Using Memory Errors to Attack a Virtual Machine

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Executive Summary

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- Observation
- Key Idea and Implementation
- Key Results
- Takeaways

Executive Summary

- Observation
  - Type-checking systems are safe under the assumption that the computer faithfully executes its specified instructions.
  - This premise is false in the presence of hardware faults.
- Key Idea and Implementation
  - Write a program that uses memory errors to overtake the system by conducting a type confusion attack.
  - Manipulate data placement to maximize the probability of a memory error resulting in a type confusion.
- Key Results
  - Single bit errors in the program’s data space can be exploited to execute arbitrary code with a probability of ~70%.
- Takeaways
  - Virtual machines that employ type checking can be vulnerable to attacks that exploit memory errors

Outline

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- Background
- Exploit
- Security Analysis
- Evaluation of the Attack
- Potential Countermeasures

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- Background
  - Isolation
  - Type checking
  - Java applets and Java Cards
  - Memory Errors
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Background

Isolation

- Separate trusted components from untrusted ones
  - Example: Virtual memory
  - Each process operates in its own virtual address space

- Type-checking for sound type systems
  - Employed in virtual machines
  - Sound type system:
    - Rejects all incorrect programs
    - Every evaluation of an expression is guaranteed to match the expression’s static type

Type Checking

- What is type checking?
  - Verifying and enforcing constraints of types
  - Static vs. dynamic type checking
- Ensure type-safety
  - Do not allow operations/conversions that violate the rules of the system
- Why type checking?
  - Allows closer coupling between trusted and untrusted components
  - Object-oriented shared memory interfaces
  - No need for message passing / remote procedure calls
  - Same address space for trusted and untrusted programs

Type Checking in JVM

- At compile time (static)
  - Simulates program execution to determine if types are correct
  - After code is verified, it is trusted
  - Done by the bytecode verifier
- At runtime (dynamic)
  - No checks for type safety
  - Exceptions:
    - Casts
    - Array stores
- Key assumption
  - Read value is the same as when it was written
  - Time-of-check-to-time-of-use – the program changes after it was checked but before it was executed

Java Applets & Java Cards

Applets

- Program with few privileges
  - No network access
  - No access to the file system
- Executed in the JVM
  - Treated as untrusted

Java Cards

- Smart Cards
- Allow execution of Java Applets
- Store secret information (e.g. cryptographic keys, PIN)

Memory Errors

- What are memory errors?
  - Incorrect recall or complete loss of information in the memory system
- Soft memory errors
  - Single event upsets (SEU) – change of state in a single bit
  - Transient – only lasts a short time
  - Caused by some kind of disturbance (e.g., RowHammer)
- Hard memory errors
  - Permanent
  - Error in the circuit (e.g. process defect)
- Frequency of memory errors
  - Once in several months (2003)
  - About 10 a day per DIMM per Year[1]

[1] *Bianca Schroeder et al., DRAM Errors in the Wild: A Large-Scale Field Study. SIGMETRICS 2009.*

Causes of Memory Errors

- Alpha particles
  - Don't penetrate matter well
- Beta rays
  - Interact too strong with plastic and metal packaging
- X-rays
  - Not enough energy
  - Not very portable
- High-energy protons and neutrons
  - Need a particle accelerator
- Infrared
  - Electronic components become unreliable at high temperatures

Related Research

- *D. Boneh et al., On the Importance of Checking Cryptographic Protocols for Faults. EUROCRYPT 1997.*
  - Used random hardware faults to recover secrets in cryptographic protocols.

- *Anderson R., Kuhn M. Low Cost Attacks on Tamper Resistant Devices. Security Protocols Workshop 1997.*
  - Studies attack techniques on smartcards and other security processors by inducing errors at specific locations at specific points in time.

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- Background
- Exploit
  - Threat Model
  - Type Confusion Attack
  - Attack Program
  - System Level Integration
- Security Analysis
- Evaluation of the Attack
- Potential Countermeasures

Exploit

Threat Model

- Target is a virtual machine that uses type checking as its protection mechanism
- Ability to provide a verified (type checked) program, which is loaded into memory and executed
- Physical Access to the machine
- No control over data memory of the program

Type Confusion Attack

- Circumvent the type-safety
  - Obtain references of different type that point to the same object
- Read or write to arbitrary location in the programs address space
  - Allows execution of arbitrary code

Attack Program

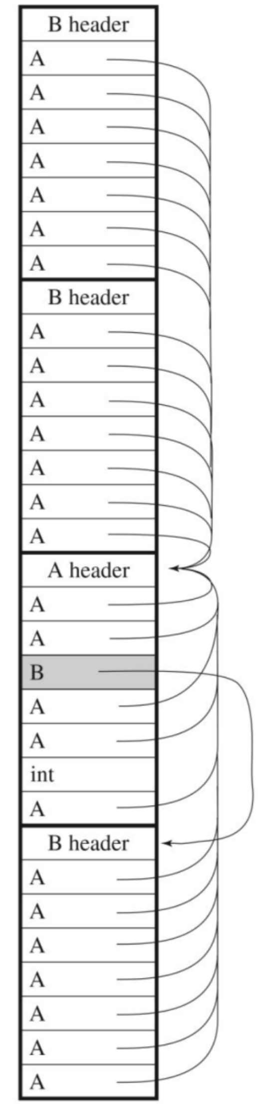
- Definition of two object types
  - Object size has to be a power of two
  - Assuming a 32-bit machine
- A acts as the pointer object
- B acts as the filler object

```
class A {                class B {
 A a1;                     A a1;
 A a2;                     A a2;
 B b;                      A a3;
 A a4;                     A a4;
 A a5;                     A a5;
 int i;                    A a6;
 A a7;                     A a7;
};                       };
```

Memory Layout

- Allocate one object of type A
  - b field points to an arbitrary object of type B
- Allocate as many objects as possible of type B
  - All fields a1 to a7 point to the single object of type A

```
class A {                class B {
 A a1;                     A a1;
 A a2;                     A a2;
 B b;                      A a3;
 A a4;                     A a4;
 A a5;                     A a5;
 int i;                    A a6;
 A a7;                     A a7;
};                       };
```



Detecting a Bit Flip

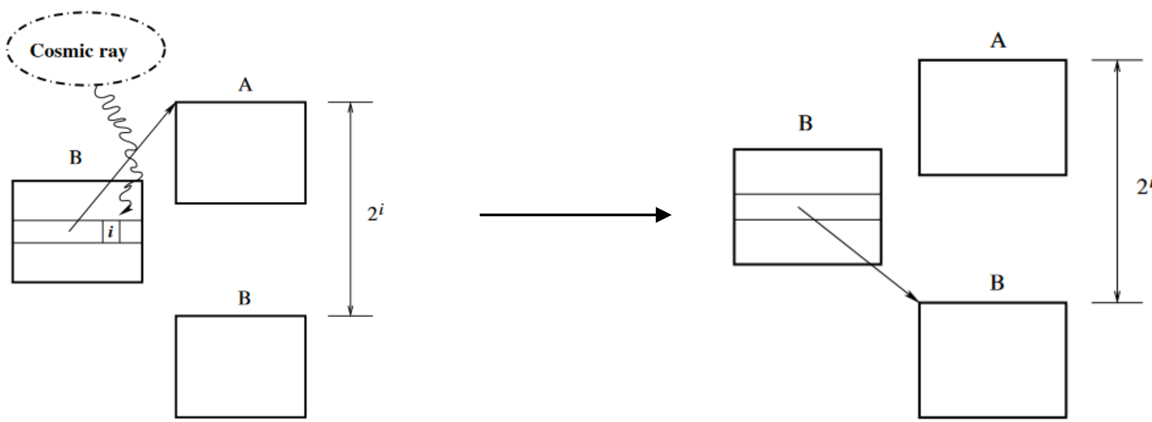
- Wait for a bit flip to happen

- Detection of a bit flip
  - Iterate over all allocated objects of type B
  - Check if all references still points to the object of type A
  - Repeat until this is not the case anymore

- Assume the object of type A is at address **x** in memory
  - All references in objects of type B store the address **x**
  - If a bit flip happens that reference stores an address that differs from **x**

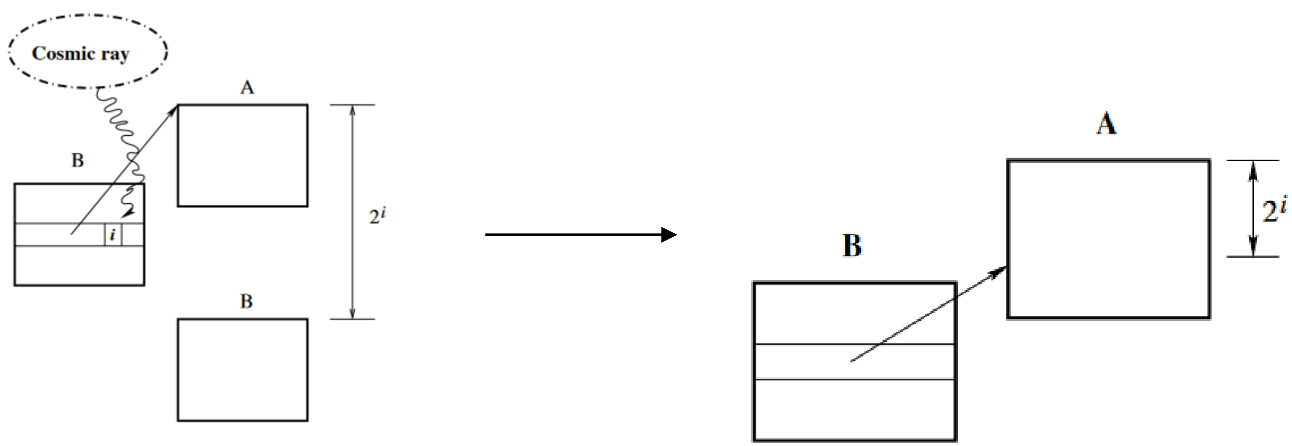
Implications of a Bit Flip

- Bitflip in bits 10 to 27
  - Reference address changes by more than the object size
  - Reference now points to header of B object



Implications of a Bit Flip

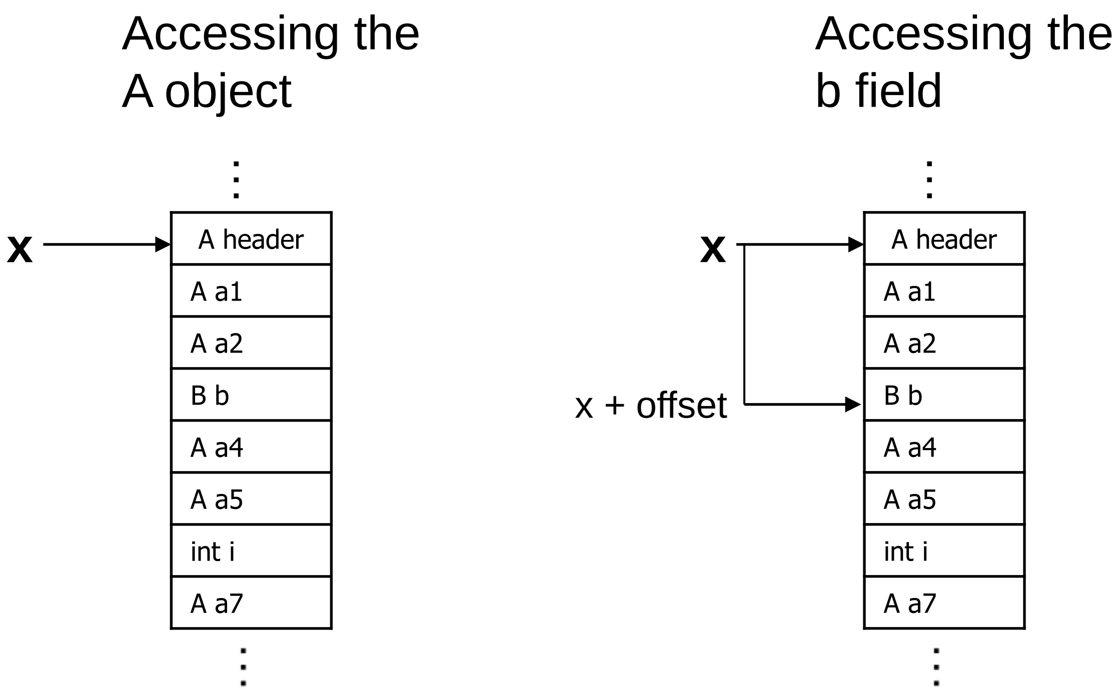
- Bits 2 – 9
  - Reference address changes by less than the object size
  - Reference now points within A object or adjacent object



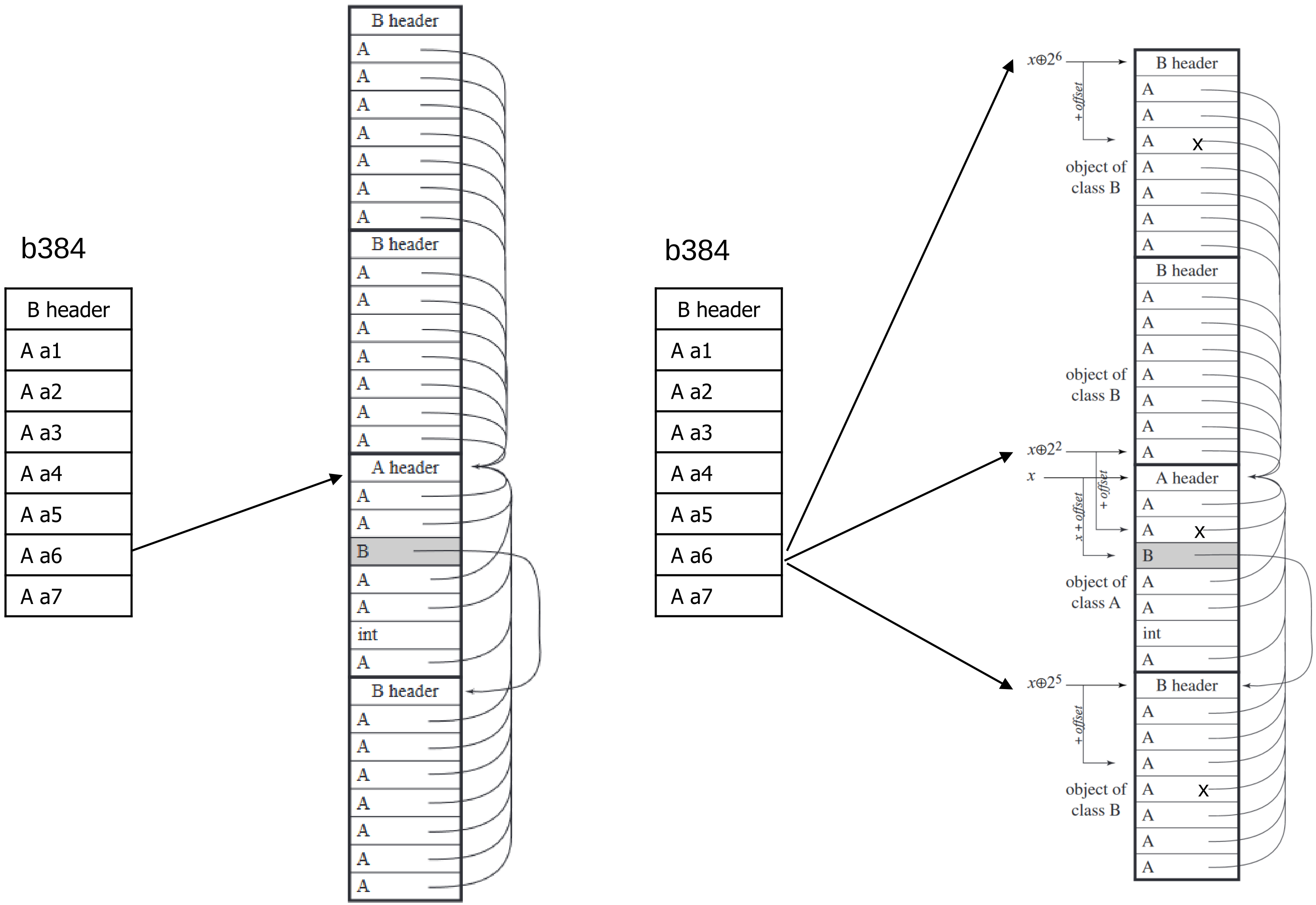
Implications of a Bit Flip

- Other bits
  - Program crashes
- Very high order bits
  - Addresses point out of bounds (outside of the allocated heap)
- Very low order bits
  - Addresses are not properly aligned

Implications of a Bit Flip



Implications of a Bit Flip



Implications of a Bit Flip

- New address + offset almost always stores the address **x**

```
A r;        B b384;            B q;
r = b384.a6;
q = r.b;
```

- *q* stores points to the A object but has type B
- *r* and *q* both store **x** but the references have different types
→ Achieved a type confusion

Violating Type Safety

- Assume we have two references of different type that point to the same object.
- Type A reference *p* & Type B reference *q*
- Write address into integer field
- Interpret integer as an address

```
A p;
B q;
int offset = 6 * 4;
void write(int address, int value) {
    p.i = address - offset ;
    q.a6.i = value ;
}
```

```
class A {                class B {
 A a1;                     A a1;
 A a2;                     A a2;
 B b;                      A a3;
 A a4;                     A a4;
 A a5;                     A a5;
 int i;  <------------>    A a6;
 A a7;                     A a7;
};                       };
```

System Level Integration

- This allows reading and writing of arbitrary addresses in the address space of the trusted process
- Fill array with machine code and overwrite virtual method table with address of array
- Overwrite the Security Manager
  - Class that enforces security policies

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Security Analysis

Analysis

- Calculate probability of a single bit flip being exploitable
- Counting of "cousin" objects
  - Objects whose addresses differ by a single bit
- Multiple bit flips can be exploited with a lower probability
  - 6-bit error about one-fourth as likely to be exploitable

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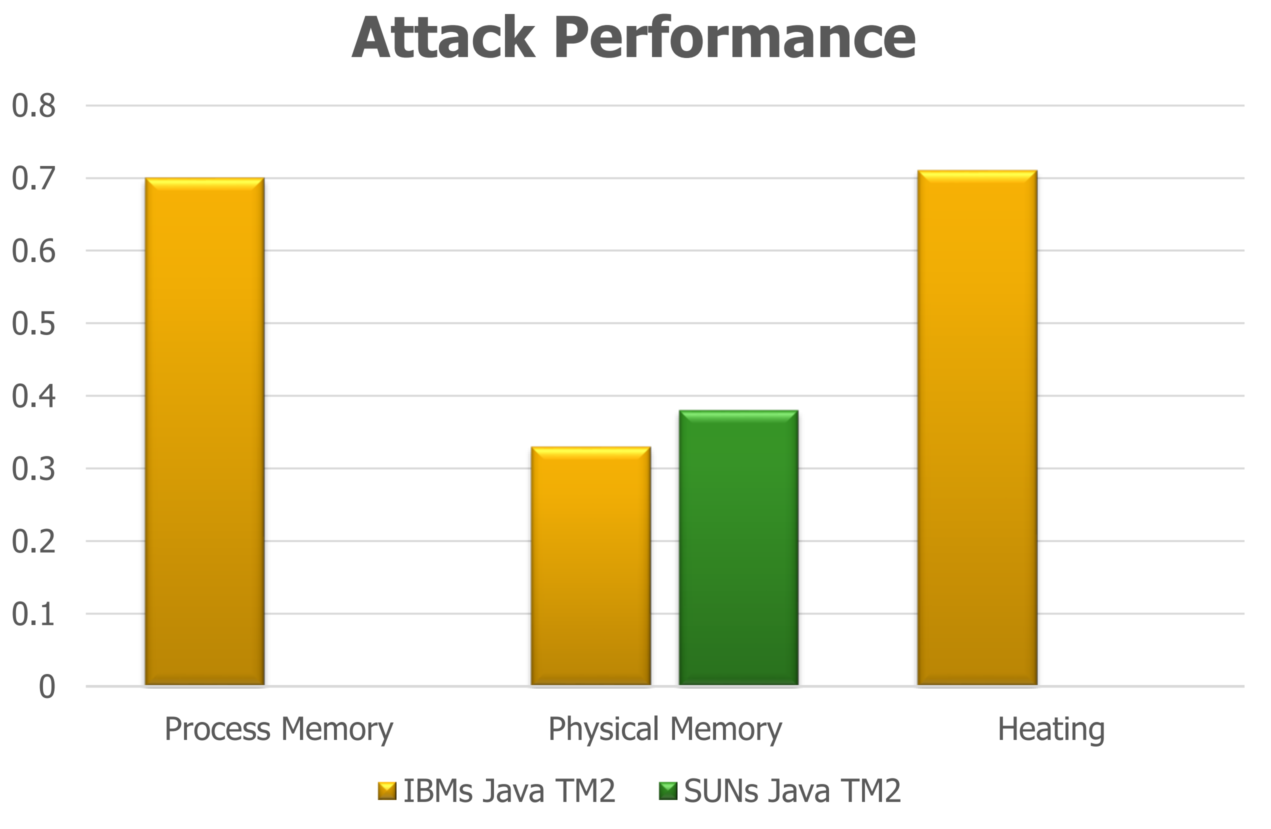
- Evaluation of the Attack
  - Methodology
  - Results
  - Exploiting before crashing
  - Safe bit flips
- Potential Countermeasures

Methodology

Methodology

- Two commercial JVMs from IBM and Sun on RedHat Linux
- Three different sets of experiments
  - Privileged Java thread inside that uses Interface to a C function that flips a bit in the processes address space
  - Unmodified JVM with separate Linux process that flips random bits in physical memory using /dev/mem
  - Unmodified JVM and induced memory errors by heating to 100 degrees Celsius

Results



Attack Performance
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Process Memory
Physical Memory
Heating
IBMs Java TM2
SUNs Java TM2

Exploiting before Crashing & Safe Bit Flips

- Errors can crash the system
  - While dereferencing or garbage collection
- Probability of exploiting the error before the system crashes is about 71% according to measurements

- Safe bit flips
  - Only exploit bit flips in the bits 10 – 27
  - Bit flips in 2 – 9 are indistinguishable from flips in the extreme high/low order bits
  - This improves the exploit-before-crash ratio to 94%

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Potential Countermeasures

Countermeasures

- Error correcting memory
  - Use error correction codes to detect and correct errors
  - Memory overhead of 12.5% to detect 1-bit and 2-bit errors
- Parity checking
  - Parity bit stores parity of number of set bits
- Software error logging
  - Log occurring errors and adapt behavior
  - Disable untrusted software
  - Shut down

- Does not cover the whole datapath

Conclusion

- Observation
- Key Idea and Implementation
- Key Results
  - Single bit errors in the program's data space can be exploited to execute arbitrary code with a probability of ~70%.
- Takeaways
  - Virtual machines that employ type checking can be vulnerable to attacks that exploit memory errors
  - Chosen program attacks alter the assumptions under which protection mechanisms should be designed
  - Hardware error-detection and correction with software logging of errors is the best defense

Critique

Strengths

- Novel idea
  - It was the first paper that used memory errors to take over a system
- Relevance to this day
  - Type confusion attacks are used to this day
  - Exploitation of memory errors escalated in relevance after the discovery RowHammer[1] (2014)
- It inspired a lot of research
- Strong verification
  - They created a proof of concept
- Affects a high number of systems

[1]*Kim et al. Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors. ISCA 2014*

Strengths & Weaknesses

- Very utopian threat model
  - Chosen program attack
  - Physical access
- No satisfactory protection mechanism
- Experimental results
  - Results only for one machine
  - Small sample size on heating experiment
- Writing is unstructured

Ideas & Takeaways

- Do error correction in the processor to solve the total datapath problem

- Dynamic type checking for dereferencing

- Address Space Layout Randomization[1]
  - Randomly arranges the address space positions of key data of a process including base of the executable and the positions of the stack, heap and libraries.

- Mark pages as non executable/read only

[1] *PaX ASLR (Address Space Layout Randomization). 2003*

Questions

Discussion

Is it possible to enable dynamic type checking with low performance overhead?

Related Research

- *Anderson et al. Checked Load: Architectural support for JavaScript type-checking on mobile processors. IEEE HPCA 2011.*
  - Low-complexity architectural extension that replaces software-based dynamic type checking.
  - Automatic type checks for memory operations.

- *Dot et al. Removing checks in dynamically typed languages through efficient profiling. IEEE CGO 2017*
  - HW/SW hybrid mechanism that allows removal of checks in optimized code.

Are the current countermeasures insufficient and can you think of different protection mechanisms?

Ideas

- Do error correction in the processor to solve the total datapath problem
- Dynamic type checking for dereferencing
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  - Randomly arranges the address space positions of key data of a process including base of the executable and the positions of the stack, heap and libraries.
- Mark pages as non executable/read only

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Can you think of any other attacks that could be performed in the same threat model?

Related Research

- *Halderman et al. Lest We Remember: Cold Boot Attacks on Encryption Keys. USENIX Security Symposium 2008.*
  - DRAM retains their content seconds to minutes after power is lost.
  - Perform a memory dump by cold booting a lightweight OS from a removable disk.
  - Circumvents full disk encryption.

- *Gruss et al. Rowhammer.js: A remote Software-Induced Fault Attack in JavaScript. DIMVA 2016.*
  - Fully automated attack to trigger faults on remote hardware.
  - Allows to trigger Rowhammer in highly restricted and even scripting environments by defeating complex cache replacement policies.

Should attacks like this be handled on a physical security level?

Are there other ways to exploit memory errors?

Related Research

- *Google Project Zero. Exploiting the DRAM rowhammer bug to gain kernel privileges. 2015.*
  - Achieving read-write access to one of its own page tables, and hence to all of physical memory.

- *V. van der Veen et al. Drammer: Deterministic Rowhammer Attacks on Mobile Platforms. ACM SIGSAC 2016.*
  - *Shows that deterministic Rowhammer attacks are feasible on common mobile platforms.*
  - *Allows attackers to take control over the mobile device by hiding it in a malicious app that requires no permission.*