Secure Virtual Architecture: Using LLVM to Provide Memory Safety to the Entire Software Stack

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What is Memory Safety?

Intuitively, the guarantees provided by a safe programming language (e.g., Java, C#)

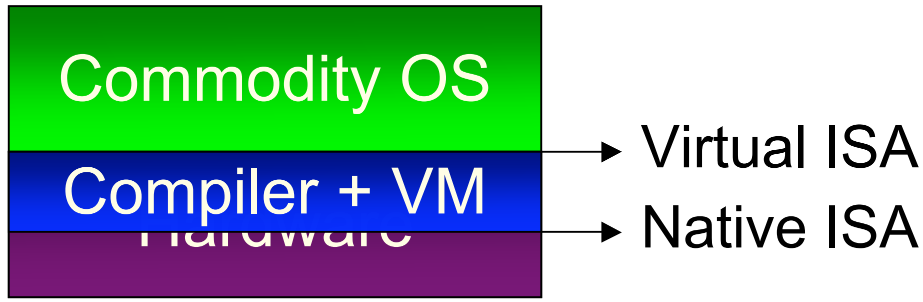
- Array indexing stays within object bounds
- No uses of uninitialized variables
- All operations are type safe
- No uses of dangling pointers
- Control flow obeys program semantics
- Sound operational semantics

Benefits of Memory Safety for Commodity OS Code

- Security
  - Memory error vulnerabilities in OS kernel code are a ***reality***[1]
- Novel Design Opportunities
  - Safe kernel extensions (e.g. SPIN)
  - Single address space OSs (e.g. Singularity)
- Develop New Solutions to Higher-Level Security Challenges
  - Information flow policies
  - Encoding security policies in type system

1. Month of Kernel Bugs (http://projects.info-pull.com/mokb/)

Secure Virtual Architecture

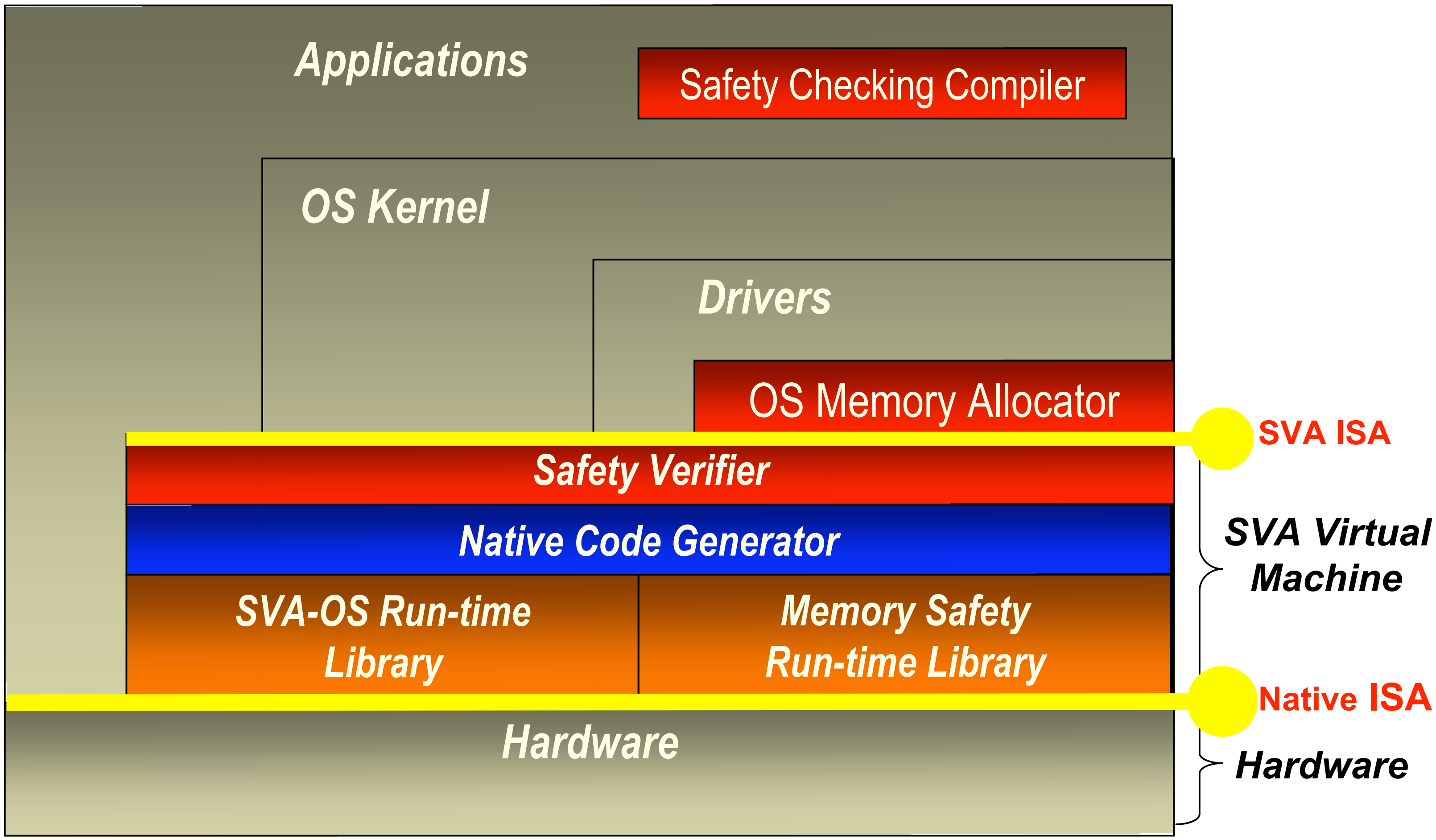


- Compiler-based virtual machine underneath software stack
  - Uses analysis & transformation techniques from compilers
  - Supports commodity operating systems (e.g., Linux)
- Typed virtual instruction set enables sophisticated program analysis
- Provide safe execution environment for commodity OSs

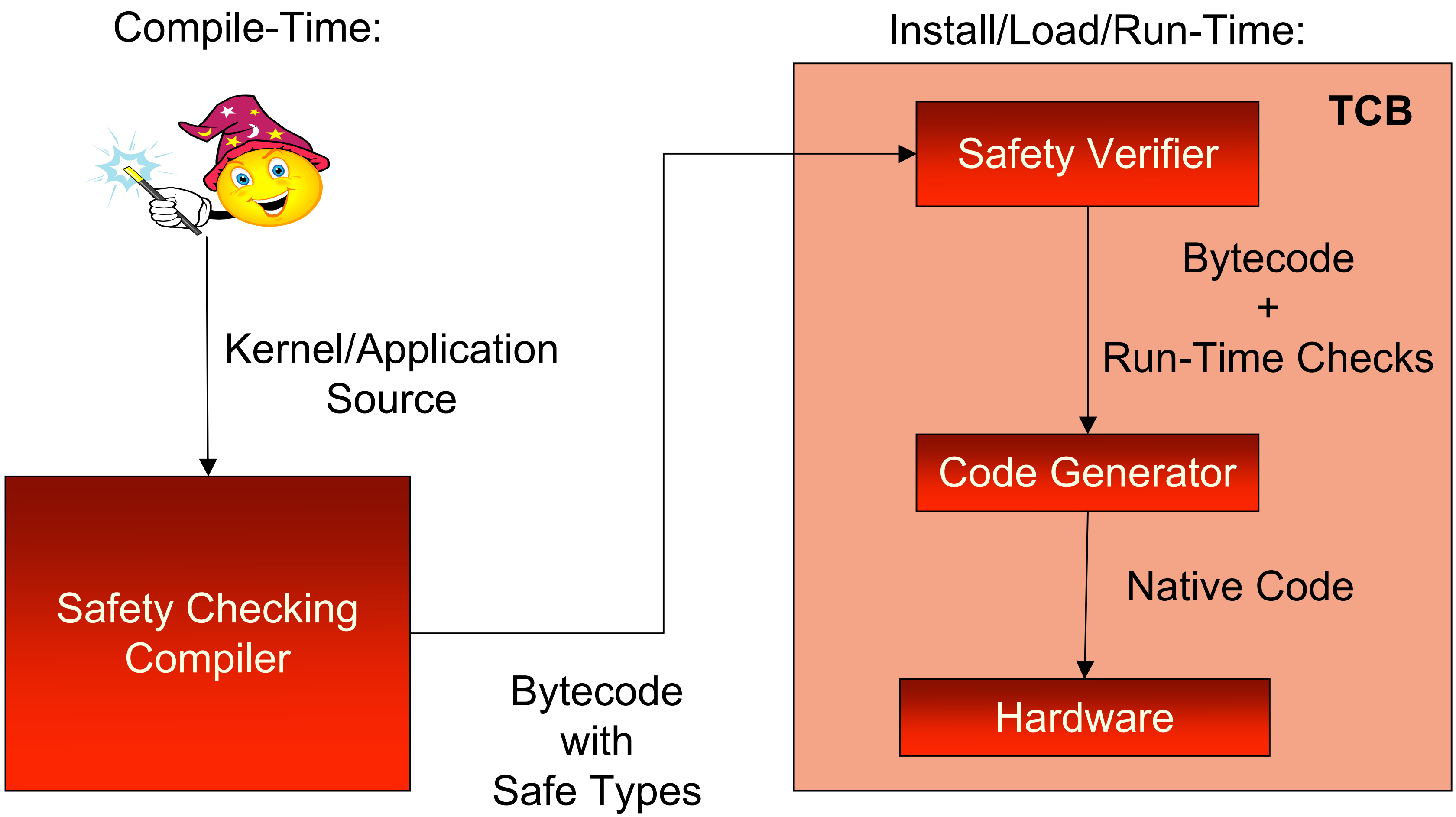
Outline

- ***SVA Architecture***
- SVA Safety
- Experimental Results

SVA System Architecture



Software Flow



Virtual Instruction Set

- SVA-Core
  - Subset of LLVM Instruction Set[1,2]
  - Typed, Explicit Control Flow Graph, Explicit SSA form
  - Sophisticated compiler analysis and transformation
- SVA-OS
  - OS-neutral instructions support commodity OSs
  - Removes difficult to analyze assembly code
  - Encapsulates privileged operations
  - Like porting to a new hardware architecture

1. [CGO 2004]
2. http://llvm.org

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SVA Safety Guarantees

Safe Language	*Secure Virtual Architecture*
Array indexing within bounds	Array indexing within bounds
No uses of uninitialized variables	No uses of uninitialized variables
Type safety for all objects	Type safety for subset of objects
No uses of dangling pointers	Dangling pointers are harmless
Control flow integrity	Control flow integrity
Sound operational semantics	Sound operational semantics

- Dangling pointers & non-type-safe objects do *not* compromise other guarantees
- Stronger than systems that do not provide *any* dangling pointer protection

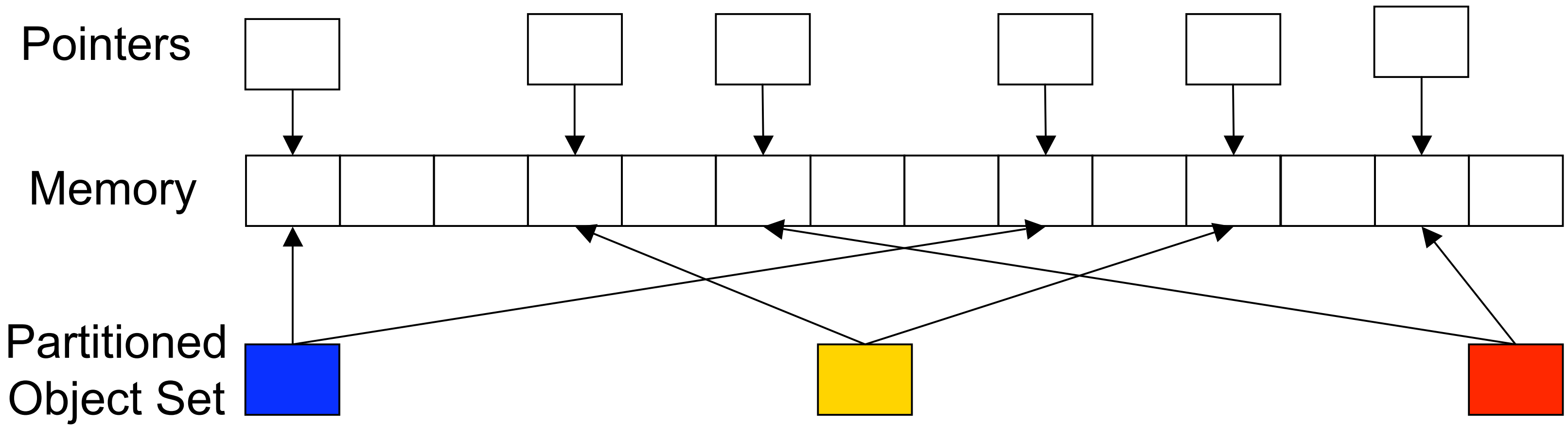
Safety Checks & Transforms

- Safety Checks
  - Load/Store Checks
  - Bounds Checks
  - Illegal Free Checks
  - Indirect Call Checks
- Safety Transforms
  - Stack to heap promotion
  - Memory initialization

<u>Object Bounds Tracking Methods</u>

- “Fat” Pointers [SafeC, CCured, Cyclone,…]
- Programmer Annotations [SafeDrive,…]
- Object Lookups [Jones-Kelly,SAFECode,…]

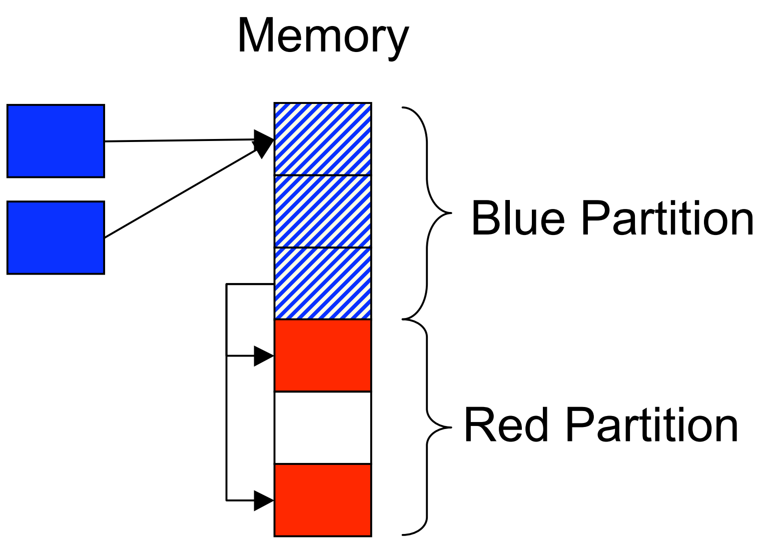
Improved Object Lookups[1]



- Alias analysis (DSA) groups objects into logical partitions
- Run-time records object allocations in partitions
- Run-time checks only consider objects in a single partition
- Reduces slowdown from 4x-11x to 10%-30% for nearly all standalone programs, daemons

1. Dhurjati et al. [ICSE 2006]

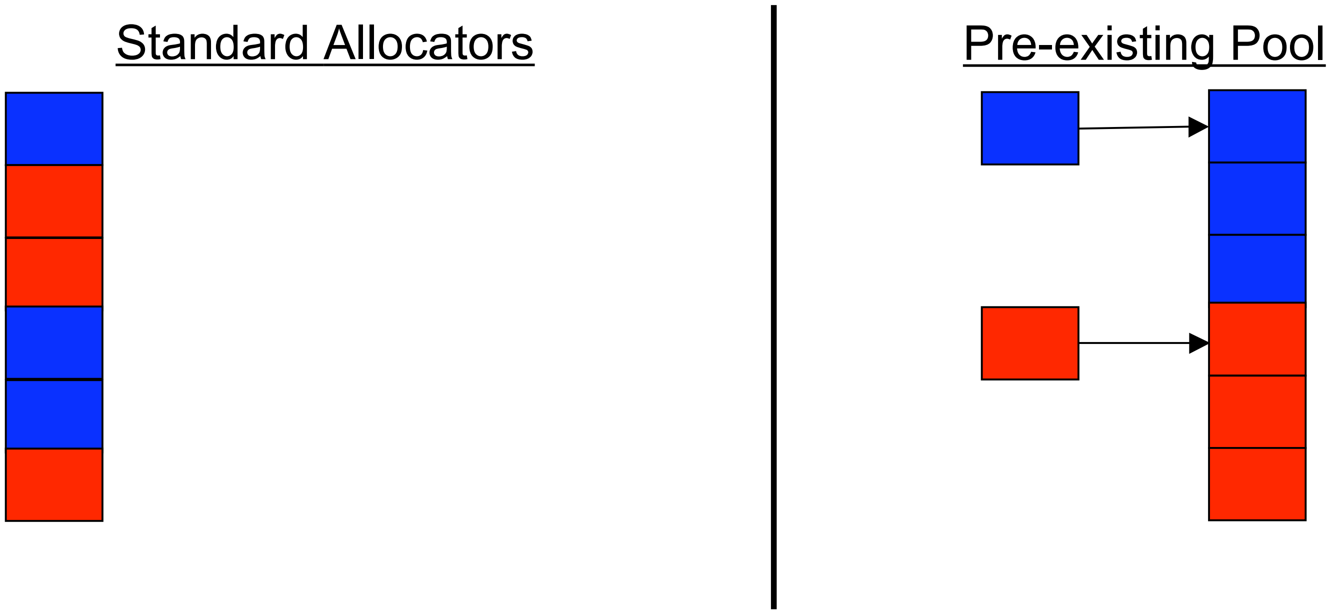
Type Safe (Homogeneous) Partitions[1]



- Alias analysis performs type inference
- Type-homogeneous partitions reduce run-time checks:
  - No load/store checks
  - No indirect call checks
  - Harmless dangling pointers
- Type-unsafe partitions require all run-time checks
- Proved sound operational semantics [PLDI 2006]

1. Dhurjati et al. [TECS 2005, PLDI 2006]

Memory Allocator Requirements



- Memory for type-homogeneous partitions cannot be used by other partitions
- Objects must be aligned at a multiple of the object size

Outline

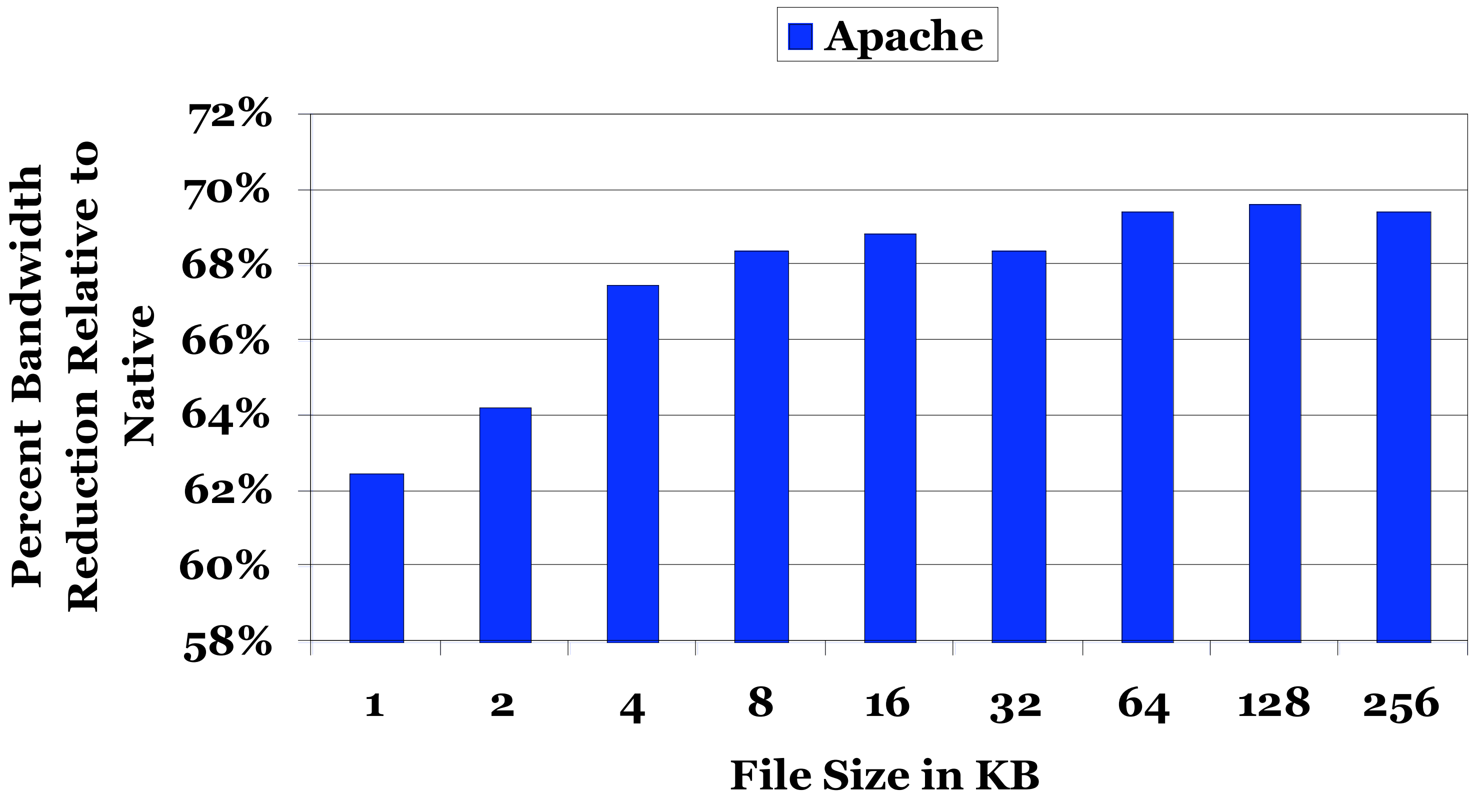
- SVA Architecture
- SVA Safety
- ***Experimental Results***

Prototype Implementation

- Ported Linux to SVA instruction set
  - Similar to porting to new hardware architecture
  - Compiled using LLVM
- Wrote SVA-OS as run-time library linked into kernel
- Provide safety guarantees to ***entire*** kernel except:
  - Memory management code
  - Architecture-dependent utility library
  - Architecture-independent utility library

Web Server Bandwidth

- Each measurement is median of 3 runs
- Memory safety overhead less than 70%



Exploits

- Tried 5 memory exploits that work on Linux 2.4.22
- Uncaught exploit due to code not instrumented with checks

BugTraq ID	***Kernel Component***	***Caught?***
11956	Console Driver	*Yes!*
10179	TCP/IP	*Yes!*
11917	TCP/IP	*Yes!*
12911	Bluetooth Protocol	*Yes!*
13589	ELF/Support Library	No

Performance Improvements

- Source code changes
- Smarter run-time checks
  - Selective use of “fat” pointers
  - Pre-checking all accesses within monotonic loops
  - Removing redundant object lookups and run-time checks
  - Very fast indirect call checks
- Improve static analysis
  - Stronger type inference
  - More precise call graph
  - Restore context sensitivity
  - Static array bounds checking

Future Work

- Ensure safe use of:
  - SVA-OS instructions
  - MMU configuration
  - DMA operations
- Novel OS Designs
  - Recovery semantics for the virtual machine
  - Private application memory
  - Information flow

SAFECode Release

- Currently building memory debugger tool
  - Array bounds checks
  - Uninitialized pointer checks
  - Invalid control flow checks
  - Optional dangling pointer detection[1]

1. Dhurjati et al. [DSN 2006]

Extras!

Questions?

See what we do at http://sva.cs.uiuc.edu