The benefits and costs of writing a UNIX kernel in a high-level language

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What language to use for developing a kernel?

A hotly-debated question but often with few facts

6.828 students: why are we using C? why not a type-safe language?

To shed some light, we focus on:

- A *new* kernel or monitor
- A language with automatic memory management (i.e., with a garbage collector)
- A traditional, monolithic UNIX kernel

C is popular for kernels

Windows

Linux

*BSD

Why C is good: complete control

Control of memory allocation and freeing

Almost no implicit, hidden code

Direct access to memory

Few dependencies

Why C is bad

Writing secure C code is difficult

40 Linux kernel execute-code CVEs in 2017 due to memory-safety errors

(execute-code CVE is a bug that enables attacker to run malicious code in kernel)

High-level languages (HLLs) provide memory-safety

All 40 CVEs would not execute malicious code in an HLL

HLL benefits

Type safety

Automatic memory management with garbage collector

Concurrency

Abstraction

HLL potential downsides

Poor performance:

- Bounds, cast, nil-pointer checks
- Garbage collection

Incompatibility with kernel programming:

- No direct memory access
- No hand-written assembly
- Limited concurrency or parallelism

Goal: measure HLL trade-offs

Explore total effect of using HLL instead of C:

- Impact on safety
- Impact on programmability
- Performance cost

...for production-grade kernel

Prior work: HLL trade-offs

Many studies of HLL trade-offs for user programs (*Hertz'05, Yang'04*)

But kernels different from user programs

(ex: more careful memory management)

Need to measure HLL trade-offs in kernel

Prior work: HLL kernels

Singularity*(SOSP'07)*, J-kernel*(ATC'98)*, Taos*(ASPLOS'87)*, Spin*(SOSP'95)*, Tock*(SOSP'17)*, KaffeOS*(ATC'00)*, House*(ICFP'05)*,...

Explore new ideas and architectures

None measure HLL trade-offs vs C kernel

Measuring trade-offs is tricky

Must compare with production-grade C kernel (e.g., Linux)

Problem: can't build production-grade HLL kernel

The most we can do

Build HLL kernel

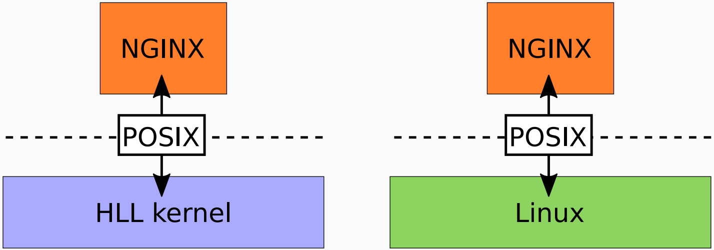
Keep important parts the same as Linux

Optimize until performance is roughly similar to Linux

Measure HLL trade-offs

Risk: measurements of production-grade kernels differ

Methodology



Built HLL kernel

Same apps, POSIX interface, and monolithic organization

Optimized, measured HLL trade-offs

Contributions

BISCUIT, new x86-64 Go kernel

- source compatibility for Linux applications

New scheme to deal with heap exhaustion

Evaluation

- Measurements of HLL costs for two popular, kernel-intensive apps
- Description of qualitative ways HLL helped

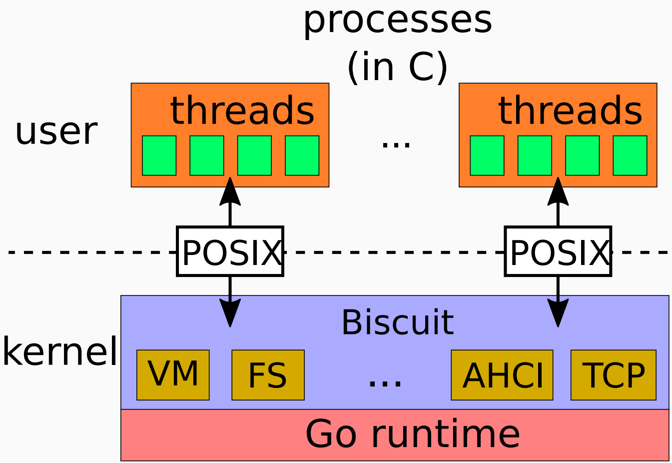
Which HLL?

Go is a good choice:

- Easy to call assembly
- Compiled to machine code w/good compiler
- Easy concurrency
- Easy static analysis
- GC (Concurrent mark and sweep)

Rust might be a fine choice too

BISCUIT overview



58 system calls, LOC: *28k Go,*

BISCUIT Features

- Multicore
- Threads
- Journaled FS (7k LOC)
- Virtual memory (2k LOC)
- TCP/IP stack (5k LOC)
- Drivers: AHCI and Intel 10Gb NIC (3k LOC)

User programs

Process has own address space

User/kernel memory isolated by hardware

Each user thread has companion kernel thread

Kernel threads are “goroutines”

System calls

User thread put args in registers

User thread executes *SYSENTER*

Control passes to kernel thread

Kernel thread executes system call, returns via *SYSEXIT*

BISCUIT design puzzles

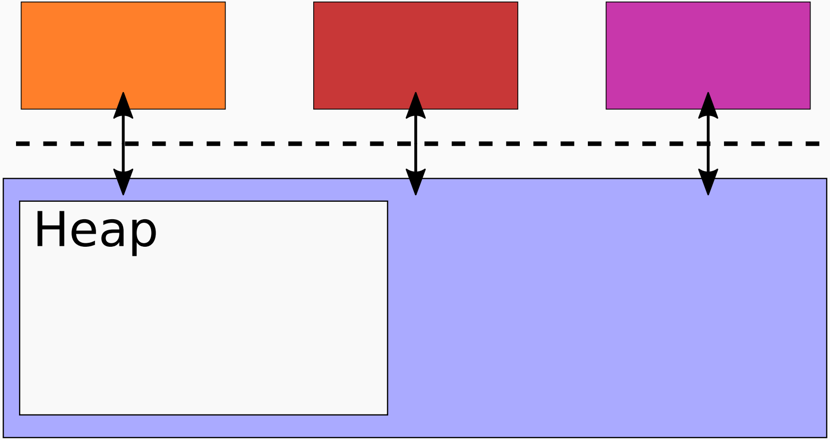
Runtime on bare-metal

Goroutines run different applications

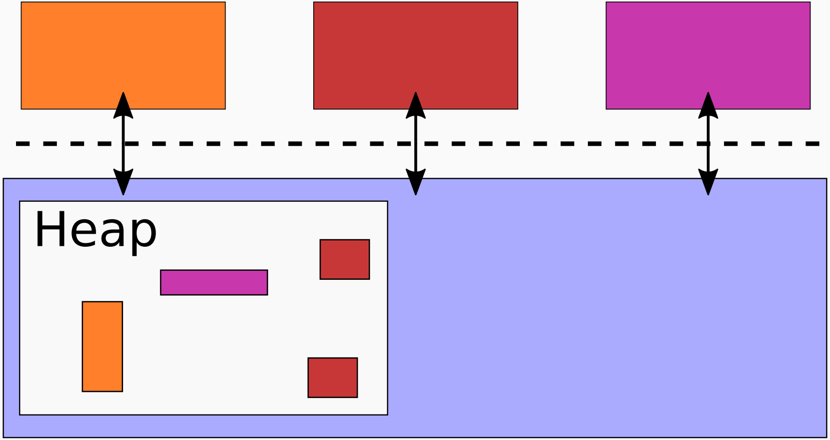
Device interrupts in runtime critical sections

Hardest puzzle: heap exhaustion

Puzzle: Heap exhaustion



Puzzle: Heap exhaustion



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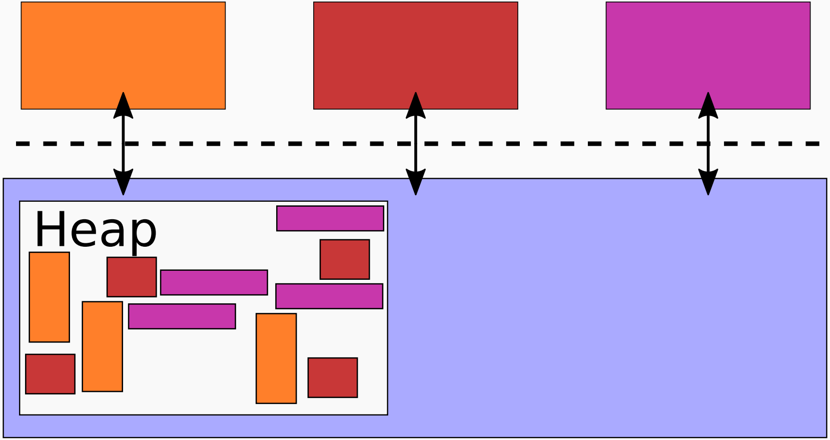

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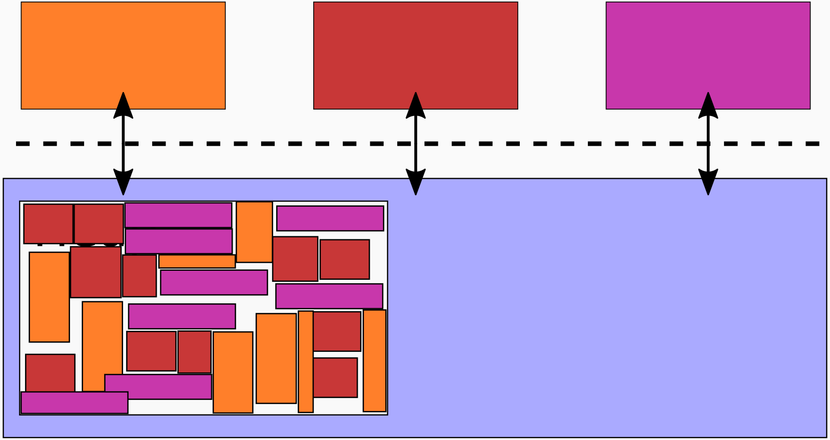

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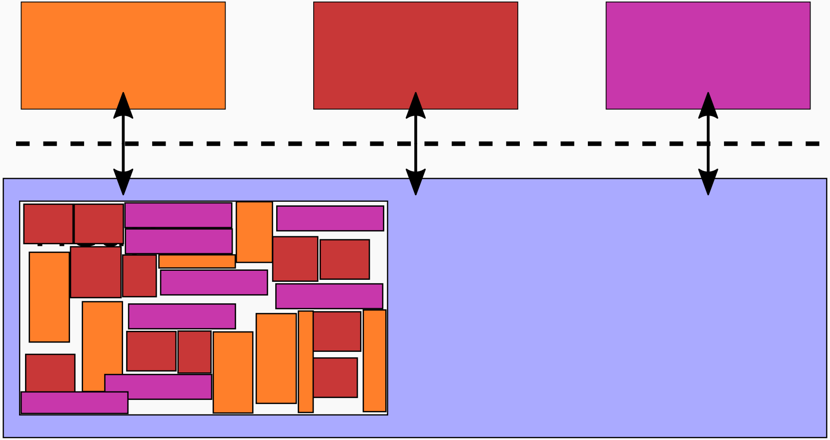

Can't allocate heap memory $\implies$ nothing works

All kernels face this problem

How to recover?

Strawman 0: panic (xv6)

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- Difficult to get right

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Strawman 1: Wait for memory in allocator?

- May deadlock!

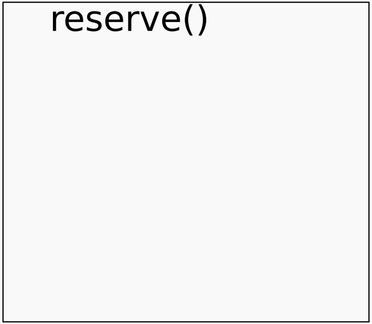
Strawman 2: Check/handle allocation failure, like C kernels?

- Difficult to get right
- Can't – Go implicitly allocates
- Doesn't expose failed allocations

Both cause problems for Linux; see "too small to fail" rule

BISCUIT solution: reserve memory

To execute system call...



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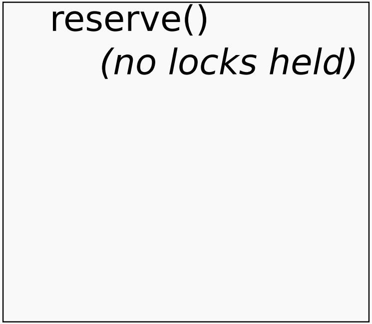

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No checks, no error handling code, no deadlock

Heap reservation bounds

How to compute max memory for each system call?

Smaller heap bounds $\implies$ more concurrent system calls

Heap bounds via static analysis

HLL easy to analyze

Tool computes reservation via escape analysis

Using Go's static analysis packages

Annotations for difficult cases

$\approx$ three days of expert effort to apply tool

BISCUIT implementation

Building BISCUIT was similar to other kernels

BISCUIT implementation

Building BISCUIT was similar to other kernels

BISCUIT adopted many Linux optimizations:

- large pages for kernel text
- per-CPU NIC transmit queues
- RCU-like directory cache
- execute FS ops concurrently with commit
- pad structs to remove false sharing

Good OS performance more about optimizations, less about HLL

Evaluation

Part 1: HLL benefits

Part 2: HLL performance costs

Evaluation: HLL benefits

Should we use high-level languages to build OS kernels?

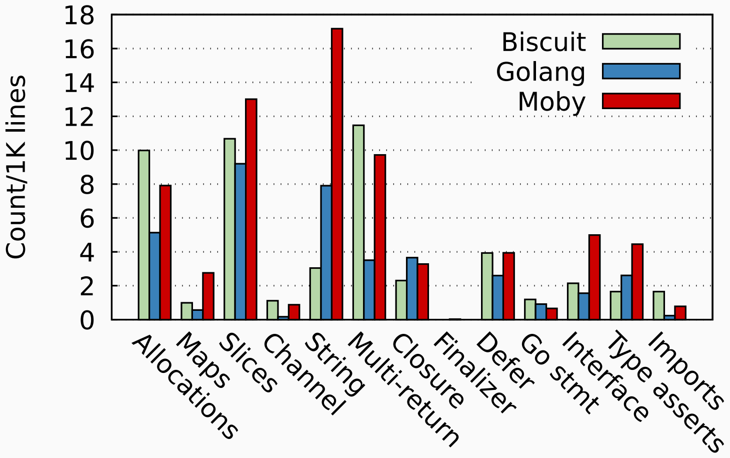
1. Does BISCUIT use HLL features?
2. Does HLL simplify BISCUIT code?
3. Would HLL prevent kernel exploits?

1: Does BISCUIT use HLL features?

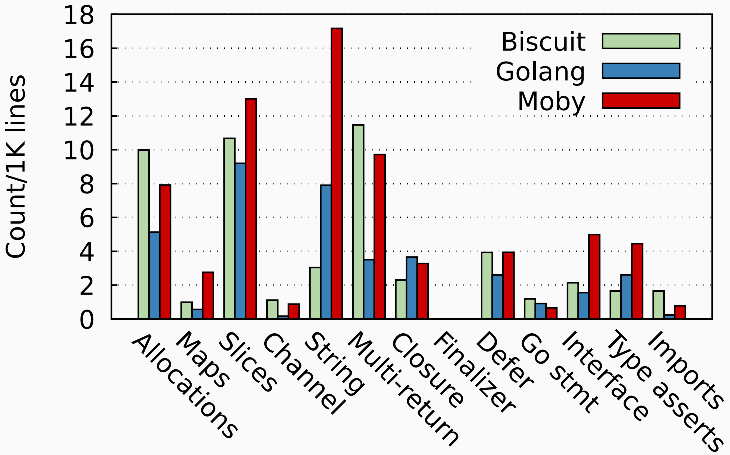
Counted HLL feature use in BISCUIT and two huge Go projects

(Moby and Golang, >1M LOC)

1: BISCUIT uses HLL features



1: Biscuit uses HLL features



Biscuit uses most HLL features similarly

2: Does HLL simplify Biscuit code?

Qualitatively, my favorite features:

- GC'ed allocation
- slices
- `defer`
- multi-valued return
- strings
- closures
- maps

Net effect: simpler code

2: Simpler concurrency

Simpler data sharing between threads

In HLL, GC frees memory

In C, programmer must free memory

2: Simpler concurrency example

```
buf := new(object_t)
// Initialize buf...

go func() {
    process1(buf)
}()
process2(buf)
// When should C code free(buf)?
```

2: Simpler read-lock-free concurrency

Locks and reference counts expensive in hot paths

Good for performance to avoid them

Challenge in C: when is object free?

2: Read-lock-free example

```
var Head *Node

func get() *Node {
    return atomic_load(&Head)
}

func pop() {
    Lock()
    v := Head
    if v != nil {
        atomic_store(&Head, v.next)
    }
    Unlock()
```

2: Simpler read-lock-free concurrency

Linux safely frees via RCU (*McKenney'98*)

Defers `free` until all CPUs context switch

Programmer must follow RCU rules:

- Prologue and epilogue surrounding accesses
- No sleeping or scheduling

Error prone in more complex situations

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GC makes these challenges disappear

HLL significantly simplifies read-lock-free code

3: Would HLL prevent kernel exploits?

Inspected fixes for all publicly-available execute code CVEs in Linux kernel for 2017

Classify based on outcome of bug in BISCUIT

3: HLL prevents kernel exploits

Category	#	Outcome in Go
—	11	unknown
logic	14	same
use-after-free/double-free	8	disappear due to GC
out-of-bounds	32	`panic` or disappear

`panic` likely better than malicious code execution

3: HLL prevents kernel exploits

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HLL would prevent kernel exploits

Evaluation: HLL performance

Should we use high-level languages to build OS kernels?

1. Is BISCUIT's performance roughly similar to Linux?
2. What is the breakdown of HLL tax?
3. How much might GC cost?
4. What are the GC pauses?
5. What is the performance cost of Go compared to C?
6. Does BISCUIT's performance scale with cores?

Experimental setup

Hardware:

- 4 core 2.8Ghz Xeon-X3460
- 16 GB RAM
- Hyperthreads disabled

Eval applications:

- NGINX (1.11.5) – webserver
- Redis (3.0.5) – key/value store
- CMailbench – mail-server benchmark

Applications are kernel intensive

No idle time; 79%-92% kernel time

In-memory FS

Ran for a minute

512MB heap RAM for BISCUIT

1: Is BISCUIT's perf roughly similar to Linux?

i.e. is BISCUIT's performace similar to production-grade kernel?

Compare app throughput on BISCUIT and Linux

Linux setup

Debian 9.4, Linux 4.9.82

Disabled features that slowed Linux down on our apps:

- page-table isolation
- retpoline
- kernel address space layout randomization
- transparent huge-pages
- ...

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Linux has more features: NUMA, scales to many cores, ...

Not apples-to-apples, but BISCUIT perf roughly similar

2: What is the breakdown of HLL tax?

Record CPU time profile of our apps

Categorize samples into HLL cost buckets

	GC cycles	GCs	Prologue cycles	Write barrier cycles	Safety cycles
CMailbench	3%	42	6%	< 1%	3%
NGINX	2%	32	6%	< 1%	2%
Redis	1%	30	4%	< 1%	2%

Benchmarks allocate kernel heap rapidly

but have few long-lived kernel heap objects

2: Prologue cycles are most expensive

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GC cost varies by program

More live data $\implies$ more cycles per GC

Less free heap RAM $\implies$ GC more frequent

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Total GC cost $\propto$ ratio of live data to free heap RAM

3: How much might GC cost?

Created two million vnodes of live data

Varied free heap RAM

Ran CMailbench, measured GC cost

3: How much might GC cost?

Live (MB)	Free (MB)	Ratio	Tput	GC%

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640	320	2	10,448	34%

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640	1280	0.5	14,430	9%

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$\Rightarrow$ Need $3\times$ heap RAM to keep GC $<$ 10%

3: GC memory cost in practice?

Few programs allocate millions of resources

MIT's big time-sharing machines:

80 users, 800 tasks, 9-16GB RSS, <2GB kernel heap

(Exception: cached files, maybe evictable)

Memory cost acceptable in common situations?

GC pauses

GC must eventually execute

Could delay latency-sensitive work

Some GCs cause one large pause, but not Go's

- Go's GC is interleaved with execution (*Baker'78, McCloskey'08*)
- Causes many small delays

4: What are the GC pauses?

Measured duration of each GC pause during NGINX

Multiple pauses occur during a single request

Sum pause durations over each request

4: What are the GC pauses?

Max single pause: 115 μs

(marking large part of TCP connection table)

Max total pauses during request: 582 μs

Less than 0.3% of requests paused $> 100\mu$s

4: GC pauses OK?

Some programs can't tolerate rare 582 μs pauses

But many probably can

99%-ile latency in service of Google's "Tail at Scale" was 10ms

5: What is the cost of Go compared to C?

Compared OS code paths with identical functionality

Chose paths that are:

- core OS paths
- small enough to make them have same functionality

Two code paths in *OSDI'18* paper

- pipe ping-pong (systems calls, context switching)
- page-fault handler (exceptions, VM)

5: What is the cost of Go compared to C?

Pipe ping-pong code path:

- LOC: 1.2k Go, 1.8k C
- No allocation; no GC
- Top-10 most expensive instructions match

5: C is 15% faster

Pipe ping-pong:

C (ops/s)	Go (ops/s)	Ratio
536,193	465,811	1.15

Prologue/safety-checks $\Rightarrow$ 16% more instructions

Go slower, but competitive

6: Does BISCUIT scale?

Can BISCUIT efficiently use many cores?

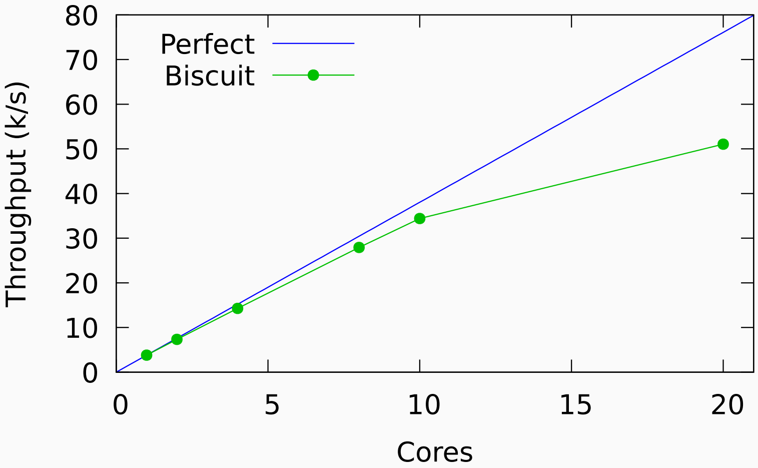
Is Go scalability bottleneck?

6: Does BISCUIT scale?

Ran CMailbench, varied cores from 1 to 20

Measured throughput

6: BISCUIT scales well to 10 cores



Lock contention in CMailbench at 20 cores, not NUMA-aware

Should one use HLL for a new kernel?

The HLL worked well for kernel development

Performance is paramount $\Rightarrow$ use C (up to 15%)

Minimize memory use $\Rightarrow$ use C ($\downarrow$ mem. budget, $\uparrow$ GC cost)

Safety is paramount $\Rightarrow$ use HLL (40 CVEs stopped)

Performance merely important $\Rightarrow$ use HLL (pay 15%, memory)

6.S081/6.828 and HLL

Should we use HLL in 6.828?

git clone https://github.com/mit-pdos/biscuit.git