Morpheus

Adaptive Defenses for Tomorrow's Secure Systems

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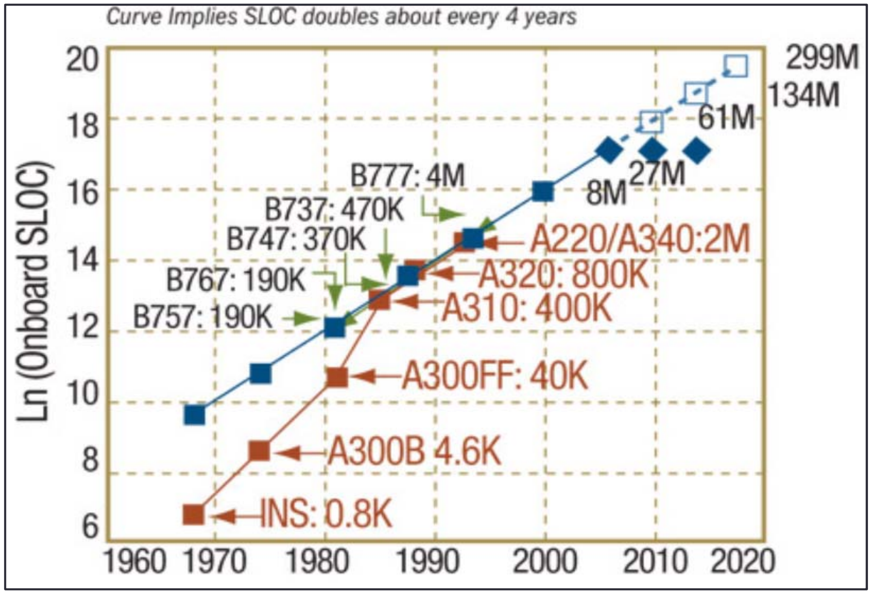
Assessing the State of Security

- Jeep hacked remotely while driving
- DHS attacks Boeing 757, details classified
- Pacemaker wirelessly infiltrated
- Mirai botnet disables DynDNS
- Entire baby monitor market hacked
- Atrium fish tank thermometer hacked

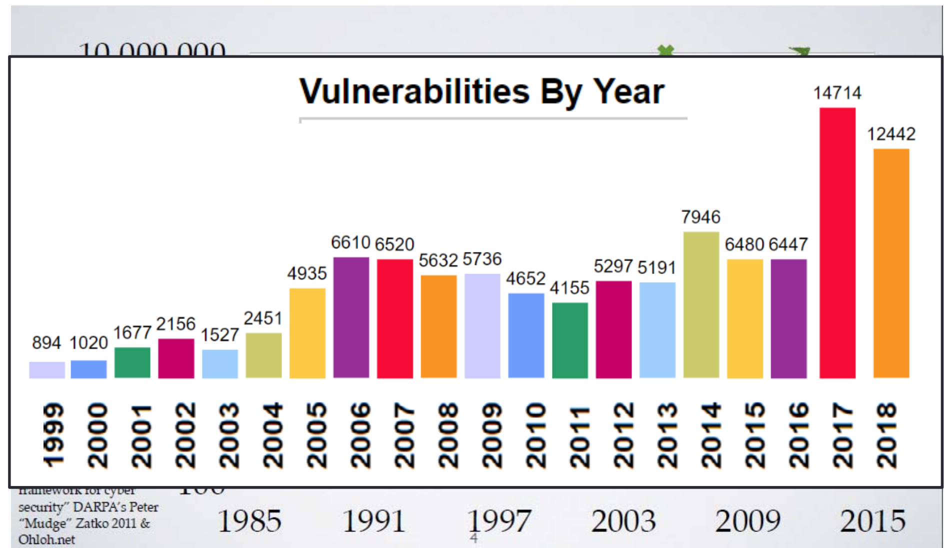
Why is Security So Hard to Get Right?

- Currently, a patch-based approach
  - Find and fix vulnerabilities
  - Complexity growth ***far outstrips*** security
  - Manual testing & analyses don't scale
- Endless ***security arms race***
  - Patch and pray…
- How do we protect against ***unknown (0-day) attacks***?
  - Anticipate the "unknown unknowns"



Attacking is Easy, Protecting is HARD

- ***Attacking is easier than protecting***
  - Attackers needs only ***one*** vulnerability
  - Protecting requires ***100% coverage***
- Related software growth rates:
  - Protections: doubles every 2 years
  - Malware: 40% growth in 30 years
- Vulnerabilities are on the rise
  - Rate of attacks is exploding



Durable Security: the Big Unsolved Challenge

- What we do well:
  - Finding and fixing vulnerabilities
  - Deploying system protections that stop well-known attacks

Valgrind

Synopsys' Coverity Tools

ARM's TrustZone

Intel's Control-Flow Enforcement

- Where we fail: ***identifying and stopping emergent attacks***

What If a Secure System Could...

- Respond lightning-fast against common attacks
- Self-adapt quickly to unknown emerging threats
- Learn and prioritize the most successful defense strategies
- Utilize a self-protecting distributed implementation

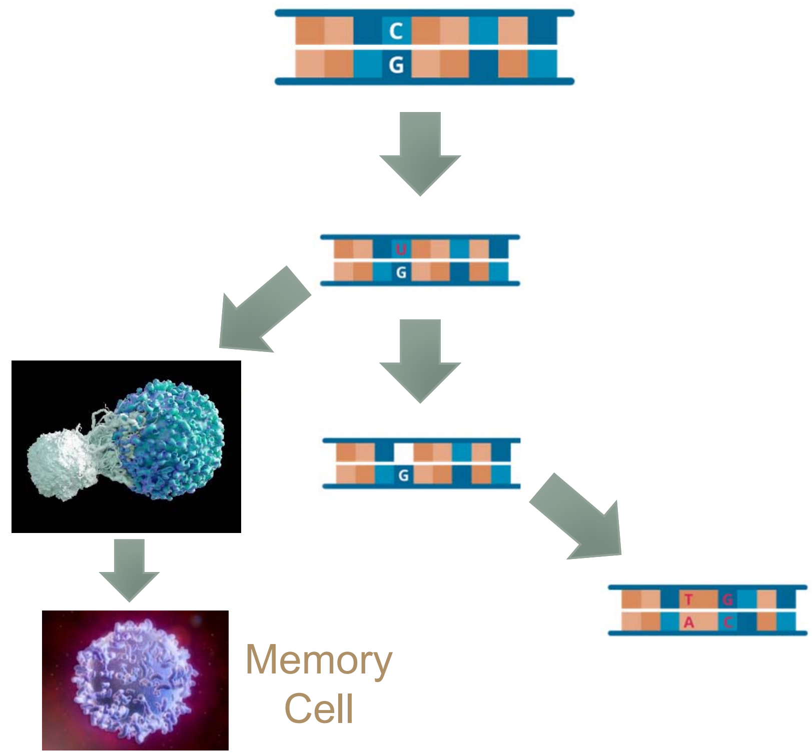
T-Cell Adaptive Immunity

Human Adaptive Immunity Primer

- T-cells receptors discern ***normal*** cells from ***malicious*** cells, via genetic markers
- To stop an unknown disease, T-cells undergo hypermutation that ***randomizes*** T-cell defense capabilities
- Boosted T-cell diversity will likely ***stop the pathogen attack***
- ***Immunological memory records successful T-cell variants*** to speed future recoveries

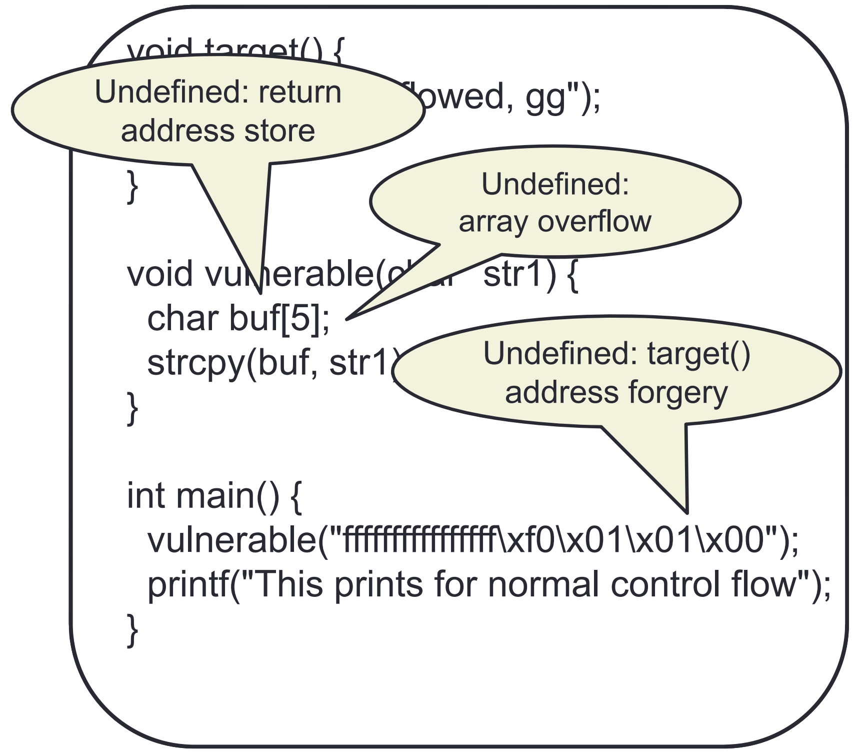
10^7 T-cell variants

10^{15} possible diseases



Morpheus Mimics Adaptive Immunity

- Morpheus attack detectors discern ***normal*** code from ***malicious*** code, via undefined semantics
- To stop an unknown attack, Morpheus ***randomizes*** a system's undefined semantics, a process called "churn"
- Churning undefined semantics ***stops security attacks***
- ***Learning mechanisms record successful defenses*** and stop future attacks quicker



Morpheus' Unique Approach to Security

Vulnerabilities + Implementation Assets = Exploit

Attack Detector

- Buffer overflow
- Code pointer arith
- Data pointer logical operation
- Code forgery
- Pointer forgery
- Uninitialized variable access
- Mem permission violation
- Integer overflow
- Shift overflow
- Code read
- Cyclic interference

→ or every 50 ms

Randomization Defenses (w/Churn)

- Code representation
- Code layout (absolute and relative)
- Code pointer representation
- Data pointer representation
- Data layout (absolute and relative)
- Function pointer representation
- Return pointer representation
- User enclave data representation
- Microarchitectural mappings

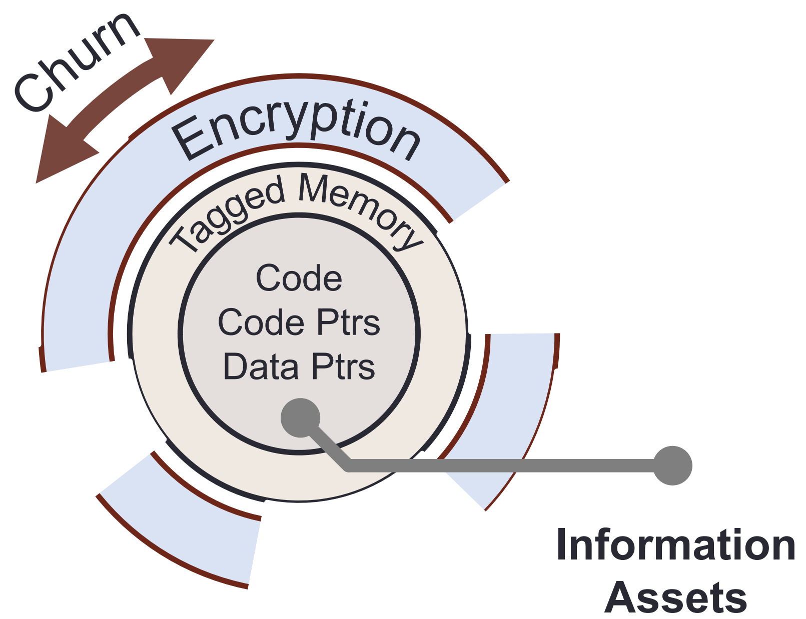
∞ 504 bits of true random entropy

Protecting Critical Assets with Encryption

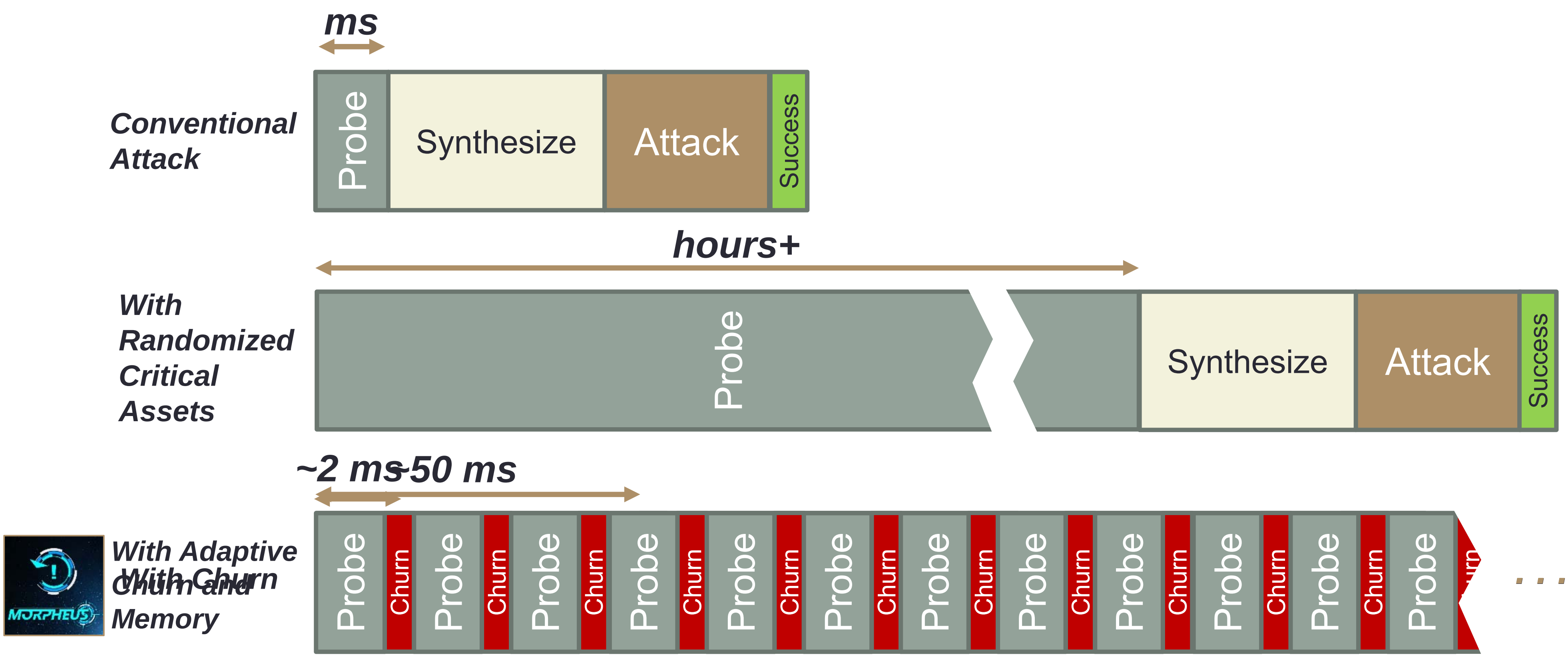
- Critical program assets are encrypted under their domain keys
  - Code, code pointers, data pointers
  - Decrypted at fetch, jumps and load/stores
  - Tracked at runtime using dynamic tagging

- Assets remain encrypted in registers, memory, buses, I/O
  - Requires strong ciphers in the pipeline

- Churn re-encrypts a domain under a new random key
  - Places a time limit on penetrating encryption

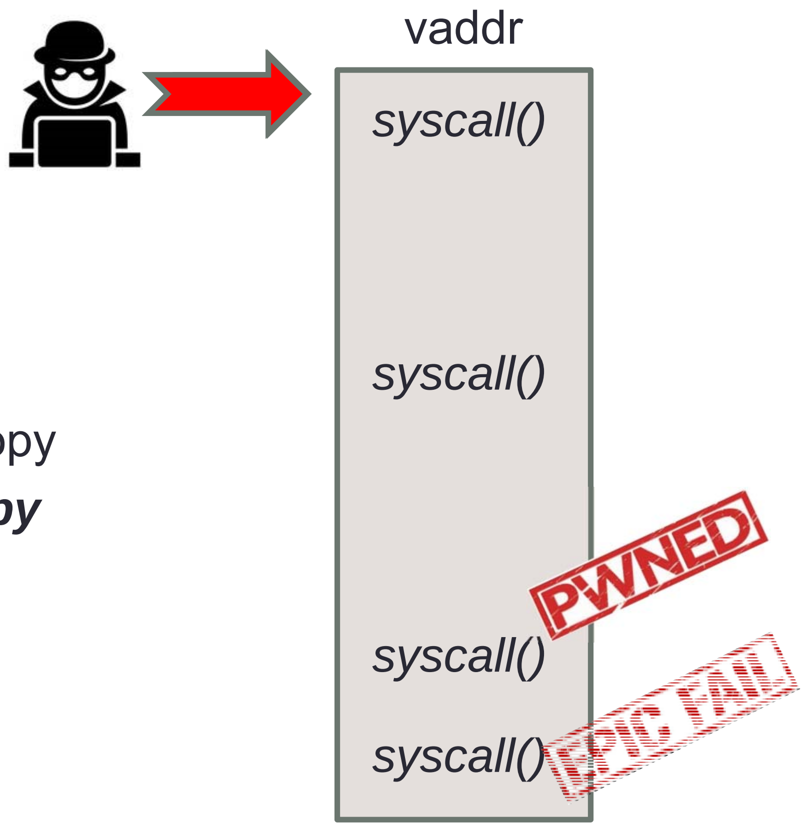


Morpheus Breaks Emergent Attacks



Fast Churn Defeats Probing

- Blind call attack example
  - Attacker attempts to call *syscall()*
- Attack success rate dependent on ***churn rate*** and degree of ***entropy***
  - State-of-the-art: no churn and low/high entropy
  - Morpheus: ***frequent churn*** and ***high entropy***
- H/W churn makes probes no more powerful than ***random guesses***
  - Impractically difficult with ***high entropy***



Morpheus Platform Details

Morpheus Secure Platform

S/W Ecosystem

- LLVM GCC/Binutils
- FreeRTOS
- Type Analysis
- Backend Metadata Emitter

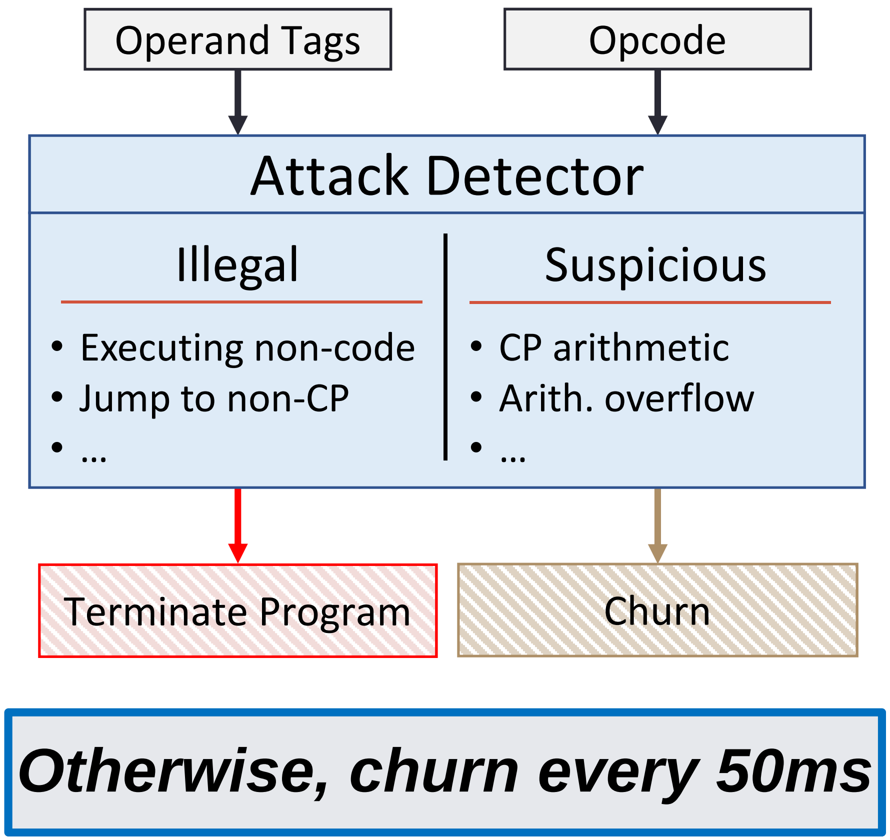
H/W Architecture

RISC-V

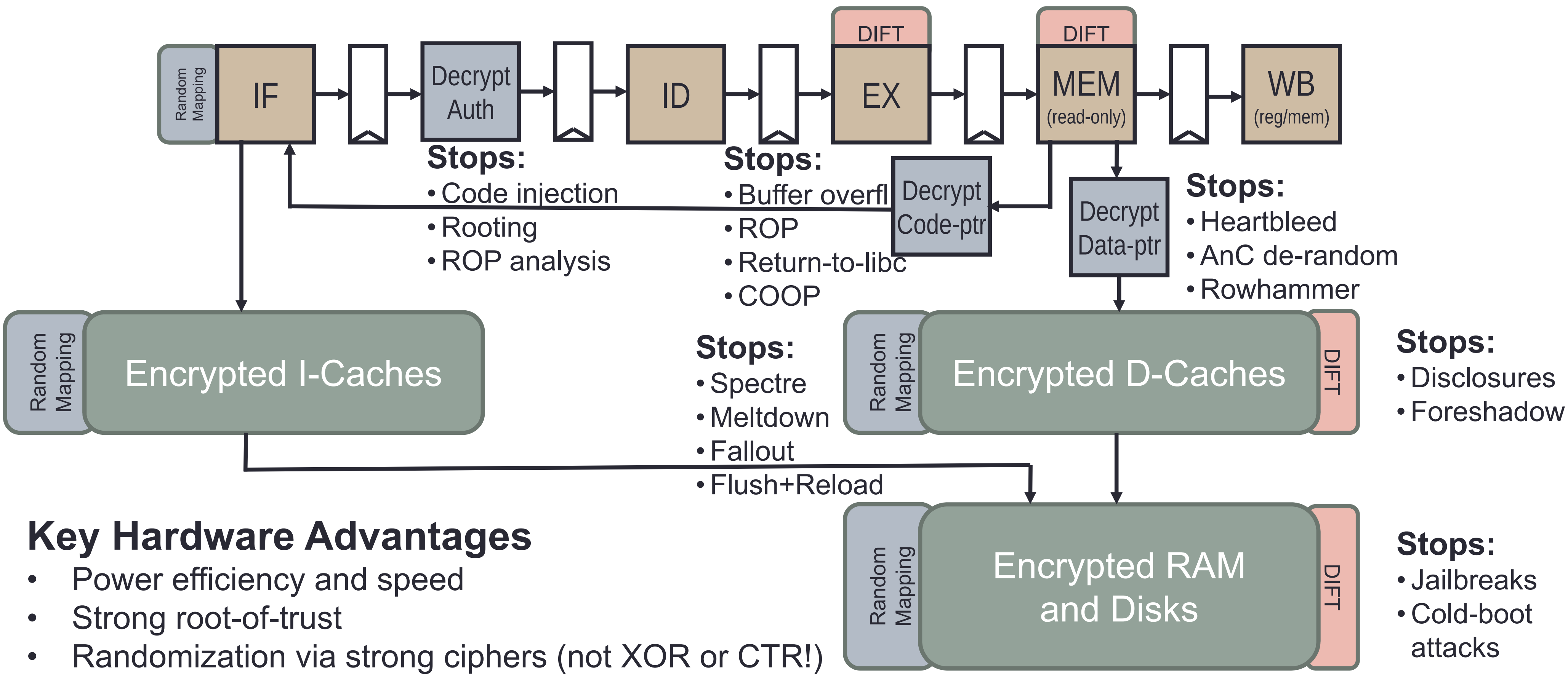
- 32/64-bit RISC-V Rocket Core
- Morpheus Defense Layers
  - Domain Encryption
  - Pointer Locking
  - Hard NULLs
- Tagged Memory
- Churn Unit

Tagging & Attack Detection

- Tags enable behavior tracking
- Illegal Ops
  - Clearly dangerous
- Suspicious Ops
  - Normal programs may perform
  - May be probes or attacks



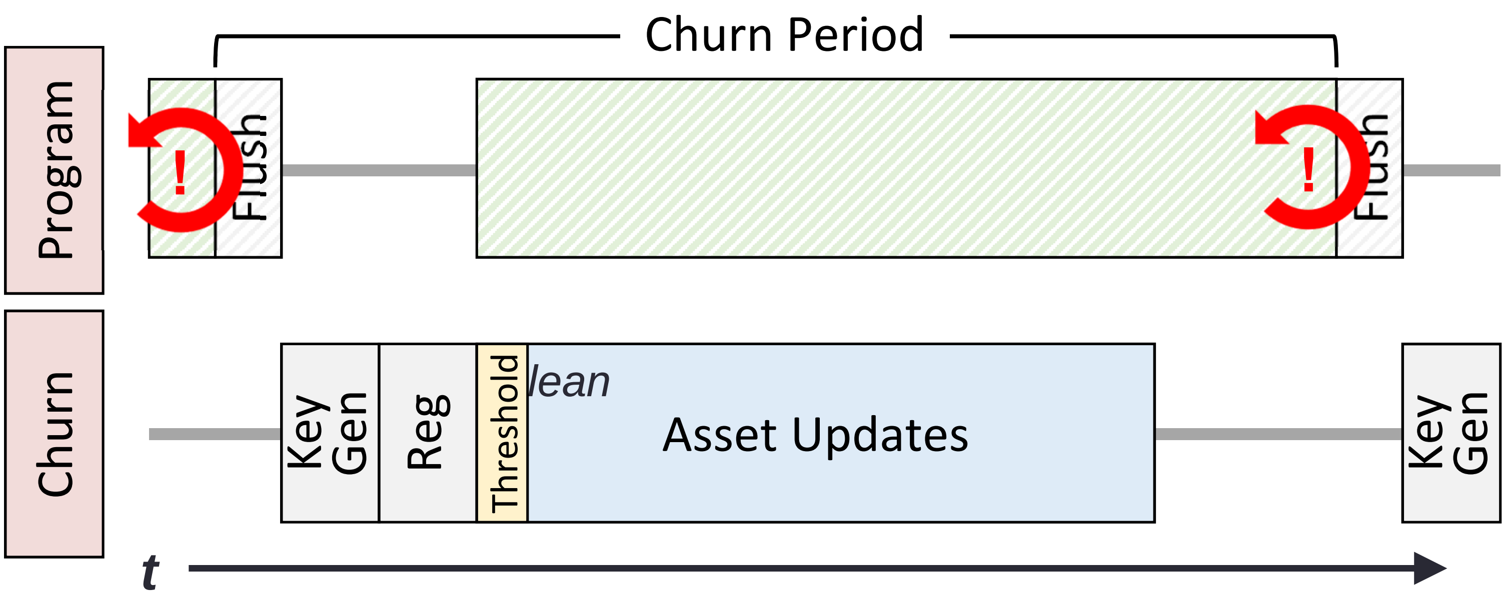
Morpheus Microarchitecture



Key Hardware Advantages

- Power efficiency and speed
- Strong root-of-trust
- Randomization via strong ciphers (not XOR or CTR!)

Churning Keys at Runtime



Stale: Under OLD key

Clean: Updated to NEW key

Assessing the Security of Morpheus

How long does it take to penetrate Morpheus defenses?

- Difficult to attack a system that is
  - Constantly changing
  - Has high entropy
- Approach: Attack a *weaker* Morpheus

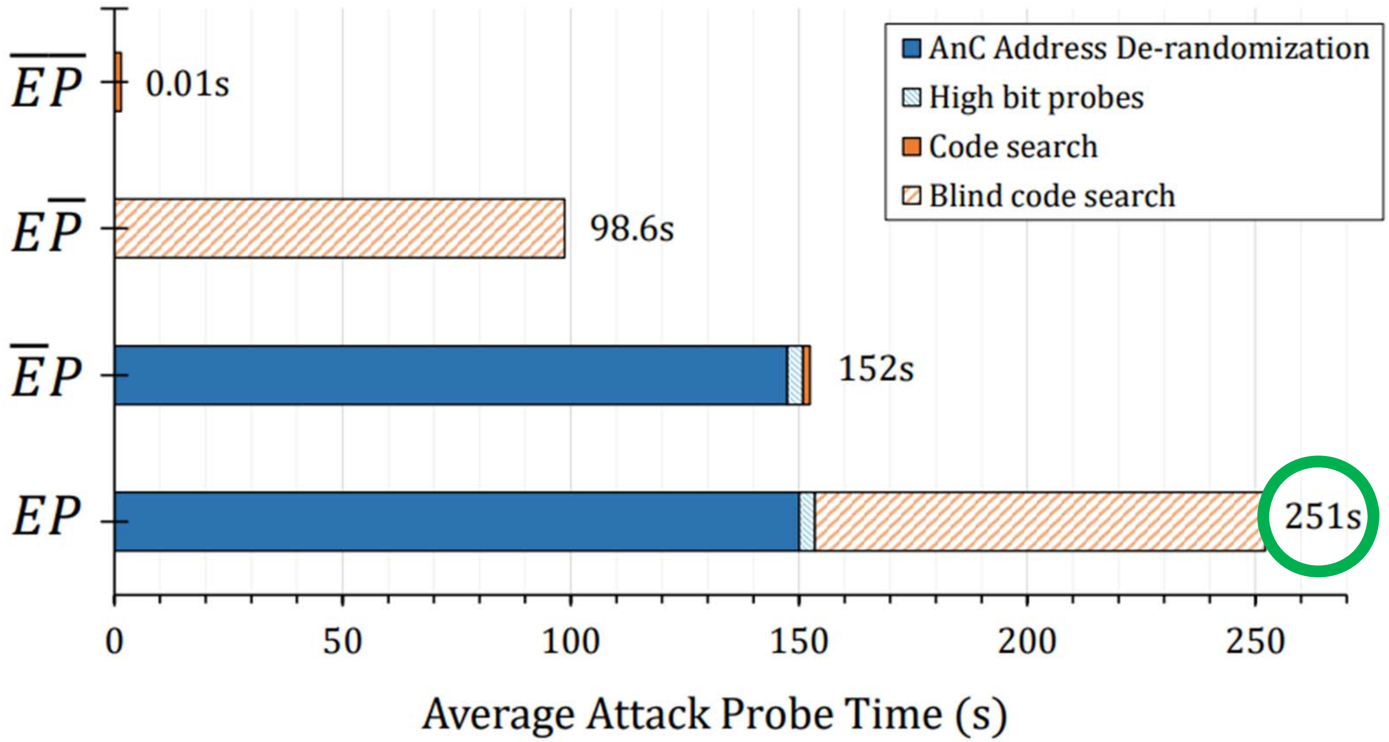
De-featured Morpheus

Churn Disabled

Shared Key for Defenses

Morpheus-- Penetration Testing Results

E == Domain encryption on (E) or off (E)
P == Pointer displacement on (P) or off (P)

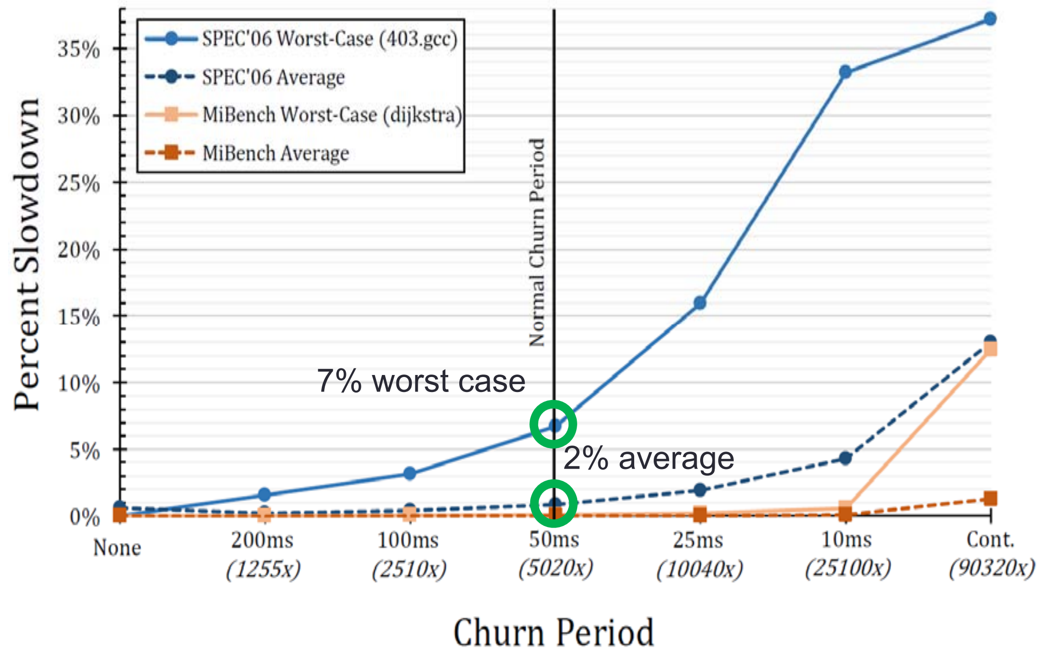


How Effective is Morpheus? Early Results

Analysis: RISC-V Morpheus on Gem5 simulated system

Early results:

- Performance cost: ***2% average slowdown*** with 504-bits of entropy and 50ms churn
- Power cost: ***2.5% power***
- Area cost: ***8% area*** increase
- Developer cost: ***No impact on normal applications***

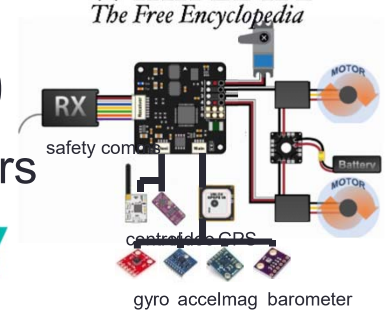


Morpheus Will Undergo Public Red-Teaming

- Why: We want to build strong confidence in our security
- How: Provide RISC-V based H/W to attacker community

- Demo 1: Voting machine at DEFCON – by Dec 2019
  - Goal: Validate security claims with black-hat community
- Demo 2: Network-facing website – by Feb 2020
  - Goal: Deploy a long-term world-attackable platform with bounty
  - Runs a subset of Wikipedia, includes an interface to inject code
- Demo 3: Secure avionics demonstration – by Jun 2020
  - Goal: Excise developer issues via engagement with defense contractors

WIKIPEDIA
The Free Encyclopedia



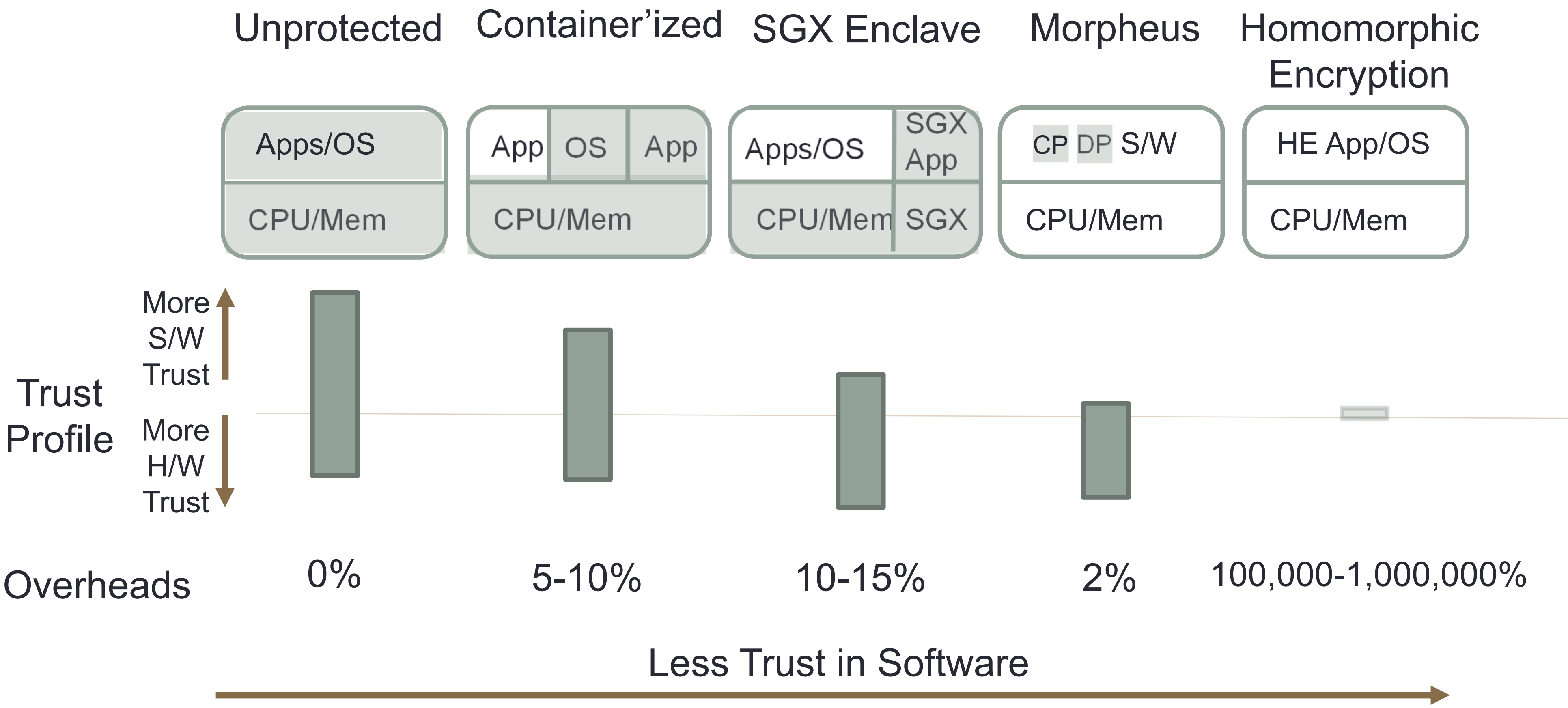
CROWD SUPPLY

Morpheus' Evolution and Beyond

- Originally Morpheus had decrypted caches
  - Foreshadow taught us that was a potential vulnerability
- Today's Morpheus has encrypted memory, caches, registers
  - And more encryption domains: data pointer, code pointer, return pointer, user data, etc…
- Observation: to build security, we deploy two durable mechanisms
  - ***Isolation*** and ***encryption***
  - History: ***physical memory*** begat ***virtual memory*** begat ***virtualization*** begat ***containers*** begat ***TEEs*** begat ***Morpheus***…
  - Each step, we accomplish the important goal of putting ***less trust in software***

- What is the endgame of security?
  - ***Total isolation*** and ***total encryption***… and ***zero trust in software***?
  - This is where I want to go next… let's work together!

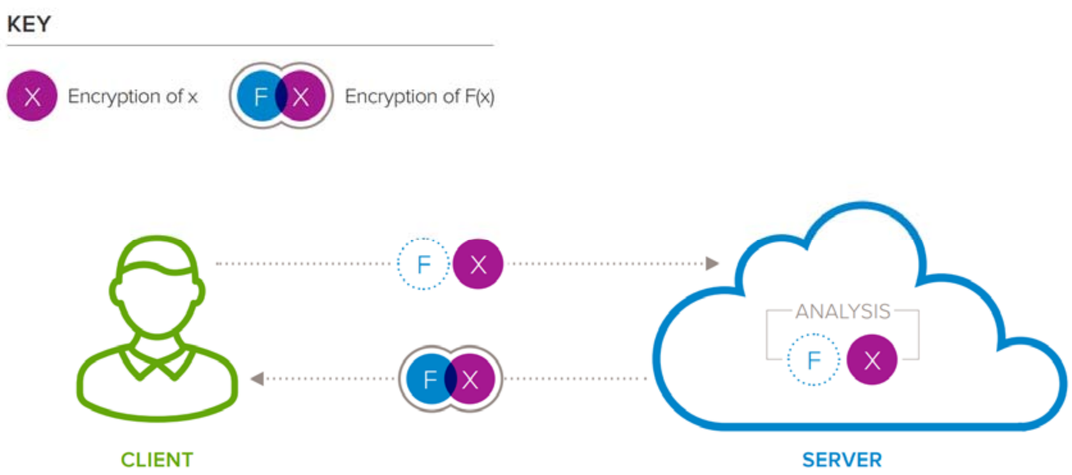
Toward Zero Trust in Software



Homomorphic Encryption Minimizes Trust

- HE advances privacy
  - No trust in S/W
  - No trust in H/W
  - Only trust in (immature) crypto

- What is the cost?
  - 10^5 – 10^6 times slower than comparable unencrypted computation
  - Can be parallelized extensively, and a focus of accelerator designers
  - Is it safe? Is it economical?



From: https://royalsociety.org/-/media/policy/projects/privacy-enhancing-technologies/privacy-enhancing-technologies-report.pdf (highly recommended!)

The Cost of Data Breaches

Varonis.com:
- 1 in 4 chance of experiencing data breach in a given year

IBM:
- Average cost per data breach in 2018: $3.86 million

Cybersecurity Ventures:
- Global cybersecurity market >$120 B in 2017
- Typical S&P 500 bank spends $500 M/year on cybersecurity

AWS Case Study	
Yearly revenue	$7.82 B
Expected total cost of data breaches for AWS user base	$1.92 B

Questions?

We demand rigidly defined areas of doubt and uncertainty!

- Douglas Adams, The Hitchhiker's Guide to the Galaxy