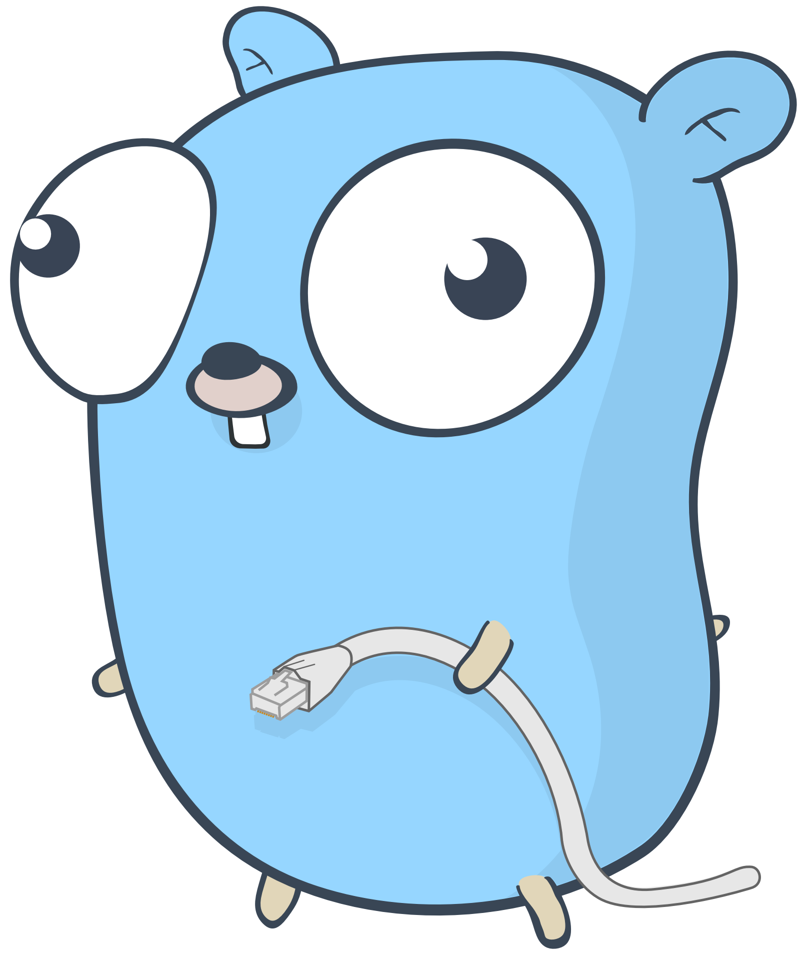
A Glimpse to **Profile-guided Optimization in Go**

Early practices of bringing PGO to production



Changkun Ou
changkun.de/s/gopgo

SIXT
Lisbon, Portugal
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SIXT

About Me

Changkun Ou (@changkun)

- SIXT, Senior Engineer @ Pricing & Yield
- Engineering interests: Non-blocking optimizations / distributed consensus / graphics
- Active in Go Communities @golang, @fyne-io, @talkgo, @golang-design, …
- Email: hi@changkun.de

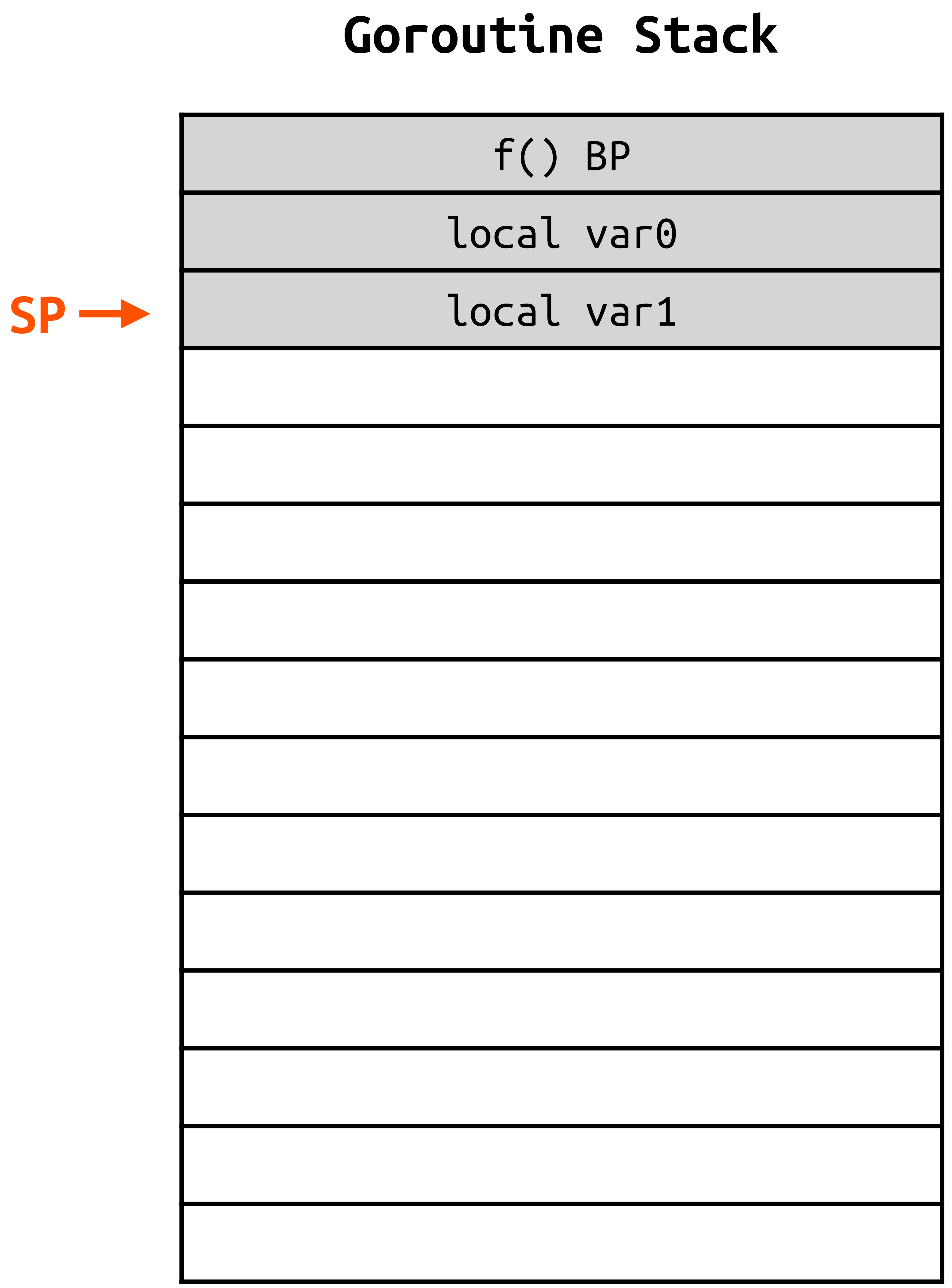
Agenda

- Invocation Overhead
- The Power of “Feedback Loop”
- Profile-guided Optimization (PGO) in Go
- Example and Applications
- Brining PGO to Production at Sixt
- Summary

Background

Invocation Overhead

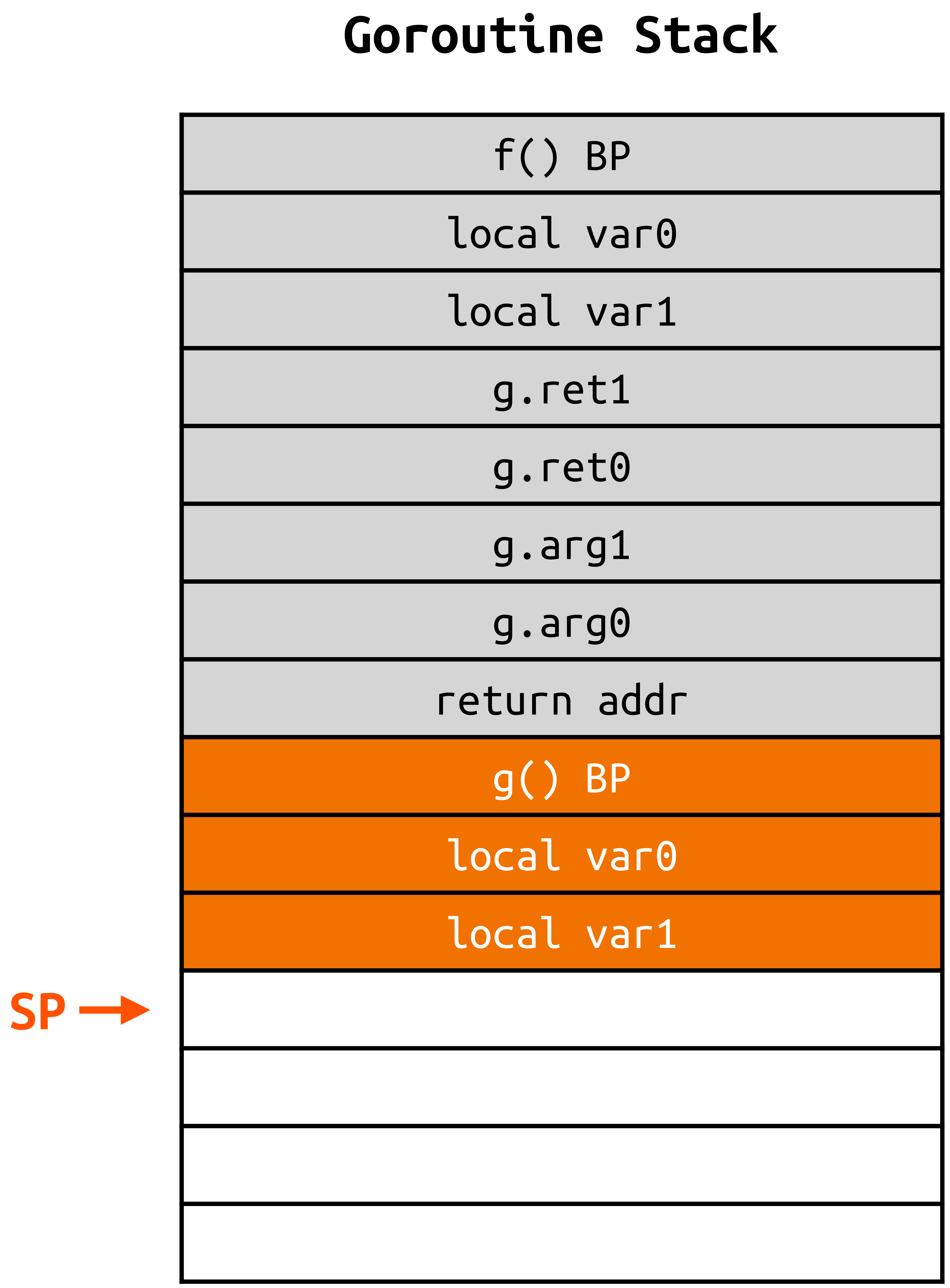
- Performing a function is not free but involve extra costs




```go
func f() {
    ...
    ret0, ret1 = g(arg0, arg1)
    ...
}
```

Invocation Overhead

- Performing a function is not free but involve extra costs
- When calling a function, arguments are copied on top of the stack

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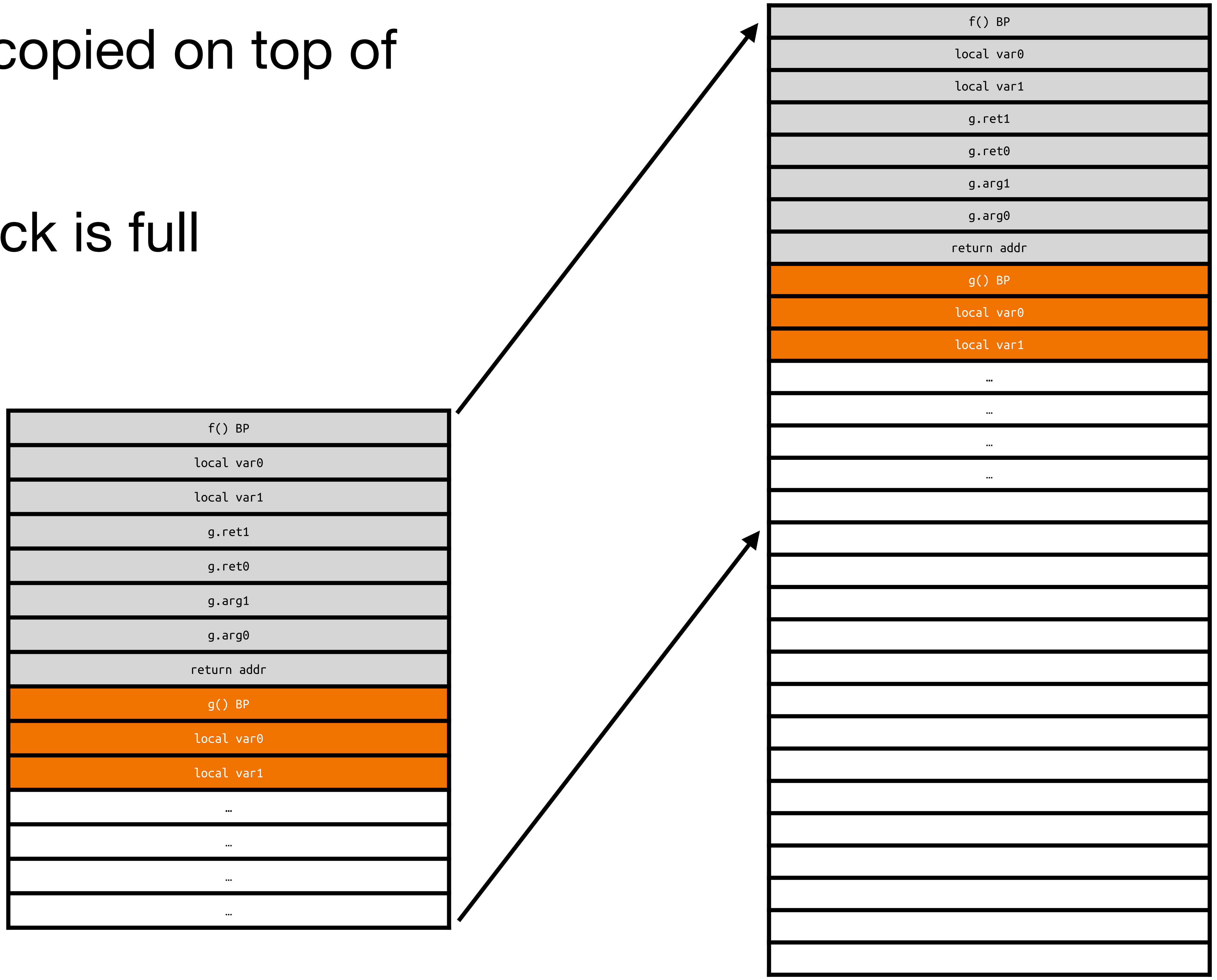
Invocation Overhead

- Performing a function is not free but involve extra costs
- When calling a function, arguments are copied on top of the stack
- The entire stack maybe copied if the stack is full

Goroutine Stack

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    ...
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    ...
}
```

Optimization: Inlining

- Inlining is a code transformation technique that replaces a function call (call site) with the body of the called function (callee)

```go
package main

func max(x, y int) int {
	if x > y {
		return x
	}
	return y
}

func main() {
	z := max(1, 2)
	println(z)
}
```

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```

→

```go
package main

func main() {
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    if 1 > 2 {
        z = 1
    } else {
        z = 2
    }
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        z = 1
    } else {
        z = 2
    }
    println(z)
}
```

→

```go
package main

func main() {
    println(2)
}
```

`//go:noinline`, `-gcflags='-N -l'` can disable inlining

Optimization: Devirtualization

```go
func read(r io.Reader) []byte {
    buf := make([]byte, 1024)
    n, _ := r.Read(buf)
    return buf[:n]
}

func main() {
    f, err := os.Open("foo.txt")
    if err != nil { … }
    defer f.Close()

    fmt.Println(string(read(f)))
}
```

Optimization: Devirtualization

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```

→

```go
func read(r io.Reader) (n []byte) {
    buf := make([]byte, 1024)
    if f, ok := r.(*os.File); ok {
        n, _ = f.Read(buf)
    } else {
        n, _ = f.Read(buf)
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    n, _ := f.Read(buf)
    fmt.Println(string(buf[:n]))
}
```

Open Questions in Static Code Analysis

- Static code analysis cannot predict the runtime

```go
if (a < b) {
    foo()
    return
}

bar()
```

```go
switch n {
case 0:
    ...
case 1:
    ...
case ...
}
```

```go
for i := 0; i < n; i++ {
    ...
}
```

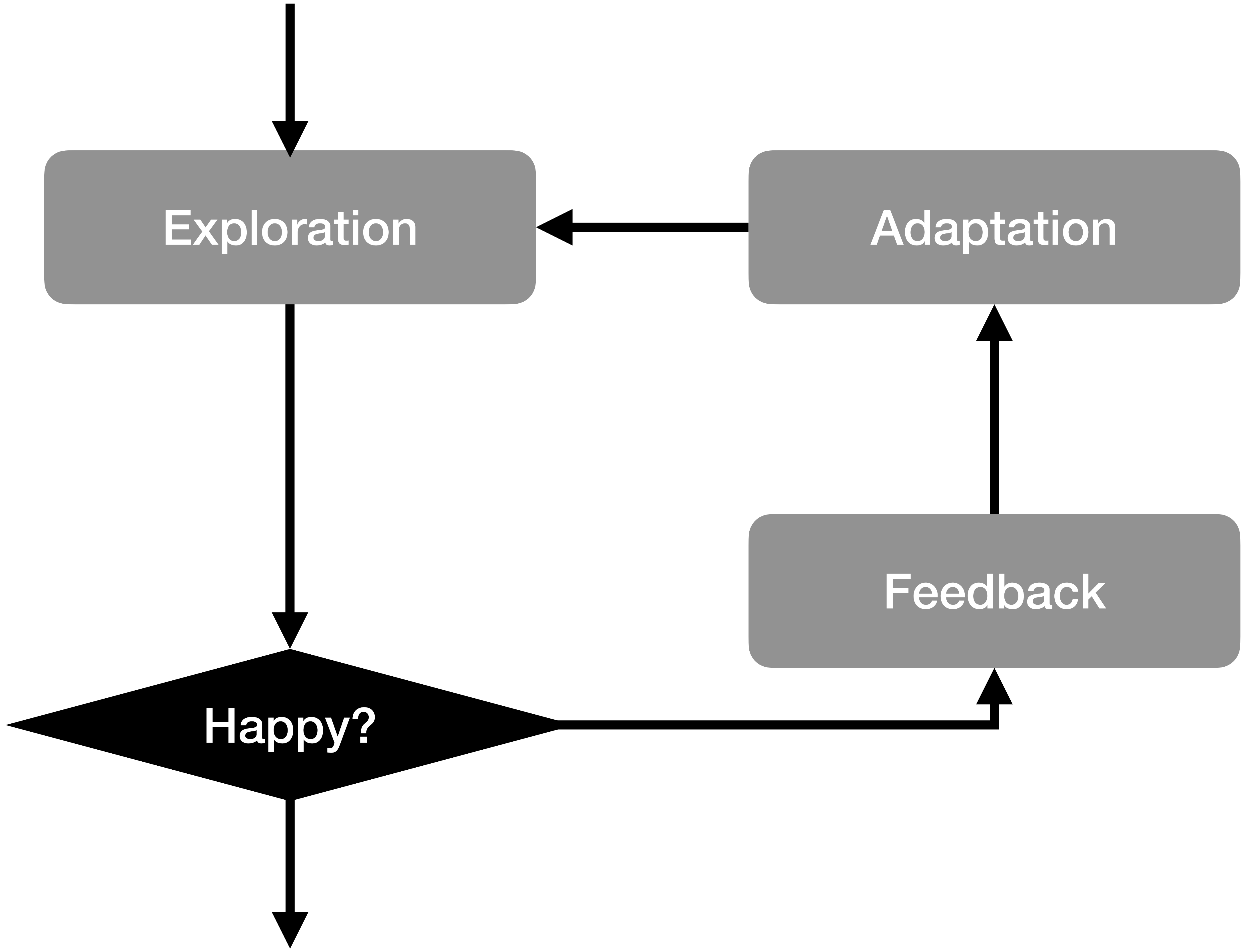
```go
type T struct {}
func (t *T) Bar() {}

type S struct {}
func (s S) Bar() {}

type Foo interface {
    Bar()
}

func foo(f Foo) {
    f.Bar()
}
```

How often is a < b?

What's the typical value of n?

What's the typical type of parameter f?

The Power of “Feedback Loop”



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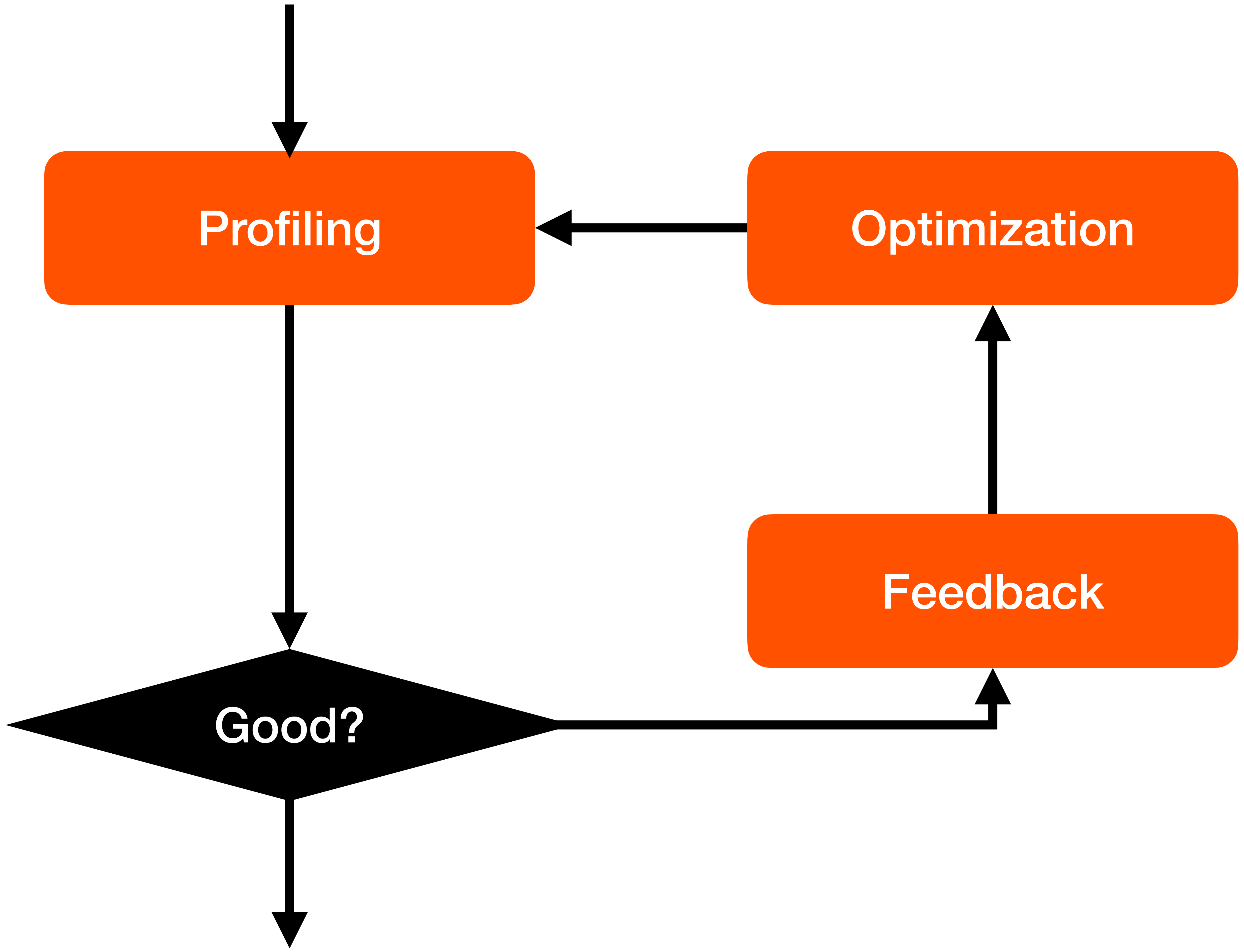

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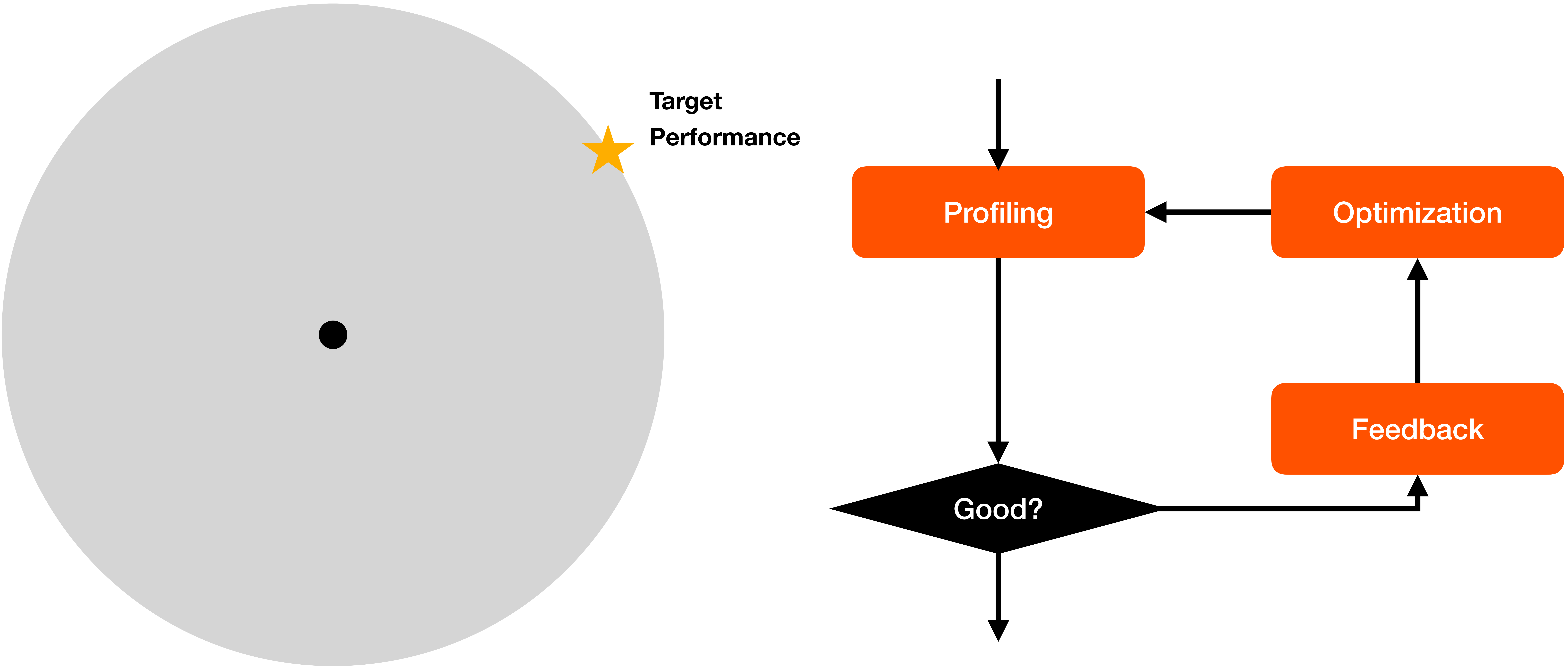

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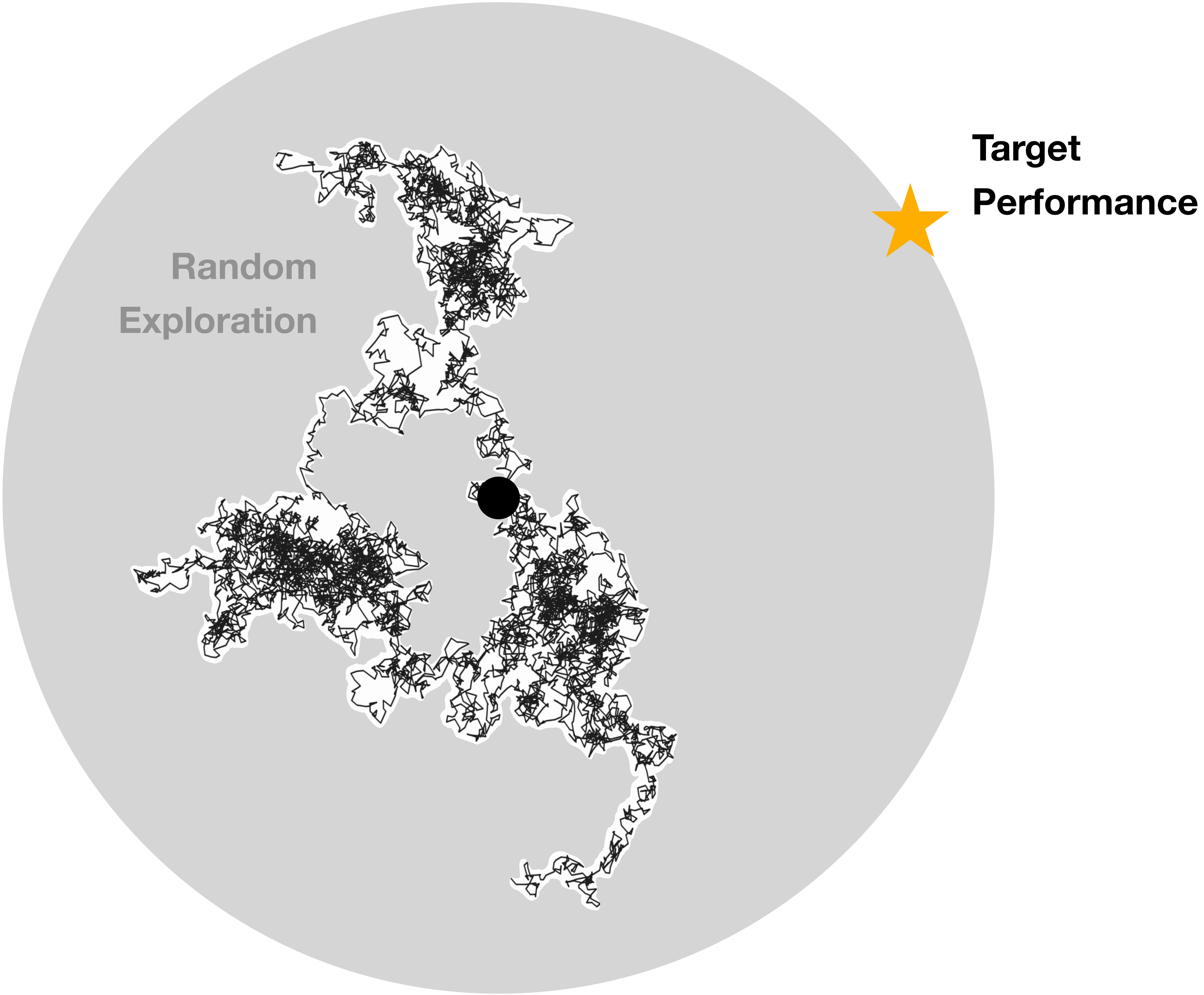

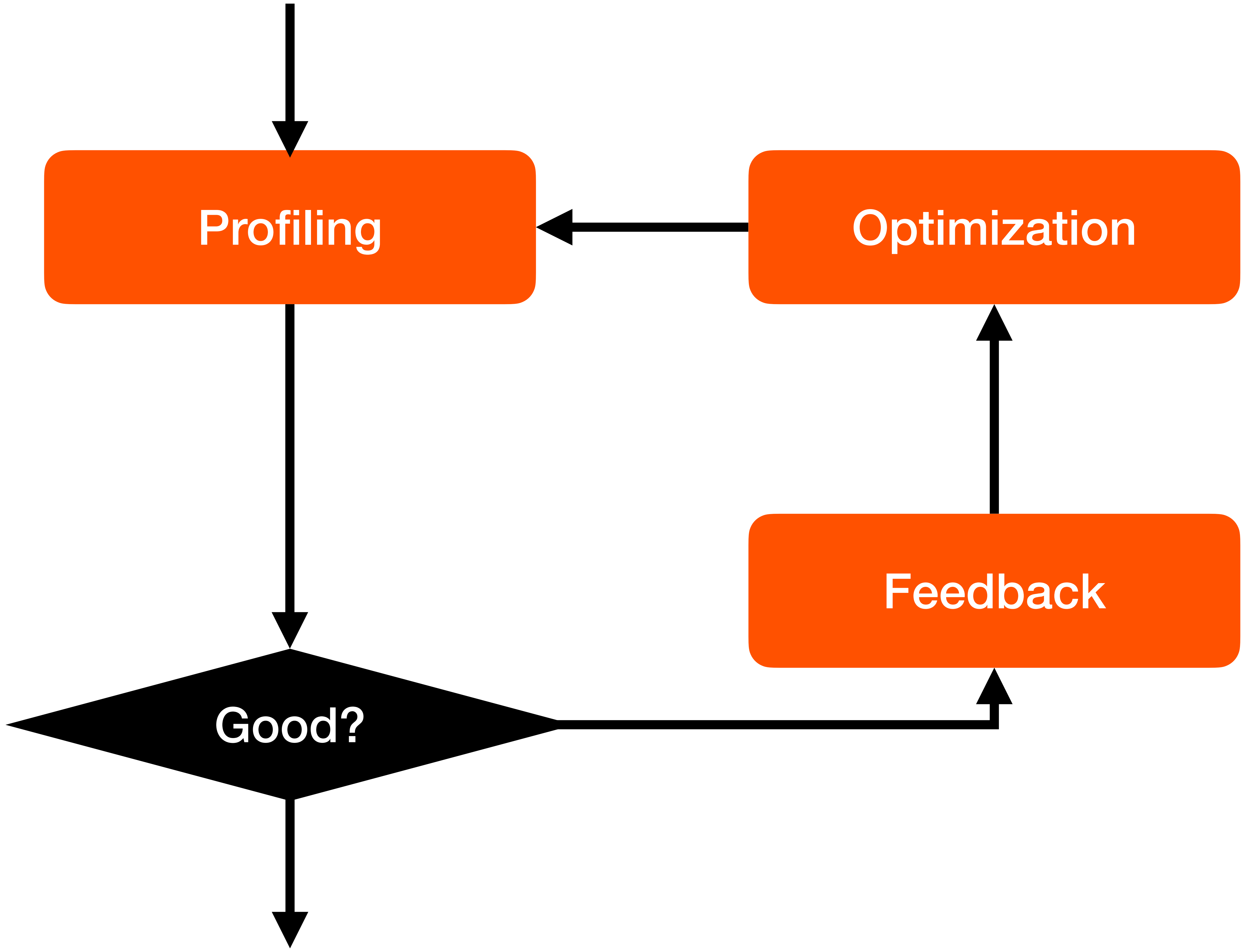

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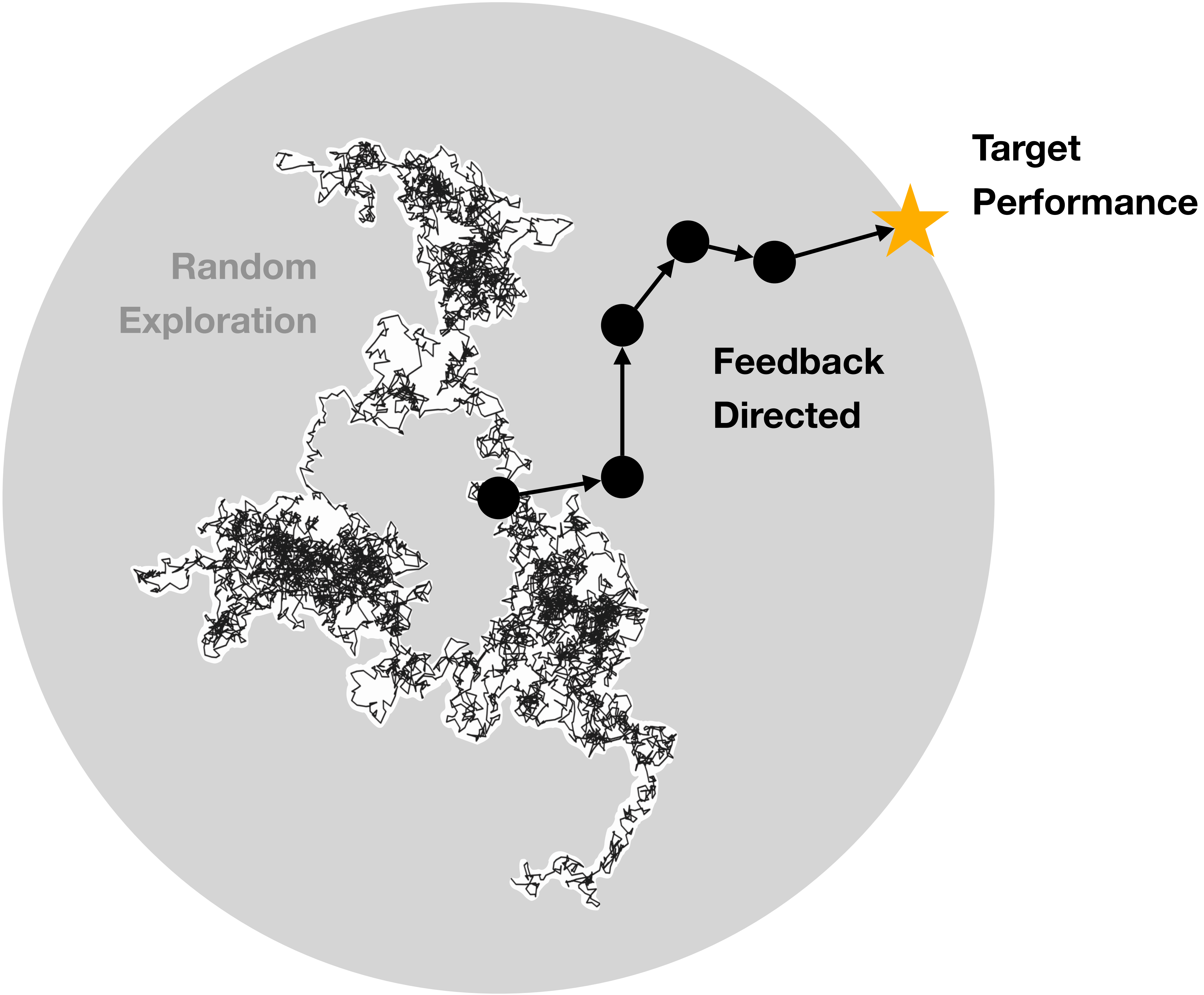

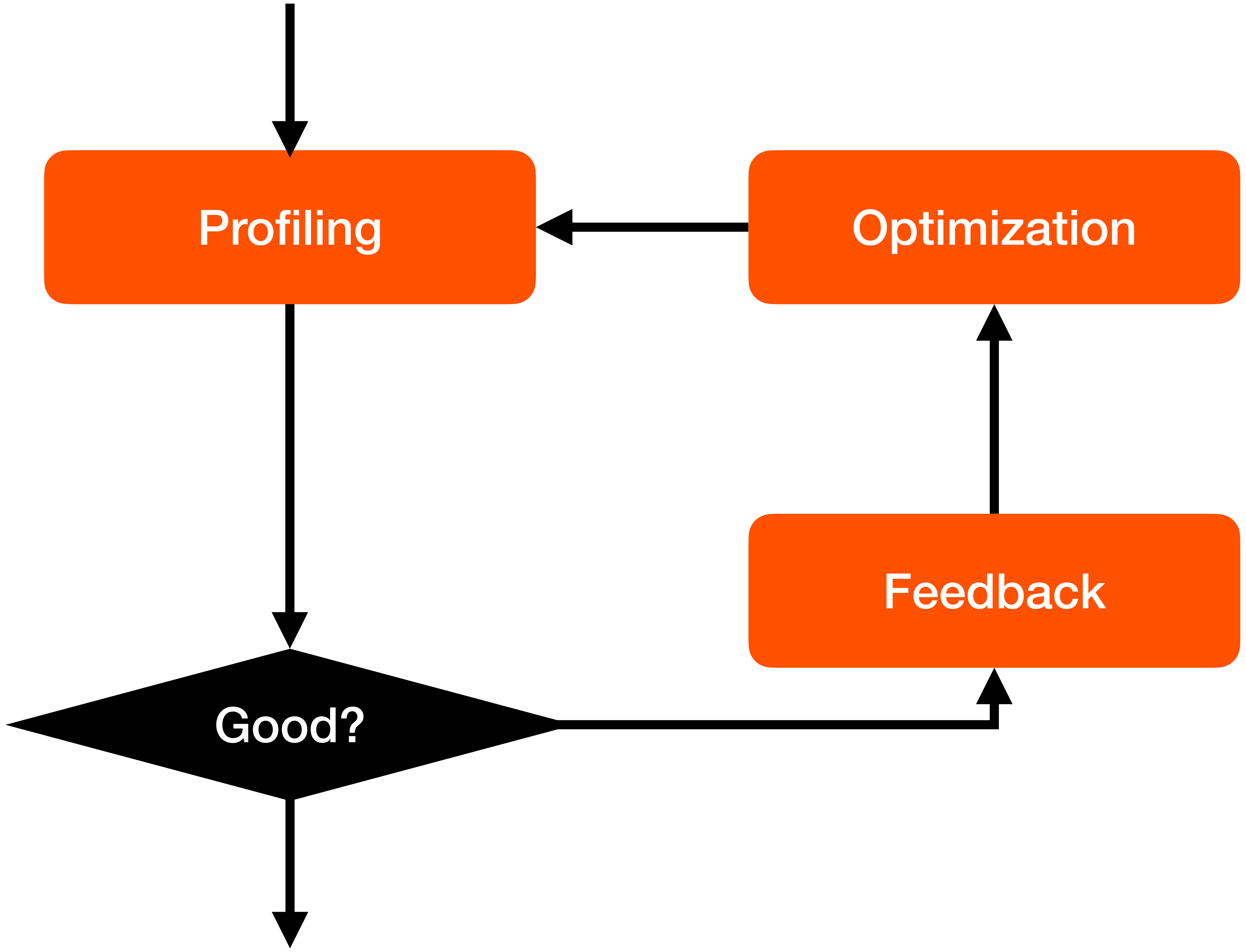

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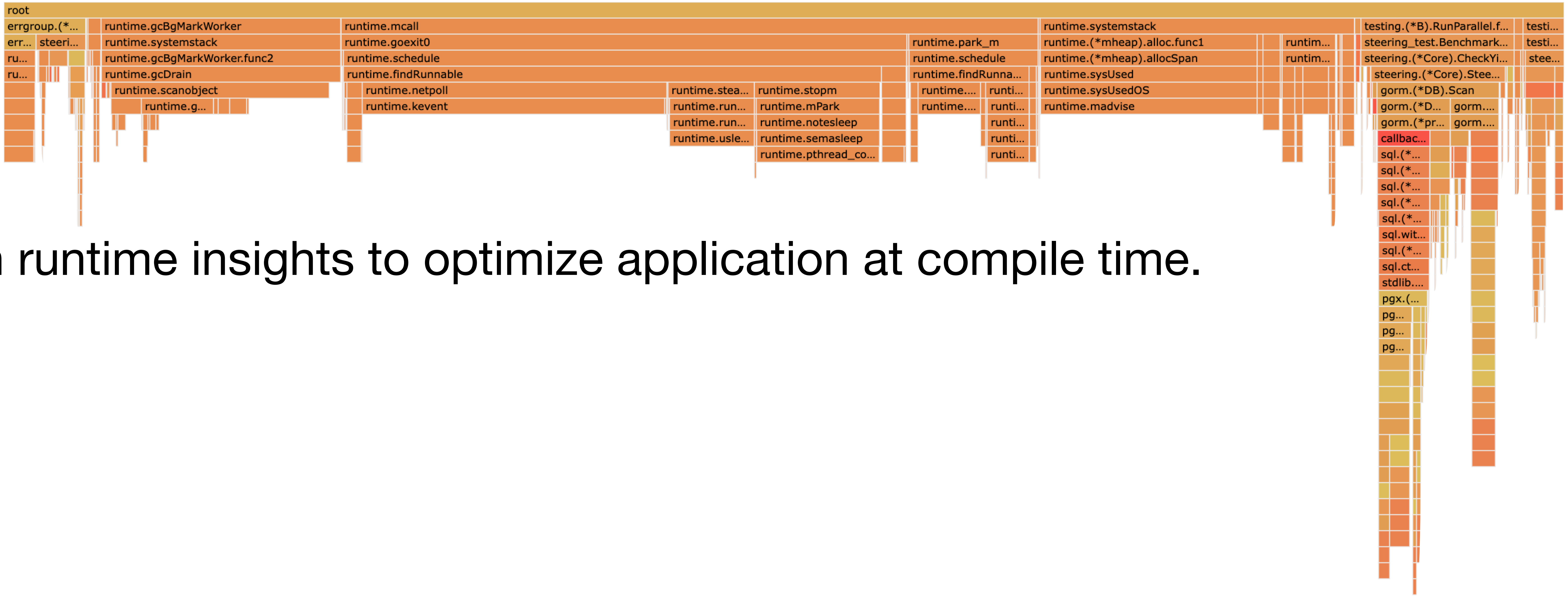
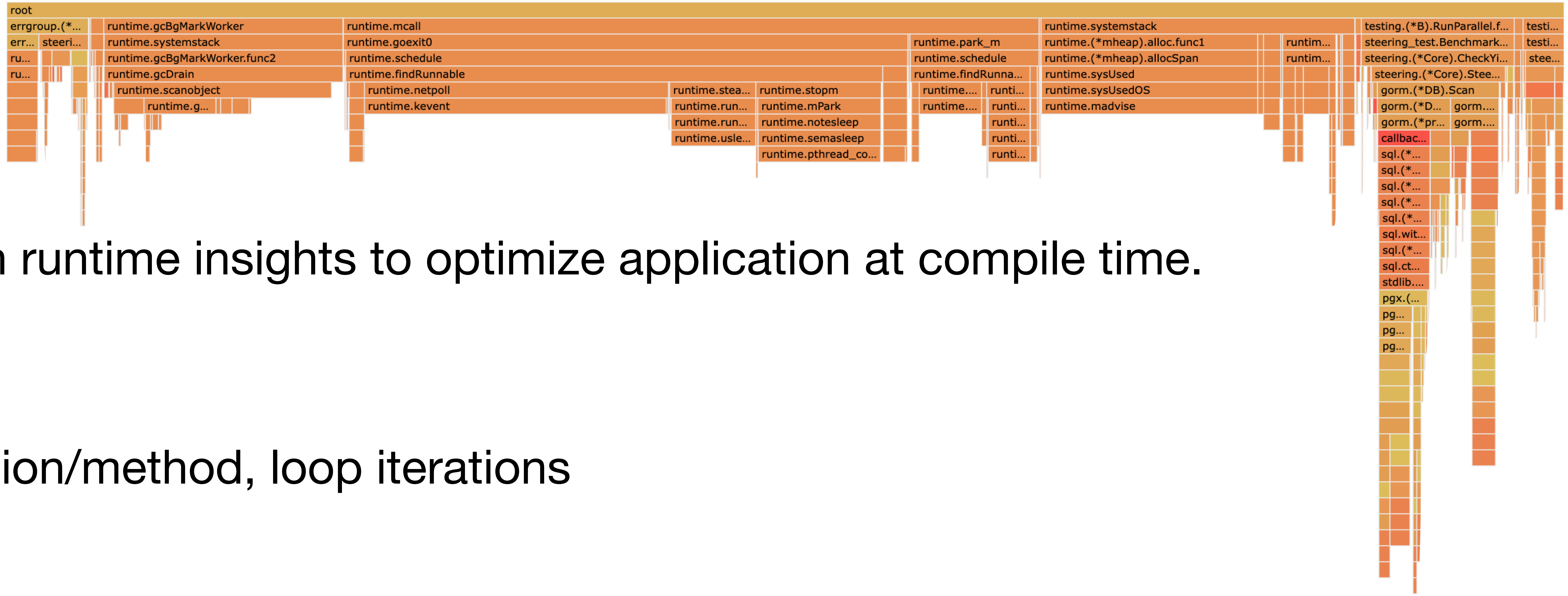
Profiling



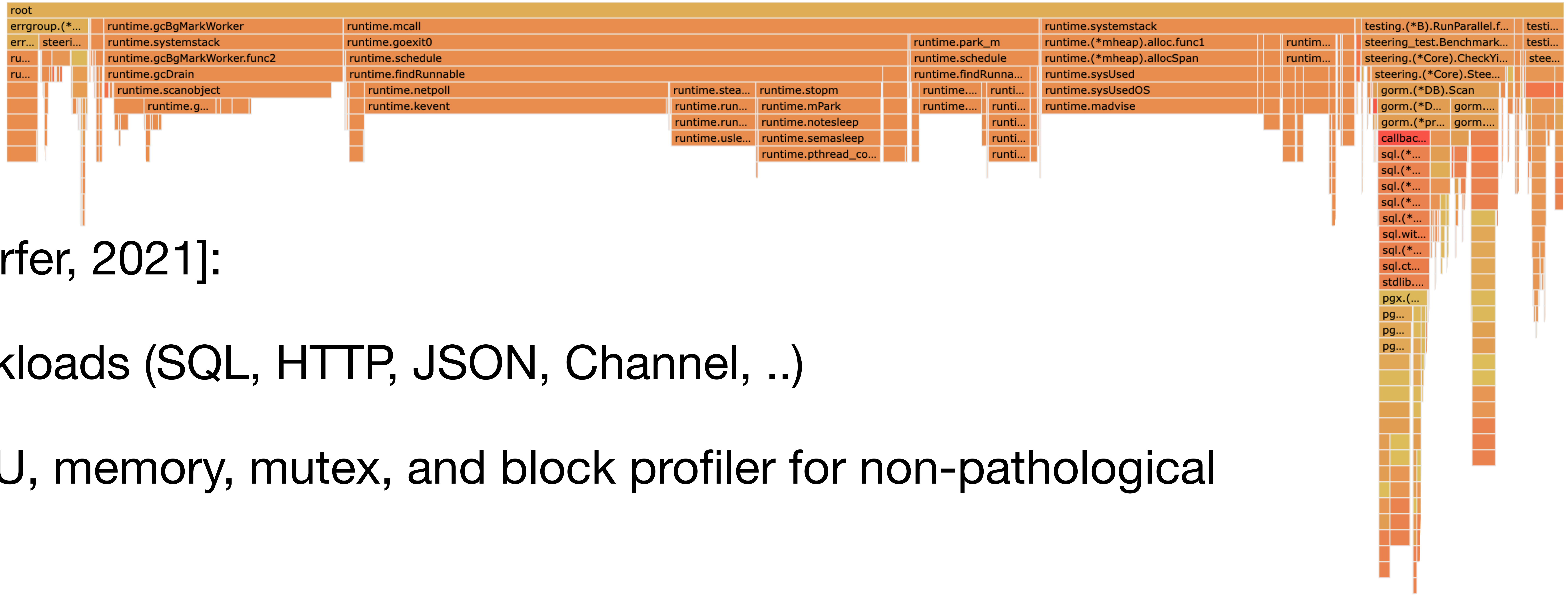
- Profiling brings data-driven runtime insights to optimize application at compile time.

Profiling



- Profiling brings data-driven runtime insights to optimize application at compile time.
- What’s profiled?
  - Number of calls to function/method, loop iterations
  - Branch probabilities
  - Memory consumption
  - Runtime activities
  - …

Profiling



Profiling overhead [Geisendörfer, 2021]:

- Measured on different workloads (SQL, HTTP, JSON, Channel, ..)
- “Very low overhead for CPU, memory, mutex, and block profiler for non-pathological workloads”

Profile-guided Optimization (PGO)

- Unlike other static compiler optimization techniques, PGO requires user involvement to collect runtime profiles and feed them back into the build processes.

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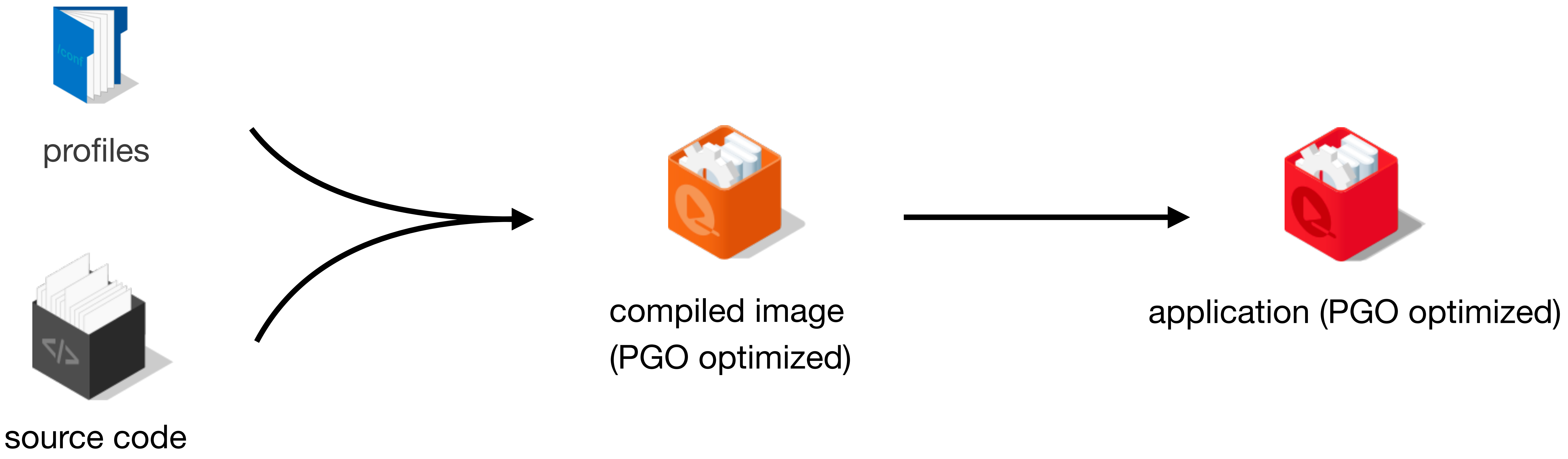
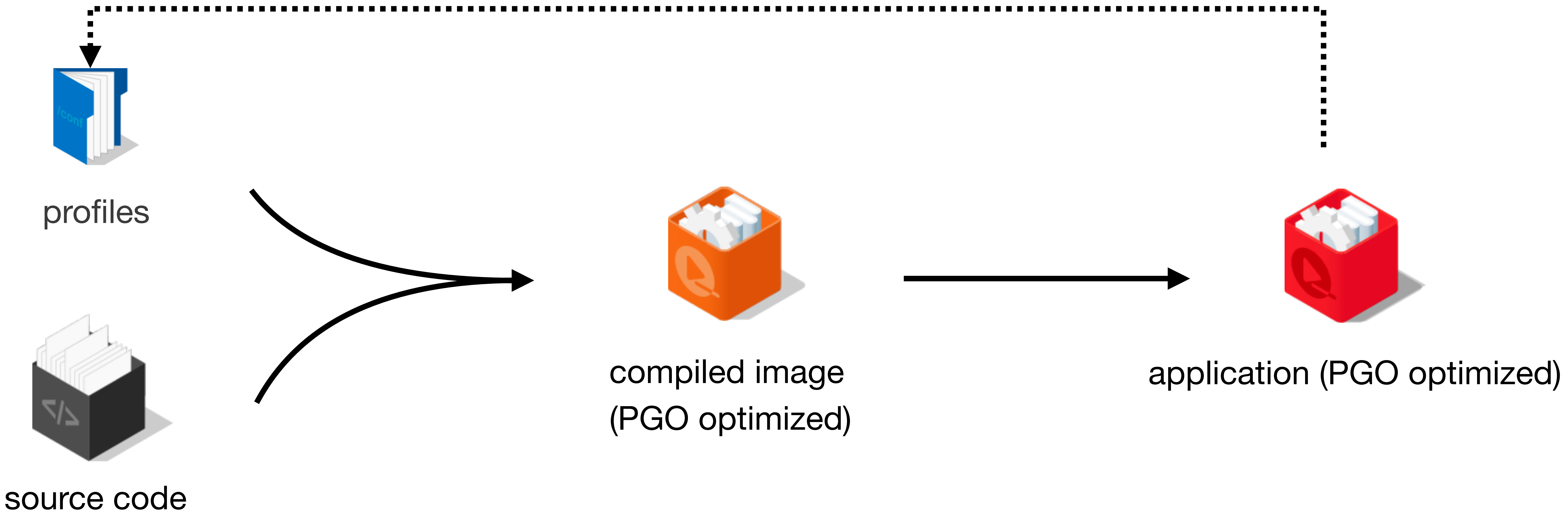


Profile-guided Optimization (PGO)

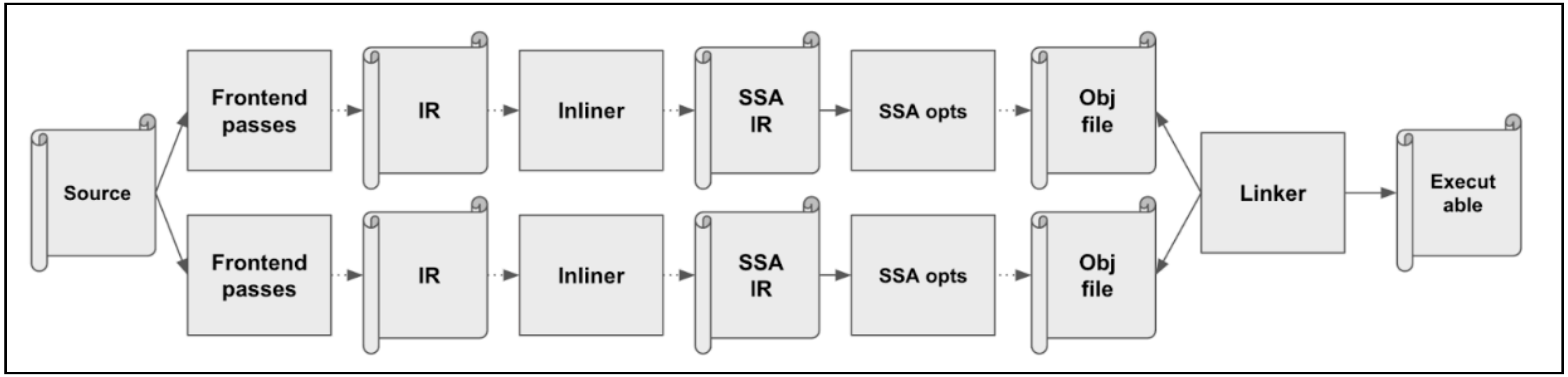
- Unlike other static compiler optimization techniques, PGO requires user involvement to collect runtime profiles and feed them back into the build processes.



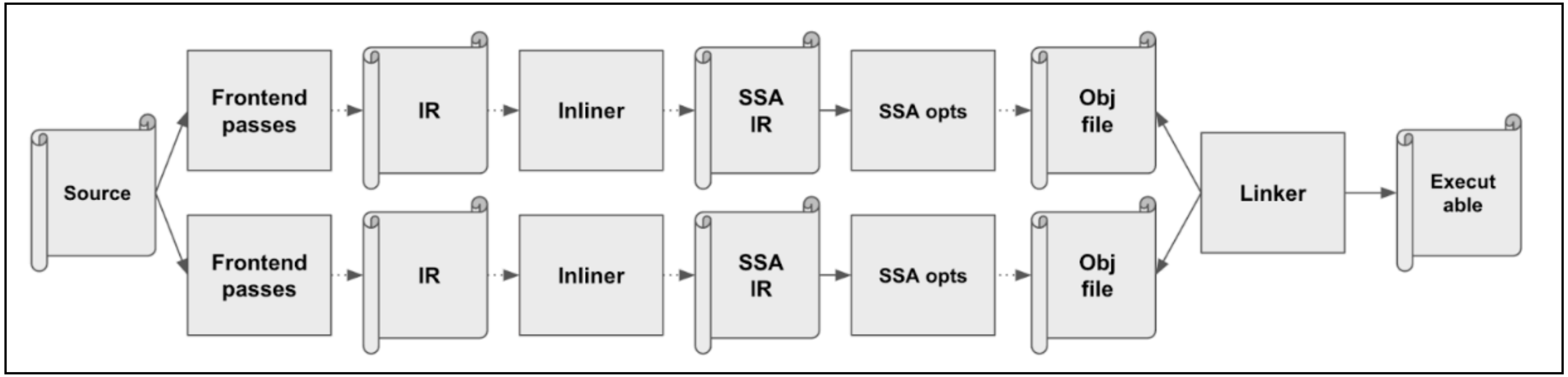
- PGO leverages runtime statistics regarding hot code paths and re-generate the same source code to execute favor and faster in those hot paths.

PGO in Go

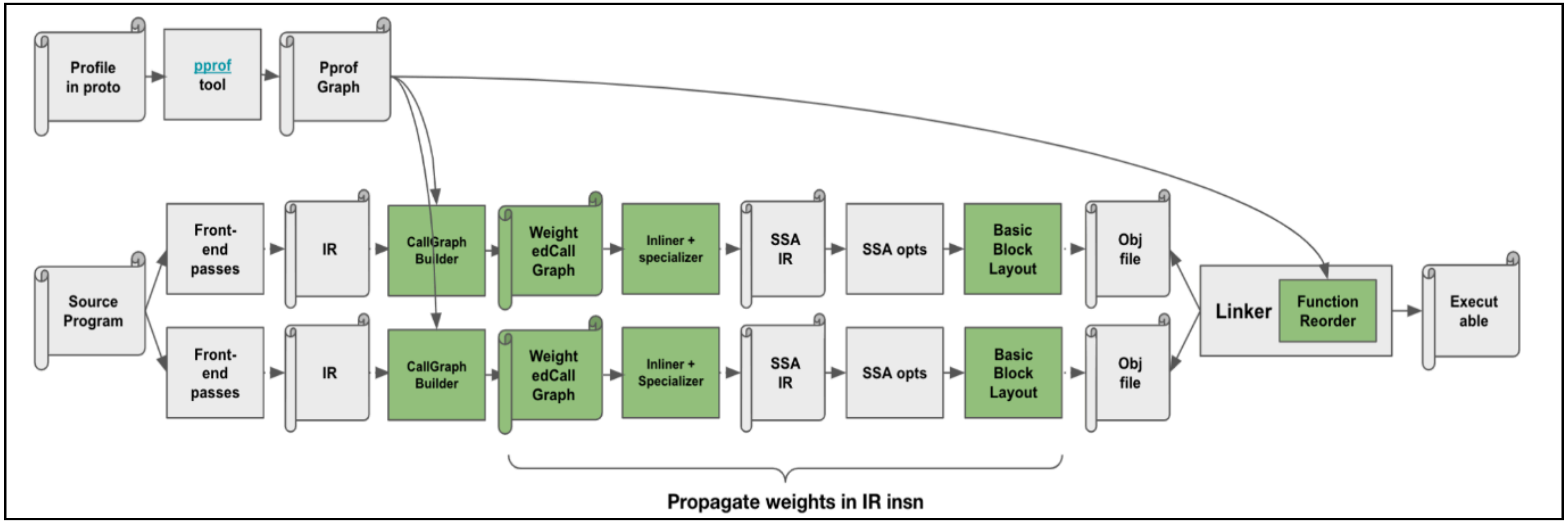
Go Code Compilation Process



Go Code Compilation Process



https://go.dev/design/55022-pgo



Enable Profiling in Go

To enable profiling in Go:

1. Using runtime/pprof or link net/http/pprof package or

```
import _ "net/http/pprof"
```

2. Run a http server:

```
go func() { http.ListenAndServe("localhost:6060", nil) }()
```

PGO in Go

To use PGO, there are essentially 3 steps:

1. Collect profiles:

```
$ wget -O cpu1.pprof http://service:6060//debug/pprof/profile?seconds=30

$ wget -O cpu2.pprof http://service:6060//debug/pprof/profile?seconds=30
```

2. Merge all profiles:

```
$ go tool pprof -proto cpu1.pprof cpu2.pprof > default.pgo
```

3. Build the binary using collected profile:

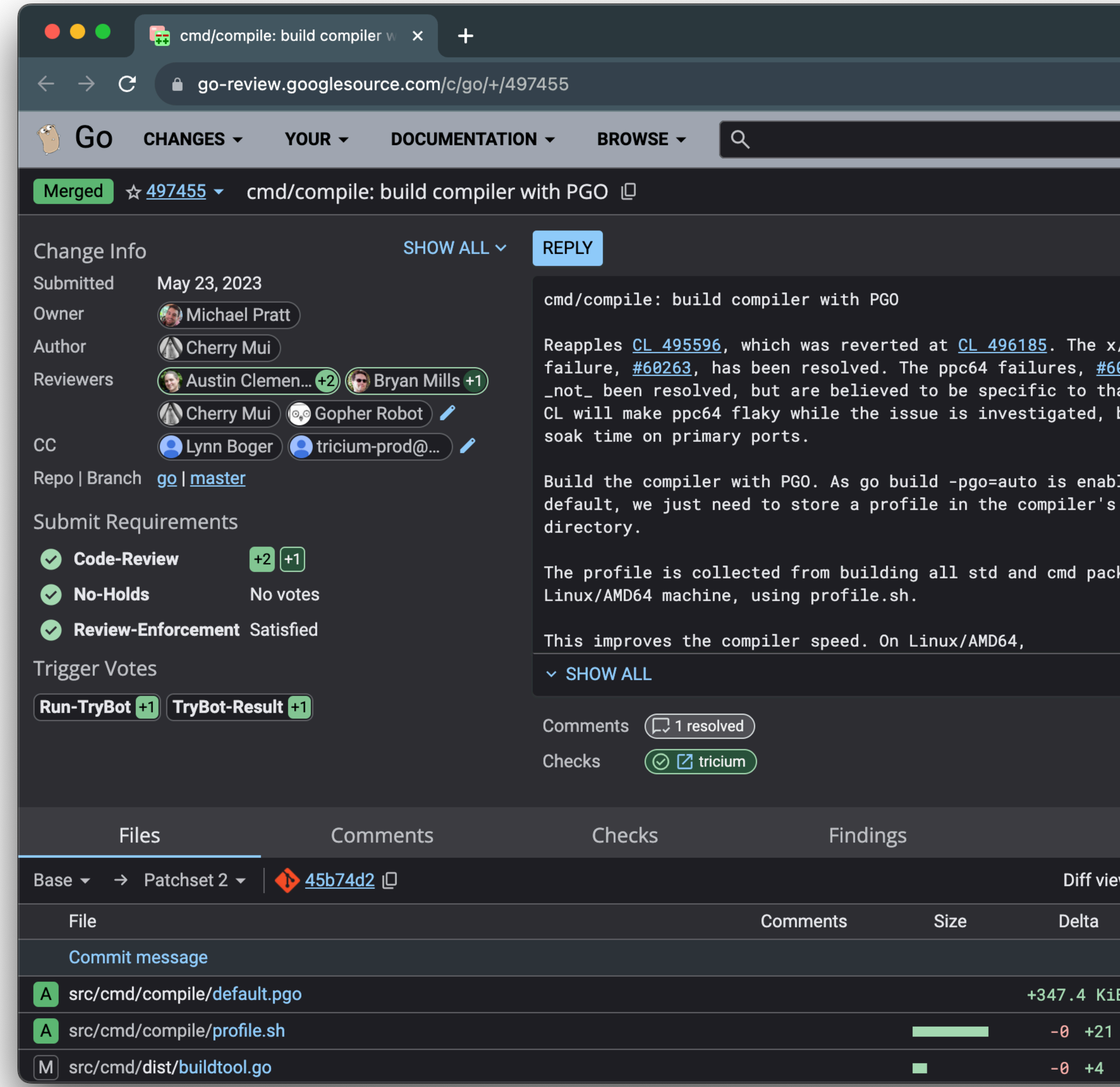
```
$ go build -pgo=default.pgo
```

As of Go 1.21, PGO in Go supports **inlining** and **devirtualization**.

Example: Optimize Go Compiler using PGO

As of Go 1.21, benchmarks for a representative set of Go programs show that building with PGO improves performance by around 2-7%.

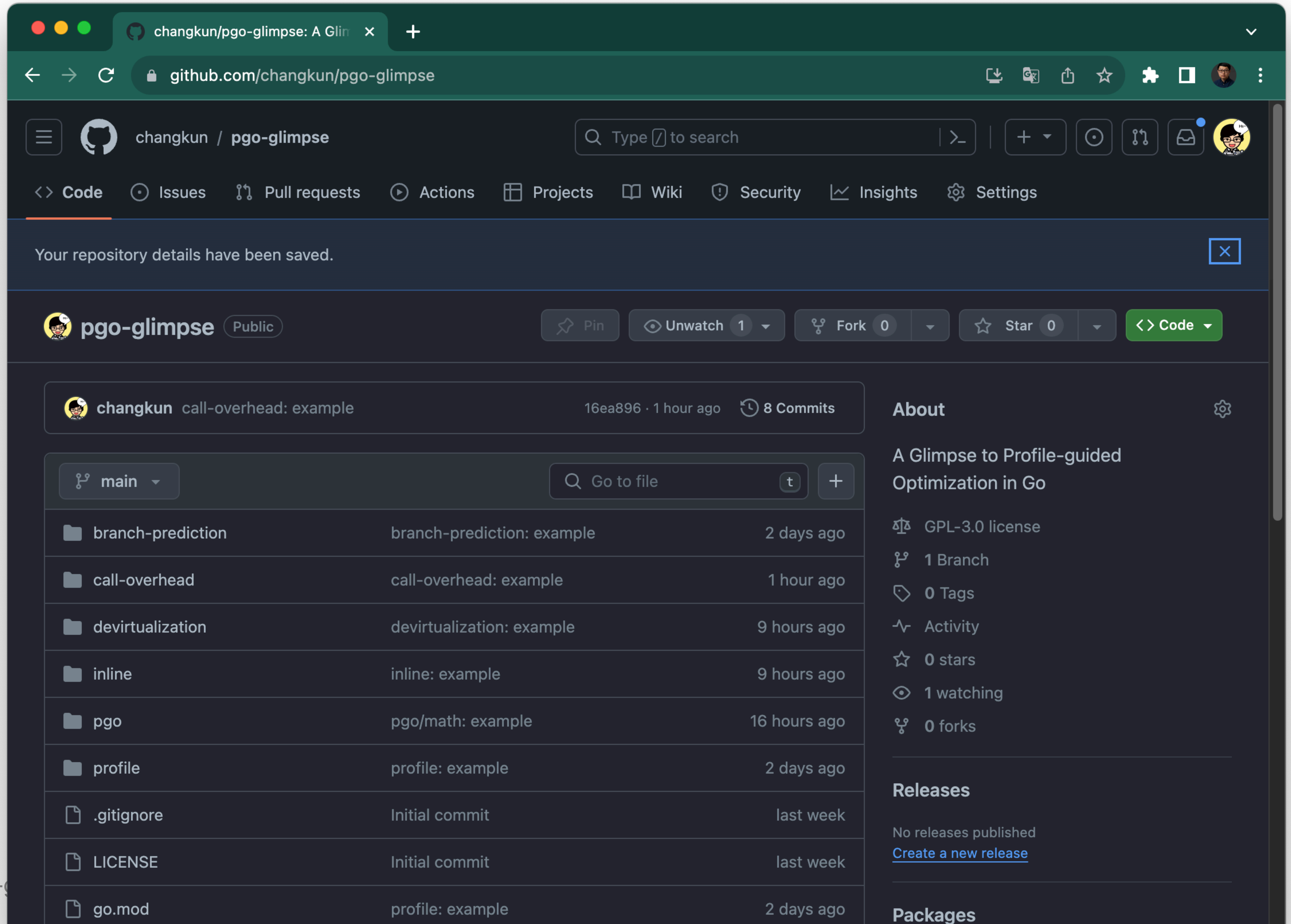
```
cmd/compile: build compiler with PGO

Build the compiler with PGO. As go build -pgo=auto is enabled by
default, we just need to store a profile in the compiler's
directory.

The profile is collected from building all std and cmd packages on
Linux/AMD64 machine, using profile.sh.

This improves the compiler speed. On Darwin/ARM64,
name          old time/op      new time/op      delta
Template        71.0ms ± 2%     68.3ms ± 2%   -3.90%  (p=0.000 n=20+20)
Unicode         71.8ms ± 2%     66.8ms ± 2%   -6.90%  (p=0.000 n=20+20)
GoTypes          444ms ± 1%      428ms ± 1%   -3.53%  (p=0.000 n=19+20)
Compiler        48.9ms ± 3%     45.6ms ± 3%   -6.81%  (p=0.000 n=20+20)
SSA              3.25s ± 2%      3.09s ± 1%   -5.03%  (p=0.000 n=19+20)
Flate           44.0ms ± 2%     42.3ms ± 2%   -3.72%  (p=0.000 n=19+20)
GoParser        76.7ms ± 1%     73.5ms ± 1%   -4.15%  (p=0.000 n=18+19)
Reflect          172ms ± 1%      165ms ± 1%   -4.13%  (p=0.000 n=20+19)
Tar             63.1ms ± 1%     60.4ms ± 2%   -4.24%  (p=0.000 n=19+20)
XML             83.2ms ± 2%     79.2ms ± 2%   -4.79%  (p=0.000 n=20+20)
[Geo mean]       127ms           121ms        -4.73%
```



https://go.dev/cl/497455

More Examples

- https://github.com/changkun/pgo-glimpse



Practices

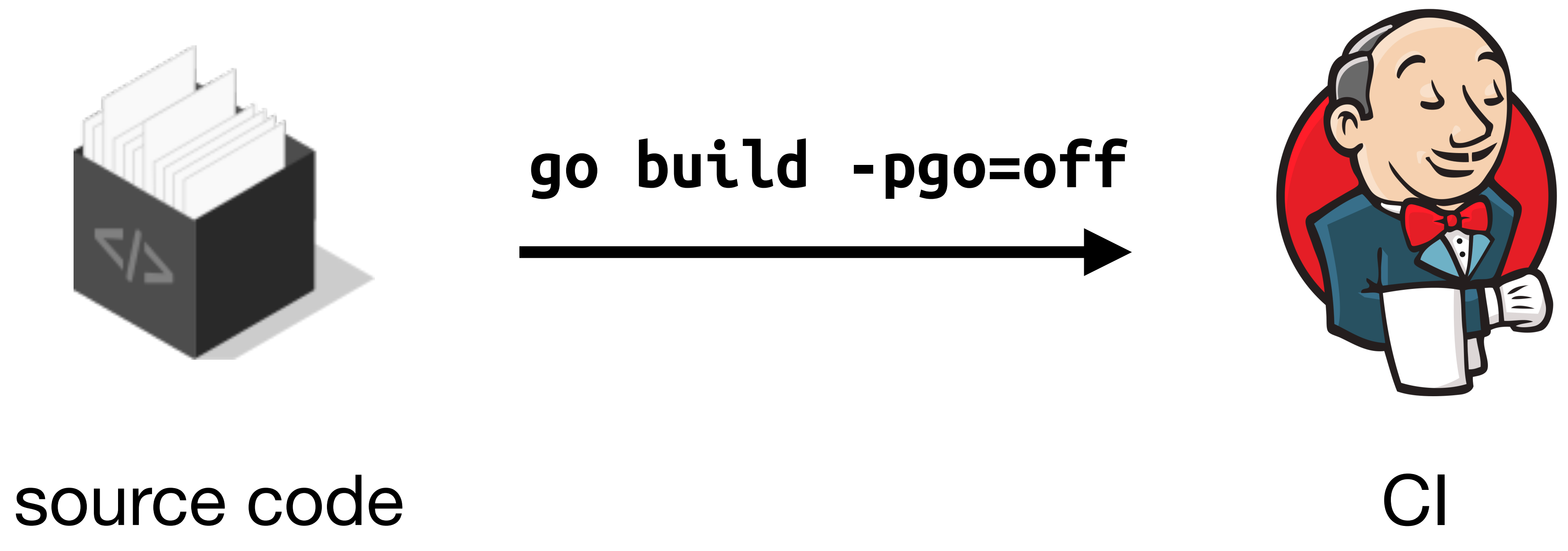
Challenges to Integrate PGO

- No platform infrastructure support :(
- No existing practices in the organization can bring strong arguments :(
- No existing practices can integrate PGO into CI/CD pipeline :(
- No baseline reference :(

CI Release Workflow

source code

CI Release Workflow



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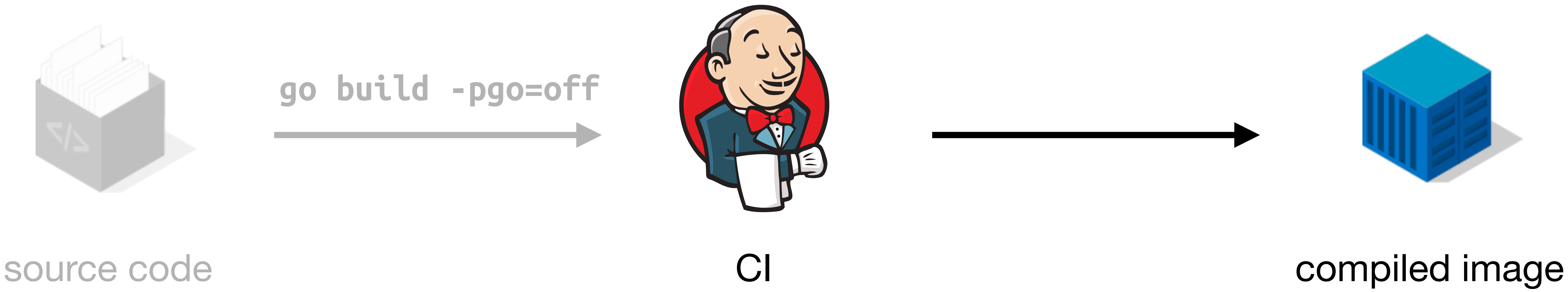

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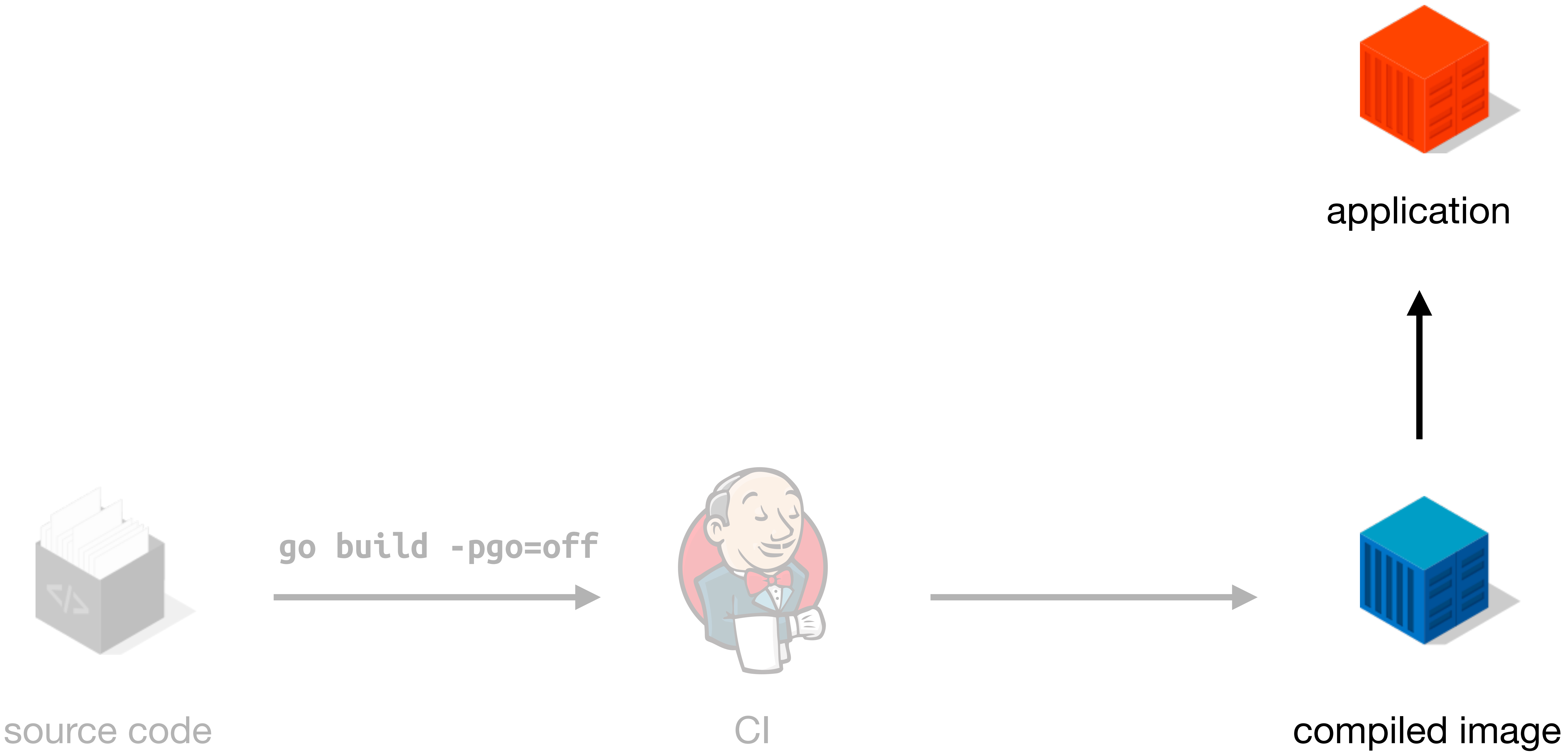
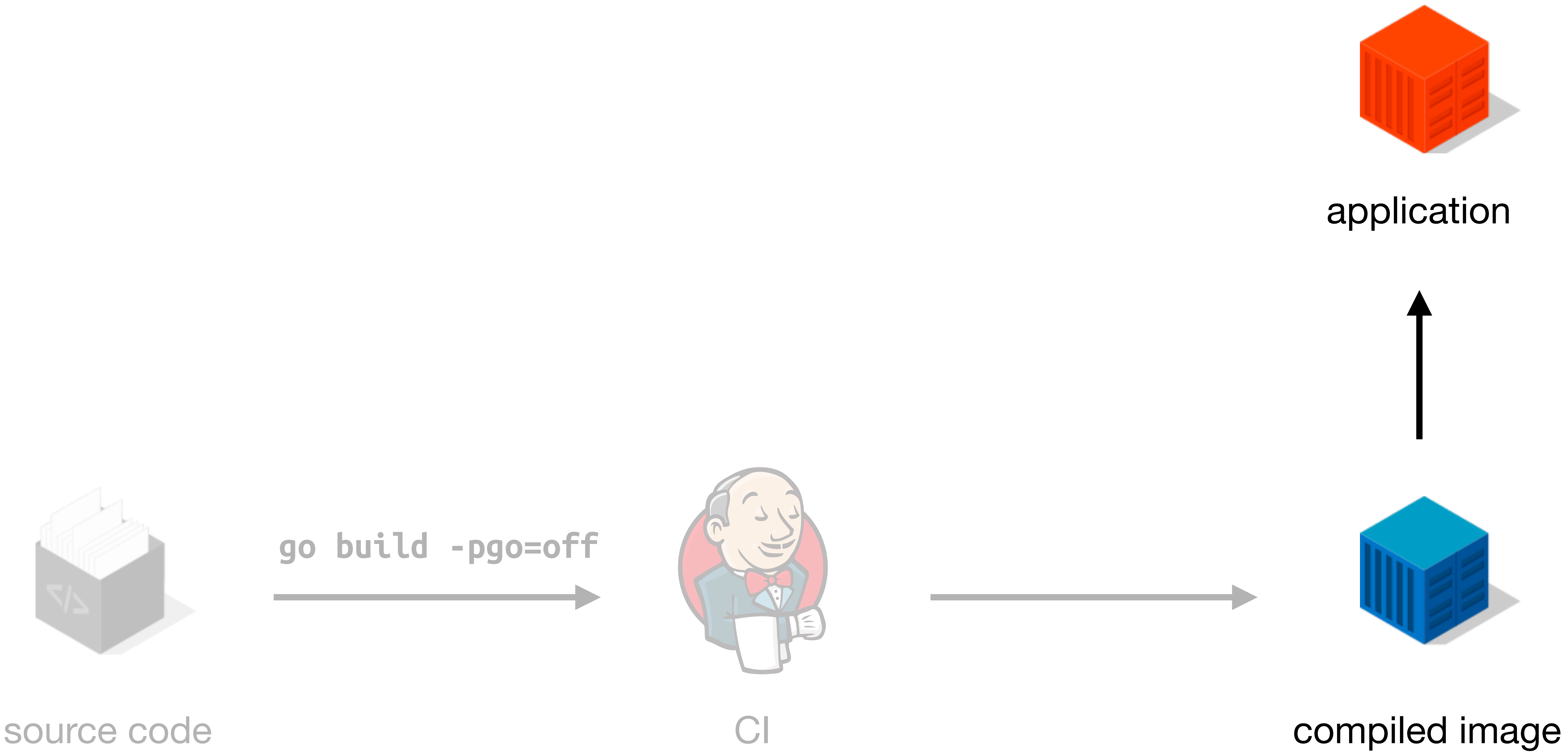
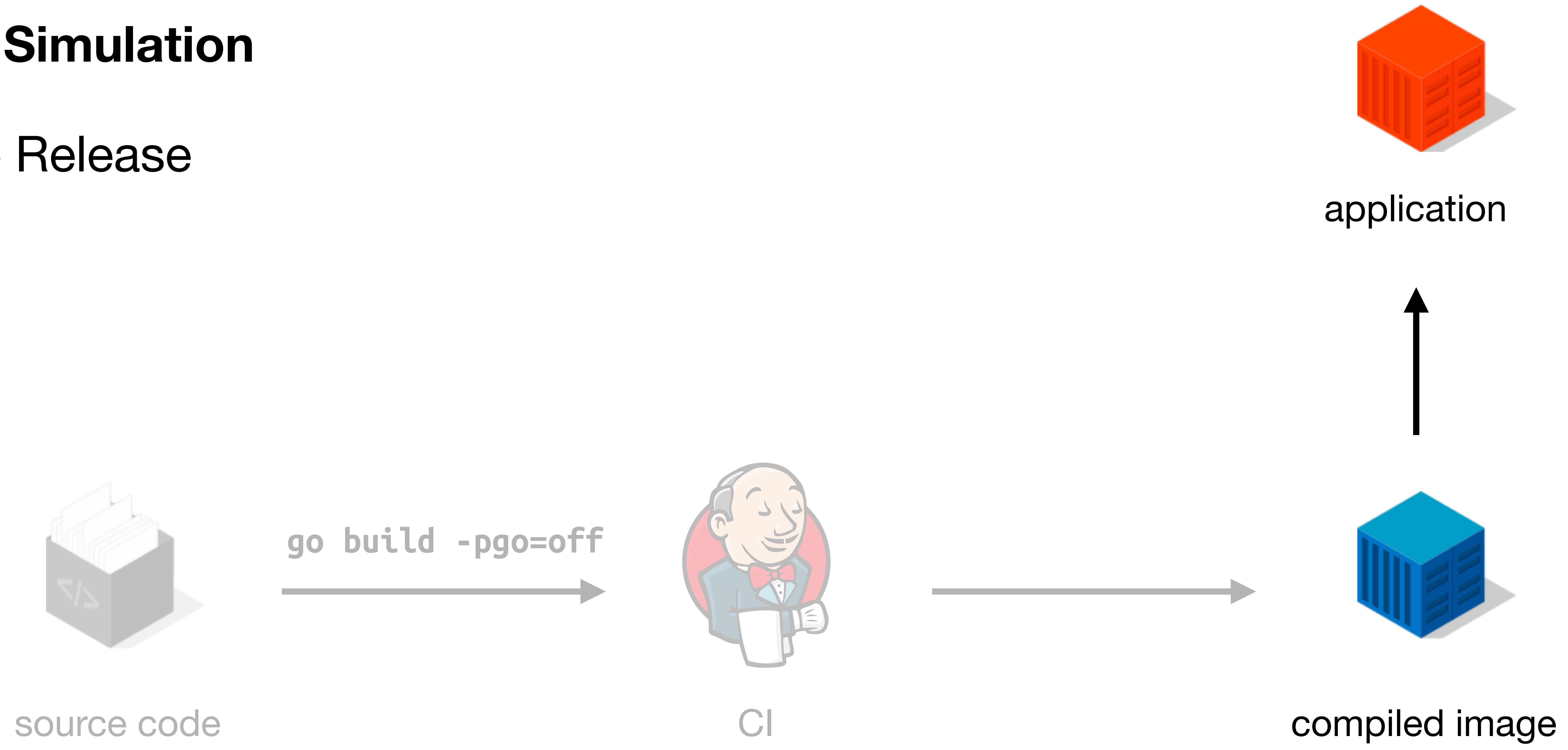


PGO Release Workflow

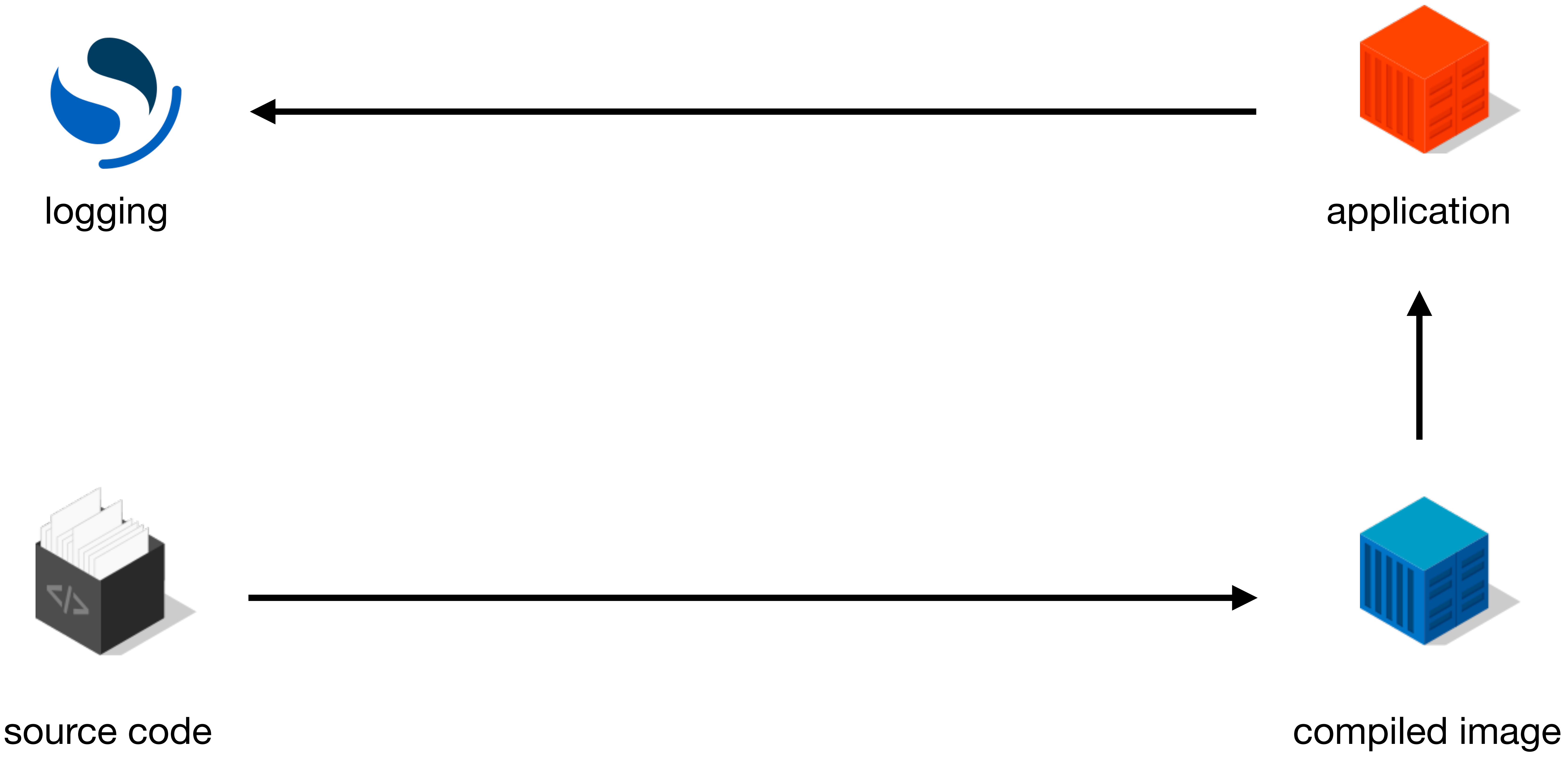


PGO Release Workflow

- There are two different approaches:
  - **Traffic Simulation**
  - Double Release



PGO Release Workflow: Traffic Simulation



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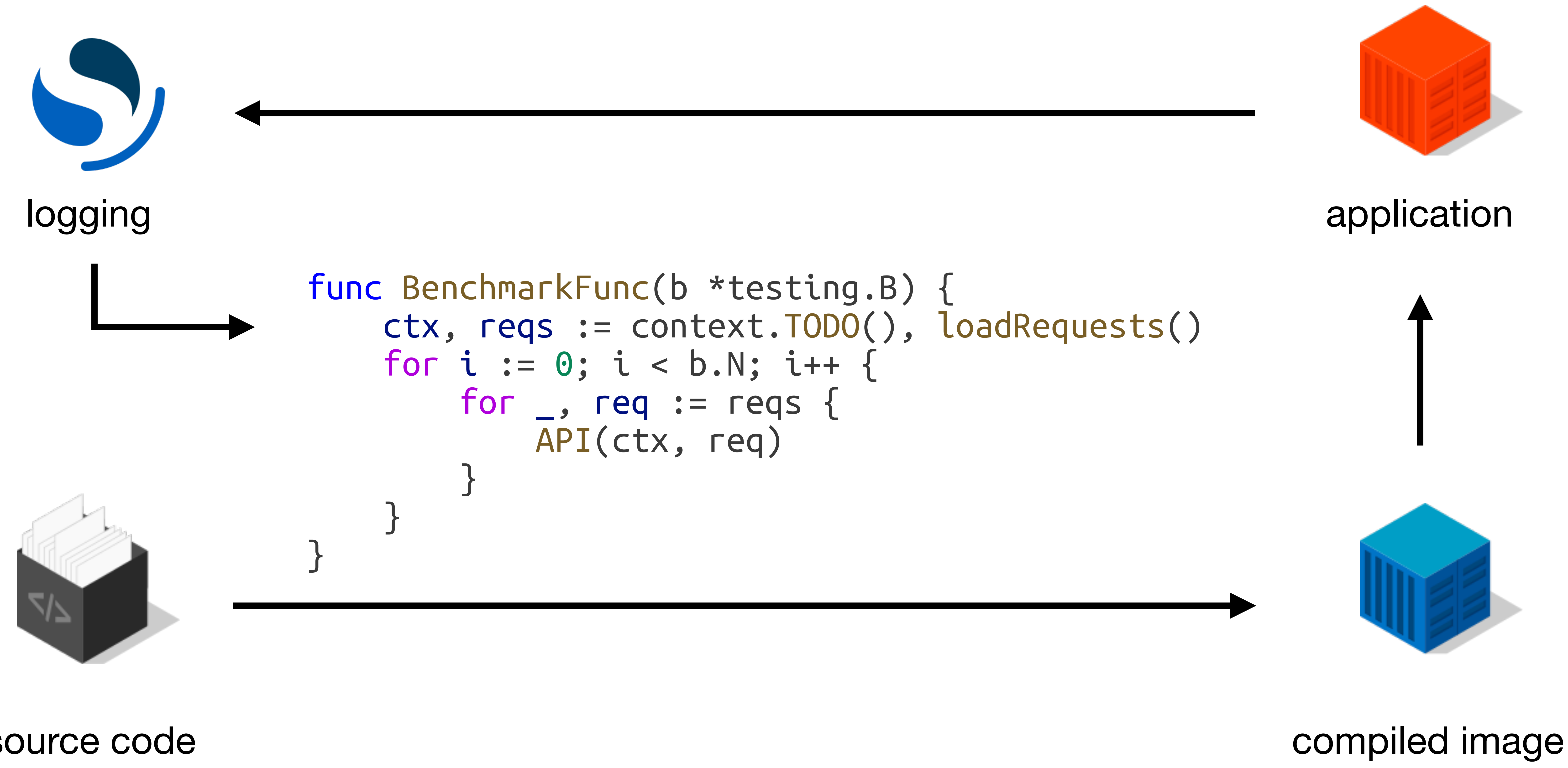
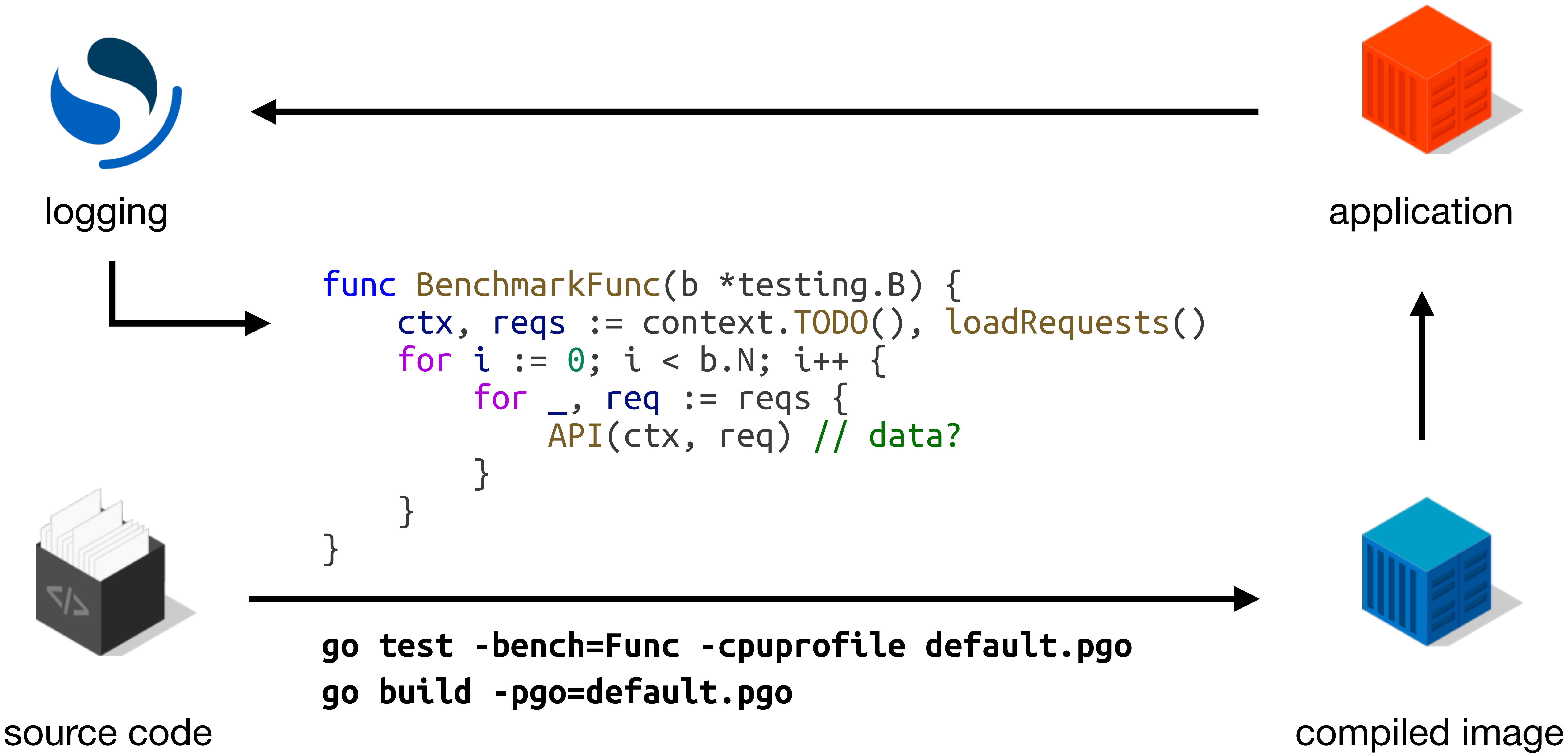



```go
func BenchmarkFunc(b *testing.B) {
	ctx, reqs := context.TODO(), loadRequests()
	for i := 0; i < b.N; i++ {
		for _, req := range reqs {
			API(ctx, req)
		}
	}
}
```

PGO Release Workflow: Traffic Simulation

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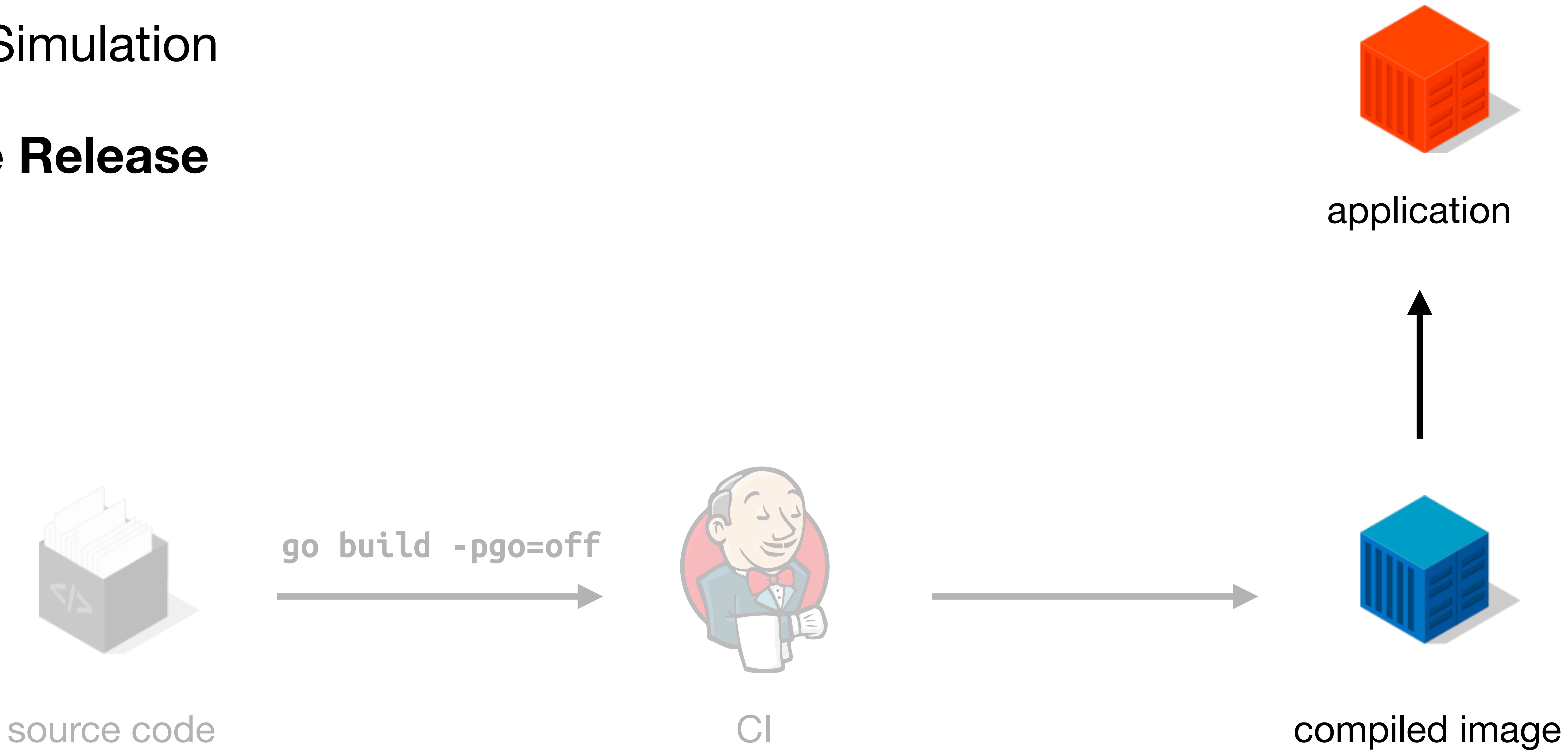
    ctx, reqs := context.TODO(), loadRequests()
    for i := 0; i < b.N; i++ {
        for _, req := range reqs {
            API(ctx, req) // data?
        }
    }
}
```

```
go test -bench=Func -cpuprofile default.pgo
go build -pgo=default.pgo
```

PGO Release Workflow

- There are two different approaches:
  - Traffic Simulation
  - **Double Release**



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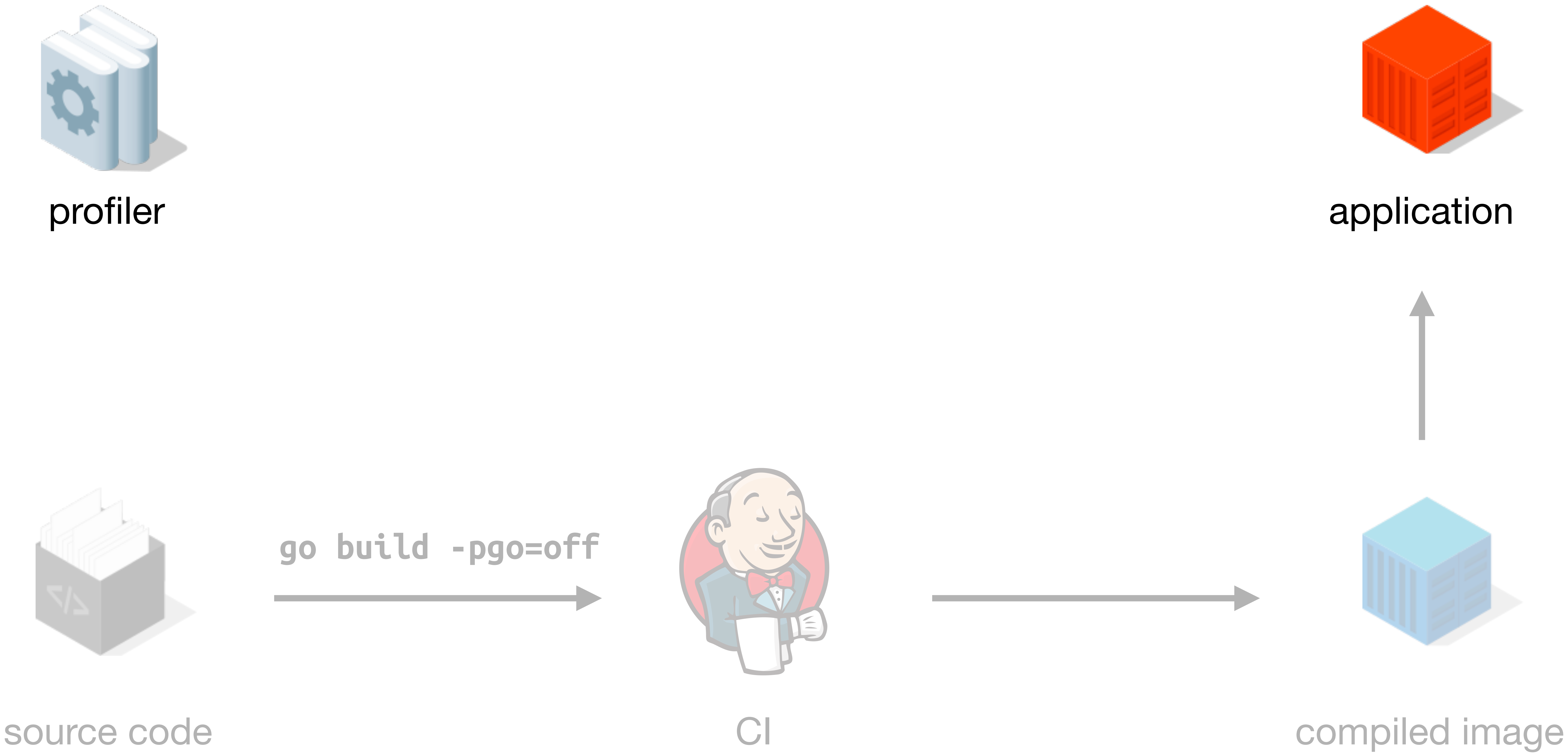

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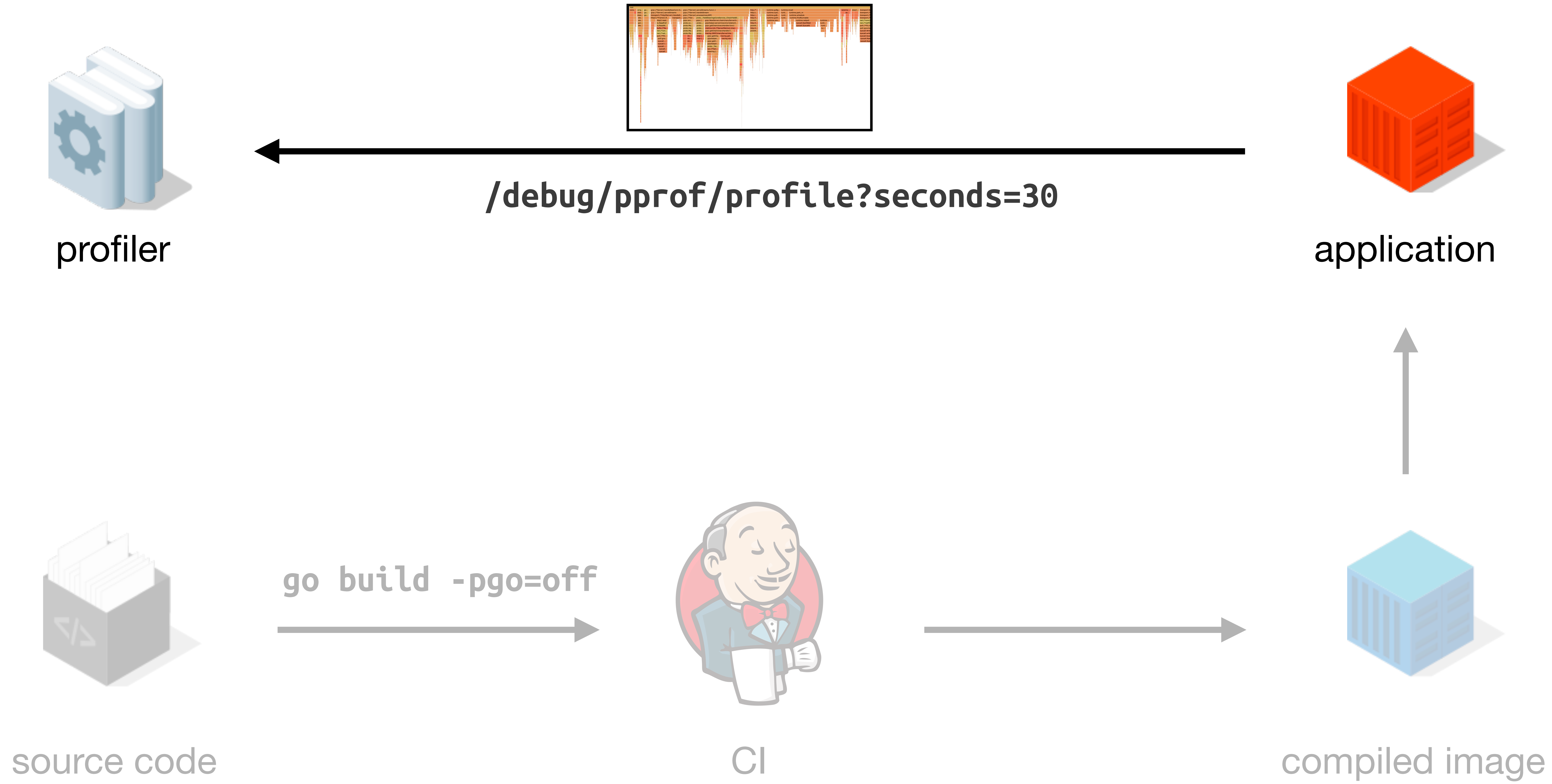

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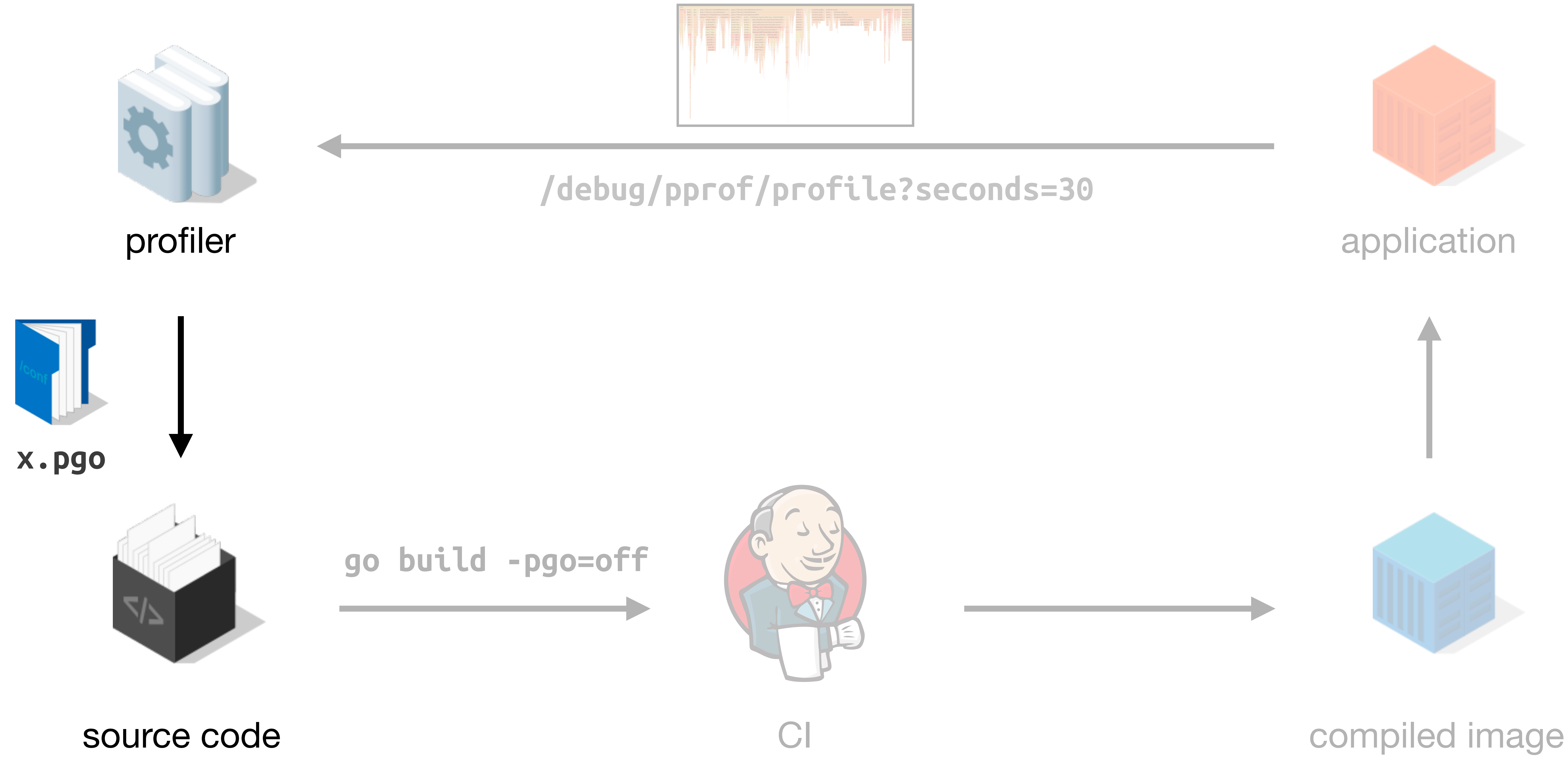

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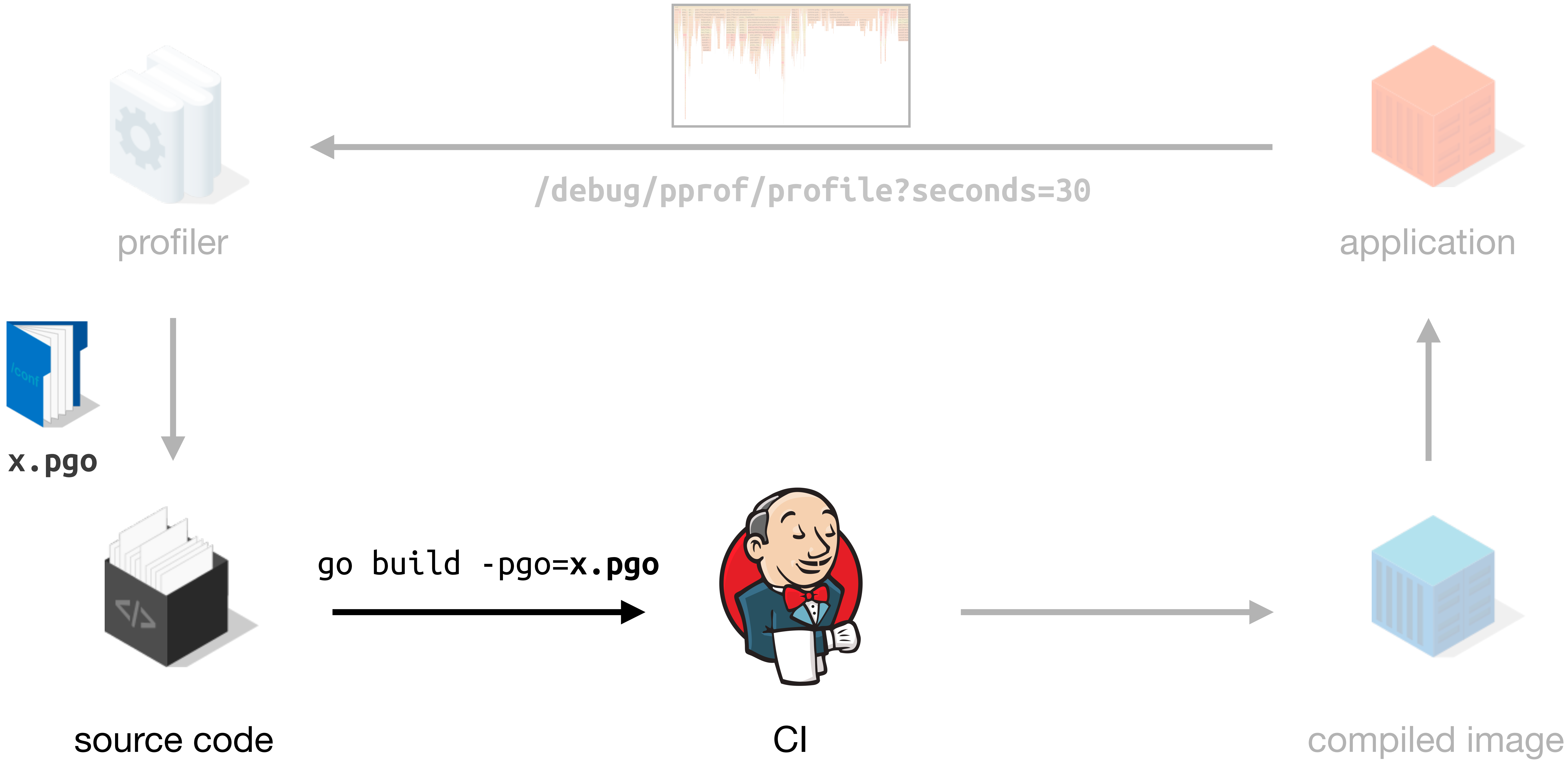

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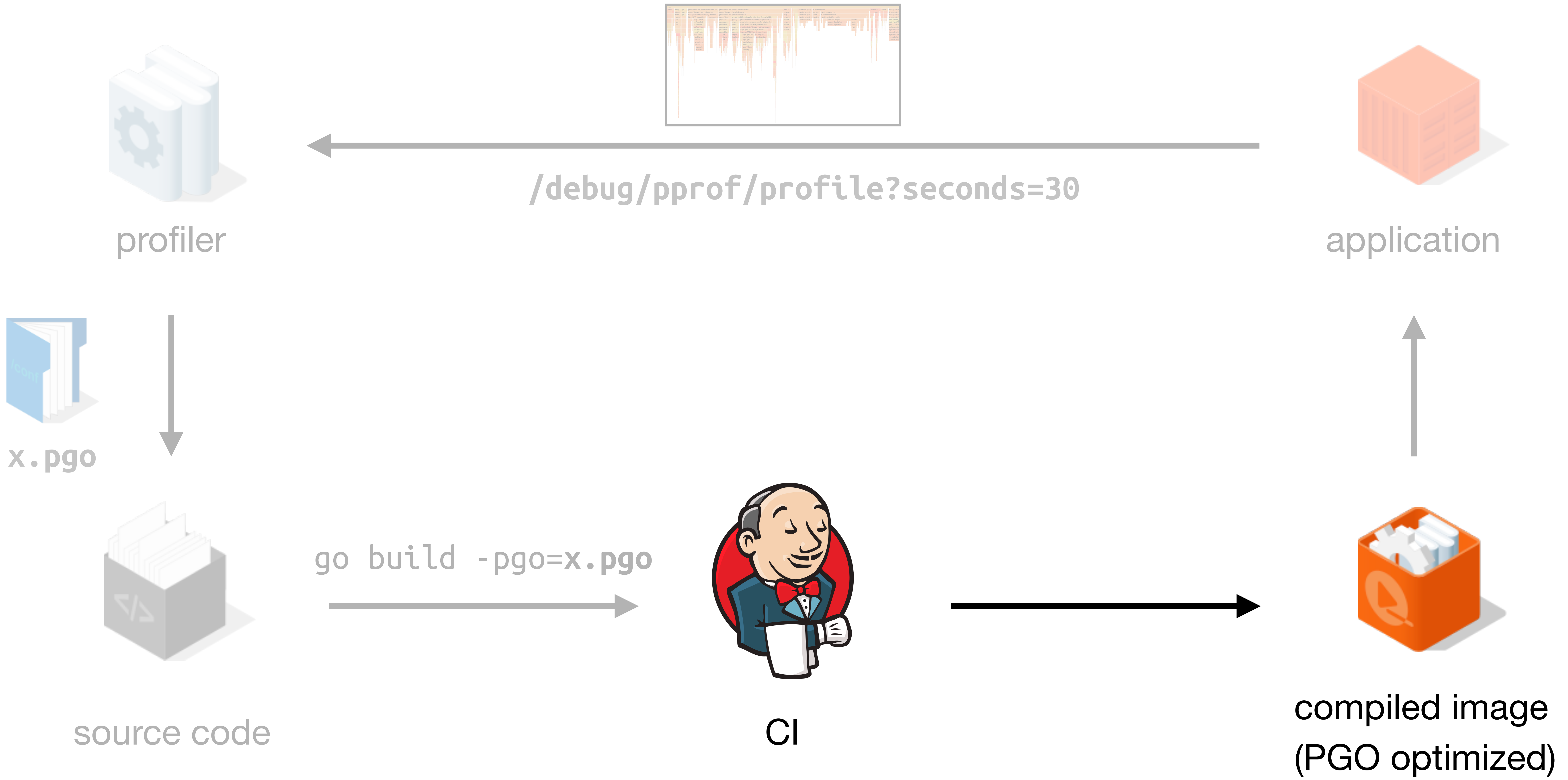
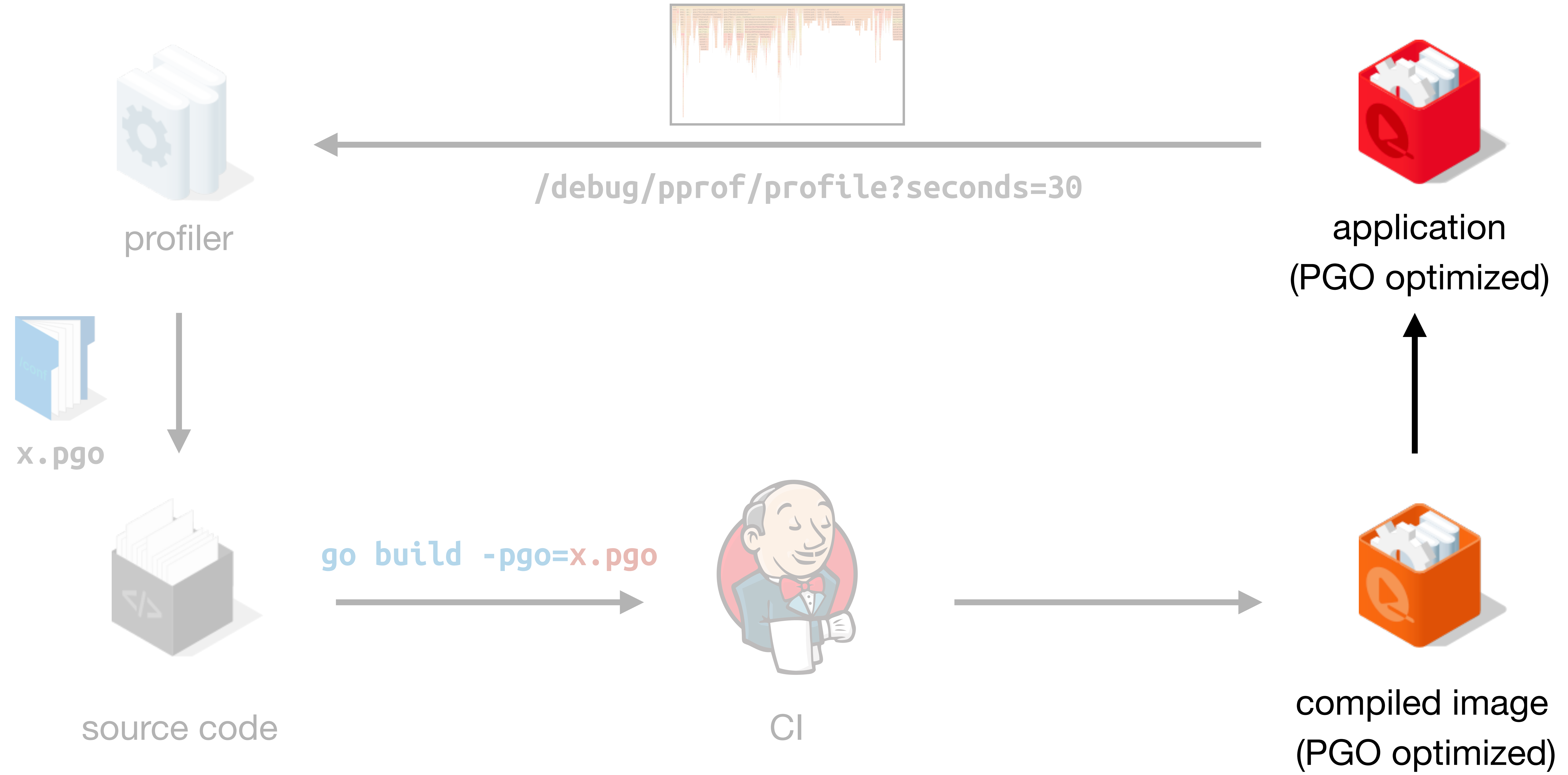


PGO Release Workflow: Feedback Loop



PGO Release Workflow

There are two different approaches:

- **Traffic Simulation**
    - Pros: Do not require deploy 2 times
    - Cons: 1) Simulate production env is non-trivial; 2) Only profiling in smaller scope
- **Double Release**
    - Pros: 1) Fit into PGO's design; 2) Profiling history for inspections
    - Cons: Complicated infrastructure required

Case Study: Production Setup

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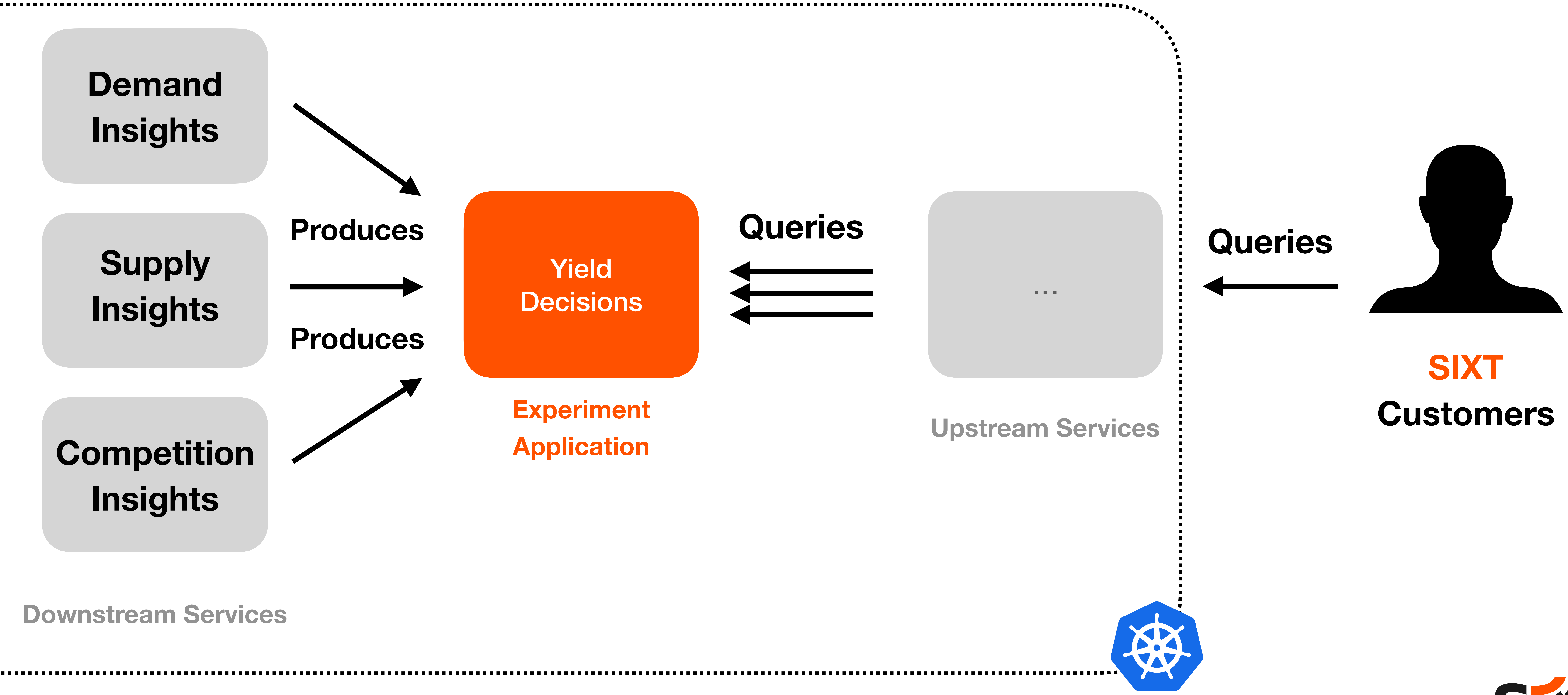

Case Study: Benchmark by Simulation

```
$ go test -pgo=off -v -run=none -bench=BenchmarkCheckYieldCondition -count=10 -cpuprofile without.pgo | tee without-pgo.txt
goos: darwin
goarch: arm64
pkg: internal/steering
BenchmarkCheckYieldCondition
BenchmarkCheckYieldCondition-8        270      5111763 ns/op    356484 B/op      6046 allocs/op
BenchmarkCheckYieldCondition-8        358      4471476 ns/op    365618 B/op      6326 allocs/op
BenchmarkCheckYieldCondition-8        362      3392595 ns/op    366421 B/op      6334 allocs/op
...
```

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BenchmarkCheckYieldCondition
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BenchmarkCheckYieldCondition-8        358     4471476 ns/op    365618 B/op      6326 allocs/op
BenchmarkCheckYieldCondition-8        362     3392595 ns/op    366421 B/op      6334 allocs/op
...

$ go test -pgo=without.pgo -v -run=none -bench=BenchmarkCheckYieldCondition -count=10 -cpuprofile with.pgo | tee with-pgo.txt
goos: darwin
goarch: arm64
pkg: internal/steering
BenchmarkCheckYieldCondition
BenchmarkCheckYieldCondition-8        355     2823859 ns/op    367670 B/op      6323 allocs/op
BenchmarkCheckYieldCondition-8        409     2463564 ns/op    362959 B/op      6360 allocs/op
BenchmarkCheckYieldCondition-8        450     2505435 ns/op    359412 B/op      6286 allocs/op
...
```
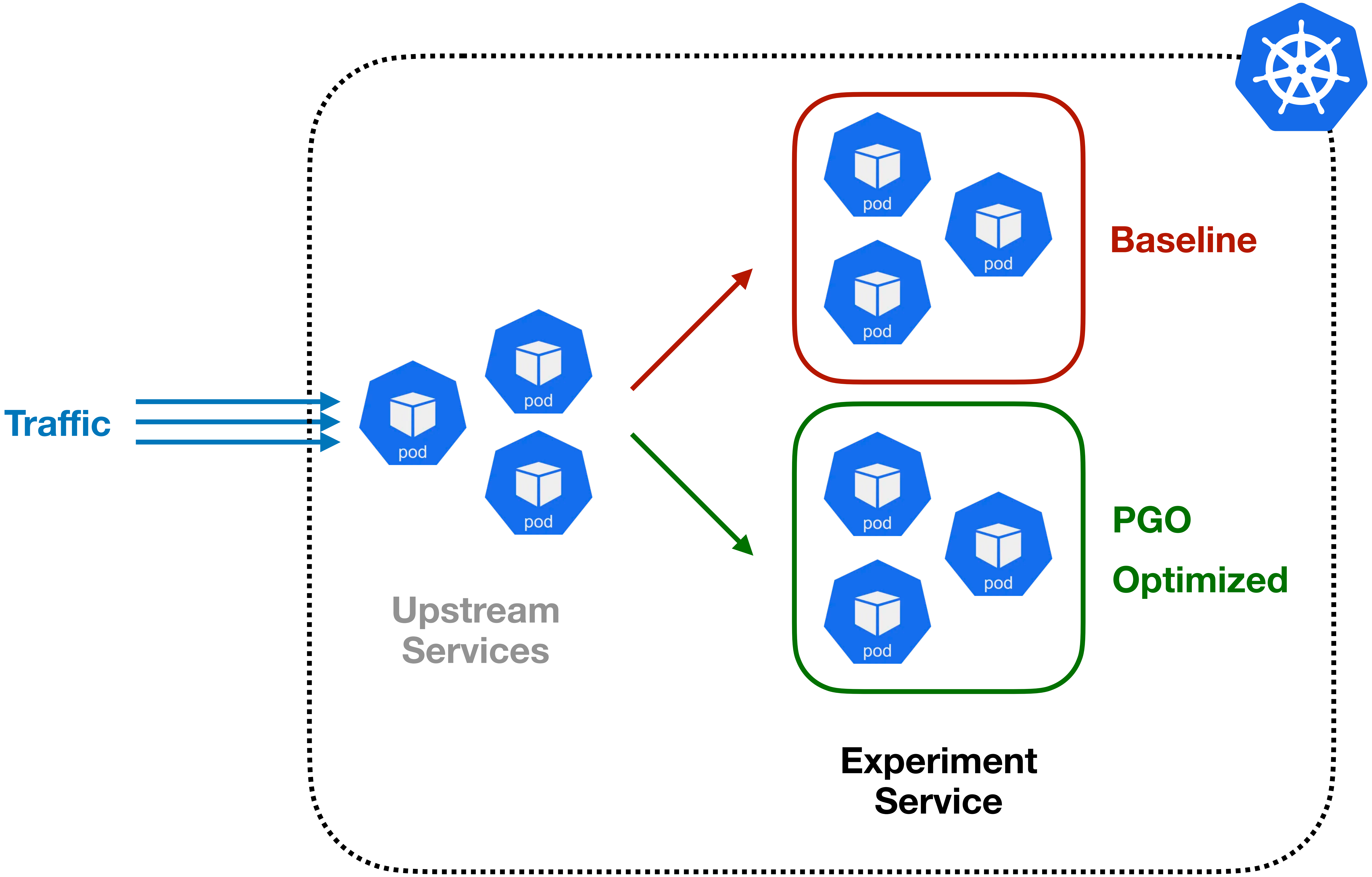

Case Study: Benchmark by Simulation

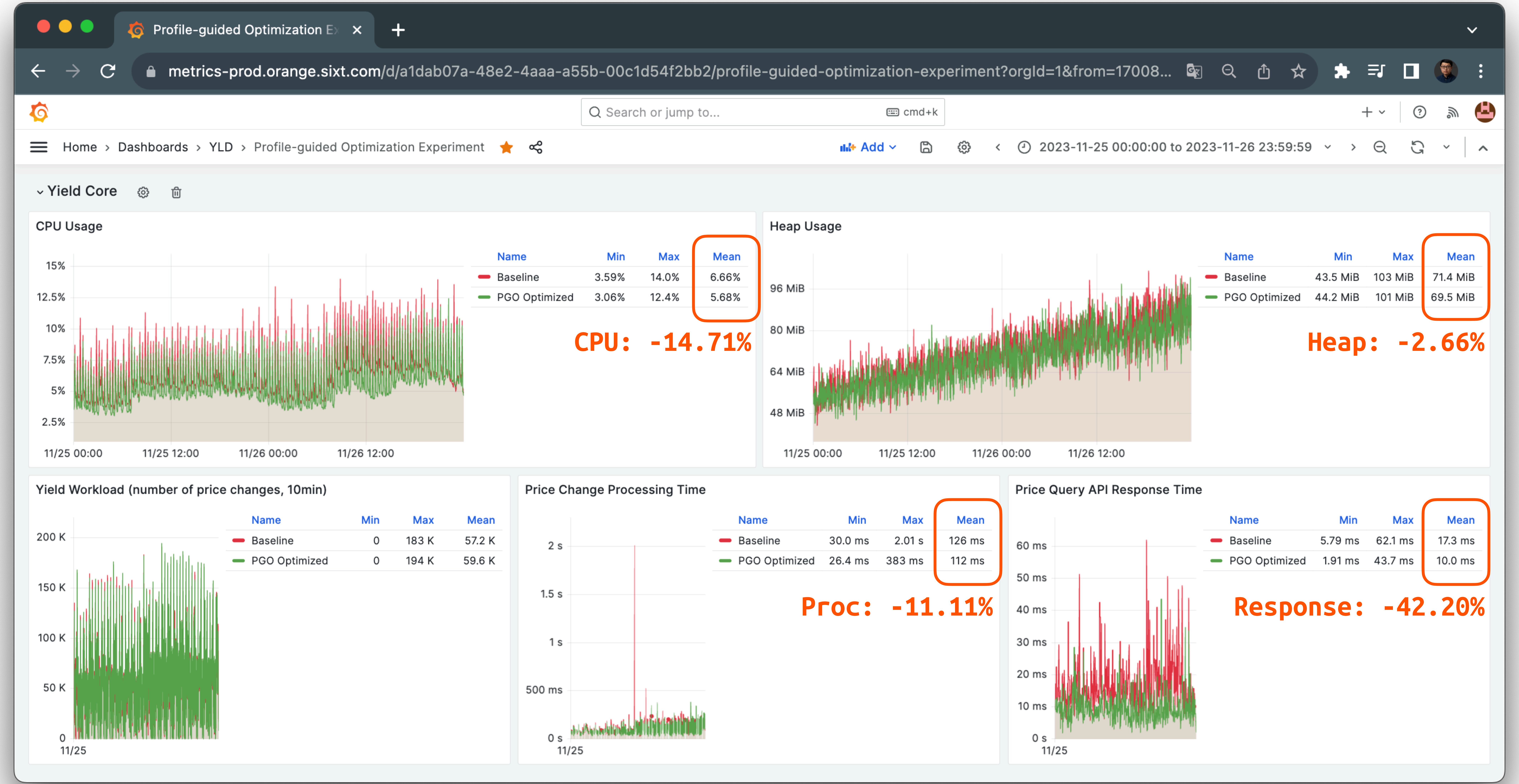
```
$ go test -pgo=off -v -run=none -bench=BenchmarkCheckYieldCondition -count=10 -cpuprofile without.pgo | tee without-pgo.txt
goos: darwin
goarch: arm64
pkg: internal/steering
BenchmarkCheckYieldCondition
BenchmarkCheckYieldCondition-8        270      5111763 ns/op    356484 B/op       6046 allocs/op
BenchmarkCheckYieldCondition-8        358      4471476 ns/op    365618 B/op       6326 allocs/op
BenchmarkCheckYieldCondition-8        362      3392595 ns/op    366421 B/op       6334 allocs/op
...

$ go test -pgo=without.pgo -v -run=none -bench=BenchmarkCheckYieldCondition -count=10 -cpuprofile with.pgo | tee with-pgo.txt
goos: darwin
goarch: arm64
pkg: internal/steering
BenchmarkCheckYieldCondition
BenchmarkCheckYieldCondition-8        355      2823859 ns/op    367670 B/op       6323 allocs/op
BenchmarkCheckYieldCondition-8        409      2463564 ns/op    362959 B/op       6360 allocs/op
BenchmarkCheckYieldCondition-8        450      2505435 ns/op    359412 B/op       6286 allocs/op
...

$ benchstat without-pgo.txt with-pgo.txt
name                   old time/op    new time/op    delta
CheckYieldCondition-8    3.15ms ±42%    2.65ms ±11%  -15.95%  (p=0.000 n=19+19)

name                   old alloc/op   new alloc/op   delta
CheckYieldCondition-8     367kB ± 1%     362kB ± 1%   -1.19%  (p=0.000 n=19+20)

name                   old allocs/op  new allocs/op  delta
CheckYieldCondition-8     6.35k ± 1%     6.34k ± 1%     ~     (p=0.723 n=19+20)
```

Case Study: Production Setup

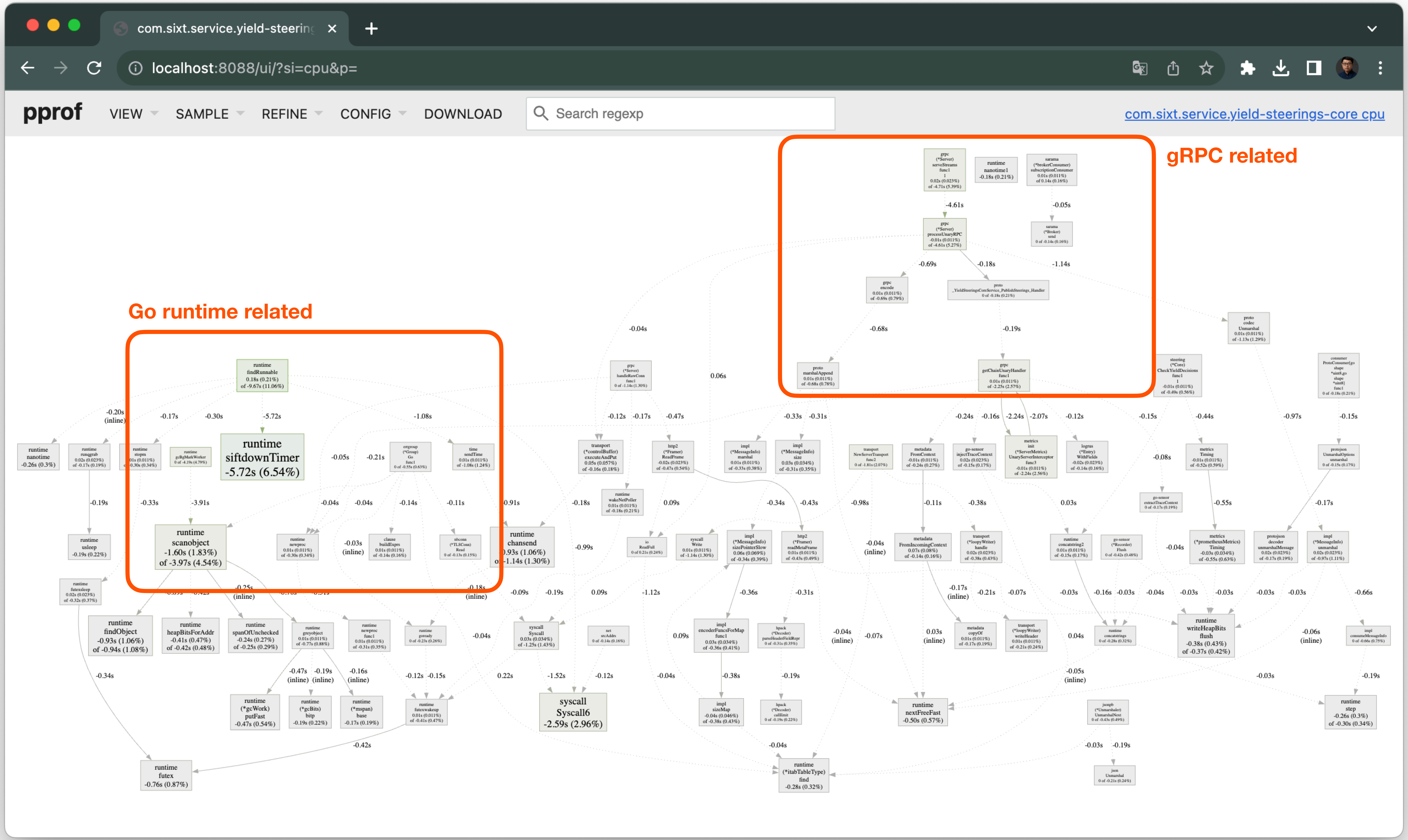
- Canary deployment
    - 5 Pods baseline
    - 5 Pods PGO optimized
- Balanced traffic
    - Each 400 read/s + 5000 write/s



Case Study: Observations

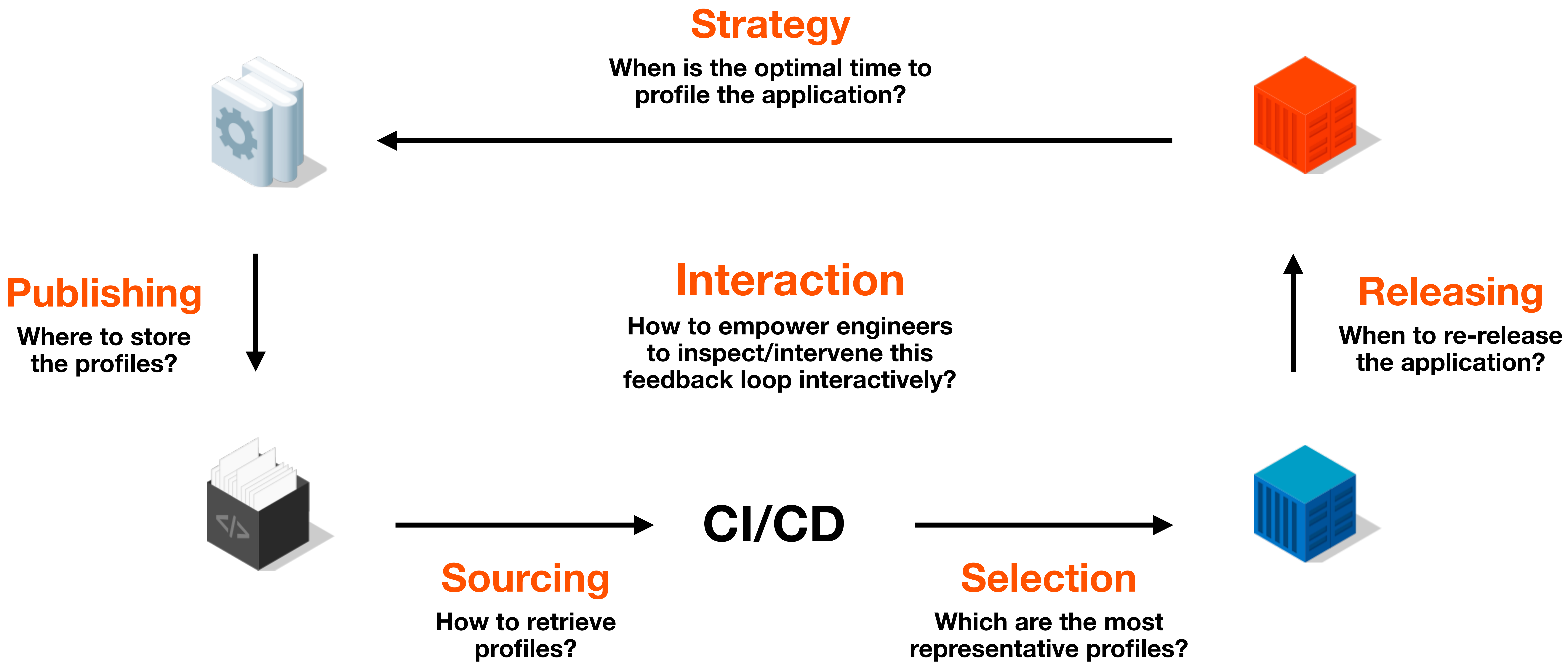


Case Study: Profiling



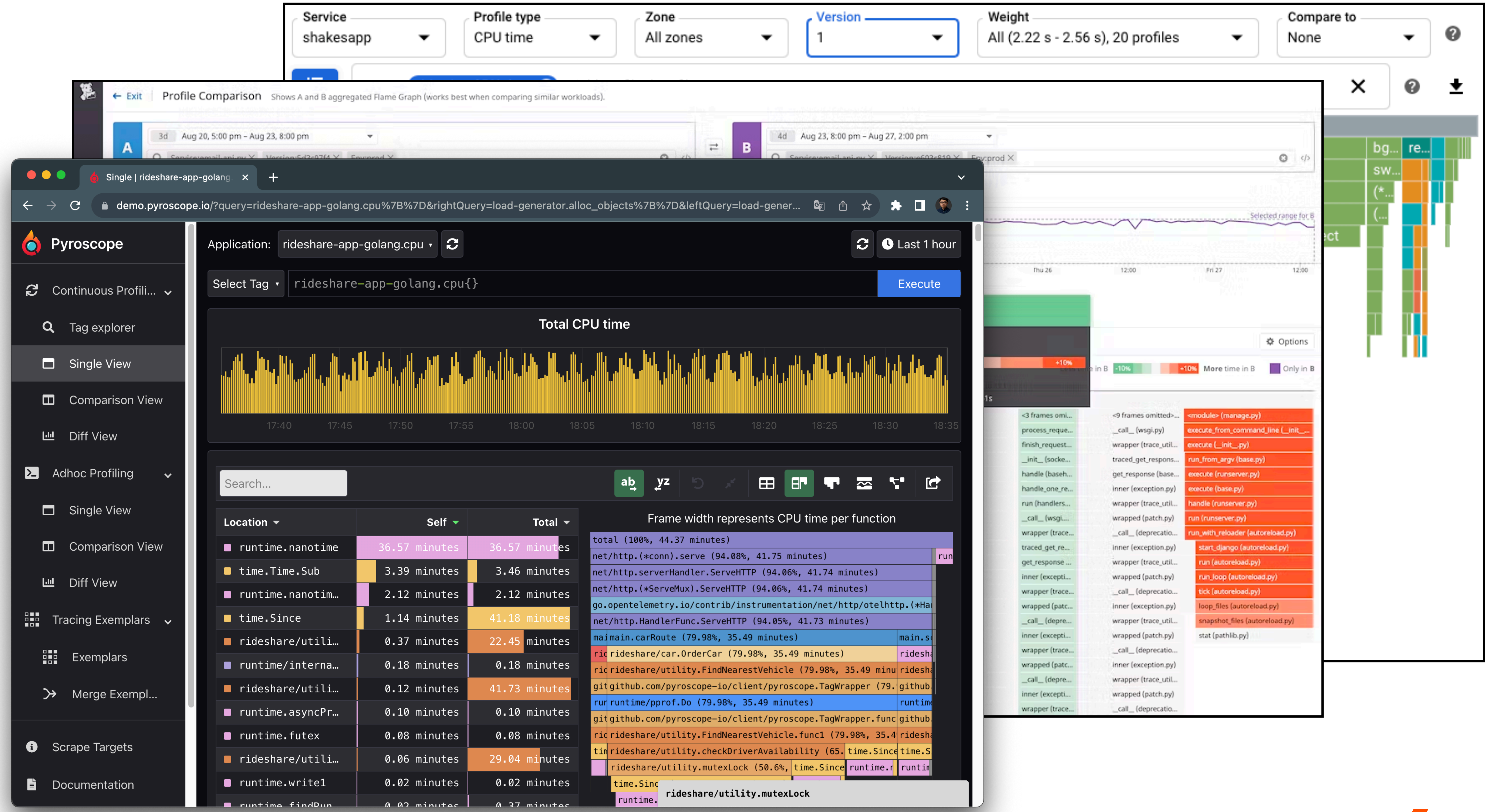
PGO Opportunities in Automation

- There are many opportunities to build solutions to automate PGO release pipeline:



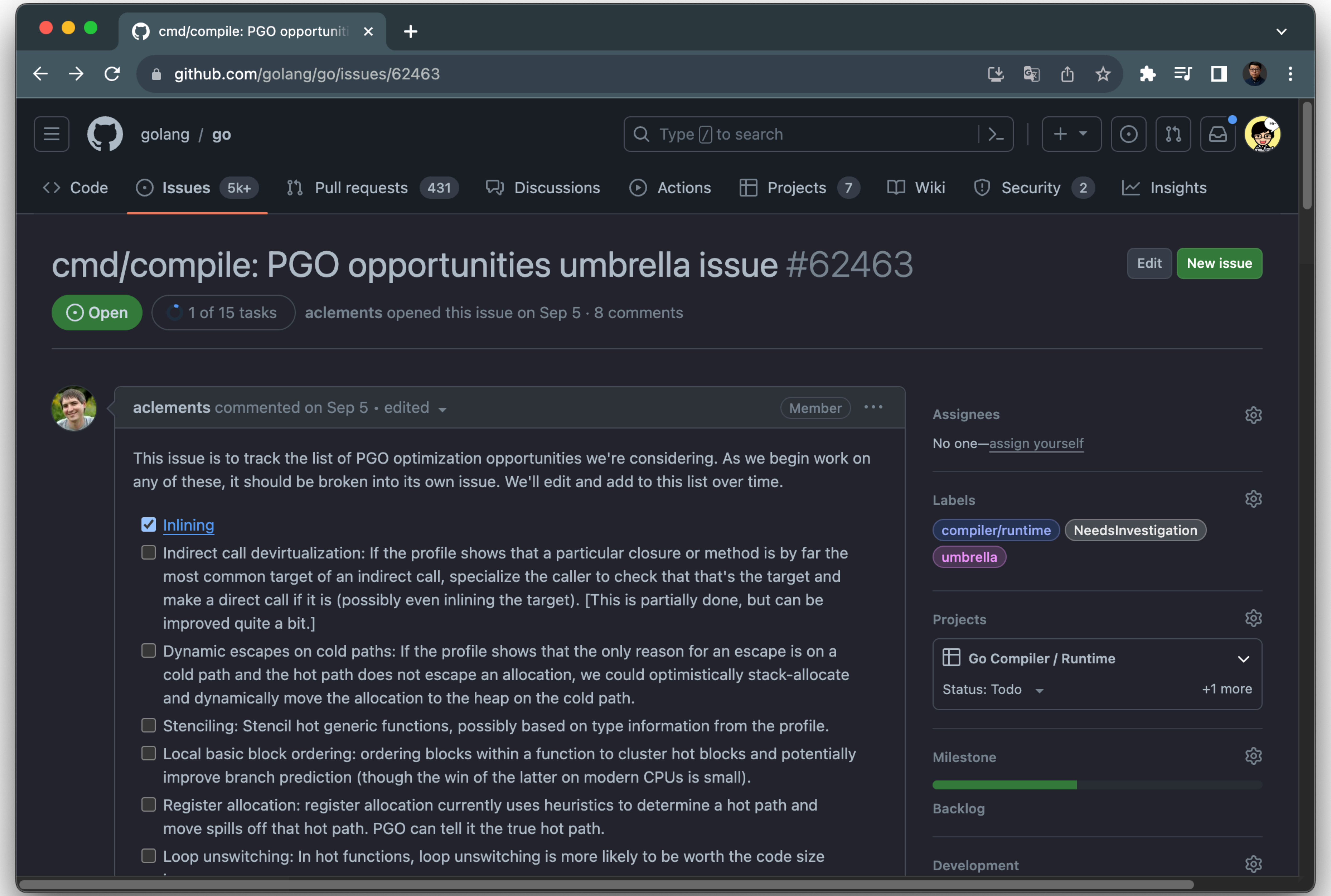
Continuous Profiler Solutions

- Many emerging solutions allow interactive profiling on temporal dimension
  - Pyroscope
  - Datadog
  - Google Cloud Profiler
  - Parca
  - …



PGO Opportunities in Go

- There are many opportunities to contribute to the Go source:
  - Indirect call devirtualization
  - Local basic block ordering
  - Register allocation
  - Function ordering
  - Loop alignment
  - …



Summary and Outlook

Summary

- The idea of data-driven compile time optimization using runtime profiling
- How to use profile-guided optimization in Go application build workflow
- The current status of PGO in Go (inlining and devirtualization)
- The benefits of integrate PGO into CI/CD pipeline
  - Continuous profiling as an infrastructure to support engineers’ daily workflow
  - Without any code changes, our practices and observations on production service showed 5~20% performance improvements and 2~5% memory consumption reduction using PGO

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