Control-Flow Integrity For COTS Binaries

Mingwei Zhang and R. Sekar
Stony Brook University
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Talk Outline

Motivation

Static analysis

Binary instrumentation

CFI properties and metric

Evaluation

Summary

Background

What is Control-Flow Integrity?

- **Program execution follows a statically-constructed control-flow graph (CFG)**

Why CFI?

- **a foundation for other low-level code defenses, e.g., SFI, sandboxing untrusted code, …**
- **defeats low level attacks on binaries**
  - **Code injection, ROP, JOP, …**
- **deterministic, not probabilistic defense**

Motivation for this work

- **Many previous works closely related to CFI**
  - CFI [Abadi et al 05, Abadi et al 2009, Zhang et al 2013]
  - Instruction bundling [MaCamant et al 2008, Yee et al 2009]
  - Indexed Hooks [2011], Control-flow locking [Bletsch et al 2011]
  - MoCFI [Davi et al 2012], Reins [Wartell et al 2012]…
- **Require compiler support, or binaries that contain relocation, symbol, or debug info**
- **Do not provide complete protection**
  - **Leave out executable, libraries, or the loader**
- **Have a difficult time balancing strength of protection and compatibility with large binaries**

Preview of Results

- **Robust on large and low-level binaries**
  - *glibc, gimp-2.6, adobe reader 9, firefox 5*
  - *executables as well as libraries*
- **Compatible yet strong policy**
  - *93% of ROP/JOP gadgets*
- **Good performance**
  - *~10% on CPU-intensive C/C++ benchmark (SPEC 2006), (~4% if restricted to C-programs)*
- **Limitations**
  - *Does not support obfuscated binaries or malware*
  - *No runtime code generation or JIT (yet)*
  - *Implemented for 32-bit Linux, tested with gcc and LLVM*

Key Challenges

- **Disassembly and Static analysis of COTS binaries**
- **Robust static binary instrumentation**
  - Without breaking low-level code
  - Transparency for position-independent code, C++ exceptions, etc.
- **Modular instrumentation**
  - Applied to executables and libraries
  - Enables sharing library code across many processes
- **Assess compatibility/strength tradeoff**

Disassembly Errors

- **Disassembly of non-code**
  - Tolerate these errors by leaving original code in place
- **Incorrect disassembly of legitimate code**
  - Instruction decoding errors (not a real challenge)
  - *Instruction boundary errors*
    - Harmful – our technique geared to find and repair them
  - Failure to disassemble (we avoid this)

Disassembly Algorithm

1 **Linear disassembly**

2 **Error detection**

- invalid opcode
- direct jump/call outside module address
- direct control into insn

3 **Error correction**

- Identify "gap:" data/padding disassembled as code
  - Scan backward to preceding unconditional jump
  - Scan forward to next direct or indirect target
    - *Indirect targets obtained from static analysis*

4 **Mark "gap," repeat until no more errors**

Static Analysis

Code pointers are needed:

- **to correct disassembly errors**
- **to constrain indirect control flow (ICF) targets**

We classify code pointers into categories:

- **Code Pointer Constants (CK)**
- **Computed Code Pointers (CC)**
- Exception handlers (EH)
- Exported symbols (ES)
- Return addresses (RA)

Static Analysis

- **Code pointer constants**
  - *Scan for constants :*
    - *at any bye offset within code and data segments*
    - *fall within the current module*
    - *point to a valid instruction boundary*
- **Computed code pointers**
  - *Does not support arbitrary arithmetic, but targets jump tables*
  - *Uses static analysis of code within a fixed-size window preceding indirect jump*

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Instrumented Module

ELF header phdr	Original code metadata, .rodata	Original data ..bss	New code New data

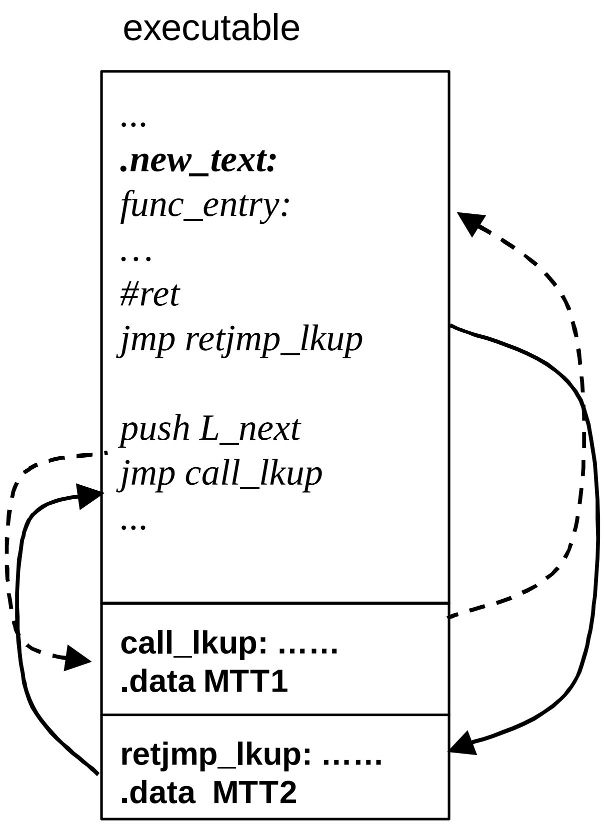
- **Translating function pointers**
  - *Appear as constants in code, but can't statically translate*
  - *Solution (from DBT): Runtime address translation*
- **Full transparency:** all code pointers, incl. dynamically generated ones, target original code [Bruening 2004]
  - *Important for supporting unusual uses of code pointers*
    - *To compute data addresses (PIC-code , data embedded in code)*
    - *C++ exception handling*

Static Instrumentation for CFI

- **Goal: constrain branch targets to those determined by static analysis**
  - *Direct branches: nothing to be done*
  - *Indirect branches: check against a table of (statically computed) valid targets*
- **Key observation**
  - *CFI enforcement can be combined with address translation!*

Modularity

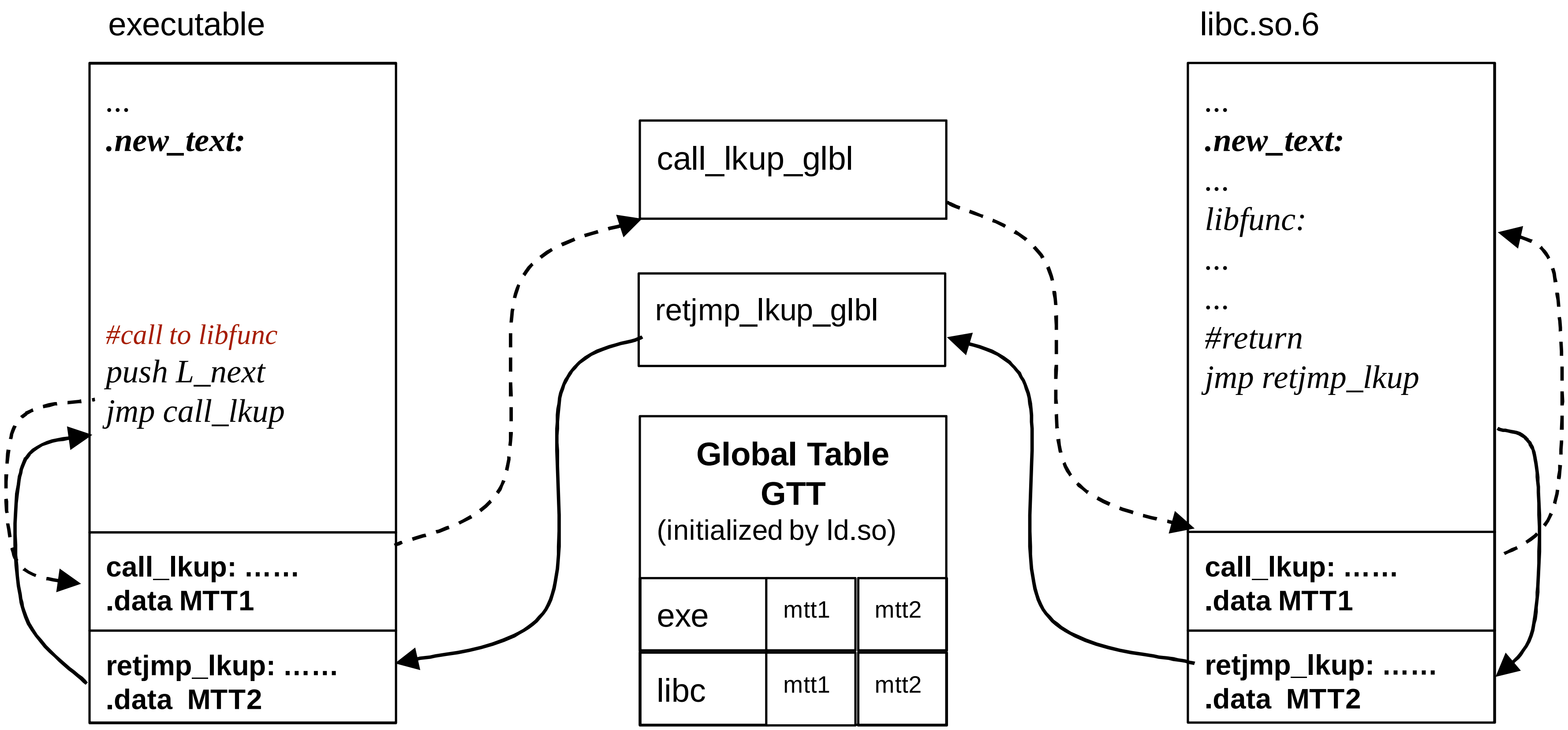
Intra-module control transfer: MTT



What if the target is out side of the module ?

Modularity

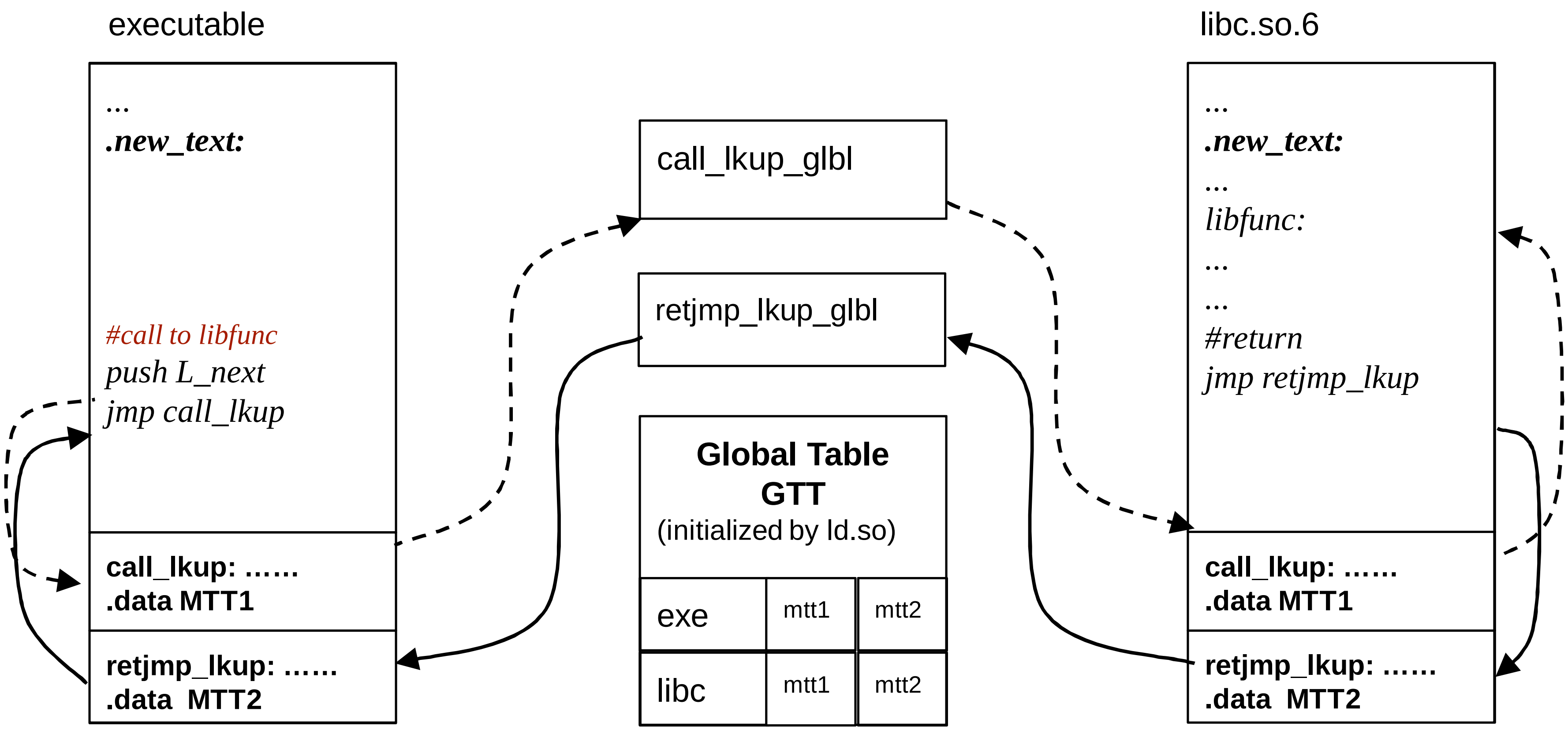
Inter-module control transfer: GTT



update of GTT is done in ld.so

Modularity

Code injection: null GTT entry



GTT only maps code !

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Basic version of CFI

- **return: target next of call**
- **call/jmp: target any function whose address is taken**
  - Obtainable from relocation info ("reloc-CFI")
  - matches implementation described in [Abadi et al 2005]

- **How to cope with missing relocation info?**
  - *Use static analysis to over-approximate function addresses taken*
- **"Strict-CFI"**

CFI Real-World Exceptions

- **special returns**
  a. *as indirect jumps (lazy binding in ld.so)*
  b. *going to function entries (setcontext(2))*
  c. *not going just after call (C++ exception)*
- **calls used to get PC address**
- **jump as a replacement of return**

binCFI Policy

bin-CFI	Returns (RET), Indirect Jumps (IJ)	Indirect Calls (IC), PLT jumps (PLT)
Return addresses (RA)	Y	
Exception handling addresses (EH)	Y (C++)	
Exported symbol addresses (ES)		Y
Code pointer constants (CK)	Y (C++, Context switch)	Y (GNU_IFUNC)
Computed code addresses (CC)	Y (return as jump)	Y (GNU_IFUNC)

Well, is this policy too weak ?

Measuring “Protection Strength”

- **Average Indirect target Reduction (AIR)**
  a. *T_j: number of possible targets of jth ICF branch*
  b. *S: all possible target addresses (size of binary)*

$$\frac{1}{n}\sum_{j=1}^{n}\left(1-\frac{|T_j|}{S}\right)$$

- **AIR is a general metric that can be applied to other control-flow containment approaches**

Coarser versions of CFI

bundle-CFI:

- **all ICF targets aligned on 2^n-byte boundary, n = 4 (PittSFIeld) or 5 (Native Client)**

instr-CFI: the most basic CFI

- **all ICFTs target instruction boundaries**

AIR metric (single module)

Name	Reloc CFI	Strict CFI	**Bin CFI**	Bundle CFI	Instr CFI
perlbench	98.49%	98.44%	**97.89%**	95.41%	67.33%
bzip2	99.55%	99.49%	**99.37%**	95.65%	78.59%
gcc	98.73%	98.71%	**98.34%**	95.86%	80.63%
gobmk	99.40%	99.40%	**99.20%**	97.75%	89.08%
……	……	……	**……**	……	……
average	**99.13%**	**99.08%**	**98.86%**	**96.04%**	**79.27%**

- **Loss due to use of static analysis is negligible**
- **Loss due to binCFI relaxation is very small**

Evaluation

Disassembly testing

Real world program testing

Gadget elimination

Disassembly Testing

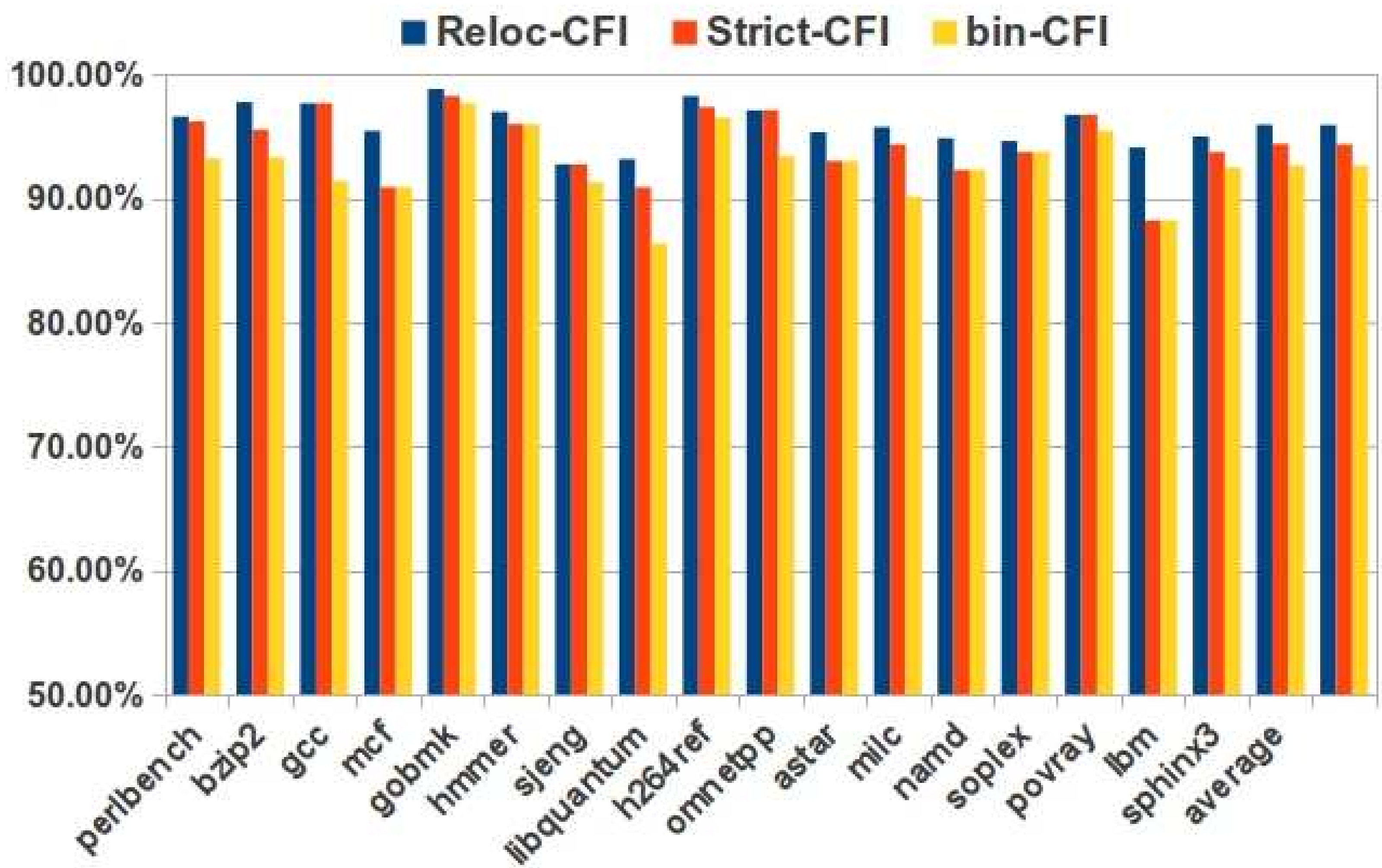
Module	Package	Size	Instruction#	errors
libxul.so	firefox-5.0	26M	4.3M	0
gimp-console-2.6	gimp-2.6.5	7.7M	385K	0
libc.so	glibc-2.13	8.1M	301K	0
libnss3.so	firefox-5.0	4.1M	235K	0
……	……	……	……	……
Total		58M	5.84M	0

"diff" compiler generated assembly and our disassembly

Real world program testing

Application Name	Experiment
firefox 5 (no JIT)	open web pages
acroread9	open 20 pdf files; scroll;print;zoom in/out
gimp-2.6	load jpg picture, crop, blur, sharpen, etc.
Wireshark v1.6.2	capture packets on LAN for 20 minutes
lyx v2.0.0	open a large report; edit; convert to pdf/dvi/ps
mplayer 4.6.1	play an mp3 file
…...	….........
Total:	12 real world programs

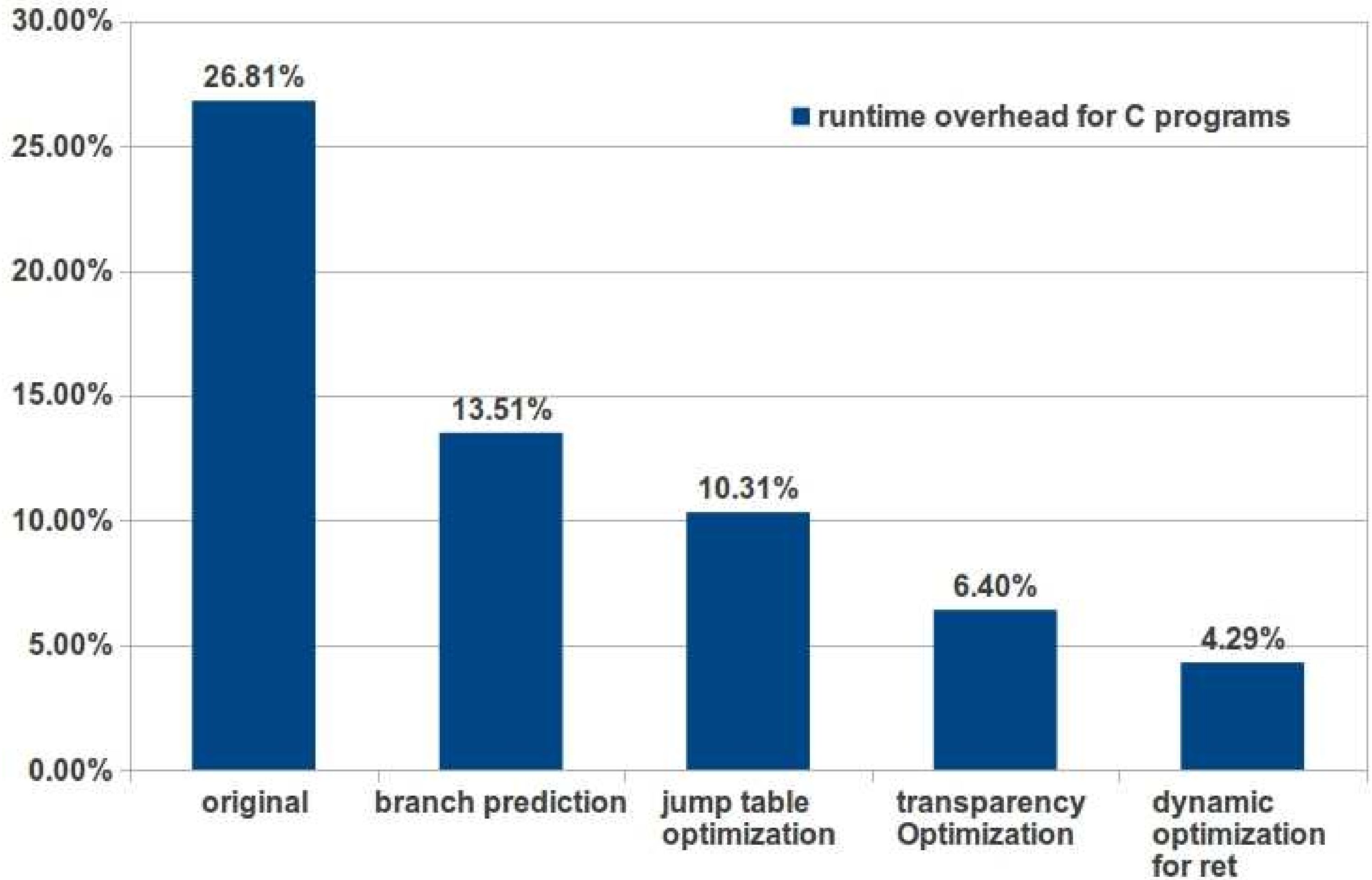
Gadget Elimination



Optimizations

- Branch prediction: Optimized translation of calls and returns, avoiding indirect jumps
- Jump table: Avoid runtime address translation in jump tables
- Transparency optimization: Avoid address translation for returns (but check validity)
- Dynamic optimization for returns: Fast check for most frequent target

Effect of Optimizations



Questions?