Code-Pointer Integrity

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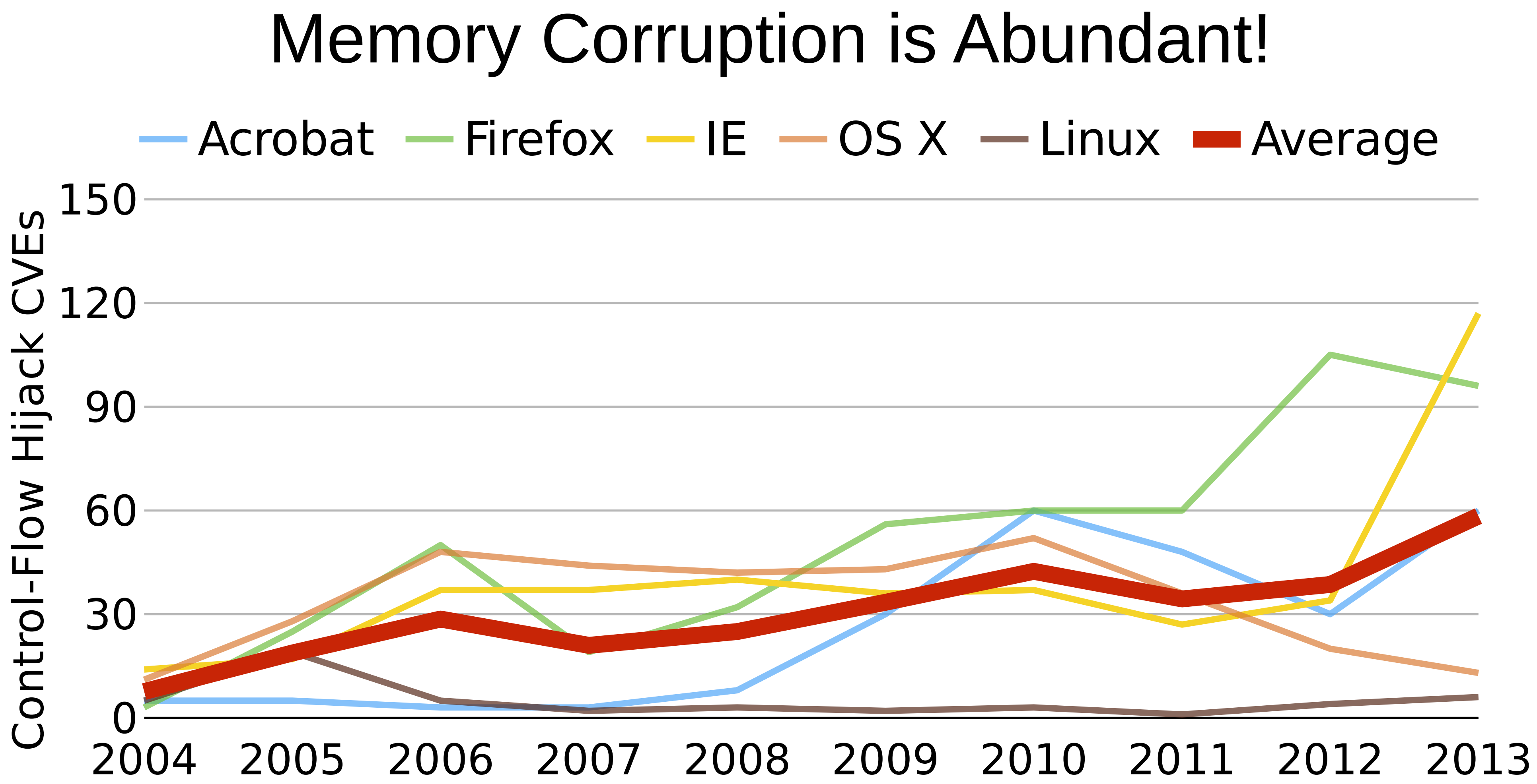
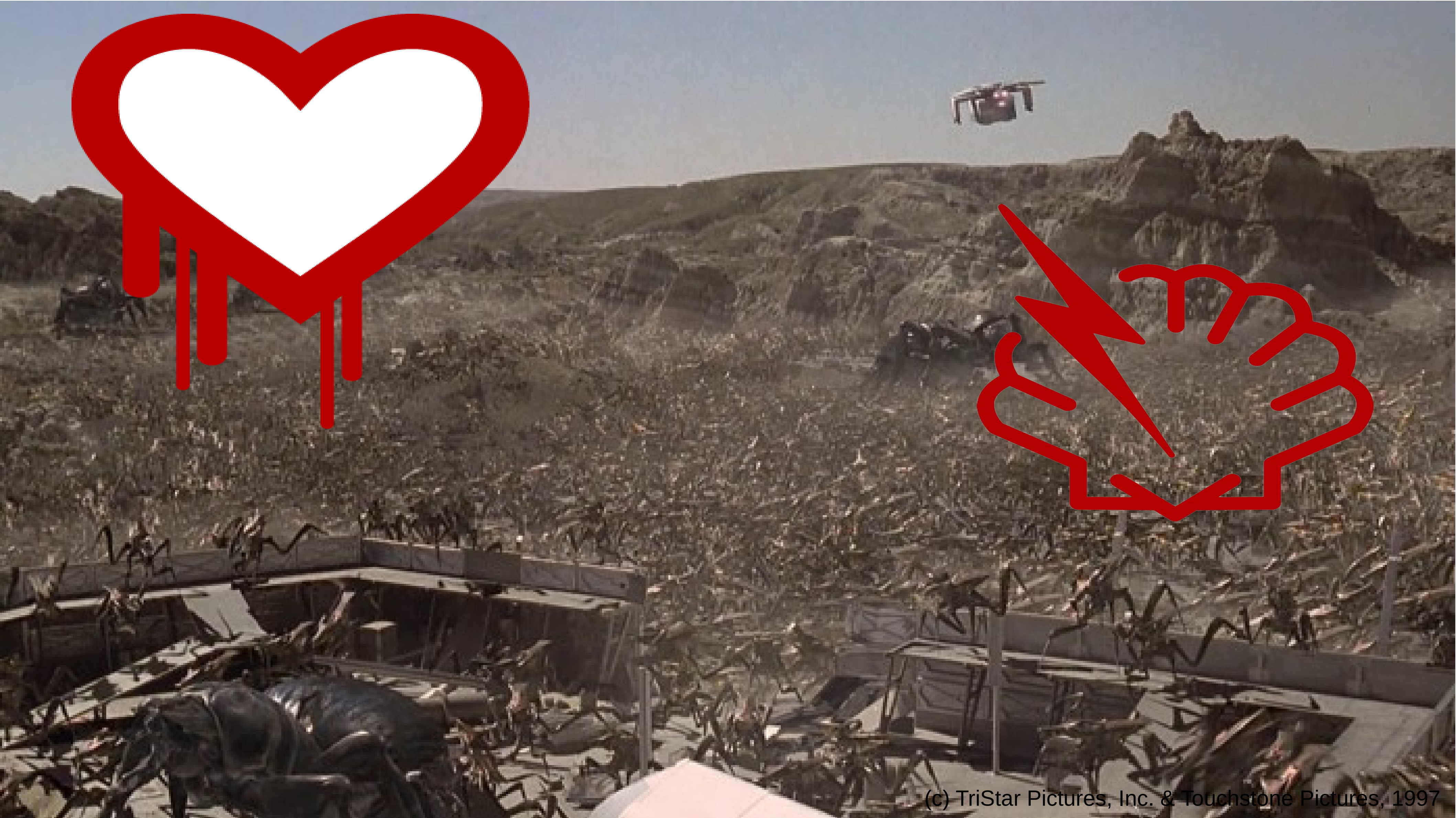

Memory Corruption is Abundant!
Acrobat
Firefox
IE
OS X
Linux
Average
Control-Flow Hijack CVEs
150
120
90
60
30
0
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013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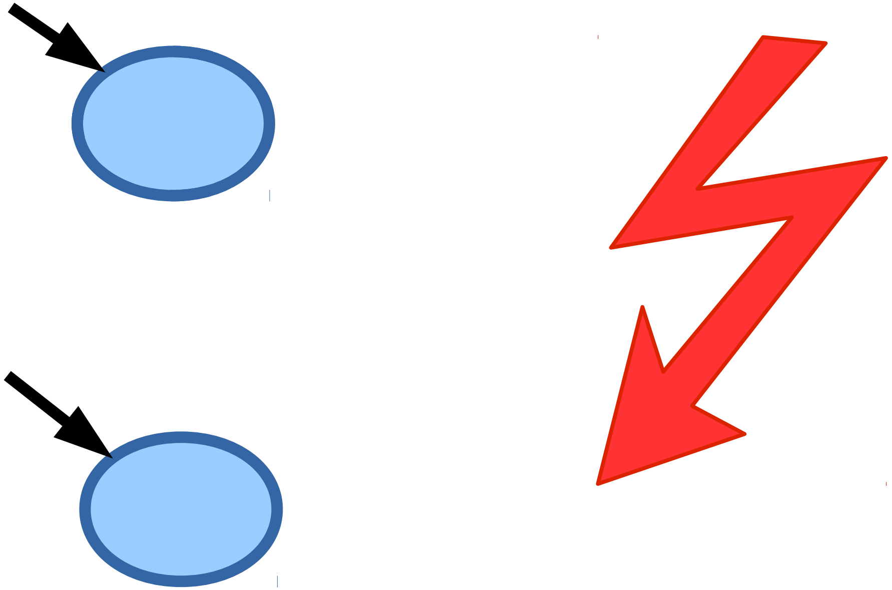
Memory safety: invalid dereference

- Violation iff
  - Pointer is read
  - Pointer is written
  - Pointer is freed
- No violation
  - Otherwise

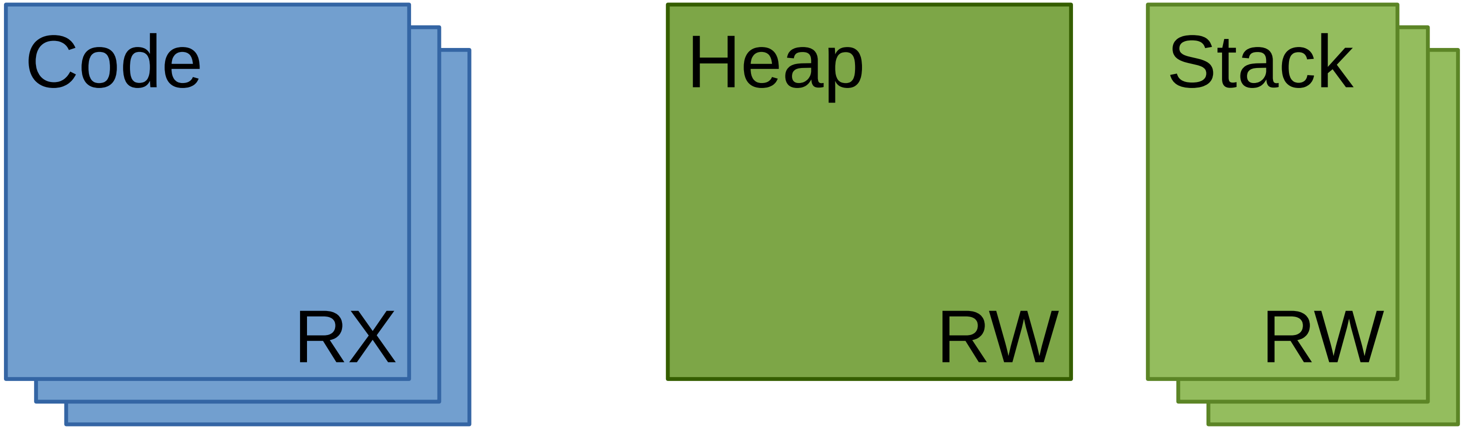
Dangling pointer: (temporal)

Out-of-bounds pointer: (spatial)



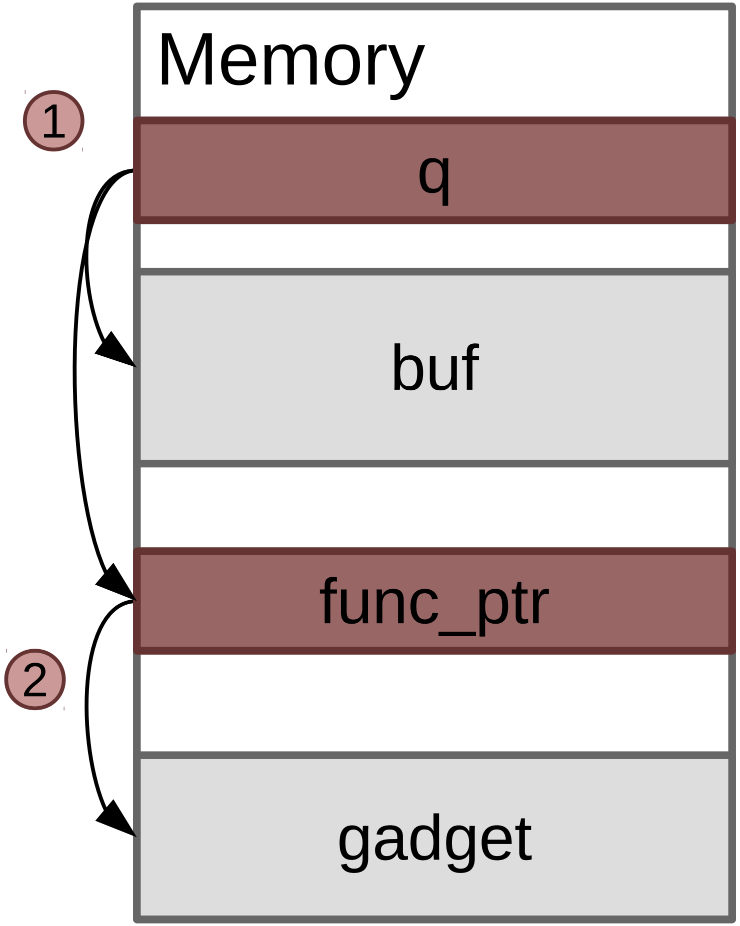
Threat Model

- Attacker can read/write data, read code
- Attacker cannot
  - Modify program code
  - Influence program loading

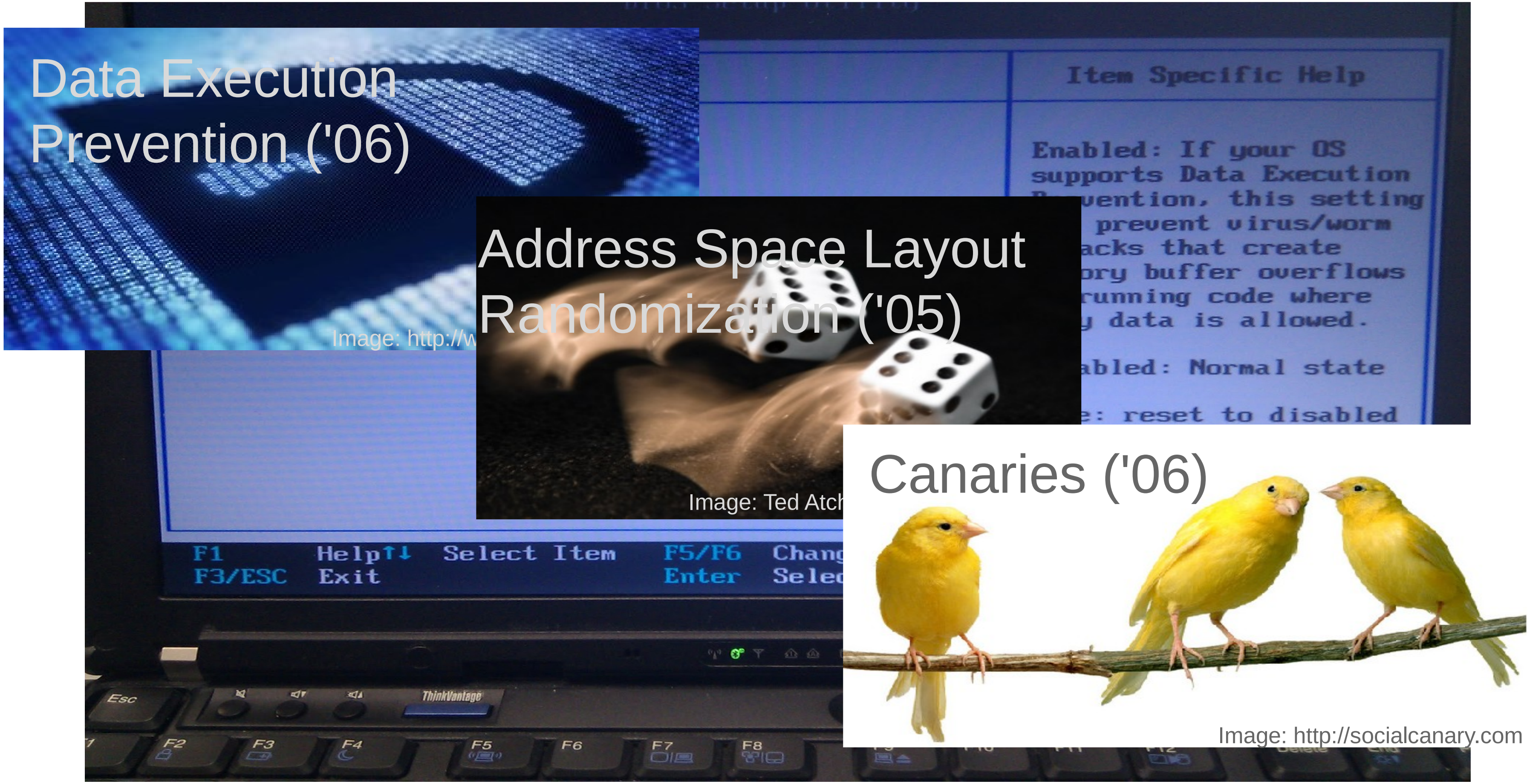


Control-Flow Hijack Attack

```
    void *(func_ptr)();
1   int *q = buf + input;
    …
    func_ptr = &foo;
    …
2   *q = input2;
    …
3   (*func_ptr)();
```



What about existing defenses?

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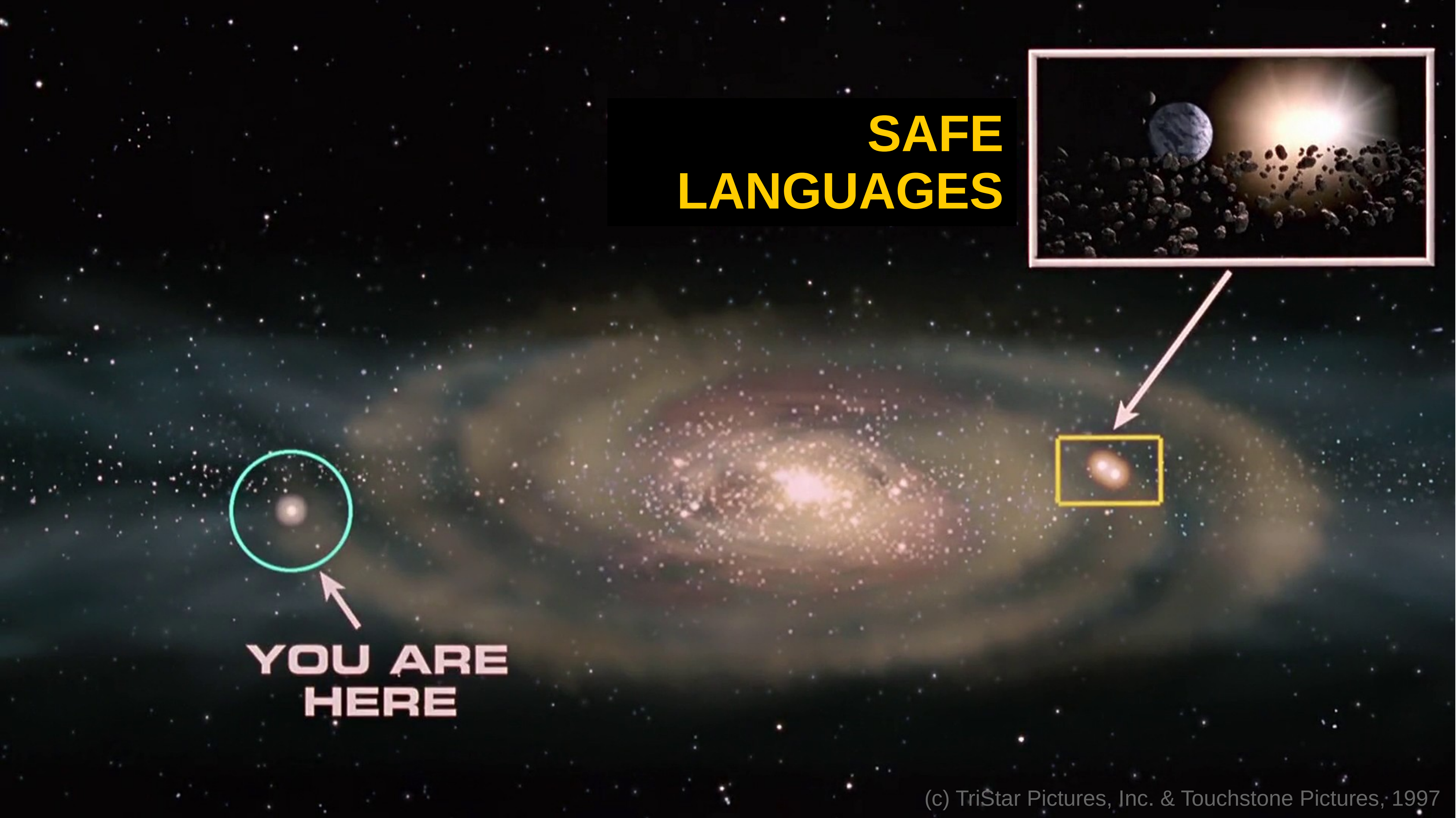
WARGAMES
MISSILE WARNING
SUB-LAUNCH DETECTION
... in memory: an evolution of attacks
Mathias Payer <mathias.payer@nebelwelt.net>
UC Berkeley
Images (c) MGM, WarGames, 1983
Presented at 30c3
http://youtu.be/CQbXevkR4us
WOULD YOU LIKE TO KNOW MORE?

Memory Safety to the Rescue

python™ Java™ C# Swift

Python code	~3 kloc
Python runtime	~500 kloc
libc	~2,500 kloc
Linux kernel	~15,803 kloc

Unsafe!


SAFE
LANGUAGES
YOU ARE
HERE

Retrofit Memory Safety

C/C++	Overhead
SoftBound+CETS	116%
CCured	56%
AddressSanitizer	73%

Memory Safety

```
char *buf = malloc(10);
b
…
c
c
i  (q   q_lo || q     q_up)
  abort();
*q = input2;
…
(*func_ptr)();
```

1. Assign meta-data

ata

3. Check meta-data

116% performance overhead

(Nagarakatte et al., PLDI'09 and ISMM'10)


Safety
vs.
Flexibility and
Performance
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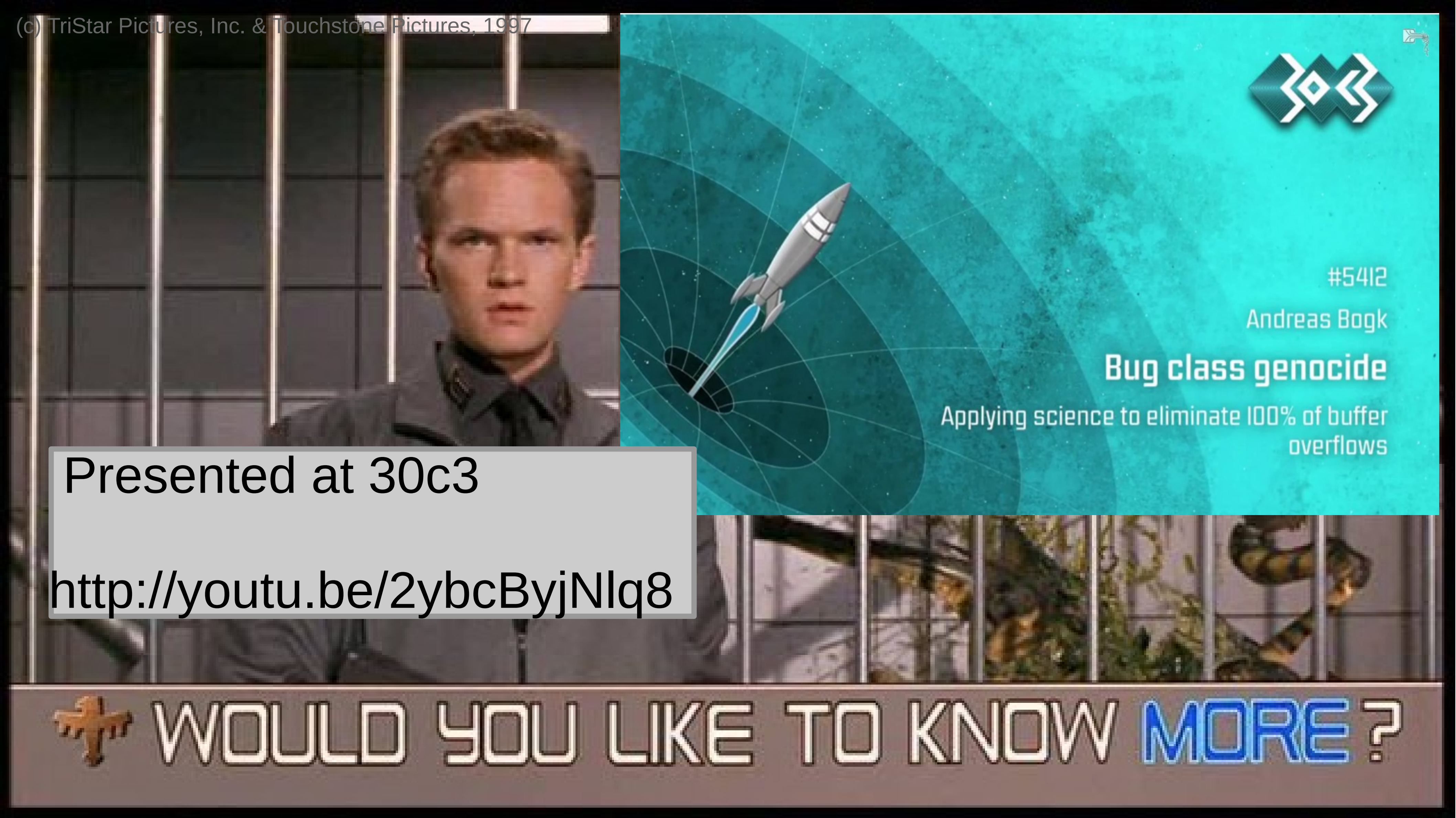
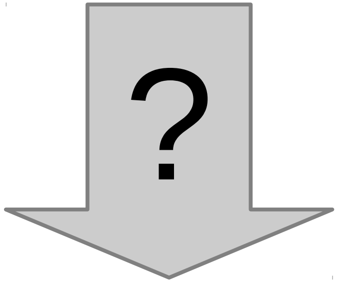

#5412
Andreas Bogk
Bug class genocide
Applying science to eliminate 100% of buffer overflows
Presented at 30c3
http://youtu.be/2ybcByjNlq8
WOULD YOU LIKE TO KNOW MORE?

New Approach: Protect Select Data

Instead of
protecting everything a little
protect a little completely

Strong protection for a select subset of data
Attacker may modify any unprotected data

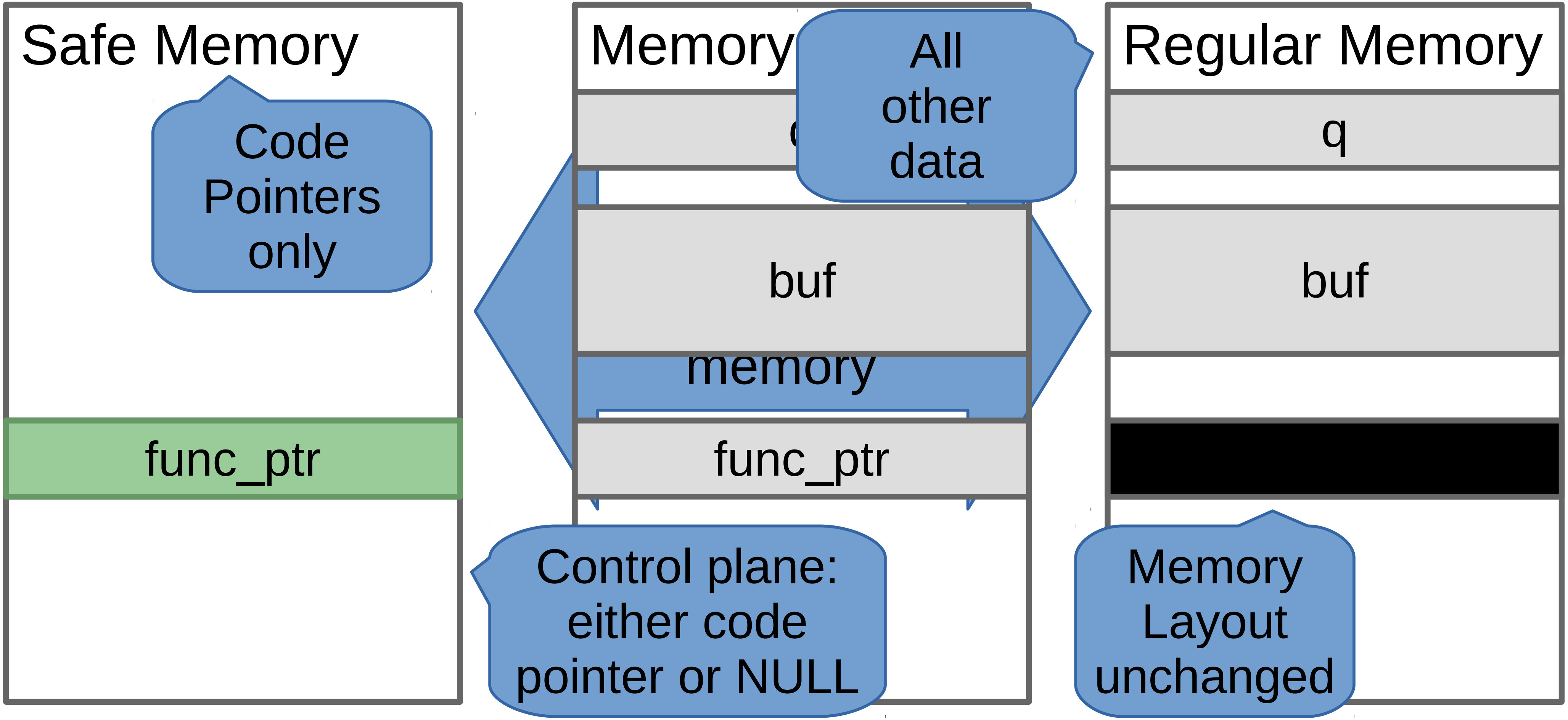
Memory Safety
(116% performance overhead)



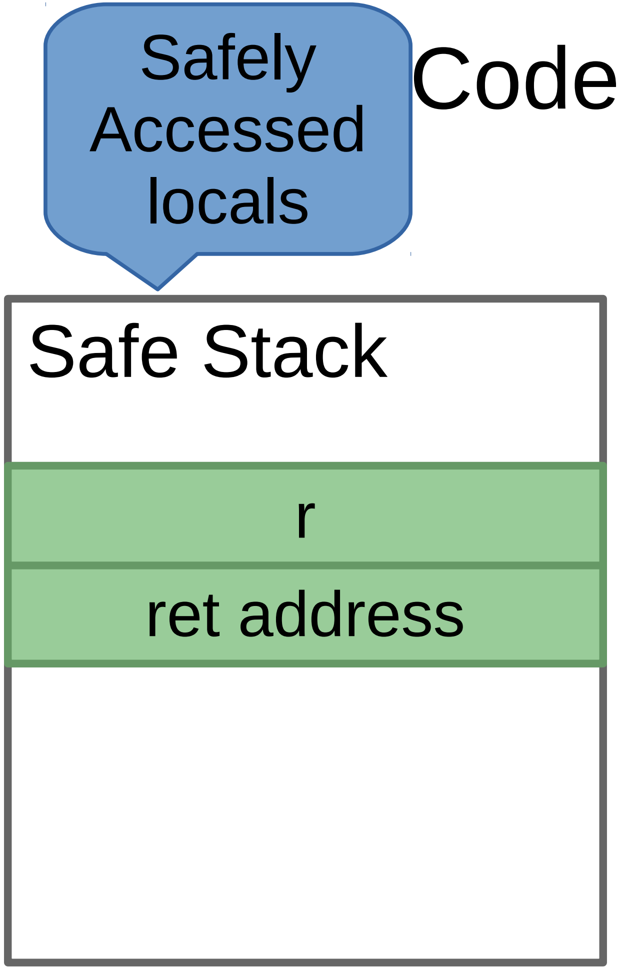
Protect only
Code Pointers

Control-Flow Hijack Protection
(1.9% or 8.4% performance overhead)

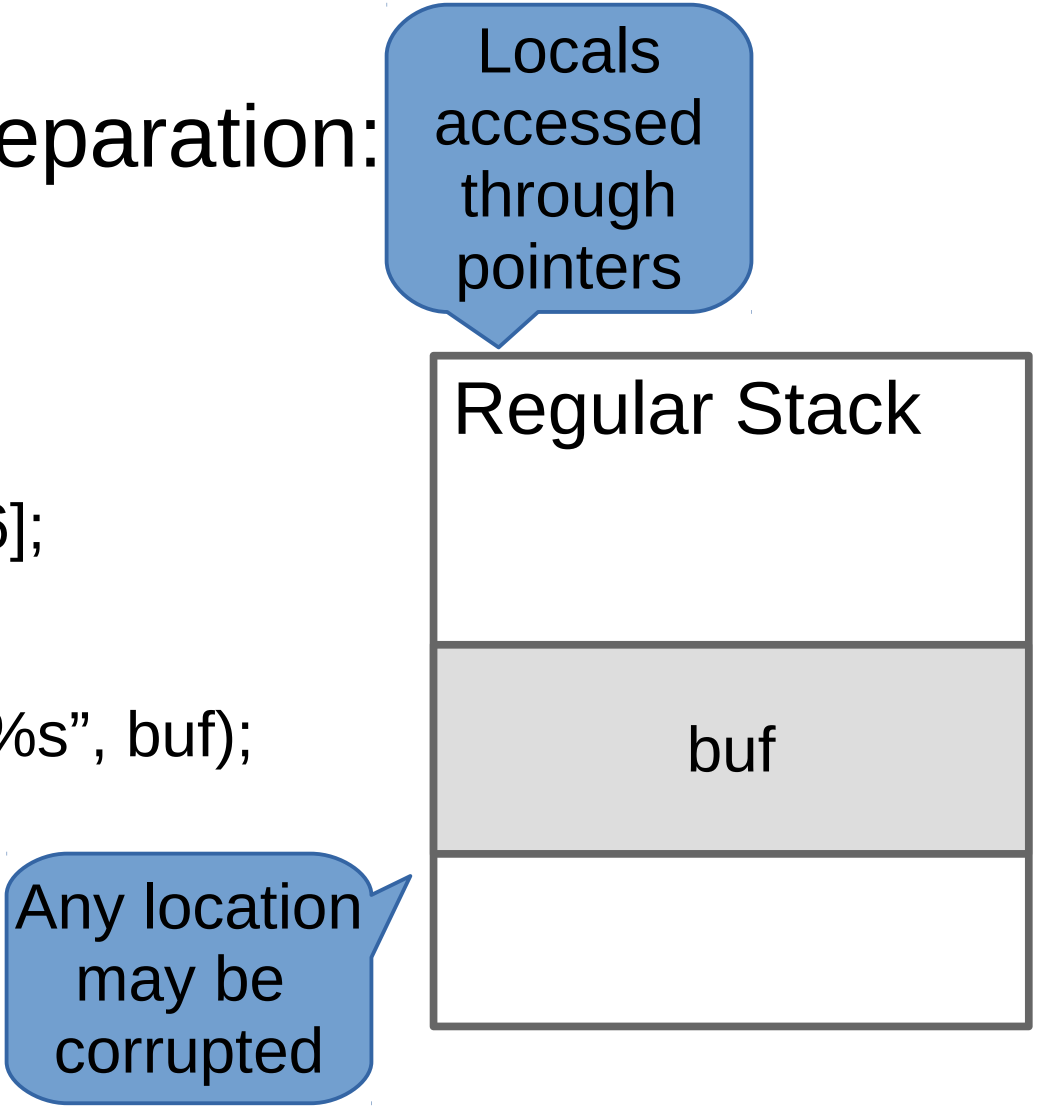
Code-Pointer Separation: Heap



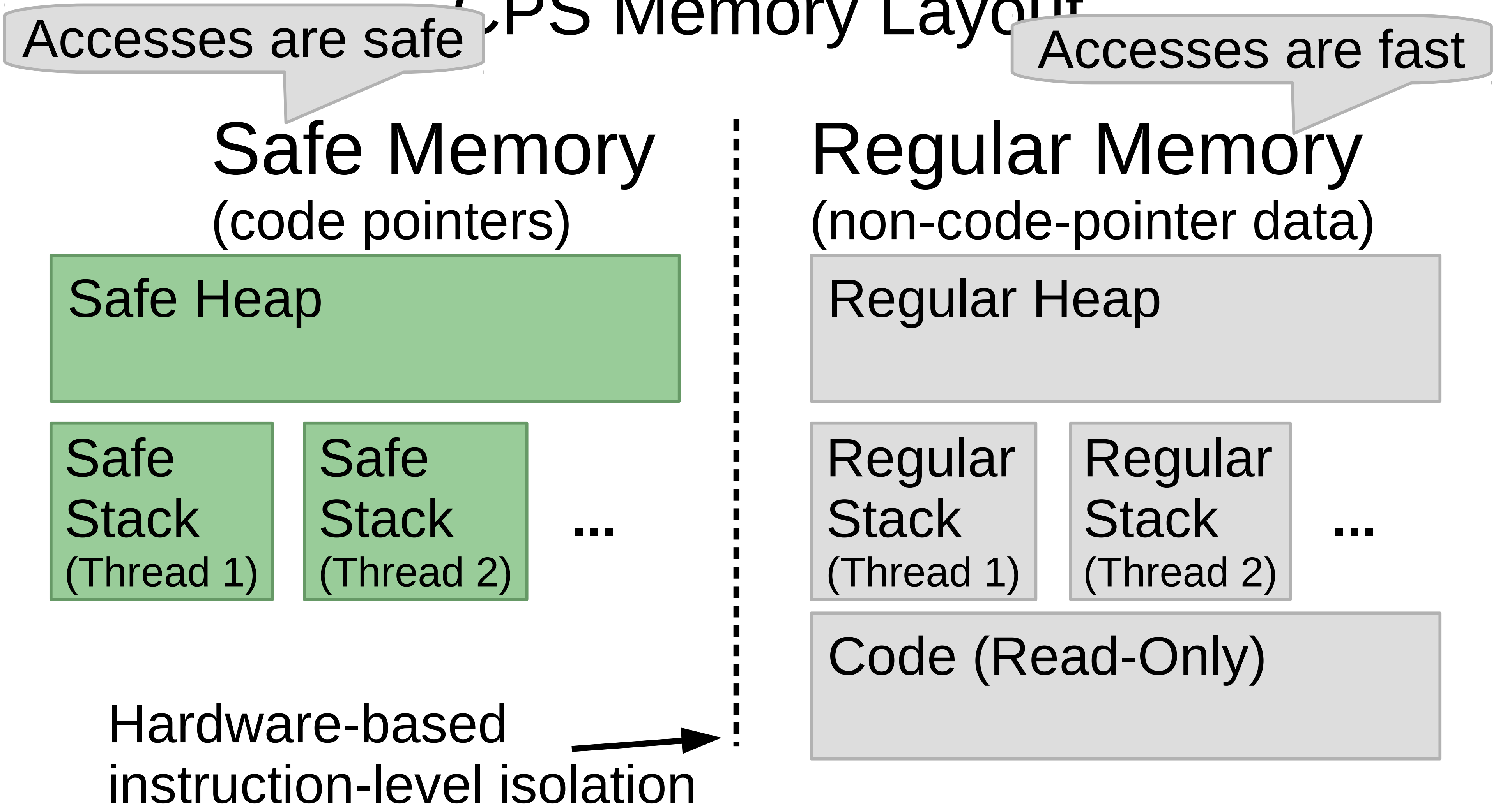
Code-Pointer Separation:




```
int foo() {
 char buf[16];
 int r;
 r = scanf("%s", buf);
 return r;
}
```

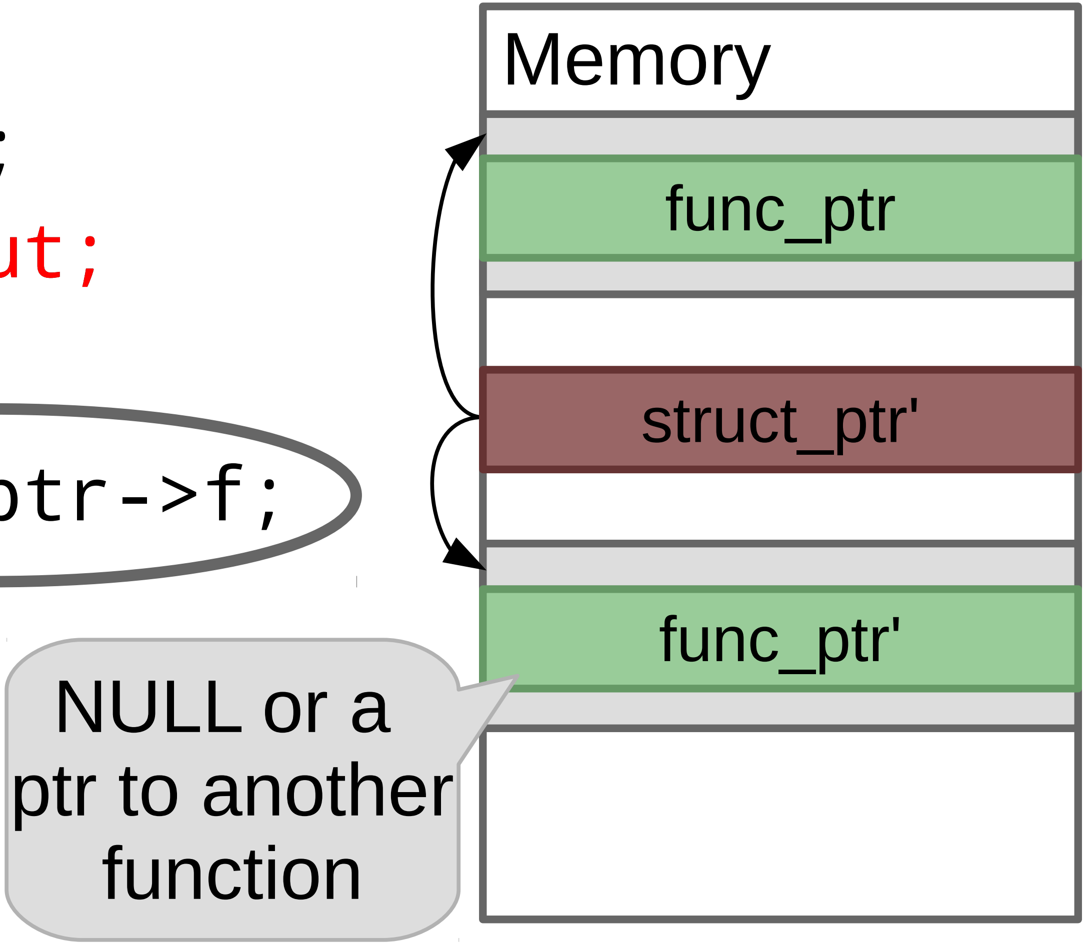


CPS Memory Layout



Attacking Code-Pointer Separation

```
void *(func_ptr)();
int *q = buf + input;
*q = input2;
…
func_ptr = struct_ptr->f;
…
(*func_ptr)();
```



Code-Pointer Separation

- Identify Code-Pointer accesses using static type-based analysis
- Separate using instruction-level isolation (e.g., segmentation)

- CPS security guarantees
  - An attacker cannot forge new code pointers
  - Code-Pointer is either immediate or assigned from code pointer
  - An attacker can only replace existing functions through indirection: e.g., foo->bar->func() vs. foo->baz->func2()

Code-Pointer Integrity (CPI)

Sensitive Pointers = code pointers and
pointers used to access sensitive pointers

- CPI identifies all sensitive pointers using an over-approximate type-based static analysis:

```
is_sensitive(v) = is_sensitive_type(type of v)
```

- Over-approximation only affects performance

  On SPEC2006 <= 6.5% accesses are sensitive

Attacking Code-Pointer Integrity

```
void *(func_ptr)();
int *q = buf + input;
q_lo = buf_lo; q_up = buf_up;
if (q < q_lo || q >= q_up)
 abort();
*q = input2;
func_ptr = struct_ptr->f;
…
(*func_ptr)();
```

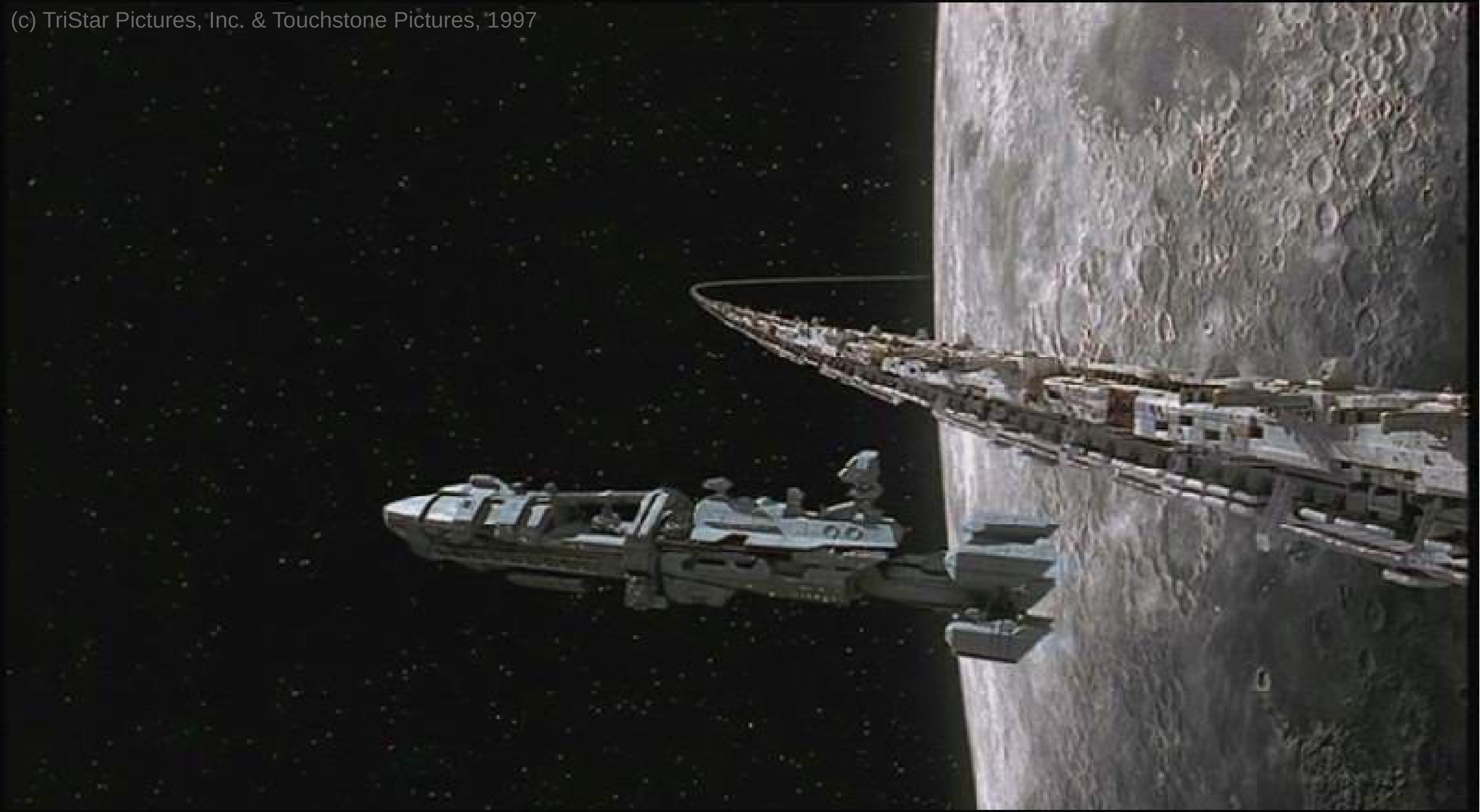
Exception when dereferenced

Code-Pointer Integrity vs. Separation

- Separate sensitive pointers from regular data
  - Type-based static analysis
  - Sensitive pointers = code pointers **+ pointers to sensitive pointers**
- Accessing sensitive pointers is **<u>safe</u>**
  - Separation **+ runtime (bounds) checks**
- Accessing regular data is **<u>fast</u>**
  - Instruction-level safe region isolation

Security Guarantees

- Code-Pointer Integrity: formally guaranteed protection
  - 8.4% to 10.5% overhead (~6.5% of memory accesses)
- Code-Pointer Separation: strong protection in practice
  - 0.5% to 1.9% overhead (~2.5% of memory accesses)
- Safe Stack: full ROP protection
  - Negligible overhead



Implementation

- LLVM-based prototype
  - Front end (clang): collect type information
  - Back-end (llvm): CPI/CPS/SafeStack instrumentation pass
  - Runtime support: safe heap and stack management
  - Supported ISA's: x64 and x86 (partial)
  - Supported systems: Mac OSX, FreeBSD, Linux

Current status

- Great support for CPI on Mac OSX and FreeBSD on x64
- Upstreaming in progress
  - Safe Stack coming to LLVM soon
  - Fork it on GitHub now: https://github.com/cpi-llvm
- Code-review of CPS/CPI in process
  - Play with the prototype: http://levee.epfl.ch/levee-early-preview-0.2.tgz
  - Will release more packages soon
- Some changes to super complex build systems needed
  - Adapt Makefiles for FreeBSD

Is It Practical?

- Recompiled entire FreeBSD userpsace
- … and more than 100 packages


DO
YOUR
PART!

Conclusion

- CPI/CPS offers strong control-flow hijack protection
  - Key insight: memory safety for code pointers only
- Working prototype
  - Supports unmodified C/C++, low overhead in practice
  - Upstreaming patches in progress, SafeStack available soon!
  - Homepage: http://levee.epfl.ch
  - GitHub: https://github.com/cpi-llvm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http://levee.epfl.ch
http://nebelwelt.net/publications/14OSDI/