Custom benefit-driven inliner in Falcon JIT

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What is Falcon?

- JIT compiler for Java based on LLVM
  - Java bytecode => native
  - Inside of a running JVM
- Final tier compiler in Azul's Prime JVM (formerly known as Zing JVM)
  - Compiles only the hottest methods
  - Focus on performance

If you want to learn more

LLVM Dev Meeting 15 - LLVM for a managed language: what we've learned
https://llvm.org/devmtg/2015-10/#talk14

LLVM Dev Meeting 17 - Falcon: An optimizing Java JIT
https://llvm.org/devmtg/2017-10/#talk12

EuroLLVM 17 - Expressing high level optimizations within LLVM
http://llvm.org/devmtg/2017-03//2017/02/20/accepted-sessions.html#10

EuroLLVM 18 - New PM: taming a custom pipeline of Falcon JIT
https://llvm.org/devmtg/2018-04/talks.html#Talk_13

LLVM Virtual Dev Meeting 20 - Control-flow sensitive escape analysis in Falcon JIT
https://llvm.org/devmtg/2020-09/slides/Pilipenko-Falcon-EA-LLVM-Dev-Mtg.pdf

Inlining

Replacement of a function call site with the body of the called function

```
int foo() {
  return bar(5);
}

int bar(int x) {
  return x + 1;
}
```

```
int foo() {
  return 5 + 1;
}

int bar(int x) {
  return x + 1;
}
```

Inlining effects

Eliminates call overhead
Enables intraprocedural optimizations
- Facilitates information flow by removing the call boundary
- Specializes the called function for the call site

Increases IR size
- Increases compile-time
- May hurt optimizations

Increases code size
- May hurt performance

Balancing these effects is critically important for performance

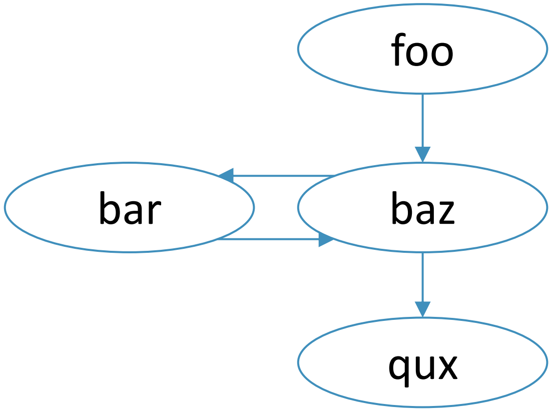
Inlining in LLVM

Inliners in LLVM

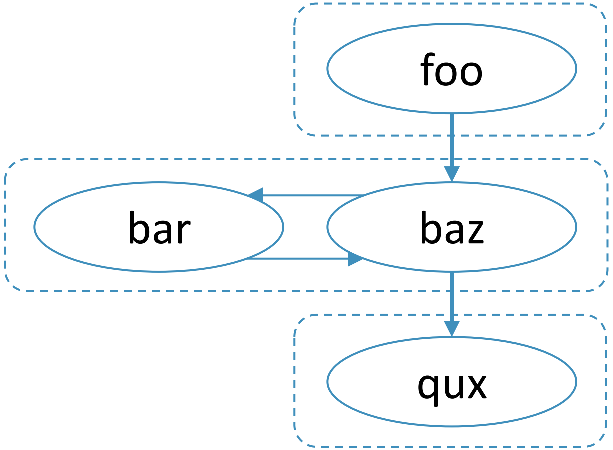
- Bottom-up inliner
  - Default inliner in standard pipelines, e.g., default inliner in Clang
  - See lib/Transforms/IPO/Inliner.cpp
- Module inliner
  - Experimental inliner
  - See lib/Transforms/IPO/ModuleInliner.cpp
- Partial inliner
  - Inlining hot region only
  - See lib/Transforms/IPO/PartialInlining.cpp

Bottom-up inliner

Traverses the strongly connected components (SCCs) of the call graph in bottom-up order



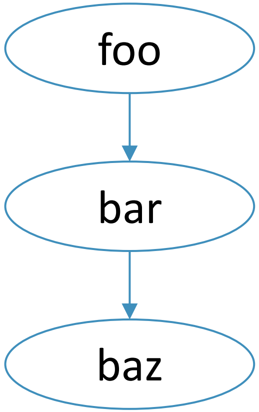
Call graph



DAG of call graph SCCs

Bottom-up inliner

- Starts with leaf SCCs (typically leaf functions)
- Inlines the callees, runs simplifications
  - Iterates if some calls were devirtualized
- Moves up to their callers



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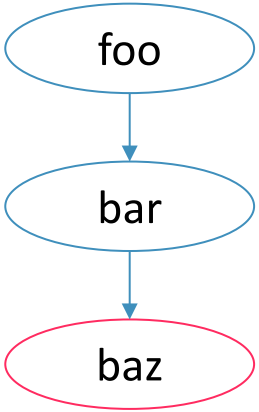

No callees to inline, just runs simplifications

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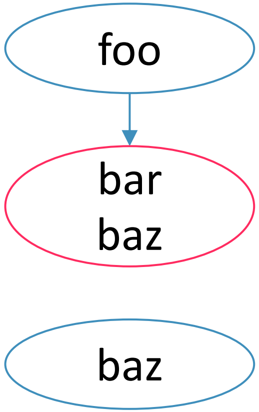

Inlines callees, then runs simplifications

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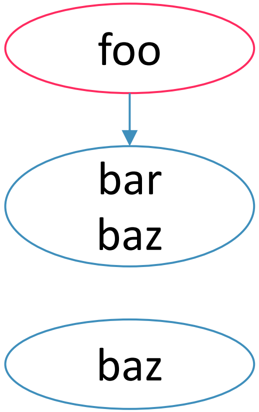

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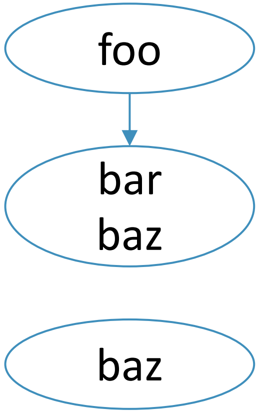


In most cases it is looking at fully simplified callees

Module inliner

- Experimental inliner
- Considers all call sites in the module within the same worklist
  - This can possibly enable heuristics that are not limited by the bottom-up traversal order
- We are not taking the advantage of it yet

InlineCost analysis

- Decides whether a given call site should be inlined
- Computes two parameters
  - Cost – estimate of the code size increase in case we inline
  - Threshold – how much cost we are willing to spend to inline this call site
    - Beneficial call sites have higher threshold
- If cost < threshold → inline

Caller context in InlineCost analysis

InlineCost takes the caller context into account

Tries to predict future simplifications enabled by inlining

```
int bar(bool f) {
  if (f) return 0;
  // lots of code
}
```

```
void foo() {
  bar(true)
}
```

InlineCost can recognize that bar(true) is free to inline

InlineCost bonuses

- When a beneficial inlining pattern is recognized, a bonus is applied to encourage inlining
  - Either by increasing the threshold, or by decreasing the cost
- For example, we give a bonus if inlining enables a devirtualization opportunity

Inlining in Falcon

Compilation model in Falcon

- Compilation unit - one Java method
- VM requests a compilation of one method and expects to get native code for this method
- The result of the compilation can inline other methods

On demand generation of inline candidates

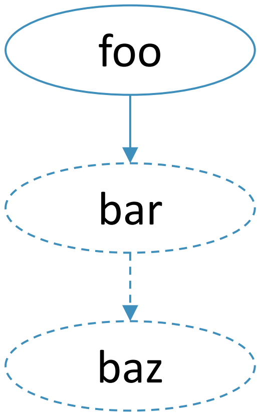
- We start with one function in the module
  - The method requested by the VM
- If we want to inline we need to request the inlining candidate from the VM
  - VM will parse Java bytecode and generate the LLVM IR
  - We import the new function into our module and can now inline

On demand generation of inline candidates

- The full call graph is not available
- We dynamically explore the call graph of functions reachable from the top-level
- Bottom-up inlining is problematic
- Top-down traversal is very straight forward

Falcon's downstream top-down inliner

- Initialize the worklist with all call sites in the top-level function
- For each call site in the worklist
  - Generate candidate
  - Simplify candidate
  - Consider for inlining using InlineCost
    - If inlined add new inlined calls into the worklist



Falcon’s downstream top-down inliner

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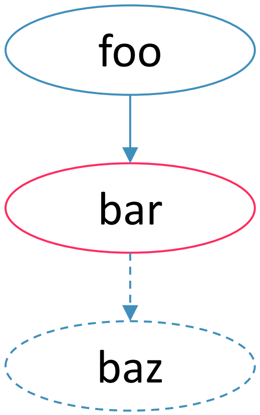

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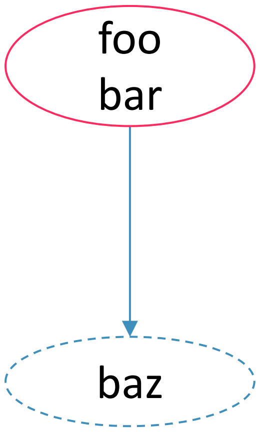

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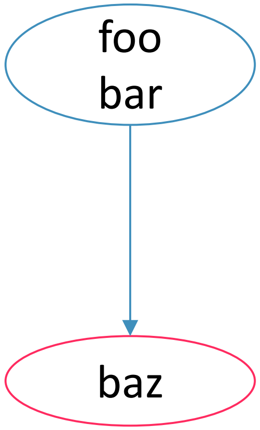

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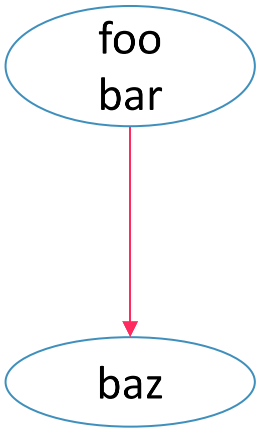
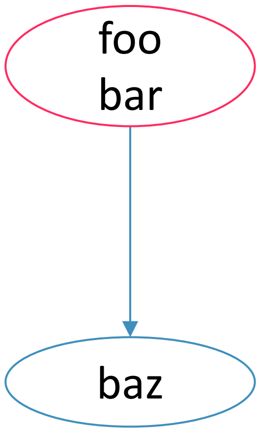


Falcon’s downstream top-down inliner

- Iterate inlining and simplifications on the top-level function until the fixed point
- Simplifications in the top-level function can open new opportunities for inlining
  - devirtualization
  - improved information about arguments



Summary

- We've implemented a downstream top-down inliner
- On-demand generation of candidates
- Iterative application of inlining and simplifications

Total budget and prioritization

Top-level function size blow up

- Top-down inlining makes it possible to blow up the size of the top-level function
  - InlineCost decisions are local
  - Iterative application of reasonable local decisions can result in overinlining
- Less of an issue for bottom-up inlining
  - As a bottom-up inliner progresses up the call graph, it increases the size of functions
  - This, in turn, prevents their inlining further up

Total budget for inlining

- We introduced a total budget for inlining into the top-level function
- With total budget the order of inlining becomes important
  - Can waste our budget on non-beneficial calls and not be able to inline beneficial calls later
- We need prioritization of call sites and a universal measure of inlining "goodness"

Cost?

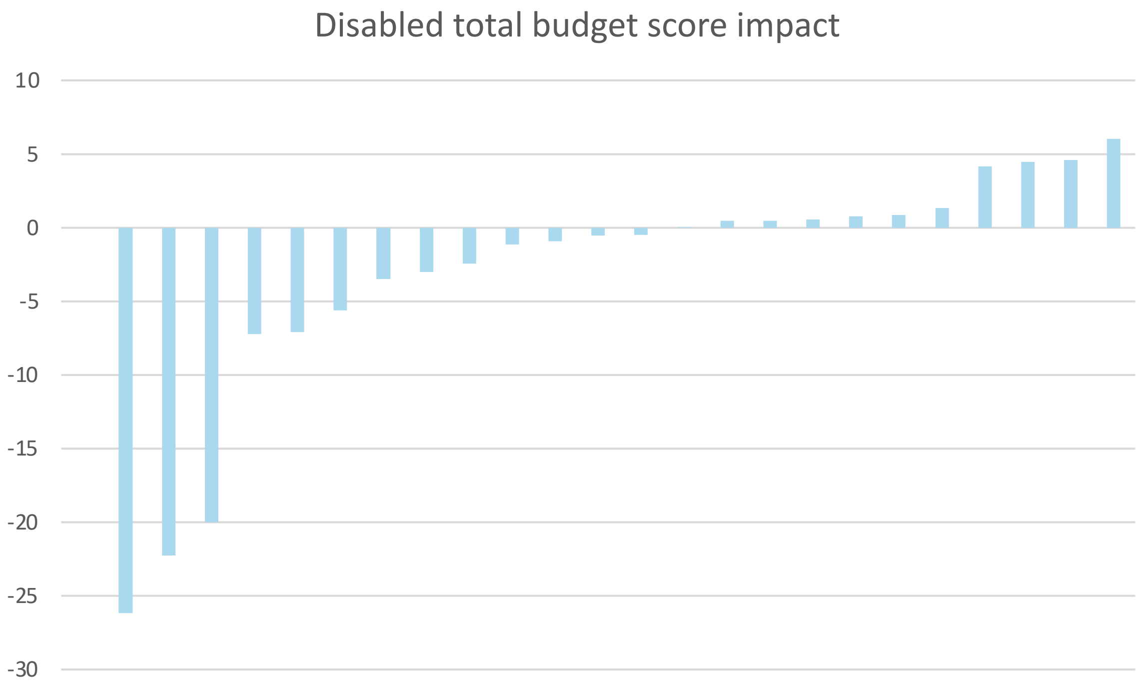
- We already have cost computed by InlineCost
- This is not enough for good prioritization
  - A large callee can be more beneficial to inline
  - E.g., out of these two we should prefer the former
    - a large callee in a hot loop that enables a devirtualization opportunity once inlined
    - small callee on a cold code path

Cost/benefit analysis

- We introduced an explicit measure of benefits and prioritize by benefit/cost ratio
- Benefits are computed by a downstream part of InlineCost
- It is based on InlineCost bonuses
  - Benefit is the sum of all the bonuses we've given
  - We've added multiple bonuses for Java-specific optimizations
- It is NOT based on cost/benefit analysis in upstream InlineCost
  - There is no good reason for us to have a separate implementation
  - Ideally, we want to merge our cost/benefit analysis with the one upstream

Performance impact – disabled total budget

- Renaissance Suite v0.11
  - 25 workloads
- Azul Prime JVM JDK 8, dev ToT build
- Intel Skylake 4 core machine
- **Total compile time +76%**
- **Geomean of scores -3.1%**



Summary

- Doing top-down inlining requires a total budget for the top-level function
- Total budget requires prioritization
- We introduced an explicit notion of benefits
  - Based on InlineCost bonuses
- Prioritize by benefit/cost ratio
  - Helps us avoid bad inlining when we exhaust the budget

Top-down vs bottom-up

Top-down vs bottom-up inlining

- Doing pure top-down we lose some benefits of bottom-up inlining
- Bottom-up inliner is looking at fully simplified candidates
  - Sees more context and more simplification opportunities
- Trivial functions like getters/setters obscure these opportunities

```
int foo() {
  return bar(5);
}

int bar(int x) {
  return x + baz();
}

int baz() {
  return 5;
}
```

Looking top-down, we can't see the constant folding opportunity

Top-down vs bottom-up inlining

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- Bottom-up inliner is looking at fully simplified candidates
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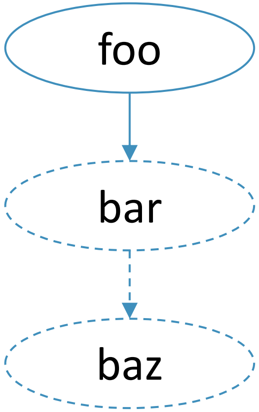
```
int foo() {
  return bar(5);
}

int bar(int x) {
  return x + 5;
}

int baz() {
  return 5;
}
```

Inlining bottom-up, the constant folding opportunity becomes apparent

Simplify-with-inlining

- We do limited form of bottom-up inlining
- We recursively apply the top-down inliner during simplifications of the candidates
- Effectively, we pregenerate 2 levels of the call graph and run bottom-up inlining



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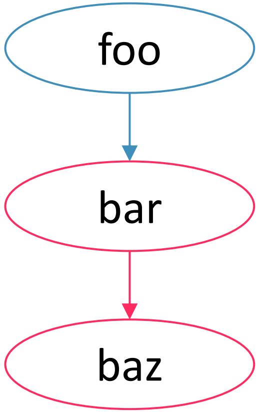

Simplifying bar, we inline baz into it

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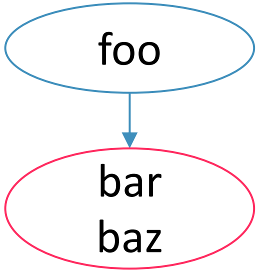
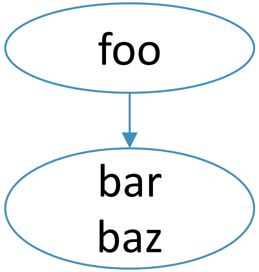


Simplifying bar, we inline baz into it

Simplify-with-inlining

- This gives us more context in the candidates
  - Enables more simplifications
  - Makes InlineCost able to recognize more simplifications after inlining
- Mitigates the situation when we need to look through several levels of inlining to see benefits



Inlining policy for inlining into candidates

- Trade-offs of inlining into candidates:

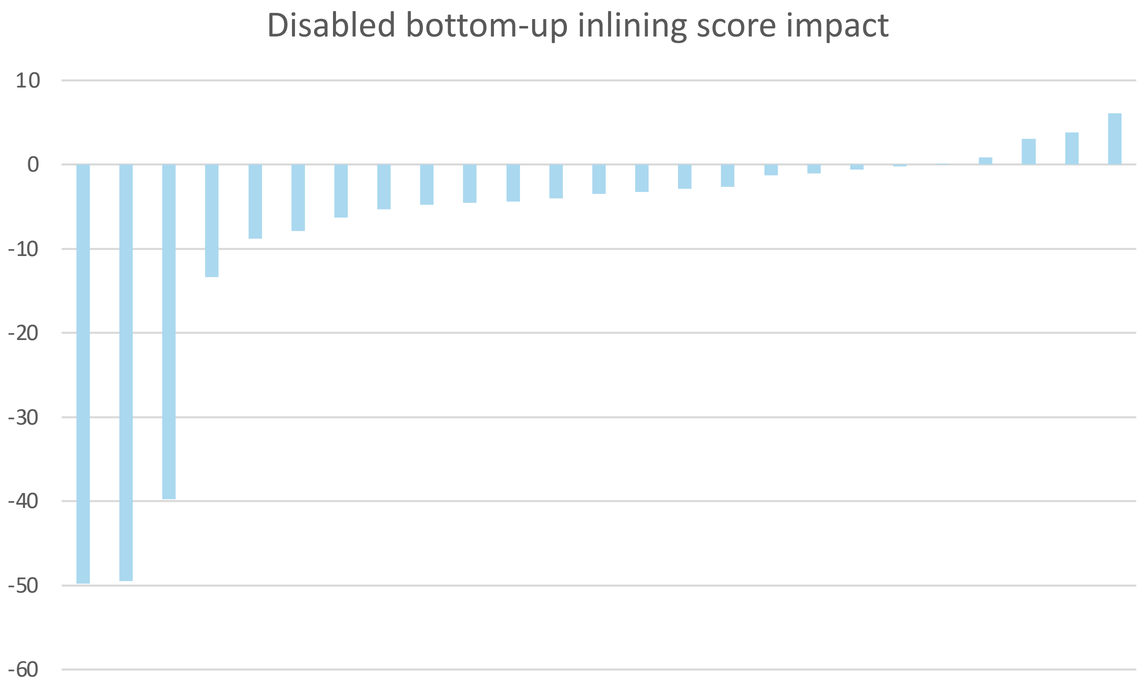
  Exposes more context in the candidate

  Inflates the candidate and prevents its inlining

  Wastes compile-time if candidate is not inlined
- Our policy
  - We use InlineCost analysis with small threshold = 45
  - For context, default inline threshold is 225
- View this inlining as canonicalization
  - Getting rid of trivial methods, like getters/setters/wrappers

Performance impact – disabled bottom-up inlining

- Renaissance Suite v0.11
  - 25 workloads
- Azul Prime JVM JDK 8, dev ToT build
- Intel Skylake 4 core machine
- **Total compile time -12.8%**
- **Geomean of scores -9.6%**



Summary

- Pure top-down inlining loses some benefits of bottom-up inlining
- We do a limited form of bottom-up inlining
  - Pregenerate 2 levels of the call graph and do bottom-up on these functions
- This has significant performance impact

Clustering

Clustering

Sometimes benefits can only be revealed if multiple call sites are inlined together

```
A a = new A()
foo(a)
bar(a)
```

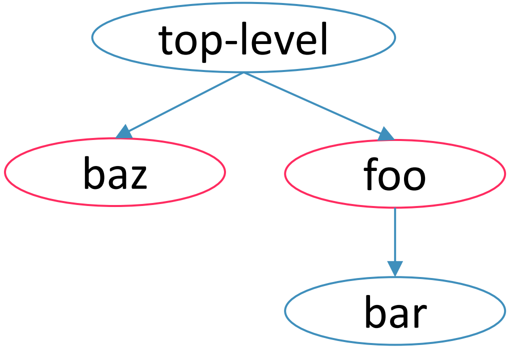
```
void foo(A a) {
  // doesn't escape a
}

void bar(A a) {
  // doesn't escape a
}
```

Inlining both foo(a) and bar(a) will make a fully unescaping

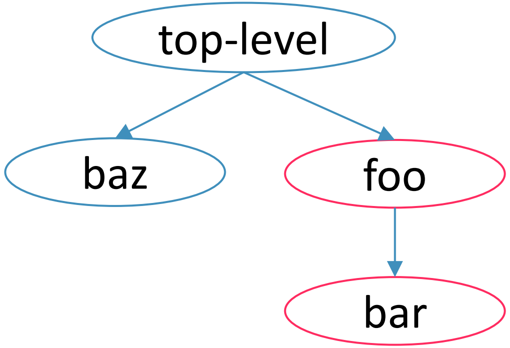
Clusters

- This kind of benefits are not recognized by a single call site inliner
- We want to be able to recognize them
- We need to consider multiple call sites for inlining together
- **Cluster – multiple call sites considered for inlining together**

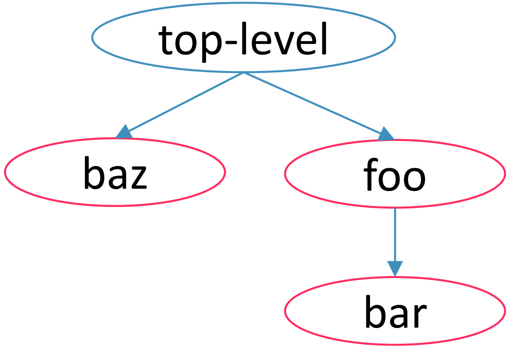
Examples of clusters




```
Cluster of
siblings:
  foo()
  baz()
```




```
Cluster of nested
calls:
  foo()
    bar()
```




```
Mixed cluster:
  foo()
    bar()
  baz()
```

Clustering

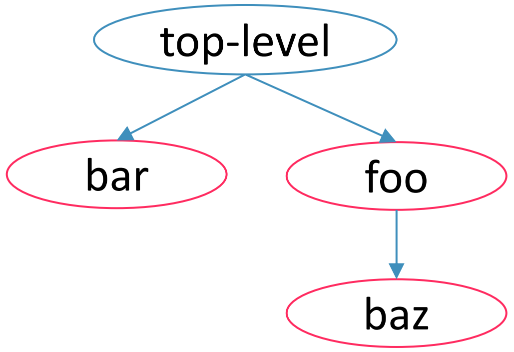
- Because of total budget for the top-level method we can't do cluster inlining outside of regular inlining
    - We may run out of budget doing regular inlining
- Clusters must be prioritized against regular inlining decisions
    - Clusters must be first-class citizens in the regular inliner
- We made our regular inliner work on clusters, not single call sites
    - A single call site is just a trivial cluster

Cluster inliner

- In order to prioritize clusters, we need to know their costs and benefits
  - It is computed as an aggregate of costs and benefits of individual call sites
  - + extra cluster benefit, e.g., the benefit for making an allocation unescaped
- Clustering heuristics look for candidate clusters, e.g., escape-analysis driven clustering
  - Different heuristics populate the priority queue
  - Prioritization takes care of the rest

Escape-analysis driven clustering heuristic

Looking for clusters that make an allocation fully unescaping




```
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foo(a) // doesn't escape a
bar(a) // doesn't escape a

void foo(A a) { baz(a); }
void bar(A a) { // doesn't escape a }
void baz(A a) { // doesn't escape a }
```

```
Cluster:
  foo()
    bar()
  baz()
```

Performance impact – disabled clustering

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- Azul Prime JVM JDK 8, dev ToT build
- Intel Skylake 4 core machine
- **Total compile time -3.3%**
- **Geomean of scores -1.5%**

Summary

- Some benefits can only be revealed if multiple call sites are inlined together
- We made our inliner work on clusters of call sites
- We implemented EA-driven clustering heuristics

Future work and conclusions

Future work

- Better estimation of benefits
  - In general and for clusters specifically
  - Merge our cost/benefit analysis with the one upstream
- New clustering heuristics
- Cluster merging

Conclusions

- We build a custom downstream inliner in Falcon
  - Top-down inliner
  - On-demand generation of candidates
  - Fixed point iteration of inlining and simplifications in the top-level function
- Total budget and prioritization by benefit/cost ratio
- Limited bottom-up inlining for 2 level of the call graph
- EA-driven cluster inlining

Thank You.