Paul E. McKenney, Meta Platforms Kernel Team

Multicore World, February 16, 2023

Cautionary Tales on Implementing the Software That People Want

Be Careful What You Wish For. You Might Get It!!!

How Did Paul Get This Way?

- High school class: IBM mainframe & HP Basic (1973-1976)
- University: Computer science & mechanical engineering, business applications (1976-1981)
  - Started supporting self by coding in ~~Summer~~ June 1977
- Contract programming (1981-1985)
- Systems administration and Internet research (1986-1990)
- Concurrent proprietary UNIX (1990-2000)
- Linux kernel concurrency and realtime (2001-present)

Cautionary Quotes

- The first secret of getting what you want is knowing what you want. *Arthur D. Hlavaty*
- If you don't know what you want, you will probably never get it. *Oliver Wendell Holmes, Jr.*
- If you don't know what you want, you end up with a lot you don't. *Chuck Palahniuk*

1990: Stochastic Fairness Queueing

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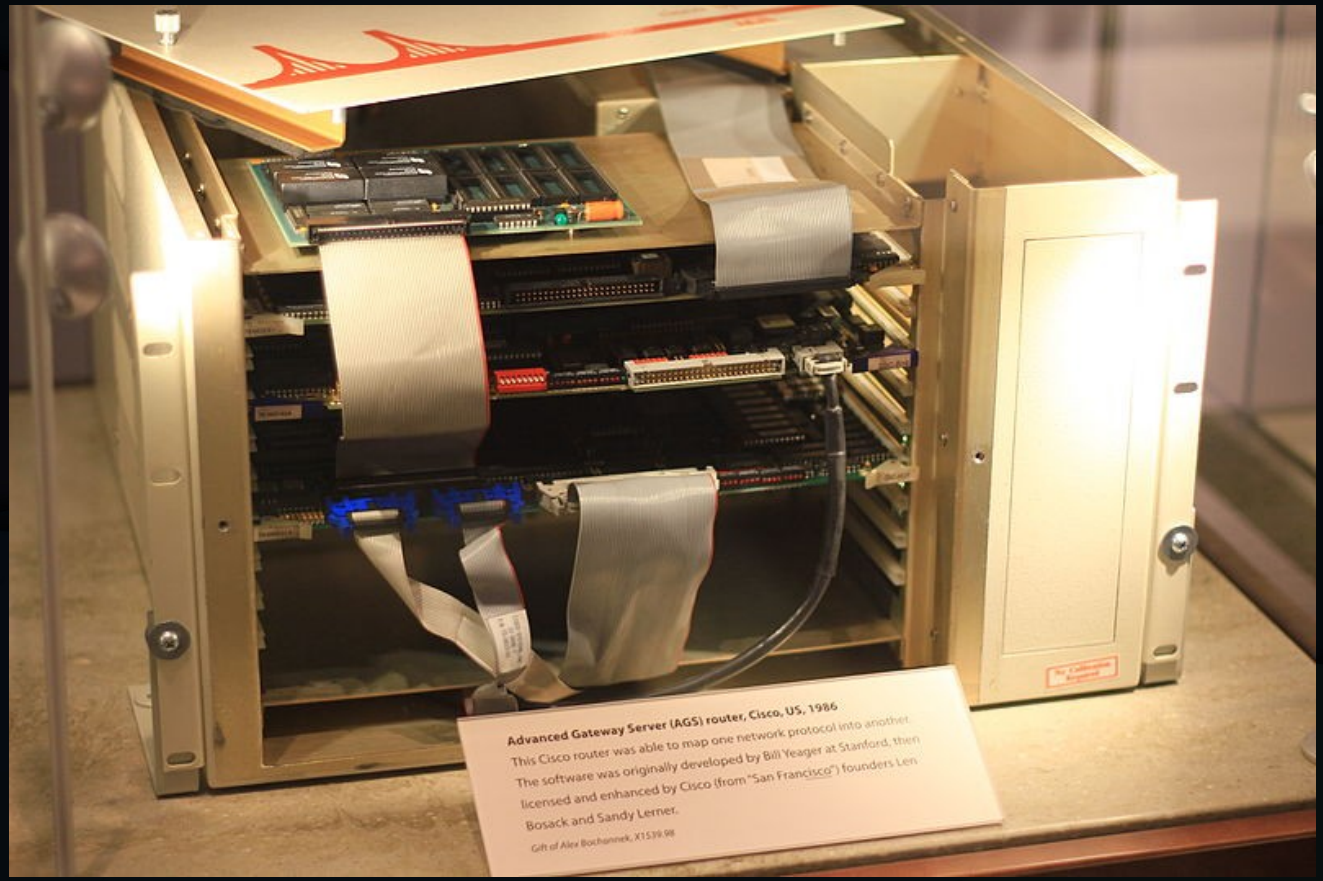
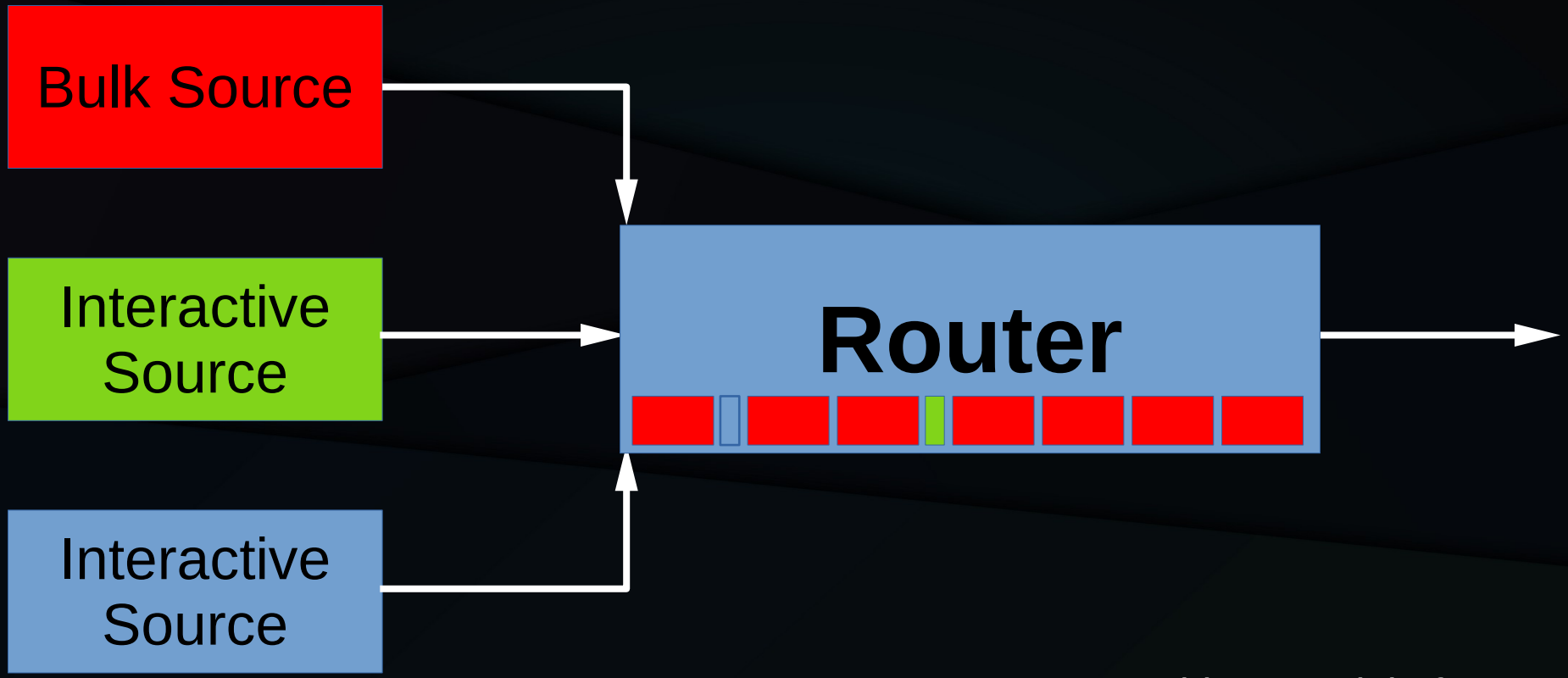


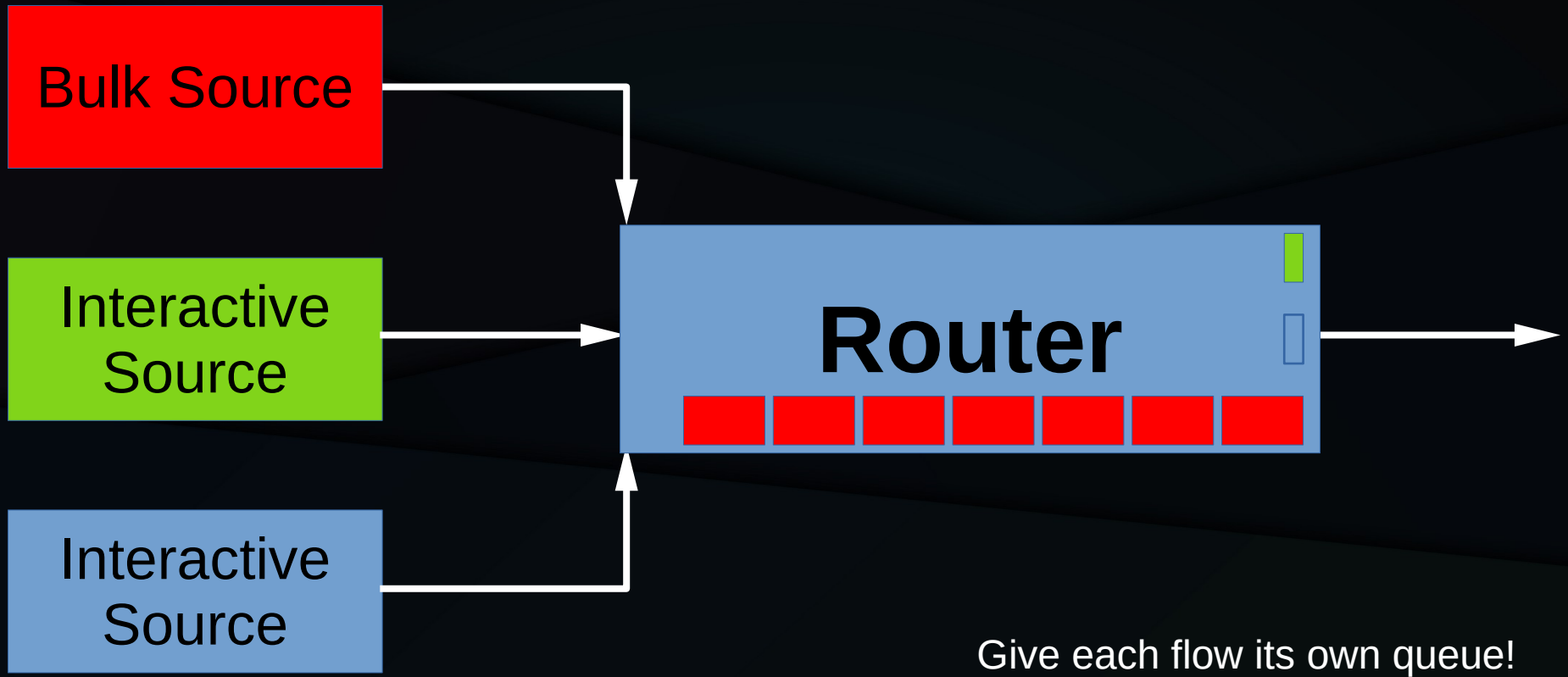
Photo: Michael Hicks, Creative Commons Attribution 2.0 Generic

1990: Queueing Problem



1 Megabit network is *fast*.

1990: Fair Queueing



Give each flow its own queue!

Yeah, you and how many 10MHz CPUs???

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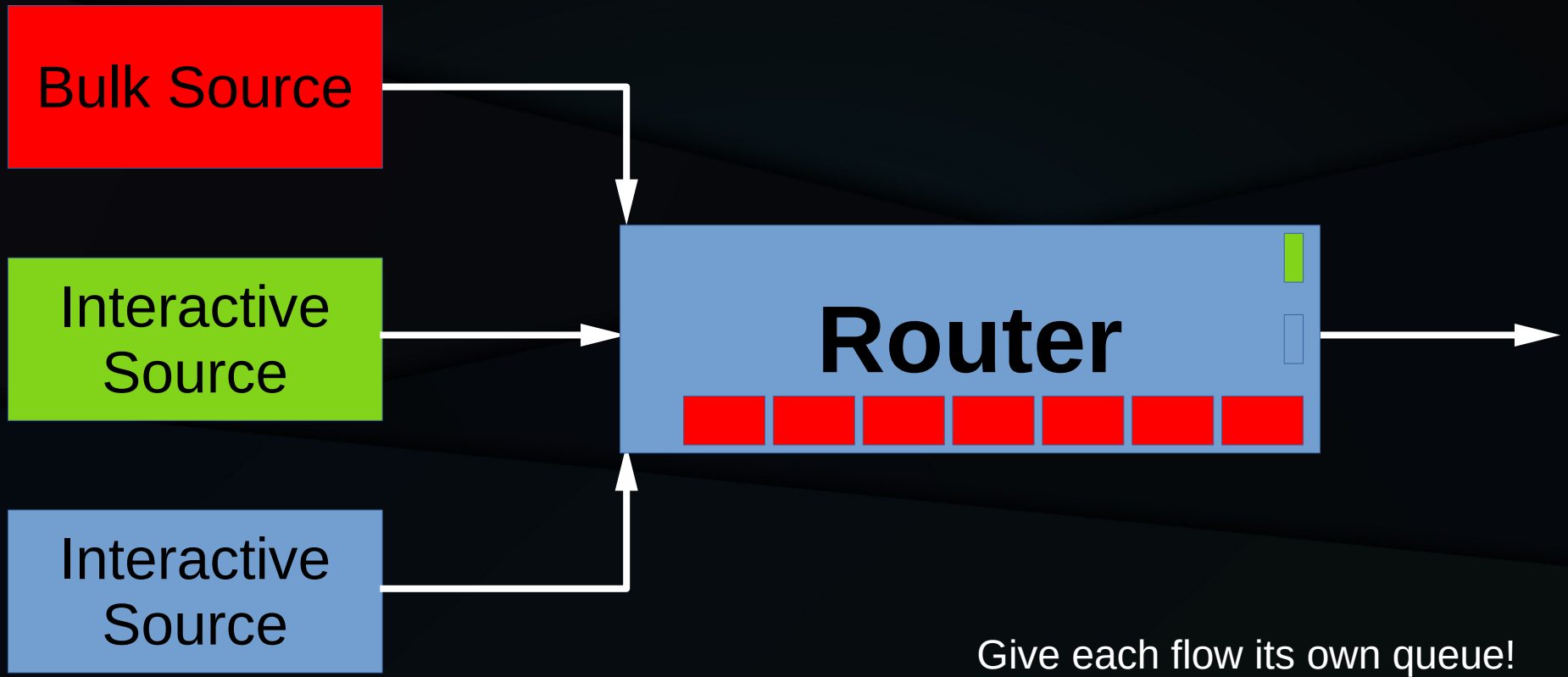

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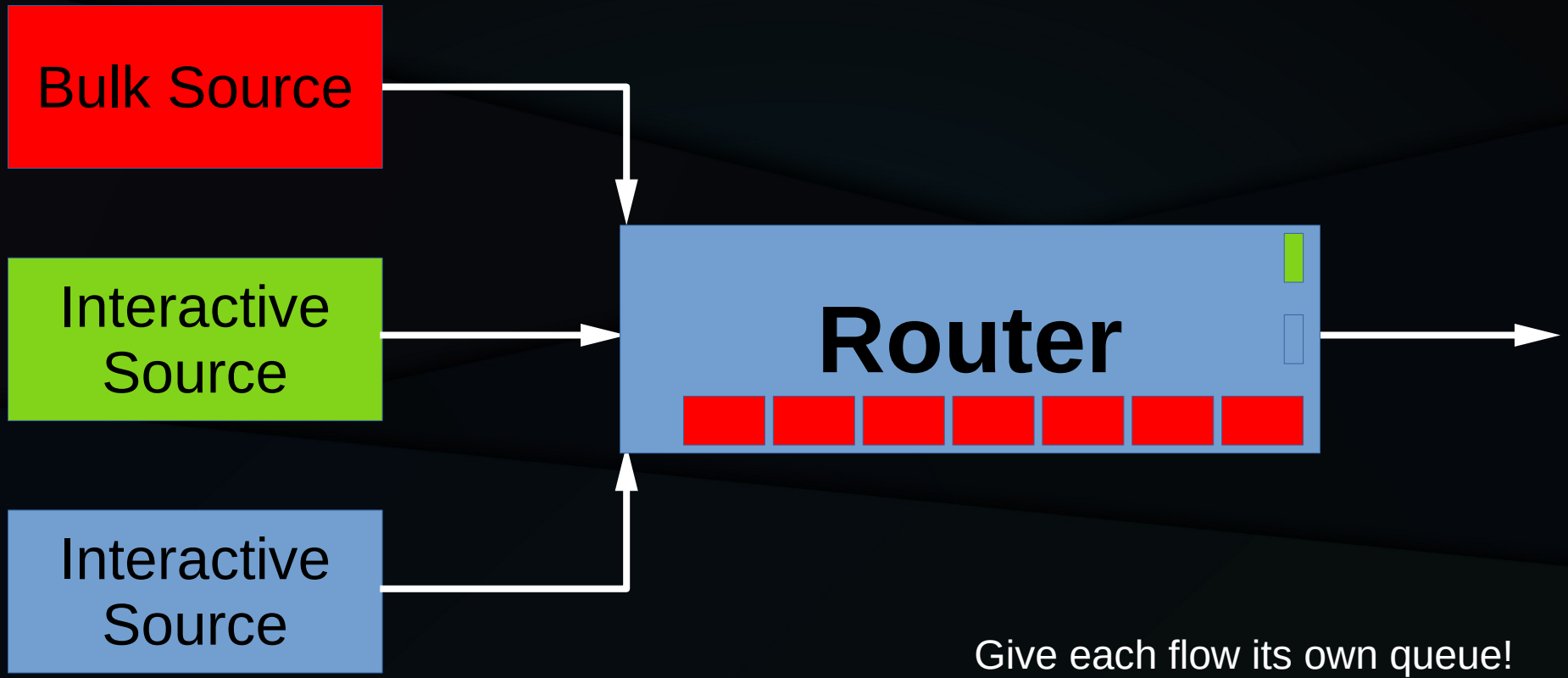
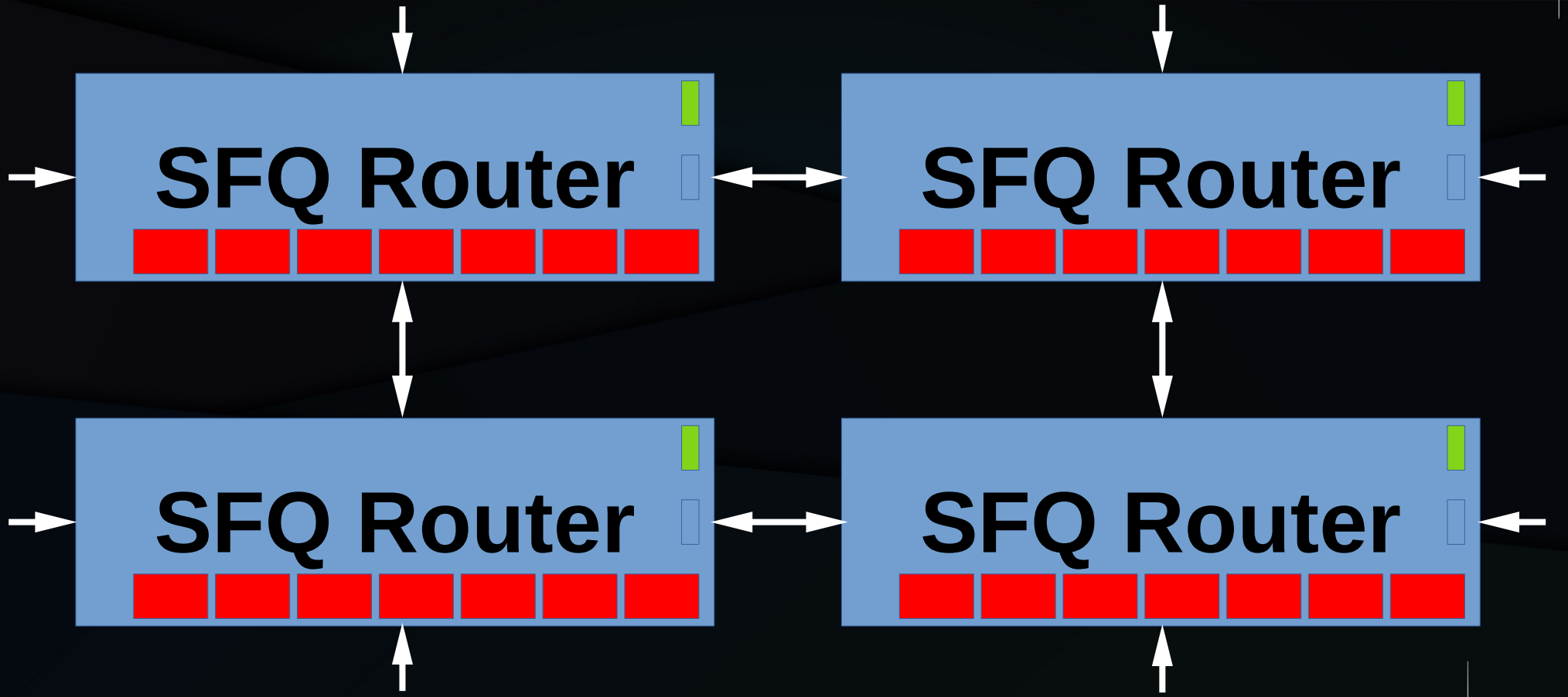
1990: Stochastic Fair Queueing: Hash



Give each flow its own queue!
But only with high probabilty!!!

Hash IP-address/Port quadruple for wonderous end-to-end fairness!!!

1990: Paul's Internet Vision



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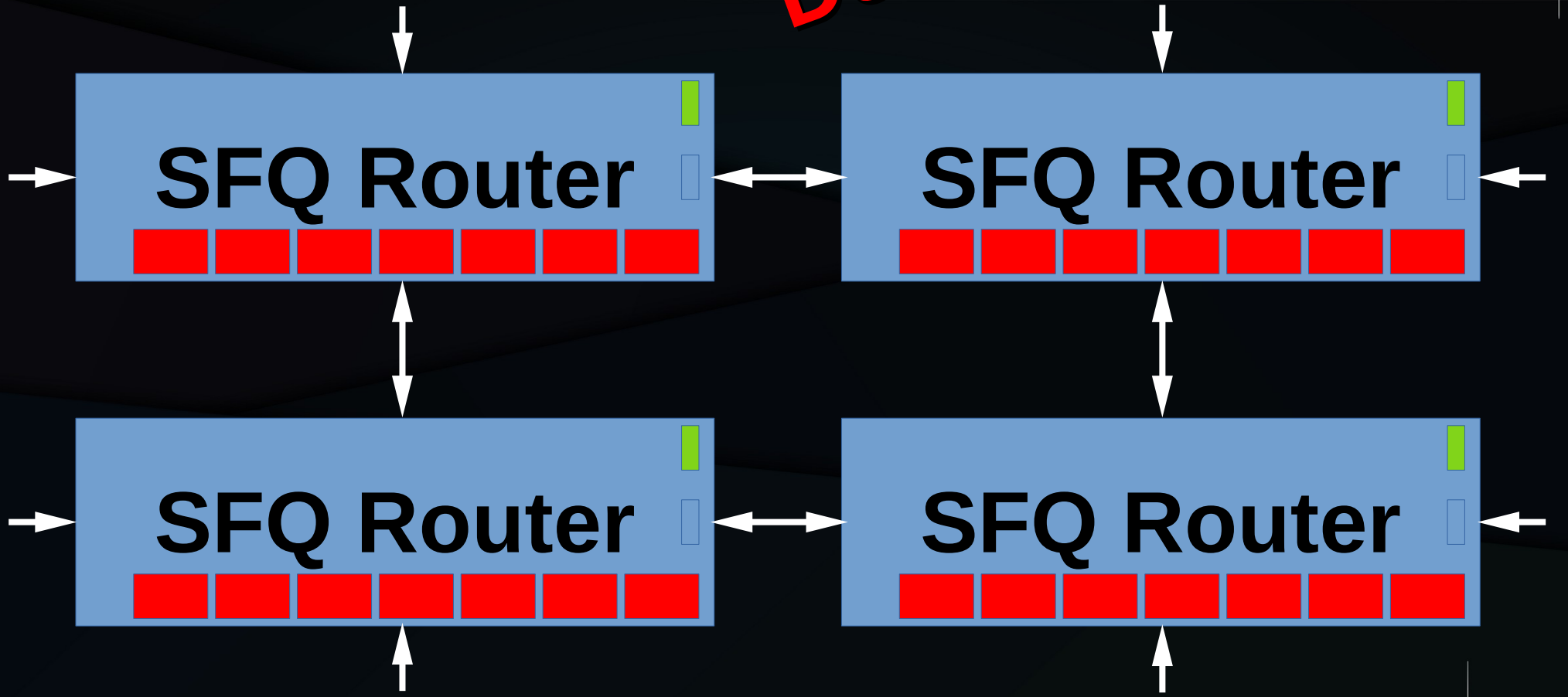
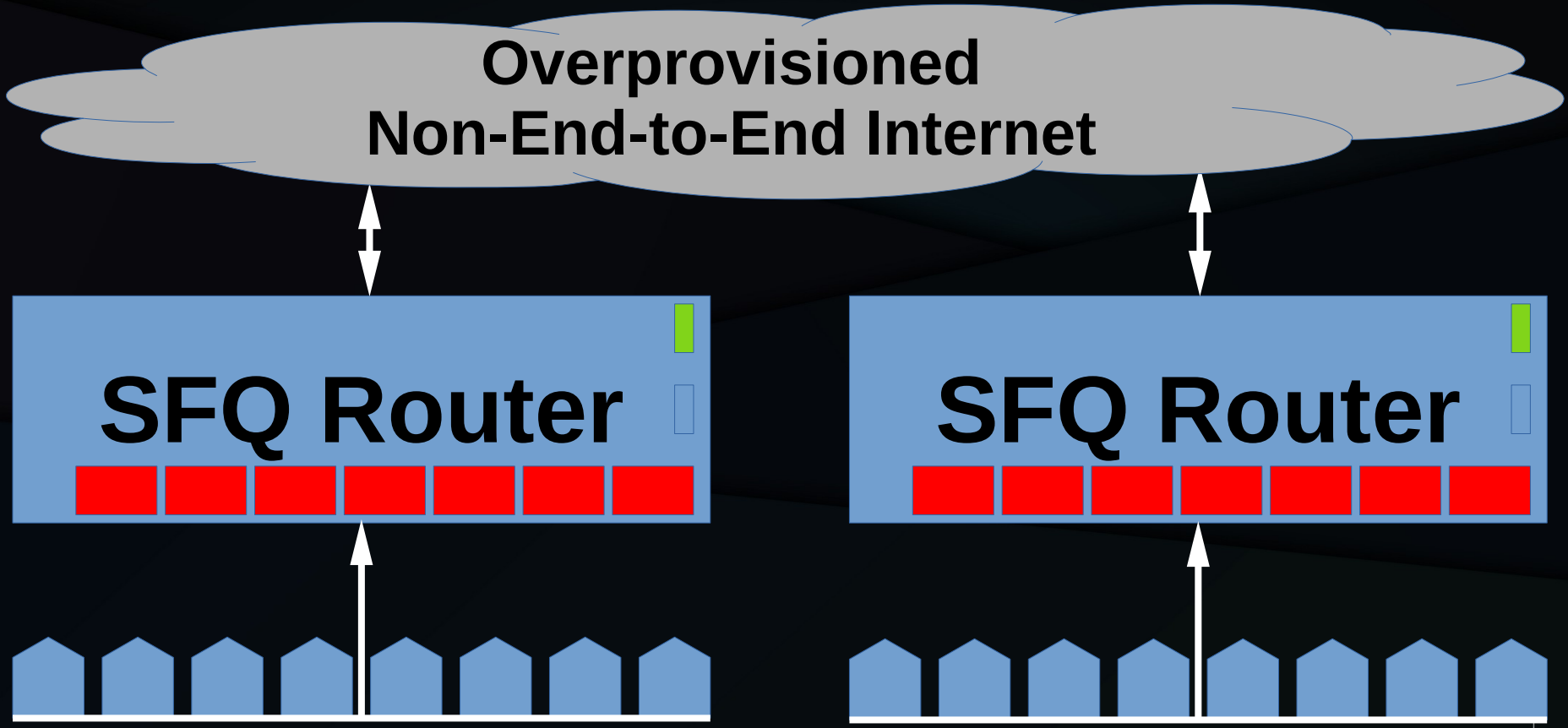
Delusion



~~Hash IP-address/Port quadruple for wonderous end-to-end fairness!!!~~

1990: What Internet Did Instead



Internet gateways hash Ethernet MAC addresses for approximate real-world fairness.

1990 SFQ: What Went Wrong?

- Solved wrong problem: End-to-end fairness
  - Correct problem: Hop-by-hop & endpoint fairness
  - By sheer dumb luck, my algorithm handled both
- Research-quality code: Get the paper out!!!
  - Cisco and Linux-kernel engineers fixed this
- Used heavily until about 2015
  - FQ-CODEL and CAKE now address bufferbloat
  - Dave Taht, Eric Dumazet, Toke Høiland-Jørgensen, ...

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Premature abstraction is the root of all evil

Bad idea but implemented, resuscitated by dumb luck

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Live among your users!!!

1980s: Eight-Bit CRM

Image source: https://www.old-computers.com/museum/photos/otrona_attache_1s.jpg

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- CRM application built to spec under contract
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Bad idea well implemented

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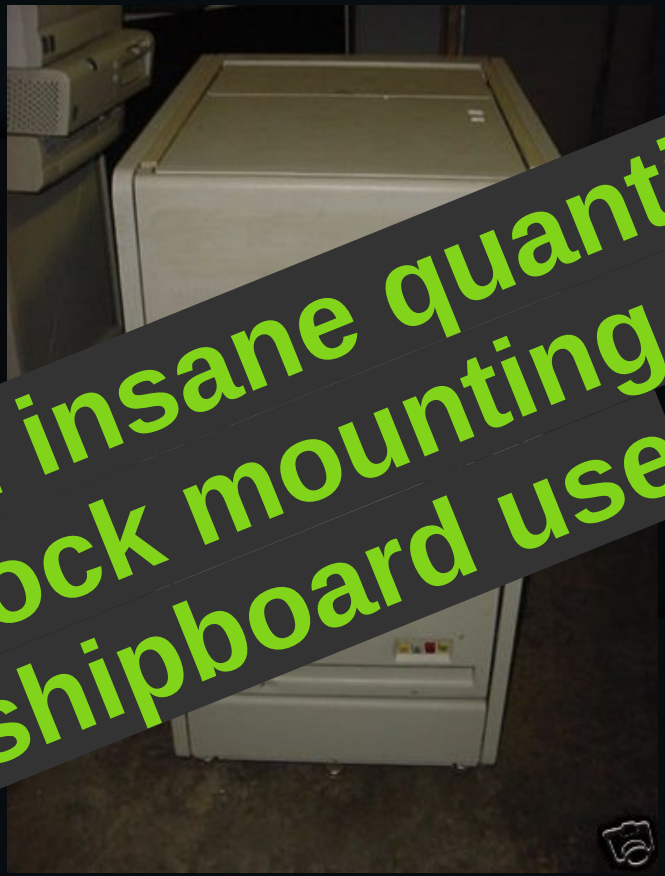
Bad idea well implemented, but hey, I got paid???

1980s: Eight-Bit CRM: What Instead?

Time and Grade: Experience

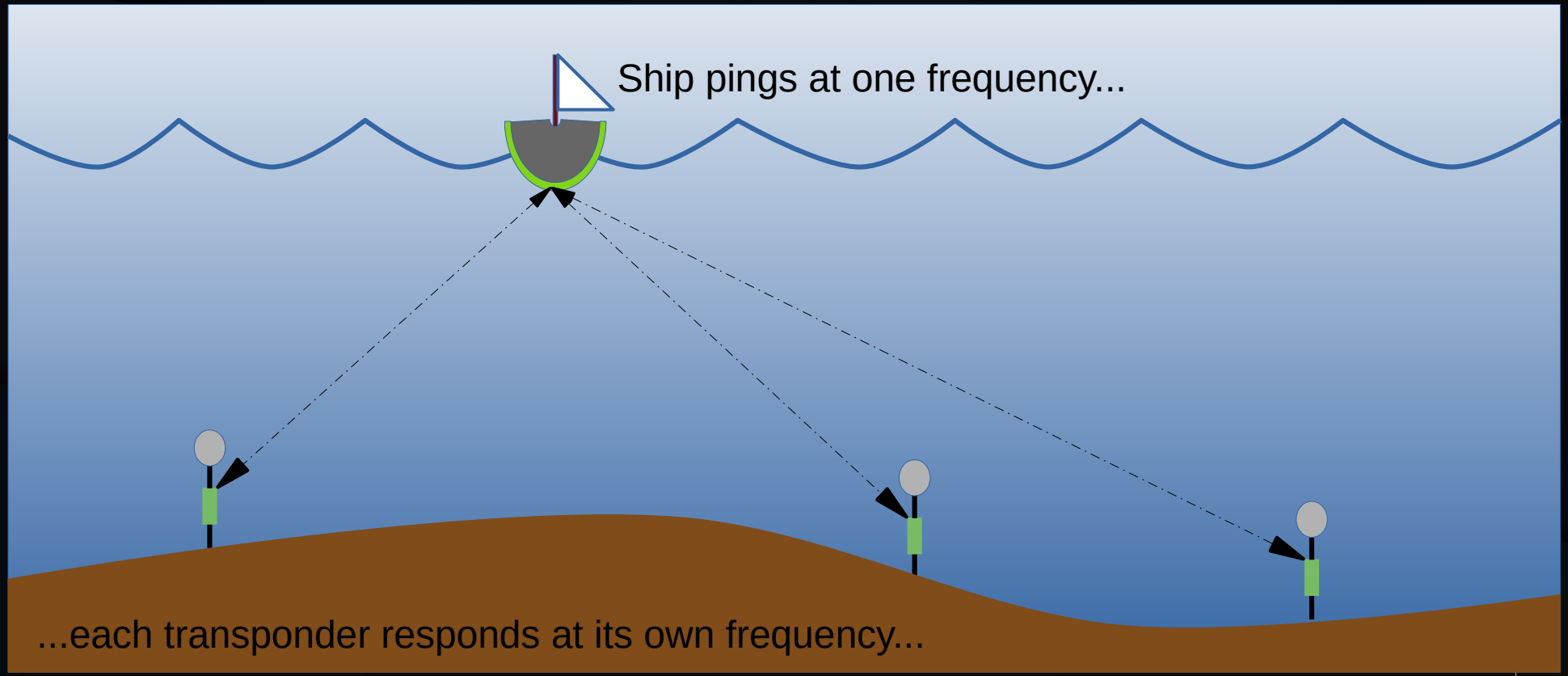
1980s: Acoustic Navigation

1980s: Acoustic Navigation



But with insane quantities of shock mounting for shipboard use

1980s: Acoustic Navigation (Pre-GPS)



...then convert time to distance and triangulate!!!

Acoustic Navigation Complications

- If the ship’s position was known when deploying the transponder, there would be no need for acoustic navigation
- Transponders do not fall exactly straight down through four miles of water
- Ocean surface is not perfectly level
- Sound does not travel in a straight line through ocean water
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- Dolphins like to play with transponders

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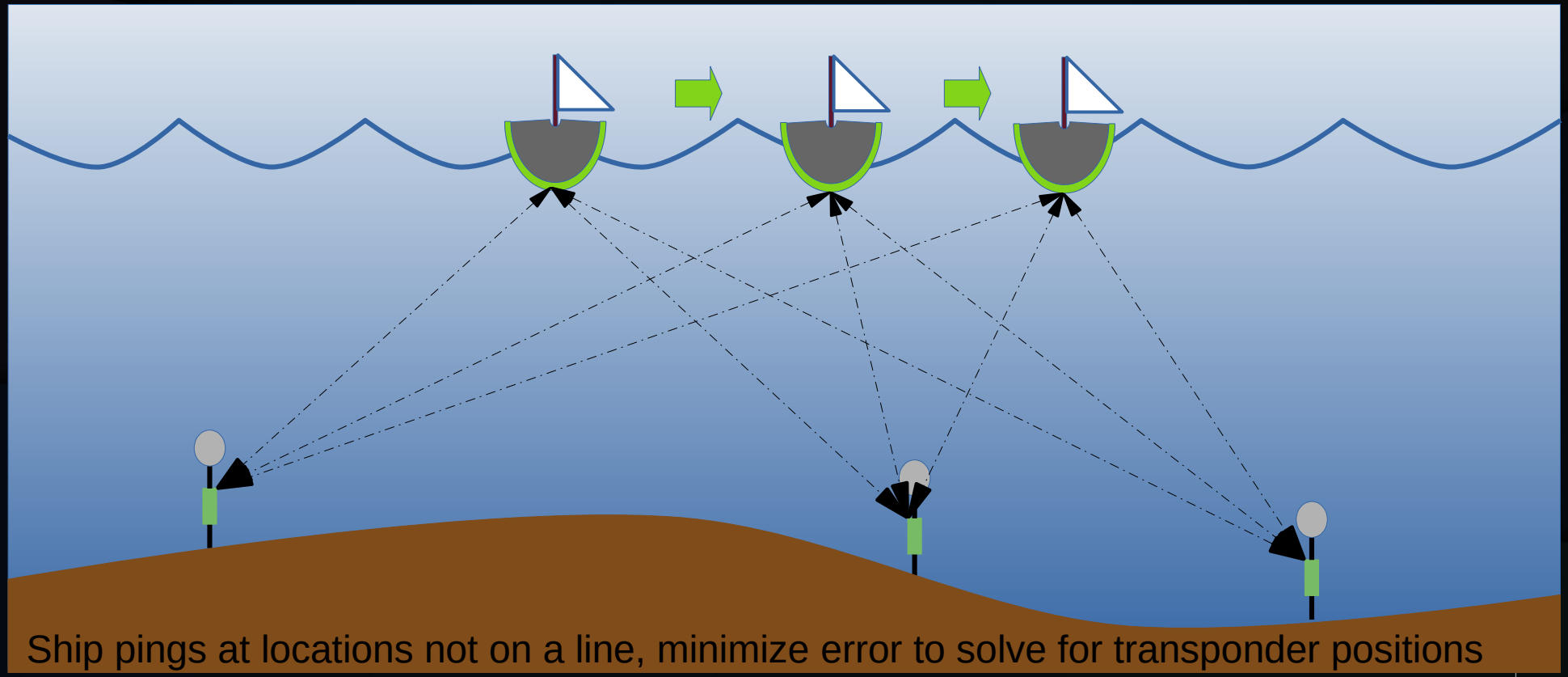

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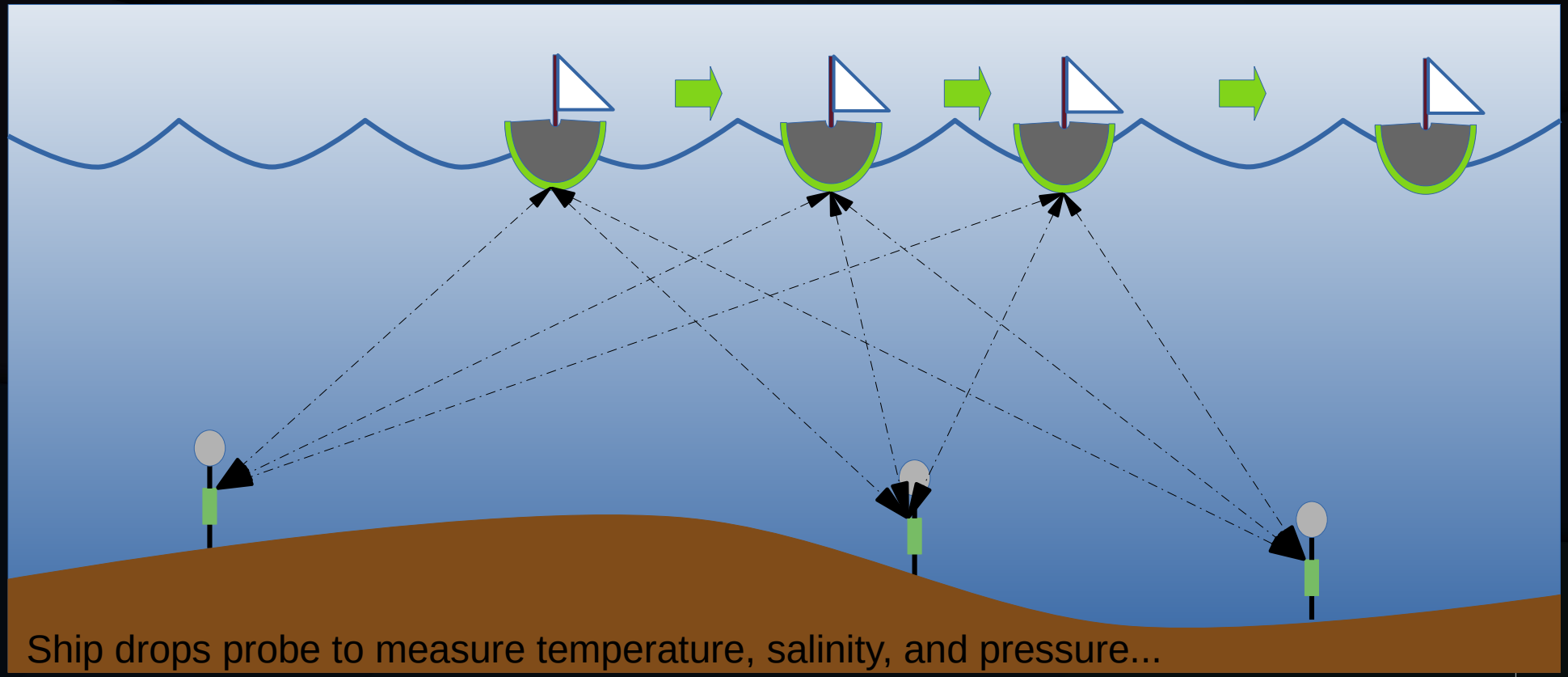

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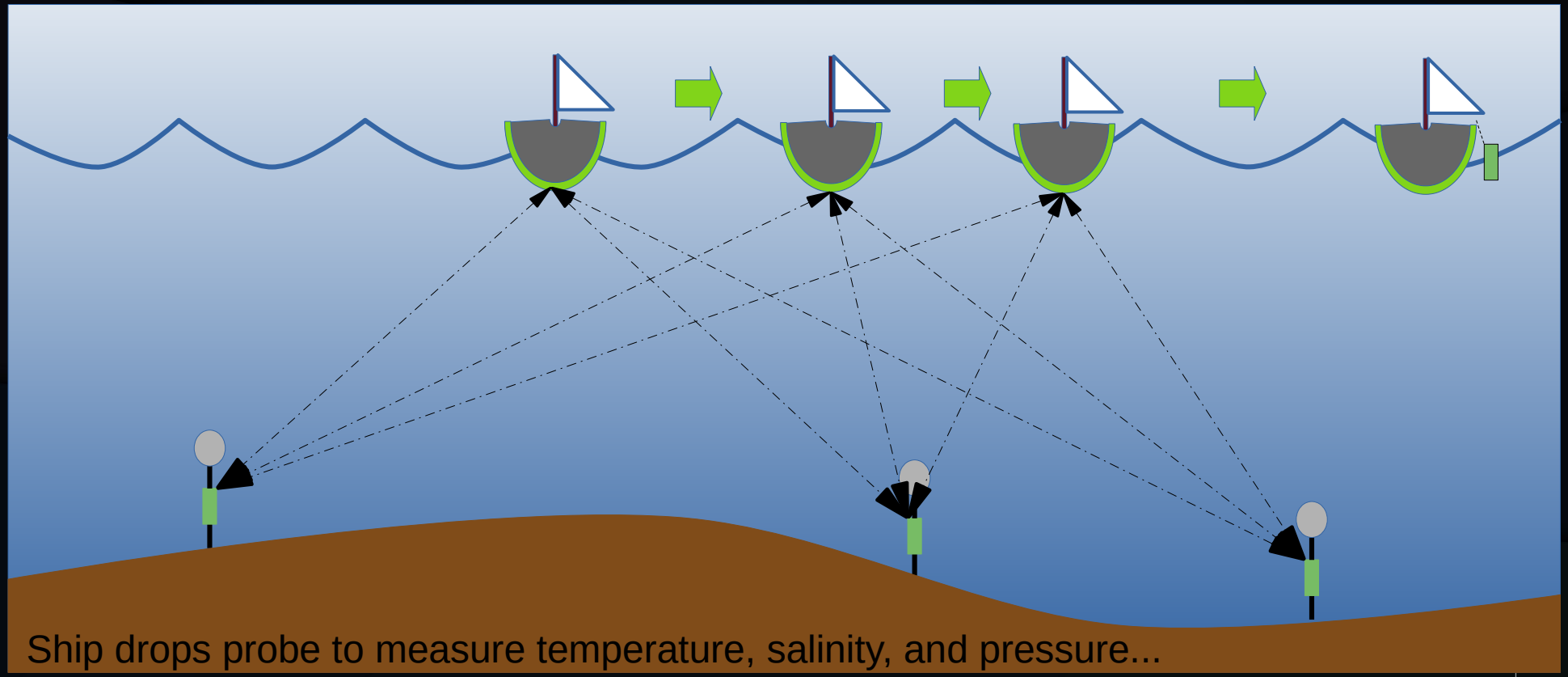

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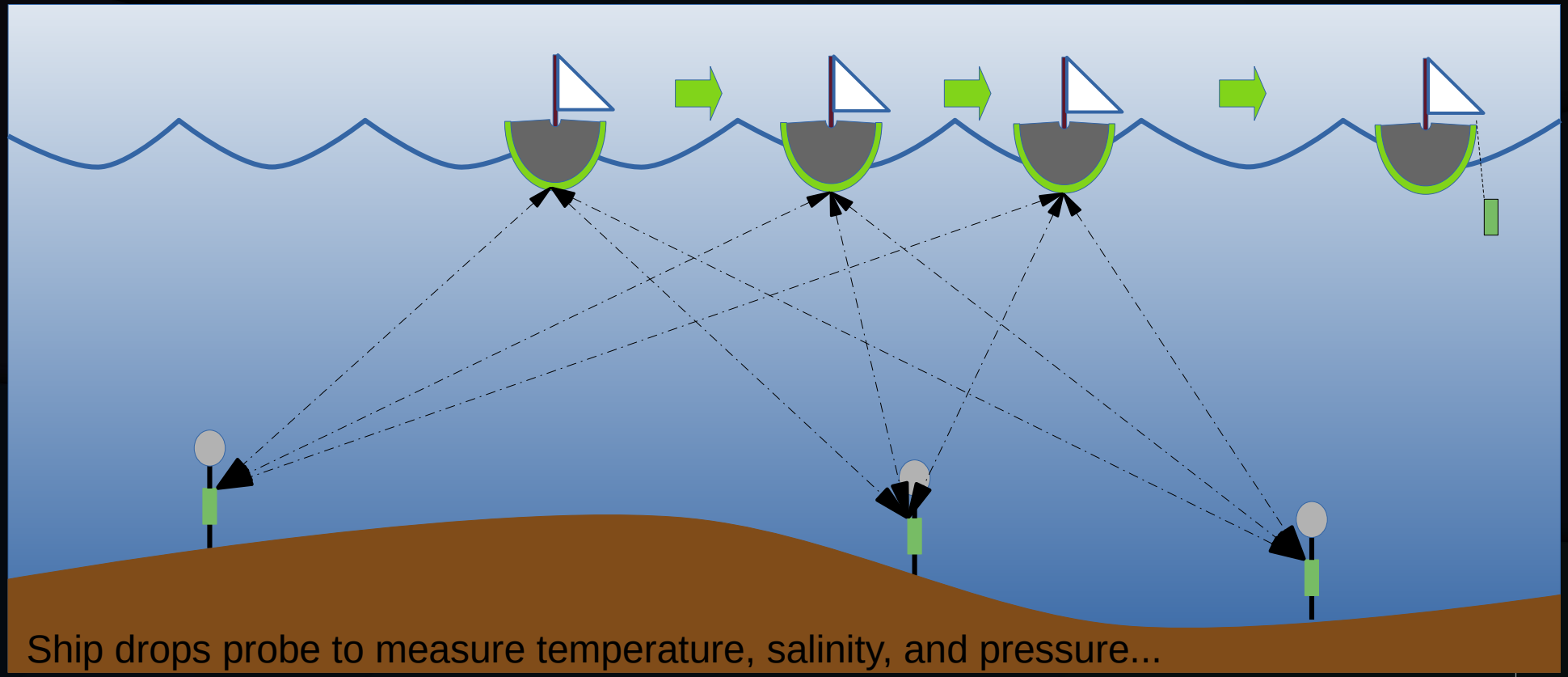

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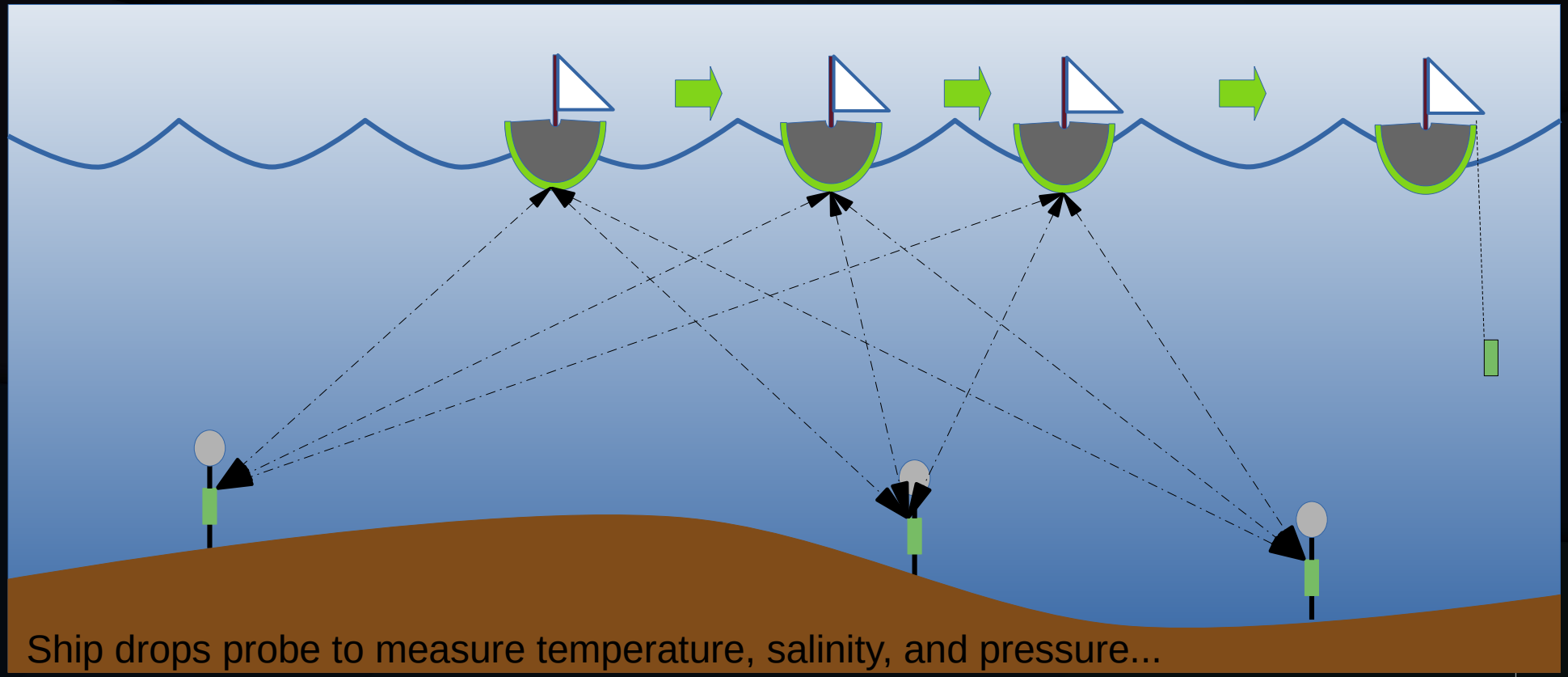

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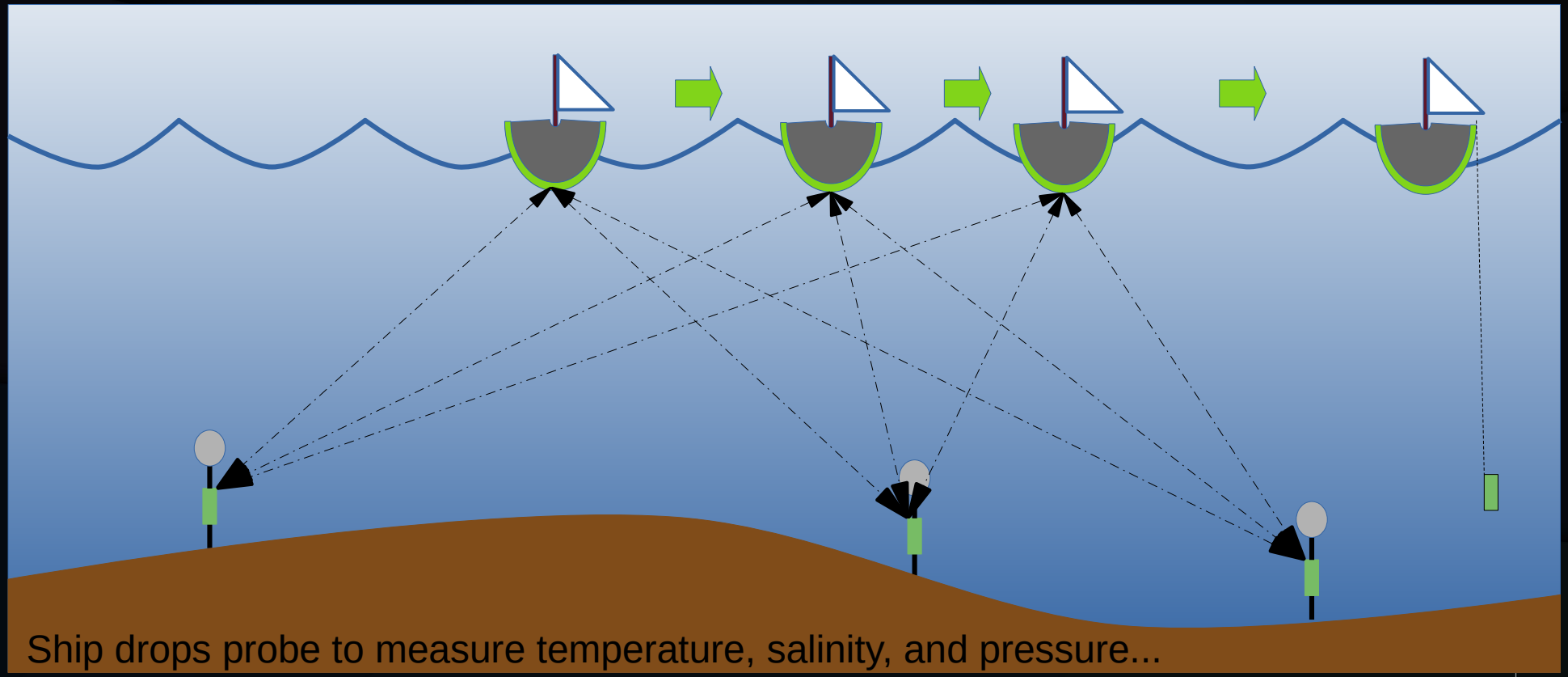

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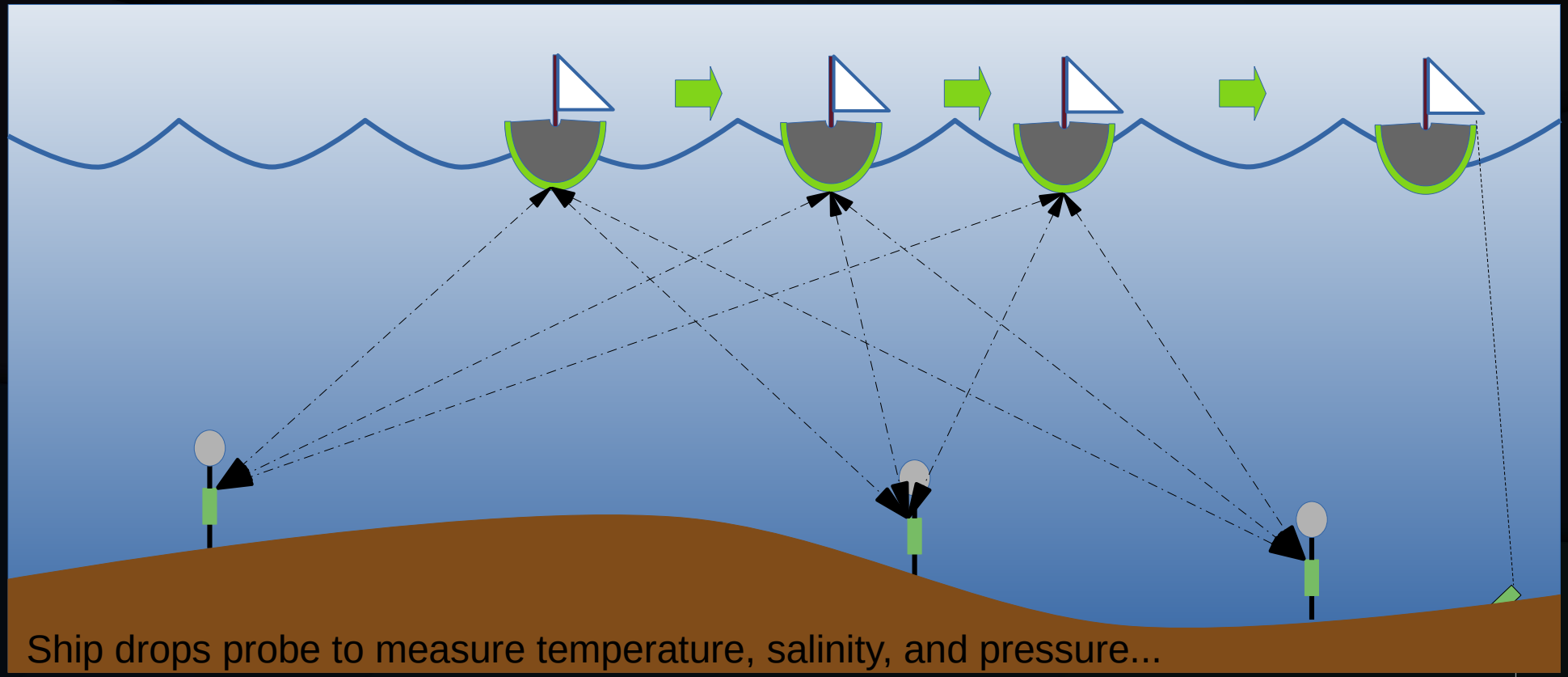

Then calculate sound velocity as a function of depth, and finally do ray-tracing.

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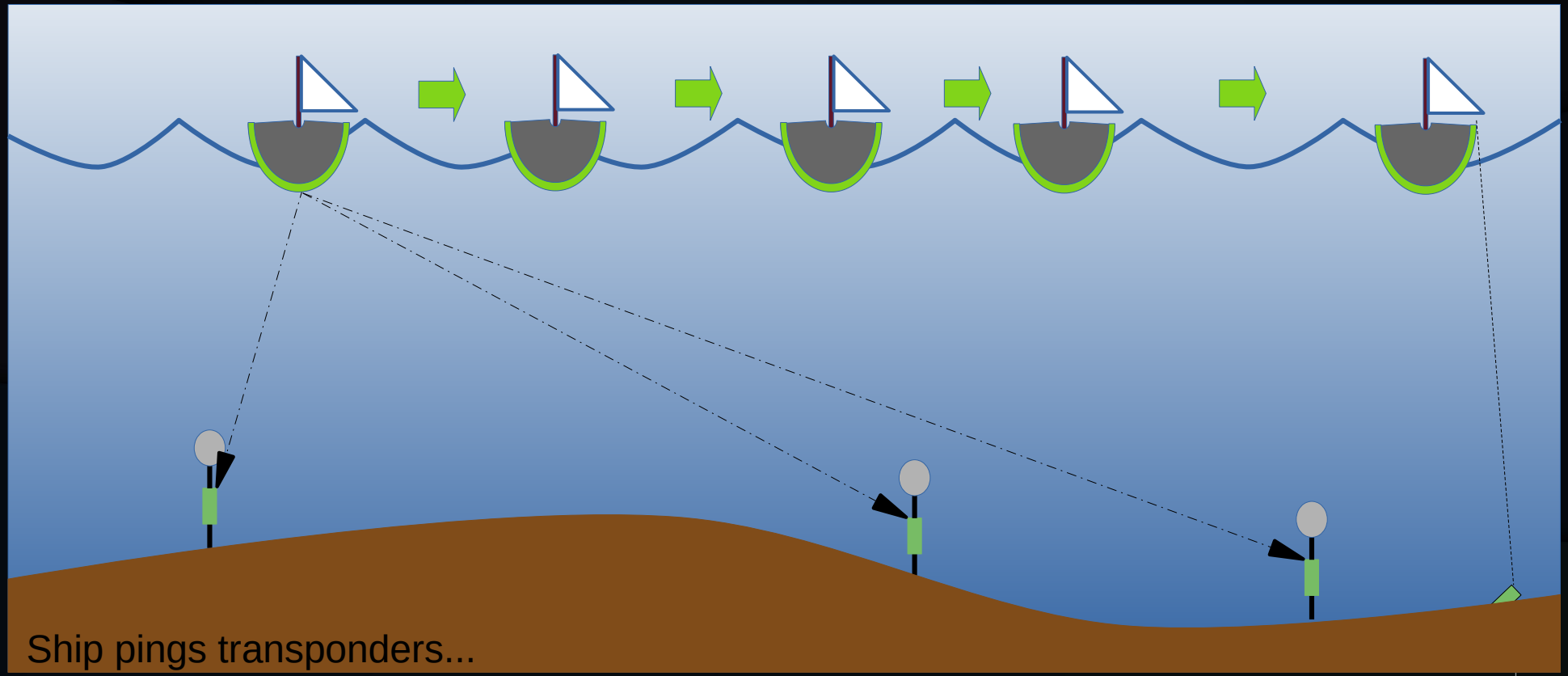
Acoustic Navigation: Measure Depth



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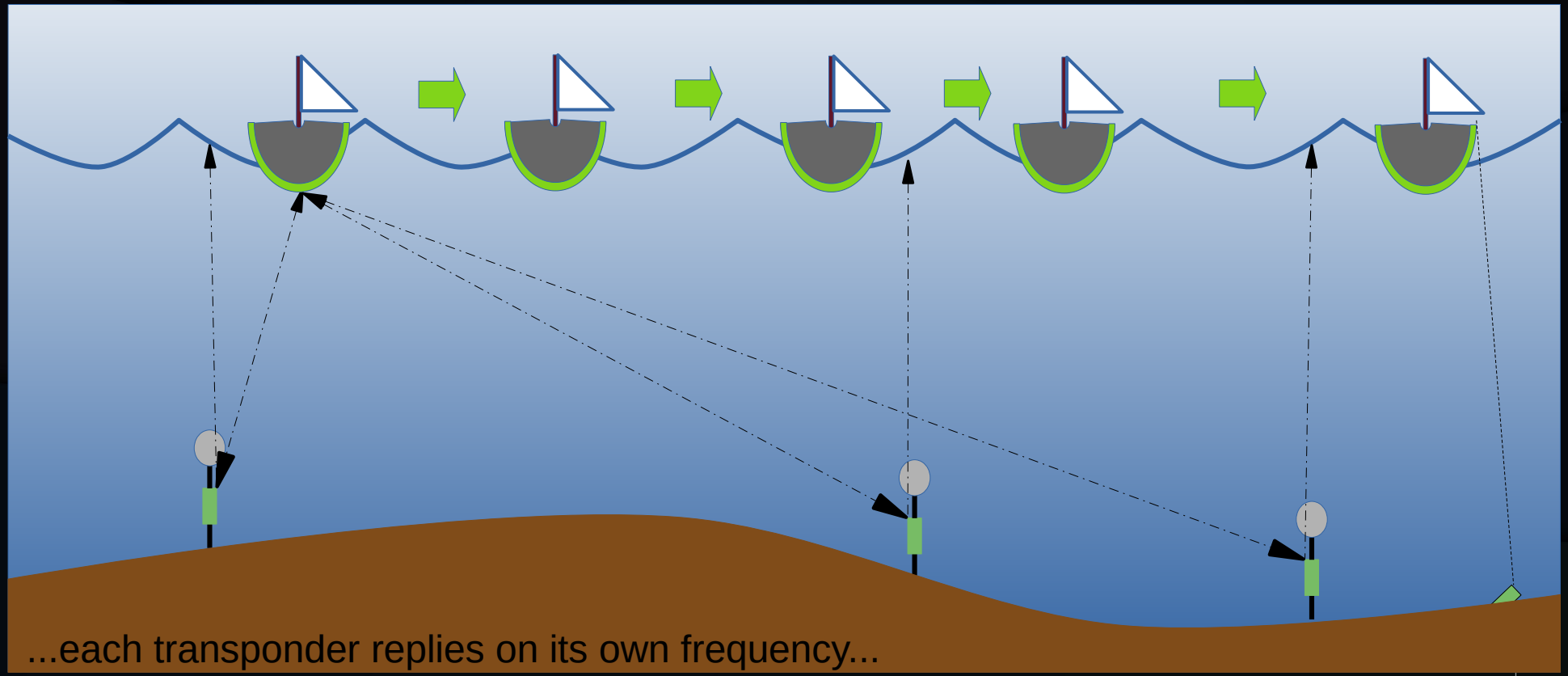

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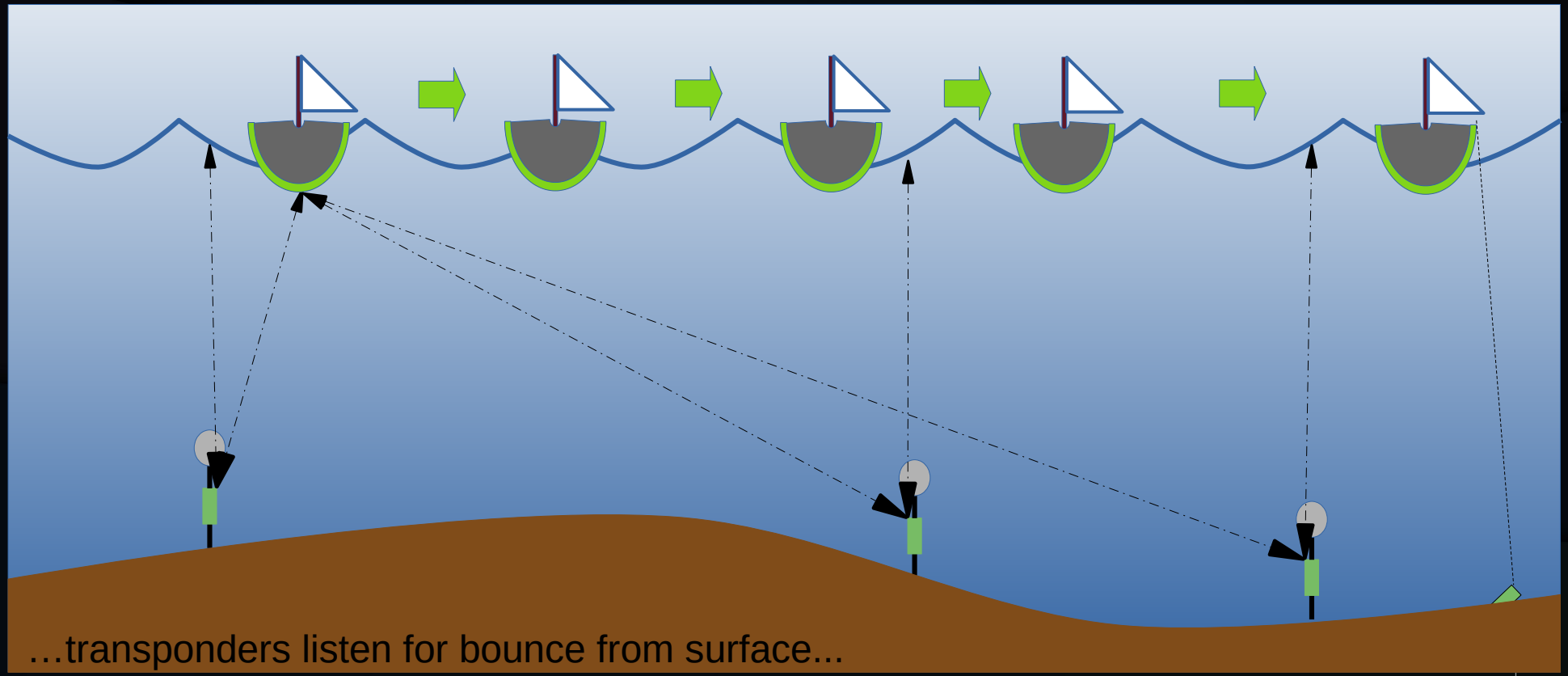

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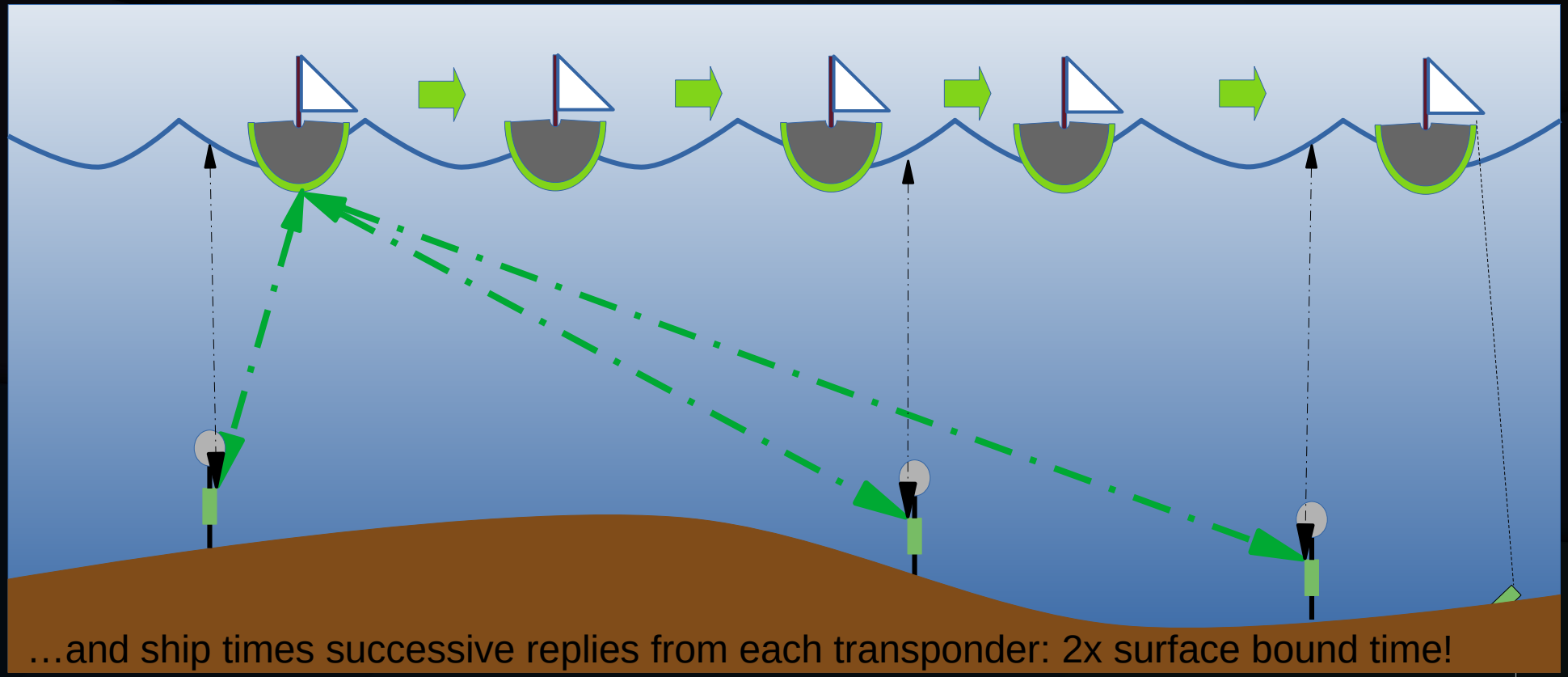

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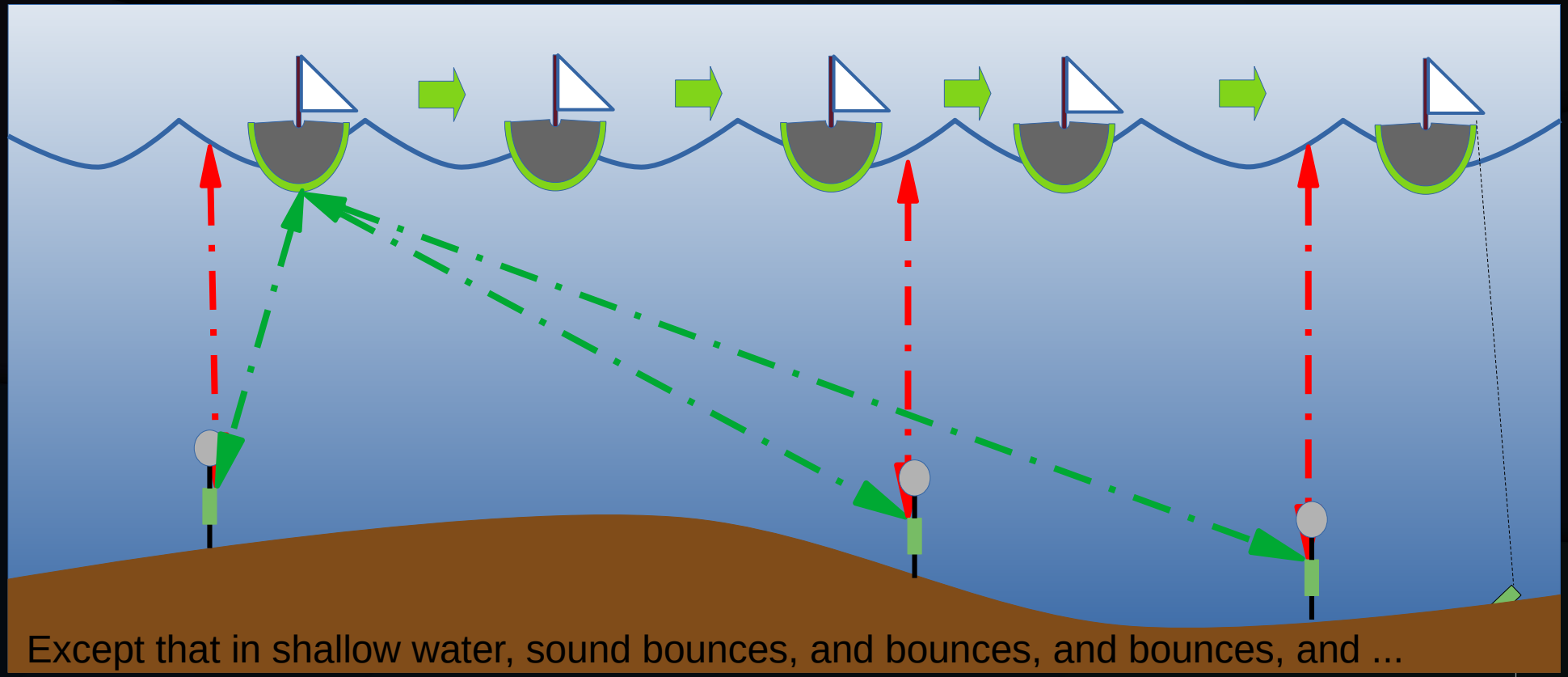

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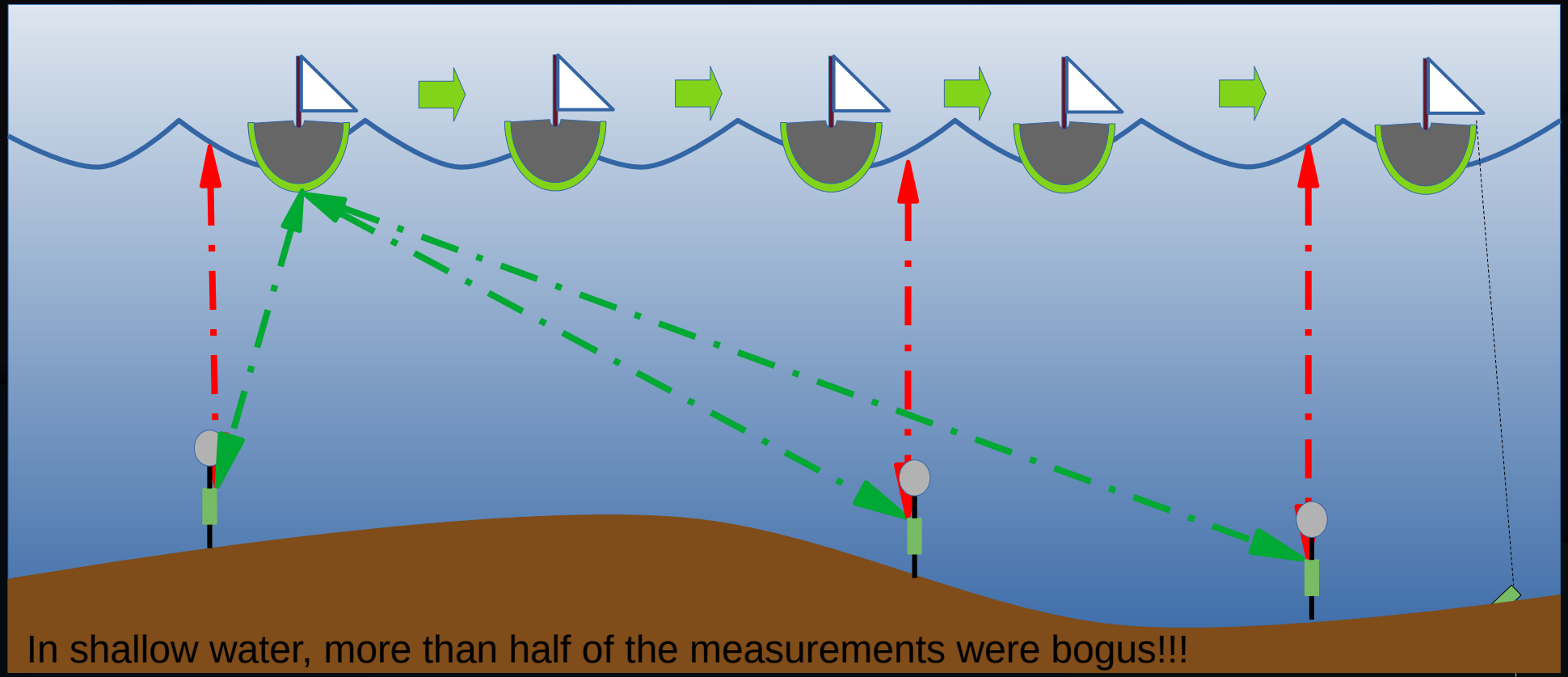

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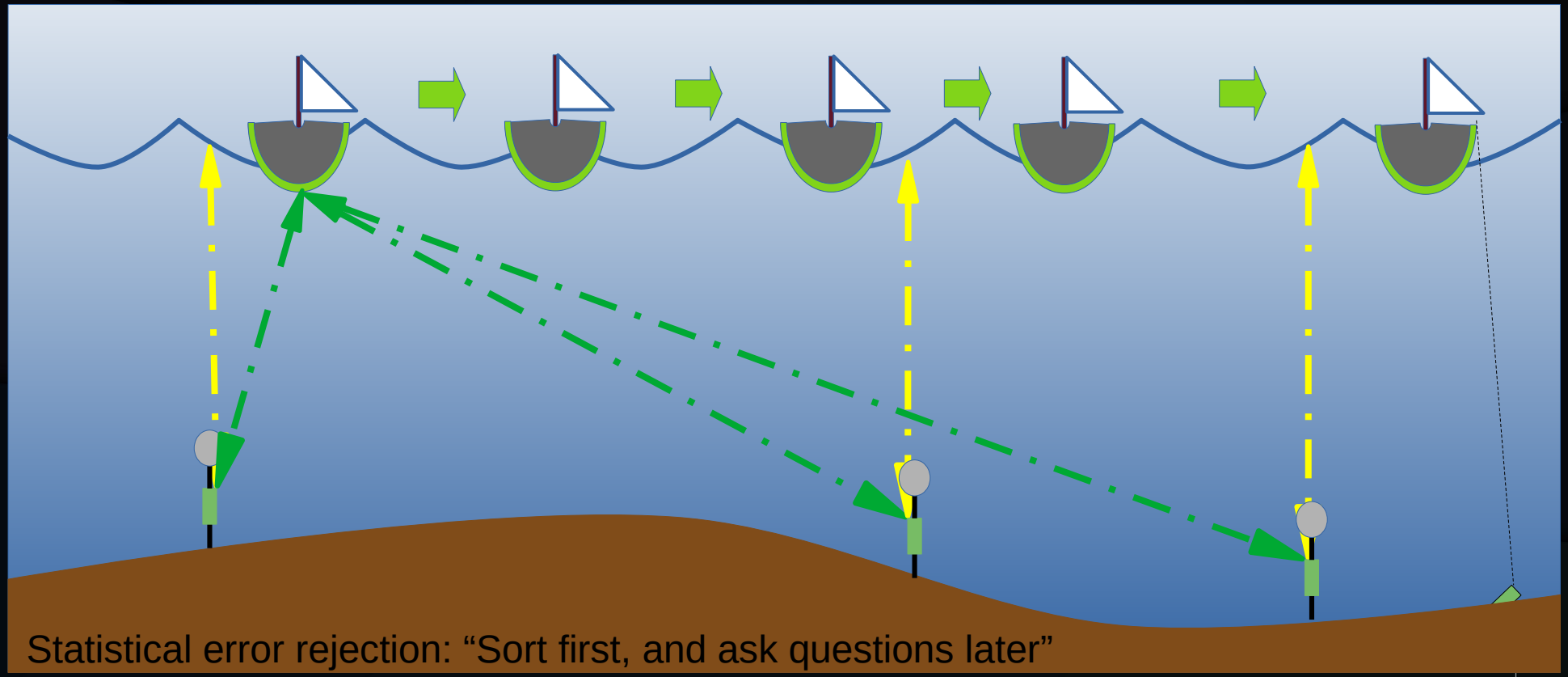

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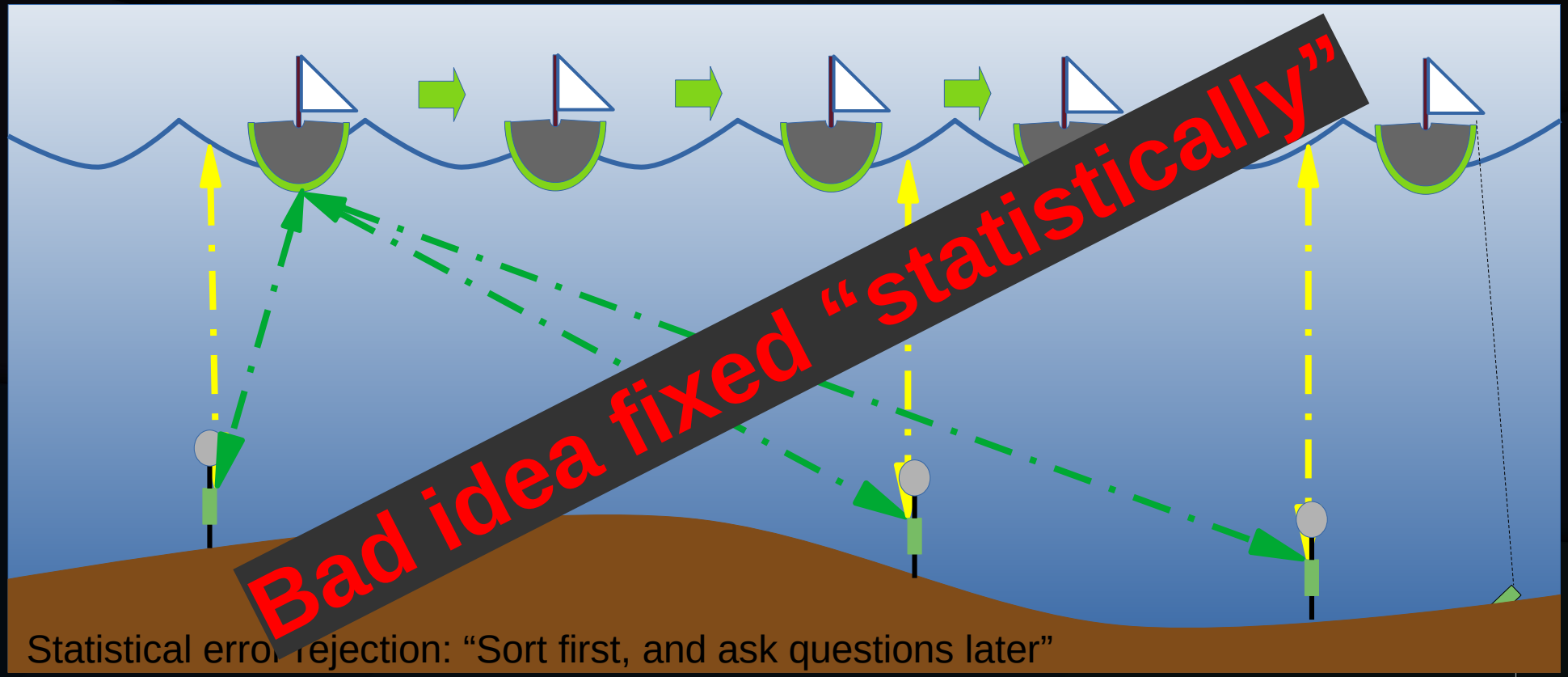

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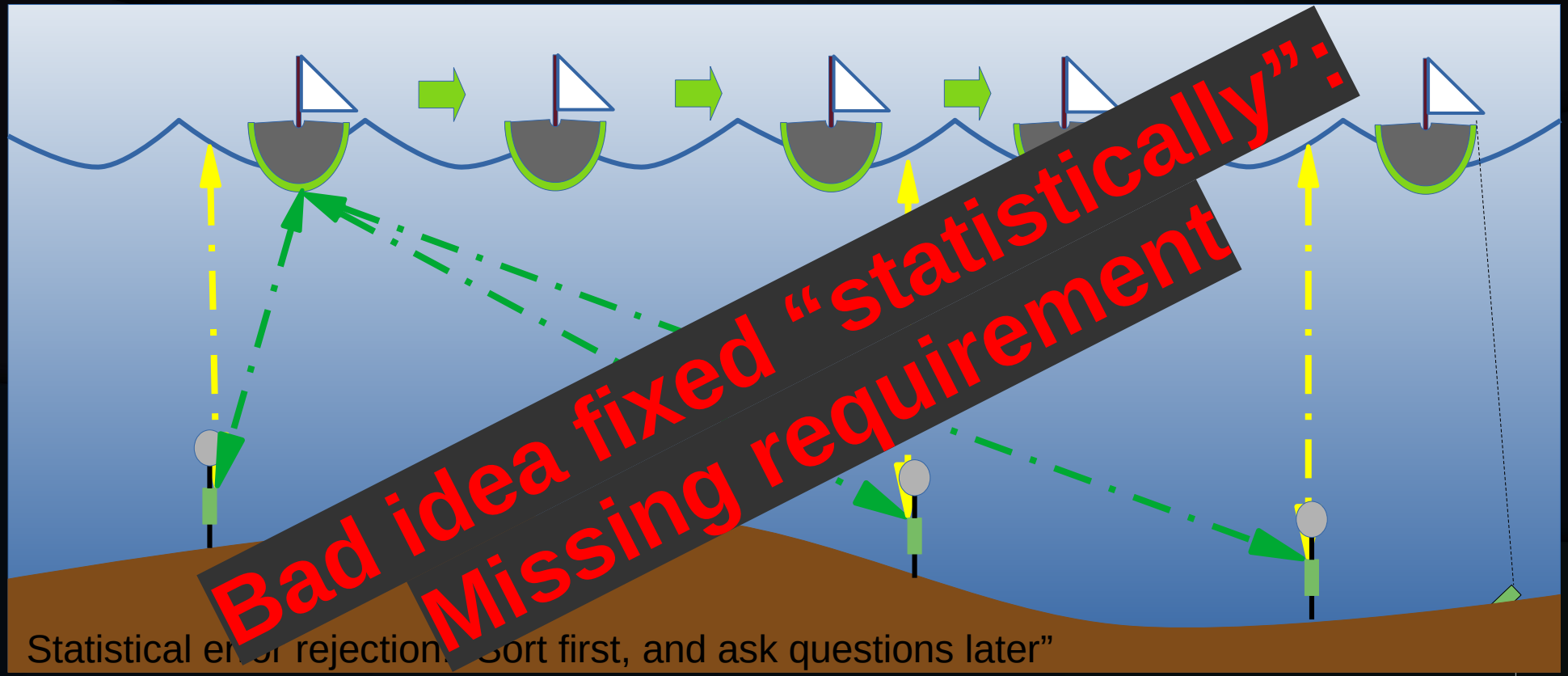

Cautionary Quote

- "Everyone knows that debugging is twice as hard as writing a program in the first place. So if you're as clever as you can be when you write it, how will you ever debug it?" - *Brian W. Kernighan*, "The Elements of Programming Style", 2nd Edition, Chapter 2.

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- While programming, you are living in blissful ignorance of important requirements. These requirements make themselves known during debugging.
- Which is but one cause of Kernighan’s observation.

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I failed to understand that I was competing with a file cabinet

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And the file cabinet won

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1970s: Student Housing System

Photo courtesy of Fundacio´n ICA: CDC 3300

1970s: Student Housing System

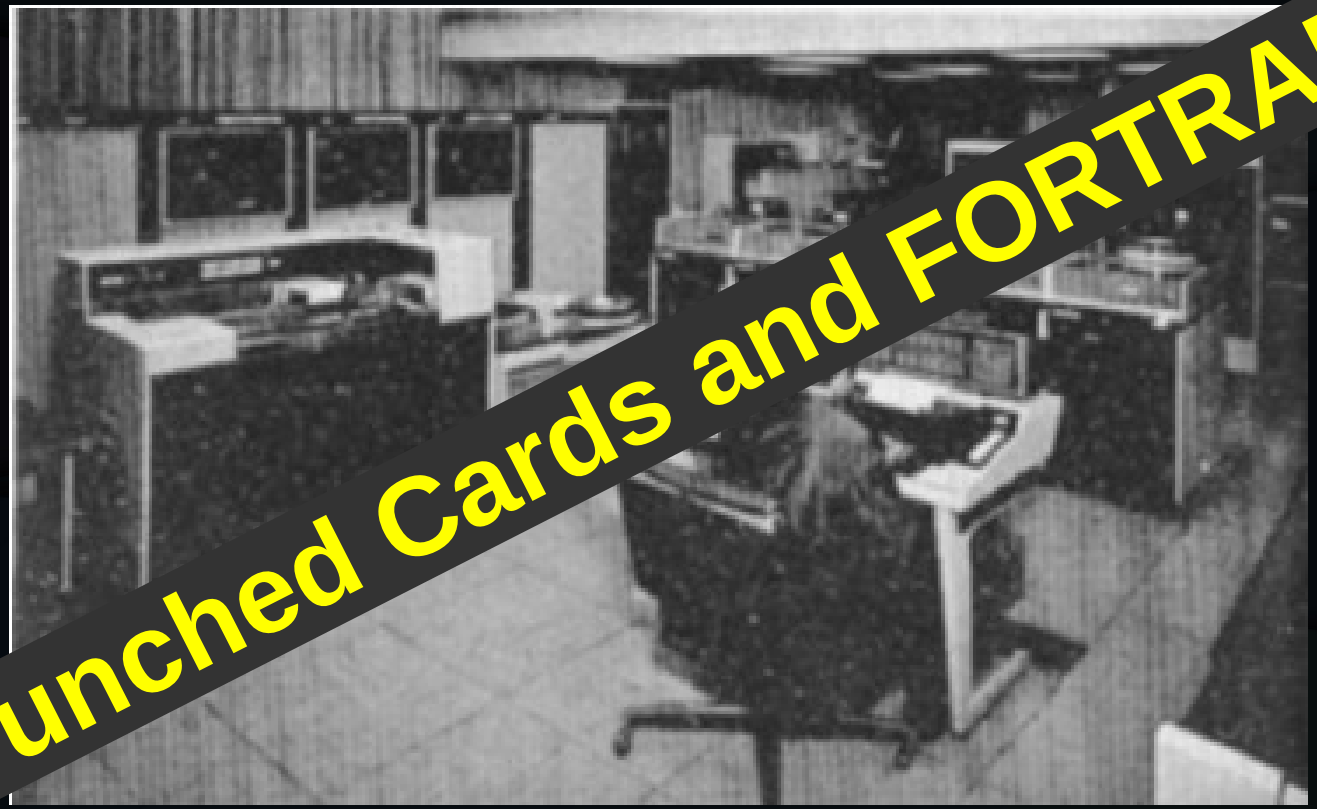

Photo courtesy of Fundacio´n ICA: CDC 3300

1970s: Student Housing System

Photo courtesy Wikipedia user Bubba CC BY-SA 4.0: CDC Cyber 73 console (rest of computer fills room)

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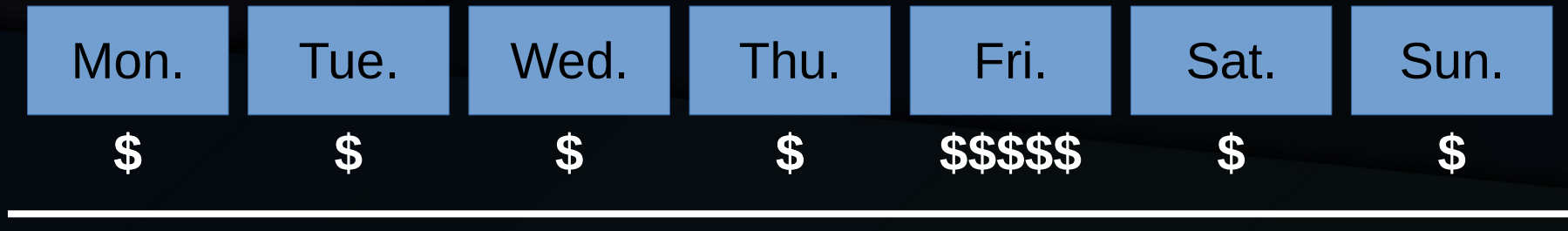
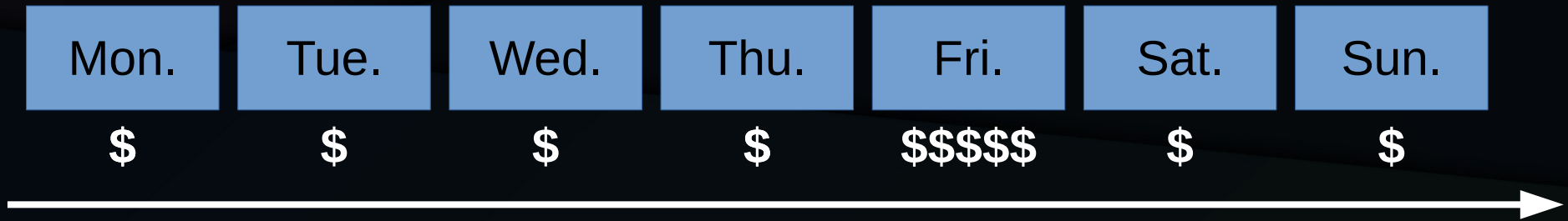
Student Housing Temporal Confusion



Student Housing Temporal Confusion

Student started on Friday and was not amused by the bill.



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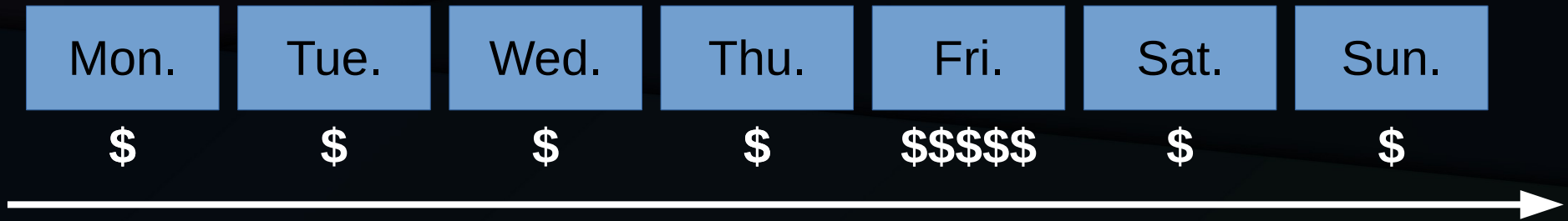

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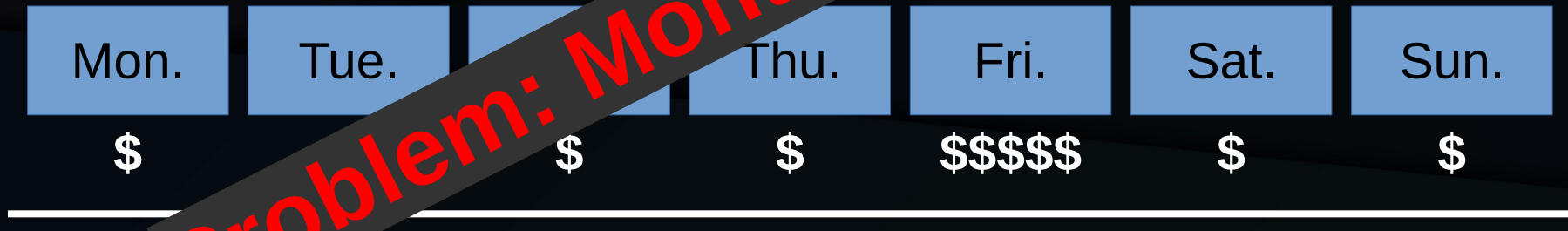

Problem: Months vary in length

Student Housing Temporal Confusion

Student start… day and
was not… the bill.
My… usual
…gestion for
…es of the money.

Problem: Months vary in length
Solution: "jdate" algorithm

"jdate" algorithm: https://aa.usno.navy.mil/faq/JD_formula

Student Housing Temporal Confusion

Student started o… day and
was not am… e bill.
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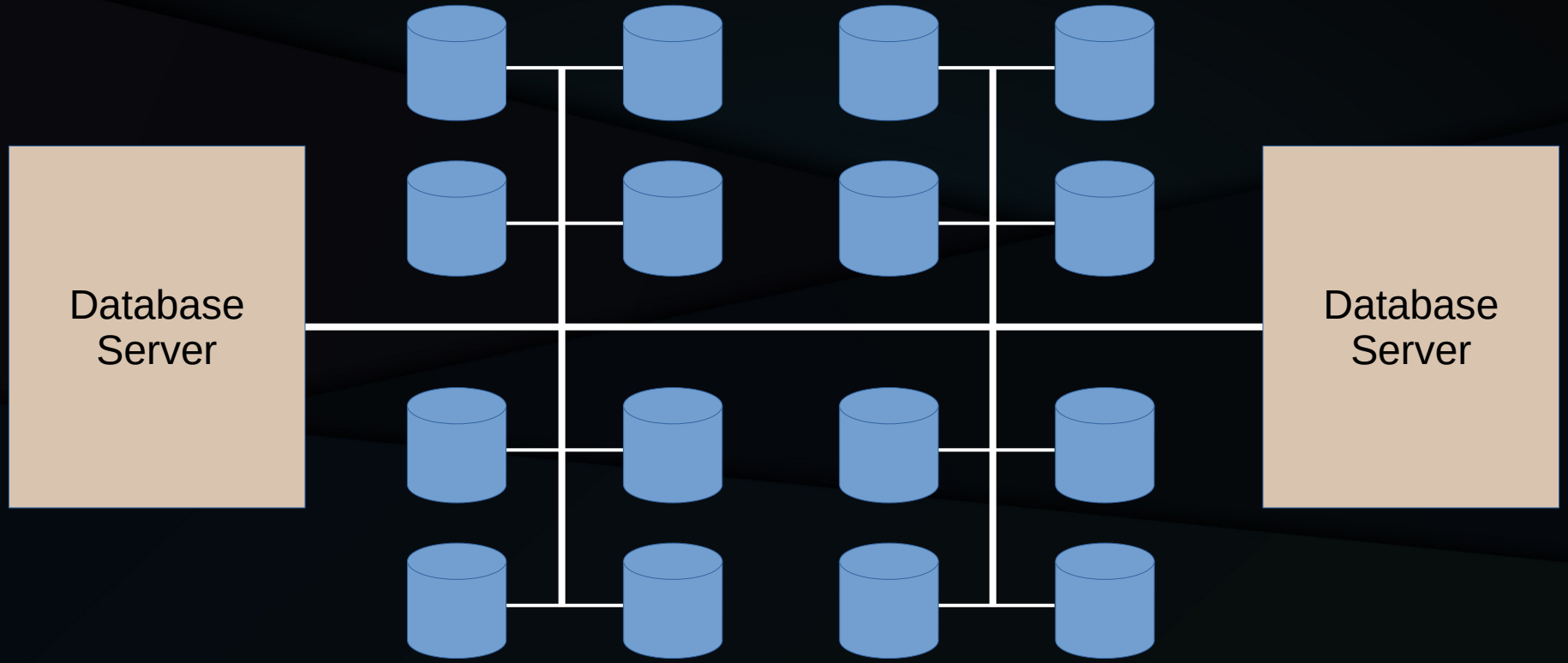
19… suggestion for
…tive uses of the money.

Good idea implemented poorly

1990s: Clustered Database Servers

Shared Disks For Availability Win!!!



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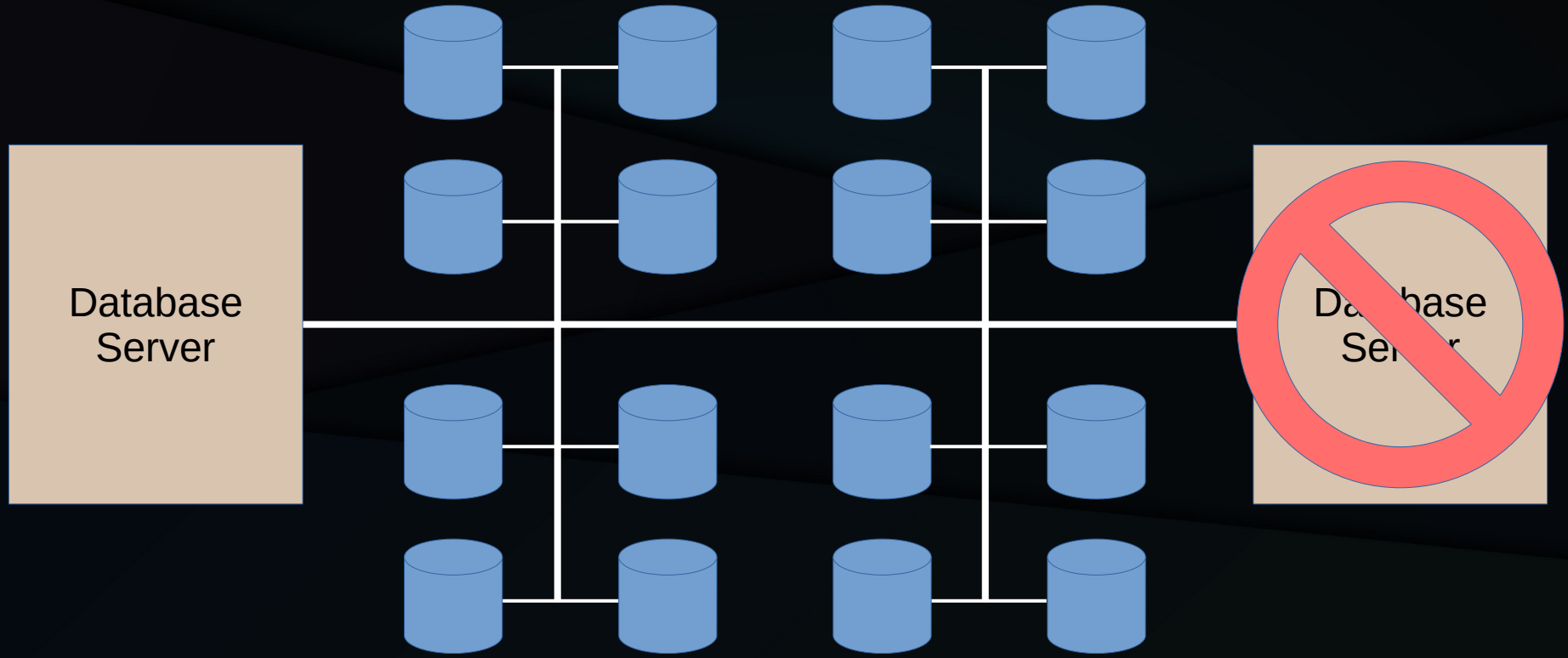

All data is still accessible!!!

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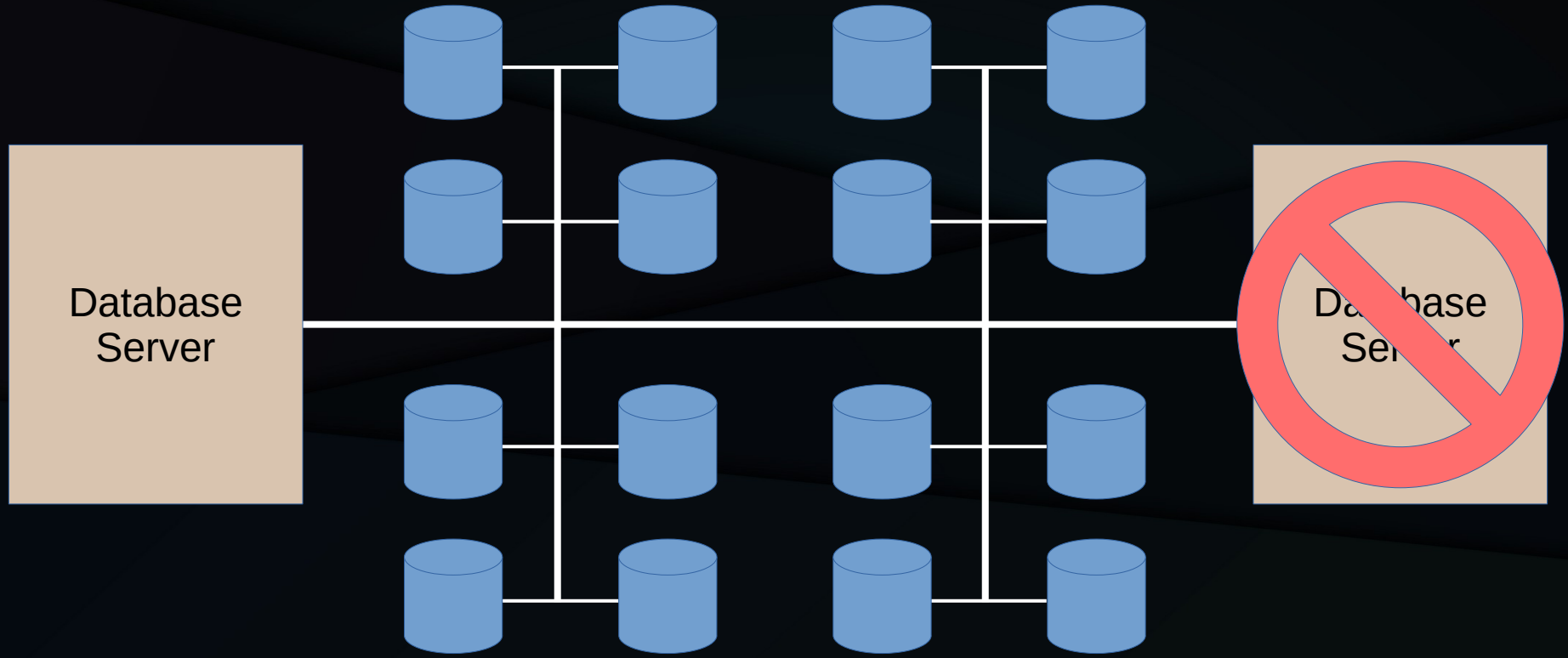

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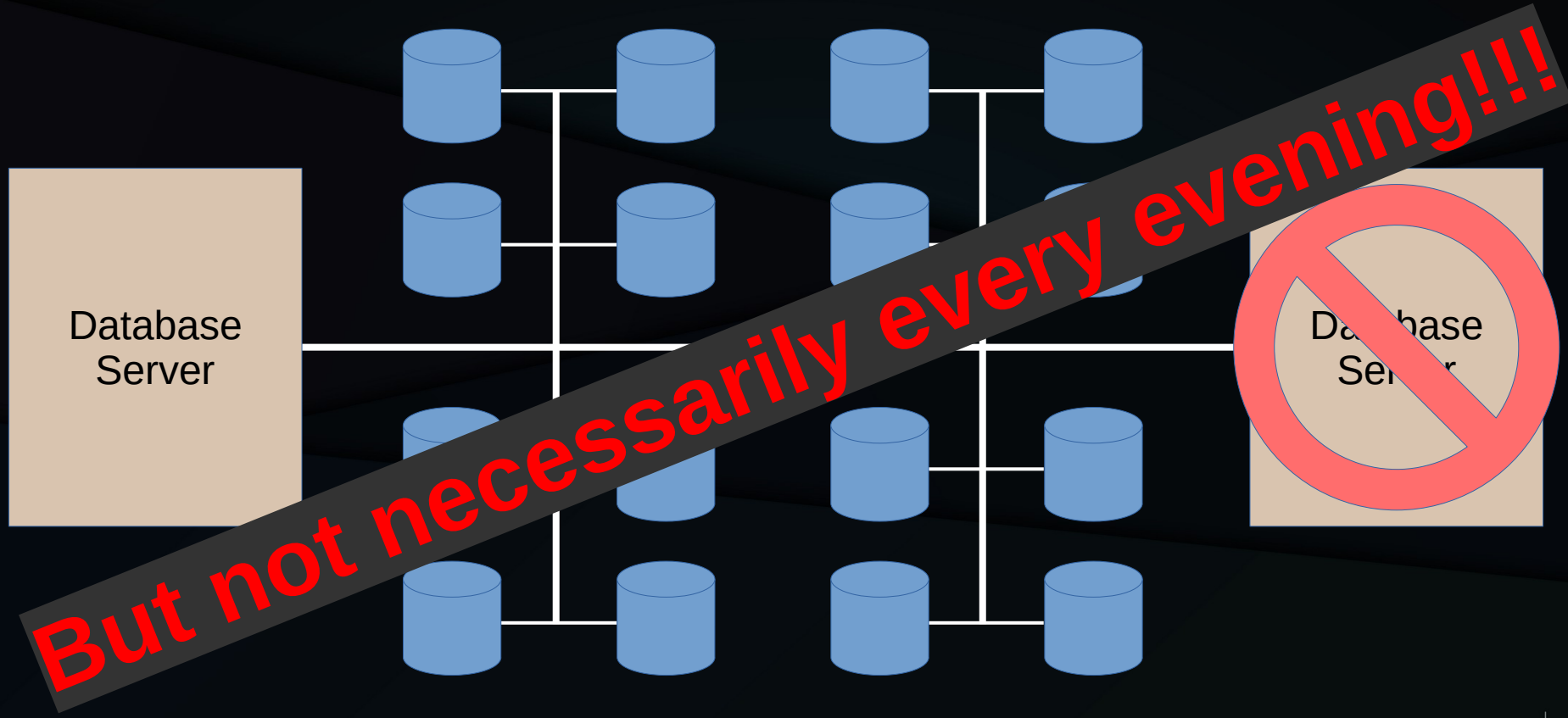

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Chaos-Monkey Challenges

- Crash dump was a complete disaster area
  - No hints for on-site debugging instrumentation
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Created rudimentary digital twin?

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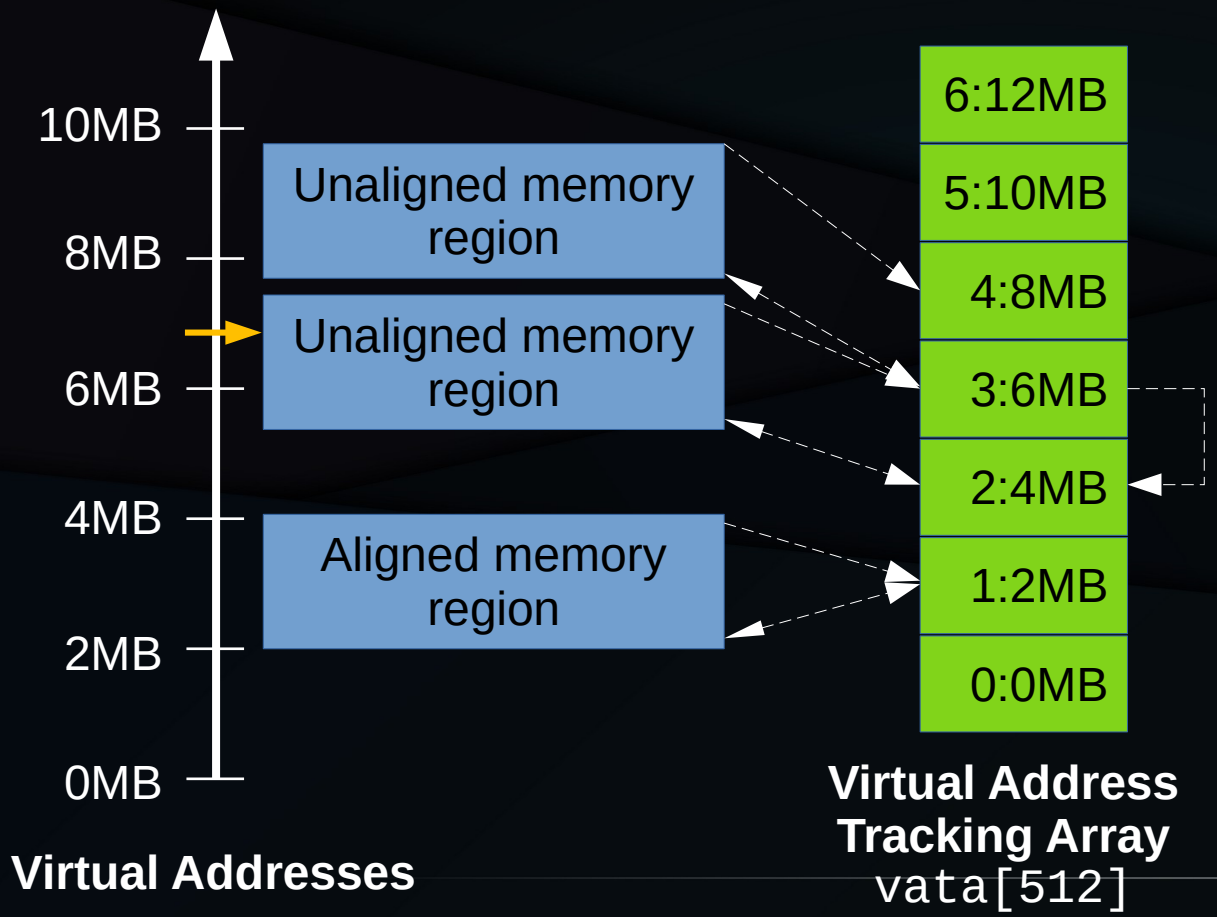
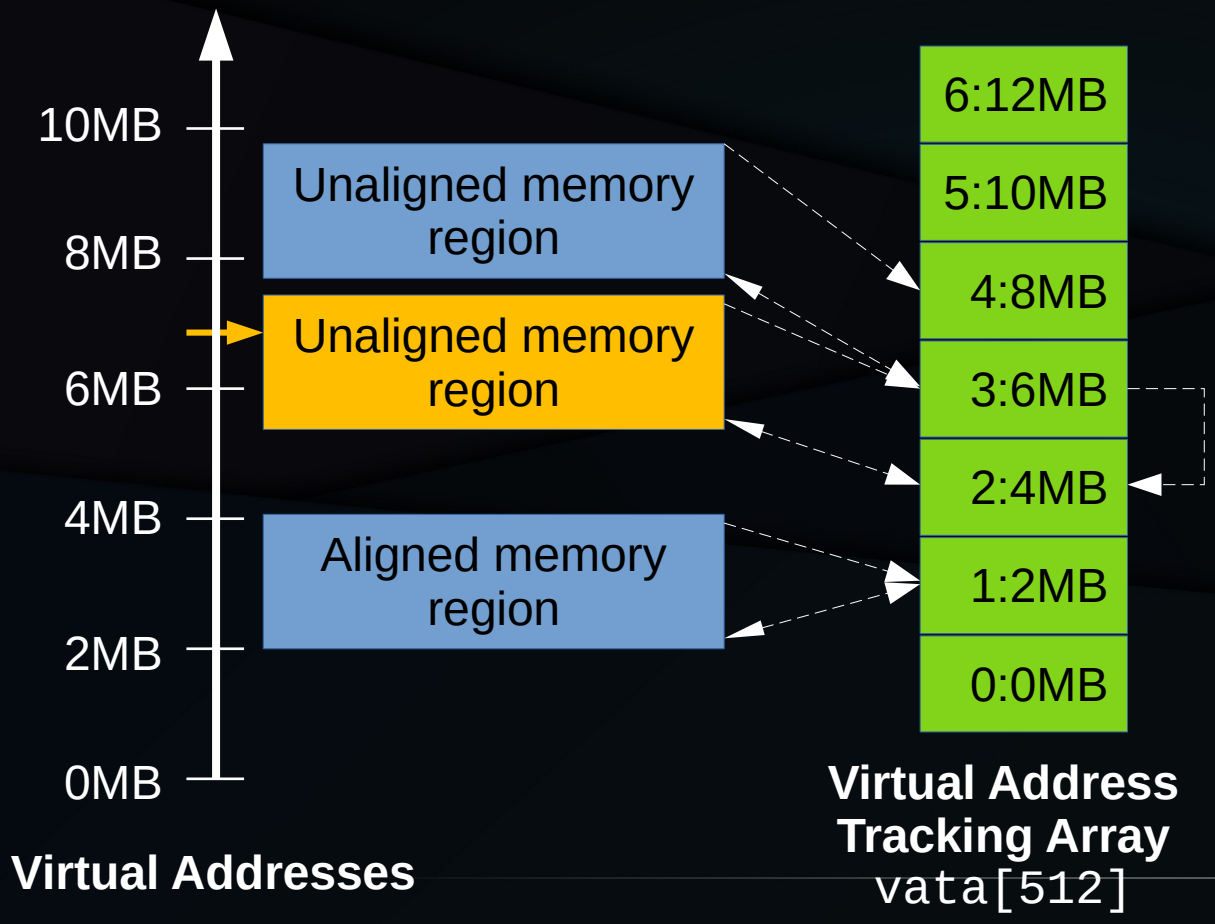
- Crash dump was a complete disaster area
  - No hints for on-site debugging instrumentation
- Unable to reproduce in the lab
- Eventually, found test case: 5-27-hour MTBF
  - But need week-long test for any alleged fix!!!
  - And it was now Memorial Day weekend...

Hint From Stack Trace



Hint From Stack Trace

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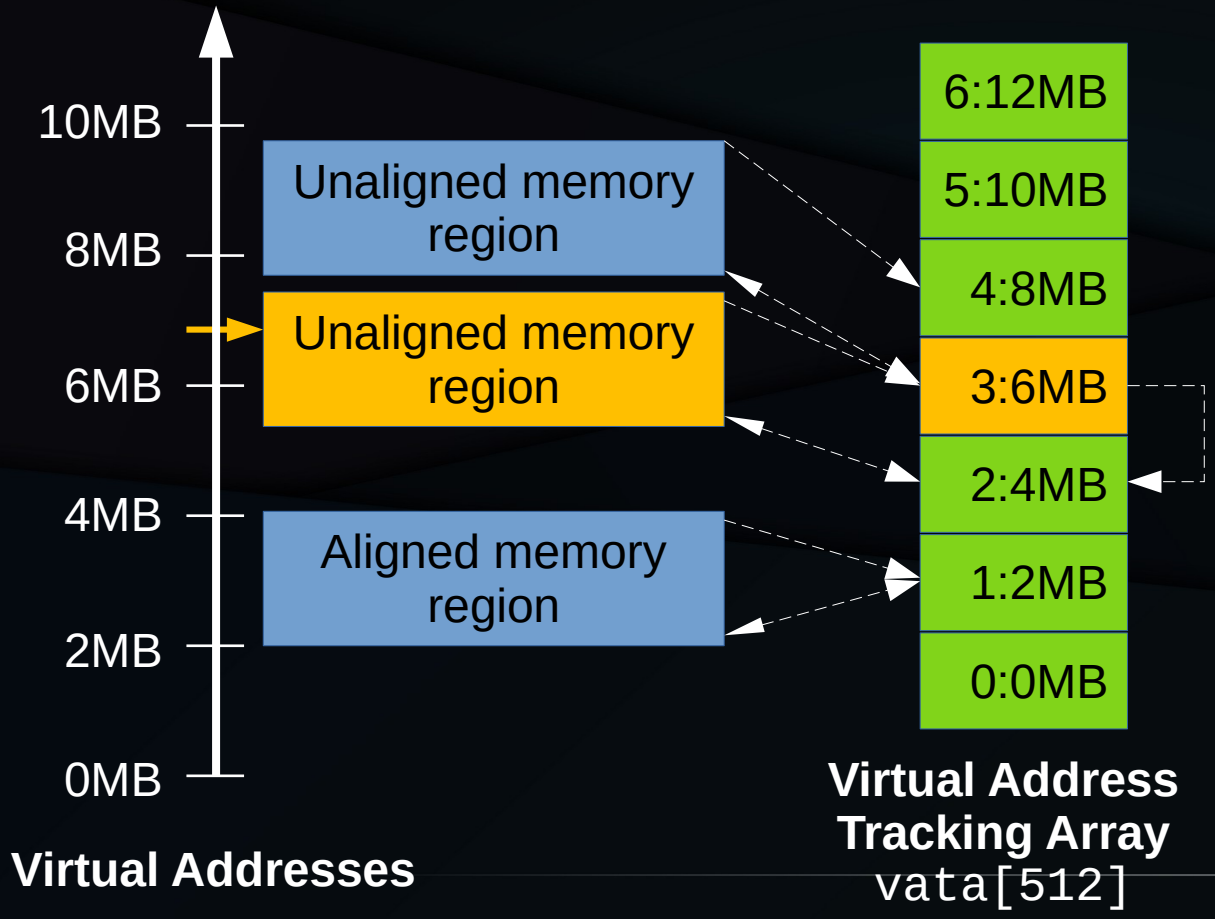
Hint From Stack Trace

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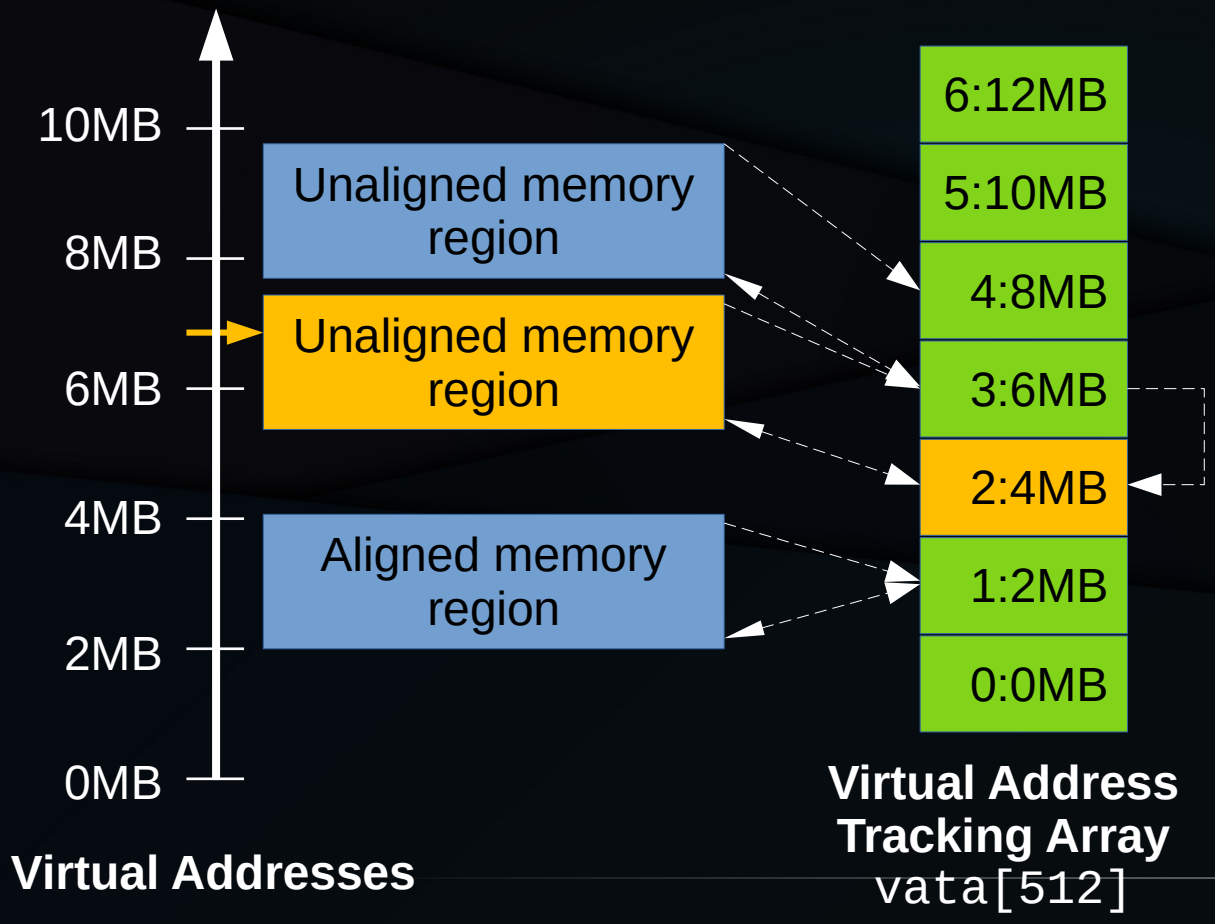


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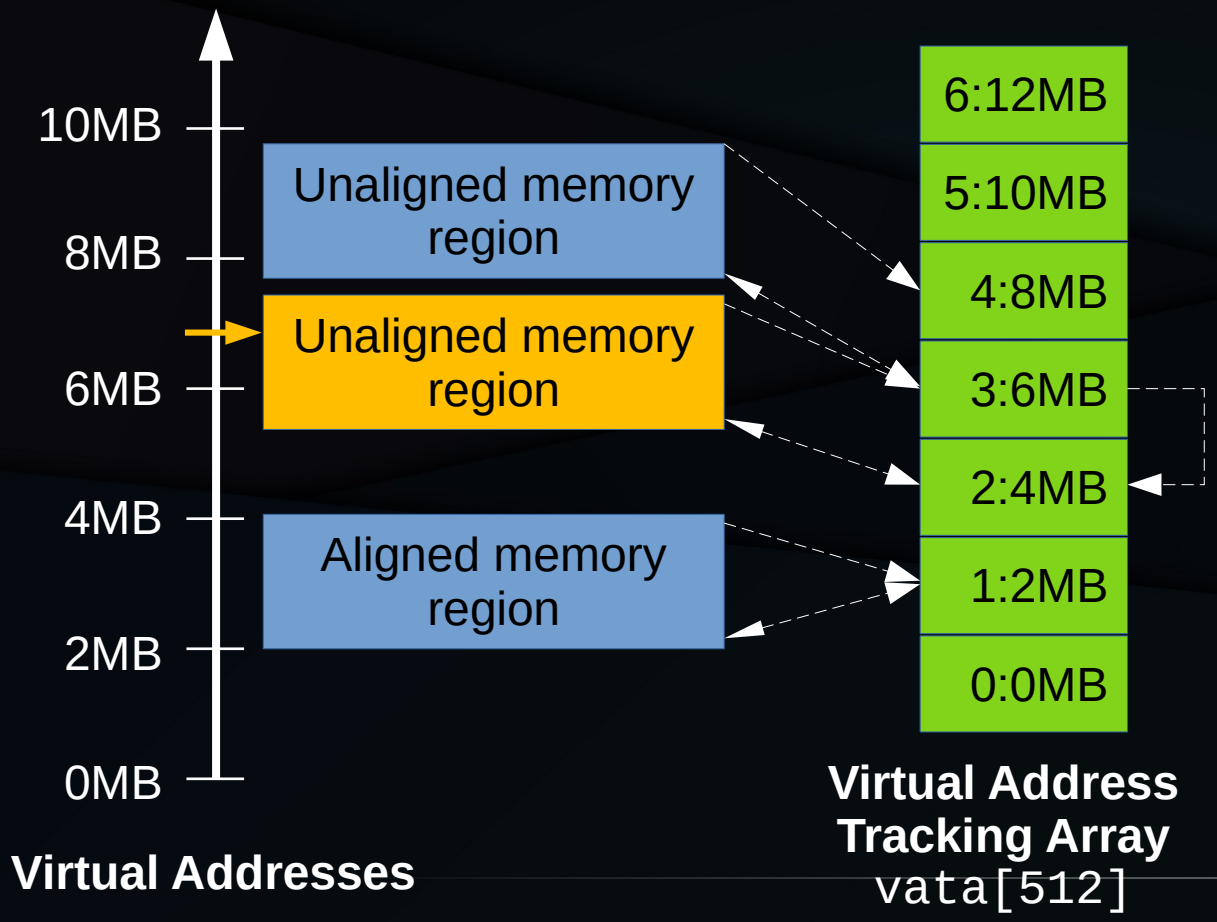
Hint From Stack Trace: Compiler Fun

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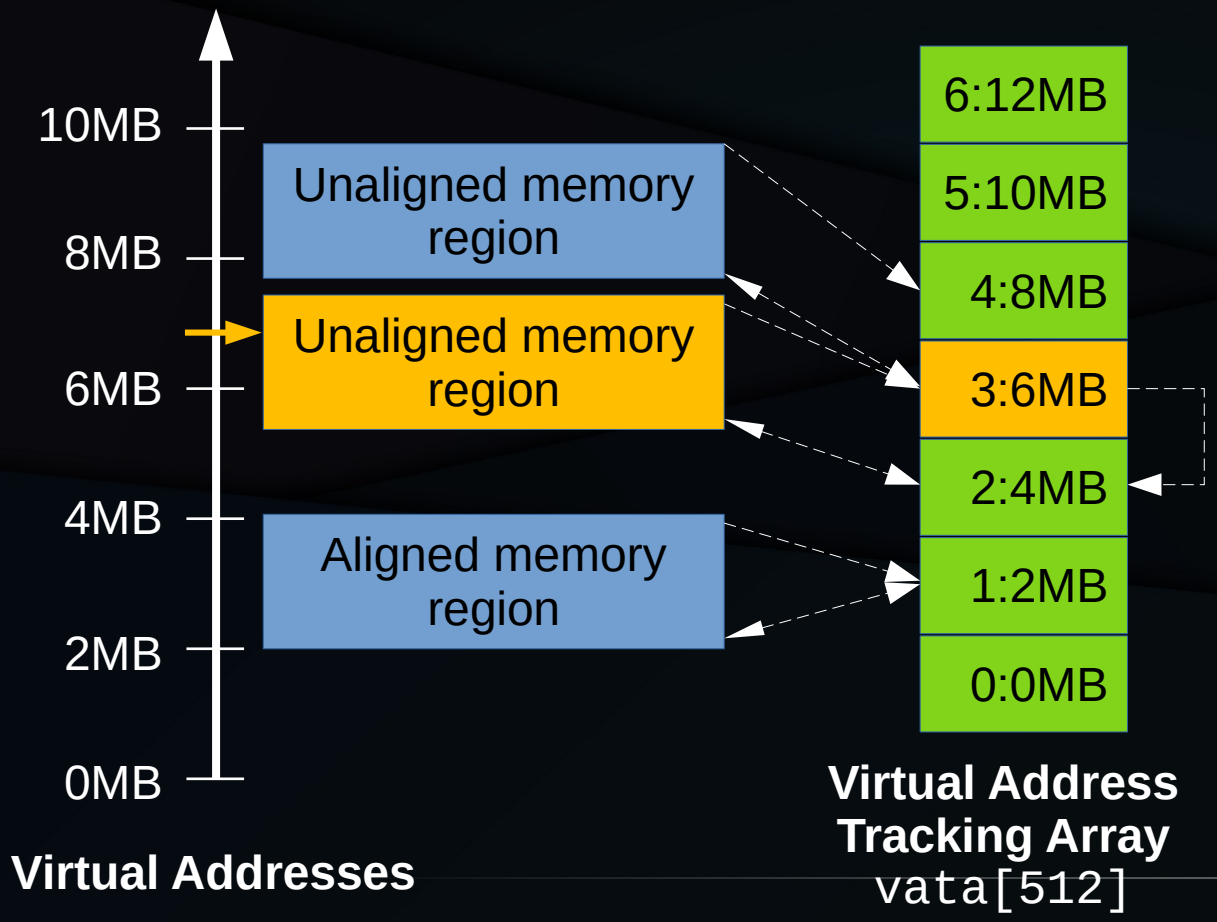
```

Compiler Fun In Failure Case

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```
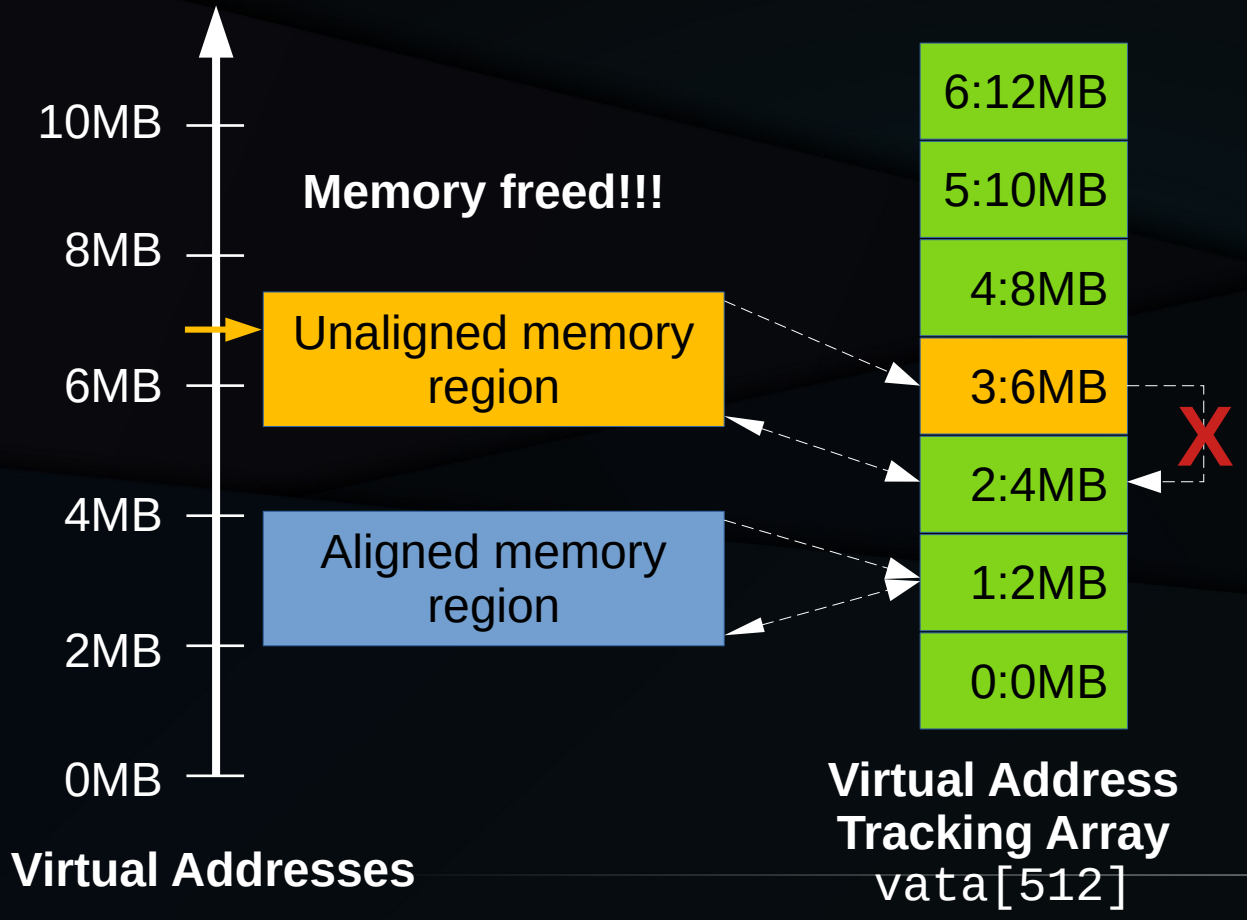

Compiler Fun In Failure Case: Update

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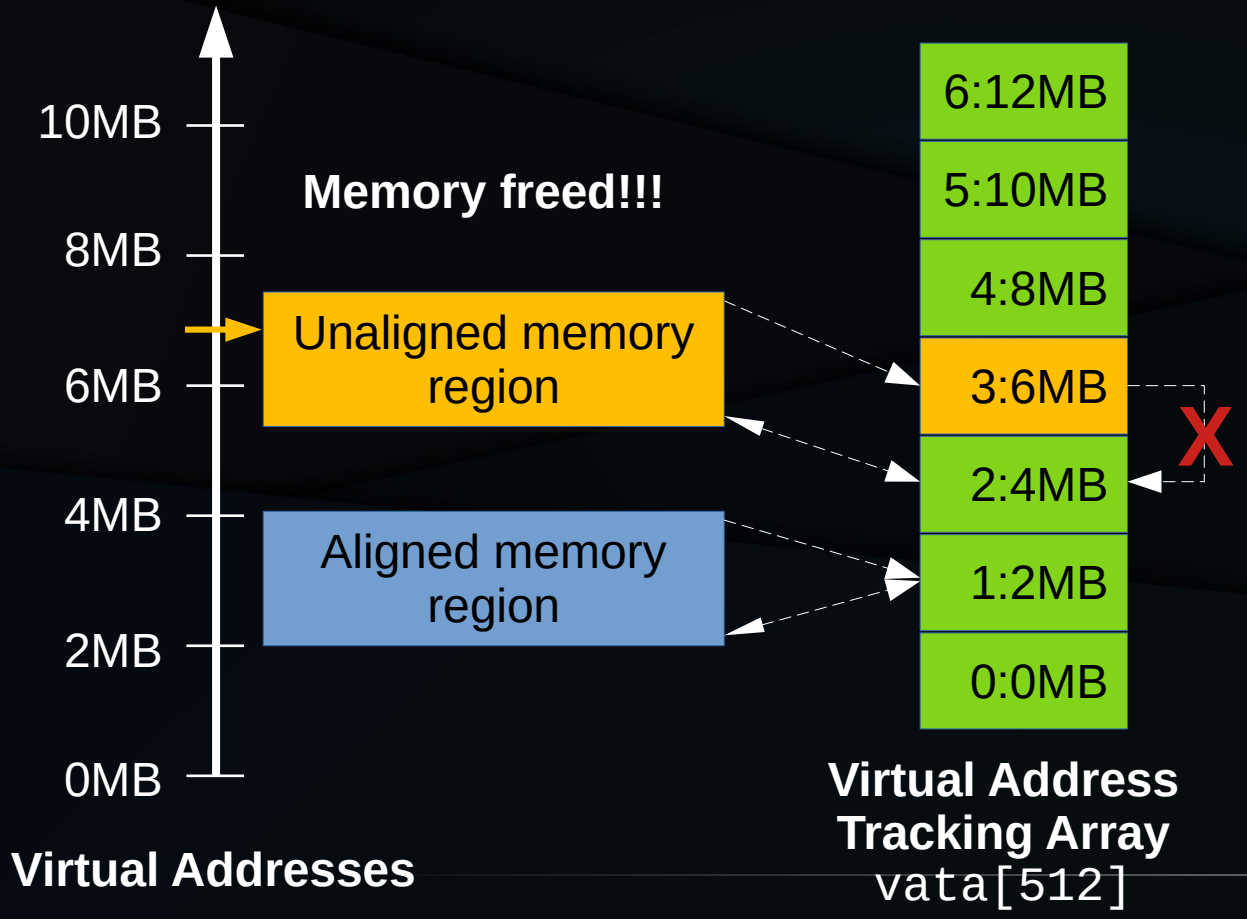
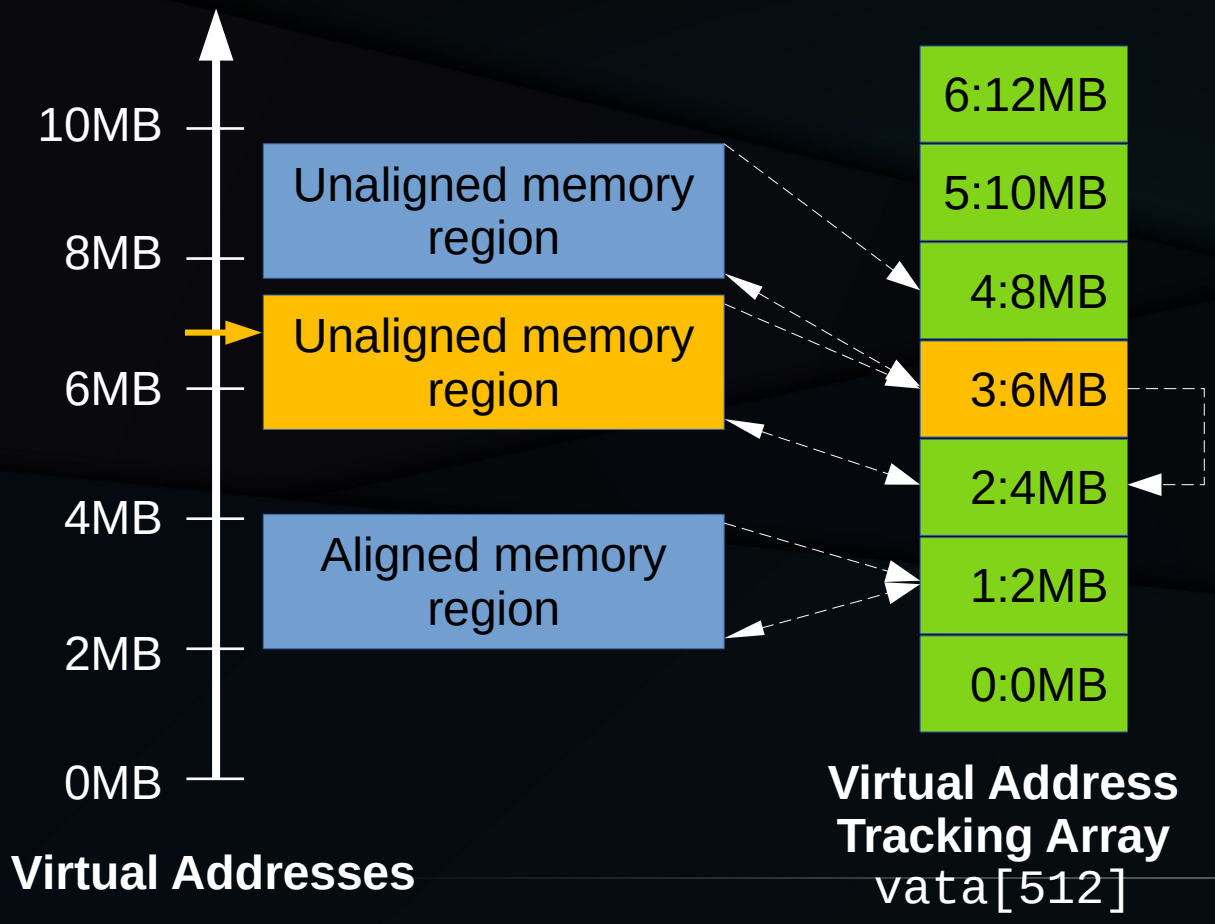
Compiler Fun In Failure Case: Update



Thwarting Compiler Fun




```
int idx = vadr / (2 * MB);
void *vta;

vta = READ_ONCE(vata[idx]);
if (!vta || vadr < vta)
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```
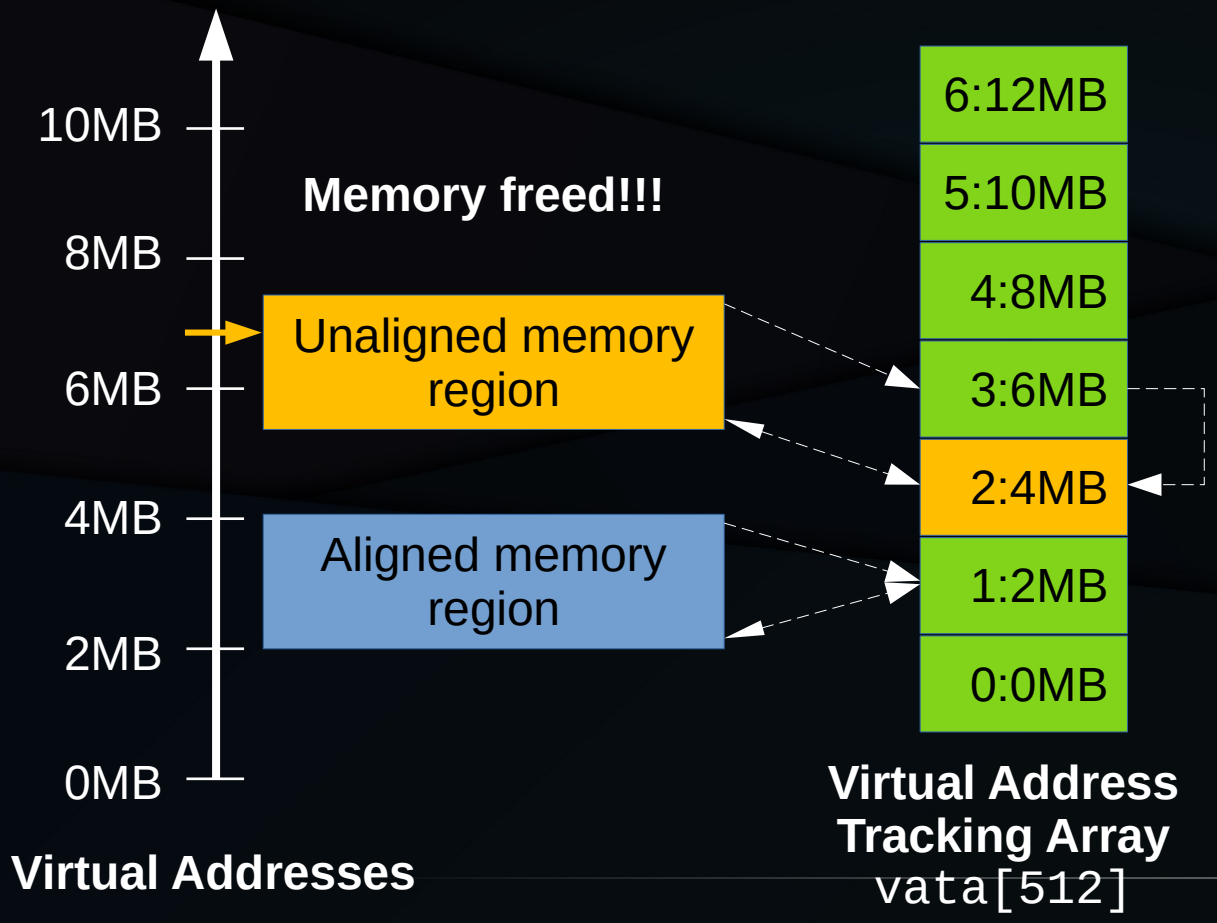

Thwarting Compiler Fun: Update OK

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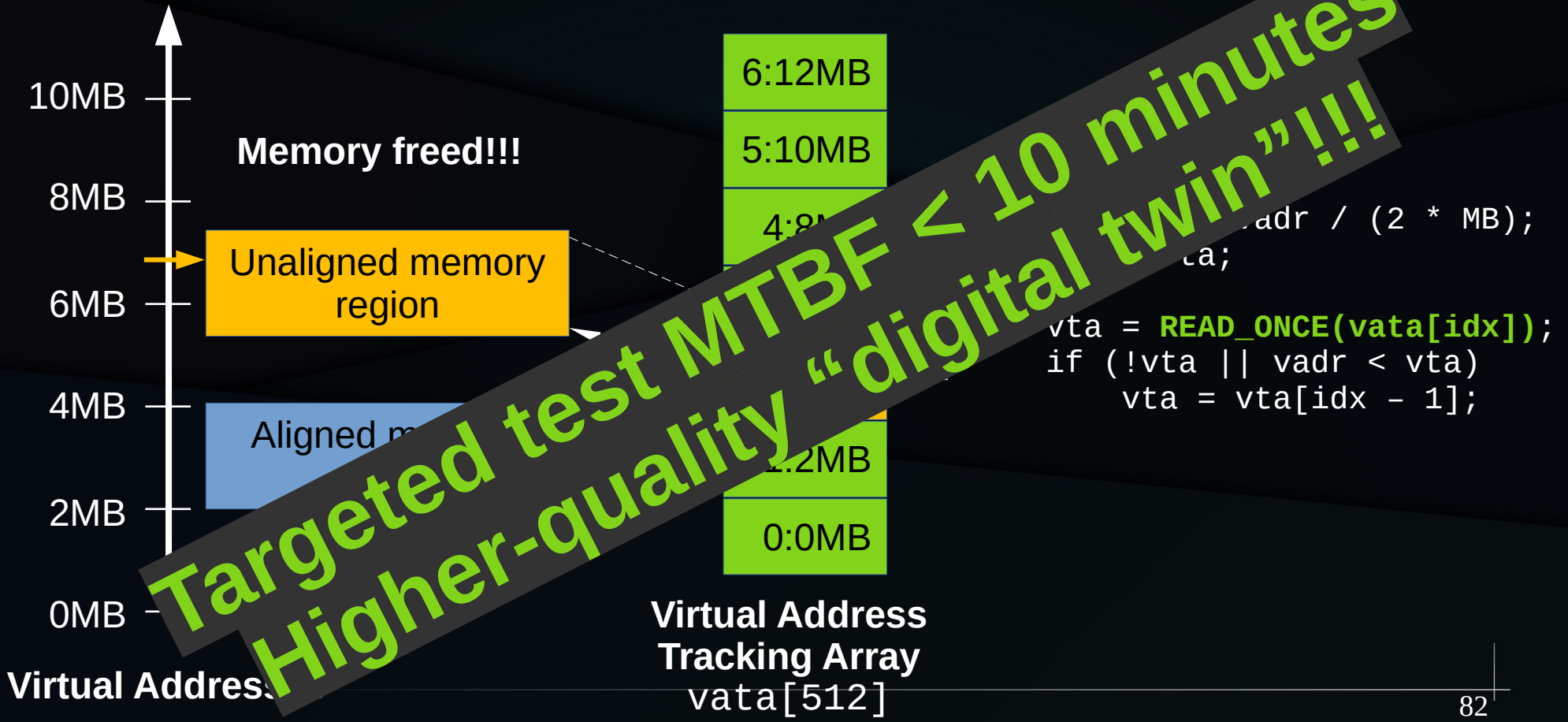


```
adr / (2 * MB);
ta;

vta = READ_ONCE(vata[idx]);
if (!vta || vadr < vta)
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```
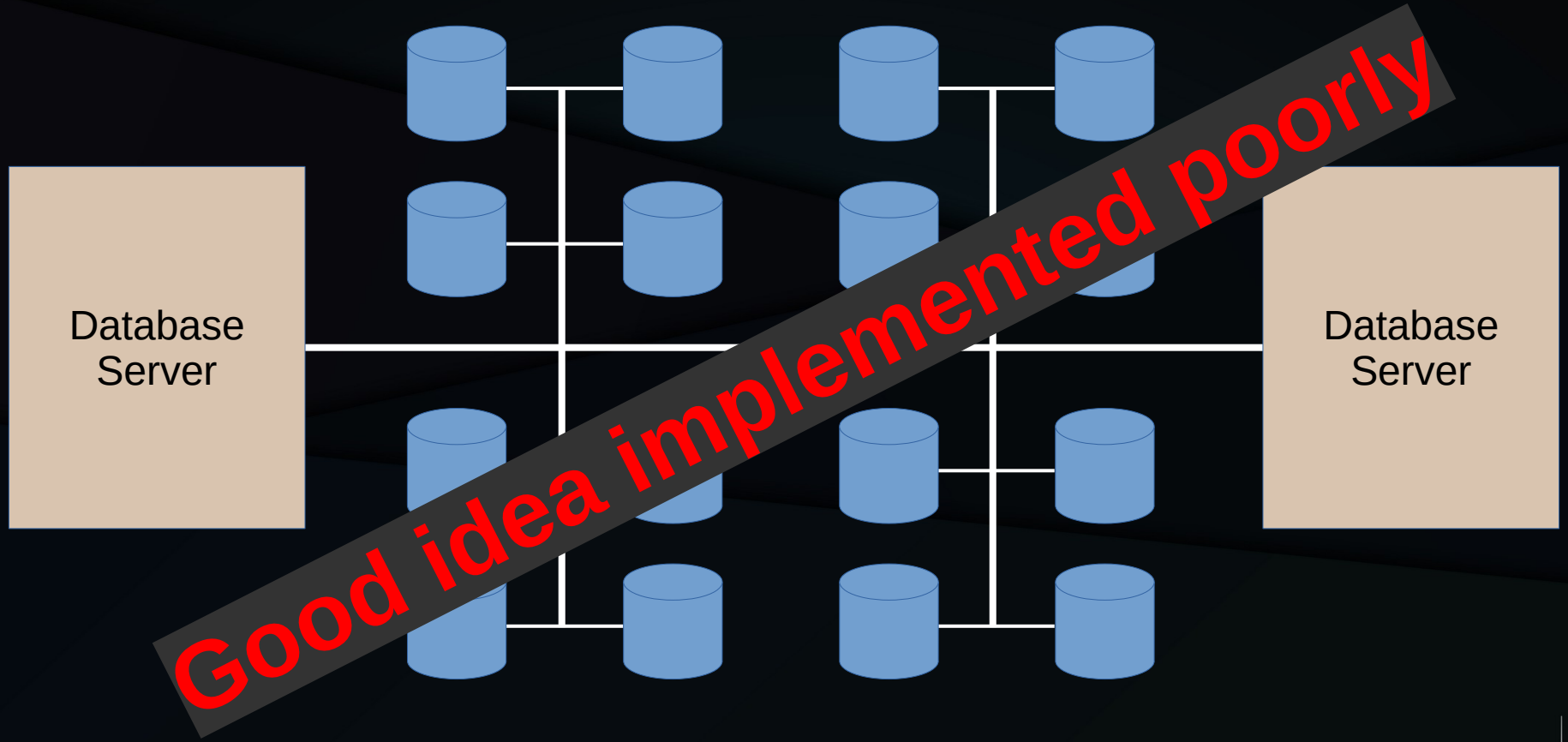
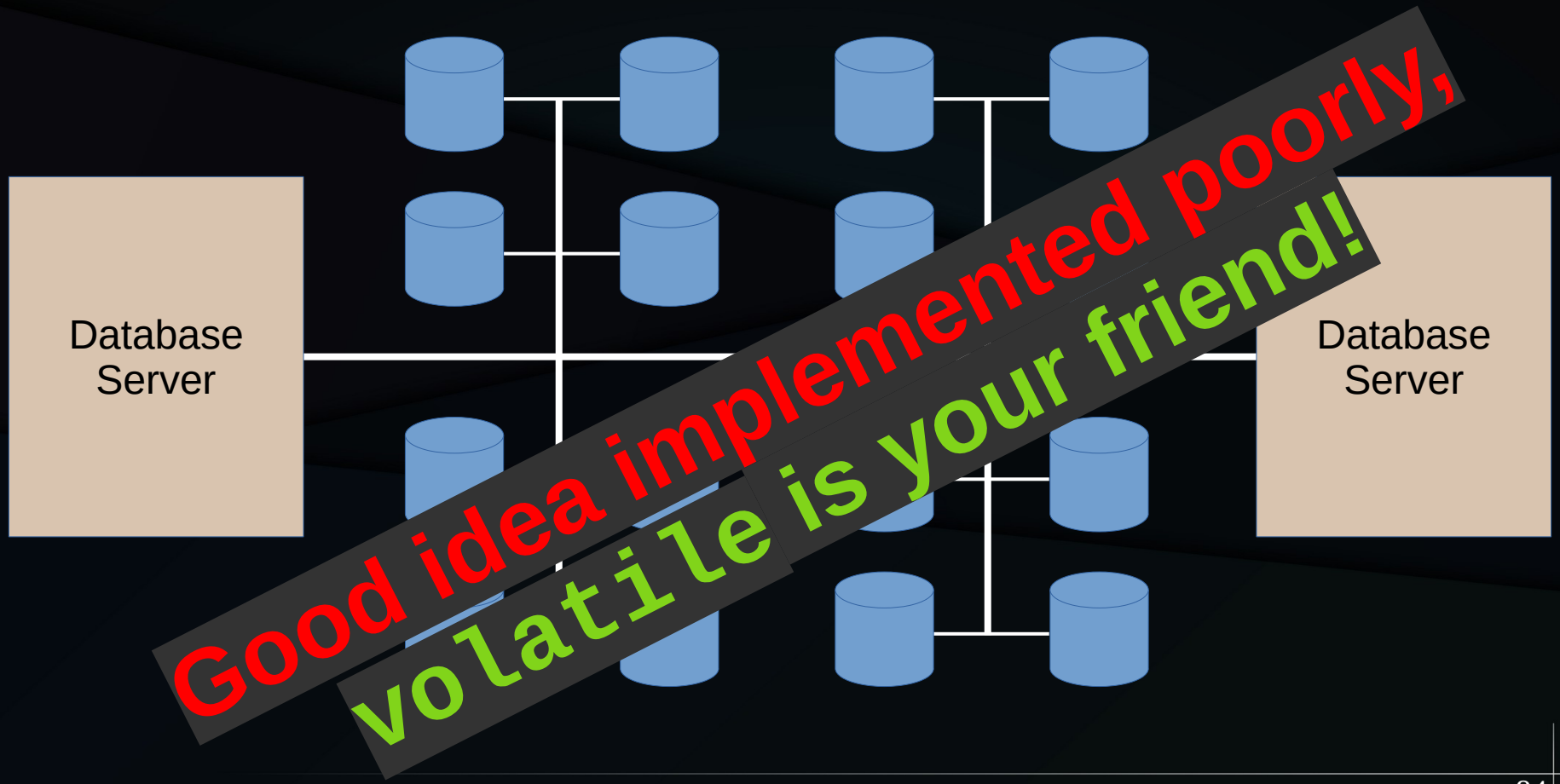

Targeted test MTBF < 10 minutes
Higher-quality "digital twin"!!!

Shared Disks For Availability Win!!!



Shared Disks For Availability Win!!!



Shared Disks For Availability Win!!!

And that is the story how I deprived myself and my colleagues of a Memorial Day weekend

1970s: My First Professional Project

Photo courtesy of Rama & Musée Bolo, CC BY-SA 2.0 fr ASR-33 Teletype

1970s: My First Professional Project

- Pro-bono computer dating program for National Honor Society fundraiser during my senior year in high school
- Questions from Home Economics teacher
- Simple Hamming-distance matching with expected 1970s constraints on matches
- Students' paper questionnaires transcribed to paper tape, then read into program
- Simple, effective, worked great!!!

One Unsatisfied Customer

- Senior girl matched only with freshmen boys
  - And she really did check the seniors-only box
- Program looked to be correct
- Turned out to be data-entry error
- Correct program is not enough
  - Environment and processes matter!!!

One Unsatisfied Customer

- Senior girl matched only with fres
  - And she really did check the only box
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Good idea implemented properly,

One Unsatisfied Customer

- Senior girl matched only with fres
  - And she really did check the
- Program looked to b
- Turned out to l error
- Correct t enough
  nd processes matter!!!

Good idea implemented properly, but I was also overall project lead!

Cautionary Quote

- A lot of success in life and business comes from knowing what you want to avoid. - *Charlie Munger*

2004: Real-Time Linux

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- Early 2000s: Many requests for real-time Linux
  - But “enterprise-grade real-time Linux”
- Except that no such thing existed
- And my employer had strict rules for contracts calling for mythical creatures

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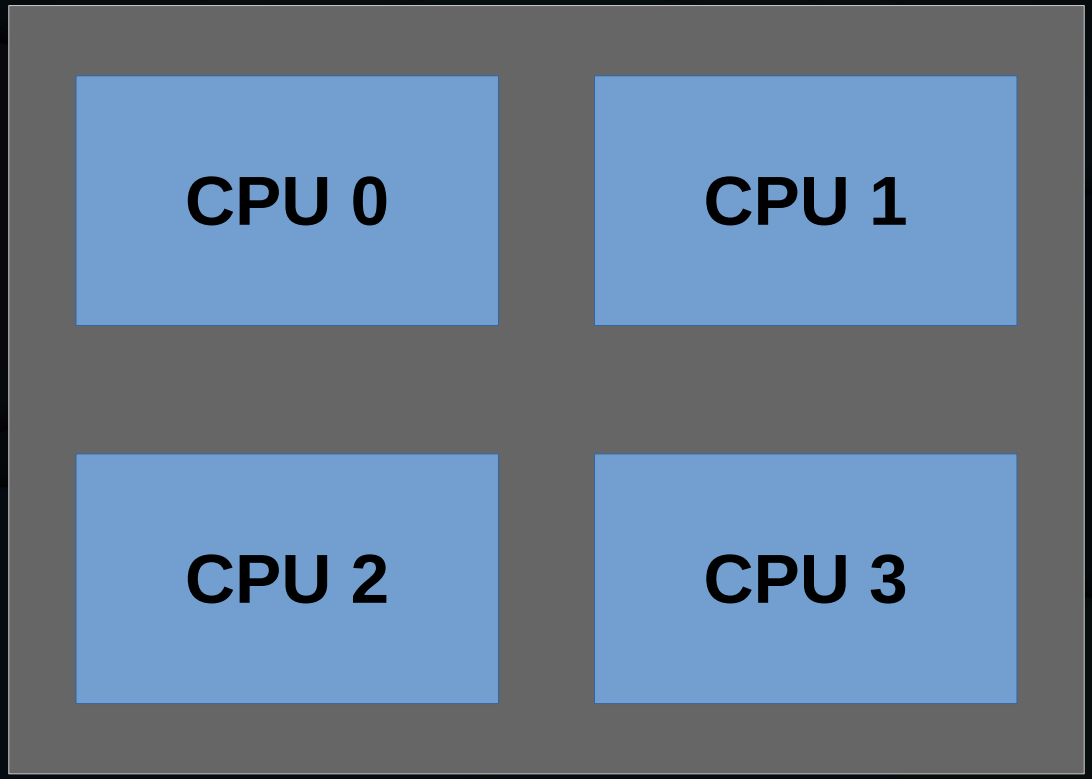
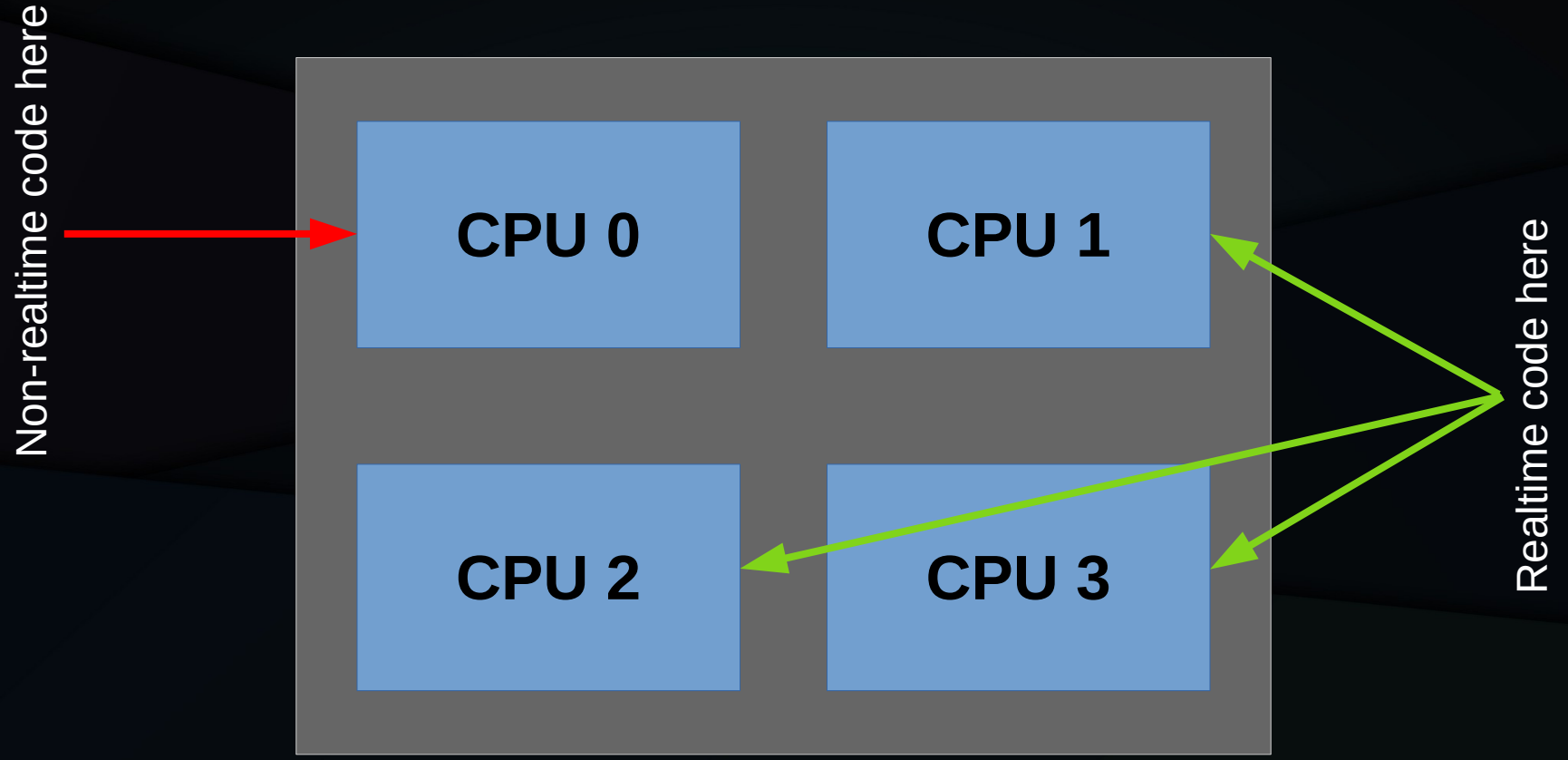
2004: Dawn of Multicore Embedded



Multicore Embedded for Real Time!!!



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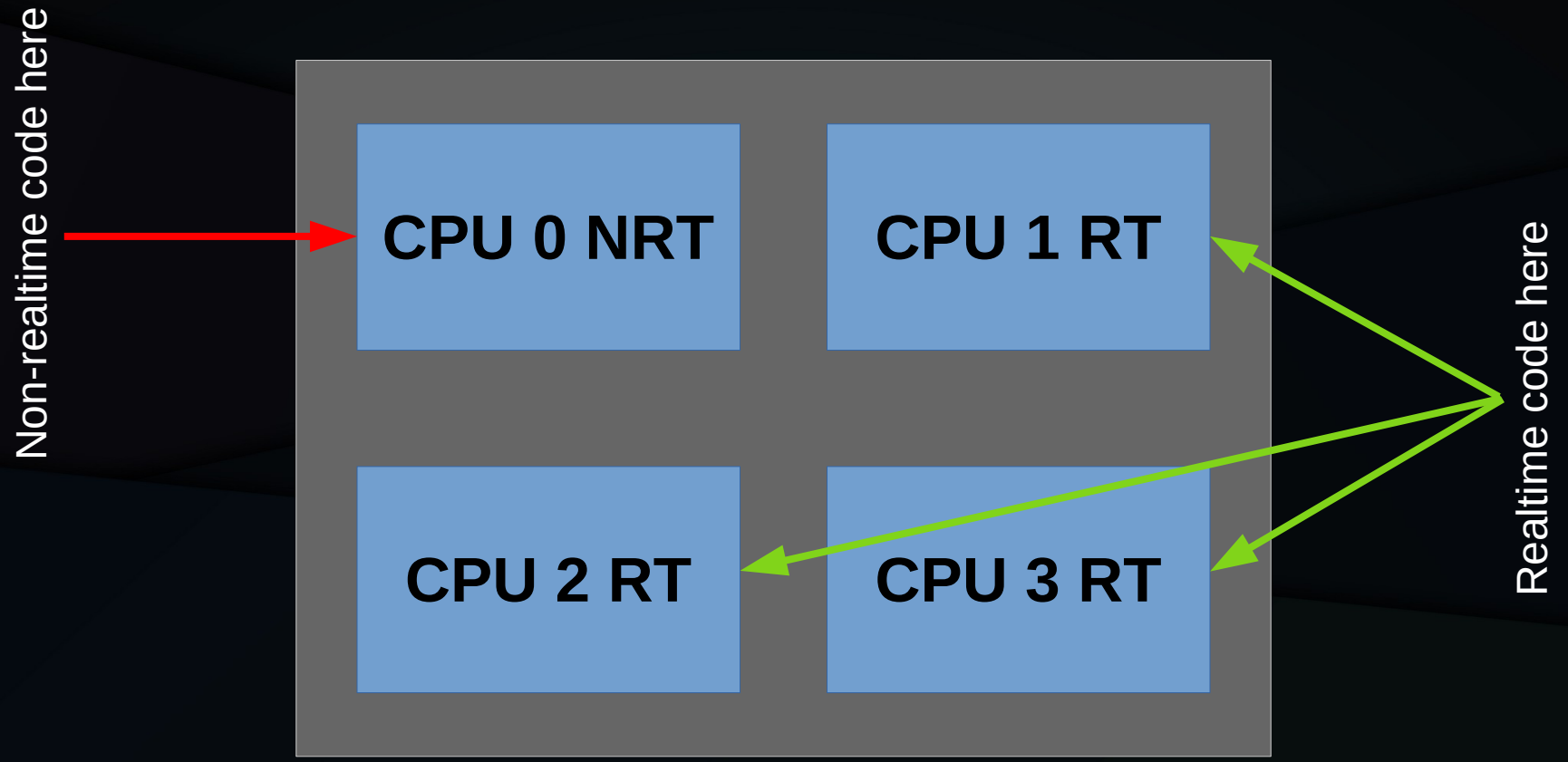

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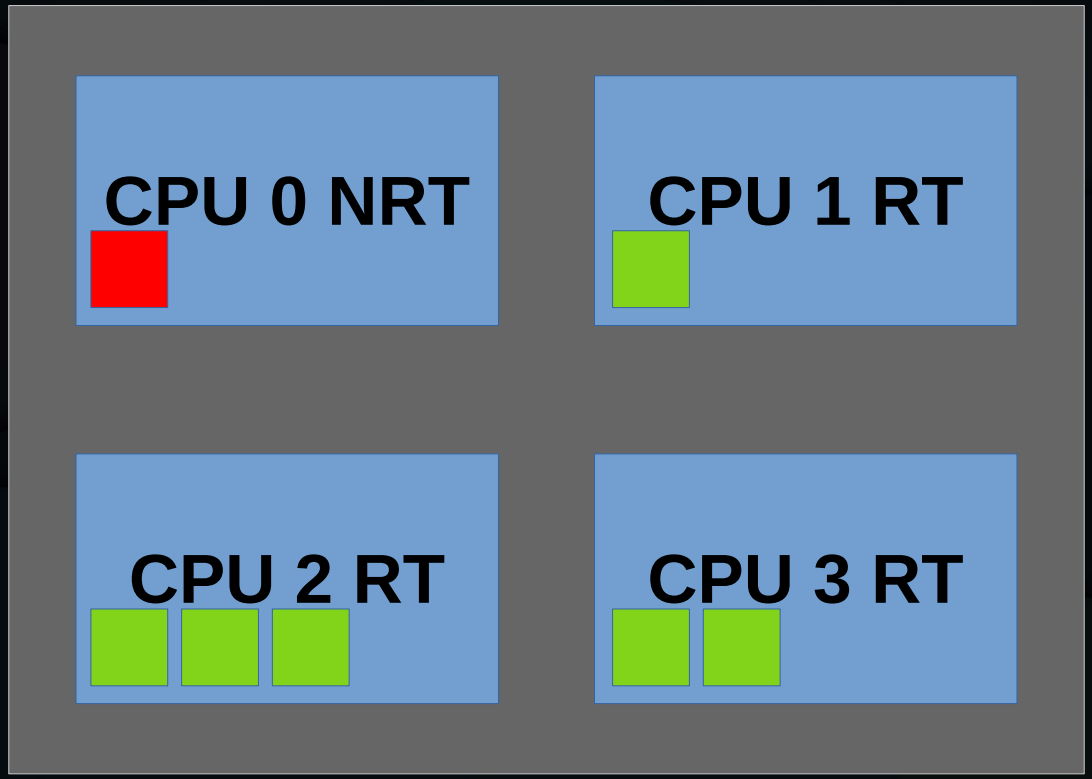

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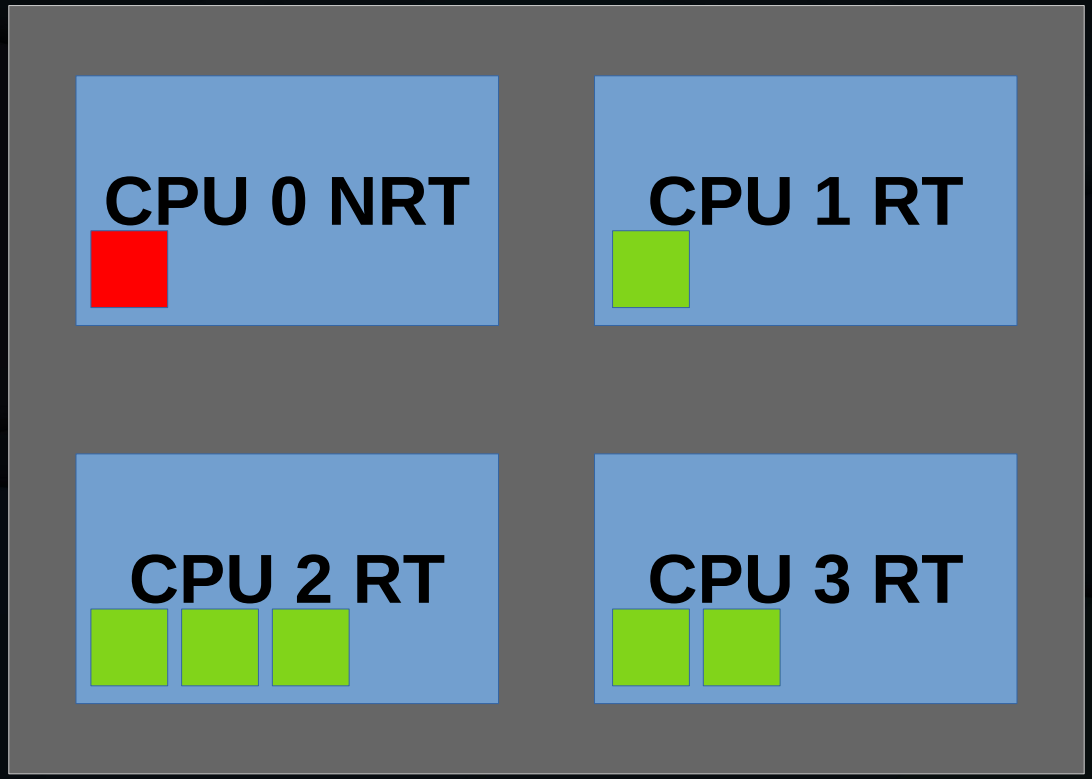
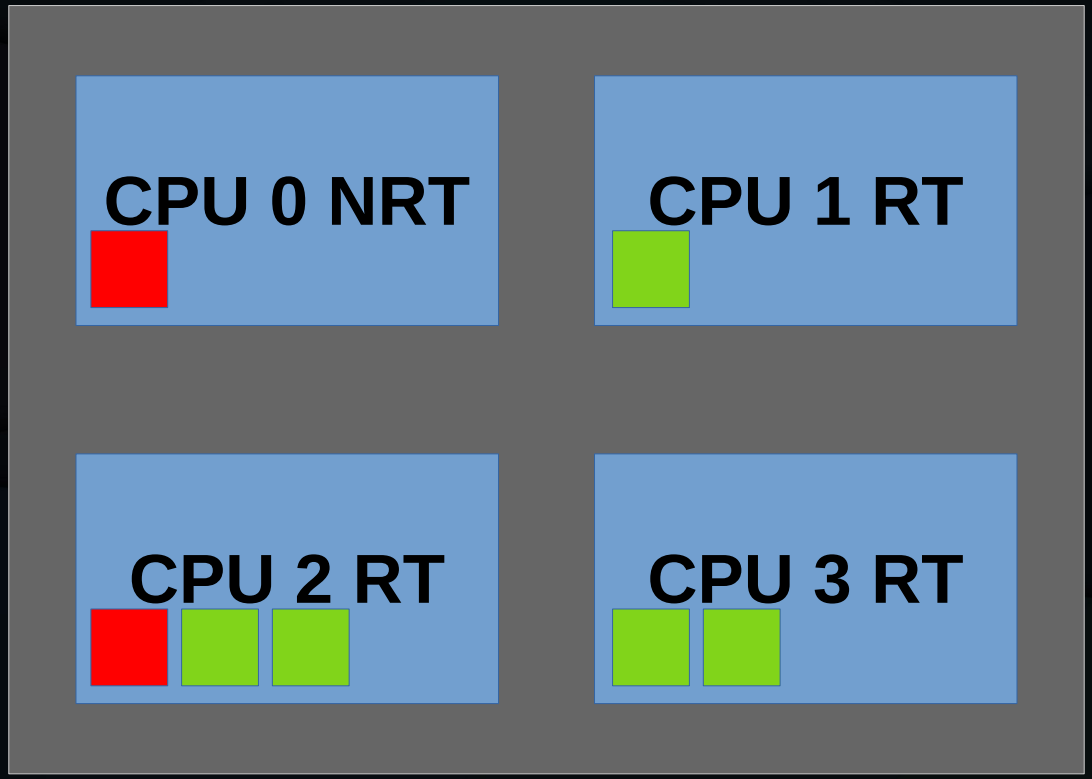


Respond to non-real-time activity by migrating.

Multicore Embedded for Real Time!!!



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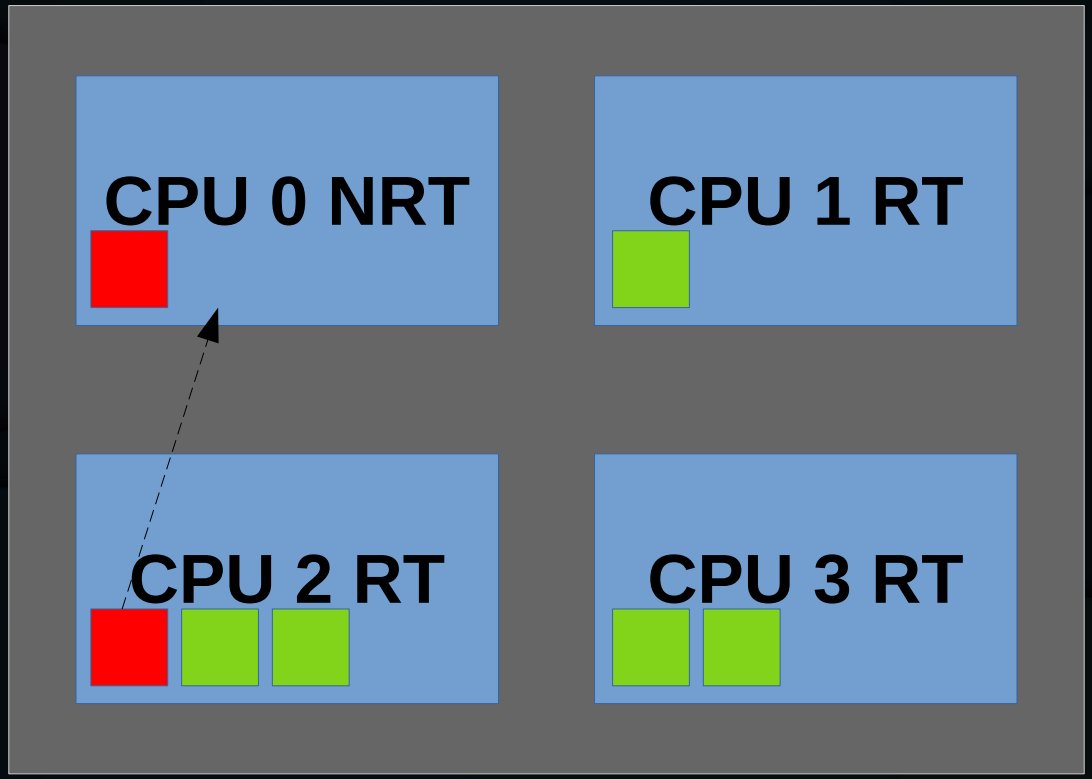

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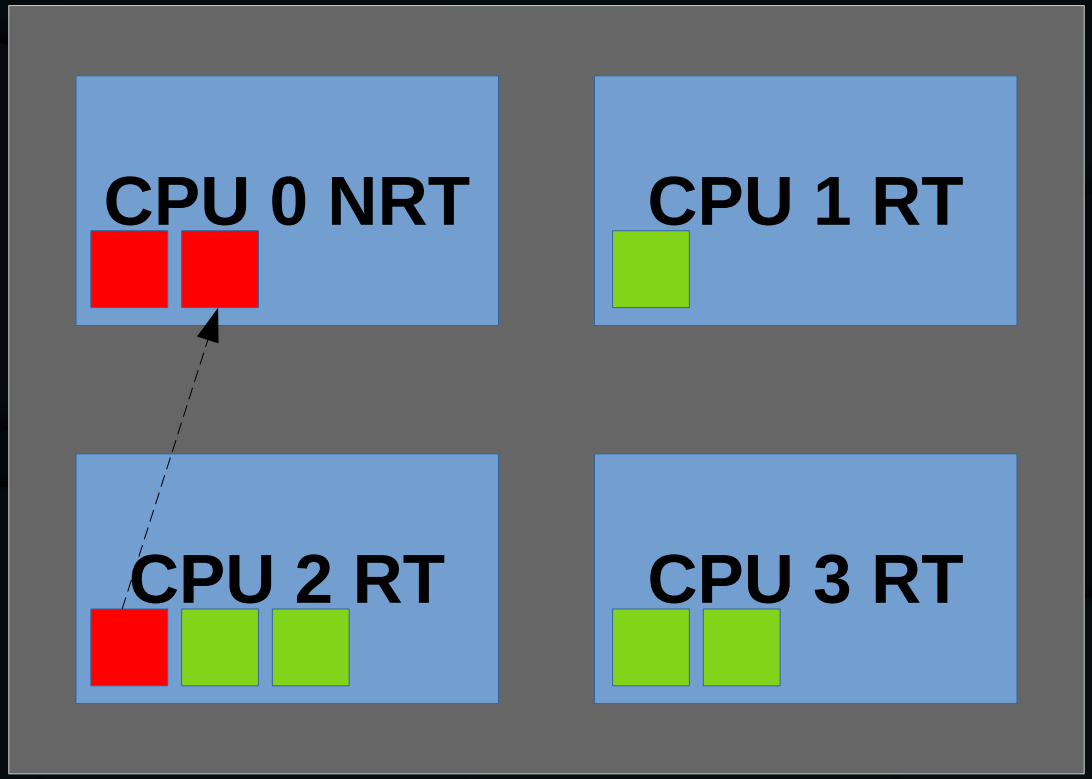

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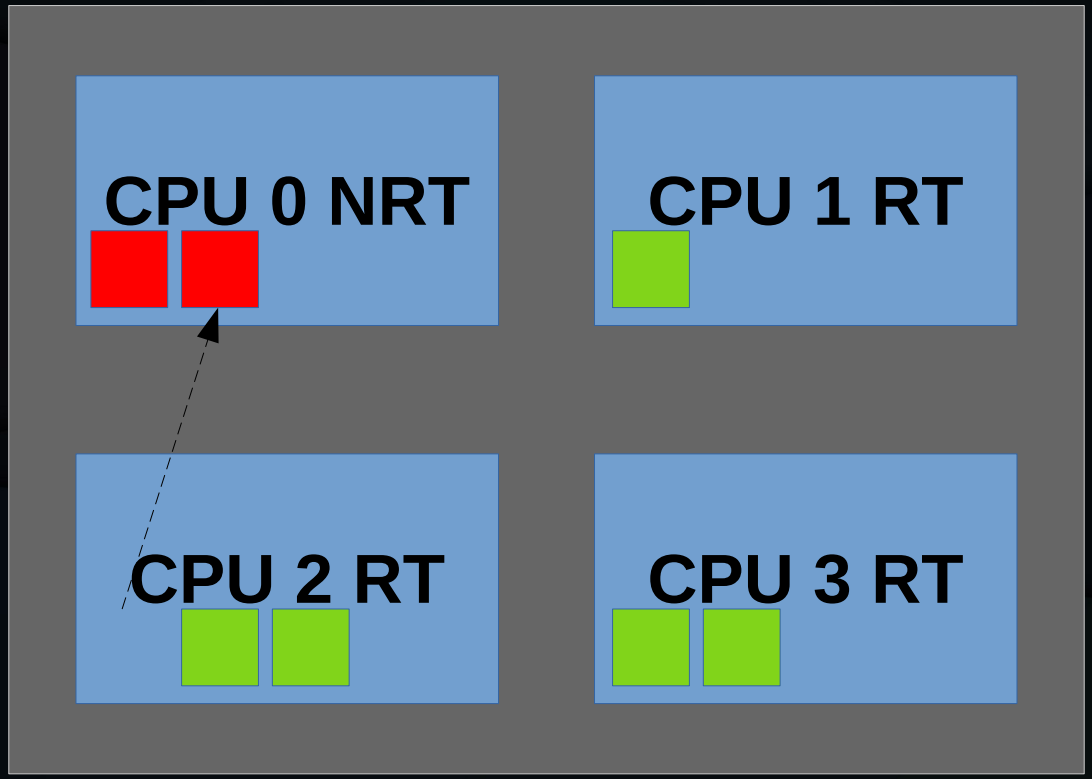

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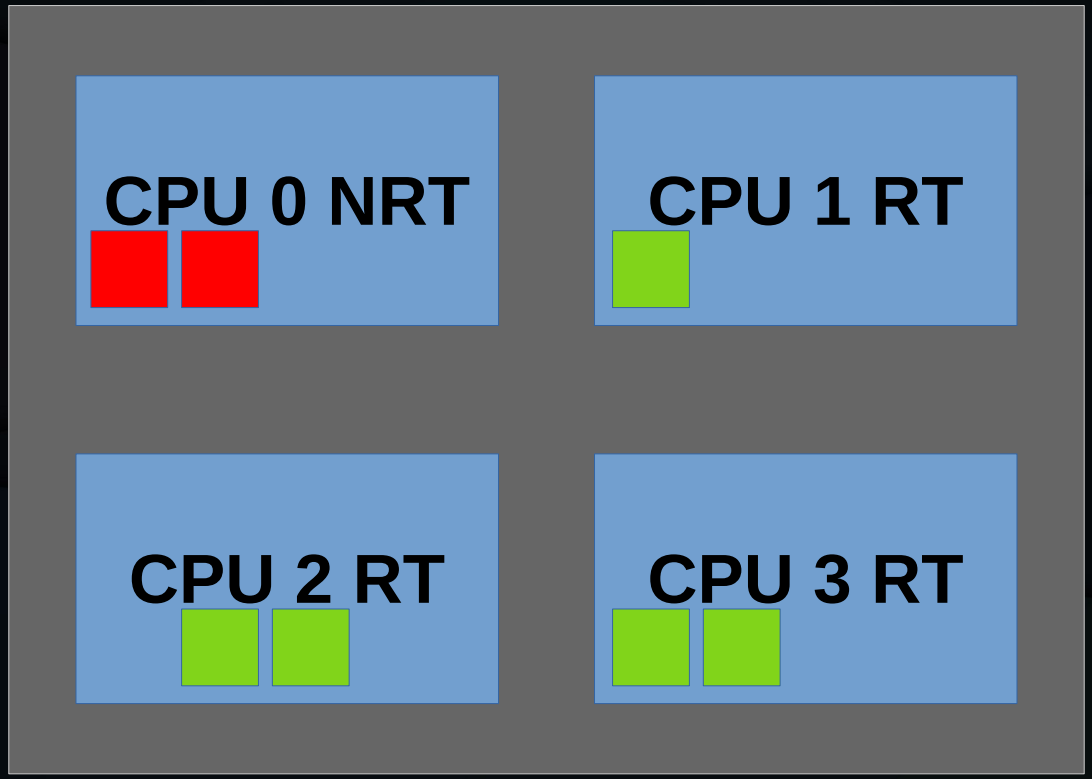

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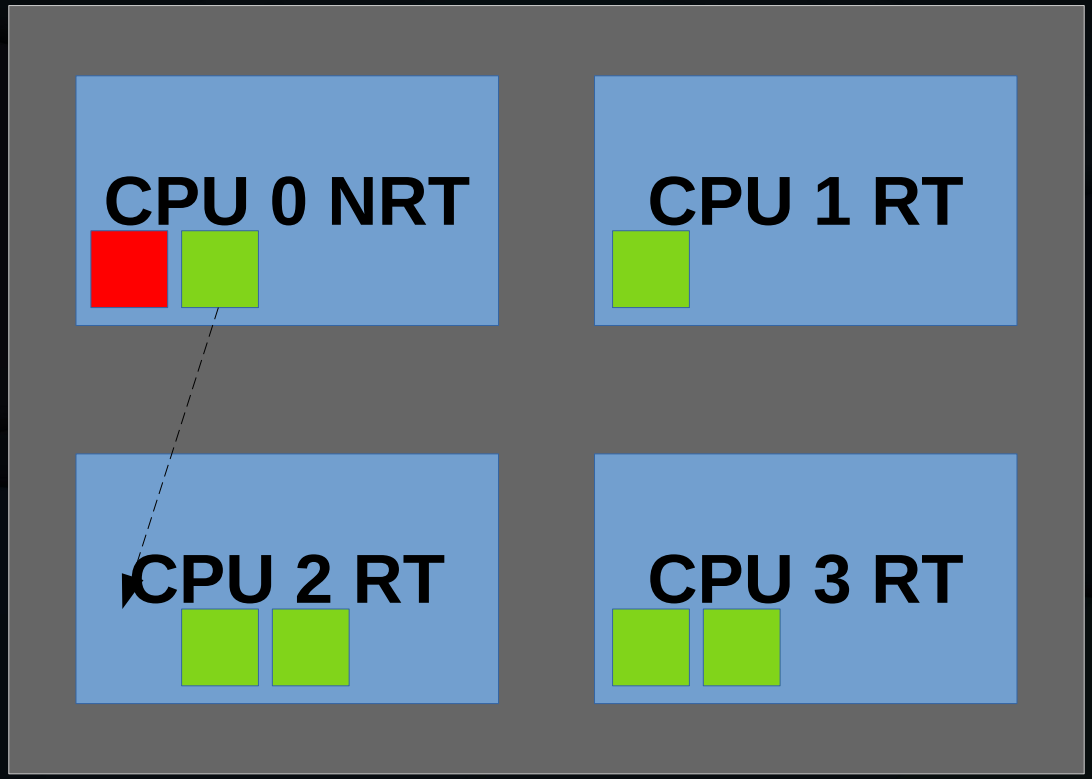
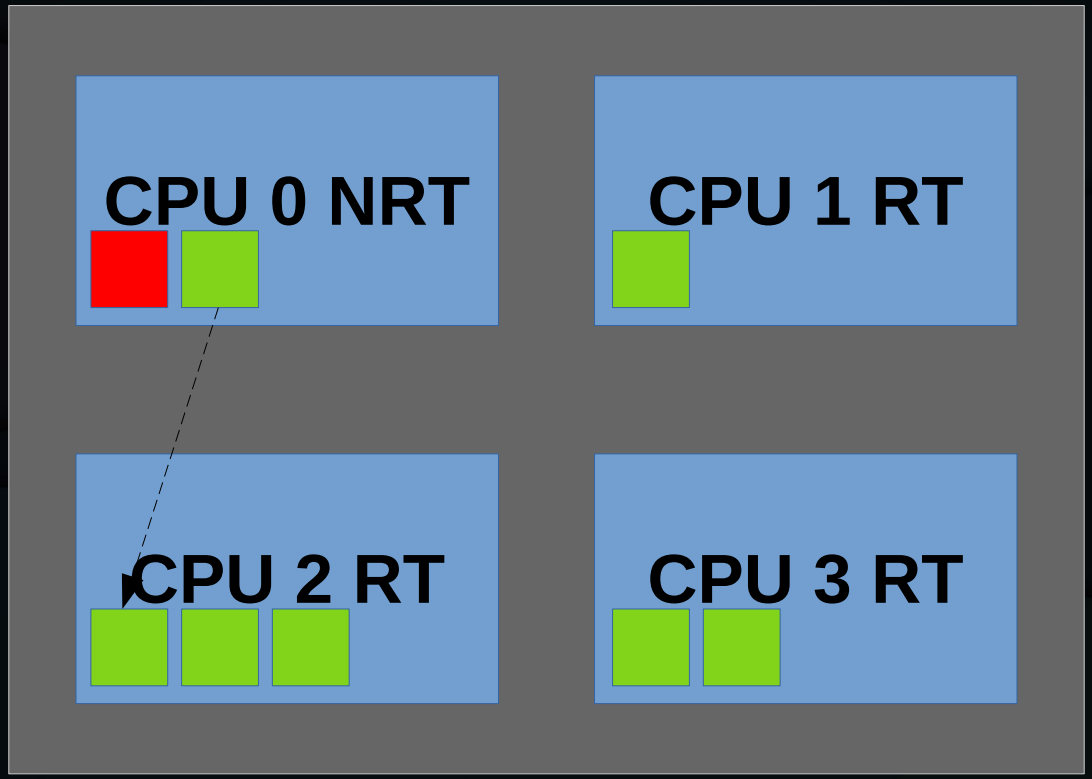


Respond to non-real-time activity by migrating.and back when done (system call).

Multicore Embedded for Real Time!!!



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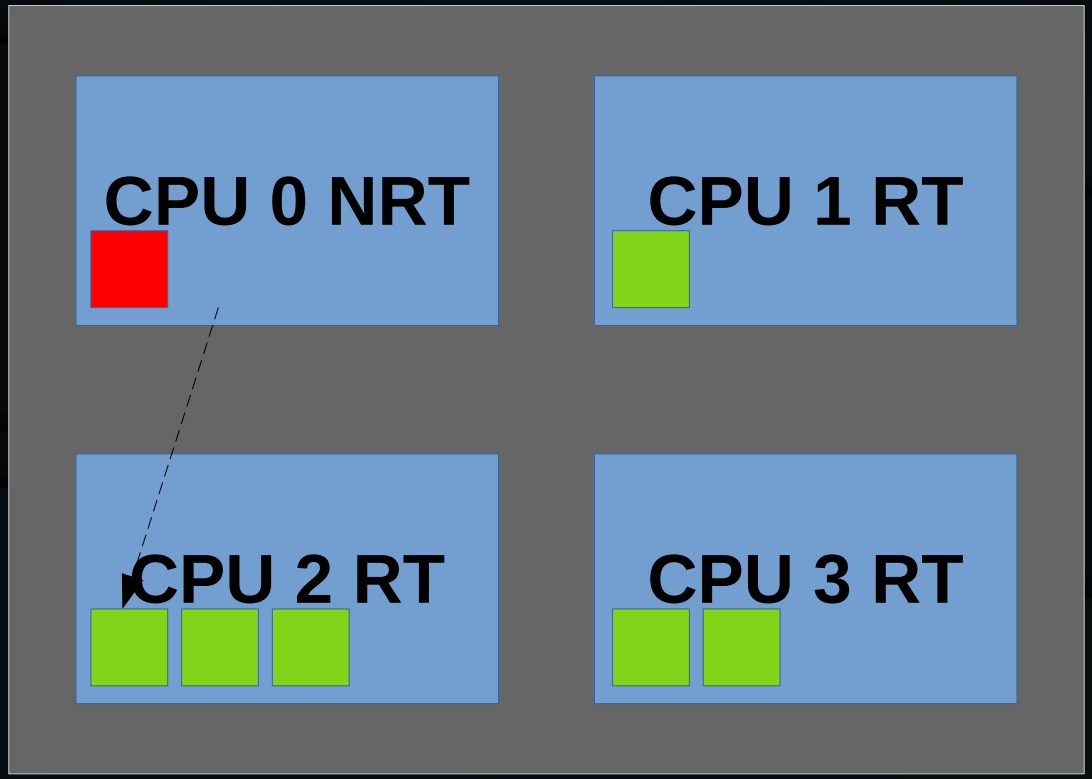

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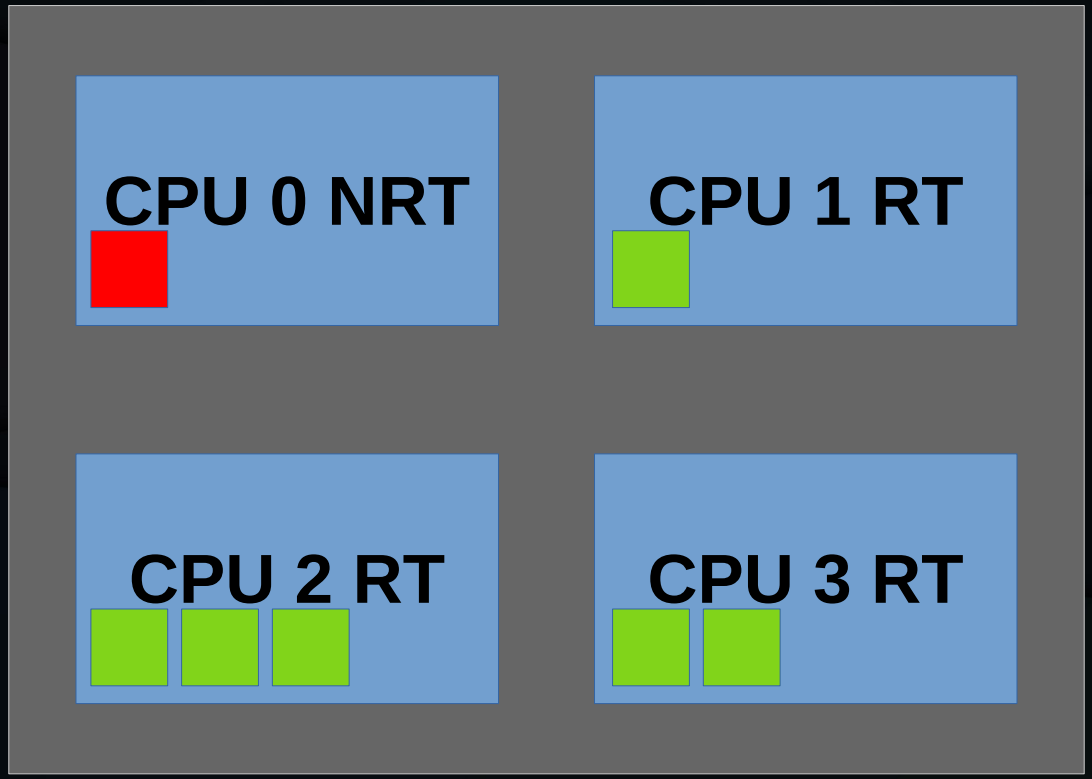

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Multicore Real Time Linux Actions

- Produce patch implementing syscall migration

Multicore Real Time Linux Actions

- Produce patch implementing syscall migration
- Test it out, works great!

Multicore Real Time Linux Actions

- Produce patch implementing sys[illegible]ion
- Test it out, works great!

There is a real-time effort spinning up.
But they are rewriting the kernel.
Pragmatism for the win!!!

Multicore Real Time Linux Actions

- Produce patch implementing syscall migration
- Test it out, works great!
- Inform executives real-time Linux is real!!!
- No more need for no-bid!!!

Multicore Real Time Linux Actions

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- And we win a large contract!!!

Multicore Real Time Linux Actions

- Produce patch implementing sys_call migration
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- Inform executives re[illegible]e Linux is real!!!
- No more need [illegible]o-bid!!!
- And we win a large contract!!!

My idea is rejected!!!

Multicore Real Time Linux Actions

- Why was my brilliant idea rejected?

Multicore Real Time Linux Actions

- Why was my brilliant idea rejected?

Photo credit: National Museum of the U.S. Navy, 2016, Public Domain Zumwalt-class DDG destroyer

Multicore Real Time Linux Actions

- Produce patch implem[illegible]g [illegible]al[illegible]igration
- Test it out, works
- Inform executi[illegible]nux is real!!!
- No more n[illegible]
- And we wi[illegible]ge [illegible]ntract!!!

Rejected!!! Except that we have contractual commitments to meet...

Multicore Real Time Linux Actions

- patch implem ng a all igration
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Remember that rewrite-the-kernel effort?

Except that we have contractual commitments to meet

Multicore Real Time Linux Actions

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Remember that rewrite-the-kernel effort?

Well, I helped them with RCU

Excep cted!!! we have

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to k

Multicore Real Time Linux Actions

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Remember that rewrite-the-kernel effort?

…cted!!! …we have …mitments

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Three from-scratch implementations

E…

contra…

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Formal Verification

Formal Verification: Why Bother?

Installed Base

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

Installed Base

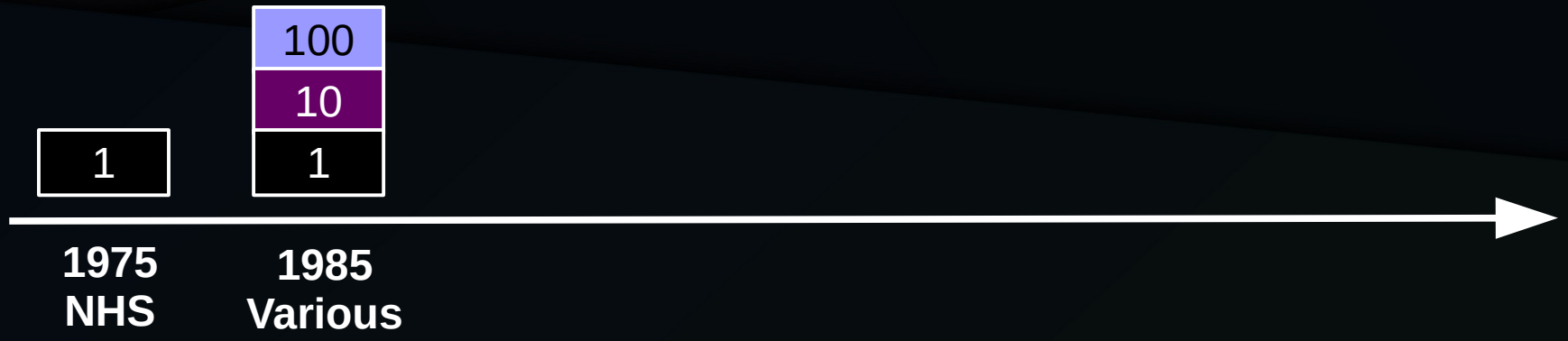
Million-Year Bug? Once In a Million Years!!!
Murphy is a nice guy: Everything that can happen, will...

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

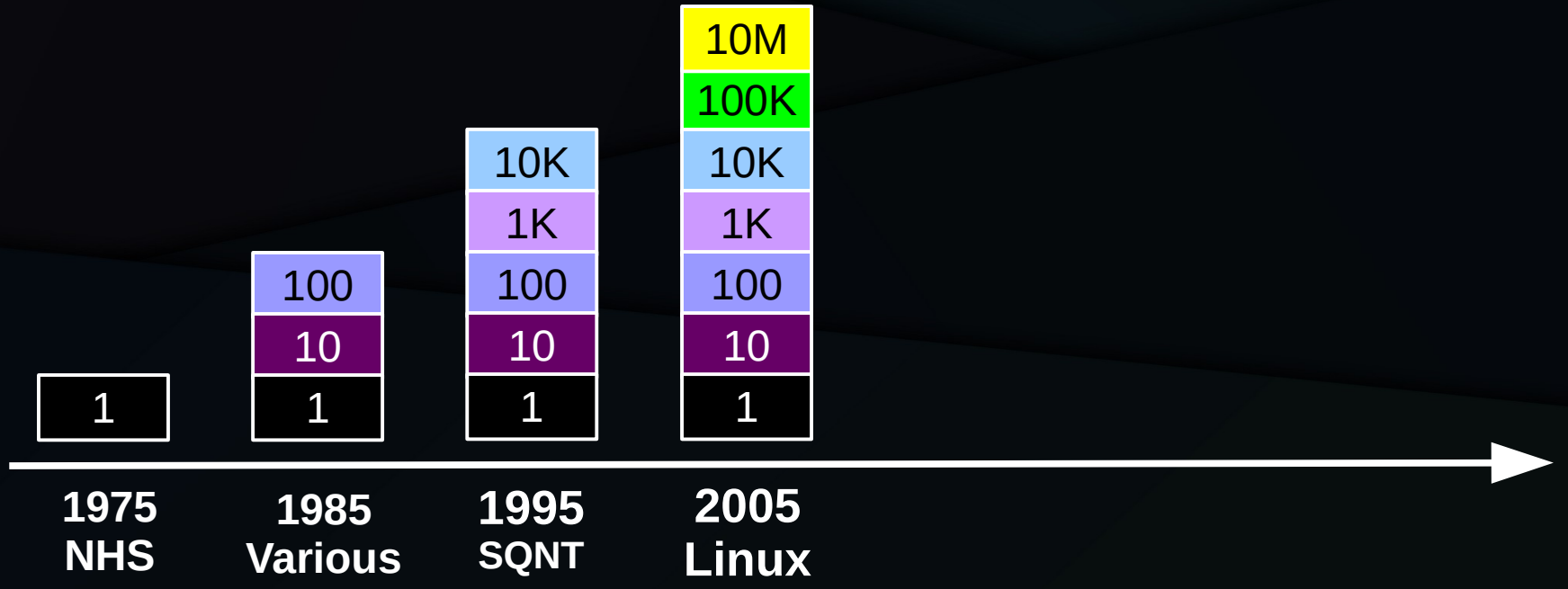


Installed Base

Million-Year Bug? Once per Century

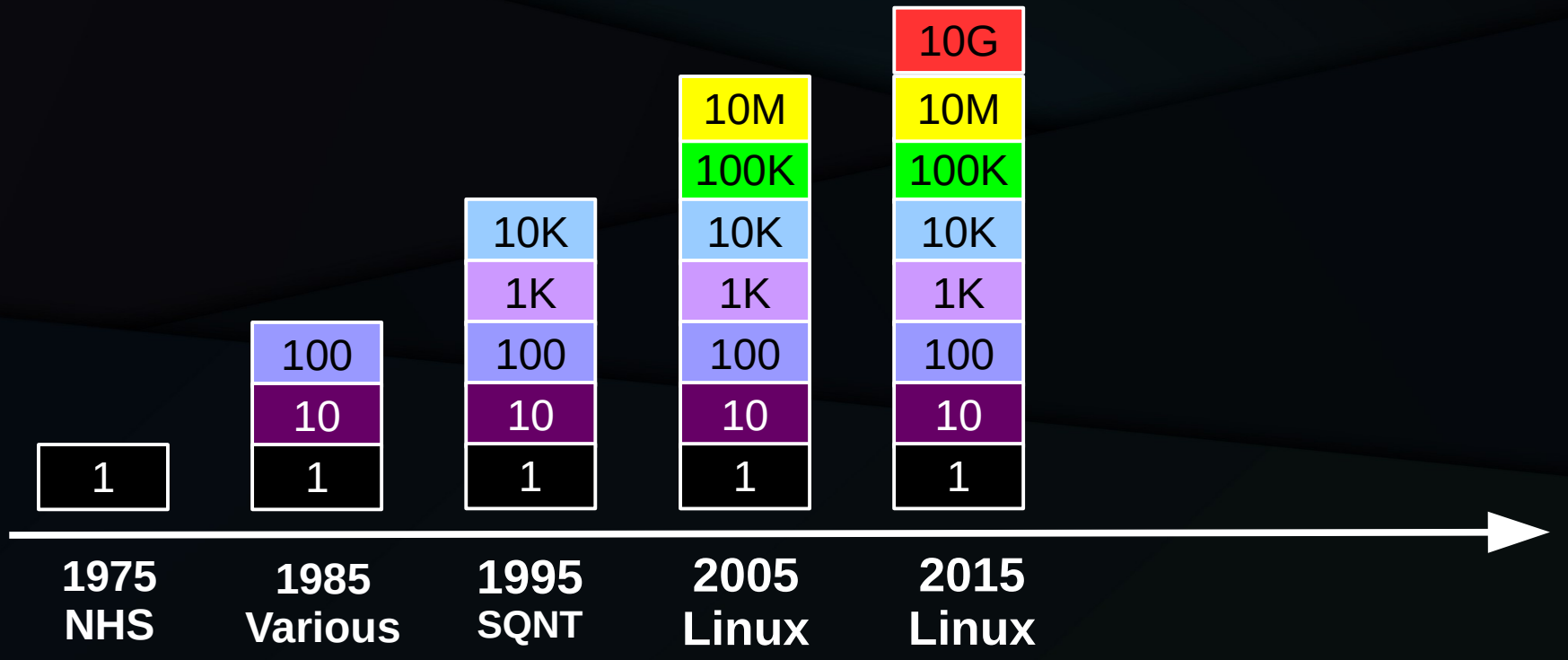
Installed Base

Million-Year Bug? Once a Month



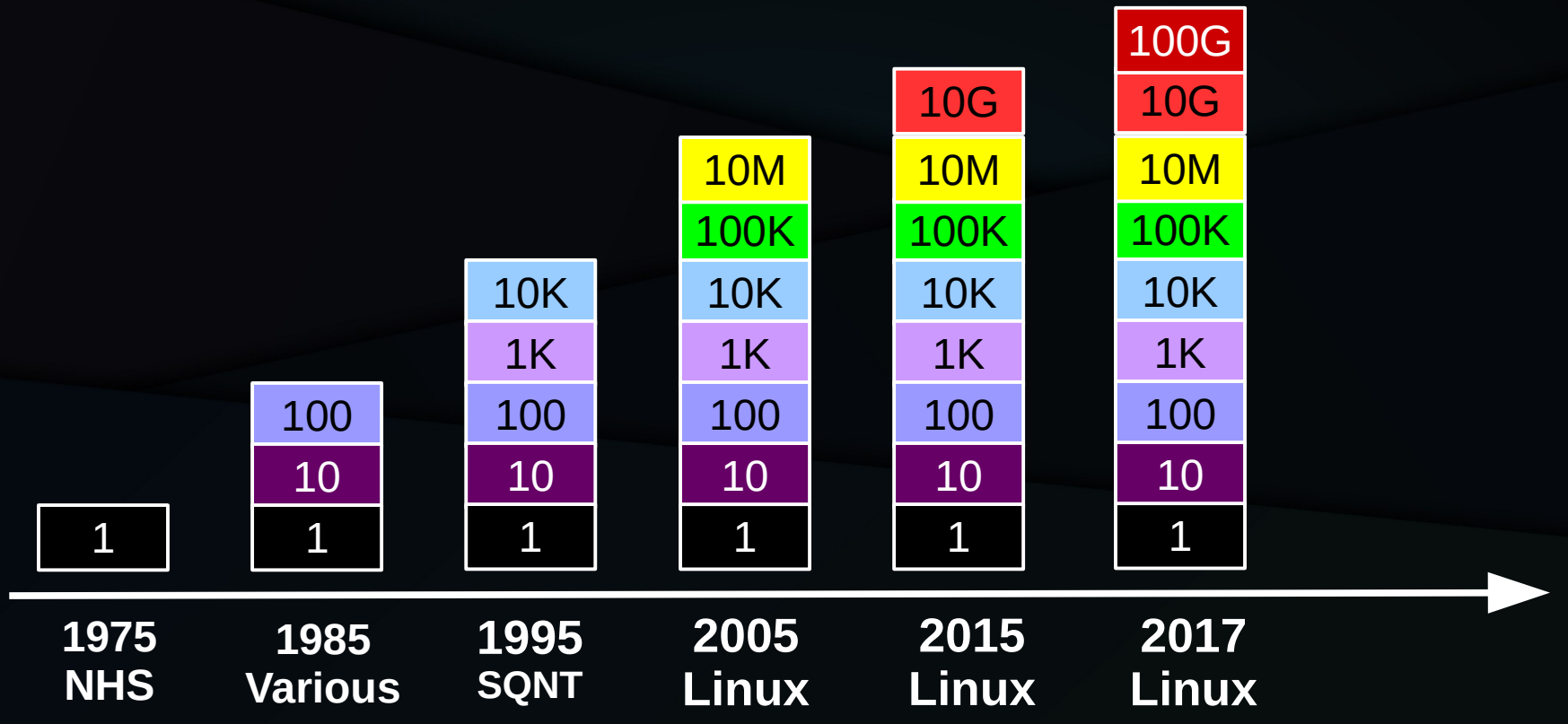
Installed Base

Million-Year Bug? Several Times per *Day*



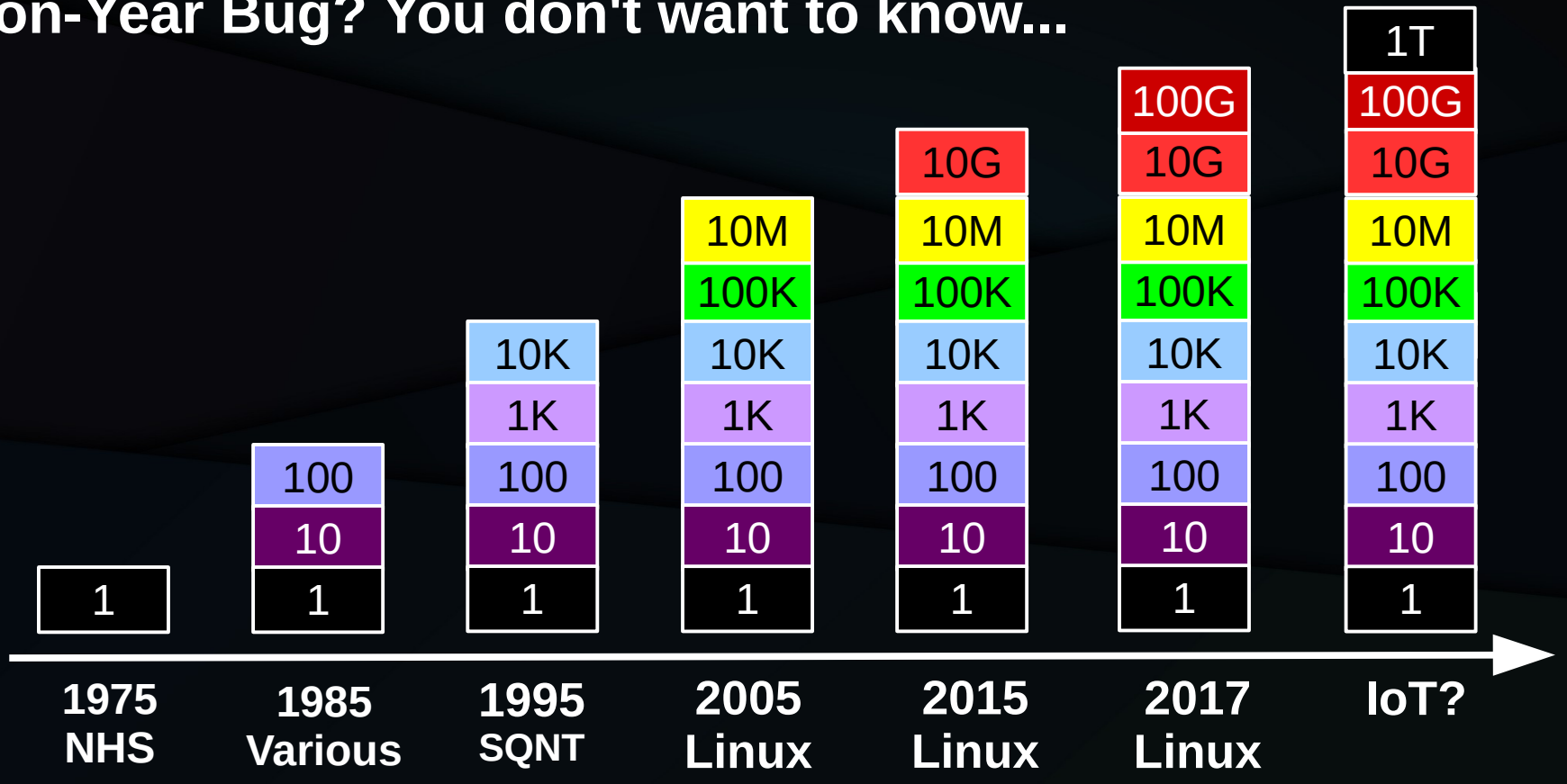
Installed Base

Million-Year Bug? Several Times per *Hour*



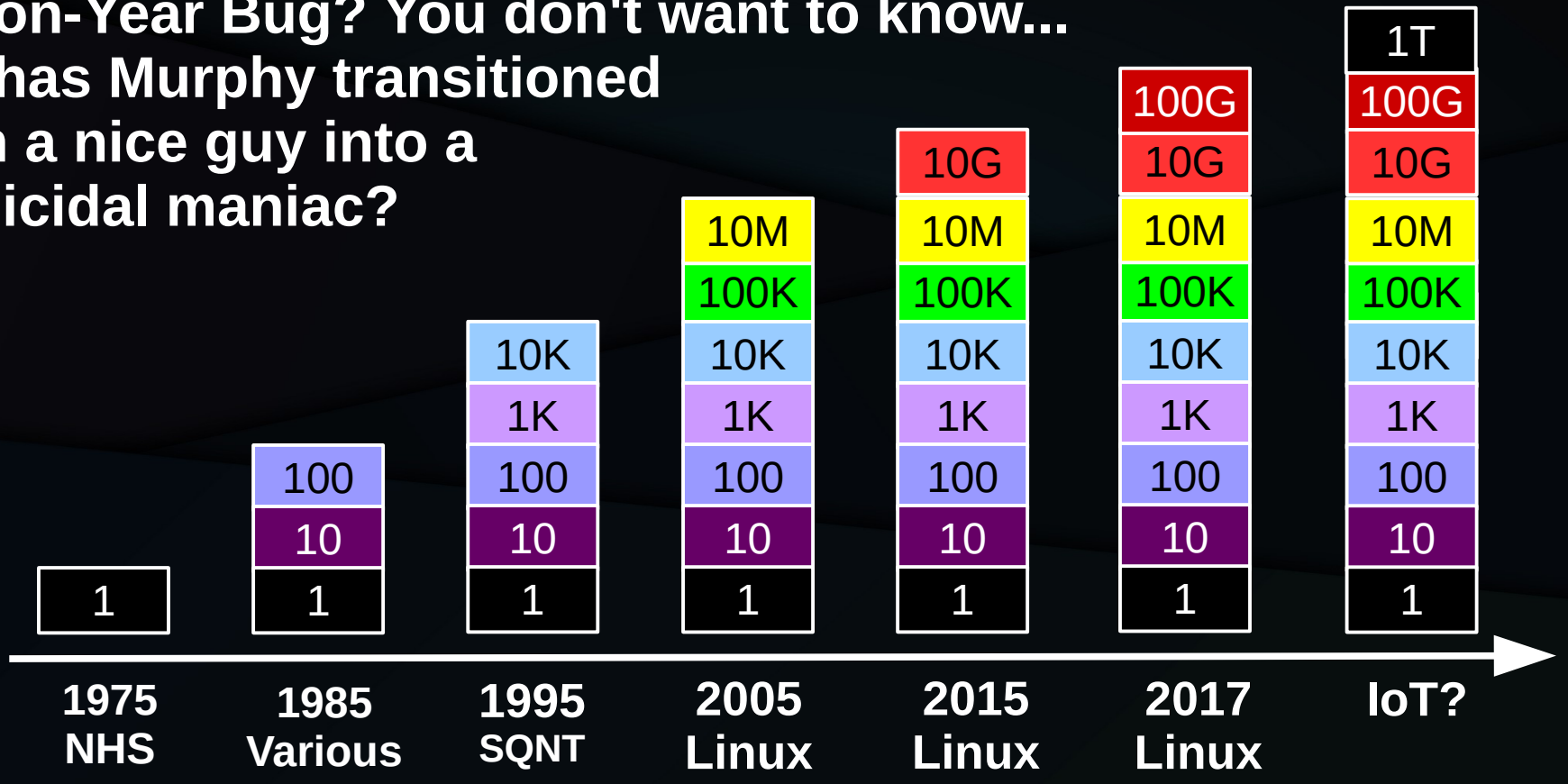
Installed Base

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?



Formal Verification: Why Bother?

- 2017: 20 billion instances of the Linux kernel
  - Million-year MTBF bug fails >50 times per day
  - New kernel version every 2-3 months
- Testing really is feasible for low-duty-cycle devices
  - But not for the ~80 million servers!!!
- Plus Linux is used in safety-critical applications!!!
- Full state-space search is quite attractive

Formal Verification Experience

- 1993: Promela/spin election algorithm
- 2007: “Quick” RCU (QRCU) verification
- 2008: RCU idle-detection for energy efficiency
- 2012: Verify userspace RCU
- 2014: Verify RCU idle detection for NMIs
- 2018-on: Heavy use of herd7 and LKMM

Formal Verification Experience

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Verifying design, not regression testing

Formal Verification Experience

- 1993: Promela/spin election algorith
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- 2012: Verify user
- 2014: Verif tection for NMIs
- 2018: e of herd7 and LKMM

Verifying design, not regression testing

Verification valid after bug fix???

Formal Verification is *Expensive*

- At best, exponential; in general, undecidable
- “Macho” verification requires full specification
  - Which is large, thus containing lots of bugs!
- Successful formal verification highly restricted:
  - Small programs, simple properties of large programs, or execution-guided verification

Formal Verification is *Expensive*

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Powerful when used properly

Formal Verification is *Expensive*

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Powerful when used properly
How to verify the verification?

Formal Verification is Heavily Used

- Several test projects on the Linux kernel
- Many proprietary projects verify each commit
- But…
  - Formal verification in the small
  - Check for undesirable properties
    - File bug reports as appropriate

Formal Verification is Heavily Used

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De-risk via one-way bet

Cautionary Quote (Redux)

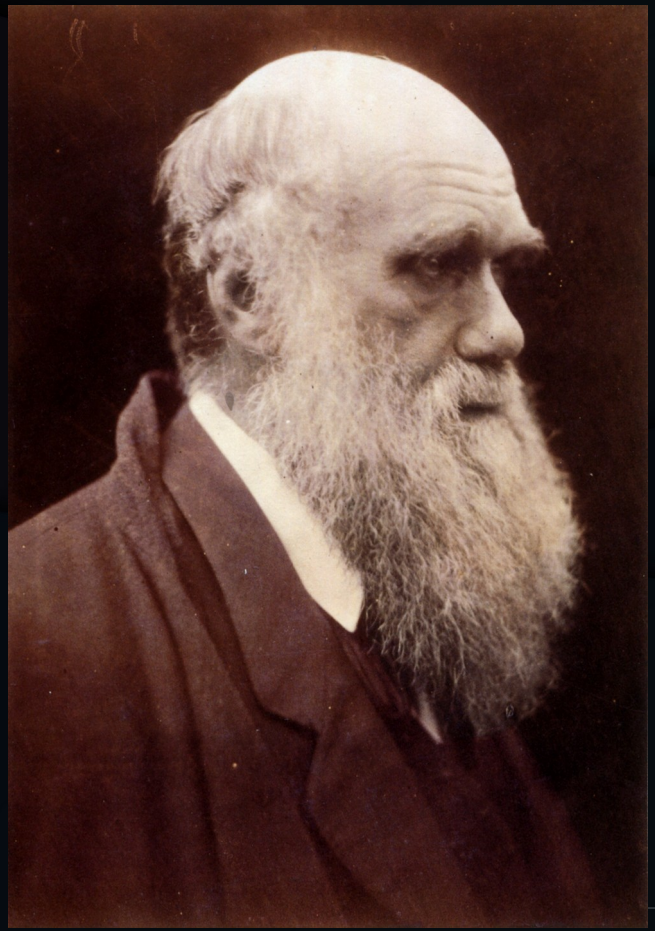
- A lot of success in life and business comes from knowing what you want to avoid. - *Charlie Munger*

Cautionary Quotes

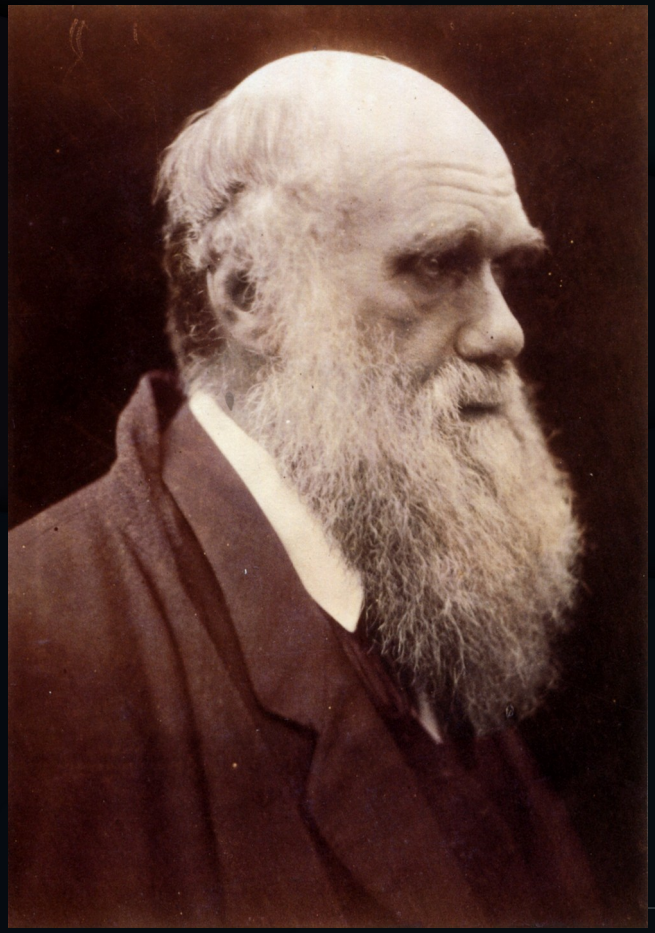
- Sometimes you don't even know what you want until you find out you can't have it. - *Meghan O'Rourke*
- Sometimes we don't know what we want until we don't get it. - *Sloane Crosley*
- We don't know what we want, but we are ready to bite somebody to get it - *Will Rogers*

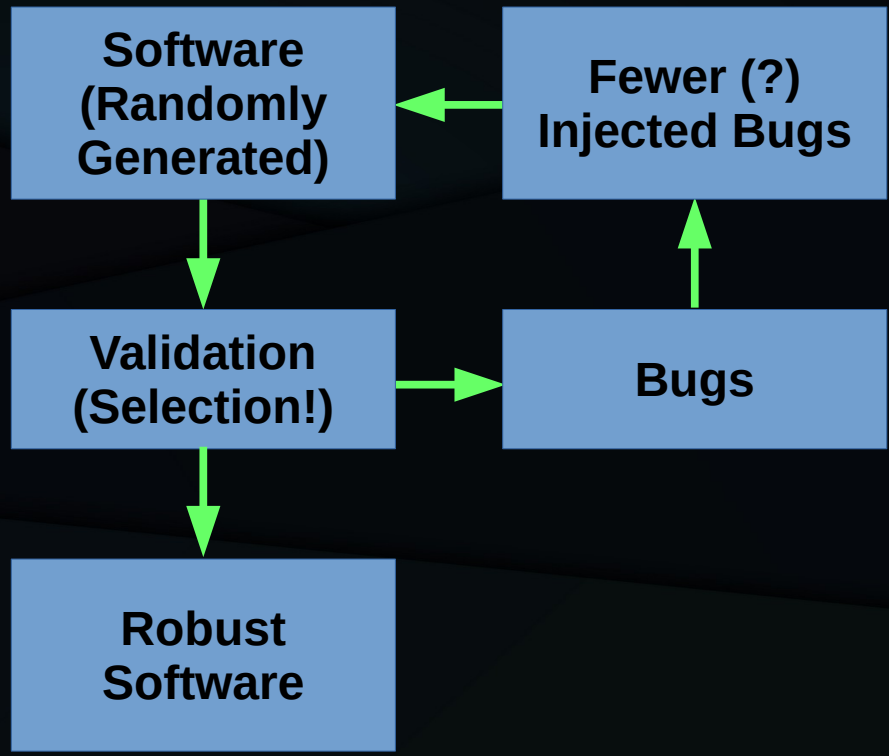
Natural Selection

Natural Selection



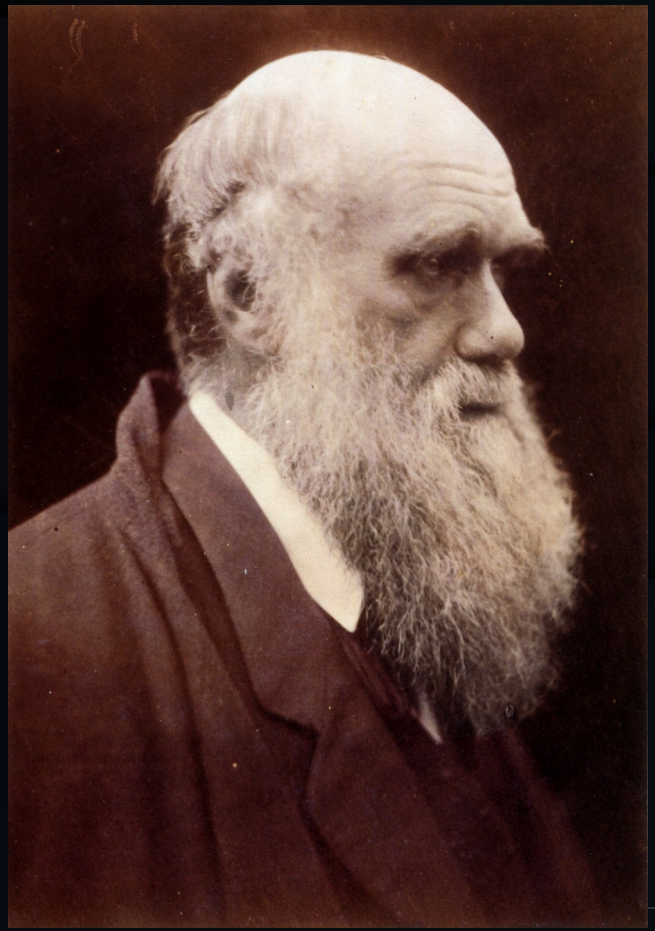
Natural Selection: Not Just Lifeforms

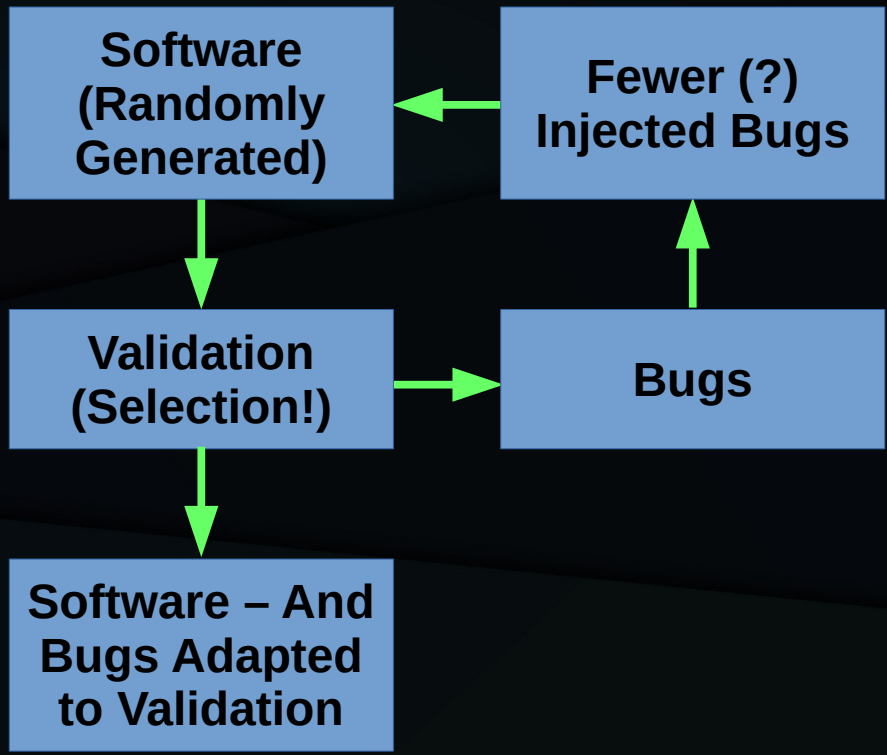




Agile methods attempt to push this methodology back to the specification

Natural Selection: Bugs are Software!





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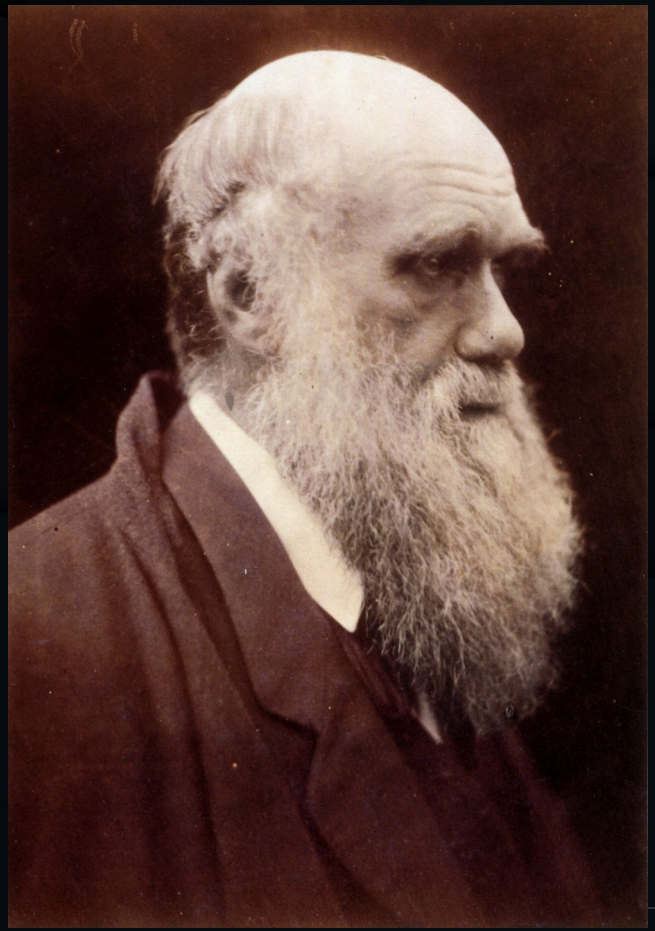
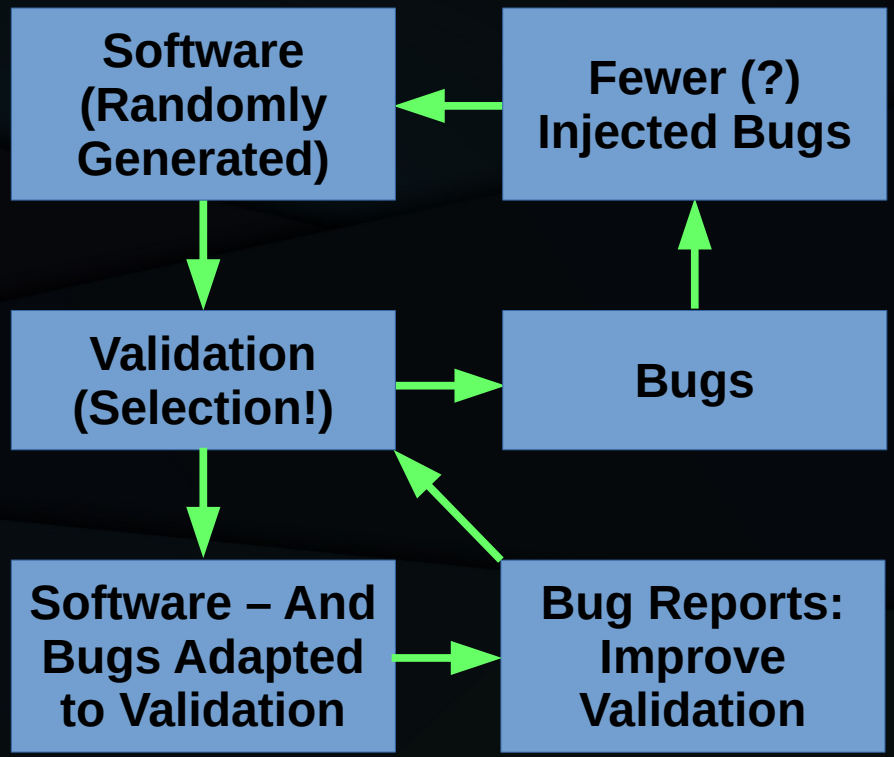
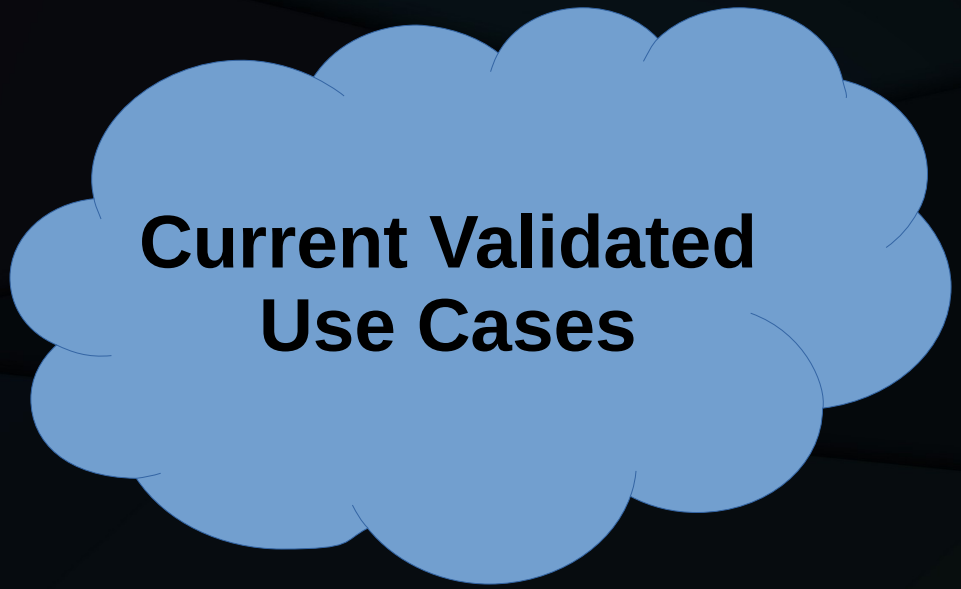


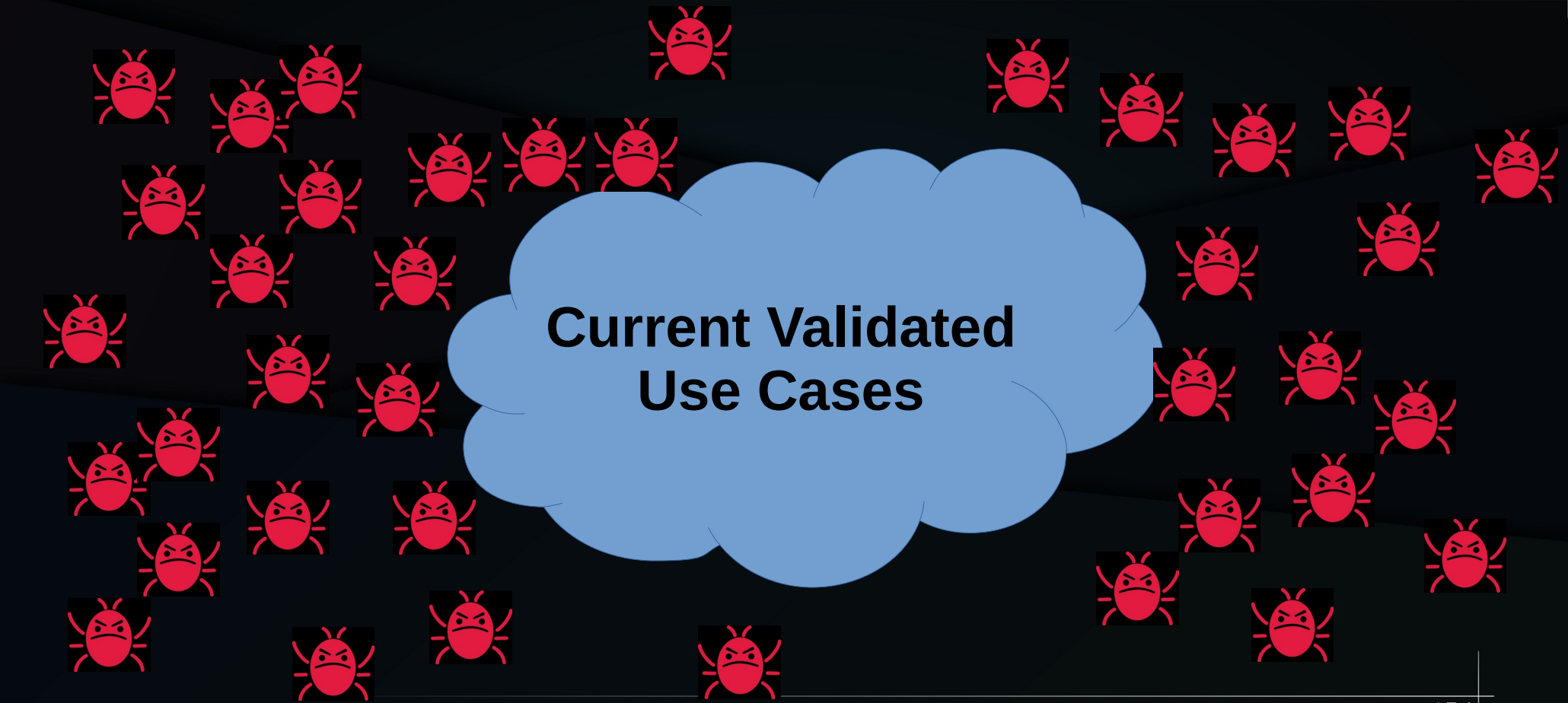


Validate Only Intended Use Cases

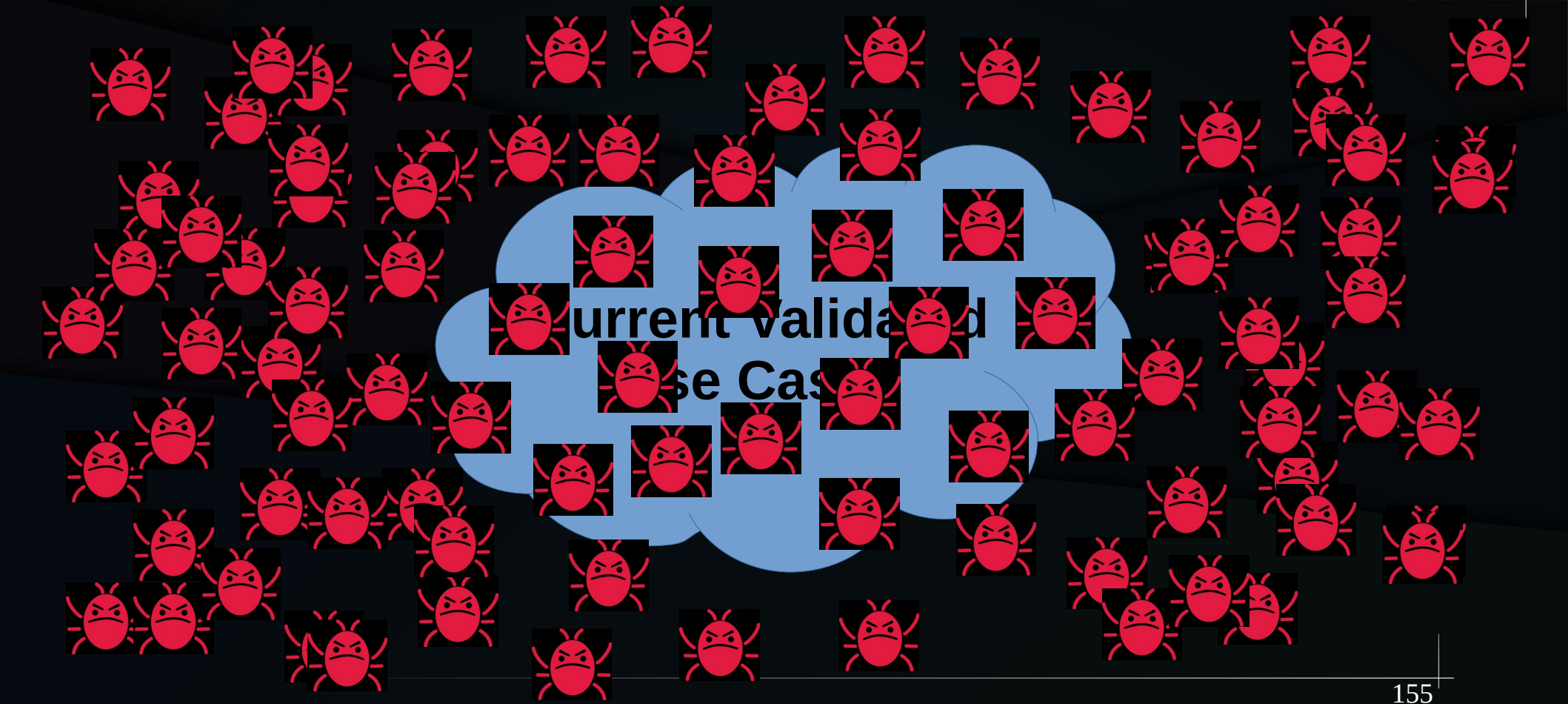


Major Development Generates Bug

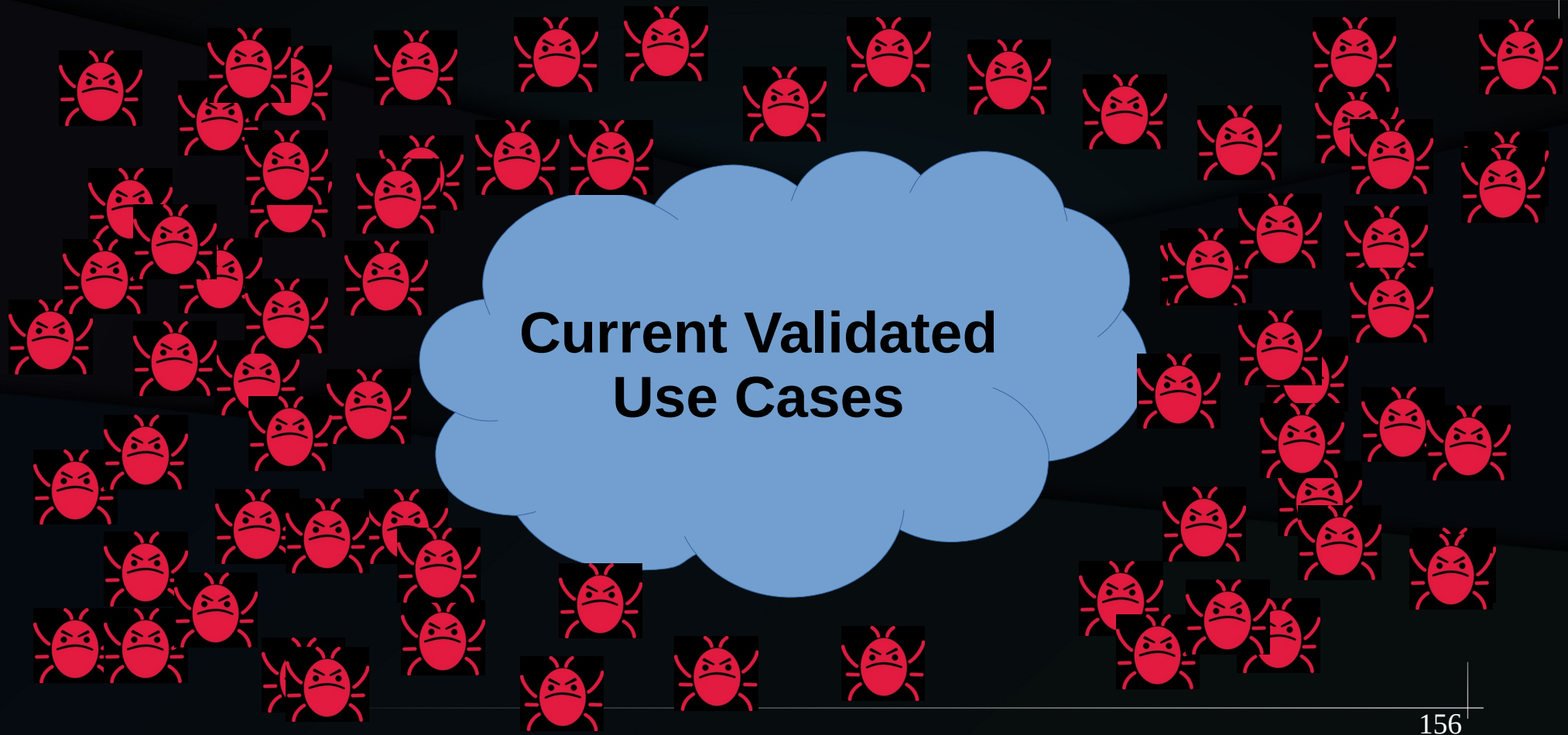
After Validation and Bug Fixing



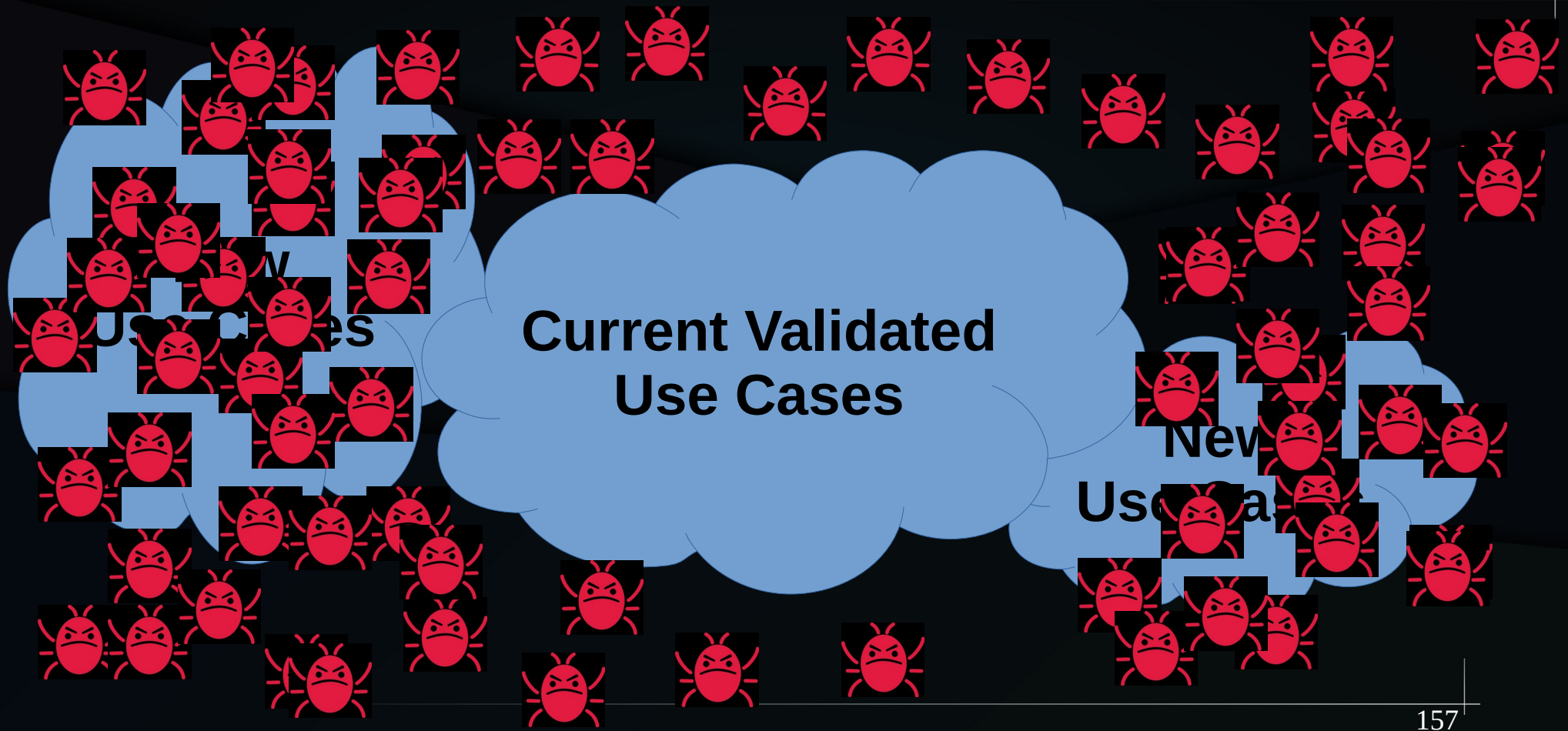
After Another Round of Development



More Validation and Bug Fixing



New Use Cases: Walls of Bugs!!!



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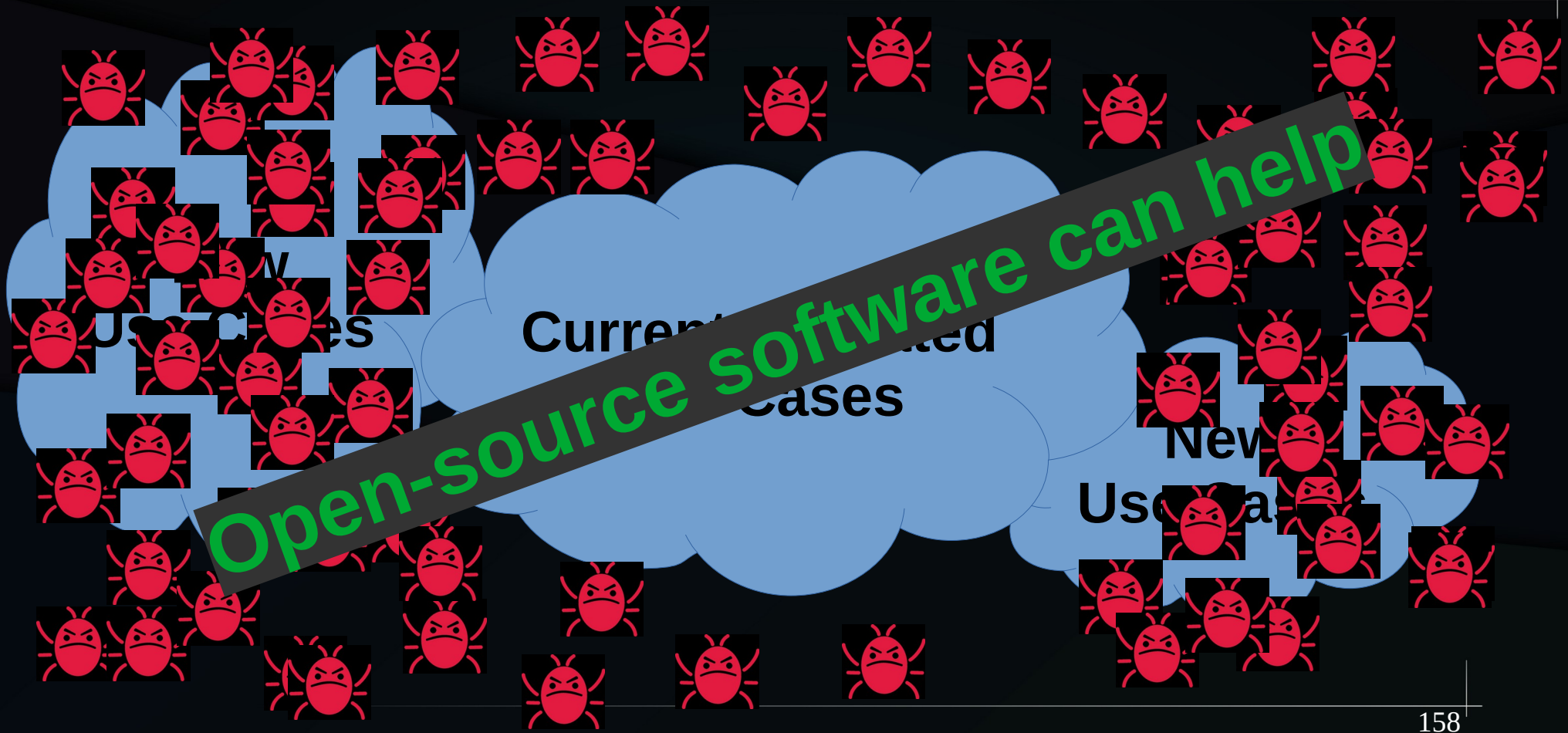

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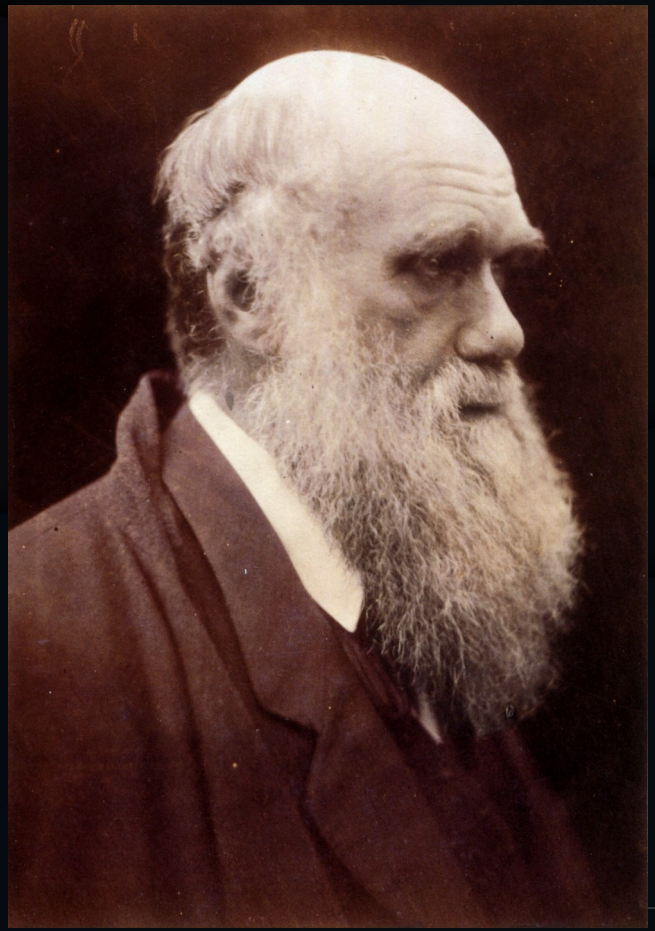

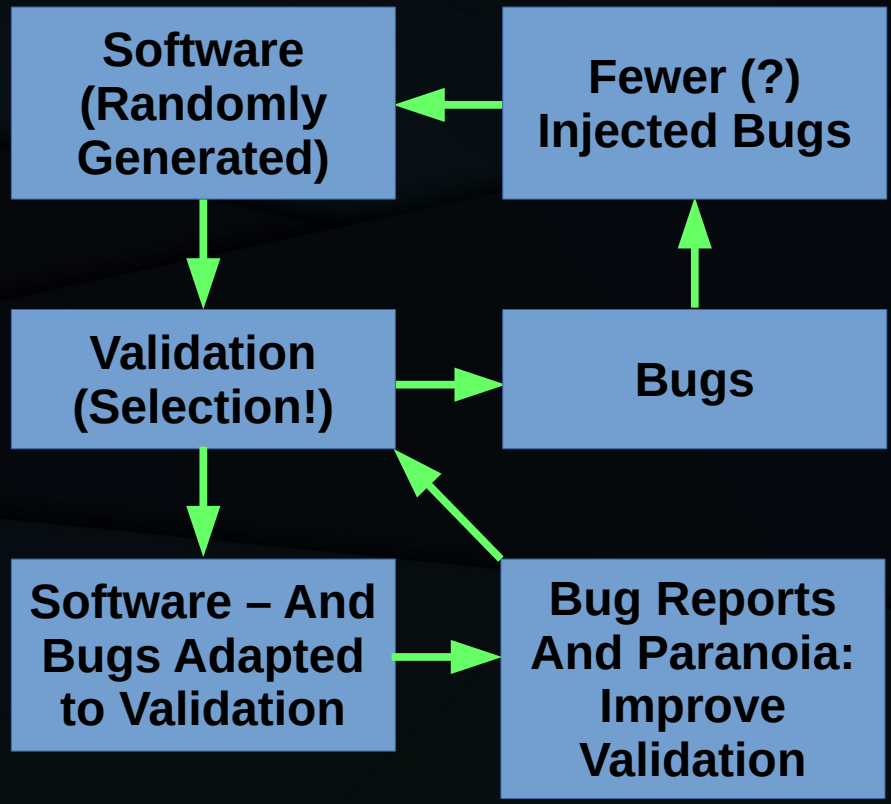

“Natural Selection” is a Euphemism

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If your tests are not failing, they are not improving your software

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If your users are not complaining, they are not improving your software

Why Would Users Fail to Complain?

- They don’t know who to complain to
- The last N times they complained:
  - Nothing useful happened
  - They were yelled at or otherwise belittled
- Your software is successful
  - And has thus “faded into the woodwork”

Cautionary Quotes

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You must live among your users

Cautionary Quotes

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You must live among your users
You must complain on their behalf

Summary

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- People don’t know what they want

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Summary

- People don’t know what they want
- But for software developers, this is no excuse
  - You have only failed if you have given up...until then it's called learning. - *Unknown*
  - You are not a failure until you start blaming others for your mistakes. - *John Wooden*

But I Had It Easy!

- High school class: IBM mainframe & HP Basic (1973-1976)
- University: Computer science & mechanical engineering, business applications (1976-1981)
  - Do the assigned work
- Contract programming (1981-1985)
- Systems administration and Internet research (1986-1990)
- Concurrent proprietary UNIX (1990-2000)
- Linux kernel concurrency and realtime (2001-present)

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  - Keep them out of court (or even out of jail)
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  - Make it fast and scalable (up to 64 CPUs)
- Linux kernel concurrency and realtime (2001-present)

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- Concurrent proprietary UNIX (1990-2000)
- Linux kernel concurrency and realtime (2001-present)
  - Make it many things...

But I Had It Easy!

- Linux kernel concurrency and realtime (2001-present):
  - Fast and scalable (up to 4096 CPUs)
  - Real-time response (sub-20-microsecond latencies)
  - Energy efficiency
  - Near-bare-metal efficiency to usermode applications
  - Robustness (20 billion instances)
  - Ease of use driven by security
  - Ease of administration (large data centers)

But I Had It Easy!

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Yes, I am proud of my accomplishments, but modern systems are far more complex and user-centric

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  - Ease of use
  - Ease of administration (large data centers)

My job is to provide reliable infrastructure

Yes, I am proud of my accomplishments, but modern problems are far more complex and user-centric

Questions?

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