Directing Function Inlining with Post-Inlining Benefits

Erick Ochoa
eochoa@ualberta.ca

Andrew Craik
ajcraik@ca.ibm.com

Karim Ali
karim@ualberta.ca

J. Nelson Amaral
jamaral@ualberta.ca

Function Inlining

```
System.out.println("Hello, " + person.getName());
```

Function Inlining

```
System.out.println("Hello, " + person.getName());
```

Function Inlining

```
System.out.println("Hello, " + person.getName());
```

```
23: aload_1
24: invokevirtual #9 // Person.getName:()Ljava/lang/String
```

Function Inlining

```
System.out.println("Hello, " + person.getName());
```

```
23: aload_1
24: invokevirtual #9 // Person.getName:()Ljava/lang/String
```

Function Inlining

```
System.out.println("Hello, " + person.getName());
```

```
23: aload_1
24: invokevirtual #9 // Person.getName:()Ljava/lang/String
```

```
public java.lang.String getName();
  Code:
     0: aload_0
     1: getfield
     4: areturn
```

Function Inlining

```
System.out.println("Hello, " + person.getName());
```

```
23: aload_1
24: invokevirtual #9 // Person.getName:()Ljava/lang/String
```

```
public java.lang.String getName();
  Code:
     0: aload_0
     1: getfield
     4: areturn
```

Function Inlining

```
System.out.println("Hello, " + person.getName());
```

```
23: aload_1
24: invokevirtual #9 // Person.getName:()Ljava/lang/String
```

```
public java.lang.String getName();
  Code:
     0: aload_0
     1: getfield
     4: areturn
```

Function Inlining

```
System.out.println("Hello, " + person.getName());
```

```
23: aload_1
24: invokevirtual #9
```

```
public java.lang.String getName();
  Code:
     0: aload_0
     1: getfield
     4: areturn
```

Function Inlining

```
System.out.println("Hello, " + person.name);
```

```
23: aload_1
24: invokevirtual #9
```

```
public java.lang.String getName();
  Code:
     0: aload_0
     1: getfield
     4: areturn
```

Function Inlining

```
System.out.println("Hello, " + person.name);
```

```
23: aload_1
24: invokevirtual #9
```

```
23: aload_1
24: getfield
```

```
public java.lang.String getName();
  Code:
     0: aload_0
     1: getfield
     4: areturn
```

Function Inlining

```
System.out.println("Hello, " + person.name);
```

```
23: aload_1
24: invokevirtual #9
```

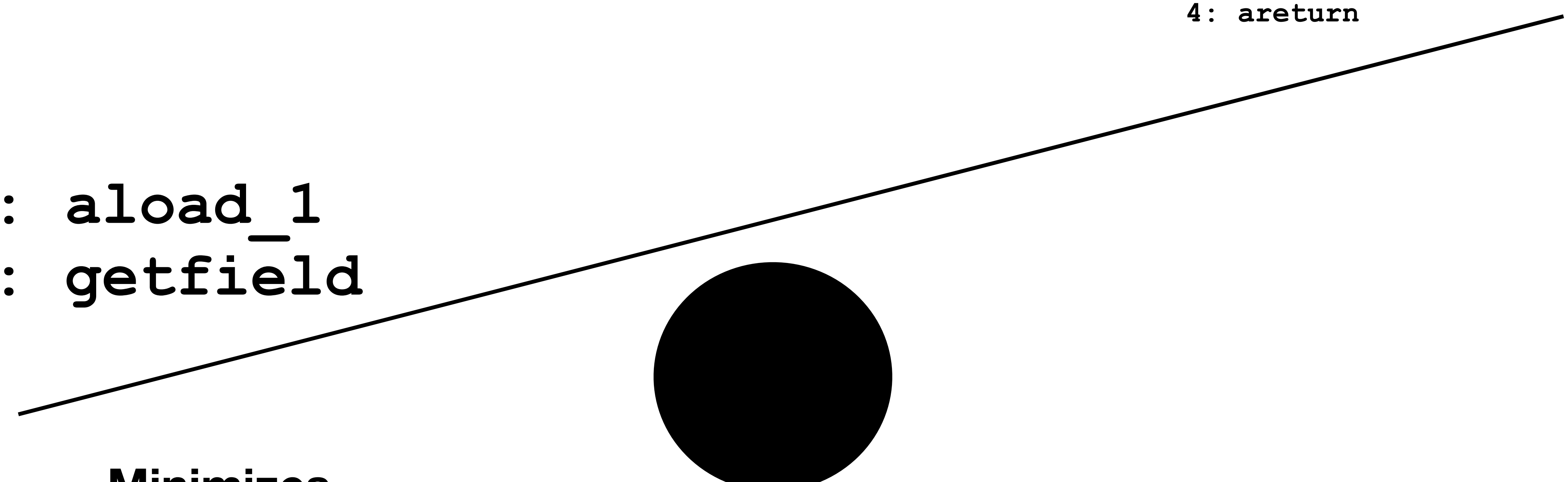
```
23: aload_1
24: getfield
```

```
public java.lang.String getName();
  Code:
     0: aload_0
     1: getfield
     4: areturn
```

Benefits vs Costs

```
23: aload_1
24: invokevirtual #9
```

```
public java.lang.String getName();
  Code:
     0: aload_0
     1: getfield
     4: areturn
```



```
23: aload_1
24: getfield
```

Minimizes
call instructions

Benefits vs Costs

```
23: aload_1
24: getfield
23: aload_1
24: getfield
23: aload_1
24: getfield
```

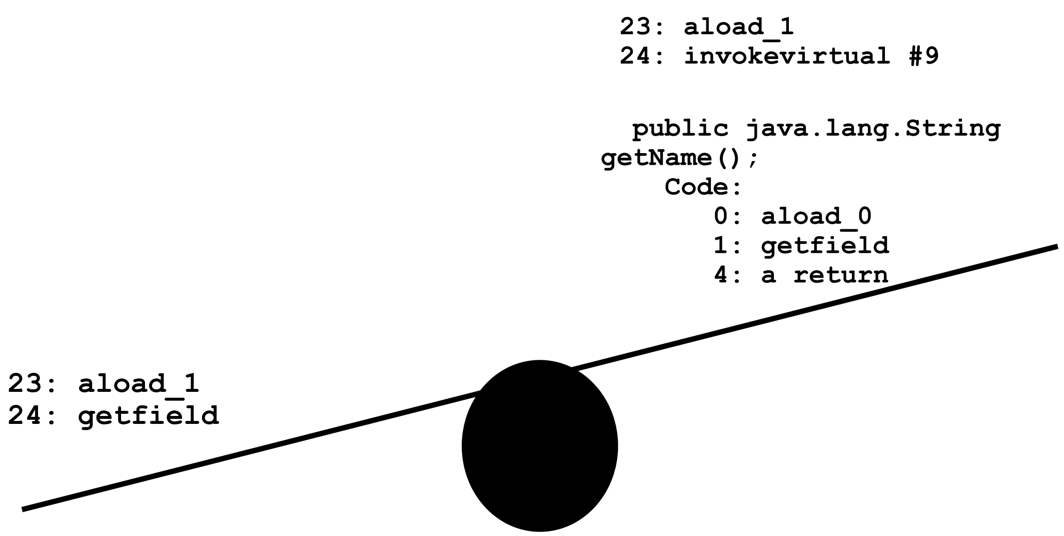
```
23: aload_1
24: invokevirtual #9
```

```
public java.lang.String getName(
  Code:
     0: aload_0
     1: getfield
     4: areturn
```

Minimizes call instructions

May increase Code size

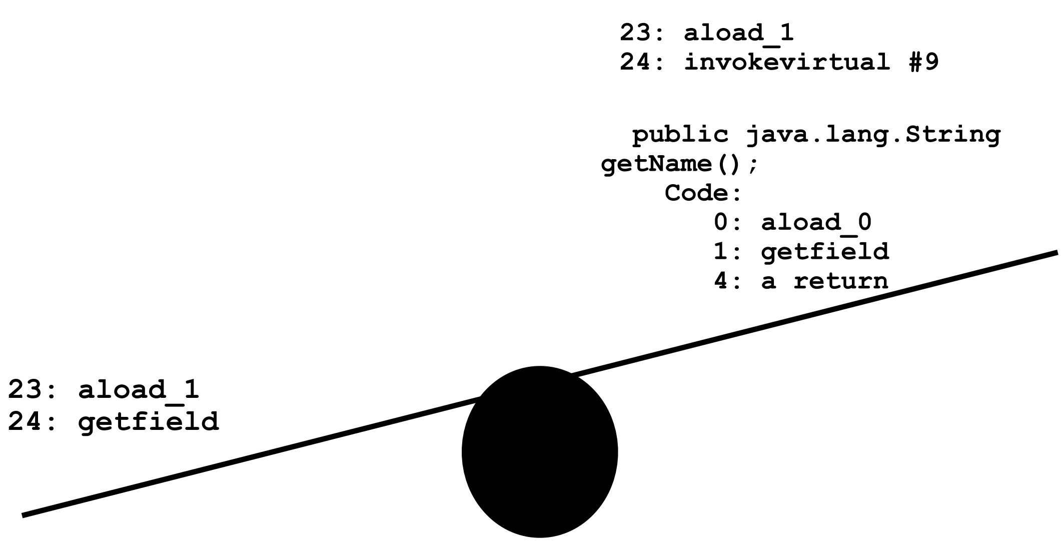
Greedy Inlining Strategy



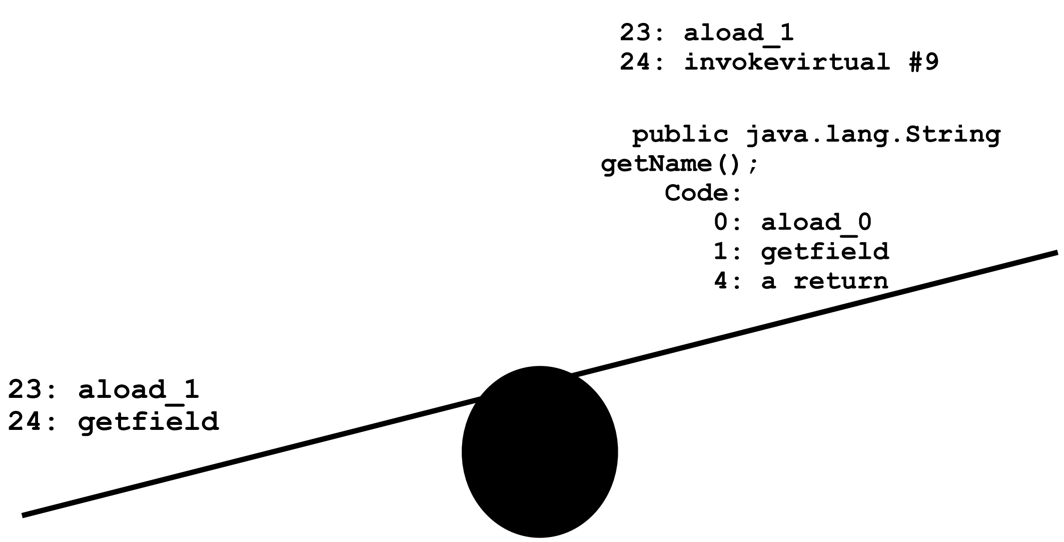
- **Focuses on direct benefits of inlining**

Greedy Inlining Strategy

- **Focuses on direct benefits of inlining**
- **Inlines smallest methods first**



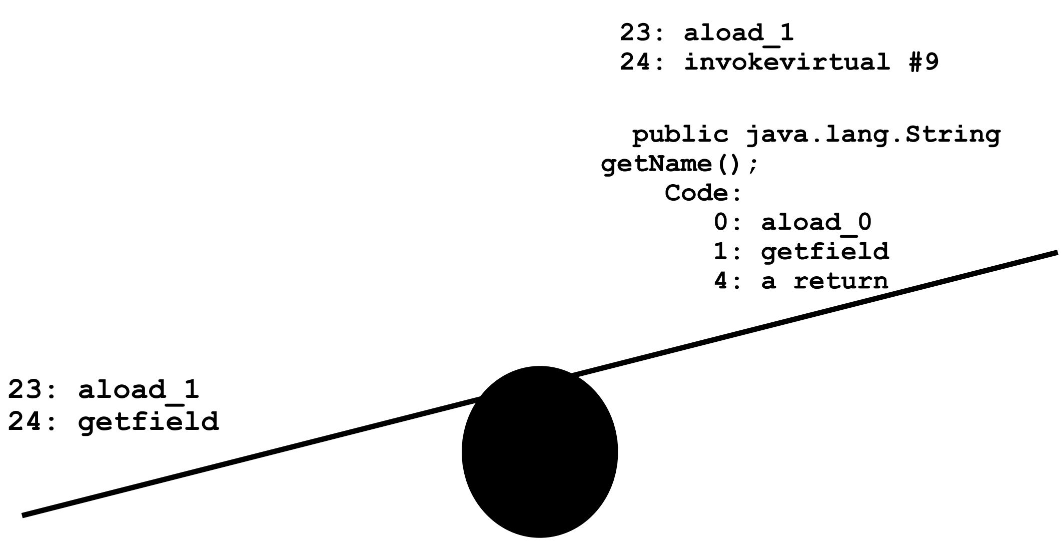
Greedy Inlining Strategy



- Focuses on direct benefits of inlining
- Inlines smallest methods first

Is inlining solved?

Greedy Inlining Strategy



- **Focuses on direct benefits of inlining**
- **Inlines smallest methods first**

Is inlining solved?
No!

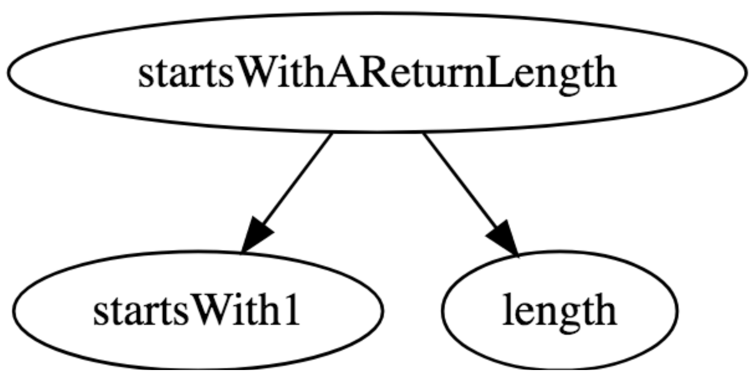
Example

Takeaway: small methods wrap around the computational expensive method


```
public int startsWithAReturnsLength(String example) {
    boolean starts = example.startsWith("A");
    return starts.length();
}
```

Example

Takeaway: small methods wrap around the computational expensive method

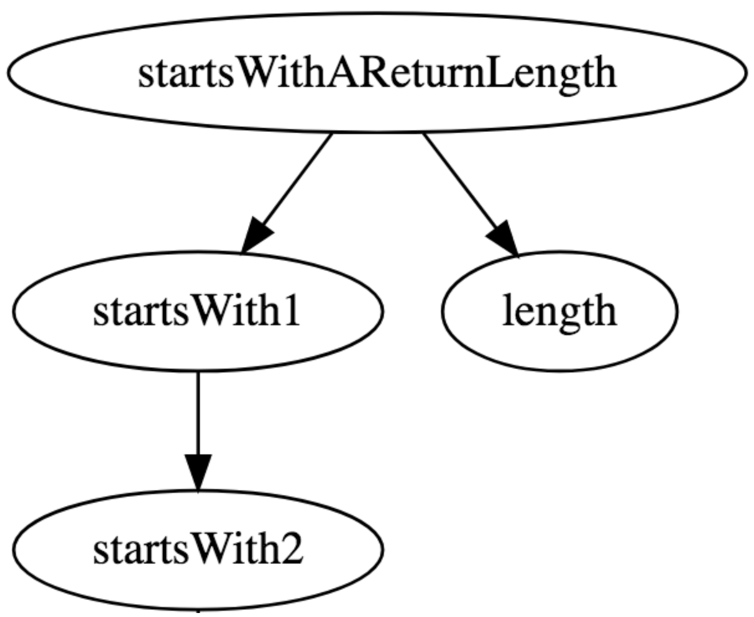



```
public int startsWithAReturnsLength(String example) {
    boolean starts = example.startsWith("A");
    return starts.length();
}

public boolean startsWith(String prefix) {
    return startsWith(prefix, 0);
}
```

```
public int length() {
    return this.length;
}
```

Example

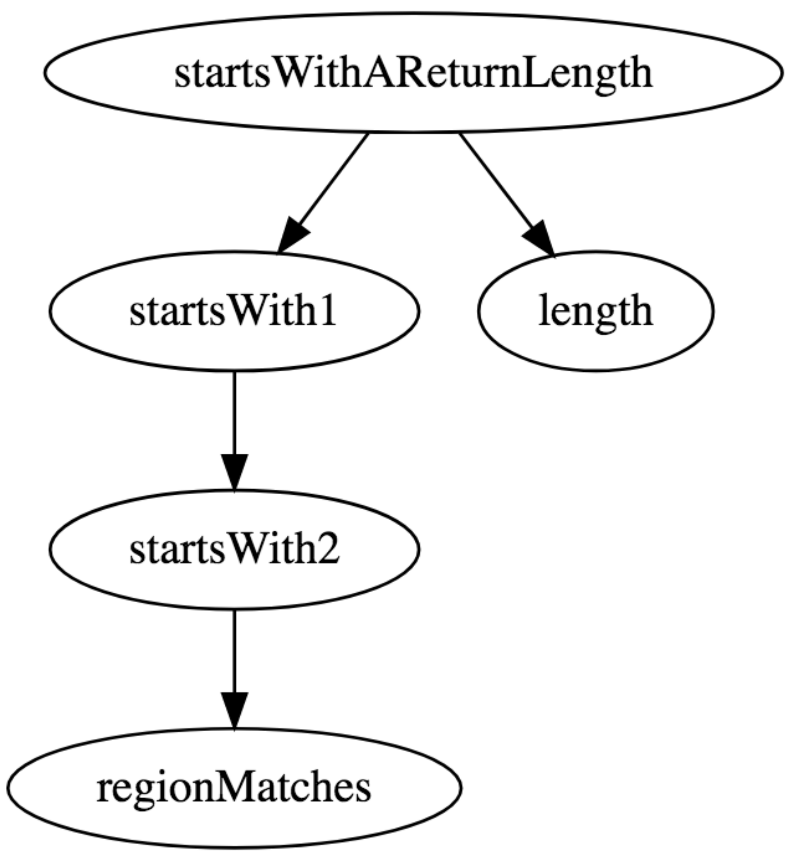
Takeaway: small methods wrap around the computational expensive method




```
public int startsWithAReturnsLength(String example) {
    boolean starts = example.startsWith("A");
    return starts.length();
}

public boolean startsWith(String prefix) {
    return startsWith(prefix, 0);
}

public boolean startsWith(String prefix, int start) {
    return regionMatches(start, prefix, 0, prefix.count);
}

public int length() {
    return this.length;
}
```

Example

Takeaway: small methods wrap around the computational expensive method

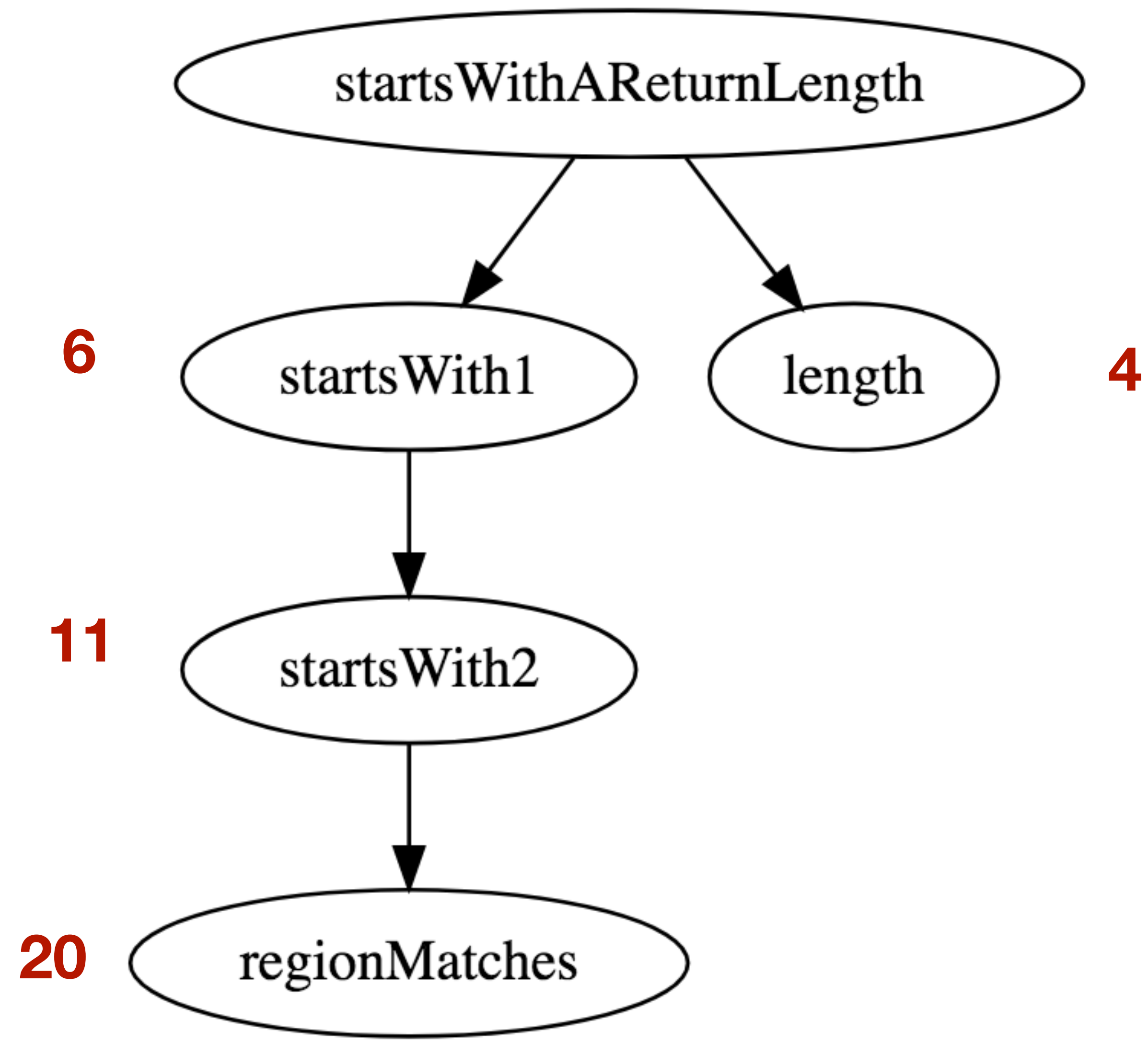



```
public int startsWithAReturnsLength(String example) {
    boolean starts = example.startsWith("A");
    return starts.length();
}

public boolean startsWith(String prefix) {
    return startsWith(prefix, 0);
}

public boolean startsWith(String prefix, int start) {
    return regionMatches(start, prefix, 0, prefix.count);
}

public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) { /* ... */ }

public int length() {
    return this.length;
}
```

Greedy Inliner

Budget = 40

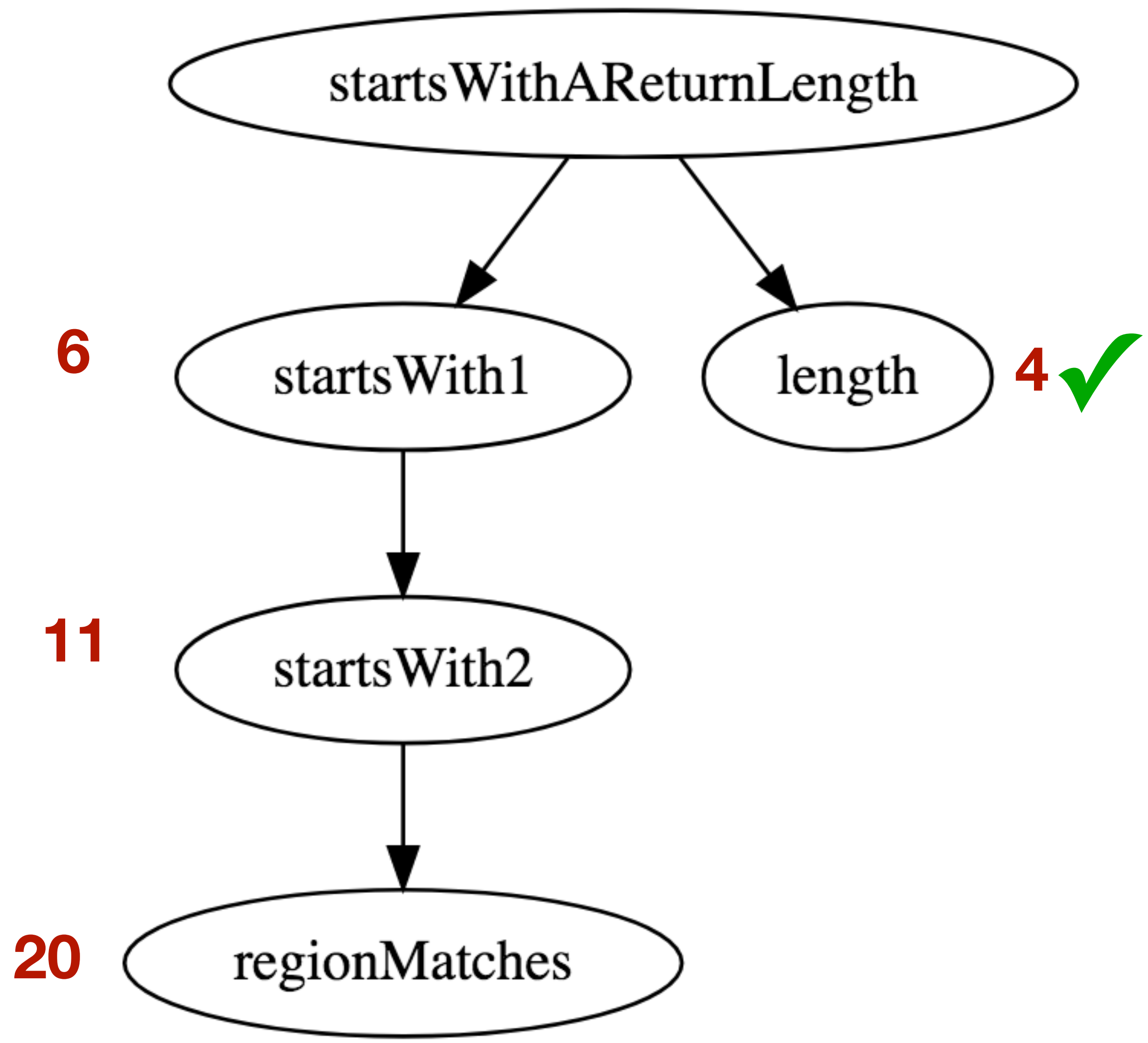
Remaining = 40



Greedy Inliner

Budget = 40

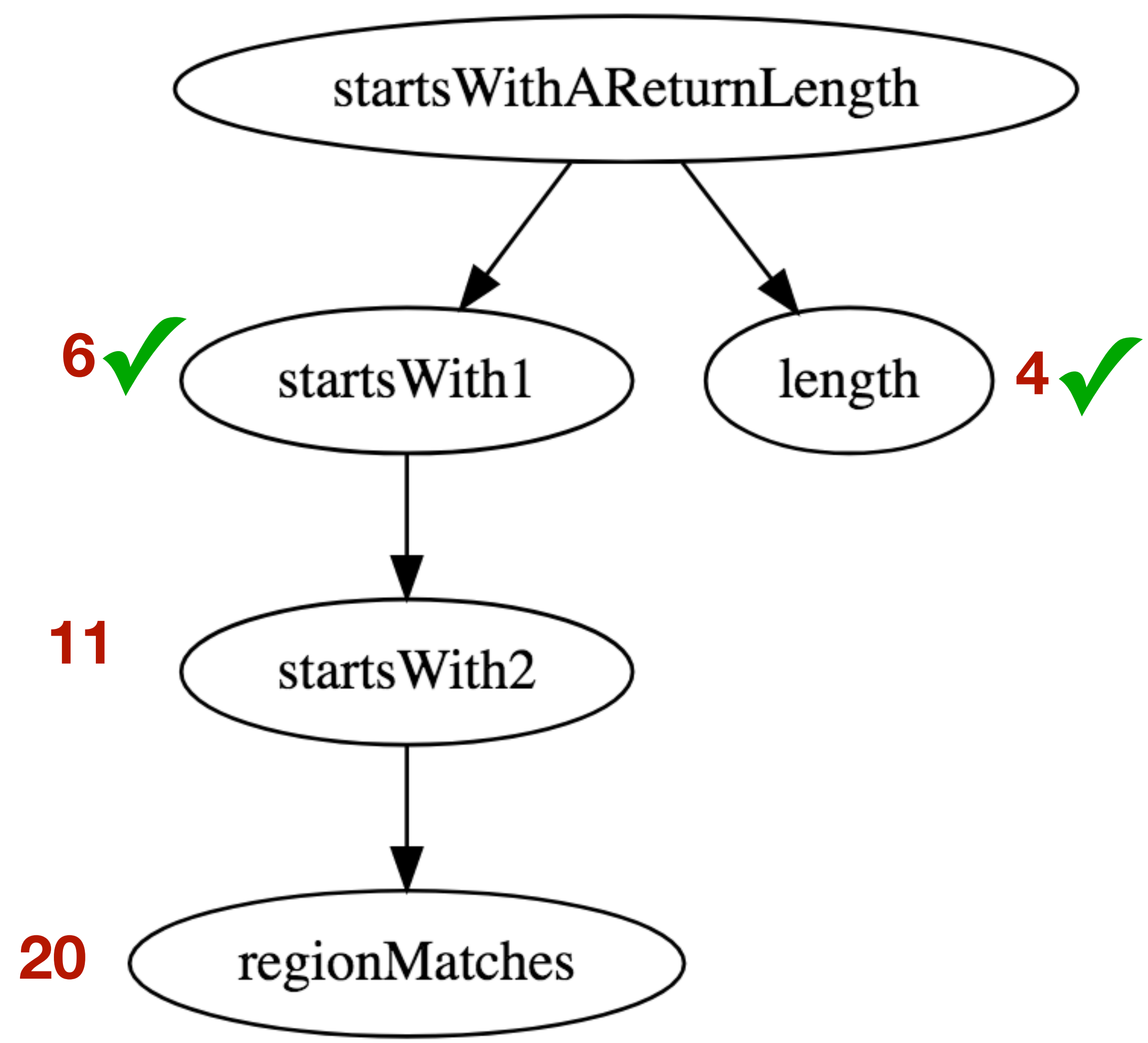
Remaining = 36



Greedy Inliner

Budget = 40

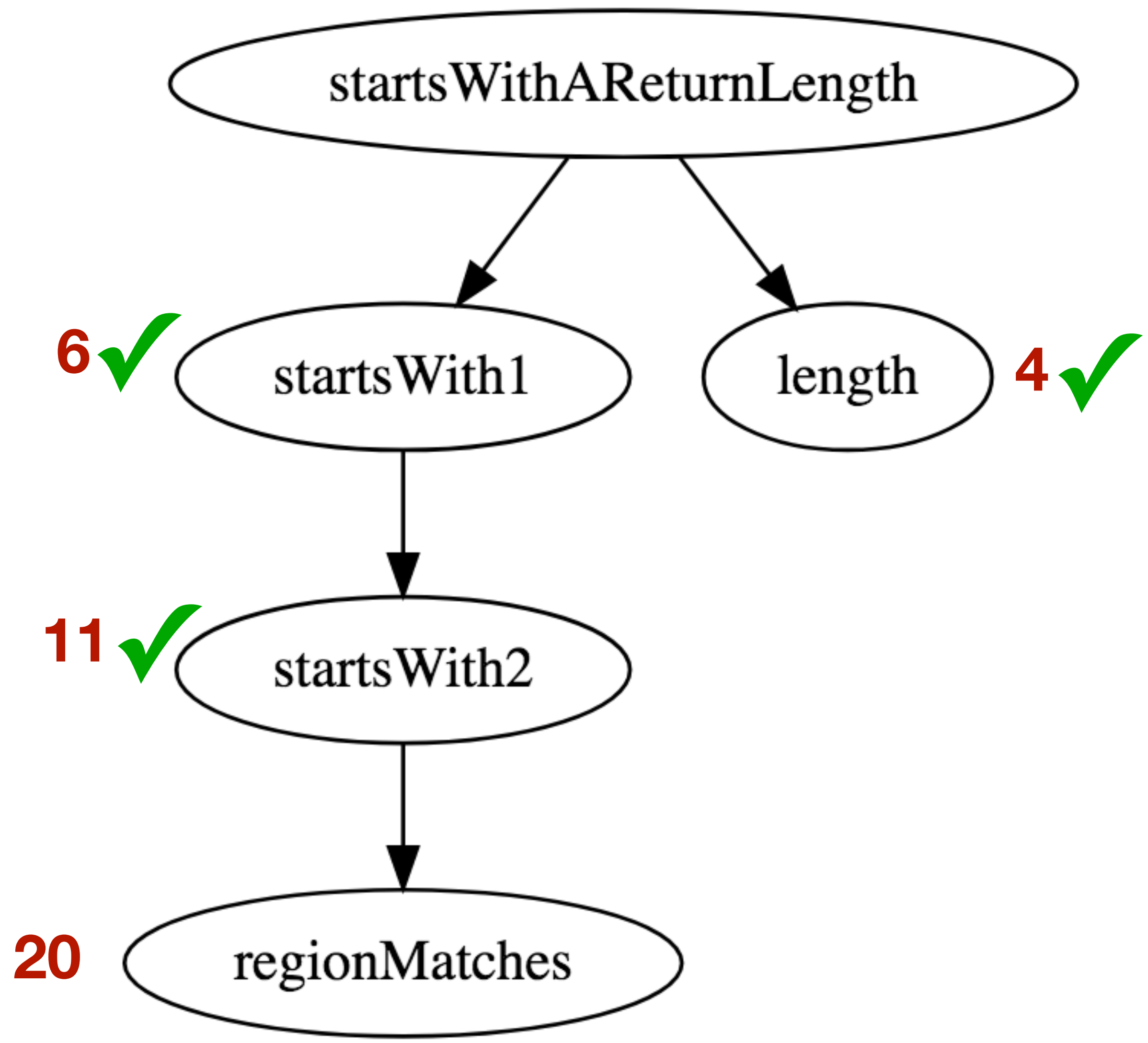
Remaining = 30



Greedy Inliner

Budget = 40

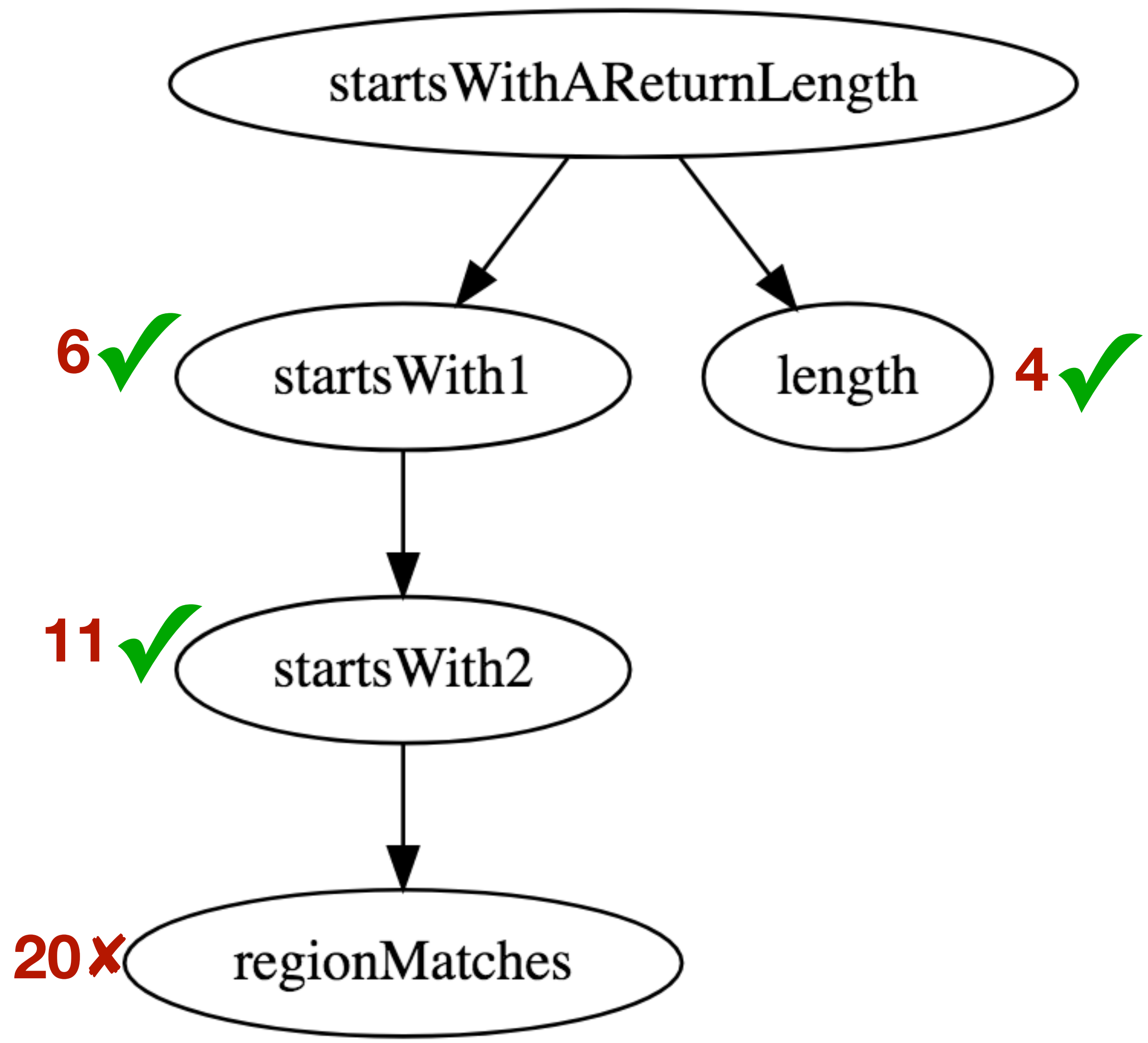
Remaining = 19



Greedy Inliner

Budget = 40

Remaining = 19

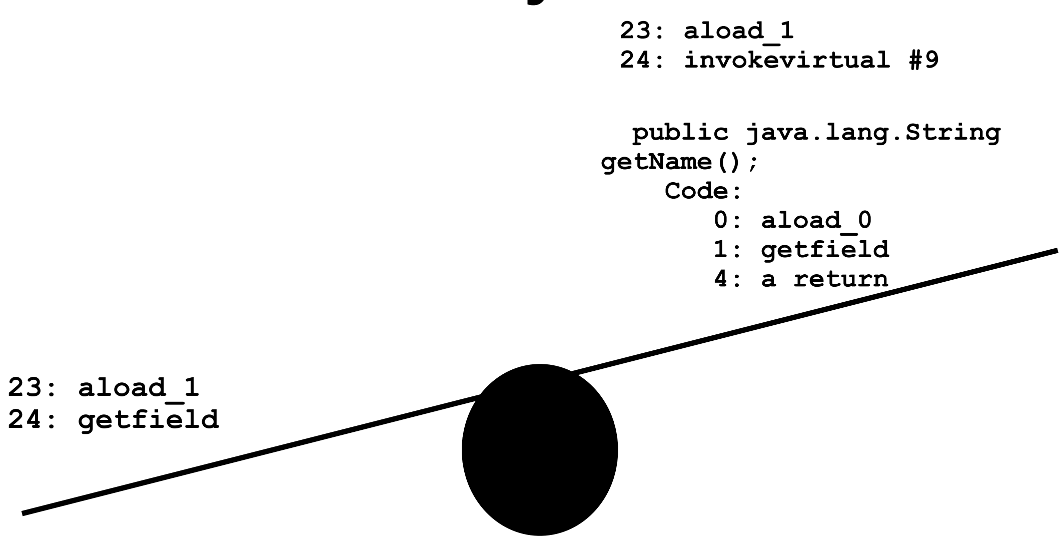


Problem?

Greedy inliner → Minimizes call instruction overhead

Problem?

Greedy inliner



What we want

Minimizes call instruction overhead

Minimizes execution time

Benefits vs Costs

Benefit

- Avoids call instruction overhead

Benefits vs Costs

Benefit

- Avoids call instruction overhead
- Improves dataflow analyses by providing additional context

Benefits vs Costs

Benefit

- Avoids call instruction overhead
- Improves dataflow analyses by providing additional context
- Other compiler transformations benefit from additional context

Benefits vs Costs

Benefit

- Avoids call instruction overhead
- Improves dataflow analyses by providing additional context
- Other compiler transformations benefit from additional context
- Inlined method specializes to its calling context

Benefits vs Costs

Benefit

- Avoids call instruction overhead
- Improves dataflow analyses by providing additional context
- Other compiler transformations benefit from additional context
- Inlined method specializes to its calling context

Costs

Benefits vs Costs

Benefit

- Avoids call instruction overhead
- Improves dataflow analyses by providing additional context
- Other compiler transformations benefit from additional context
- Inlined method specializes to its calling context

Costs

- Code growth

Benefits vs Costs

Benefit

- Avoids call instruction overhead
- Improves dataflow analyses by providing additional context
- Other compiler transformations benefit from additional context
- Inlined method specializes to its calling context

Costs

- Code growth
- Potential negative cache effects

Benefits vs Costs

Benefit

- Avoids call instruction overhead
- Improves dataflow analyses by providing additional context
- Other compiler transformations benefit from additional context
- Inlined method specializes to its calling context

Costs

- Code growth
- Potential negative cache effects
- Increase compile time and analysis time

Problem?

Greedy inliner → Minimizes call instruction overhead

Benefits

- Avoids call instruction overhead

Benefits

- Avoids call instruction overhead
- **Improves dataflow analyses by providing additional context**
- **Other compiler transformations benefit from additional context**
- **Inlined method specializes to its calling context**

Towards Better Inlining Decisions Using Inlining Trials

Jeffrey Dean and Craig Chambers

Department of Computer Science and Engineering
University of Washington

Abstract

Inlining trials are a general mechanism for making better automatic decisions about whether a routine is profitable to inline. Unlike standard source-level inlining heuristics, an inlining trial captures the effects of optimizations applied to the body of the inlined routine when calculating the costs and benefits of inlining. The results of inlining trials are stored in a persistent database to be reused when making future inlining decisions at similar call sites. Type group analysis can determine the amount of available static information exploited during compilation, and the results of analyzing the compilation of an inlined routine help decide when a future call site would lead to substantially the same generated code as a given inlining trial. We have implemented inlining trials and type group analysis in an optimizing compiler for SELF, and by making wiser inlining decisions we were able to cut compilation time and compiled code space with virtually no loss of execution speed. We believe that inlining trials and type group analysis could be applied effectively to many high-level languages where procedural or functional abstraction is used heavily.

1 Introduction

Inlining is an important implementation technique for reducing the performance costs of language abstraction mechanisms. Inlining (also known as procedure integration and unfolding) not only confers the direct benefits of eliminating the procedure call and return sequences but also facilitates optimizing the body of the called routine in the context of the call site; sometimes these indirect post-inlining benefits dwarf the direct benefits. Inlining has long been applied to languages like C and Fortran, but it may be even more beneficial in the context of higher-level languages. Functional languages such as Scheme and ML [Rees & Clinger 86, Milner *et al.* 90], pure object-oriented languages such as Smalltalk and Eiffel [Goldberg & Robson 83, Meyer 92], and reflective systems such as CLOS and SchemeXerox [Bobrow *et al.* 88, Adams *et al.* 93] encourage programmers to write general, reusable routines and solve problems by composing existing functionality, leading to programs with very high call frequencies. Compilers and partial evaluators, such as Similix and Schism [Bondorf 91, Consel 90], can exploit inlining to reduce the cost of these abstraction mechanisms and thereby foster better programming styles.

Inlining is possible only when the compiler can determine statically the single target routine invoked by a call; in functional and object-oriented languages, this determination can require sophisticated analysis [Shivers 88, Hall & Kennedy 92, Chambers & Ungar 90, Palsberg & Schwartzbach 91]. But even if the call site is *potentially* inlinable, inlining may not be *profitable*. Care must be taken not to inline too much, or compilation time and compiled code could swell prohibitively. Inlining should only be applied where the benefits obtained by inlining outweigh the costs.

In many systems, the profitability of inlining a particular routine is hard-wired into the compiler. For example, the Smalltalk-80 compiler hard-wires the definition and optimized implementation of several basic functions from its standard library, and the Haskell standard prelude is fixed so that compilers can implement the functions in the standard library more efficiently [Hudak *et al.* 90]. A drawback of the hard-wiring approach is that built-in routines usually run much faster than user-defined routines, discouraging programmers from defining and using their own abstractions. Other systems, including C++, Modula-3, T Scheme, SchemeXerox, Common Lisp, Similix, and Schism [Stroustrup 91, Nelson 91, Slade 87, Adams *et al.* 93, Steele 90], allow programmers to indicate explicitly which routines are profitable to inline. While granting programmers fine control over the compilation process, this approach requires programmers to have a fair understanding of the language's implementation issues (an assumption becoming less likely as implementations become more sophisticated) and can be tedious if inlining must be applied heavily to get good performance. Additionally, most explicit declaration-based mechanisms do not allow programmers to specify that inlining is profitable only in certain contexts, or that inlining should only take place at particular high-frequency calls of some routine.

Our research investigates techniques for automatically deciding when inlining is profitable. Making good inlining decisions depends crucially on accurately assessing the costs and benefits of inlining. Previous automatic decision makers used simple techniques for estimating costs based on an examination of the target routine's source code (or unoptimized intermediate code), and consequently they failed to take into account the effect of post-inlining optimization of the target routine. Our work corrects this deficiency, leading to more accurate cost and benefit estimates and therefore better inlining decisions.

Our system assesses the costs and benefits of inlining by first experimentally inlining the target routine, in the process measuring the actual costs and benefits of that particular inline-expansion, and then amortizing the cost of the experiment (called an *inlining trial*) across future calls to that routine by storing the results of the trial in a persistent database. Because the indirect costs and benefits of inlining can depend greatly on the amount of the static information available at the call site (e.g., the static value or class of an argument), our system performs *type group analysis* to determine the amount of available call-site-specific static information that was exploited during optimization. Each database entry is guarded with type group information, restricting reuse of the information derived from an inlining trial to those call sites that would generate substantially the same compiled code.

We implemented and measured this approach in the context of an optimizing compiler for SELF [Ungar & Smith 87, Chambers & Ungar 91], a pure object-oriented language similar to Smalltalk but without any hard-wired operations or control structures. The SELF

Permission to copy without fee all or part of this material is granted provided that the copies are not made or distributed for direct commercial advantage, the ACM copyright notice and the title of the publication and its date appear, and notice is given that copying is by permission of the Association of Computing Machinery. To copy otherwise, or to republish, requires a fee and/or specific permission.

LISP 94 - 6/94 Orlando, Florida USA
© 1994 ACM 0-89791-643-3/94/0006..$3.50

1994

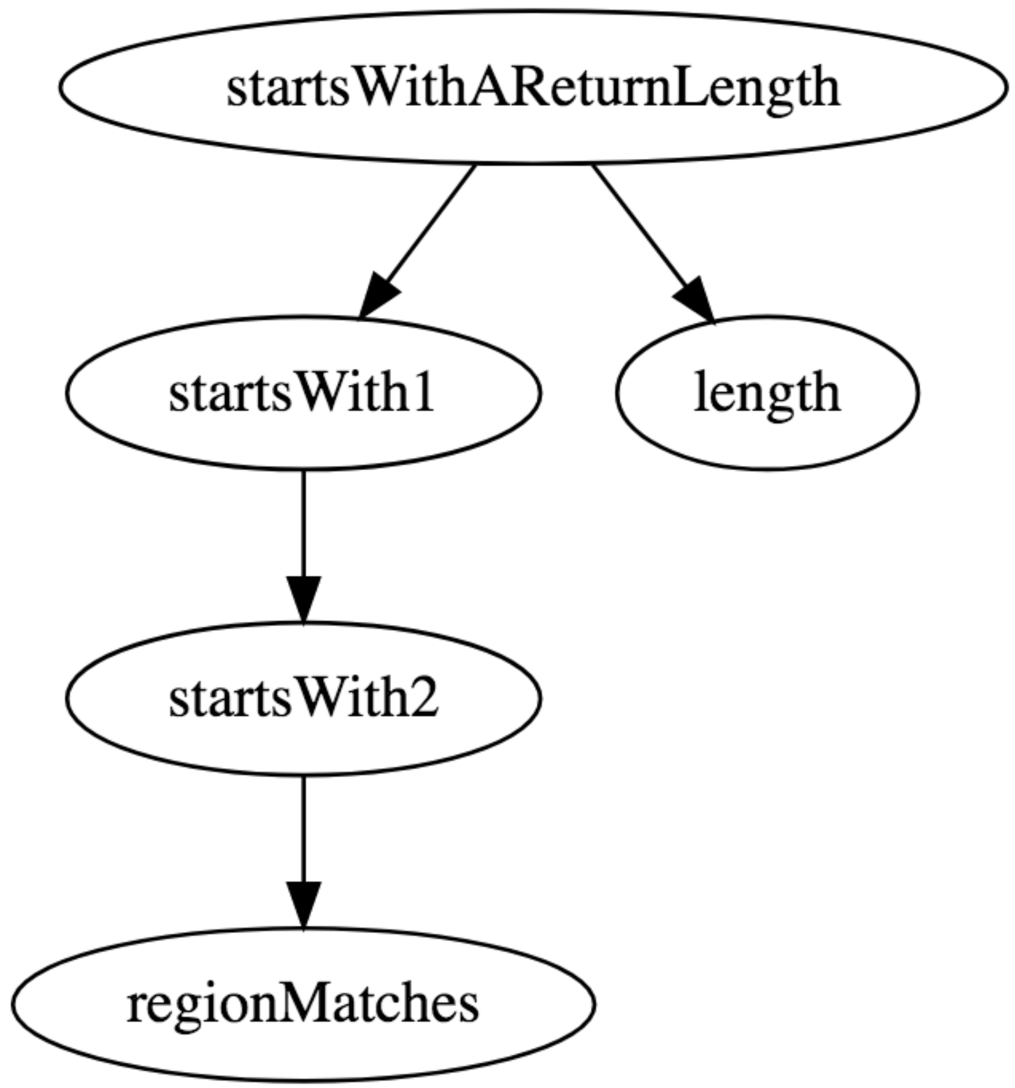
Problem?

Greedy inliner	➡	Minimizes call instruction overhead
What we want	➡	Minimizes execution time
Cost-Benefit Inliner	➡	Maximizes Benefit

Steps

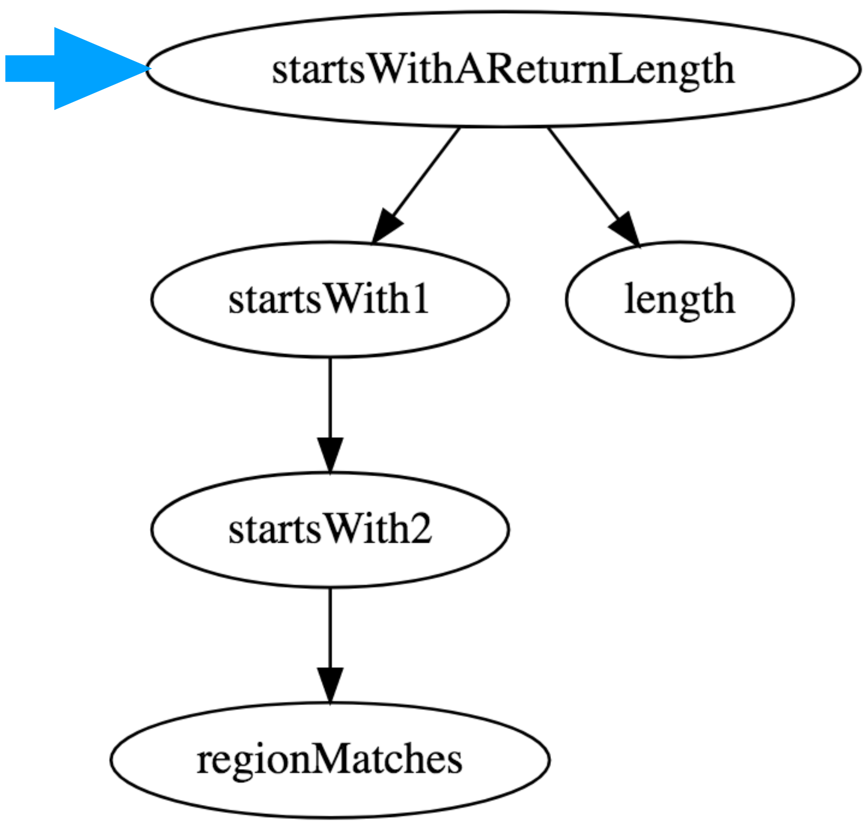
1. **Call Graph Construction**
2. **Transfer static information**
3. **Calculate the benefit metric**
4. **Obtain inlining plan**

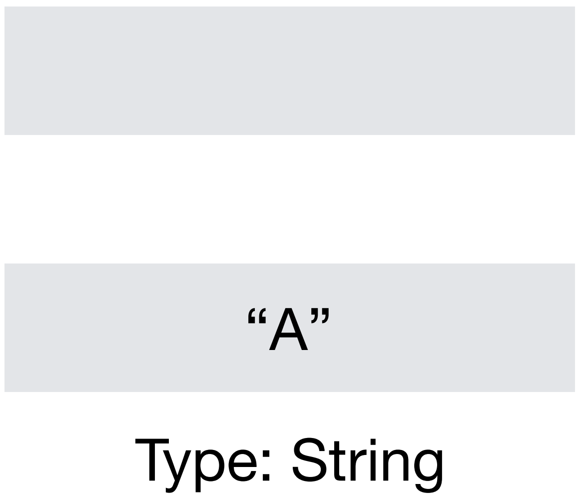
Call Graph Construction



Static Information Transfer

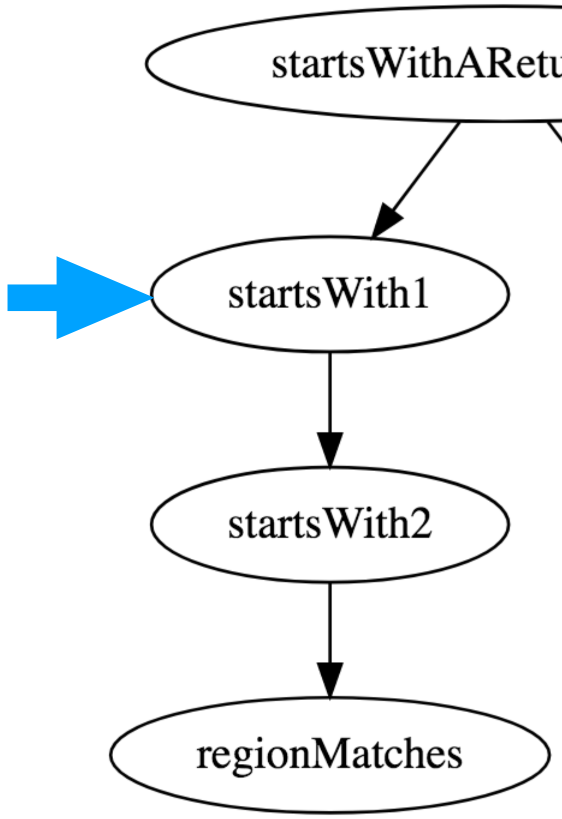
```
public int startsWithAReturnsLength(String example) {
   boolean starts = example.startsWith("A");
   return starts.length();
}
```

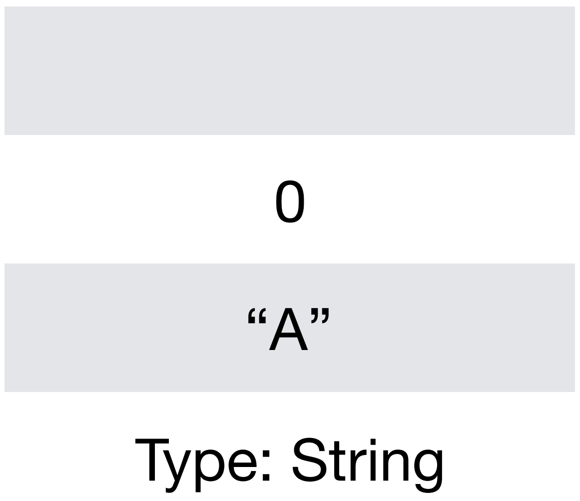




Static Information Transfer

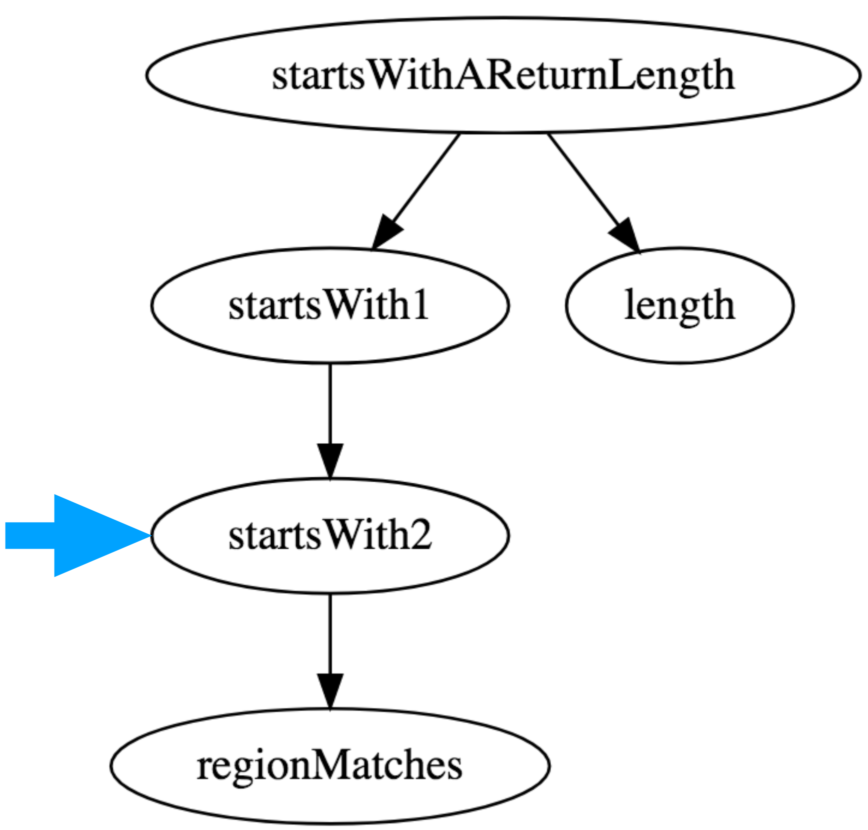
```
public boolean startsWith(String prefix) {
   return startsWith(prefix, 0);
}
```





Static Information Transfer

```
public boolean startsWith(String prefix, int start) {
   return regionMatches(start, prefix, 0, prefix.count);
}
```



1

0

“A”

0

Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {

    if (start < 0 || string.count - start < length) return false;
    if (thisStart < 0 || count - thisStart < length) return false;
    if (length <= 0)  return true;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {

    if (start < 0 || string.count - start < length) return false;
    if (thisStart < 0 || count - thisStart < length) return false;
    if (length <= 0)  return true;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {

    if (              string.count - start < length) return false;
    if (thisStart < 0 || count - thisStart < length) return false;
    if (length <= 0)  return true;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
      String string,
      int start,
      int length) {

   if (             string.count - start < length) return false;
   if (thisStart < 0 || count - thisStart < length) return false;
   if (length <= 0)  return true;

   /* ... */

   int end = length - 1;
   for (int i = 0; i < end; ++i) {
      if (source[o1 + i] != target[o2 + i])
         return false;
   }

   return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {

    if (                                         ) return false;
    if (thisStart < 0 || count - thisStart < length) return false;
    if (length <= 0)  return true;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {


    if (thisStart < 0 || count - thisStart < length) return false;
    if (length <= 0)  return true;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {

    if (thisStart < 0 || count - thisStart < length) return false;
    if (length <= 0)  return true;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {


    if (                    count - thisStart < length) return false;
    if (length <= 0)  return true;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
      String string,
      int start,
      int length) {

   if (                  count              <   1    ) return false;
   if (length <= 0)  return true;

   /* ... */

   int end = length - 1;
   for (int i = 0; i < end; ++i) {
      if (source[o1 + i] != target[o2 + i])
         return false;
   }

   return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {

    if (                    count               <    1    ) return false;
    if (length <= 0)  return true;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {

    if (                  count              <   1   ) return false;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
      String string,
      int start,
      int length) {

   if (                    count              <   1   ) return false;

   /* ... */

   int end = length - 1;
   for (int i = 0; i < end; ++i) {
      if (source[o1 + i] != target[o2 + i])
         return false;
   }

   return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Benefit in method = 0.5

***Still work in progress**

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {


    if (                    count               <   1   ) return false;


    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

If end was different to 0, then we could unroll the loop.

Post Inlining Benefit

```
public boolean regionMatches(int thisStart,
        String string,
        int start,
        int length) {

    if (start < 0 || string.count - start < length) return false;
    if (thisStart < 0 || count - thisStart < length) return false;
    if (length <= 0)  return true;

    /* ... */

    int end = length - 1;
    for (int i = 0; i < end; ++i) {
        if (source[o1 + i] != target[o2 + i])
            return false;
    }

    return true;
}
```

length = 1

start = 0

string = “A”

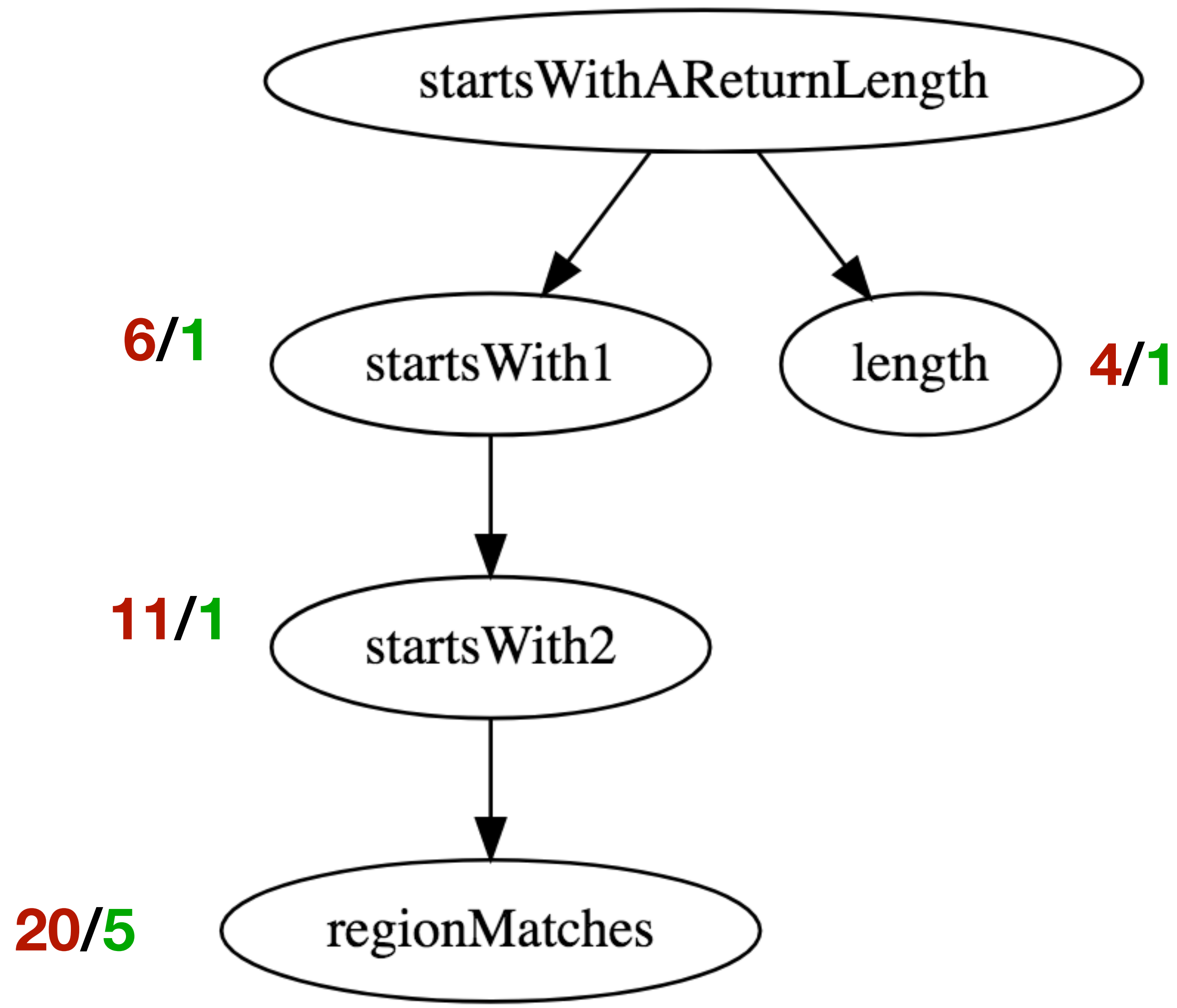
thisStart = 0

this = Type: String

If end was different to 0, then we could unroll the loop.

Benefit Analysis

Budget = 40

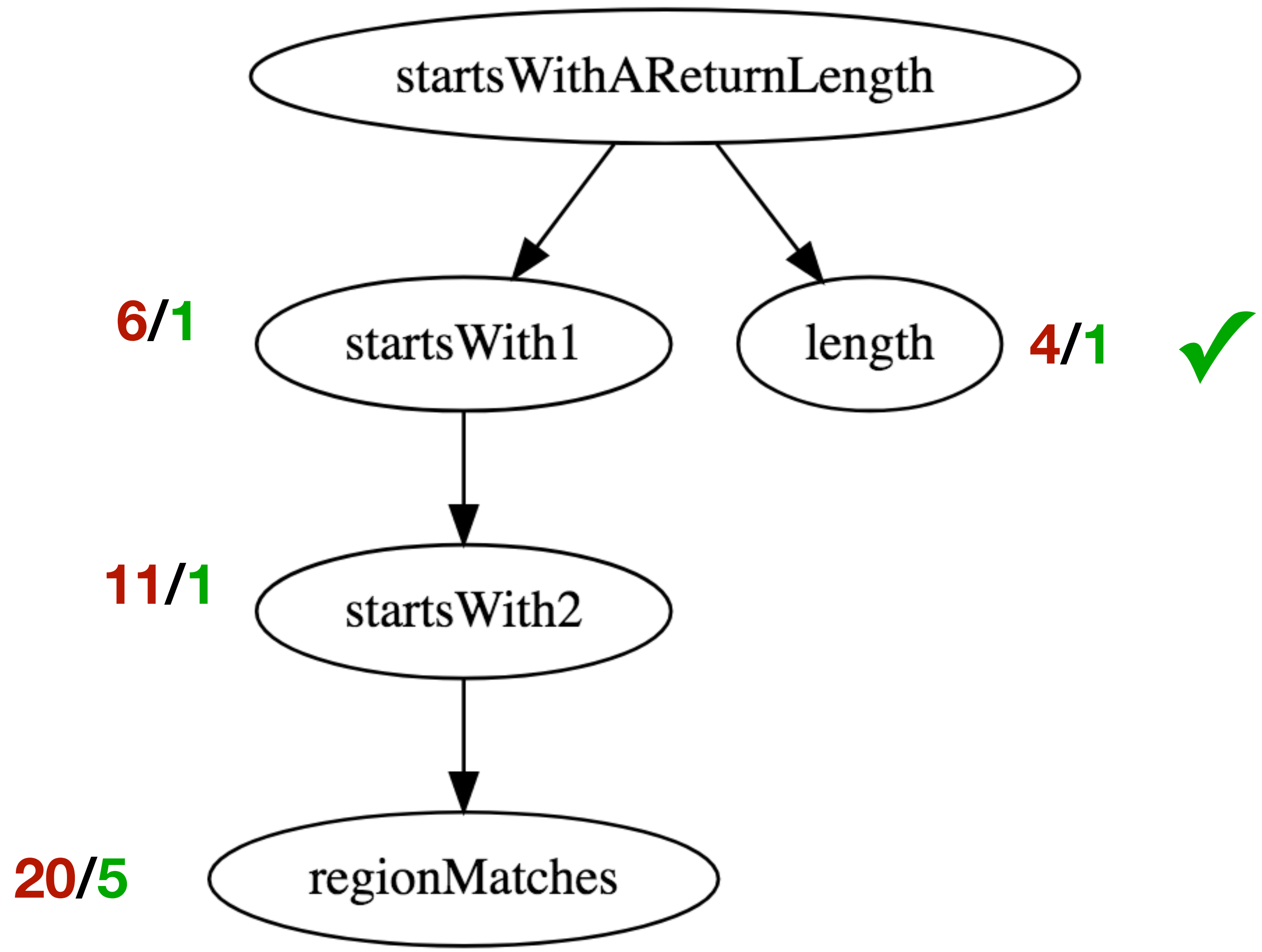


Cost/Benefit

Benefit Analysis

Budget = 40

Remaining = 36

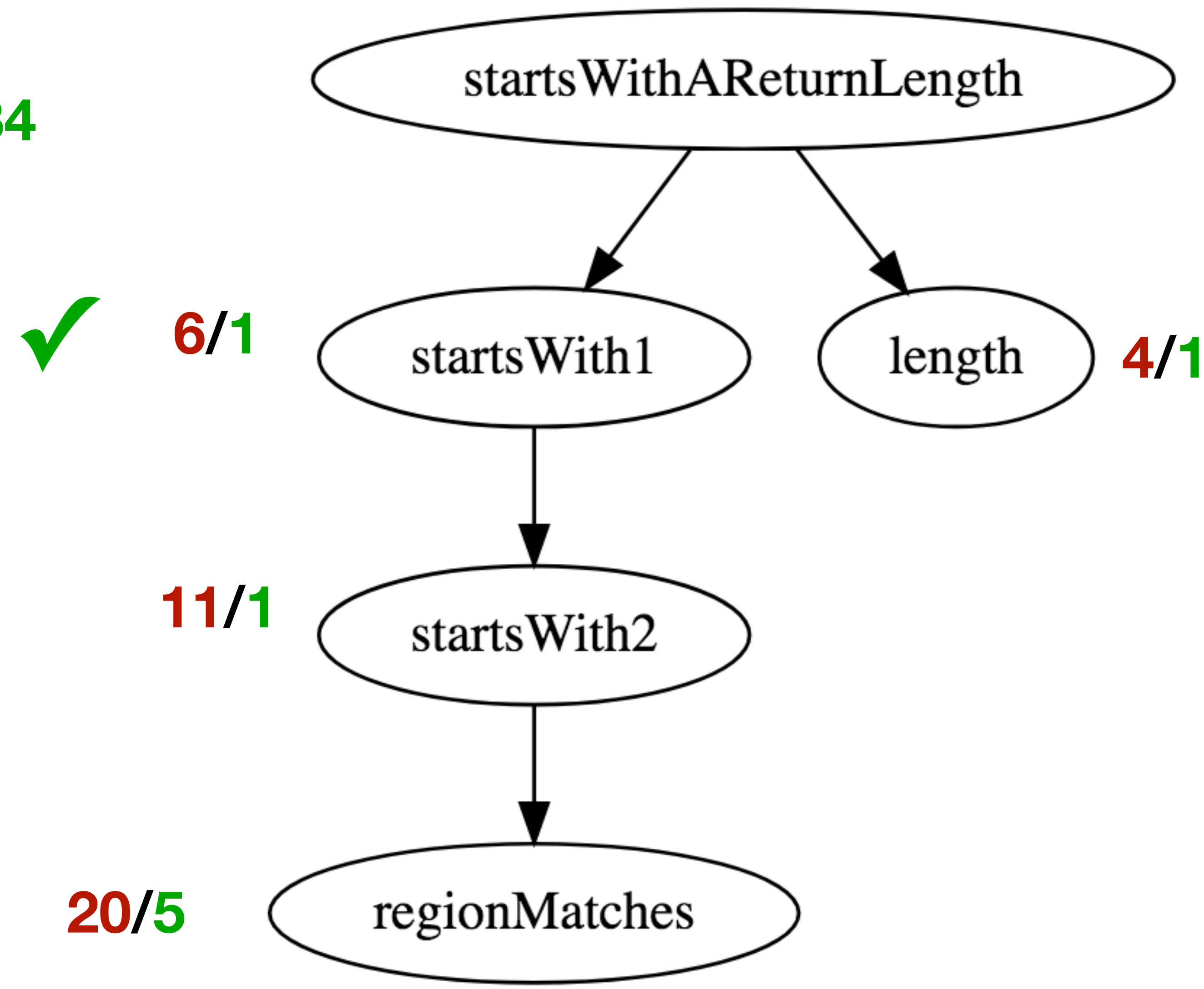


Cost/Benefit

Benefit Analysis

Budget = 40

Remaining = 34

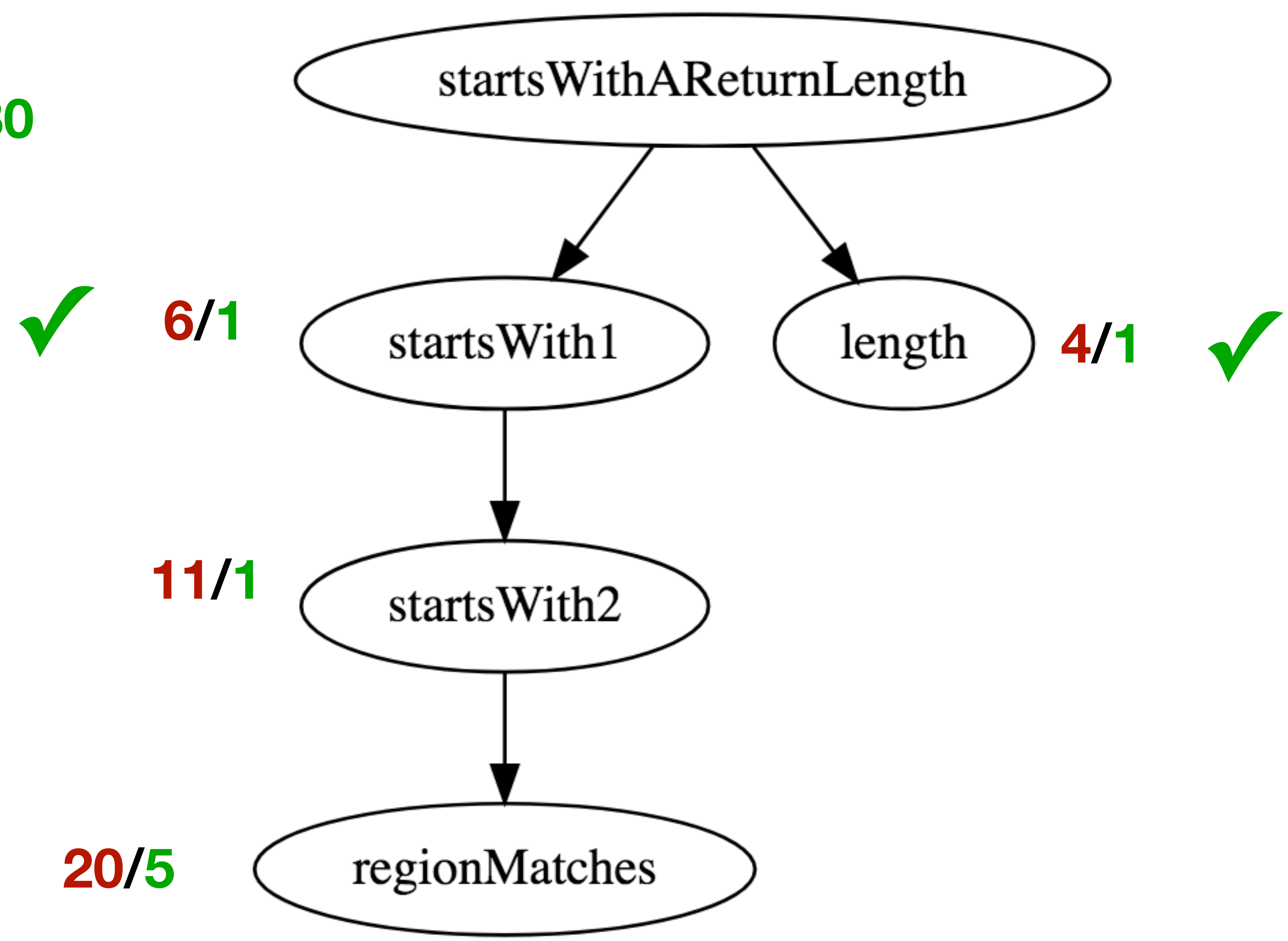


Cost/Benefit

Benefit Analysis

Budget = 40

Remaining = 30

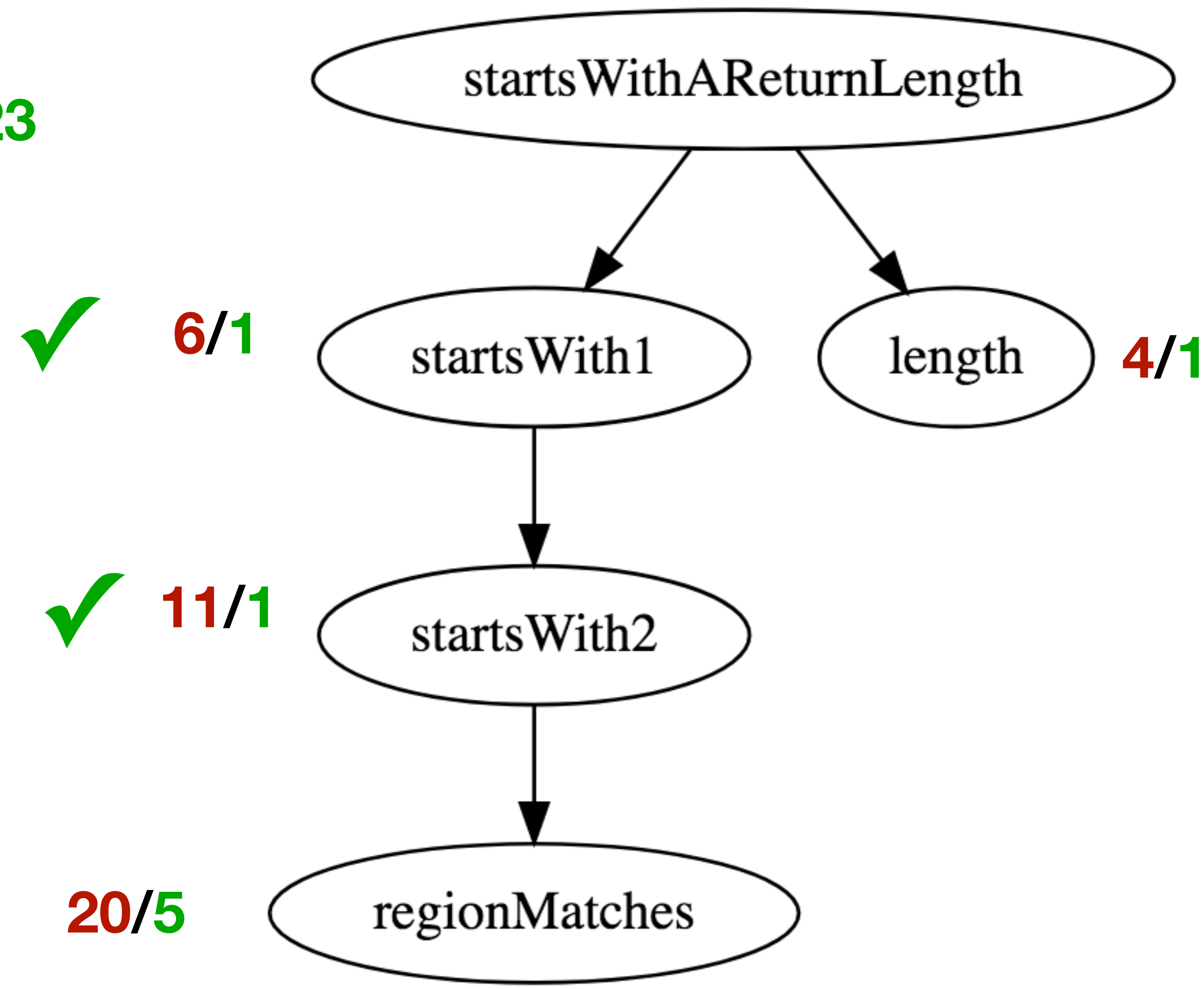


Cost/Benefit

Benefit Analysis

Budget = 40

Remaining = 23

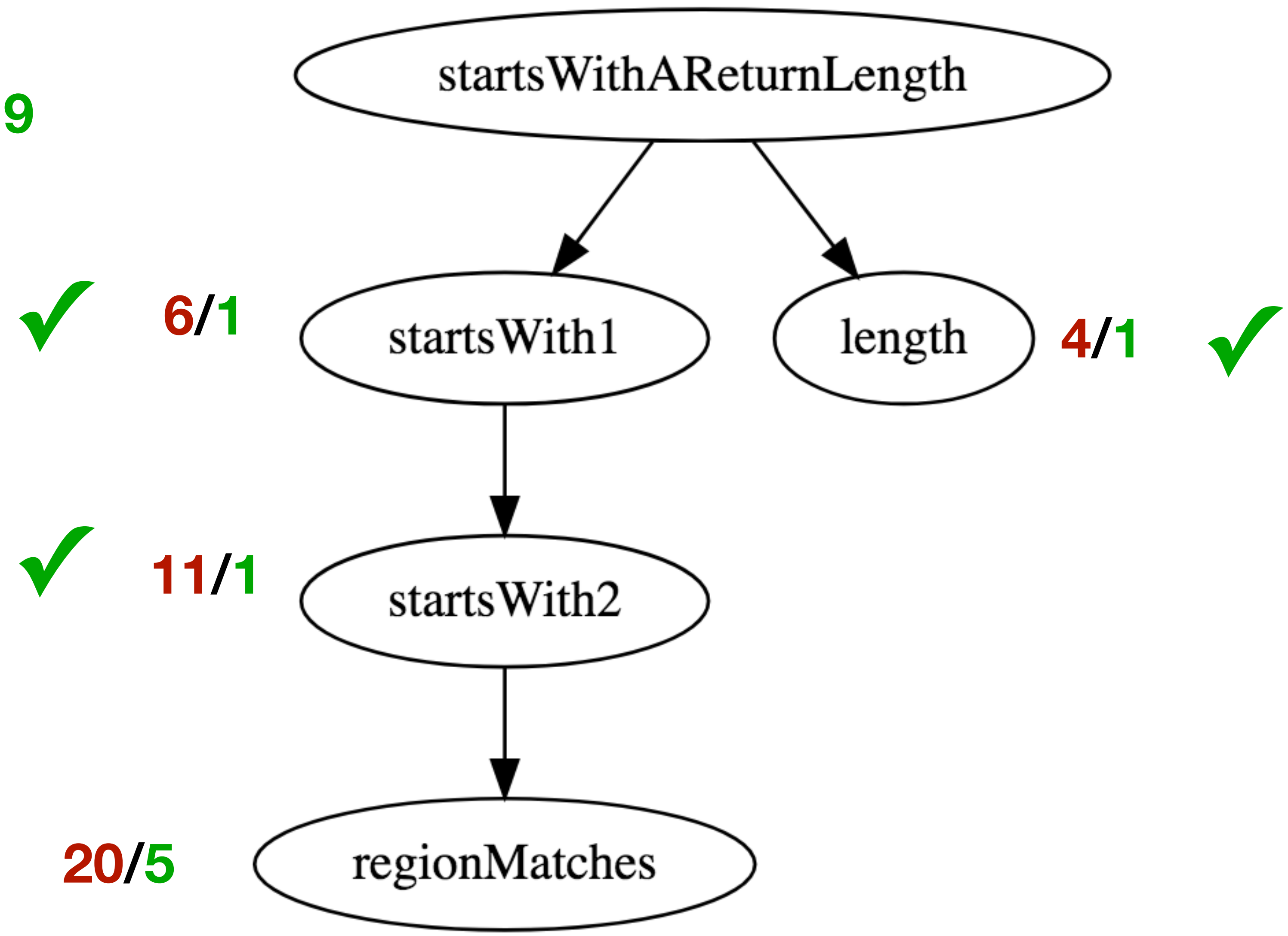


Cost/Benefit

Benefit Analysis

Budget = 40

Remaining = 19

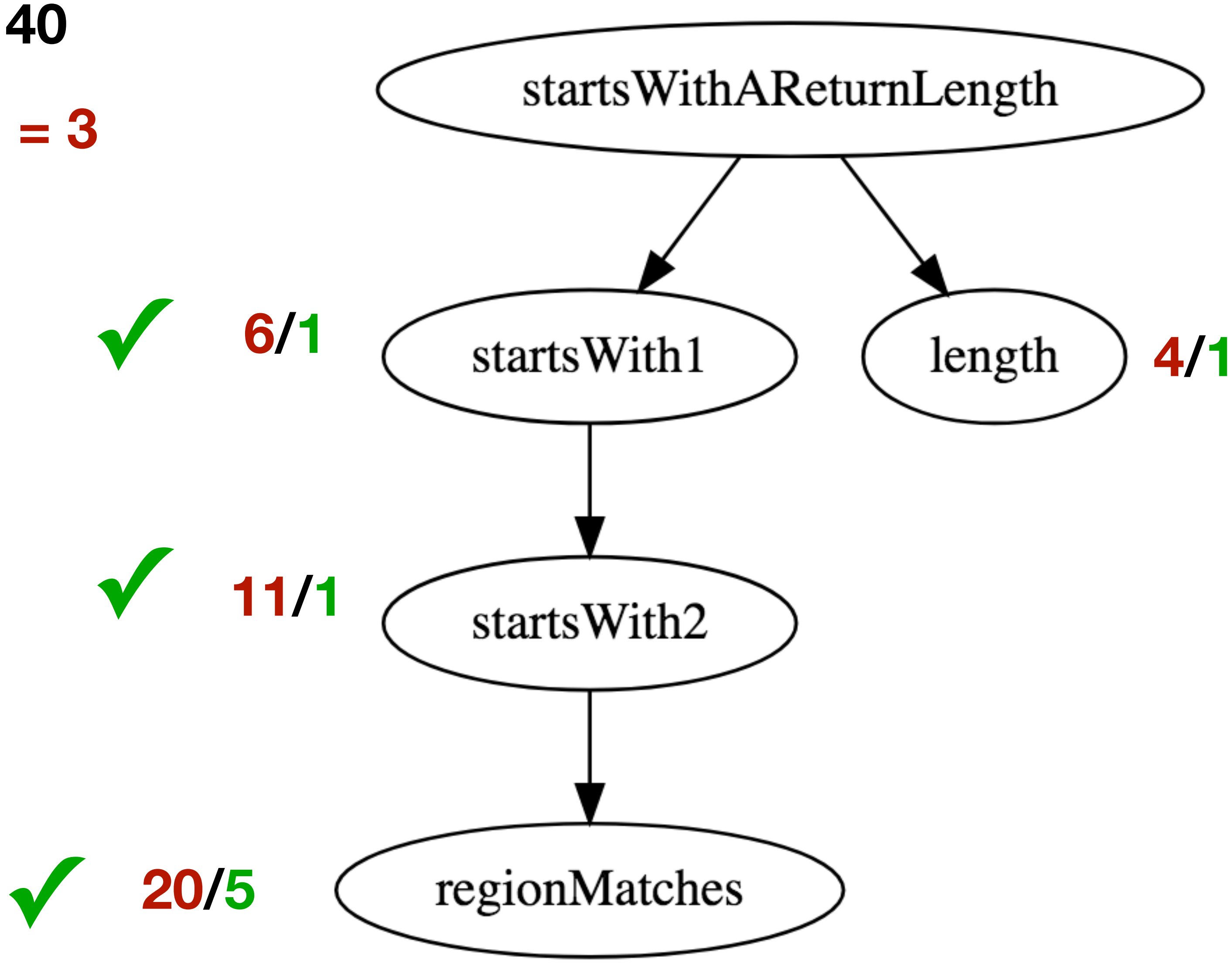


Cost/Benefit

Benefit Analysis

Budget = 40

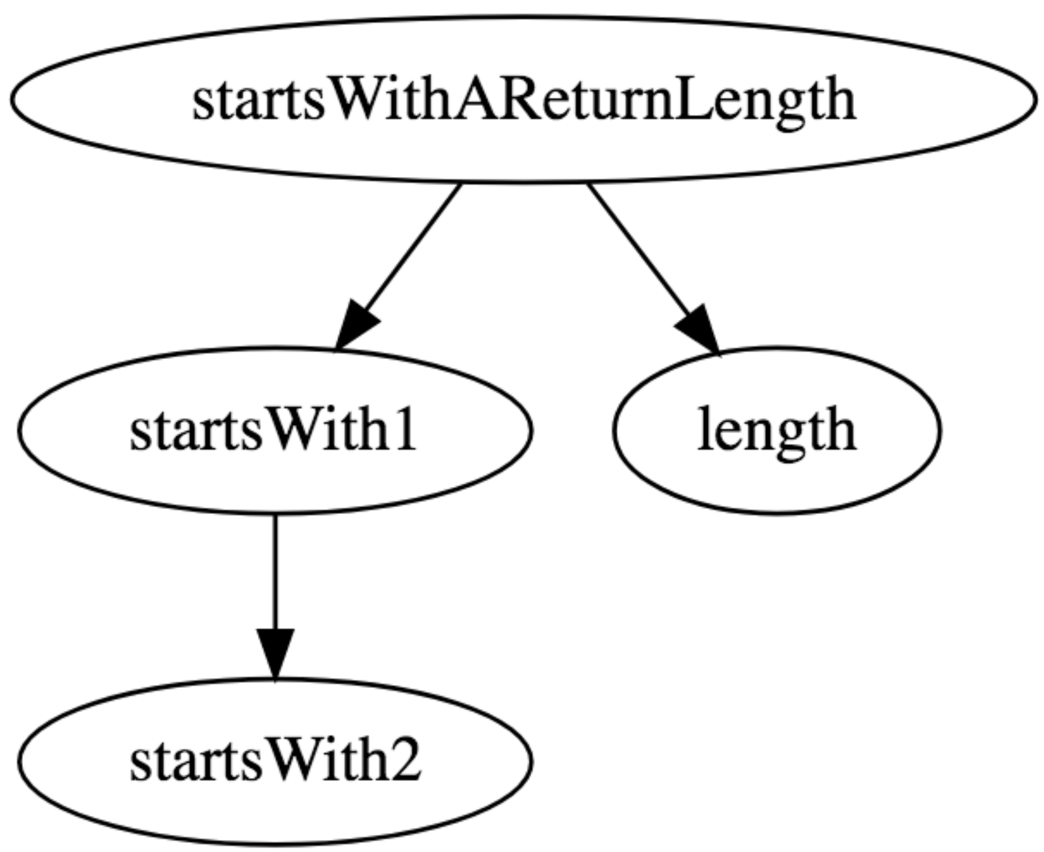
Remaining = 3



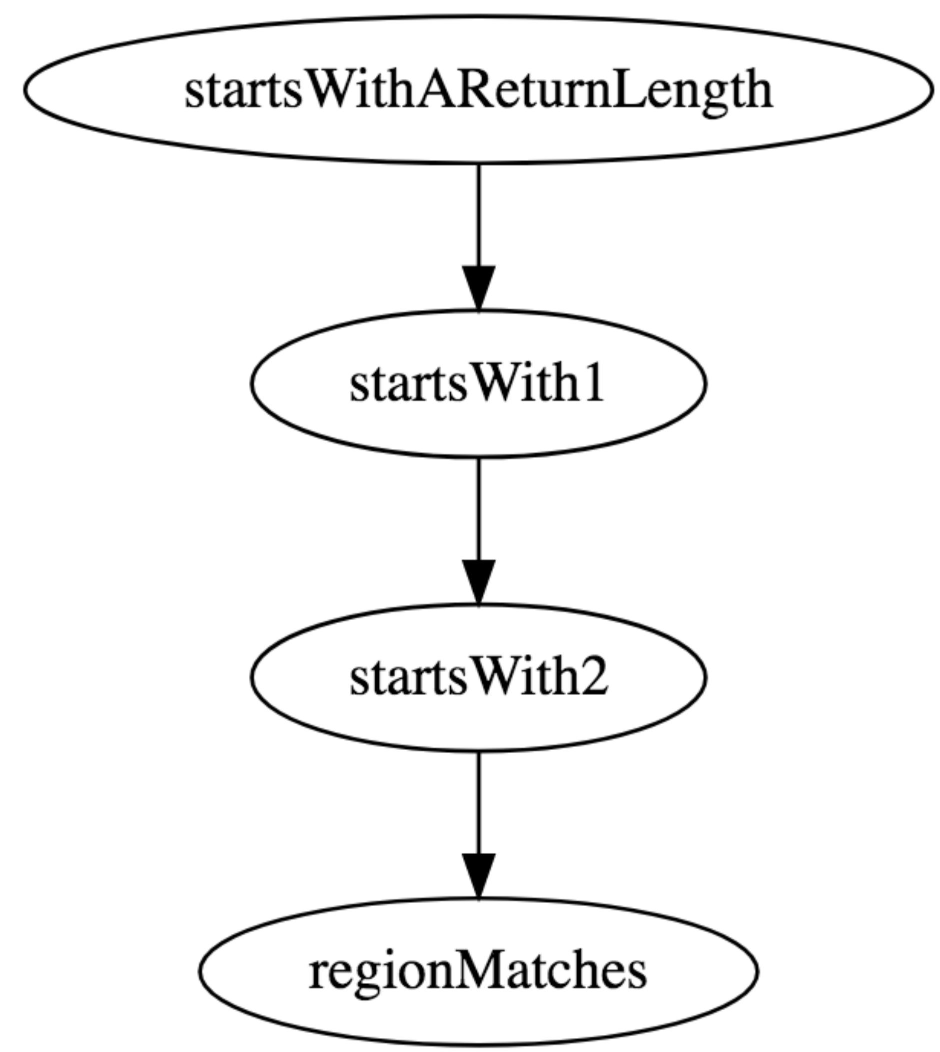
Cost/Benefit

Comparison

Greedy inlining plan



Cost benefit analysis inlining plan



Some Challenges

- Virtual functions (do not consider all targets, prioritize heavily called targets.)

Some Challenges

- Virtual functions (do not consider all targets, prioritize heavily called targets.)
- Limiting big search space (profiling information + updating IDT while doing analysis)

Some Challenges

- Virtual functions (do not consider all targets, prioritize heavily called targets.)
- Limiting big search space (profiling information + updating IDT while doing analysis)
- Determining adequate trade-off between compile-time and analysis-time (approximate analysis)

Some Challenges

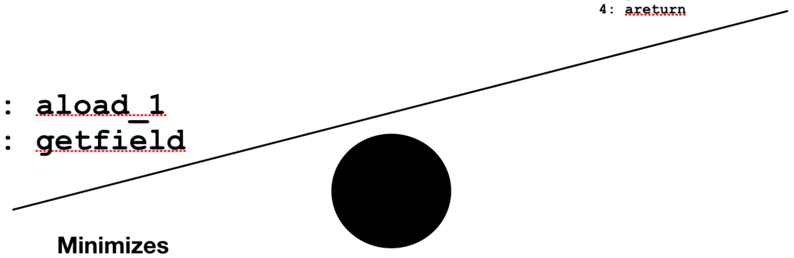
- Virtual functions (do not consider all targets, prioritize heavily called targets.)
- Limiting big search space (profiling information + updating IDT while doing analysis)
- Determining adequate trade-off between compile-time and analysis-time (approximate analysis)
- What other optimizations to consider? (escape analysis)

Benefits vs Costs

```
23: aload_1
24: invokevirtual #9
```

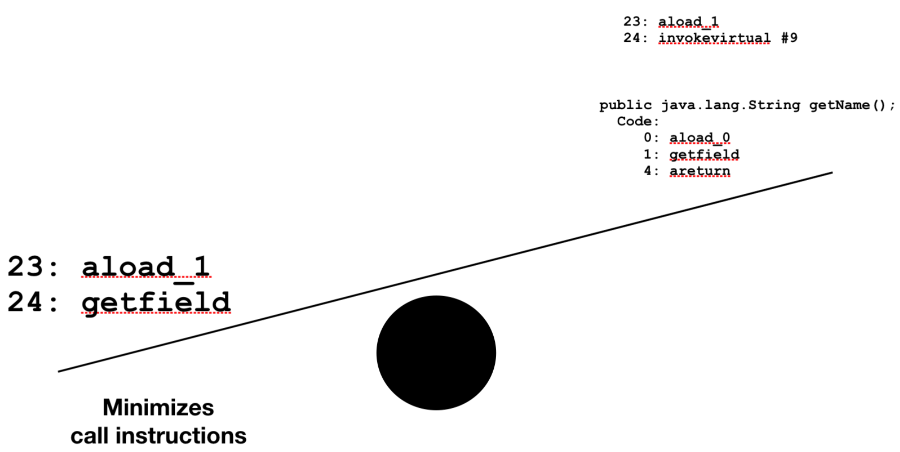
```
public java.lang.String getName();
  Code:
     0: aload_0
     1: getfield
     4: areturn
```

```
23: aload_1
24: getfield
```

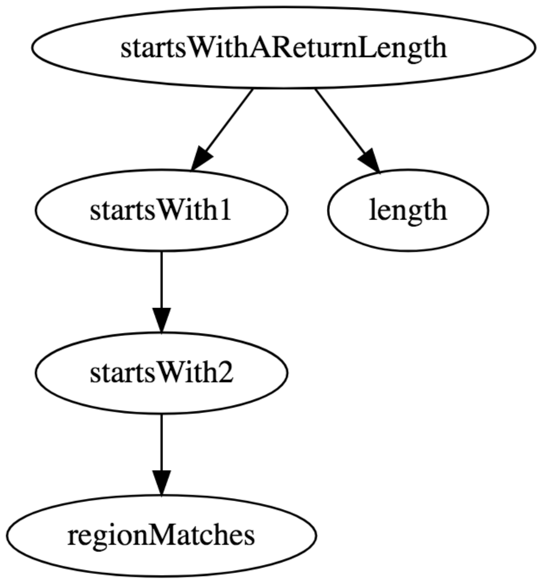


Minimizes
call instructions

Benefits vs Costs

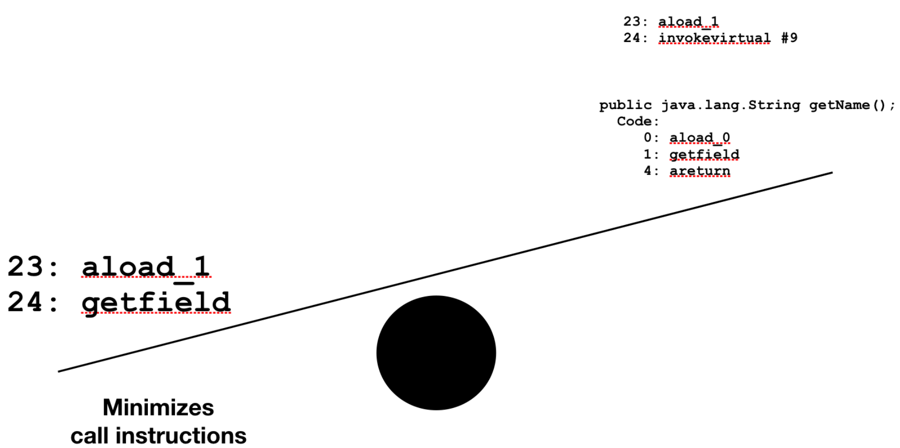


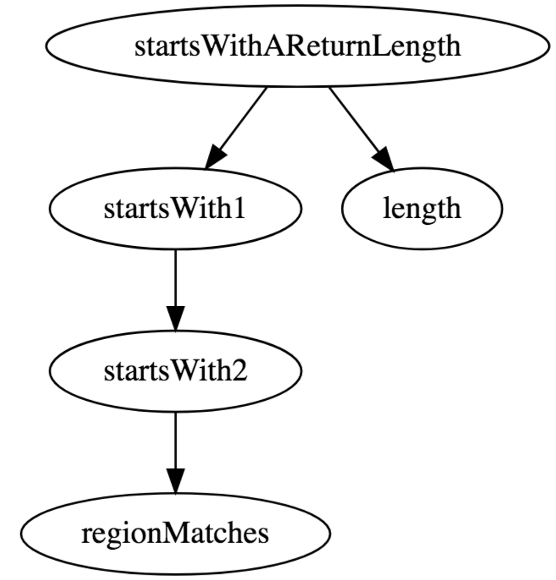
Cost-Benefit Inliner ➜ Maximizes Benefit



Cost-Benefit Inliner → Maximizes Benefit

Benefits vs Costs





length = 1

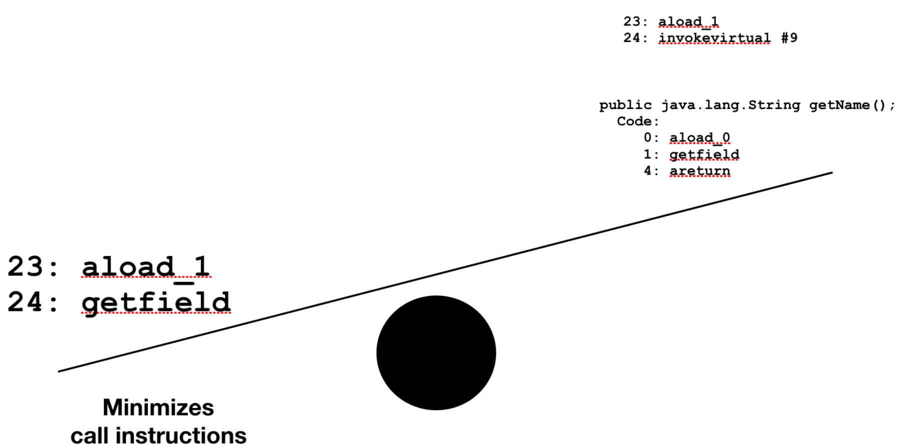
start = 0

string = “A”

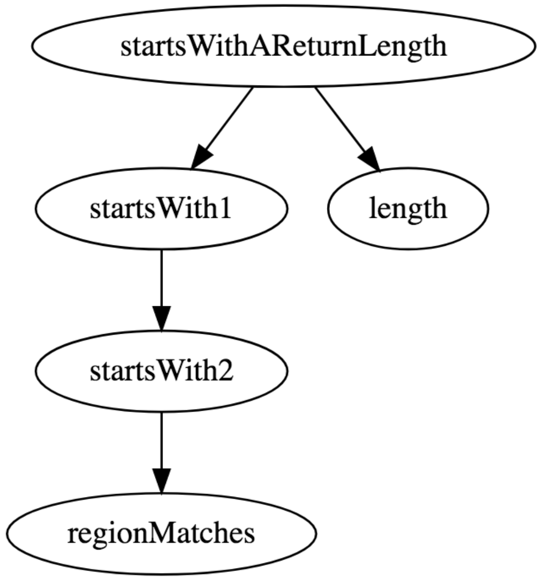
thisStart = 0

this = Type: String

Benefits vs Costs



Cost-Benefit Inliner → Maximizes Benefit



length = 1

start = 0

string = “A”

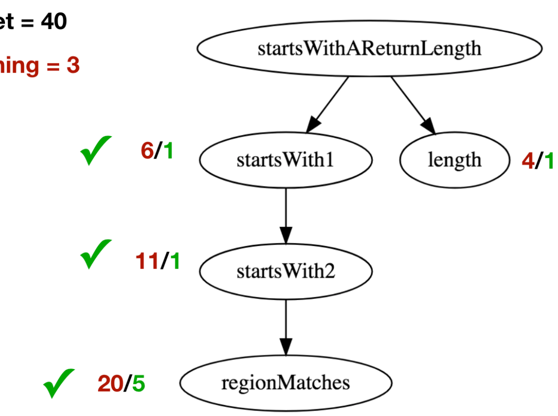
thisStart = 0

this = Type: String

Benefit Analysis

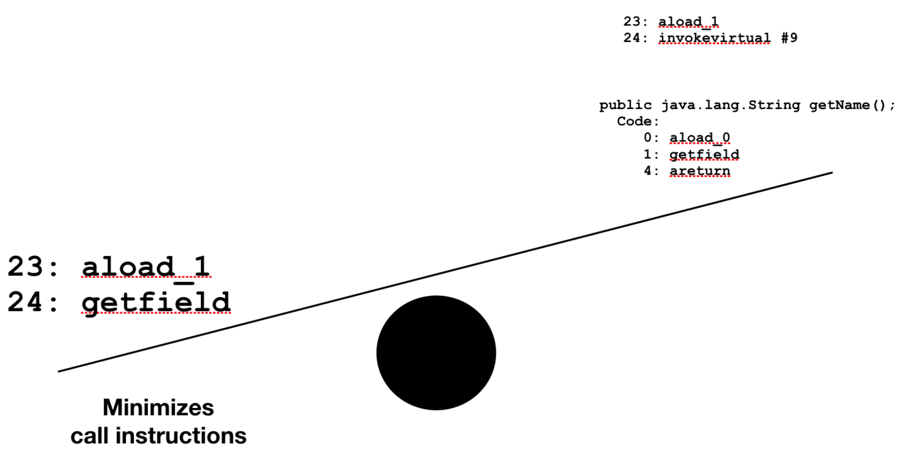
Budget = 40

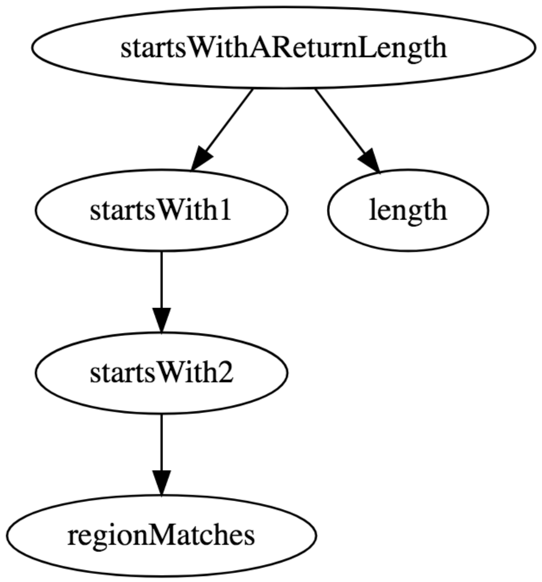
Remaining = 3



Cost-Benefit Inliner → Maximizes Benefit

Benefits vs Costs





Erick Ochoa
eochoa@ualberta.ca

length = 1

start = 0

string = “A”

thisStart = 0

this = Type: String

Benefit Analysis

Budget = 40

Remaining = 3