Generating Low-Overhead Dynamic Binary Translators

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Motivation

- Binary Translation (BT) well known technique for “late” transformations
  - Extend or add features on the fly

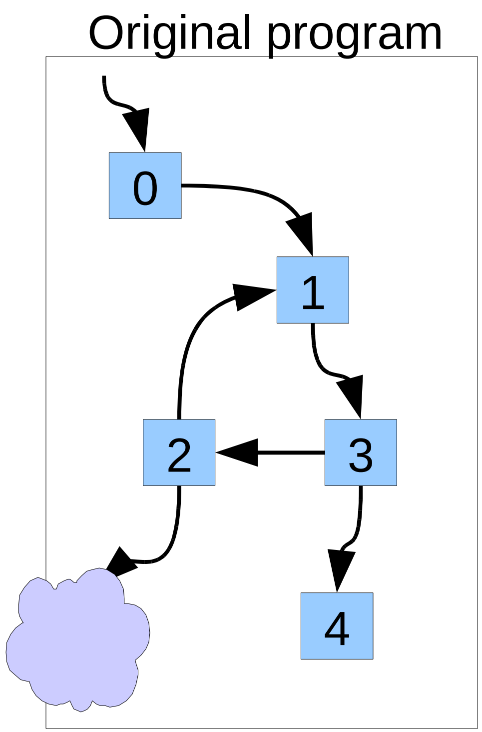
- Flexibility of dynamic software BT incurs runtime overhead

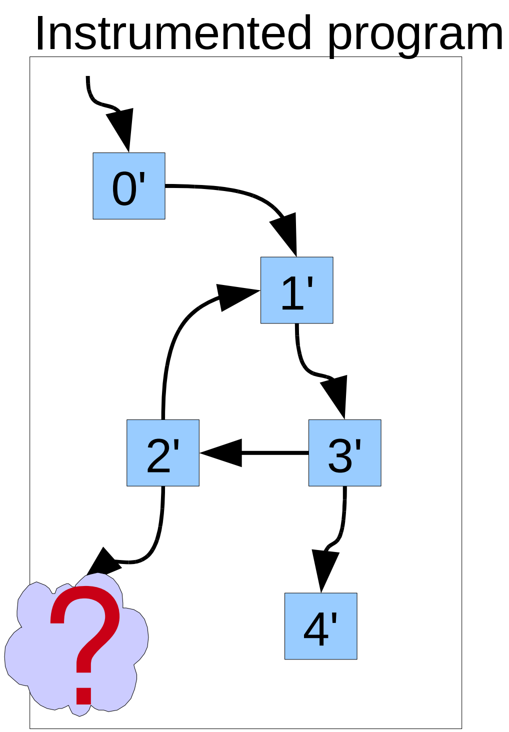
- Complexity of transformations can be a challenge
  - Offer a high-level interface at compile time, compile into effective translation tables

Outline

- Introduction
- Design and Implementation
  - Table generation
  - Translator
- Optimization
- Conclusion

Binary Translation in a Nutshell



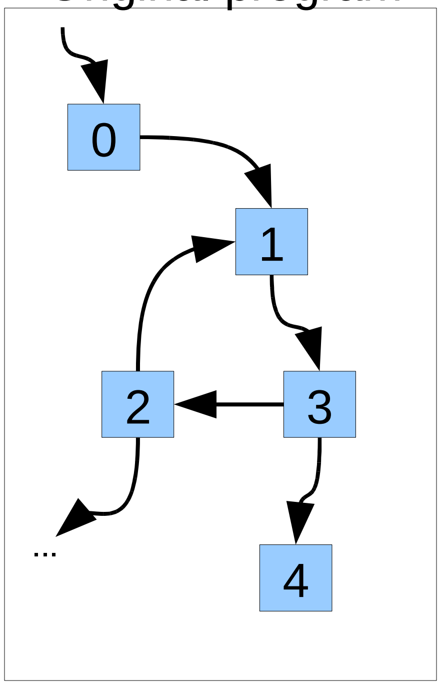


What about:

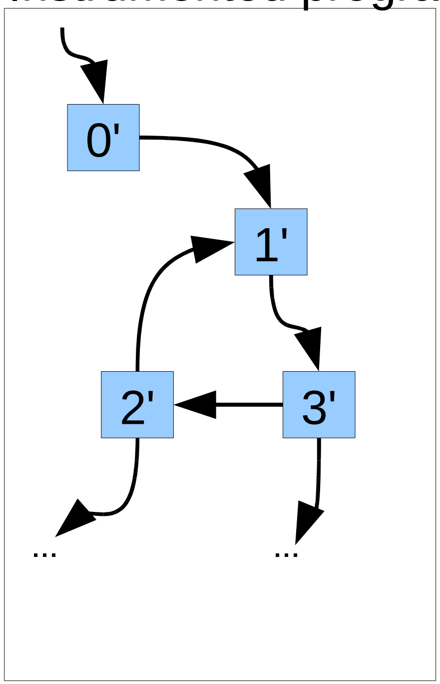
- Self modifying code?
- Shared libraries?
- Obfuscated Code?

Binary Translation in a Nutshell

Original program



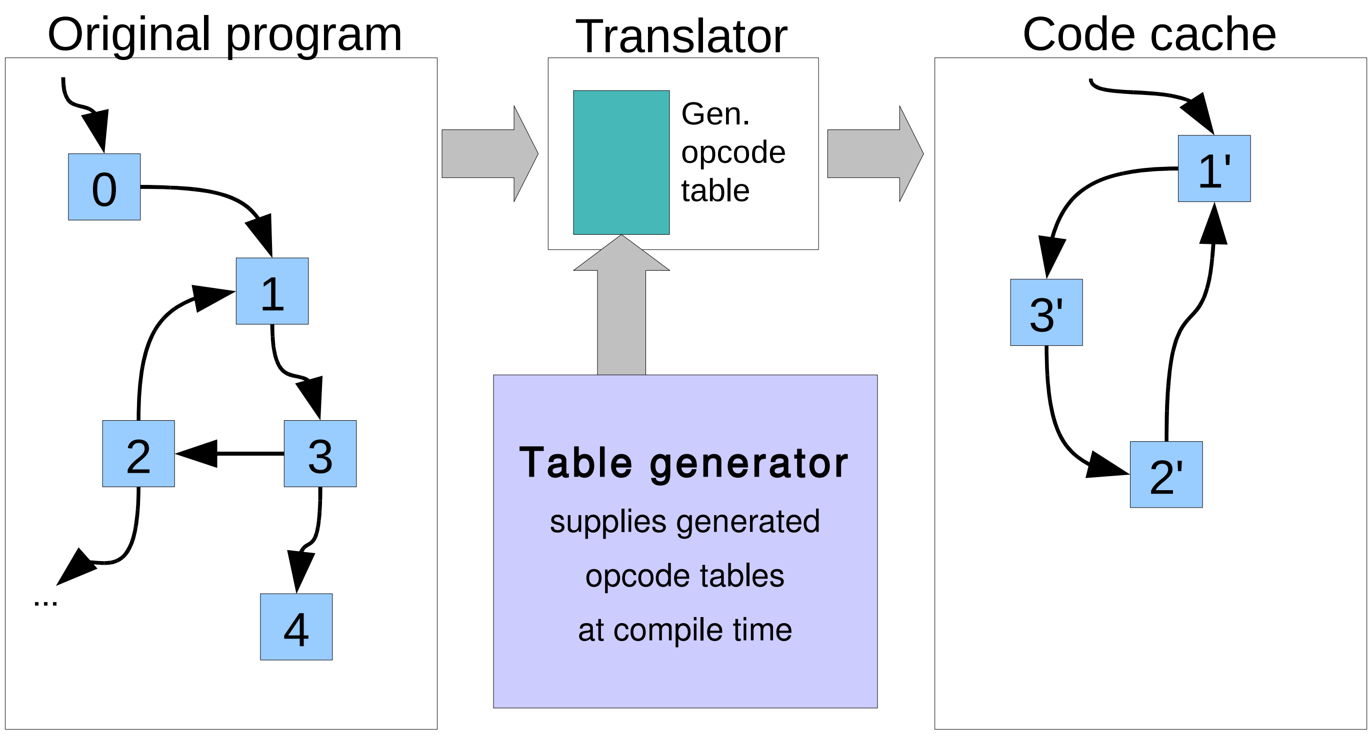
Instrumented program



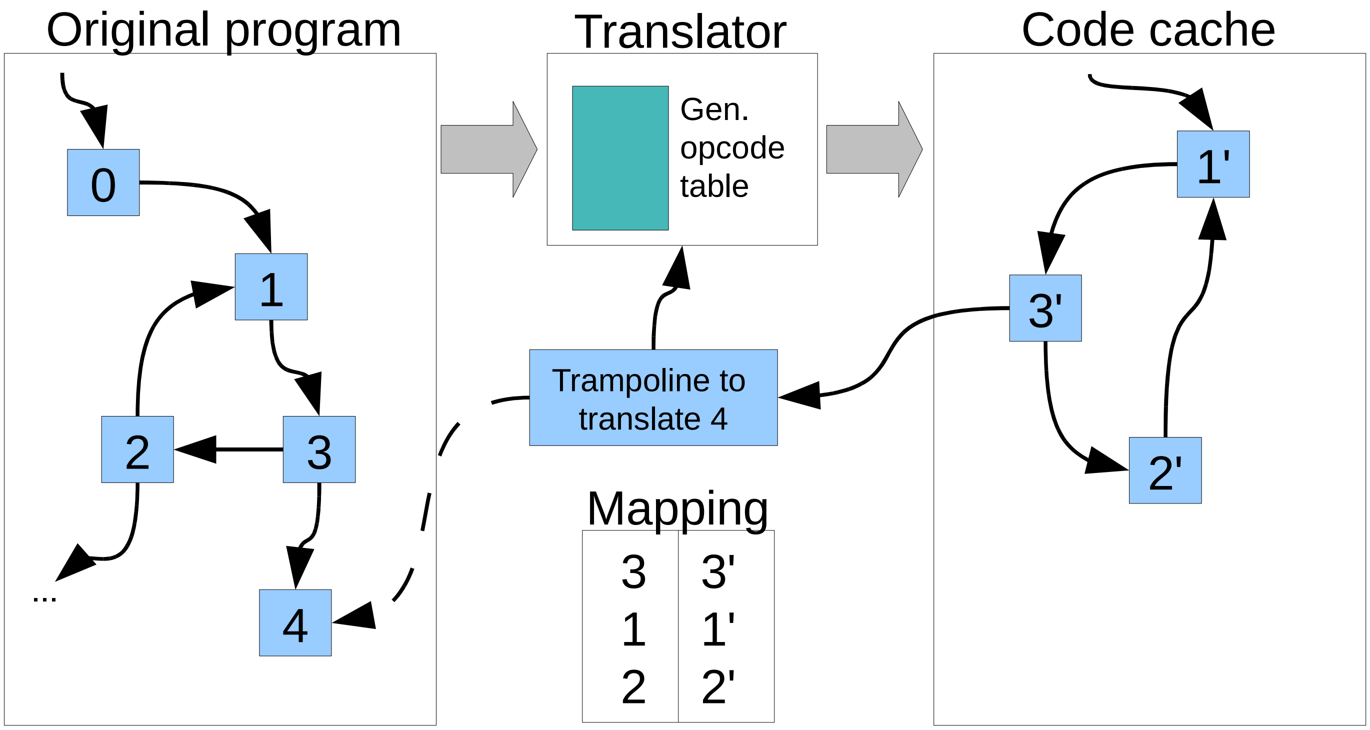
Features:

- Translates all executed code
- Captures all indirect control flow transfers
- Just in time translation

Binary Translation in a Nutshell



Binary Translation in a Nutshell



Mapping

3	3'
1	1'
2	2'

fastBT

- Prototype for a dynamic BT system
- Machine-independent, OS-independent
  - Focus of this talk: IA32, Linux

Table Generation

- Translation tables describe individual instructions and are used to select the correct adapter functions

- Manual table construction is hard & cumbersome
  - Many instructions, write machine-code tables by hand

- Use automation and high level description!
  - Information about opcodes, possible encodings, and properties
  - Specify default translation actions

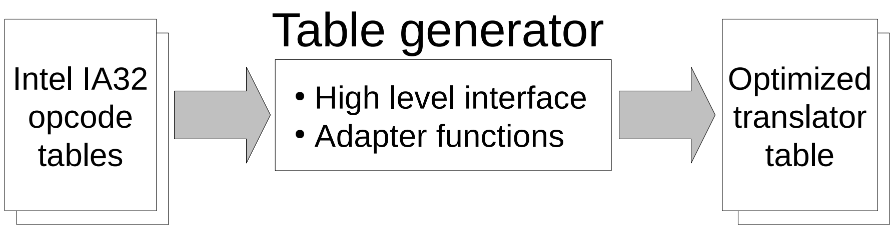


Table Generation

- Use table generator to offer high-level interface
  - Transforming opcode tables into runtime translation tables
  - Add analysis functions to control the table generation
    - Memory access?
    - What are src, dst, aux parameters?
    - FPU usage?
    - What kind of opcode?
    - What opcode class (load, store, arithmetic, control flow, ...)?
    - Immediate value as pointer?
    - etc.

Translator implementation

- Translator uses an iterator based approach and per-instruction actions

- Fundamentals to master low overhead:
  - Code cache
  - Inlining
  - Master (indirect) control transfers

Optimization

- Indirect control flow transfers are expensive
  - Runtime lookup and patching required
  - Indirect control transfer replaced by software trap
- Optimizations in fastBT:
  - Local branch prediction
  - Inlining a fast lookup into the code cache
  - Building on-the-fly shadow jump tables

Optimization: Branch prediction

- Cache the last one or two targets
- If there is a cache hit
  - No lookup is needed
  - Results in 3 to 5 instructions
- If there is a cache miss
  - Lookup the target and cache it for future use
  - Updating the cache costs additional instructions

Optimization: Fast lookup

- Emit an inlined fast lookup into the code cache
  - Uses the mapping table to translate the target
  - Optimized for direct hit in the mapping table
  - Results in 13 or 14 instructions

Optimization: Shadow jump table

- Build a shadow jump table, iff the original indirect control transfer uses a jump table
  - Initialize all entries with catch-all function
  - Lazy lookup and write-back in catch-all
  - Results in 5 instructions if the target is translated

Optimization: Problem

- Each optimization is only effective for some program locations and a specific program behavior
  - Low number of targets, few changes
    - Use a cache
  - High number of targets, many changes
    - Use fast lookup
  - Location has many different targets, all close to each other
    - Use a shadow jump-table

- An adaptive runtime optimization can select the best optimization for each indirect control transfer

Adaptive Optimization

- fastBT offers an adaptive optimization for indirect control transfers
  - Start with a prediction for 1 or 2 locations, count misses
  - Recover to a fast lookup, if count exceeds threshold
  - Construct a shadow jump-table, if the control transfer uses a jump table
- Adaptive optimizations bring competitive performance!

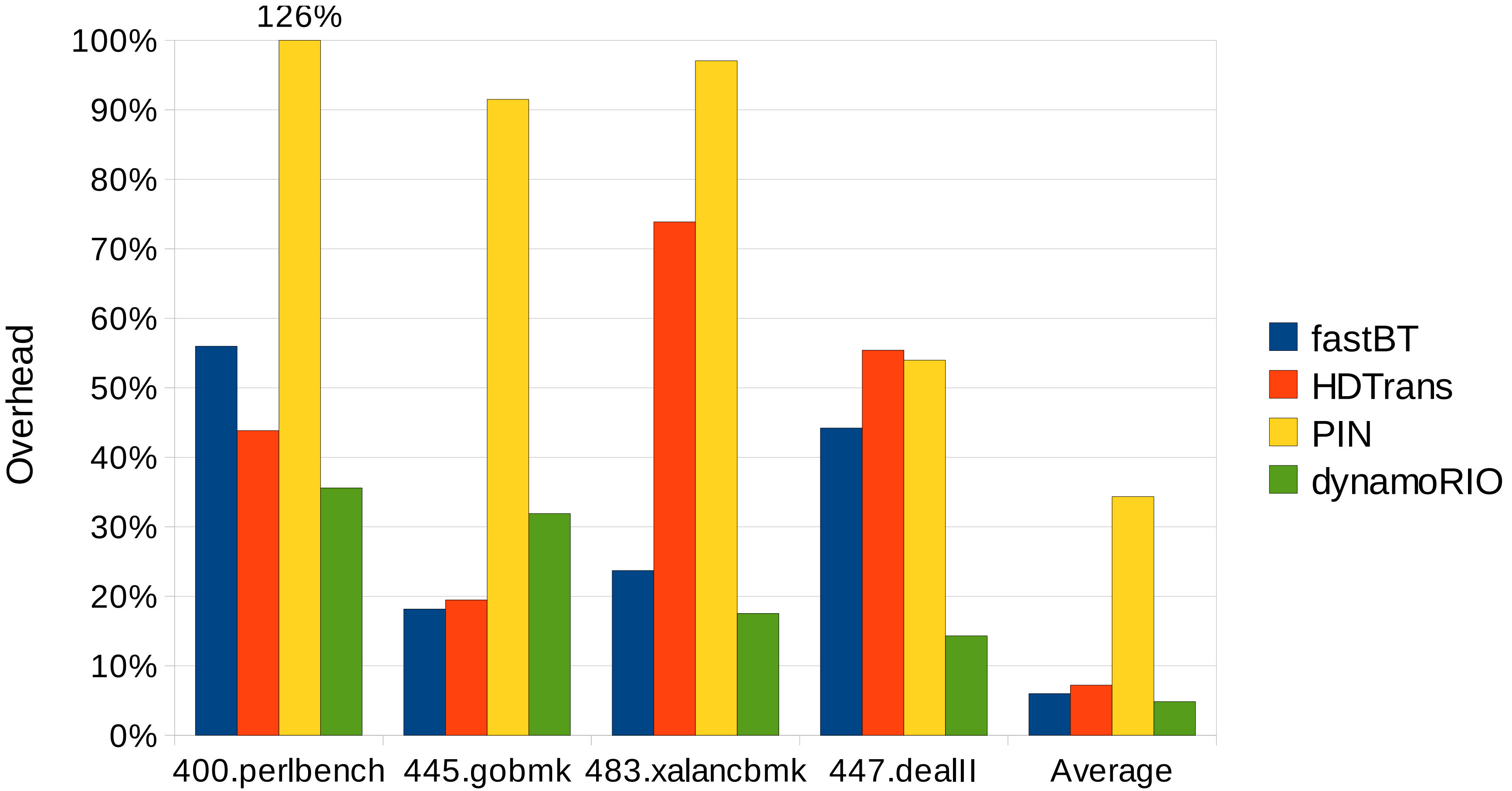
Benchmarks: Setup

- Used null-transformation to show translation overhead
- Used SPEC CPU2006 benchmarks to evaluate performance
  - We use the Test dataset for short running programs and the Ref dataset for long running programs
- Machine: E6850 Intel Core2Duo @ 3.00GHz

Related work

- HDTrans
  - S. Sridhar et al. HDTrans: a low-overhead dynamic translator. SIGARCH'07
  - Table based dynamic BT, no high level interface
- DynamoRIO
  - D. Bruening et al. Design and implementation of a dynamic optimization framework for windows. In ACM Workshop Feedback-directed Dyn. Opt. (FDDO-4) (2001).
  - IR based optimizing BT, does not export a translation interface
- PIN
  - C.-K. Luk et al. Pin: building customized program analysis tools with dynamic instrumentation. In PLDI'05
  - High overhead, offers high level interface

Benchmarks: Ref dataset

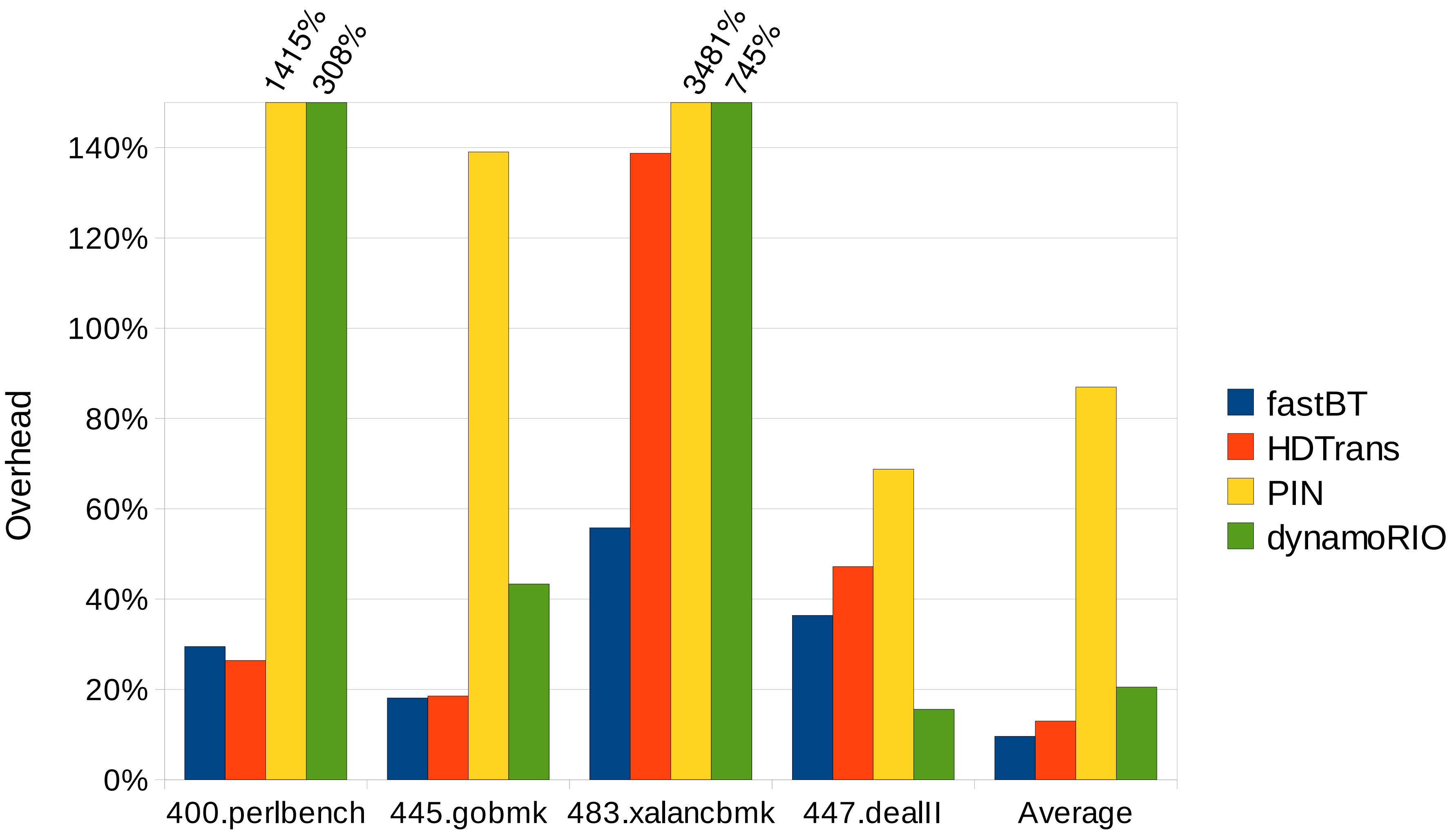


Benchmarks: Ref dataset

Benchmark	**Function calls** [1)]	inlined	**Indirect jumps** [1)]	jmptbl	pred	**Indirect calls** [1)]	pred
400.perlbench	25'814	8.1%	21'930	93.7%	6.3%	3'903	7.4%
445.gobmk	18'001	1.3%	93	1.0%	99.0%	185	4.1%
483.xalancbmk	28'888	10.6%	2'627	27.0%	63.6%	9'161	96.1%
447.dealII	52'756	54.5%	21'147	1.7%	98.3%	540	98.4%

[1)] All numbers are $*10^6$

Benchmarks: Test dataset



Benchmarks: Ref vs. Test Dataset

	Ref dataset		Test dataset	
Benchmark	no BT [s]	fastBT	no BT[s]	fastBT
400.perlbench	486	56%	4	29%
445.gobmk	611	18%	21	18%
483.xalancbmk	371	24%	<1	56%
447.dealII	552	44%	25	36%
Average	839	6%	8	10%

Benchmarks: Summary

- High overhead:
  - Many indirect control transfers
    - Function calls incur high overhead, even with optimizations
    - Indirect control transfers without caches or jump tables add overhead
  - High collision rate in mapping table
    - Expensive recoveries, try different rescheduling strategies
- Low overhead:
  - Few indirect control transfers
  - Cost of indirect control transfers is reduced through optimizations

Conclusion

- fastBT shows that it is possible to combine ease of use with efficient binary translation
- Adaptive optimizations select best optimization for individual locations
- Adaptive optimizations are necessary for low overhead in table based binary translators

Thanks for your attention!

?

- *fastBT* project page: http://nebelwelt.net/fastBT
- Contact: mathias.payer@inf.ethz.ch
- Kudos to:
  - Marcel Wirth, Peter Suter, Stephan Classen, and Antonio Barresi for code contributions
  - My colleagues for endless comments and reviews

Table Generation: Analysis Function

```
bool isMemOp (const unsigned char* opcode,
        const instr& disInf, std::string& action)
{
        bool res;
        /* check for memory access in instr. */
        res  = mayOpAccessMem(disInf.dstFlags);
        res |= mayOpAccessMem(disInf.srcFlags);
        res |= mayOpAccessMem(disInf.auxFlags);

        /* change the default action */
        if (res) { action = "handleMemOp"; }

        return res;
}

// in main function:
addAnalysFunction(isMemOp);
```

Optimization: Efficient Code

- Static ind. call: `call *(fixed_location)`

```
pushl src_addr

jmp *xx(ind_target)
```

```
pushl src_addr                                  (1)

cmpl $cached_target, *xx(i_trgt)                (2)

je $trans_target

pushl *xx(ind_target)                           (3)

pushl $tld

pushl $addr_of_cached_target

call fix_ind_call_predict
```

1. Push original src IP

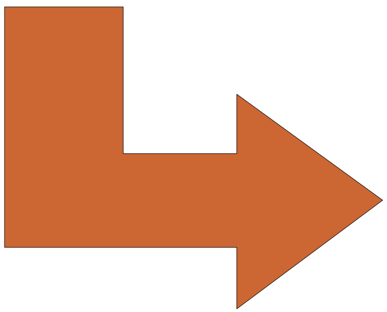
2. Compare actual target w/ cached target & branch if prediction ok

3. Recover if there is a misprediction

Optimization: Efficient Code

- Dynamic ind. call: `call *(reg)`

```
pushl src_addr
jmp *(reg)
```



```
pushl src_addr, *(reg), %ebx, %ecx

movl 12(%esp), %ebx        # load target
movl %ebx, %ecx            # duplicate ip

andl HASH_PATTERN, %ebx    # hash fct
cmpl hashtlb(0, %ebx, 8), %ecx    # check

jne nohit

movl hashtlb+4(0, %ebx, 8), %ebx # load trgt
movl %ebx, (tld->ind_jmp_targt)

popl %ecx, %ebx            # epilogue
leal 4(%esp), %esp         # readjust stack
jmp *(tld->ind_jmp_targt) # jmp to trans.trgt

nohit: use ind_jump to recover
```