Using Memory Errors to Attack a Virtual Machine

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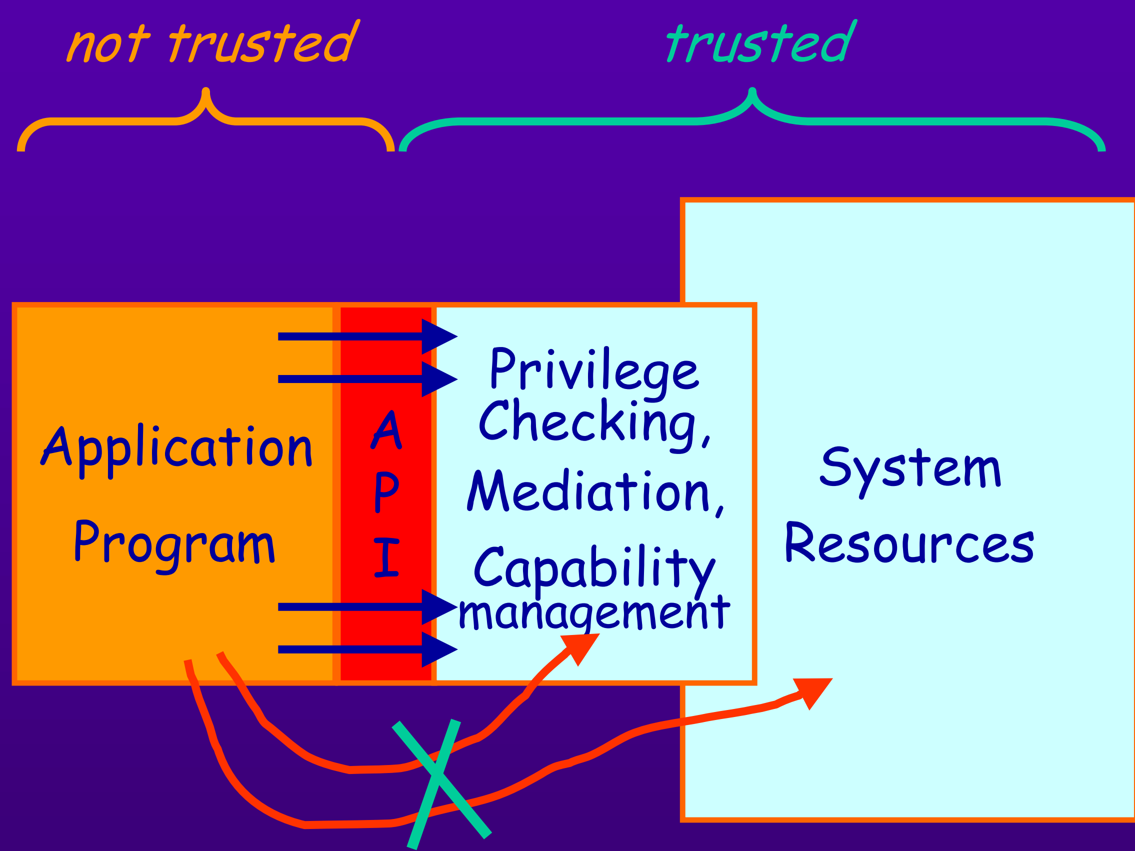
Introduction

- Java and .NET use static checking for security
- Proved sound
- We use natural memory errors to defeat them
- We execute arbitrary code and obtain complete access to the VM

Success ratio: $10^{-9} \longrightarrow 0.70$

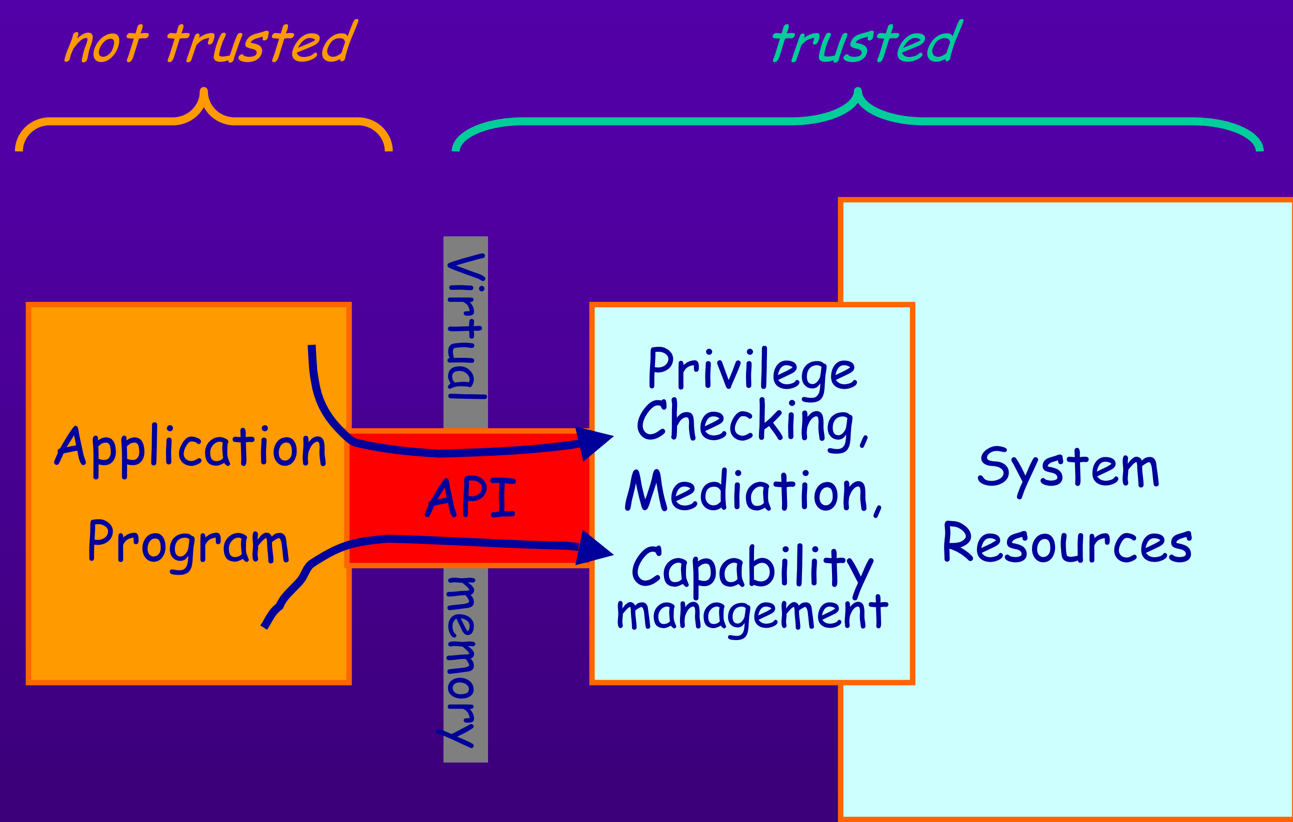
Typical system architecture

Access to system resources mediated by API



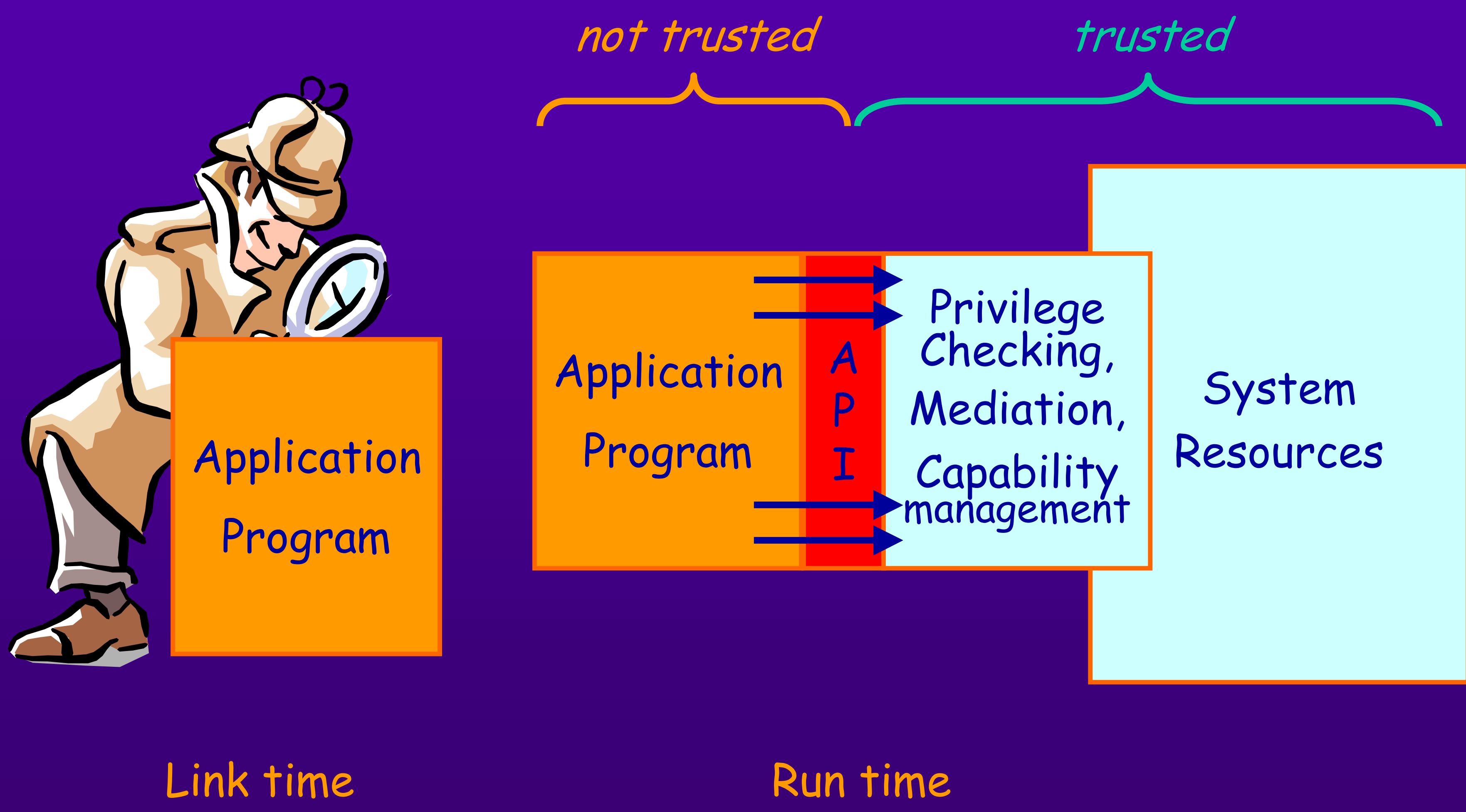
Must prevent capability management from being bypassed

Operating systems, virtual memory



Crossing virtual-memory boundary is slow and clumsy

Static checking



Java

- Efficiently compiled to machine code
- Portable
- Byte code verifier guarantees safety of program
- After verification, trusted and untrusted components run in the same address space
- Proved type sound; subsets machine checked.

Overview

- Security is premised on type safety

Single memory error

↓

Type-safety violation

↓

Memory-safety violation

↓

Executing arbitrary code

```
class SecurityManager {
    .
    .
    private   bool allowFileAccess;
    .
    .
}
```

- Attack possible due to hardware error

The class definitions

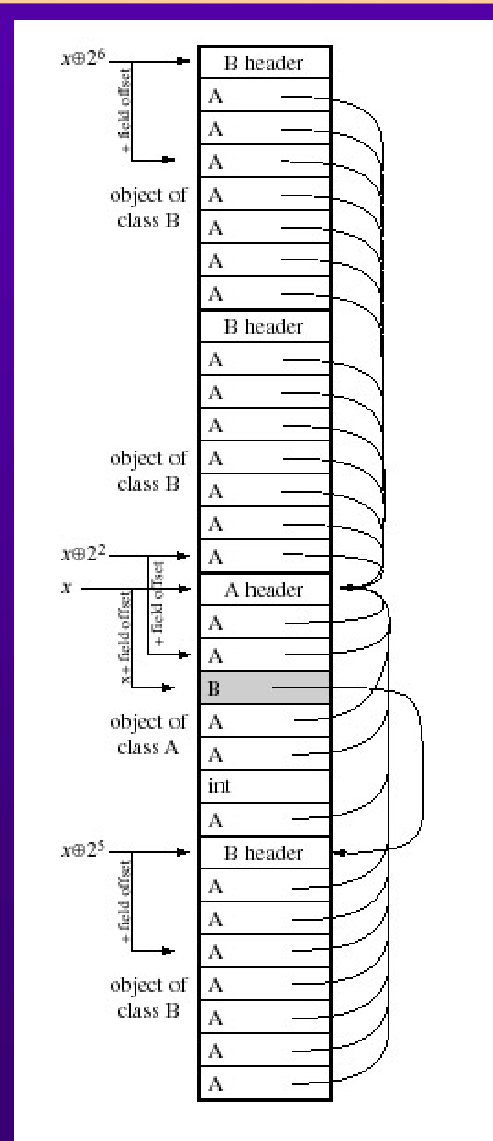
```
class A {
        A a1;
        A a2;
        B b;
        int i;
        A a5;
        A a6;
        A a7;
}
```

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

Object : 32 bytes, field : 4 bytes, header : 4 bytes.

The attack applet

- Inviting to attack type safety.
  - Segment size : Data >> text
- Attack applet allocates a lot of memory like this
- Applet waits for a memory error
- Random pointer dereference will fetch from an A field.
- Type safety violated
  - Pointer of type B points to an A object



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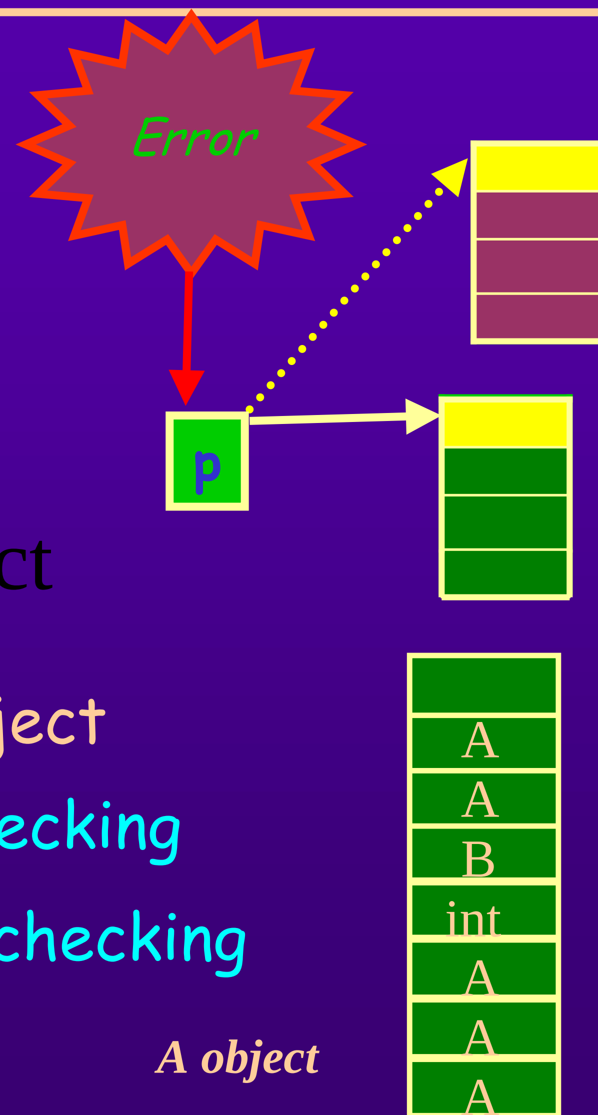
Detecting and exploiting the bit flip

- Wait for a flip; detect it
  - for each pointer p of type A,
    - if (p != a) …
    - Now p.b points to a A object

- VM thinks p.b type is B
- But, we can typecast p.b to an A object
  - Object r = p.b;   Static checking
  - A q = (A) r;   Dynamic checking
- Result : undetected type system violation



Detecting : the code

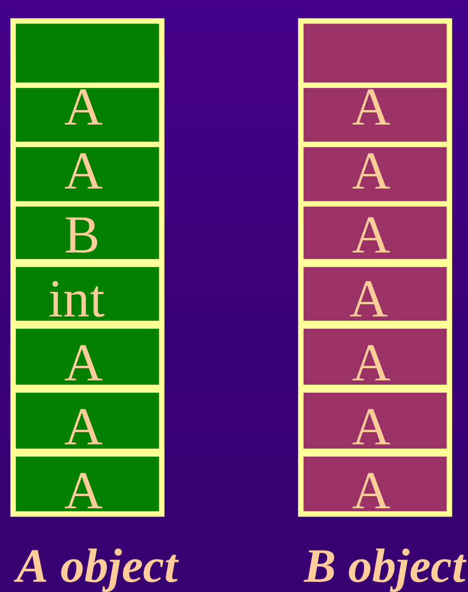
```
A p, q;
A ref_A; // the A object
while (true)
    for each pointer p of type A
        if (p != ref_A)  { // bit flipped
            Object r = p.b;
            q = (A)  r;
            .  // use p.b  and q, which contain same pointer, but are of diff
               types
            .
            .
        }
```

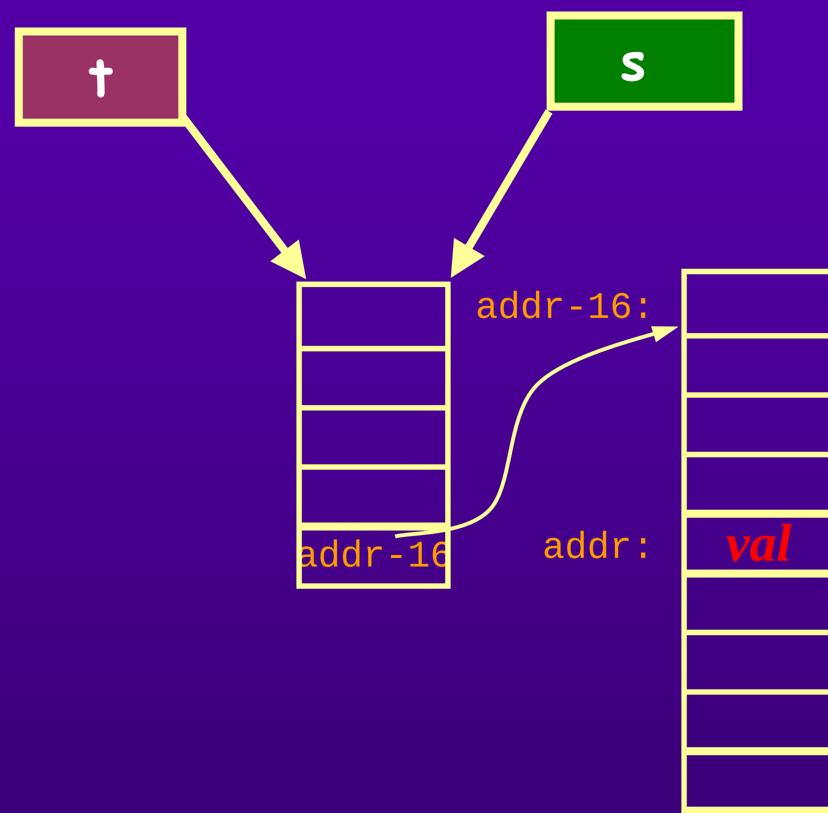
Obtaining memory safety violation

```
write (A s, B t, val, addr) {

 // s == t

  s . i = addr - 16;
  t.a4.i = val;
}
```



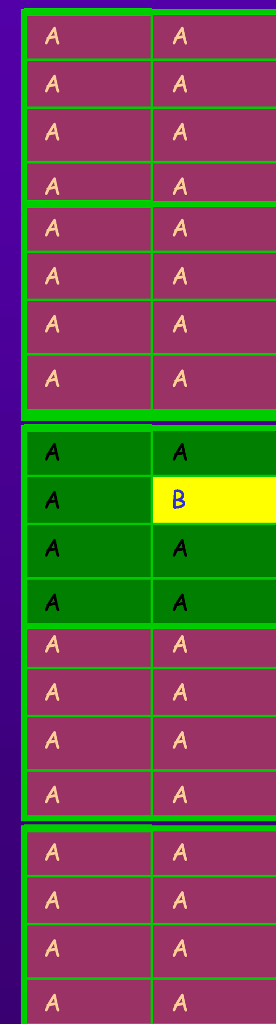


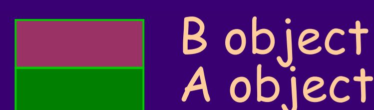
Using the memory safety violation

- We can write any data at any address
  - Fundamental safety property is violated
- Pointer forging — Clumsy ☹
  - Fill array with machine code
  - Forge function pointer table
- Security Manager — Elegant and portable ☺
  - Obtain the address of the security manager
  - Then turn off the security manager
  - Load and execute arbitrary code !
  - complete access to the VM !

Obtaining the layout

- Allocate a random number of B objects
- Allocate an A object
- Exhaust memory with B objects
- Set each A field of each object to the A object.
- Set the B field of the A object to any B object





Larger objects

- Object header overhead less
- More control on layout
- Maximum Hamming distance
- What if bits 2…9 flip?


```
class A {
        A a1;
        .
        A a125;
        B b
        A a127;
        .
        A a254;
}
```

Efficiency 25 % already!

Cousin number

- p, q are cousins if p, q differ in a bit
- x, y are cousins; different types; bit flip implies type error

- Cousin number(p) : number of cousins of p

- a is the single object of type *A*
- Cousin number(a) is large $\Rightarrow$ bit flip in large number of bits gives type error.

How much is cousin number ?

- N objects, each of size 1024 bytes

- Ideal case
  - Object size s, number of objects N is a power of 2
  - All objects are at contiguous locations
  - In this case, C(any object) = $\log_2 N$

- Relaxed case
  - Very likely that C(any object) is approximated well by $\log_2 N$

  - In particular, C(the A object) ~ $\log_2 N$

Measured distribution of cousin numbers

- Measured the cousin numbers in one particular run
- Object : 1024 bytes, word : 4 bytes
- N= 426,523; $\log_2 N = 18.7$
- Empirical measurement
  - mean cousin number = 17.56
- $\log_2 N$ is really a good predictor of cousin number!

Cousin number	# of objects
0,1	2
3	13
4	7
5	59
6	30
7-12	0
13	614
14	2,868
15	32
16	29,660
17	110,640
18	282,576

Number of exploitable bits

32 bit A-pointer

	$log_2 N$	8	2
32	28	10	2

0

- C(the A object) ~ $\log_2$ N
  - Flip in any $\log_2$ N bits in bits 31…10 usable
- flip in bits 9..2 is anyway usable
- flip in bits 1..0 results in an alignment error
- extreme high bits flip : core dump

We were able to use any flip in the bits 2 … 27

General Discussion

- This attack works on all virtual machines
  - Portable
  - Same code worked for IBM and Sun JVMs
- .NET attack similar

Experiment #1

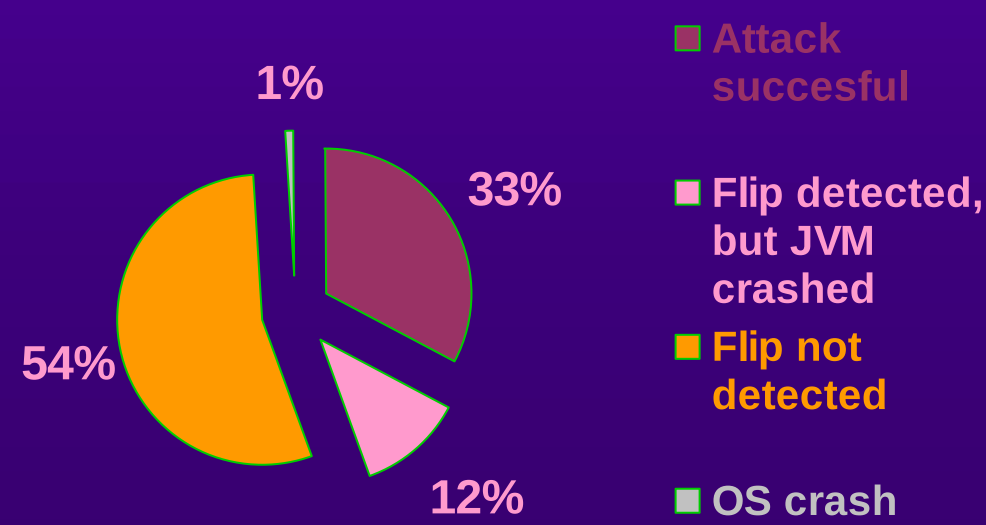
- Use a privileged process to inject single-bit "errors" in physical memory
  - Unix /dev/mem interface to physical memory
  - Measure the efficiency of our attack
  - 128 MB physical memory

- Linux

- IBM, Sun JVMs

Results : /dev/mem to inject errors.

- IBM JVM
- 128 MB memory
  - 57,753 objects
  - 3,035 trials
  - Efficiency : Expected 0.32   Actual 0.34
  - JVM allocates max of 60% of physical memory



Attack scenarios

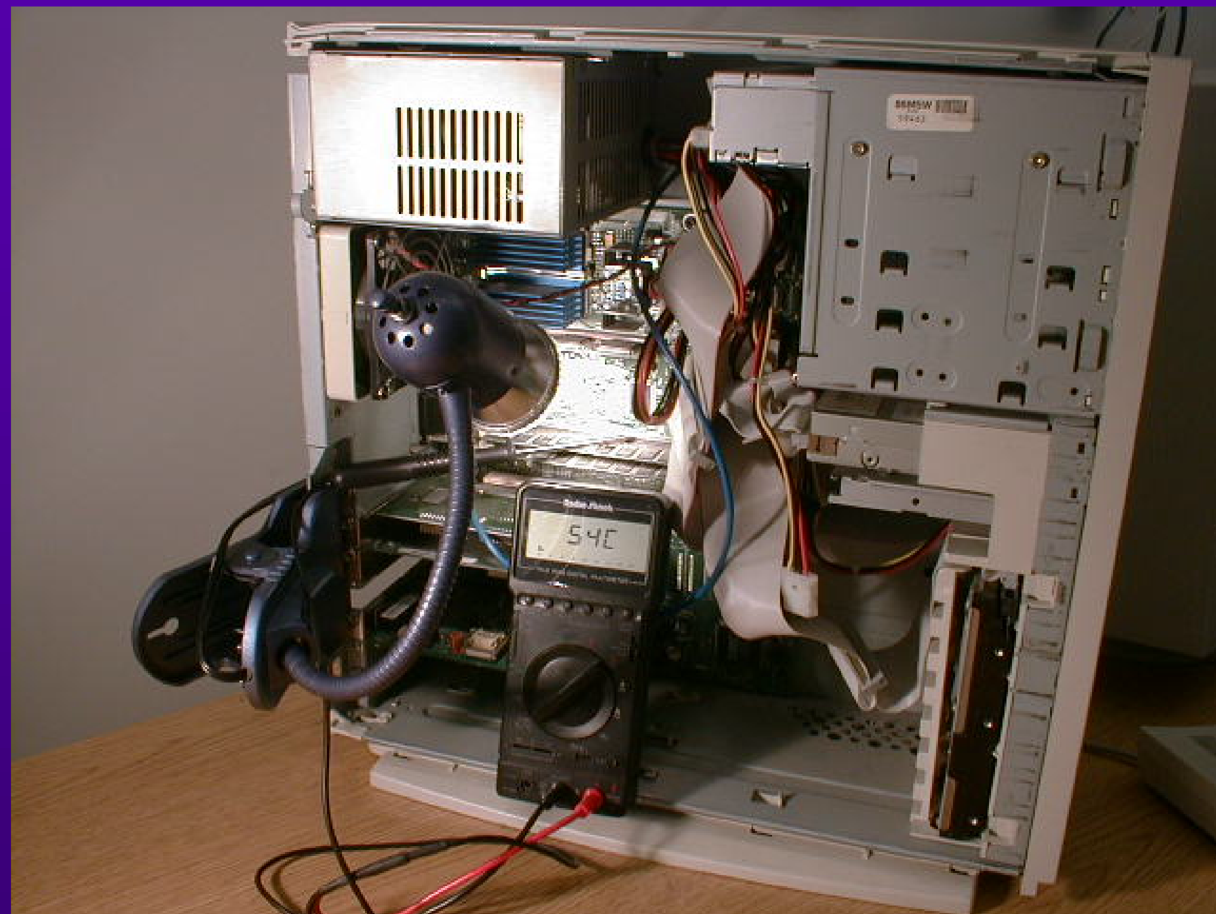
- No physical access
  - SETI @ HOME in Java
  - About one error per month (? Hard to find data)
  - Web browsers
- Complete physical access
  - Screwdriver to remove HDD
- Limited physical access
  - Supply program
  - Induce errors

Susceptibility of DRAM to faults

- Alpha particles
  - Significant in 1990, now insignificant
- Beta rays (high-energy electrons)
  - Don't penetrate packaging
- X-rays
  - Too low energy to affect a DRAM capacitor
- High-energy protons, neutrons (cosmic rays)
  - Yes, but need particle accelerator; available to a few large nation states only
- Thermal neutrons
  - Yes, but where to get a source? Oil drilling...
- Heat
  - Now we're talking!

Experiment #2 : using heat

- Old PC
- Clip-on lamp
- 50-watt spotlight bulb
- Variable AC power supply
- Digital thermometer



Result: between 80° - 100°C, memory starts to have a small number of few-bit-per-word errors. Attack applet is successful.

Defenses against this attack

- Error-Correcting-Code (ECC) memory
  - Not used in most desktop PCs because of cost
- ECC fault logging
  - When unusual numbers of errors seen, shut down
  - Difficult to create 3 bit errors without 1 bit errors
- Total datapath coverage for ECC
  - Old ECC coverage based on "natural fault" model, not a coordinated attack
  - Some new high-end x86 chips (Intel, AMD) have this
- More than 2-bit error detection
  - Need more than 72 bits to represent 64-bit word

Optimising for IBM JVM

hashCode

- Provides good hash function.
- Typically address based to reduce collisions.
- Don't want to expose address for security risks.

```
A = 2 * sp + clock()

B = 2 * sp + time() - 70

int hashCode (address) {
    t1 = address >> 3
    t2 = t1 ^ A
    t3 = (t2 << 15) | (t2 >> 17)
    t4 = t3 ^ B
    t5 = t4 >> 1
    return t5
}
```

Addresses differ in a bit iff hashcodes differ in a bit.

Cousin number can be computed !

Optimising for IBM JVM

- Allocate a large number of objects of type B.
- Compute cousin number of each object.
- Choose an object with maximum cousin number. Let address be x.
- Deallocate the object.   Address x is added to the front of the free list by the mark-and-sweep garbage collector. (Object size being 1024 is useful)
- Invoke System.GC().
- Allocate object of type A. Address x is reused and hence this new object has the max cousin number. Base the attack on this object.

IBM JVM : Defeating address obfuscation

hashCode

```
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B = 2 * sp + time() - 70
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    return t5
}
```

- sp is predictable(#frames, argv, envp)
- clock depends on the time to initialise the JVM. Empirically, it is among 9 … 19
- time can be estimated by System.currentTimeMillis()
- XOR is reversible
- Given hashCode, address can be restricted to a small set

Conclusion

- Allowing attacker to choose the program alters many assumptions
- Attack possible as machine does not execute instructions correctly
- Especially the following are vulnerable:
  - Conventional Java virtual machines
  - Conventional .NET virtual machines
  - In fact, any system relying on static (type) checking to enforce security
- Always use ECC hardware with error logging
  - Shut down if too many errors
- Having a good heat sink is important!

Acknowledgments

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Check out the paper and my commentary, available at my website, regarding the discussion of this work in slashdot.org!