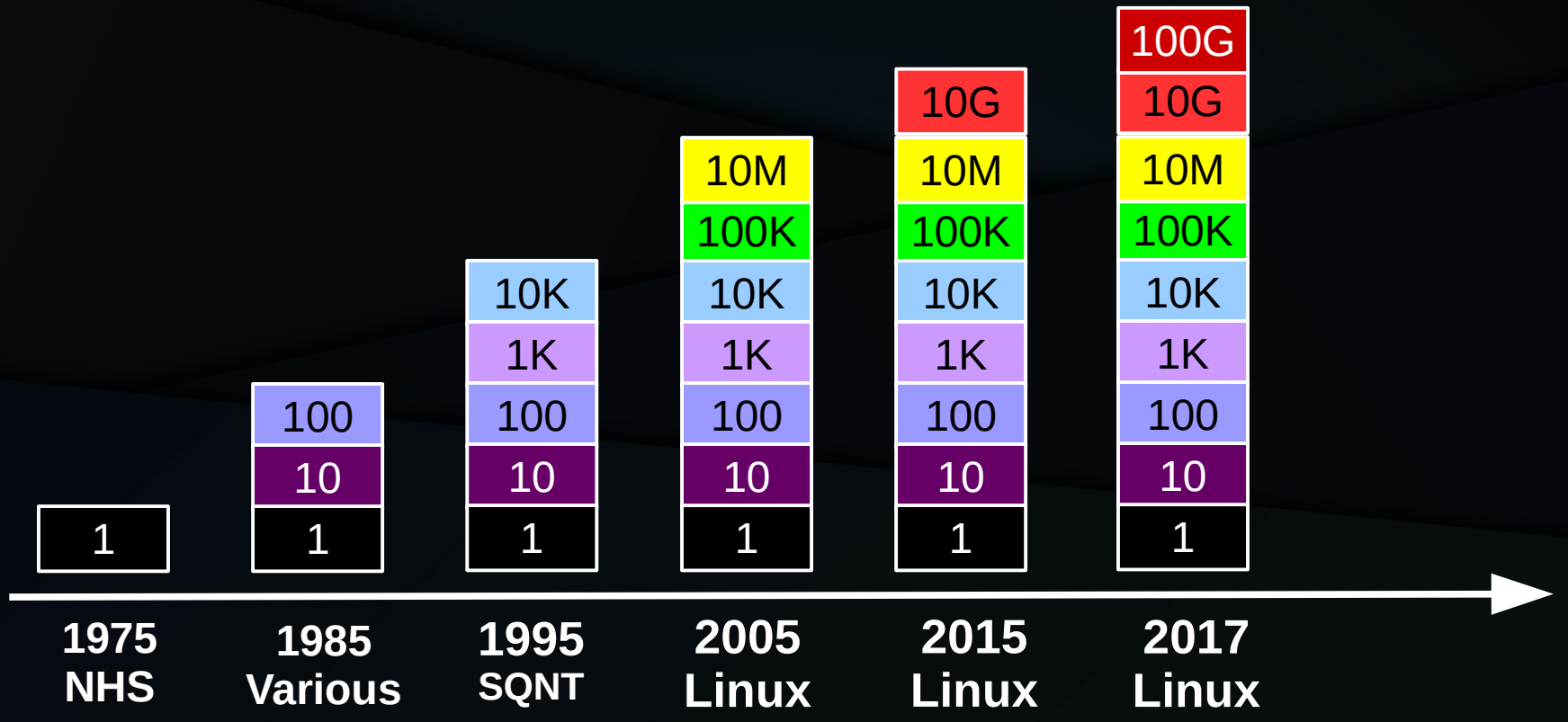
Installed Base

Million-Year Bug? Several Times per *Day*



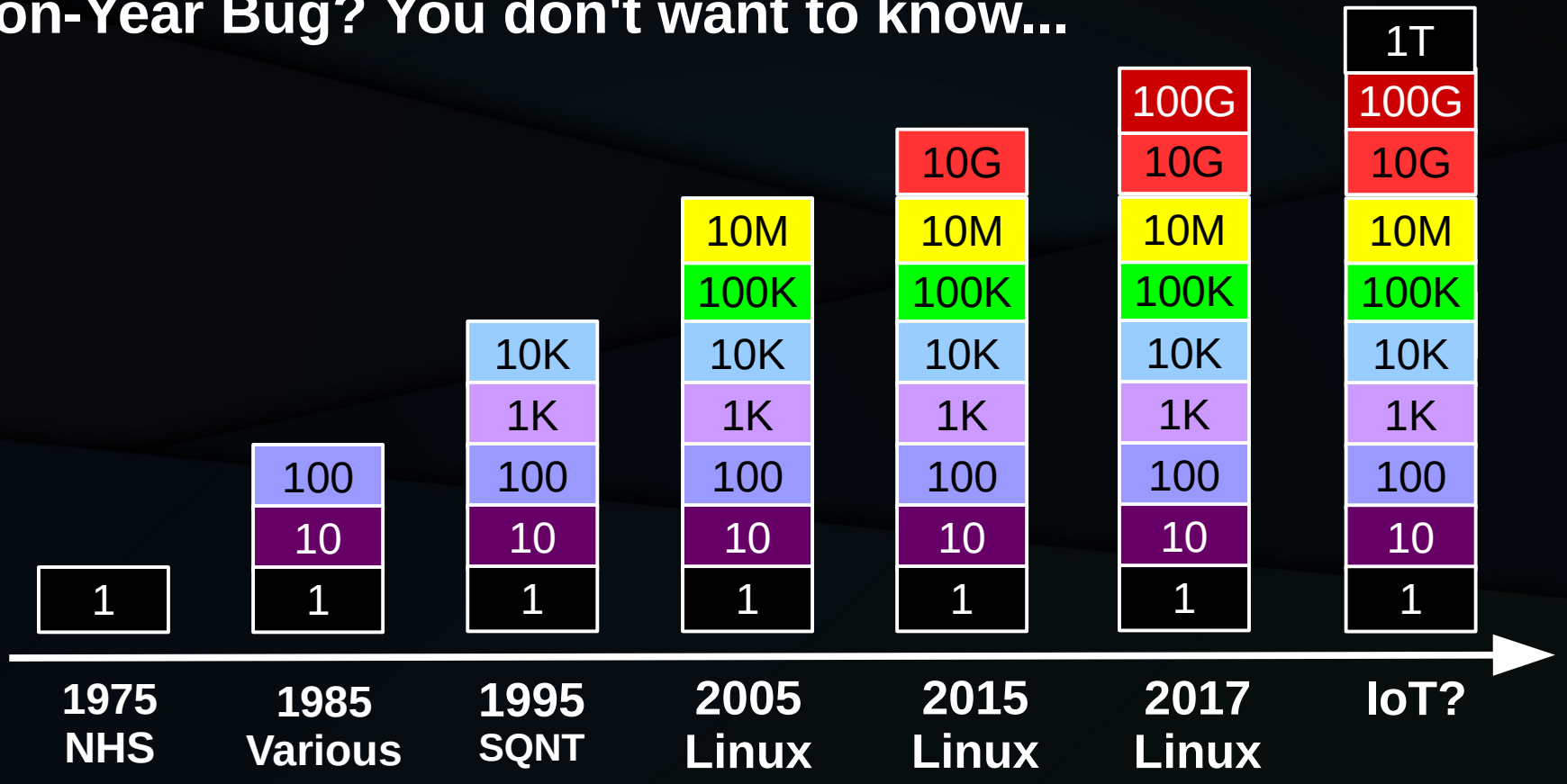
Installed Base

Million-Year Bug? Several Times per *Hour*



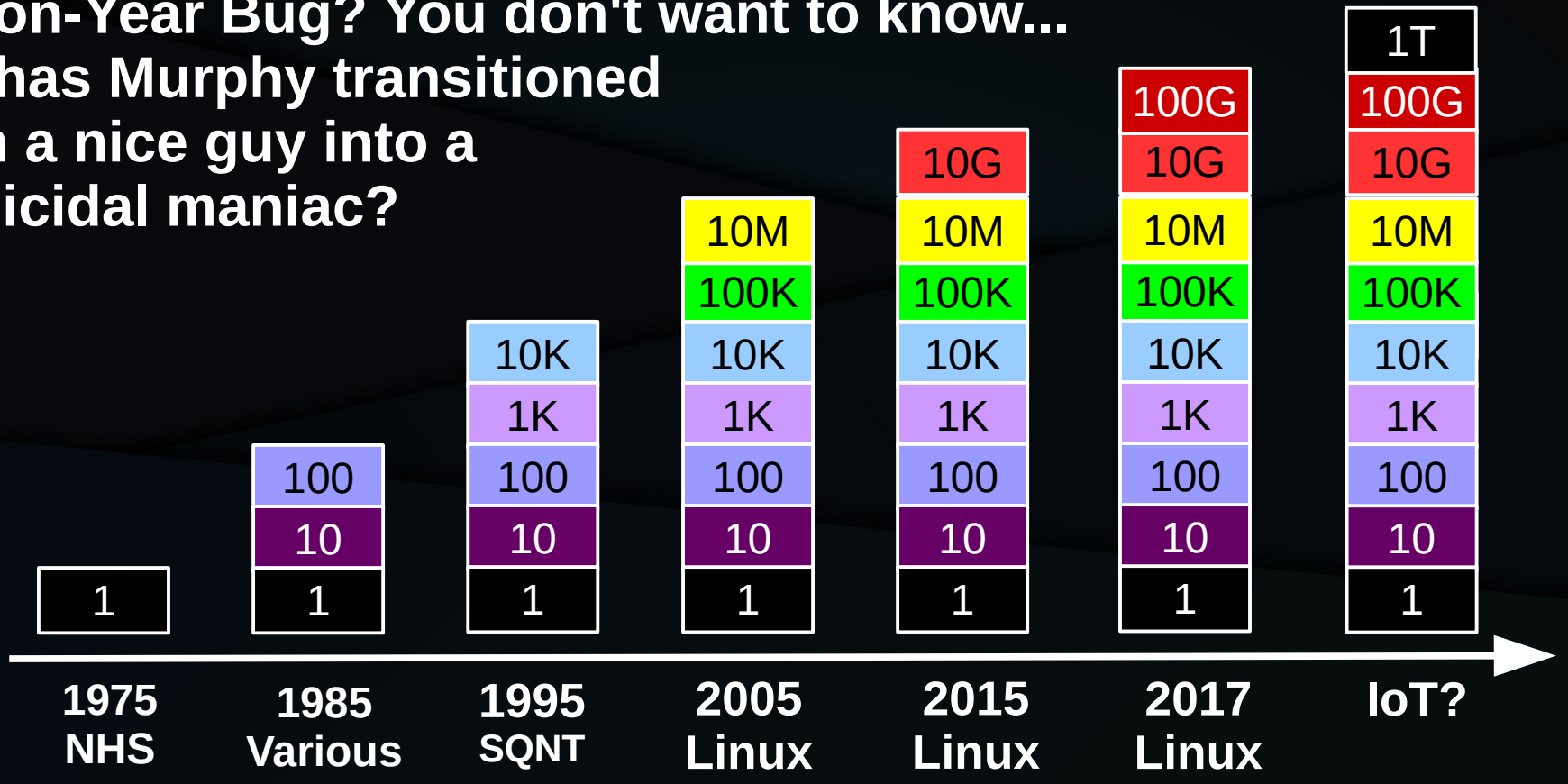
Installed Base

Million-Year Bug? You don't want to know...



Installed Base

Million-Year Bug? You don't want to know...
But has Murphy transitioned from a nice guy into a homicidal maniac?



Natural Selection

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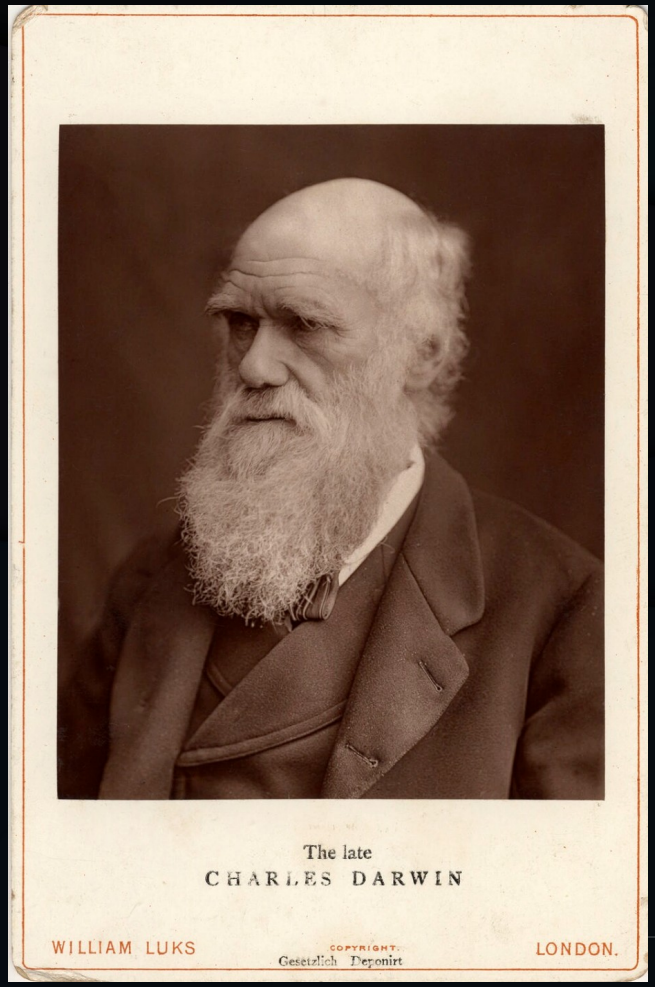
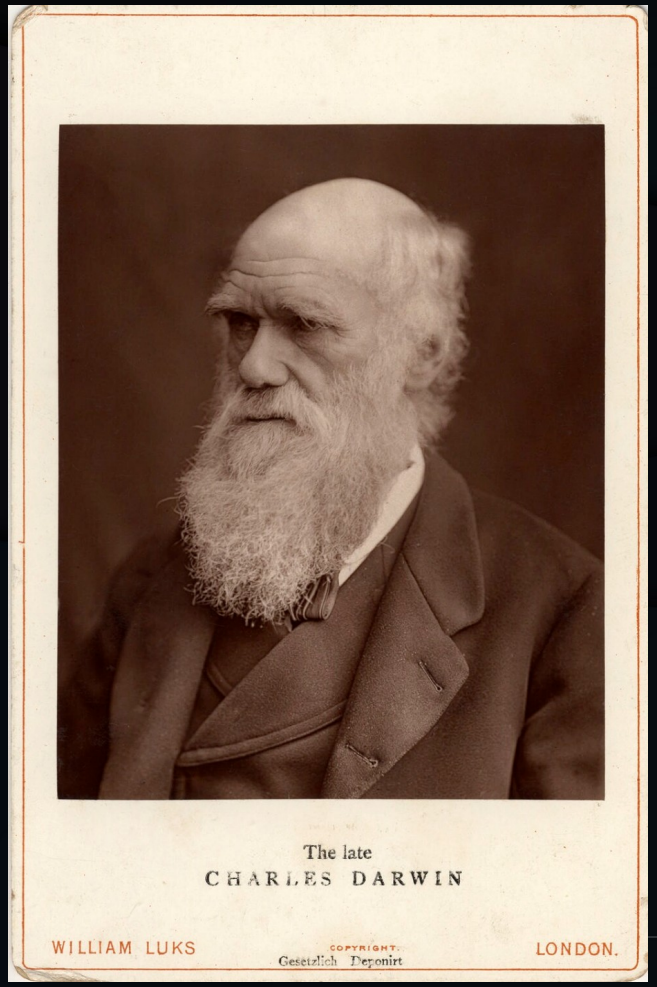
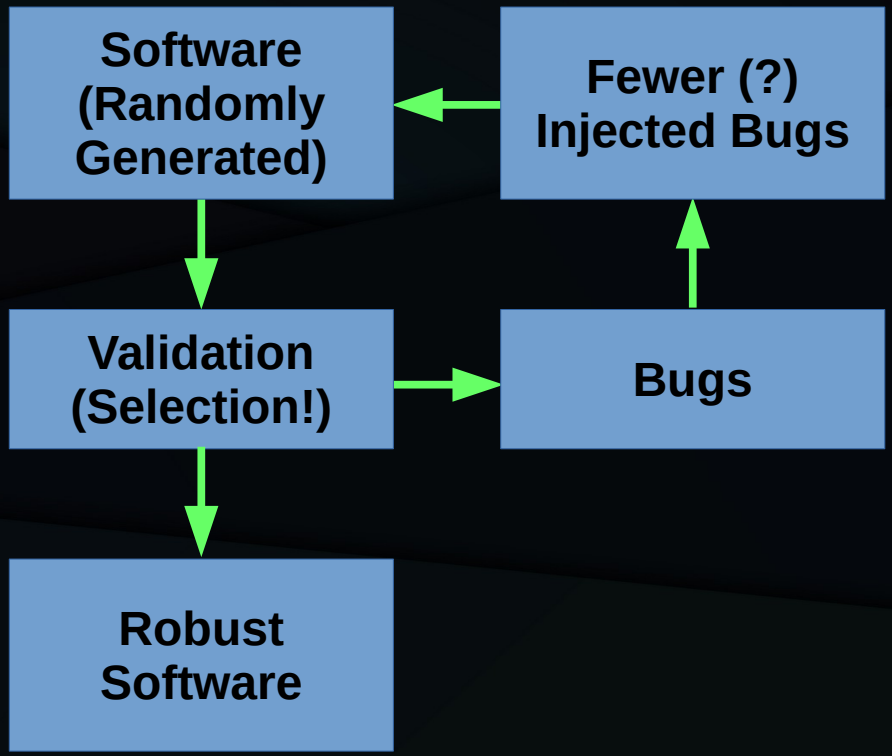
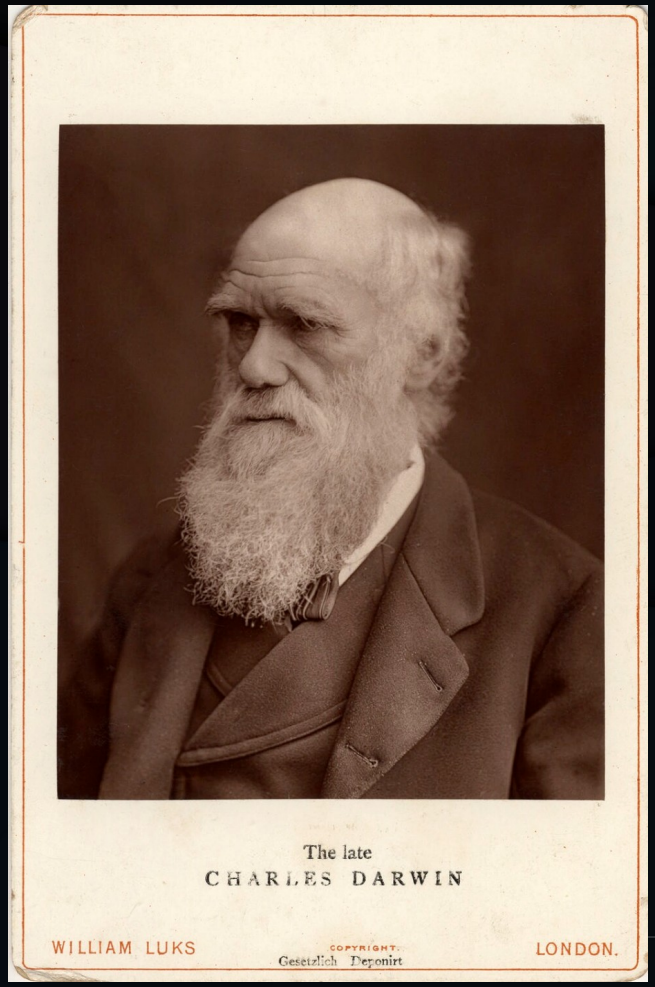


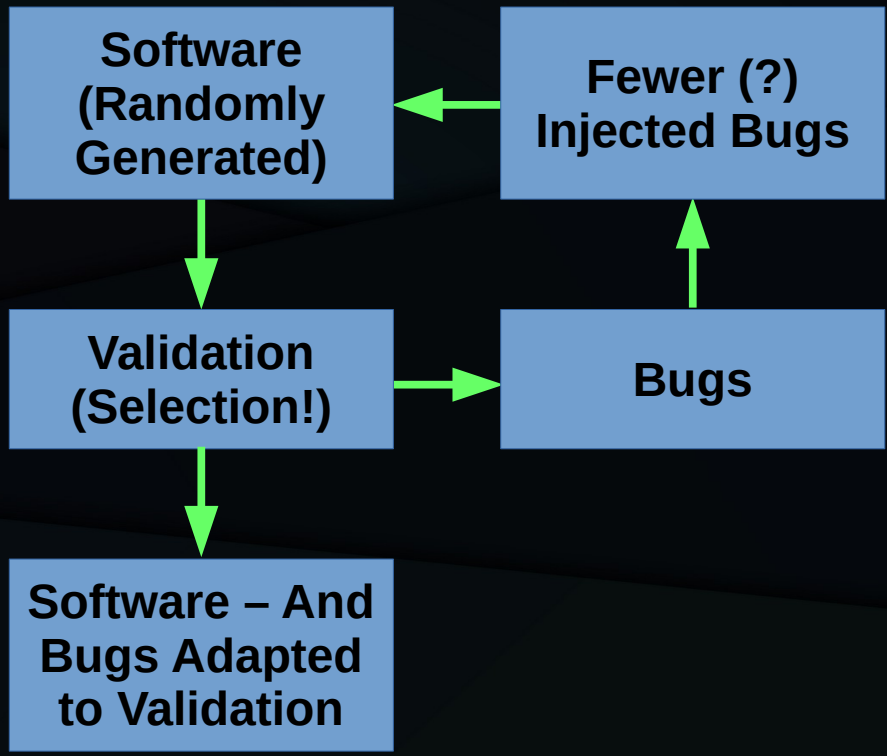
Natural Selection: Not Just Lifeforms





Natural Selection: Bugs are Software!





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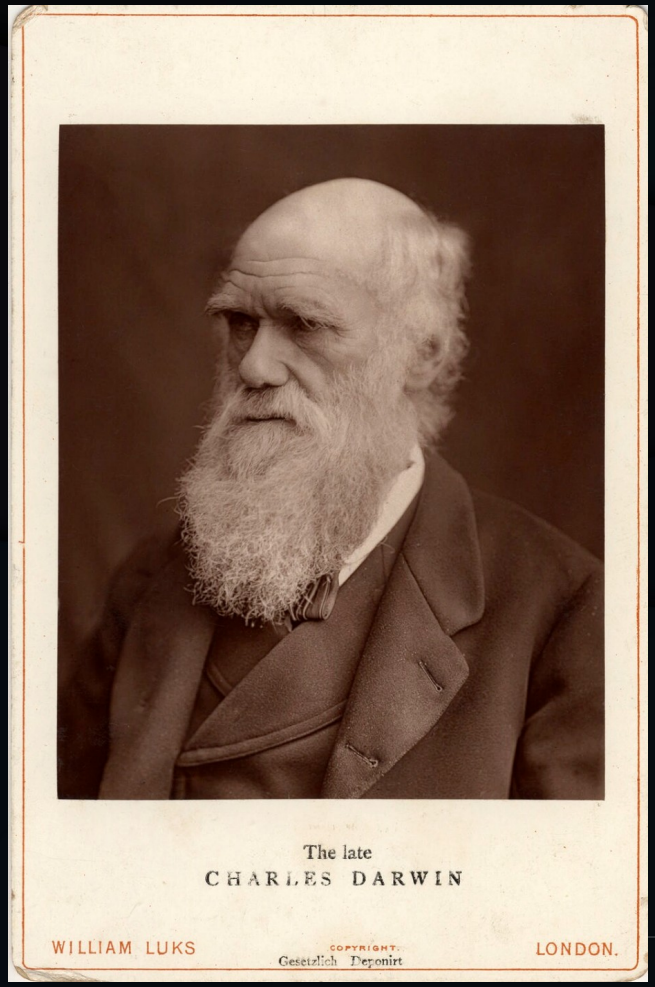
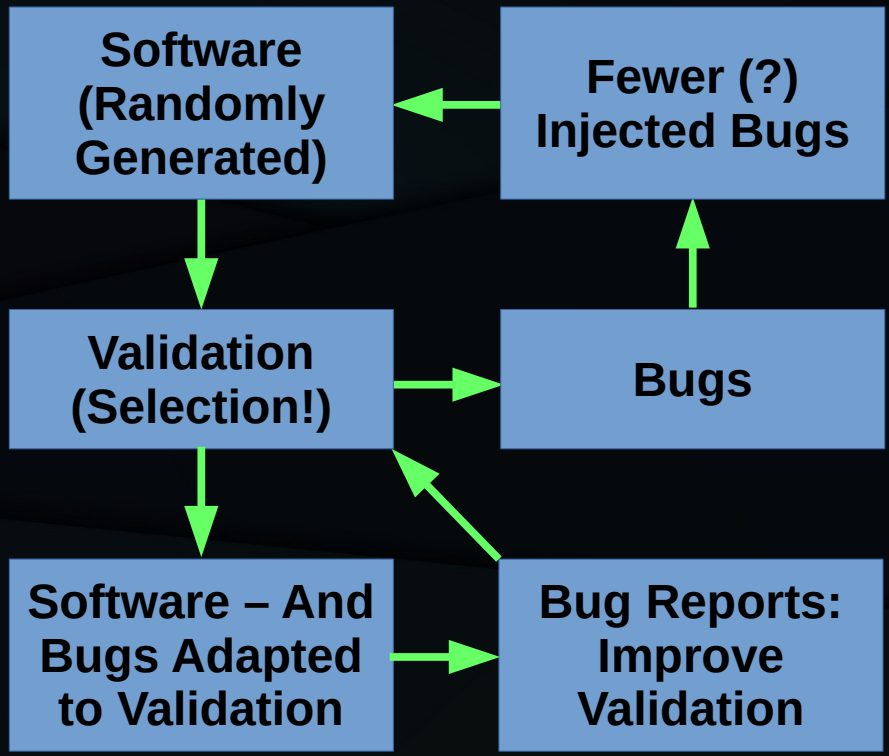
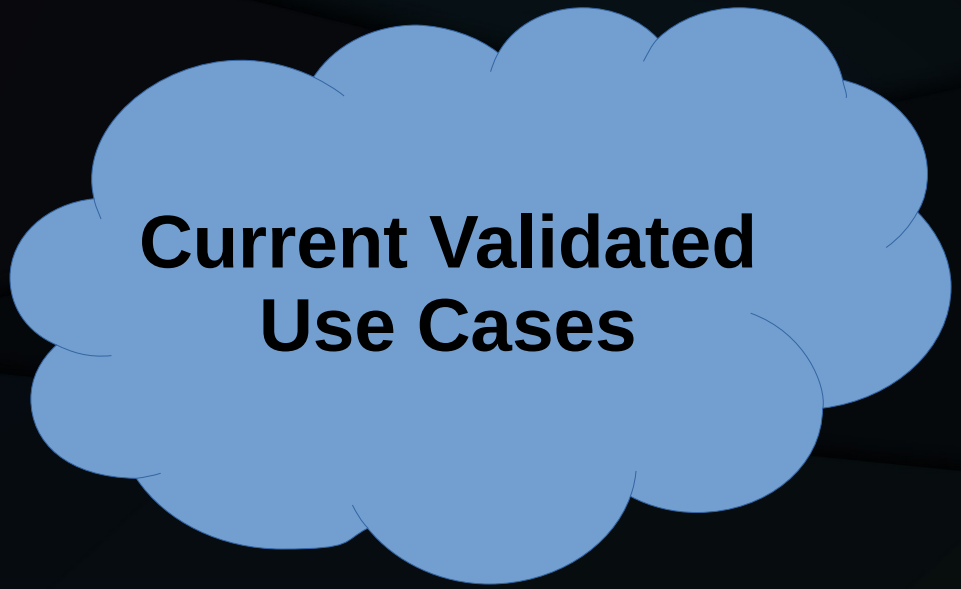


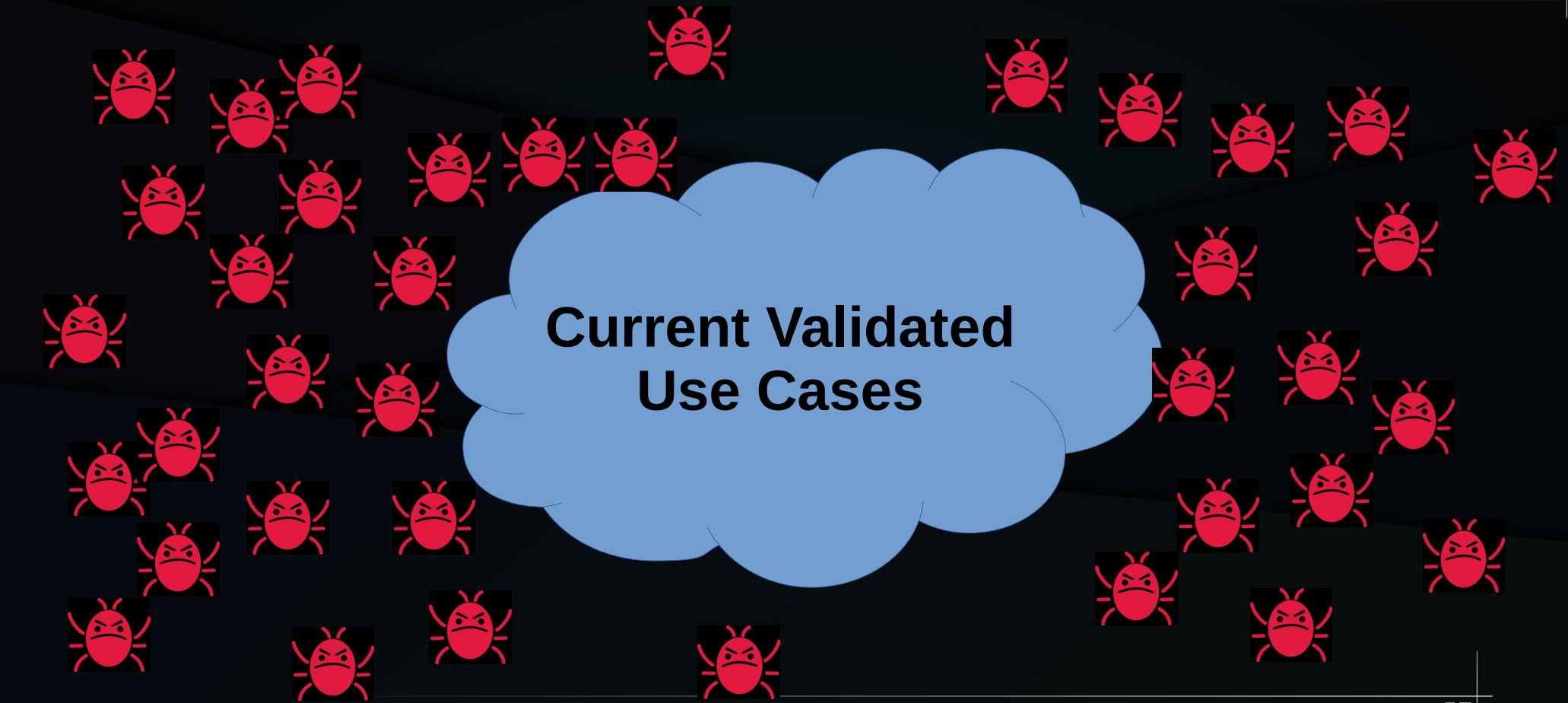


Validate Only Intended Use Cases

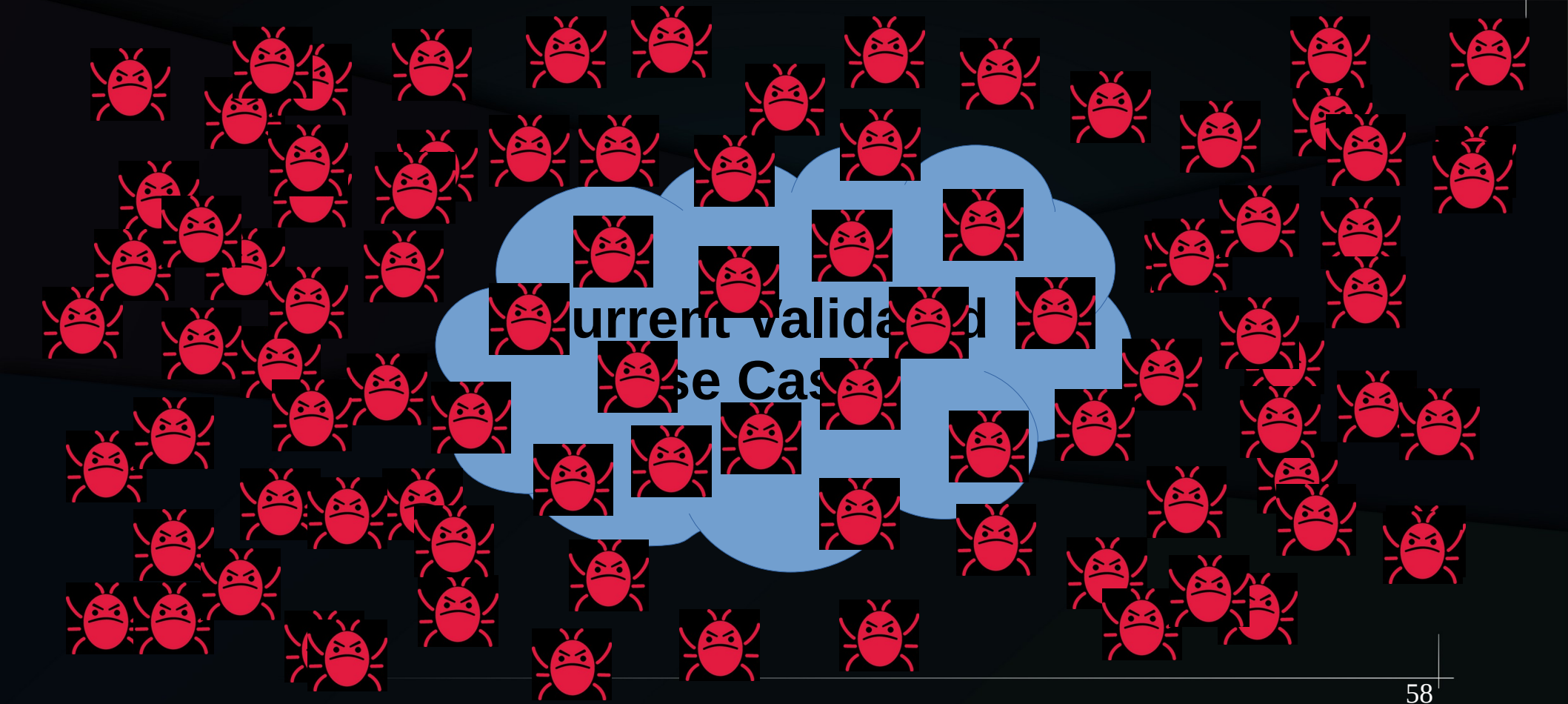


Major Development Generates Bug

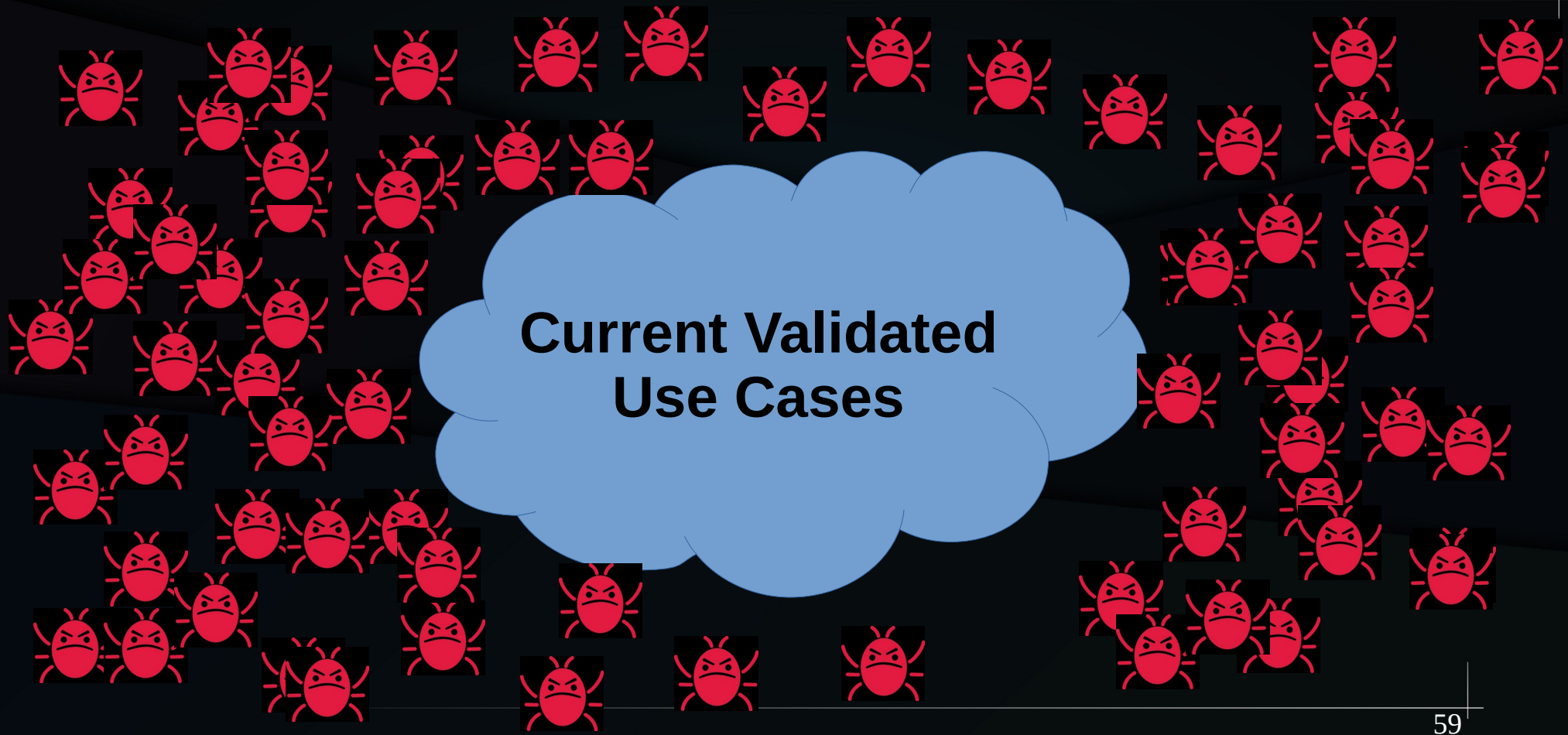
After Validation and Bug Fixing



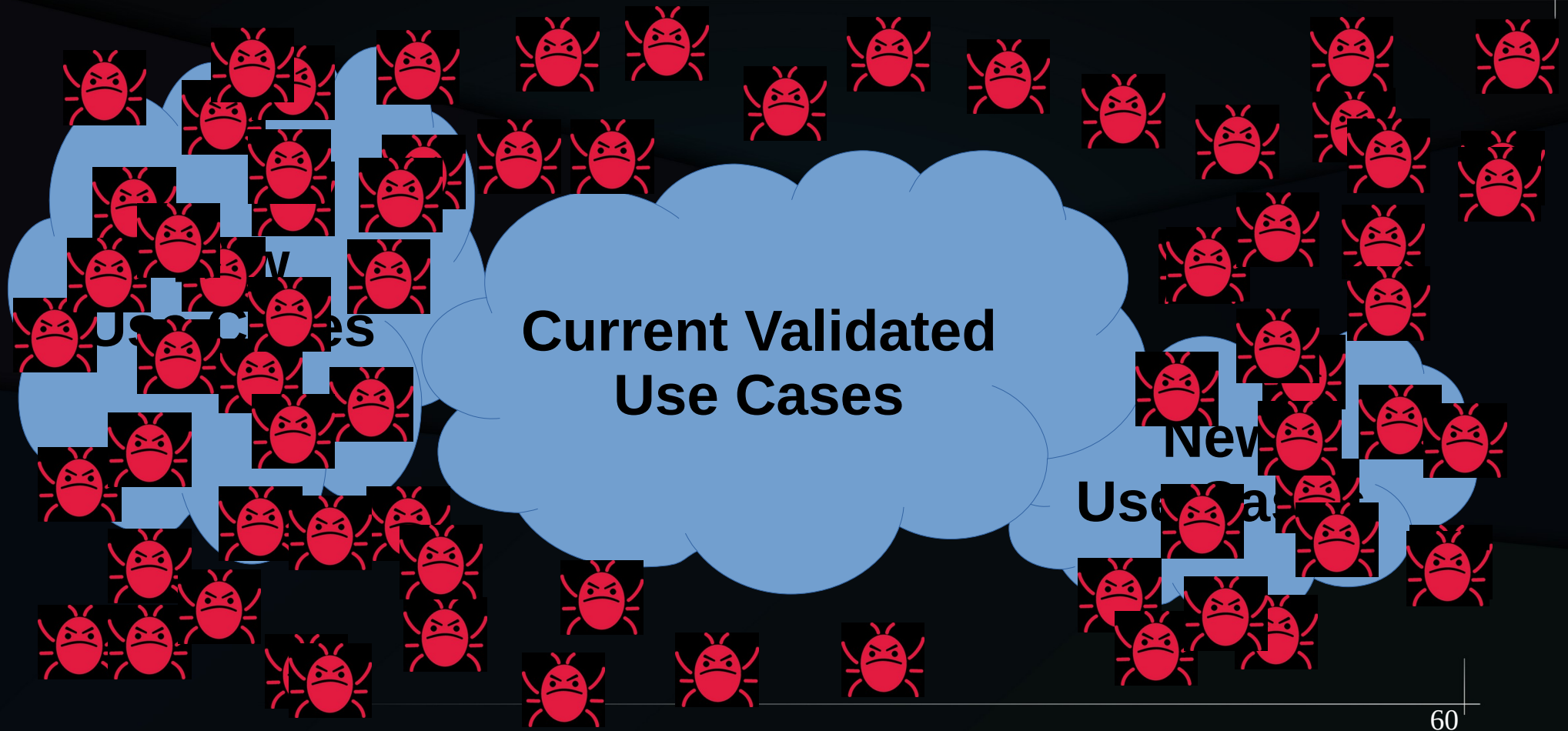
After Another Round of Development



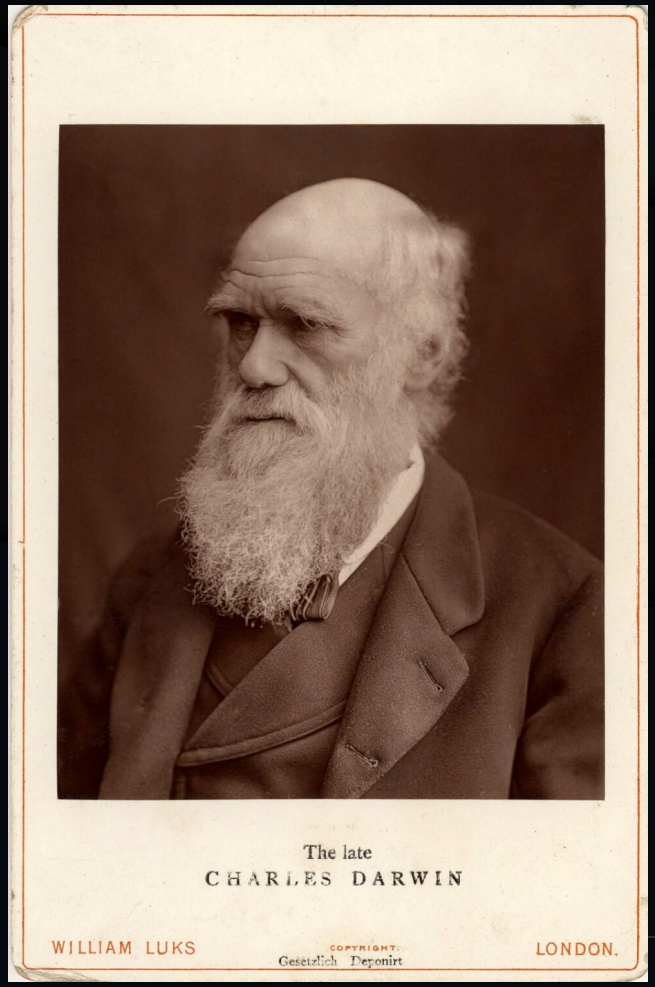
More Validation and Bug Fixing

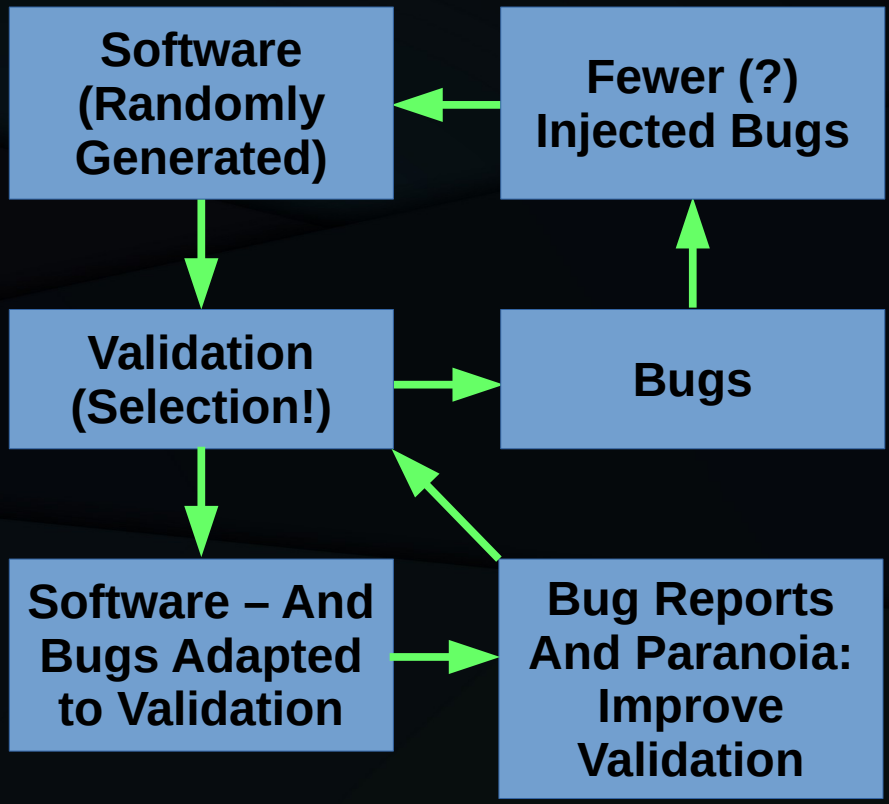


New Use Cases: Walls of Bugs!!!



Natural Selection: Bugs are Software!





“Natural Selection” is a Euphemism

If your tests are not failing, they are not helping to improve your software

https://paulmck.livejournal.com/61158.html

Summary

- How to torture RCU, including using gdb
- Tracking down heisenbugs
- The role of RCU semantics
  - Limited but perhaps increasing over time
- Validation via natural selection, good, bad, ugly

Once Again, Applause for Testers!!!

But Watch Out For These Guys!!!

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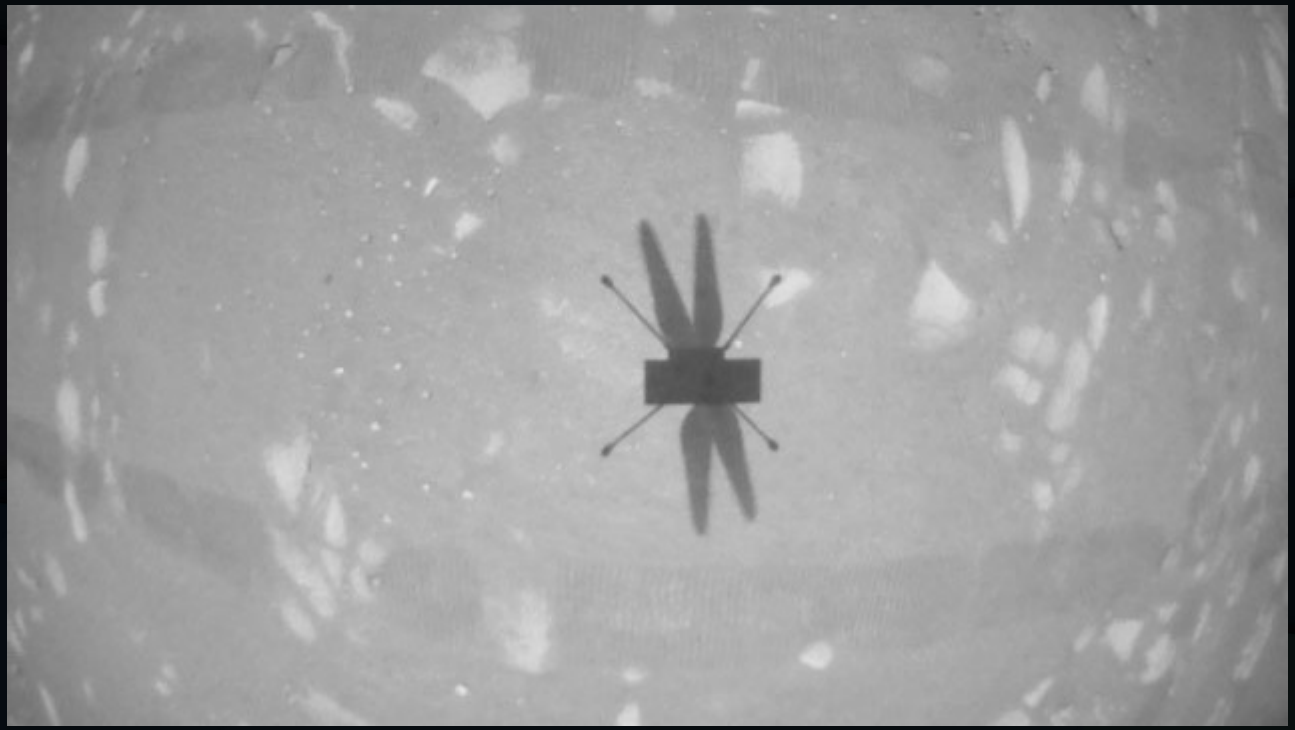
Yes, they tortured software with new workloads, but that wasn't enough for them!

These Guys *Banished* SW!!!

These Guys *Banished* SW!!! To Mars!



For More Information (1/2)

- Validating RCU in particular and concurrent software in general:
  - “Stupid RCU Tricks: A tour through rcutorture”: https://paulmck.livejournal.com/61432.html
  - “Verification Challenge 6: Linux-Kernel Tree RCU”: https://paulmck.livejournal.com/46993.html
  - “Is Parallel Programming Hard, And, If So, What Can You Do About It?”: https://mirrors.edge.kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html
    - “Validation” chapter, especially “Probability and Heisenbugs” section
    - “Formal Verification” chapter
  - “Hunting Heisenbugs” blog posts:
    - https://paulmck.livejournal.com/14639.html
    - https://paulmck.livejournal.com/14969.html
  - Linux-kernel source code:
    - kernel/rcu/{rcutorture.c,rcuref.c,rcuscale.c}, kernel/torture.c, kernel/locking/locktorture.c
    - tools/testing/ tools/testing/selftests/rcutorture

For More Information (2/2)

- RCU specification, which is a function of time:
  - Documentation/RCU/Design/Requirements/ in kernel source
  - “RCU Usage In the Linux Kernel: One Decade Later”:
    - http://www.rdrop.com/~paulmck/techreports/survey.2012.09.17a.pdf
    - http://www.rdrop.com/~paulmck/techreports/RCUUsage.2013.02.24a.pdf
    - 2020 update: https://dl.acm.org/doi/10.1145/3421473.3421481