Enforcing Forward-Edge Control-Flow Integrity in GCC & LLVM

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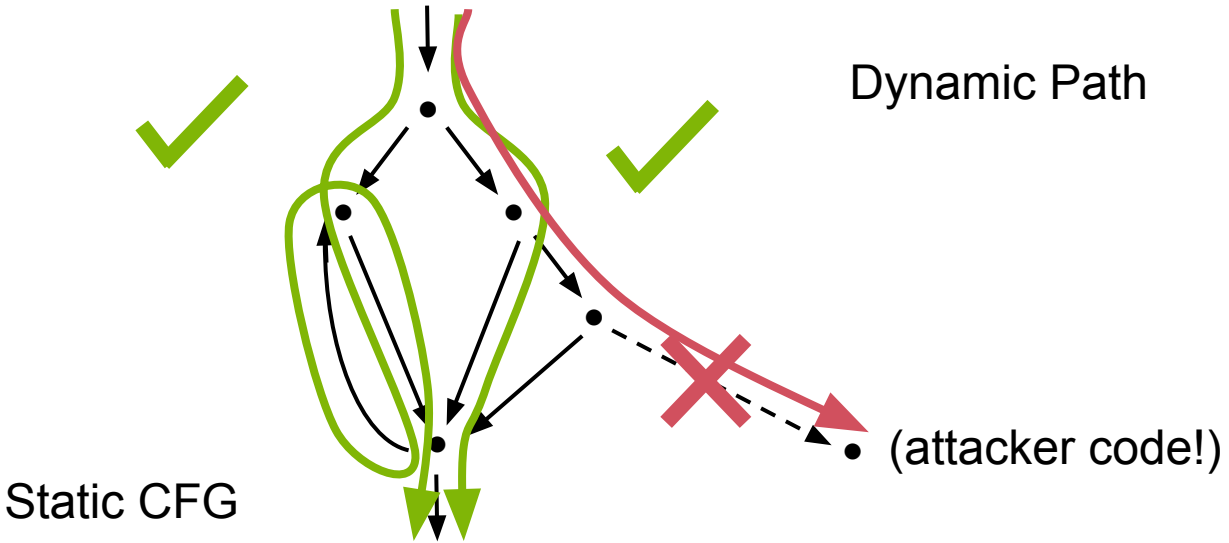
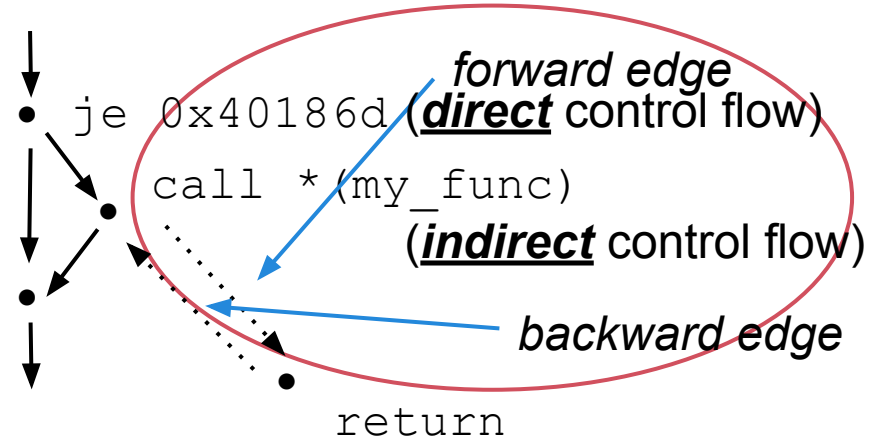
What is Control-Flow Integrity?

Control Flow Integrity (CFI) is a security policy that dictates that the software execution must follow the path of a previously determined control flow graph (CFG).



How can branch targets be attacked?

- Targets are hard-coded (in non-writable memory)...
- ...except when on the heap…
- ...or on the stack.



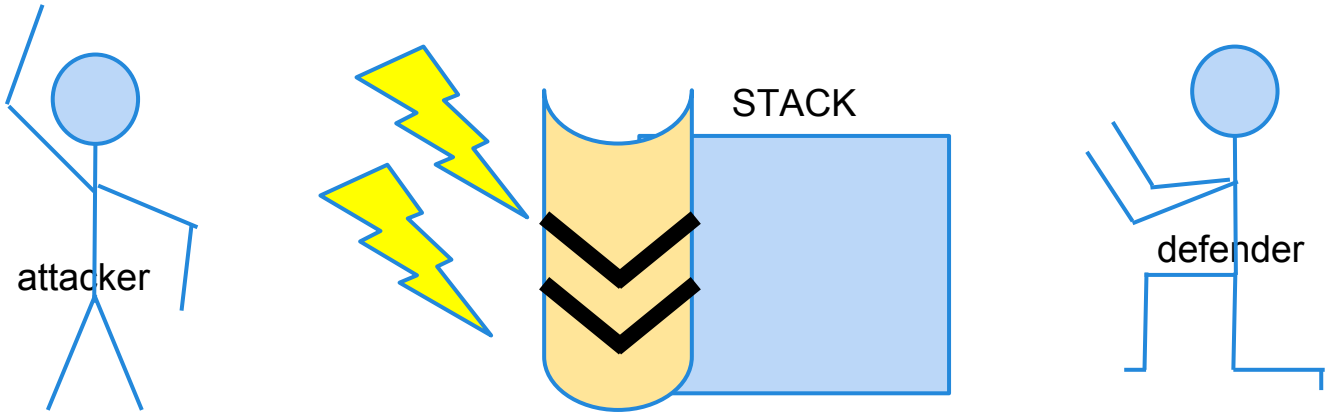
Heap

```
my_func: 0x123
```

Stack

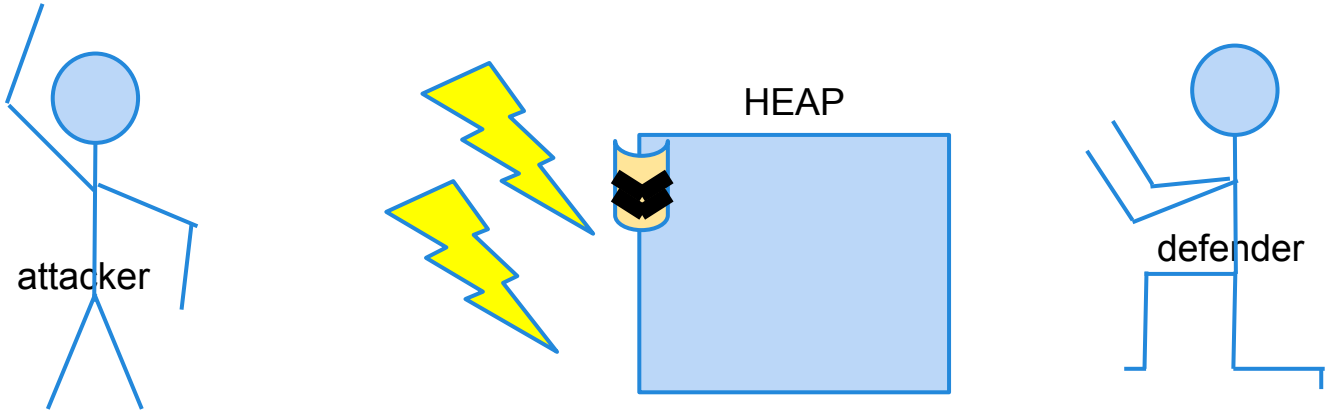
```
<ret addr>:
0xabc
```

So...why focus on *forward-edge*?



Attacks	Defenses
Buffer Overflow	Stack Canaries, Layout Reordering
Return-Oriented Programming	Address-Space Layout Randomization (ASLR)
Return-to-libc	Coding patterns that avoid stack buffers

Status of forward-edge defenses?



Attacks	Defenses
Buffer overflow / fake vtables	Heap-Metadata Canaries
Exploit use-after-free bugs	Address-Space Layout Randomization
Heap spraying / feng shui	Various ad hoc CFI attempts

Our Overall Contribution

Practical CFI enforcement in production compilers,
for forward edges.

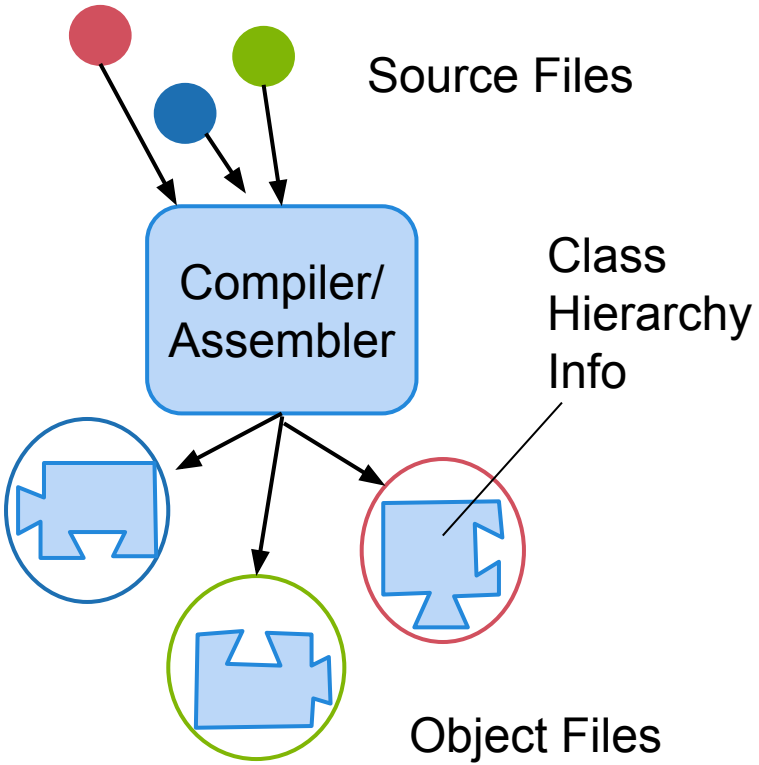
What do we have to offer?

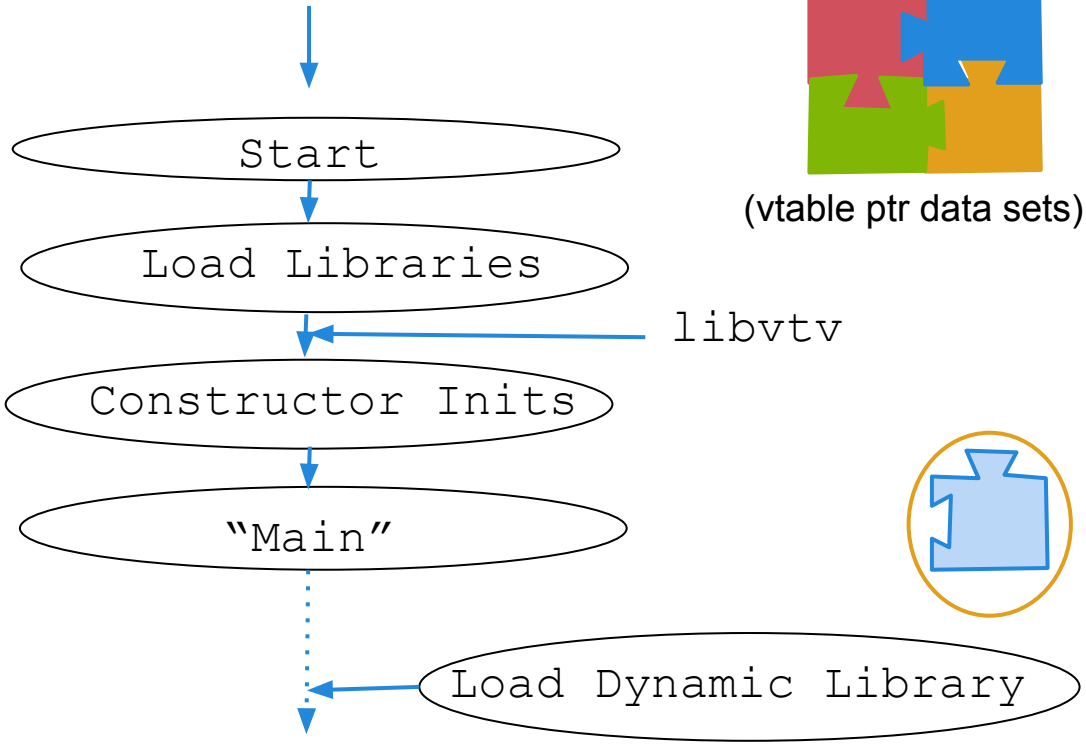
- Integrated forward-edge CFI into GCC & LLVM.
- No restrictions or simplifying assumptions.
- Scales completely.
- Strong security guarantees.
- Low performance degradation.

What *exactly* did we do?

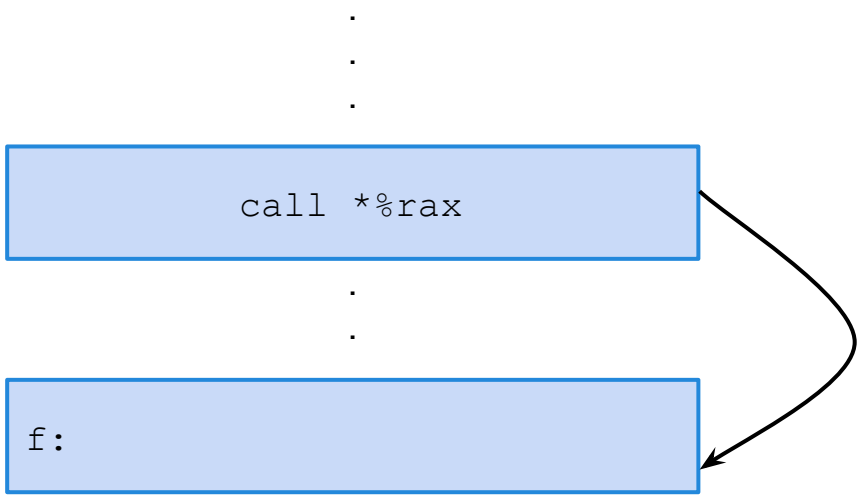
- Vtable Verification (VTV), in GCC 4.9
- Indirect Function Call Checker (IFCC), in LLVM
- Indirect Function Call Sanitizer (FSan), in LLVM

VTV Pointer Data Set details

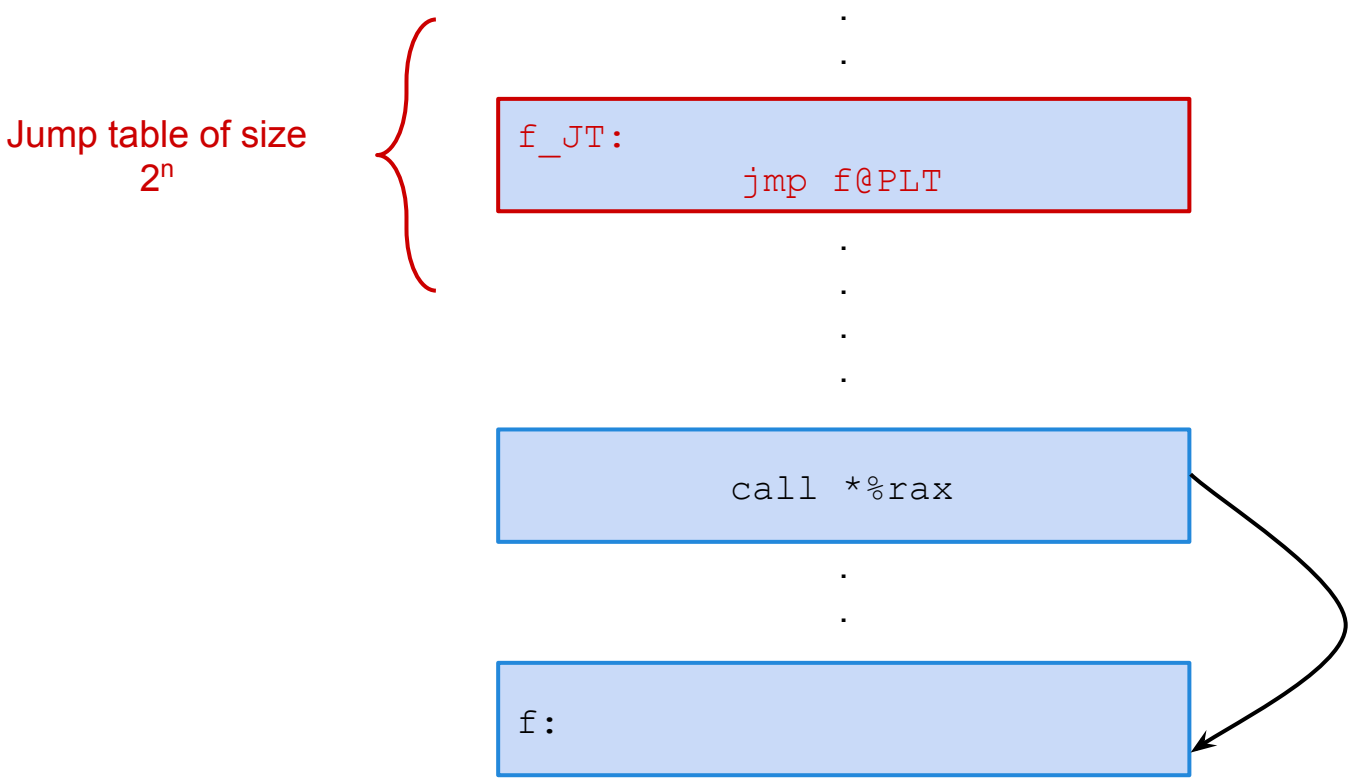




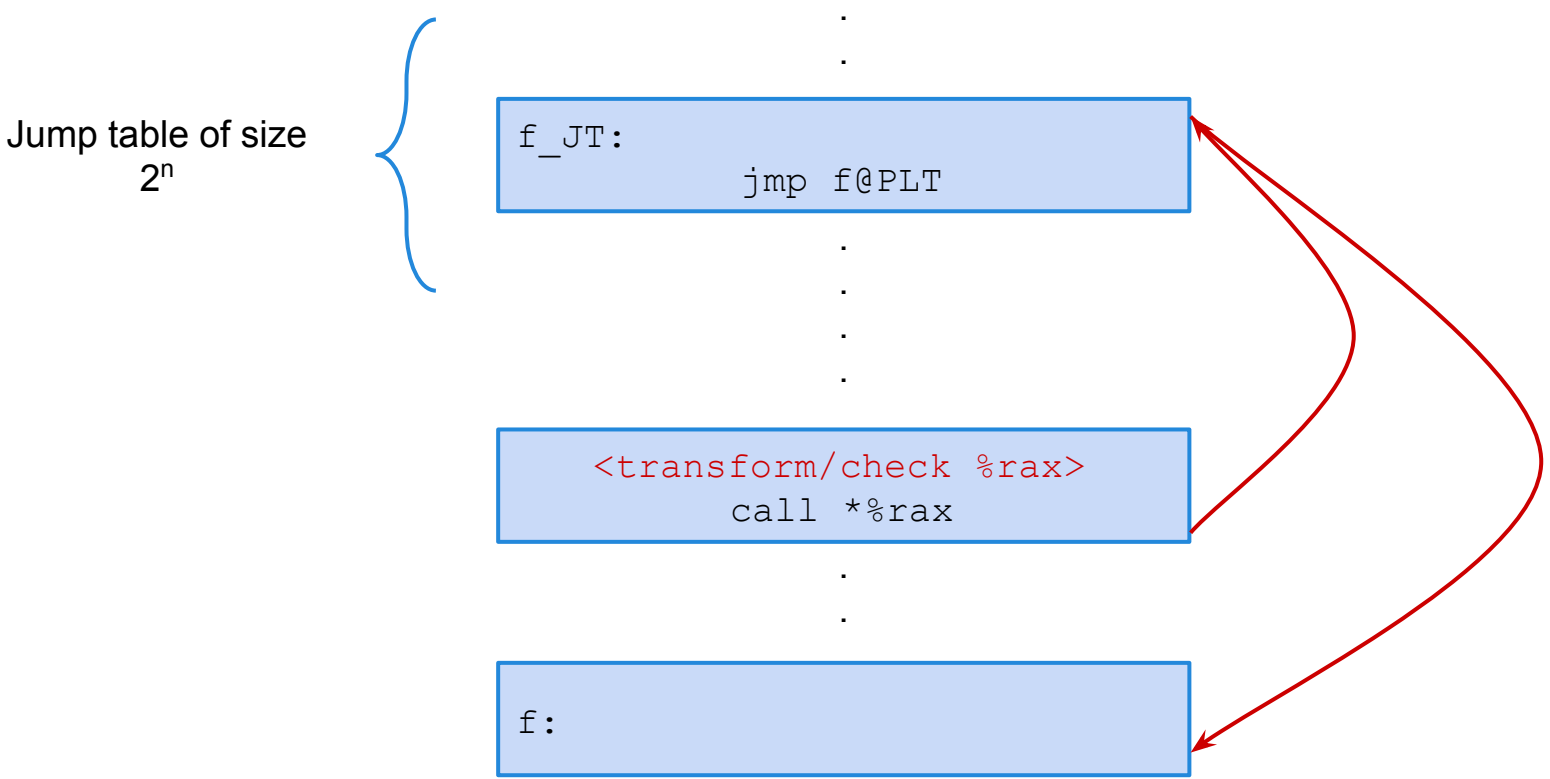
IFCC: Function Verification Details



IFCC: Function Verification Details



IFCC: Function Verification Details



Measurements: What & How?

- Security
  - AIR = Average Indirect-target Reduction [Zhang '13]
    - ~ fraction of protected indirect control flow insns.
    - *f*AIR = "forward-edge AIR"

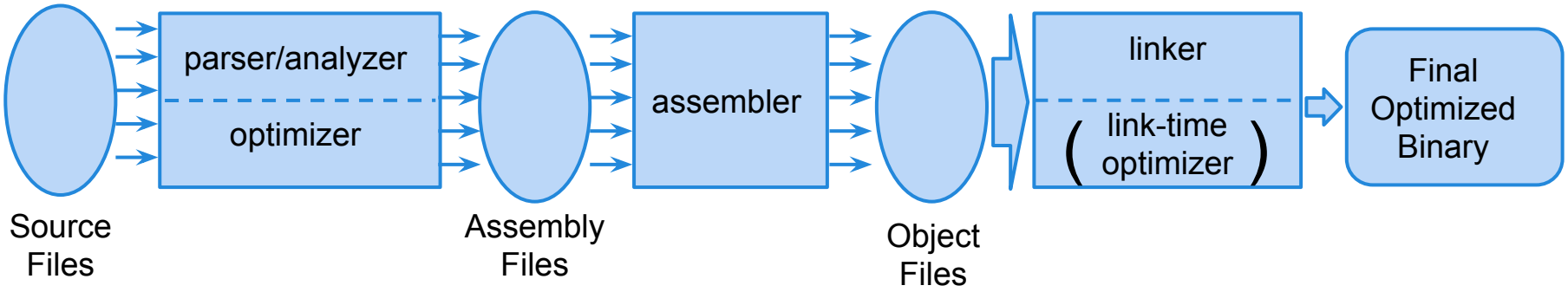
- Run-time performance degradation
  - SPEC 2006 C++ benchmarks
  - Chromium web browser
    - dromaeo, sunspider, octane benchmarks

How do they compare?

	VTV	IFCC	FSan
Security	*f*AIR = 95.2%	*f*AIR = 99.8%	NA
Performance Penalty	1.6% - 8.7%	1.9% - 3.4% (0.6% - 5.8%)	2.2% - 9.1%
Precision guarantees	Target is in a *correct* class for call site.	Target is a function (of correct arity) in original program.	Target has correct signature.
Applicability	- C++ only - Virtual calls only	- Any LLVM lang. - All indirect calls	- C++ only - All indirect calls

What have we learned?

- Fully integrating CFI w/compiler helps with performance.
- Do security analysis on *final* compiler output.
  - Some optimizations could affect security passes.
- Incremental compilation: Incomplete data => false +'s (execution aborts -- MUST AVOID!!).



What have we learned (cont.)?

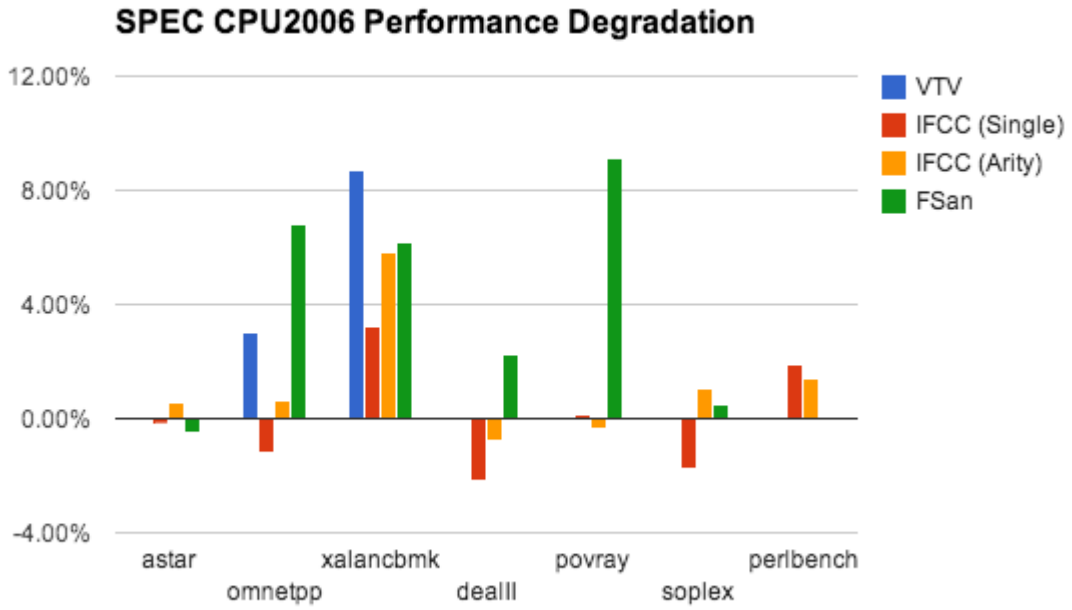
- Need to support dynamic library loading.
  - Purely statically linked binaries are hard to find!
- Mixed verified & unverified code (e.g. libraries):
  - Another source of incomplete information!
  - Requires ability for programmer intervention:
    - IFCC: Allows explicitly disabling verification for specified functions.
    - VTV: Allows modifying the failure function, e.g. w/whitelist or secondary verification.

Questions & Answers...

Practical CFI enforcement in production compilers for forward edges.

Back up slides come next.

Performance - SPEC CPU2006



Performance - Chromium