Advanced Program Analyses for Object-oriented Systems

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Lecture 4 - Outline

- Empirical results from dynamic sampling analysis
- Optimizations for OO programs
    - Method inlining w & w/o guards
        - Pre-existence
    - Control-flow path splitting
    - Method specialization
    - Object layout for better cache performance
    - JIKES RVM online FDO experiments

Dynamic Analysis - Experiences

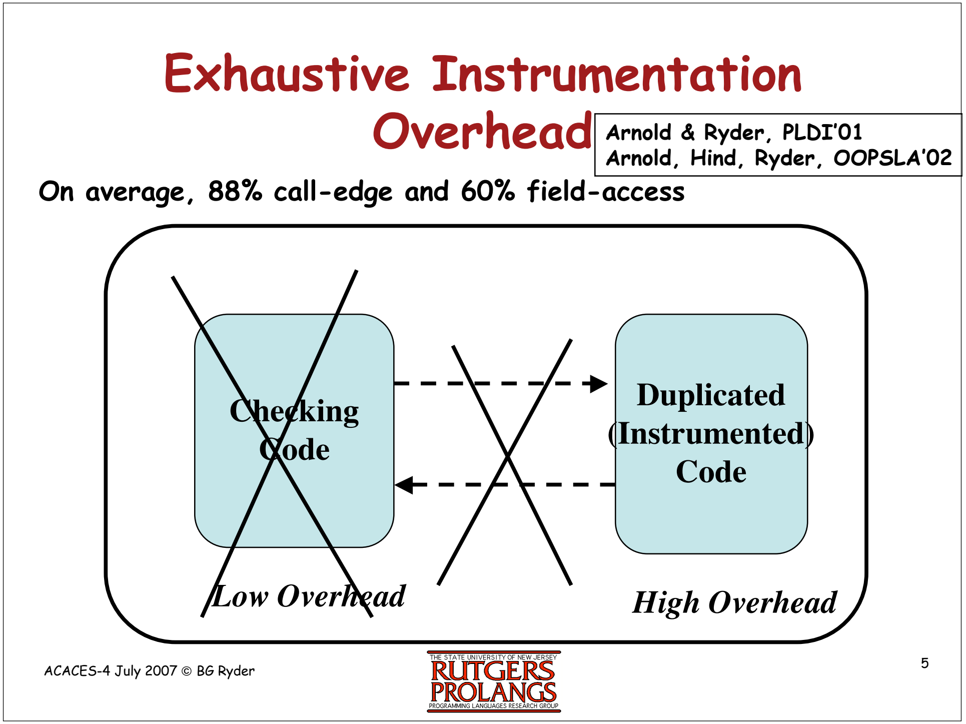
- Empirical experience in IBM's Jalapeno JVM
- 10 benchmarks
  - *SPECjvm98*(input size 10), *Volano, pBob, opt-compiler*
  - Running times from 1.1-4.8 seconds
  - Class file sizes from 10K-1,517K bytes
  - Machine 333Mz IBM RS/6000 powerPC 604e with 2096Mb RAM running AIX 4.3
- Instrumented all methods in applications and libraries

Arnold & Ryder, PLDI'01
Arnold, Hind, Ryder, OOPSLA'02

Instrumentation

- Call-edge
  - Collect caller, callee, call-site within caller at method entry
  - One counter per call edge
- Field-access
  - One counter per field of each class
  - Each *putfield, getfield* access instrumented

Arnold & Ryder, PLDI'01
Arnold, Hind, Ryder, OOPSLA'02



Exhaustive Instrumentation Overhead

Arnold & Ryder, PLDI'01
Arnold, Hind, Ryder, OOPSLA'02

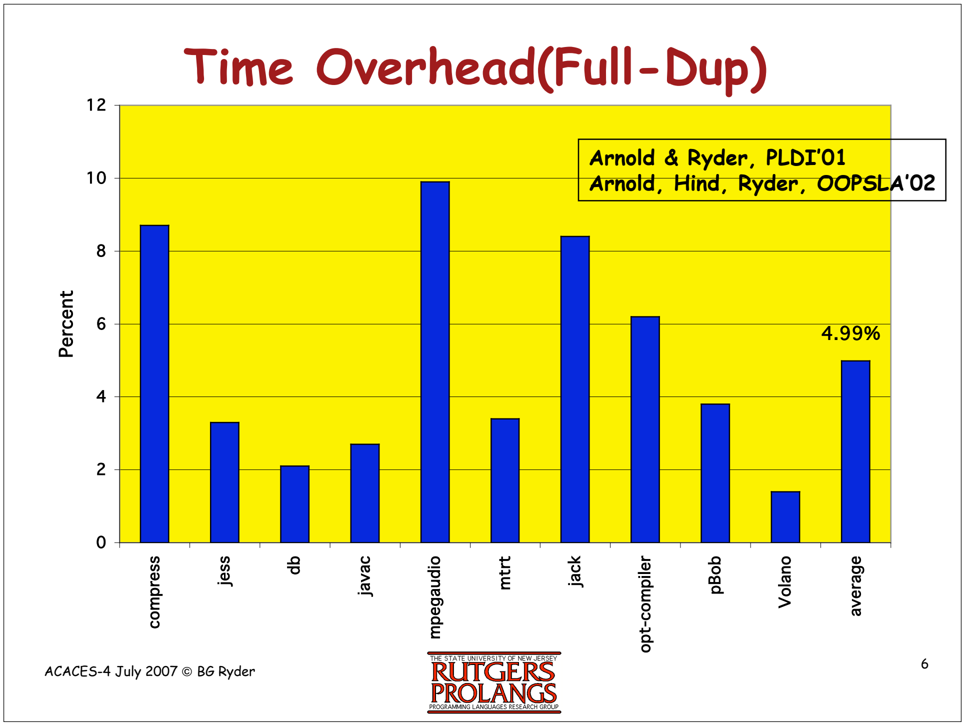
On average, 88% call-edge and 60% field-access

Checking Code

Duplicated (Instrumented) Code

Low Overhead

High Overhead



Time Overhead(Full-Dup)

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Cost + Accuracy

Sample Interval	Overhead (Full-Dup)	Call-edge Accuracy	Field-access Accuracy
1	182%	100%	100%
10	29%	99%	100%
100	10%	98%	99%
1,000	**6%**	**94%**	**97%**
10,000	**5%**	**82%**	**94%**
100,000	5%	71%	83%

OO Opts Using Dynamic Analysis

- **Guarded inlining with dynamic dispatch**
- **Path splitting**
- **Method specialization**
- **Object layout for locality**
- **Adaptive compilation with FDO**

Optimizing Dynamic Dispatch

- Early optimizations-how to do lookup quickly?
  - Use observed profiling information about calls, to predict most likely methods called
- Encode method call as guarded inlining

```
if (shape instanceof Circle)//inline code for Circle.area()
else if (shape instanceof Square) //inline code for
   Square.area()
else shape.area();//regular dynamic dispatch
```

- Also can encode as runtime method selection

```
if (shape instanceof Circle)//call Circle.draw()
else if (shape instanceof Square)//call Square.draw()
else shape.draw();//regular dynamic dispatch
```

Guarded Inlining for C++

Aigner and Holzle, "Eliminating Virtual Function Calls in C++ Programs", ECOOP96

- C++ source-to-source compiler changed virtual method calls to guarded inlined method calls
  - Most frequent class represents 40% of receivers at call site
  - Optimize call sites that account for over 0.1% of calls in run
- Results: profiling feedback more successful than CHA-based analysis, but gains varied over benchmarks

Tradeoffs

- Need to balance costs versus benefits
  - Can increase cost of dynamic dispatch for classes not in the tests
  - Can decrease overall cost of dynamic dispatch if the tested classes occur frequently enough and if further optimizations are possible in the inlined code
    - Example, in Vortex research compiler
      - Do guarded inlining if there are a small (<=3) number of candidate classes and all methods can be inlined
      - Devised a quick run-time type test for objects

J. Dean, G. DeFouw, D. Groave, V. Litvinov, C. Chambers, "Vortex: An Optimizing Compiler for OO Languages", OOPSLA'96.

Speculative Guarded Inlining

- In JikesRVM
  - Can be in response to CHA or profiling
  - Guard with class/method test
  - May avoid test with pre-existence

`void f(A a){ … a.m();…)`

if object referred to by `a` can be shown to have been created prior to when `f` is invoked, then it is valid when executing the inlined code.

Using Pre-existence

- Eliminates the need for a run-time guard on inlined method code
- Applies to call sites that are currently monomorphic, but might become polymorphic due to future class loading
  - Want to inline target method safely wrt classes being loaded
  - Find call sites where receiver is guaranteed to have been created prior to invocation of f(); can apply inlining safely for them

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Pre-existence

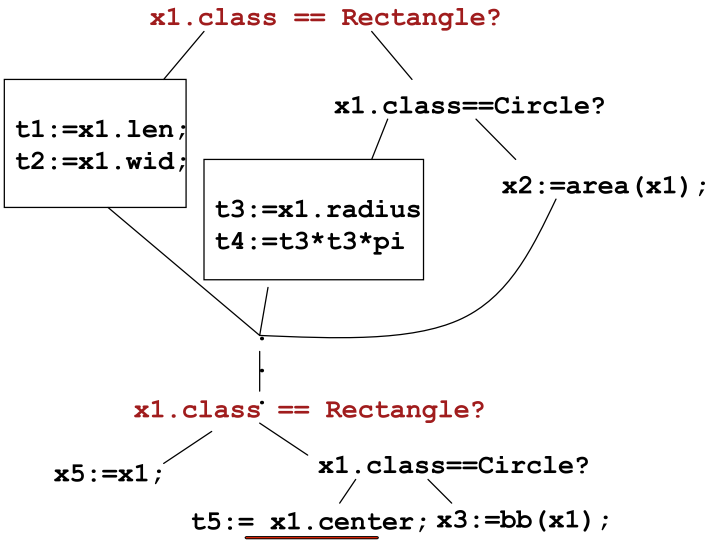
At runtime the order of events goes like this:

1) f() is invoked and is on the stack
2) Class loading occurs and extends some classes that affect f()'s call sites
3) f() is recompiled so that new invocations of f() are guaranteed to execute correctly.
4) Existing invocations of f() contain code that is technically incorrect, but will be ok due to pre-existence. If a call site was directly inlined based on pre-existence, it is known that receiver objects at those sites *preexist* the invocation of f(), and thus preexist the class loading, so they cannot be of an unsafe type.

Path Splitting

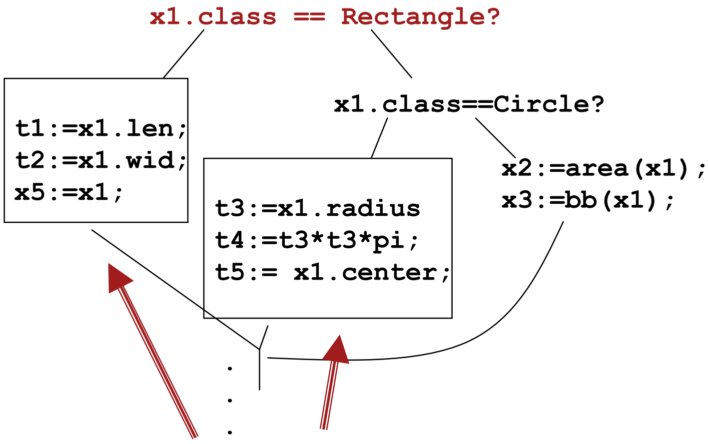
- **Idea:** to avoid redundant tests and increase extent of code for which types of some objects are known
- To avoid redundant type tests, split control flow path between merge following one occurrence of a class test and the next occurrence of same class test
  - Duplicates code
- Vortex does this lazily
- Feedback-directed splitting in adaptive JikesRVM

Example



```
x1.class == Rectangle?
t1:=x1.len;
t2:=x1.wid;
x1.class==Circle?
t3:=x1.radius
t4:=t3*t3*pi
x2:=area(x1);
x1.class == Rectangle?
x5:=x1;
x1.class==Circle?
t5:= x1.center;
x3:=bb(x1);
```

Example



```
x1.class == Rectangle?
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t1:=x1.len;
t2:=x1.wid;
x5:=x1;
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```
x1.class==Circle?
```

```
t3:=x1.radius
t4:=t3*t3*pi;
t5:= x1.center;
```

```
x2:=area(x1);
x3:=bb(x1);
```

know type of x1 at compile-time here

Method Specialization

- Factoring shared code into base classes which contain virtual calls to specialized behavior in subclasses hurts run-time performance (SELF)
  - Compiler must *undo* effects of factorization
- At compile-time translating a *customized* version of code, assuming known type information (e.g., receiver type)
- Drawbacks
  - Overspecialization - multiple specialized versions may be too much alike; can lead to code bloat
  - Under-specialization - methods may only be specialized on receiver type, when could use other parameters

Vortex Profile-guided Specialization

- **Idea:** given weighted call graph derived from profile data, eliminate heavily traveled, dynamically dispatched calls by specializing to particular patterns in their parameters
- *Pass-through call sites* use formals of caller as arguments to callee, *specializable call sites*
  - `f(A a,B b,C c){…a.s(c )….}` can specialize `s()` for set of known static types of `a` and `c`

J. Dean, G. DeFouw, D. Groave, V. Litvinov, C. Chambers, "Vortex: An Optimizing Compiler for OO Languages", OOPSLA'96.

Questions asked in Vortex

- How is set of classes which enable specialization of pass-through arc calculated?
- How should specializations for multiple call sites to same method be combined?
- If a method *f* is specialized, how can we avoid converting statically bound calls to *f* into dynamically bound calls?
- When is an arc important to specialize?

J. Dean, G. DeFouw, D. Groave, V. Litvinov, C. Chambers, "Vortex: An Optimizing Compiler for OO Languages", OOPSLA'96.

Object Layout for Locality

- **Idea:** want good cache performance so profile usage of object fields; rearrange object storage, so frequently used fields occupy same cache line, where possible
  - Avoids cache misses
  - Affects data layout in storage
- *Structure splitting* for Java objects to improve cache performance of objects comparable to or larger than a cache block

T. Chilimbi, B. Davidson, J.R. Larus,
“Cache-conscious Structure Definition”, PLDI’99

Structure Splitting

- **Idea:**
  - Profile use of fields of objects to identify some as hot (frequently used) vs cold (seldom used);
  - Automatically split class to associate cold fields of an object with another class only accessed indirectly
  - Change all existing references to the new structure
  - Payoff: all the hot fields are cache-resident
- Performance improvements of 18-28%, with 22-66% of improvement coming from class splitting

T. Chilimbi, B. Davidson, J.R. Larus,
“Cache-conscious Structure Definition”, PLDI’99

Benchmarks

Table 1: Java benchmark programs.

Program	Lines of Code[a]	Description
cassowary	3,400	Constraint solver
espresso	13,800	Martin Odersky's drop-in replacement for javac
javac	25,400	Sun's Java source to bytecode compiler
javadoc	28,471	Sun's documentation generator for Java source
pizza	27,500	Pizza to Java bytecode compiler

a. Plus, a 13,700 line standard library (JDK 1.0.2).

Chilimbi et al, PLDI'99

Experimental Procedure

- Analyzed and instrumented bytecode to collect field info (type, size) from application
- Execute instrumented code to obtain field access frequencies and numbers/kinds of objects created
- Split classes, choosing based on static + dynamic data
- Java bytecode recompiled to reflect splitting decisions

Chilimbi et al, PLDI'99

Sizes of Live Java Objects

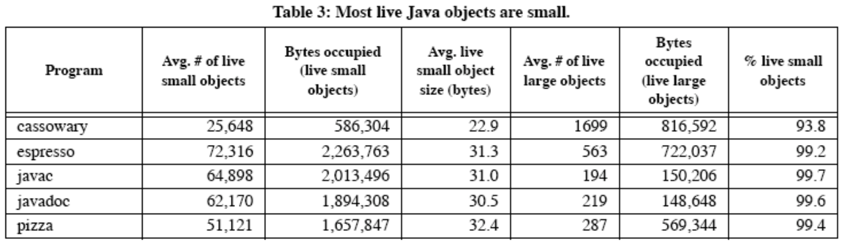
Table 3: Most live Java objects are small.

Program	Avg. # of live small objects	Bytes occupied (live small objects)	Avg. live small object size (bytes)	Avg. # of live large objects	Bytes occupied (live large objects)	% live small objects
cassowary	25,648	586,304	22.9	1699	816,592	93.8
espresso	72,316	2,263,763	31.3	563	722,037	99.2
javac	64,898	2,013,496	31.0	194	150,206	99.7
javadoc	62,170	1,894,308	30.5	219	148,648	99.6
pizza	51,121	1,657,847	32.4	287	569,344	99.4

Observations: sizes of live objects after a GC averaged over execution; note smaller size than 64byte cache block

Chilimbi et al, PLDI'99

Findings

Chilimbi et al, PLDI'99

- Measured class splitting potential with 2 inputs per benchmark
  - 17-46% of all accessed classes are candidates with 26-100% having field access profiles that justify splitting
    - Claim the splitting algorithm is insensitive to input data used to profile (measured between the 2 inputs)
  - Split classes account for 45-64% total number of program field accesses
    - Temperature differentials high (77-99%) indicating strong differences between hot and cold field accesses
    - Modest additional memory needs (13-74KB)

Optimization Results

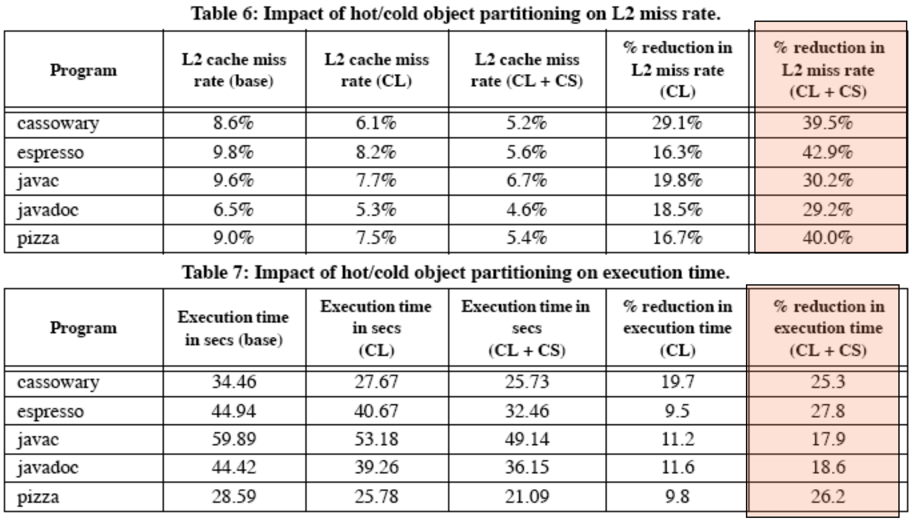

Table 6: Impact of hot/cold object partitioning on L2 miss rate.

Program	L2 cache miss rate (base)	L2 cache miss rate (CL)	L2 cache miss rate (CL + CS)	% reduction in L2 miss rate (CL)	% reduction in L2 miss rate (CL + CS)
cassowary	8.6%	6.1%	5.2%	29.1%	39.5%
espresso	9.8%	8.2%	5.6%	16.3%	42.9%
javac	9.6%	7.7%	6.7%	19.8%	30.2%
javadoc	6.5%	5.3%	4.6%	18.5%	29.2%
pizza	9.0%	7.5%	5.4%	16.7%	40.0%

Table 7: Impact of hot/cold object partitioning on execution time.

Program	Execution time in secs (base)	Execution time in secs (CL)	Execution time in secs (CL + CS)	% reduction in execution time (CL)	% reduction in execution time (CL + CS)
cassowary	34.46	27.67	25.73	19.7	25.3
espresso	44.94	40.67	32.46	9.5	27.8
javac	59.89	53.18	49.14	11.2	17.9
javadoc	44.42	39.26	36.15	11.6	18.6
pizza	28.59	25.78	21.09	9.8	26.2

Chilimbi et al, PLDI'99

Dynamic Compilation w FDO

- **Idea:** only optimize performance-critical sections of code
  - Reduces compilation delays and time cost
- **Adaptive optimization**: discover and optimize *hot spots* in the code
  - Idea: use online profile info to optimize methods
- **IBM's Jikes RVM** for Java explored many of the ideas initially presented in SELF compilers and is refining the methodology of adaptive optimization, using online profiling and FDO

Online FDO Experiments

Arnold, et. al
OOPSLA'02

- Embed full duplication framework in Jikes Research VM for adaptive optimization trials
  - Insert instrumentation at highest optimization level (O2) so see optimization effects in profile
  - Instrumentation is intraprocedural edge counters
  - Optimizations used: splitting, code positioning (for code locality), loop unrolling, adaptive inlining

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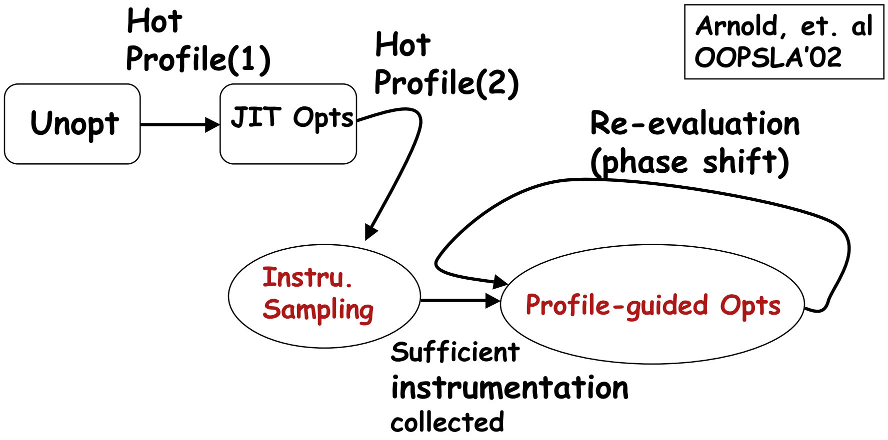
Online Profiling Strategy

Arnold, et. al
OOPSLA'02

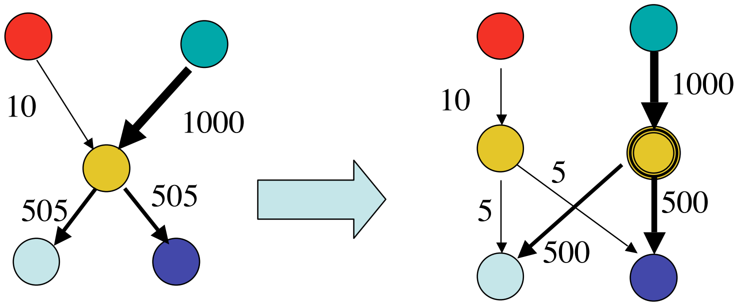


Arrows represent recompilation steps in the 2-phased profiling

Splitting

Arnold, et. al
OOPSLA'02

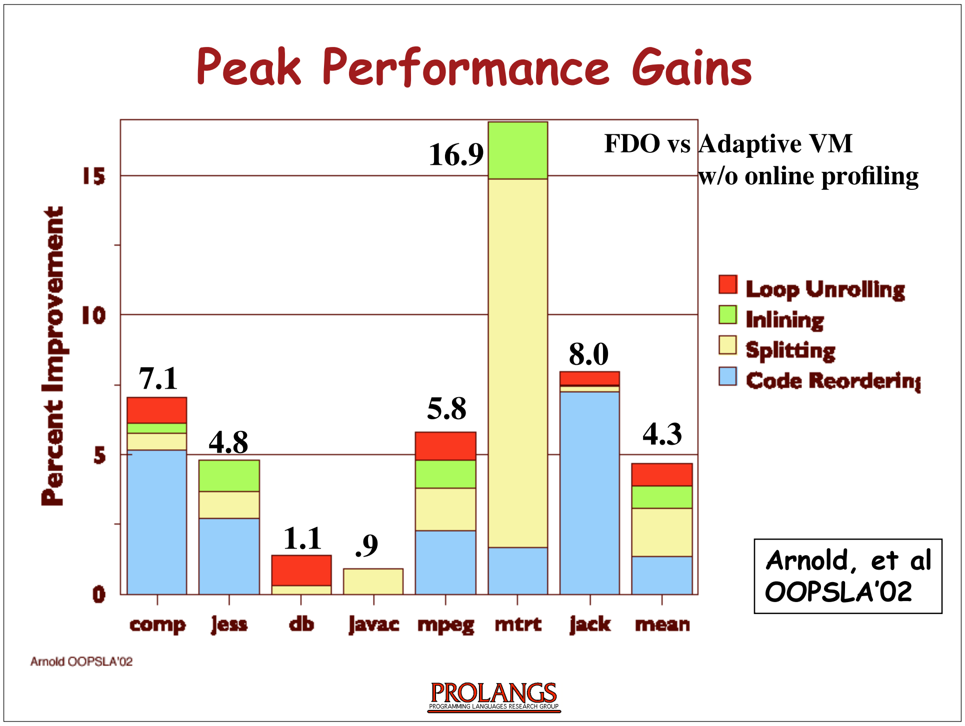
- Splitting is tail duplication of code to eliminate merges that cause dataflow info to be lost



How to measure performance?

Arnold, et. al
OOPSLA'02

- Factors
  - Overhead of instrumentation
  - Effectiveness of FDO's
  - Underlying adaptive optimization system
- Measure steady-state performance of SpecJvm98 codes
  - Requires running benchmarks in harness multiple times (to total time of 4 minutes on size 100)

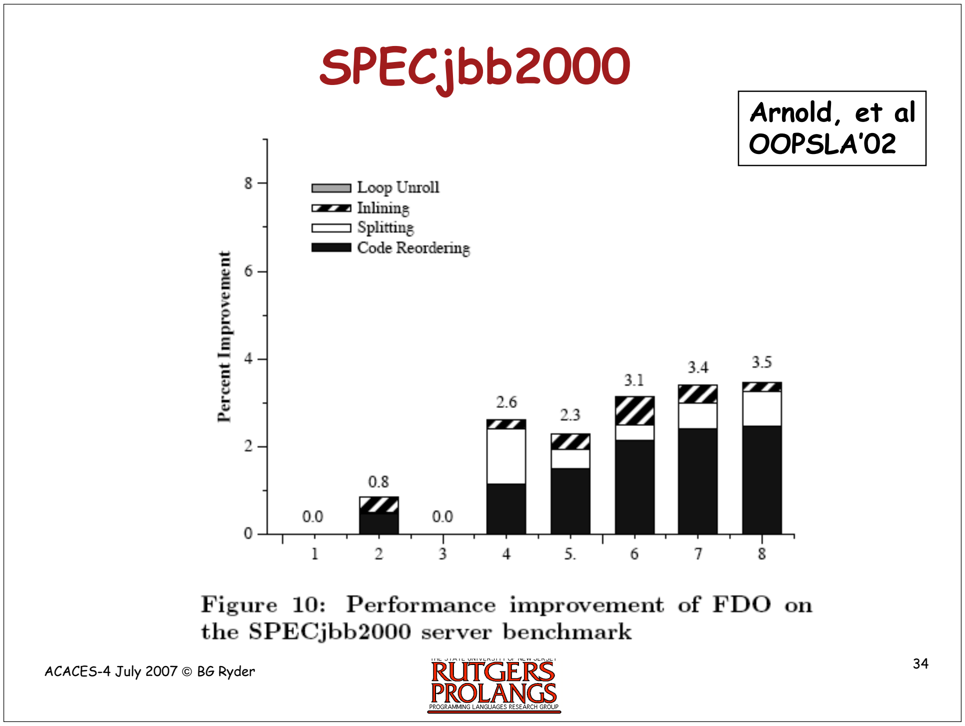


Peak Performance Gains

FDO vs Adaptive VM
w/o online profiling

Arnold, et al
OOPSLA'02

Arnold OOPSLA'02



SPECjbb2000

Arnold, et al
OOPSLA'02

Figure 10: Performance improvement of FDO on the SPECjbb2000 server benchmark

Measuring Precision

- Run sampling framework to record call edges
- Run *perfect profile* recording every call
- Compare percentage of sample collected attributed to a particular call edge to corresponding percentage in the perfect profile.

Measuring Accuracy

- *Overlap* is minimum of these two percentages
- *Overlap percentage* is sum of overlaps for all edges (Feller 98)
  - Any sample will be less than or equal to 100%
  - A sample identical to perfect profile has 100% overlap
  - If sampling overestimates the percentage for some call site then it must underestimate the percentage for another call site

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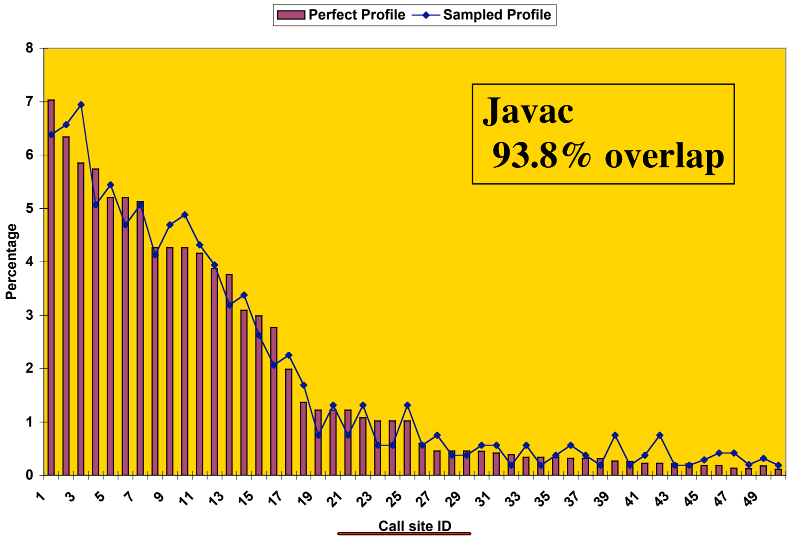
Sample & Perfect Profiles (Javac)



Setup

T. Chilimbi, B. Davidson, J.R. Larus, "Cache-conscious Structure Defn", PLDI'99

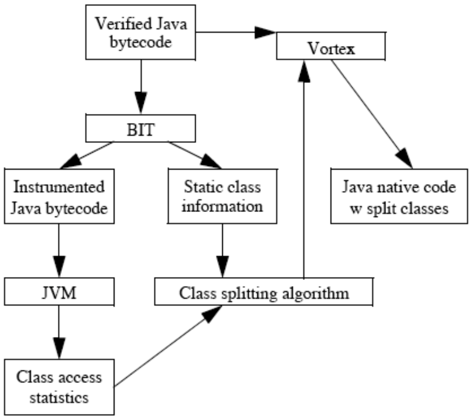


Figure 3. Class splitting overview.

Details

- **Tradeoffs**
  - Pack more hot class instances into cache block
    - Cost of additional reference from hot to cold portion; Code growth; More objects in memory overall; Extra indirection for each cold field access
- **Heuristics to choose classes**
    - Only split *live* classes with total field accesses exceeding a threshold: A_k ≥ LS / (100*C)
      - A_k: #fields accesses in class k; LS: total # field accesses; C: total number of classes with at least one field access

    Plus larger than 8 bytes with 3 or more fields.

Details

- Heuristics to choose fields
  - Cold fields accessed no more than A_k/(2*F_k) times where F_k is # fields in class k
  - To split requires at least 8 bytes cold
  - Use heuristics to avoid overly aggressive splitting
- Split class transformation
  - Hot classes and their accesses are same
    - Additional new field per object refers to new cold class
    - Need to alter constructors to create new cold class instance and assign it to the new field
  - Cold field counterpart class created with public fields, inherits from Object, only method is constructor
  - Change accesses to cold fields to indirect accesses through new field