Varan and Mx: Safe Software Updates via Multi-version Execution

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Motivation

Software evolves, with new versions and patches being released frequently

Software updates often present a high risk

Many users refuse to upgrade their software…

…relying instead on outdated versions flawed with vulnerabilities or missing useful features and bug fixes

Many admins (70% of those interviewed) refuse to upgrade

Crameri, O., Knezevic, N., Kostic, D., Bianchini, R., Zwaenepoel, W.
Staged deployment in Mirage, an integrated software upgrade testing and distribution system. SOSP'07

> “The fundamental problem with program maintenance is that fixing a defect has a substantial (20-50%) chance of introducing another. So the whole process is two steps forward and one step back.”
>
> — Fred Brooks, 1975

≥14.8~24.4% for major operating system fixes

Yin, Z., Yuan, D., Zhou, Y., Pasupathy, S., and Bairavasundaram, L.
How Do Fixes Become Bugs? In ESEC/FSE' 11

One solution: Patch Testing [joint work with Marinescu, ESEC/FSE'13]

KATCH automatically tests each submitted patch, looking for potential bugs it introduces.

Study on all patches in 19 applications over a combined period of 6 years:

- Significantly improved patch coverage
- Found previously unknown bugs

Of course, bugs inevitably make it into released code

Paul Marinescu, Cristian Cadar
KATCH: High-Coverage Testing of Software Patches. In ESEC/FSE' 13

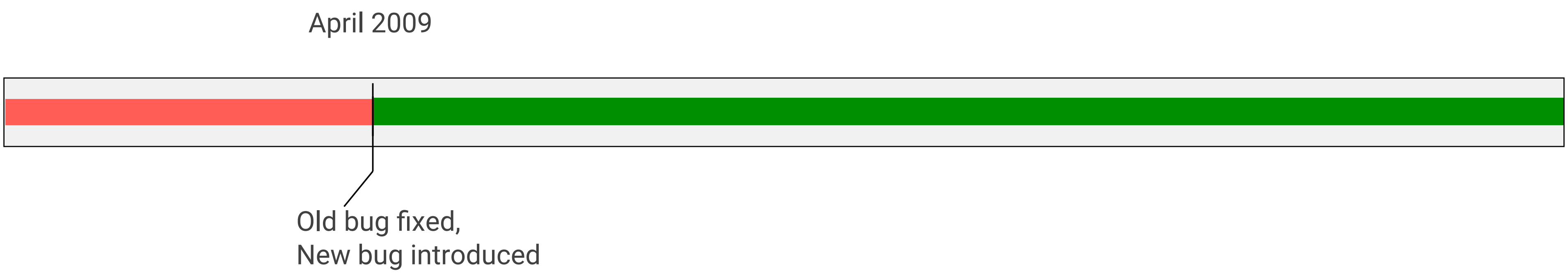
LIGHTTPD
fly light.

Single-threaded event-driven web server

Powers several popular sites such as YouTube, Wikipedia, Meebo

HTTP ETag hash value computation in etag_mutate

```
for (h = 0, i = 0; i < etag->used; ++i)
     h = (h << 5) ^ (h >> 27) ^ (etag->ptr[i]);
```



HTTP ETag hash value computation in etag_mutate

```
for (h = 0, i = 0; i < etag->used - 1; ++i)
    h = (h << 5) ^ (h >> 27) ^ (etag->ptr[i]);
```

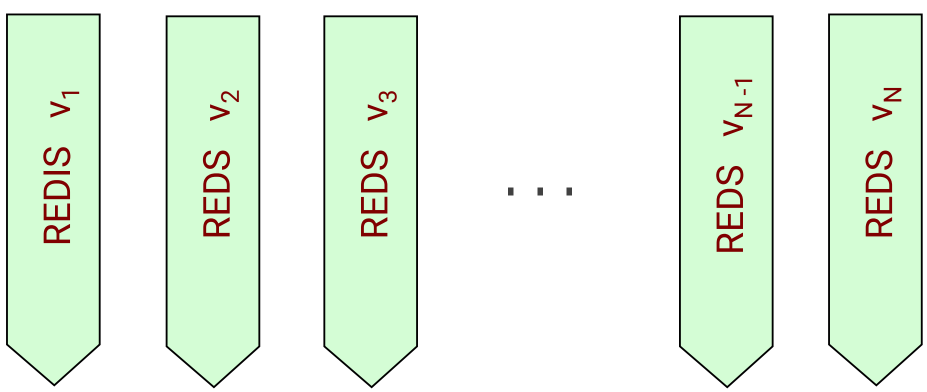
File (re)compression in mod_compress_physical

```
if (use_etag)
    etag_mutate(con->physical.etag, srv->tmp_buf);
}
```

Safe Updates via Multi-Version Execution

When a new version becomes available

Run it in parallel with the old versions!

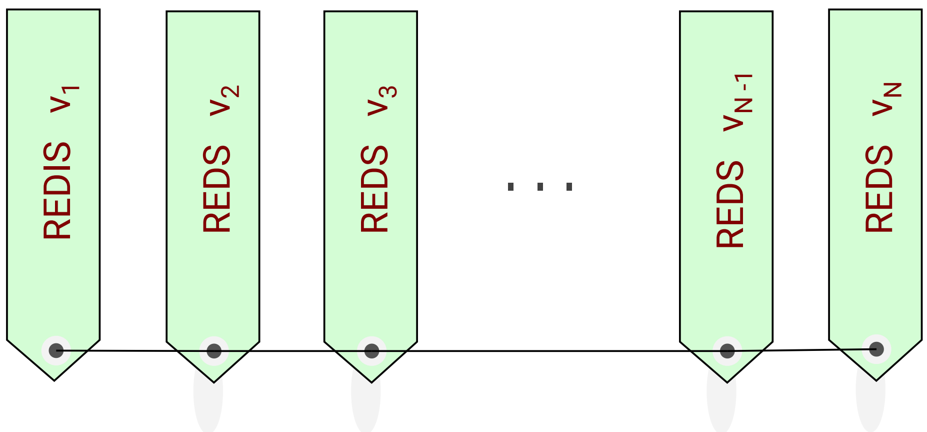


N = available (idle) cores

Safe Updates via Multi-Version Execution

When a new version becomes available

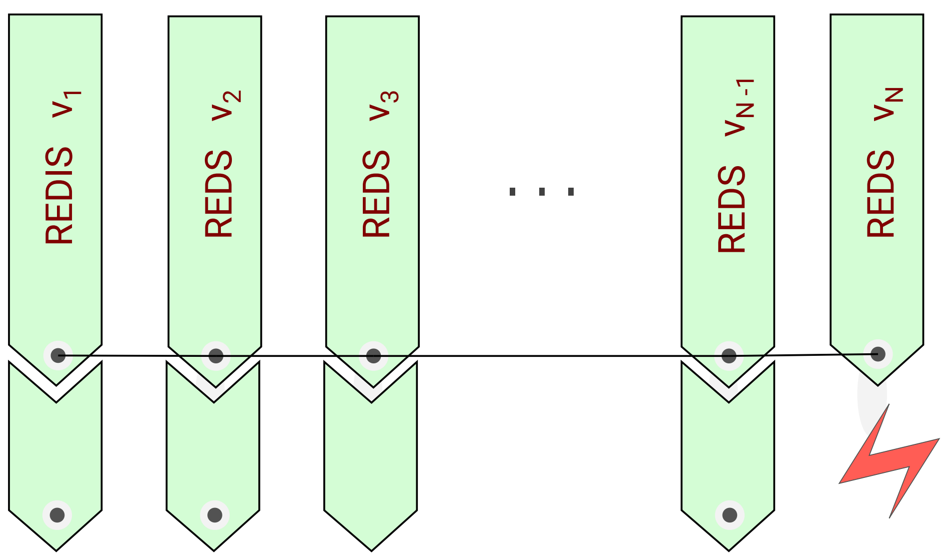
- Run it in parallel with the old versions!
- Synchronise all versions to act as one to the outside world



Safe Updates via Multi-Version Execution

When a new version becomes available

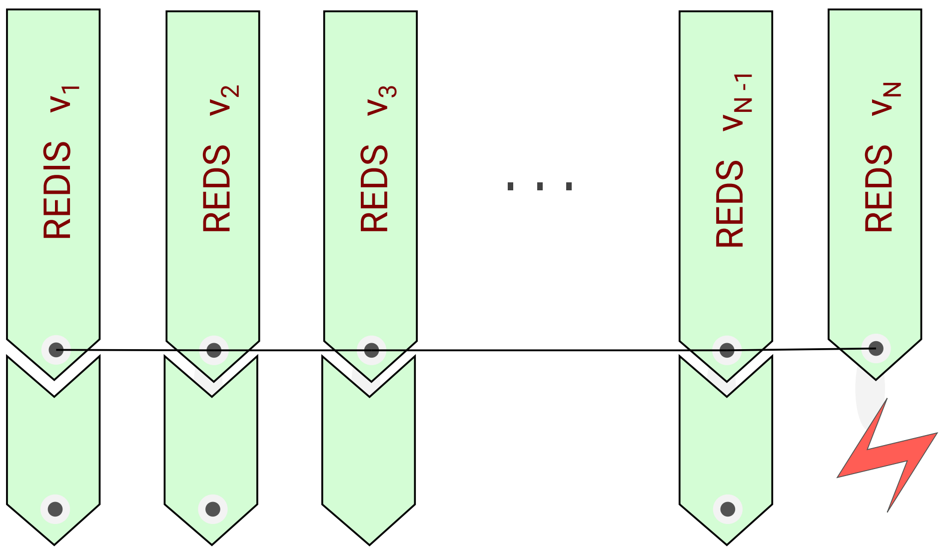
- Run it in parallel with the old versions!
- Synchronise all versions to act as one to the outside world
- Transparently survive crashes occurring in some versions



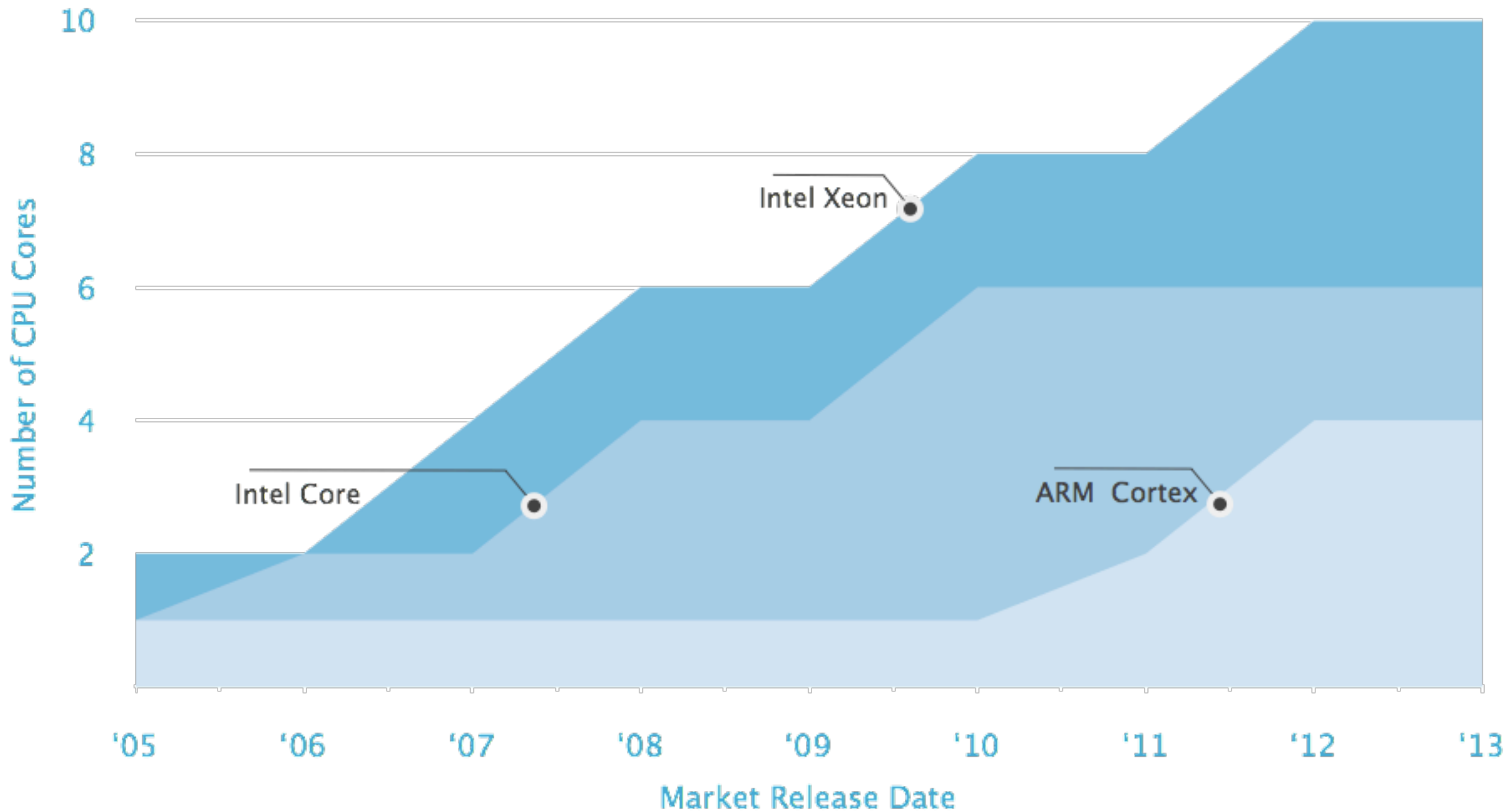
Safe Updates via Multi-Version Execution

Could do so until enough confidence is gained in the new version(s)

Or as long as enough idle cores are available



MultiCore CPUs becoming standard
...with no benefit to inherently sequential apps



Idle parallel resources, with no benefit to inherently sequential applications

Cristian Cadar, Peter Pietzuch, Alex Wolf *Multiplicity computing: A vision of software engineering for next-generation computing platform applications.* FoSER'10

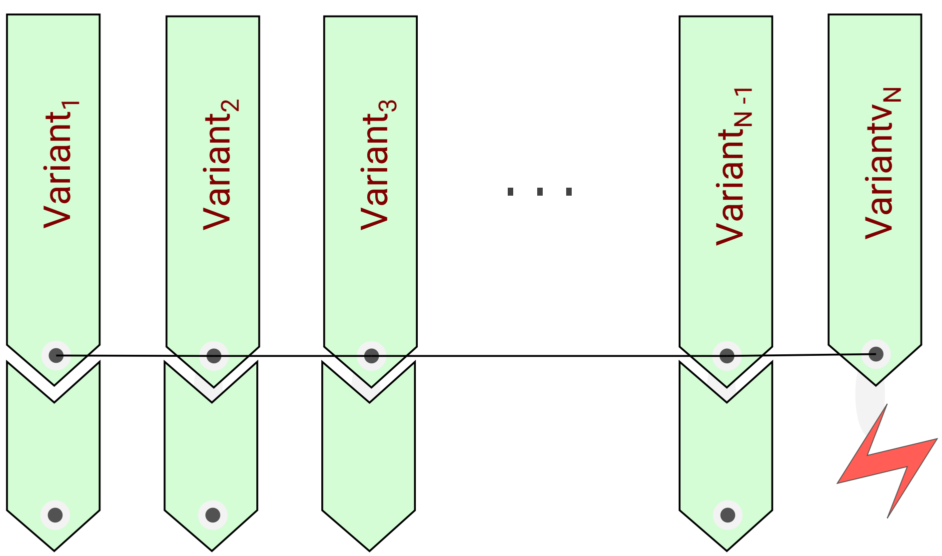
Similar Idea: Automatically Generated Variants

Run two variants with stacks growing in different directions [Orchestra]

Any divergence is a possible attack: fail safe

Run multiple variants with different placement of objs in mem [DieHard]

Survive some errors due to memory corruption



Challenges of Multi-Version and Multi-Variant Execution

Common challenges:

Synchronise and virtualise the executions of multiple versions <u>efficiently</u>

Specific to multi-version execution

Allow for (small) differences in behaviour

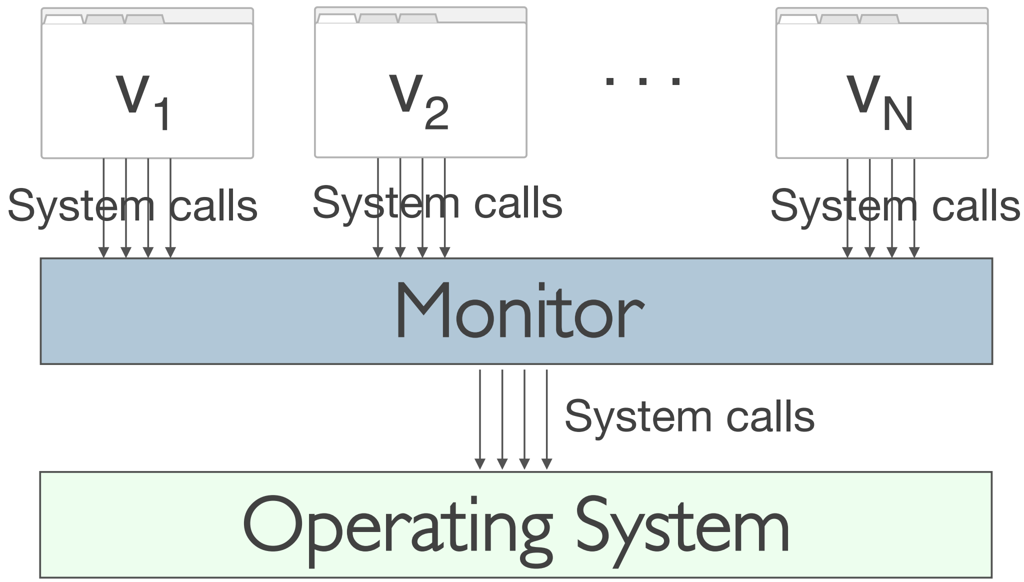
Our proposed solution addresses both of these

Synchronisation

Possible at different levels of abstraction/granularity

- Application inputs/outputs
- Library calls
- System calls

Synchronisation at System Call Level



Advantages

General

System calls the only way to interact with outside world

Small number of system call types

System Calls Define External Behavior

Version 1

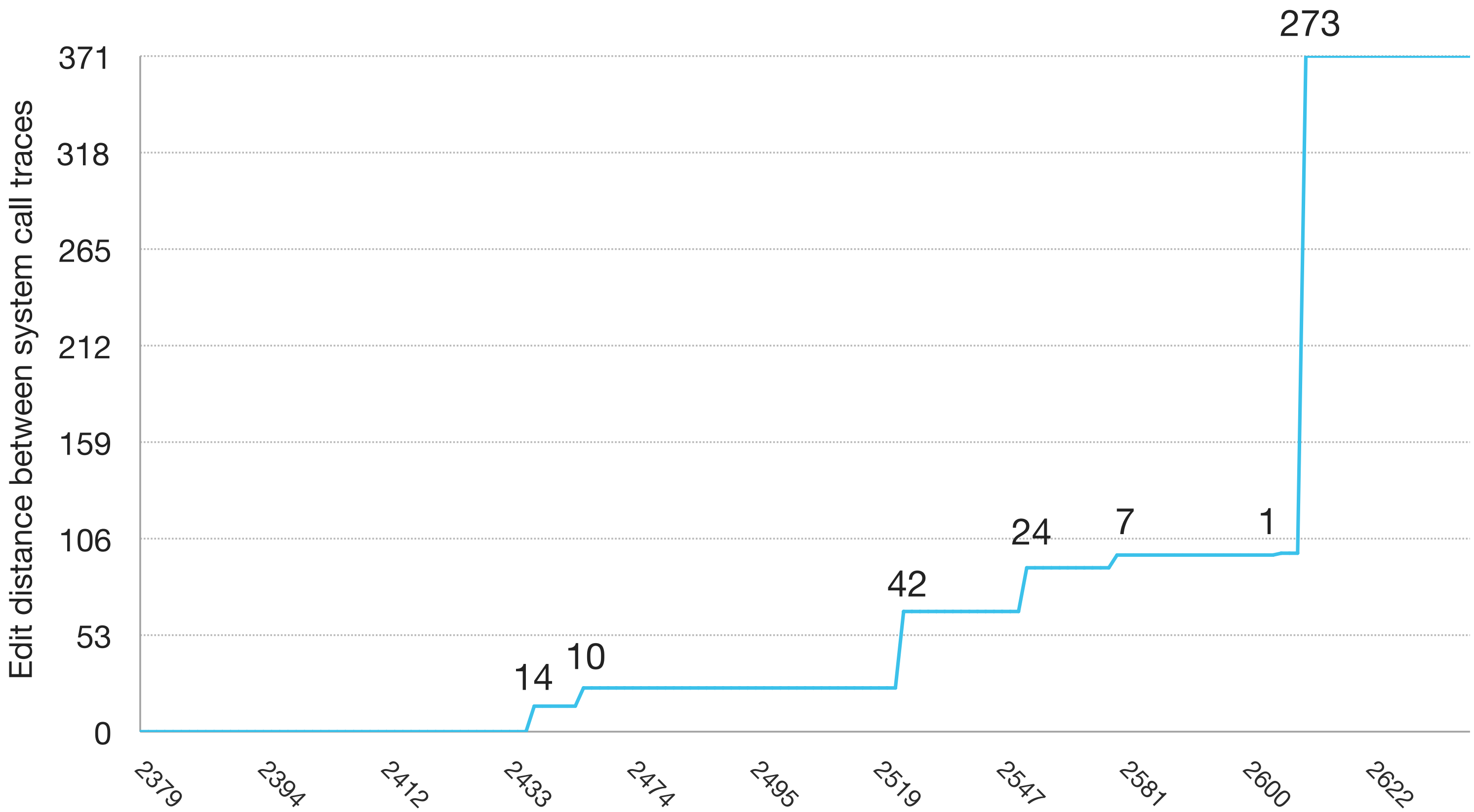
```
void even_odd(int *a, size_t len) {
  int i, even = 0;

  for (i=0; i<len; i++)
    if (a[i] % 2 == 0)
      even++;

  printf("%d\n", even);
  printf("%d\n", len - even);
}
```

Version 2

```
void even_odd(int *a, size_t len) {
  int i, odd = 0;

  for (i=len-1; i>=0; i--)
    if (a[i] % 2 != 0)
      odd++;

  printf("%d\n", len - odd);
  printf("%d\n", odd);
}
```

```
int arr[] = { 6, 3, 2, 4 };
even_odd(arr, 4);

...
write(1, "3\n", 2) = 2
write(1, "1\n", 2) = 2
...
```

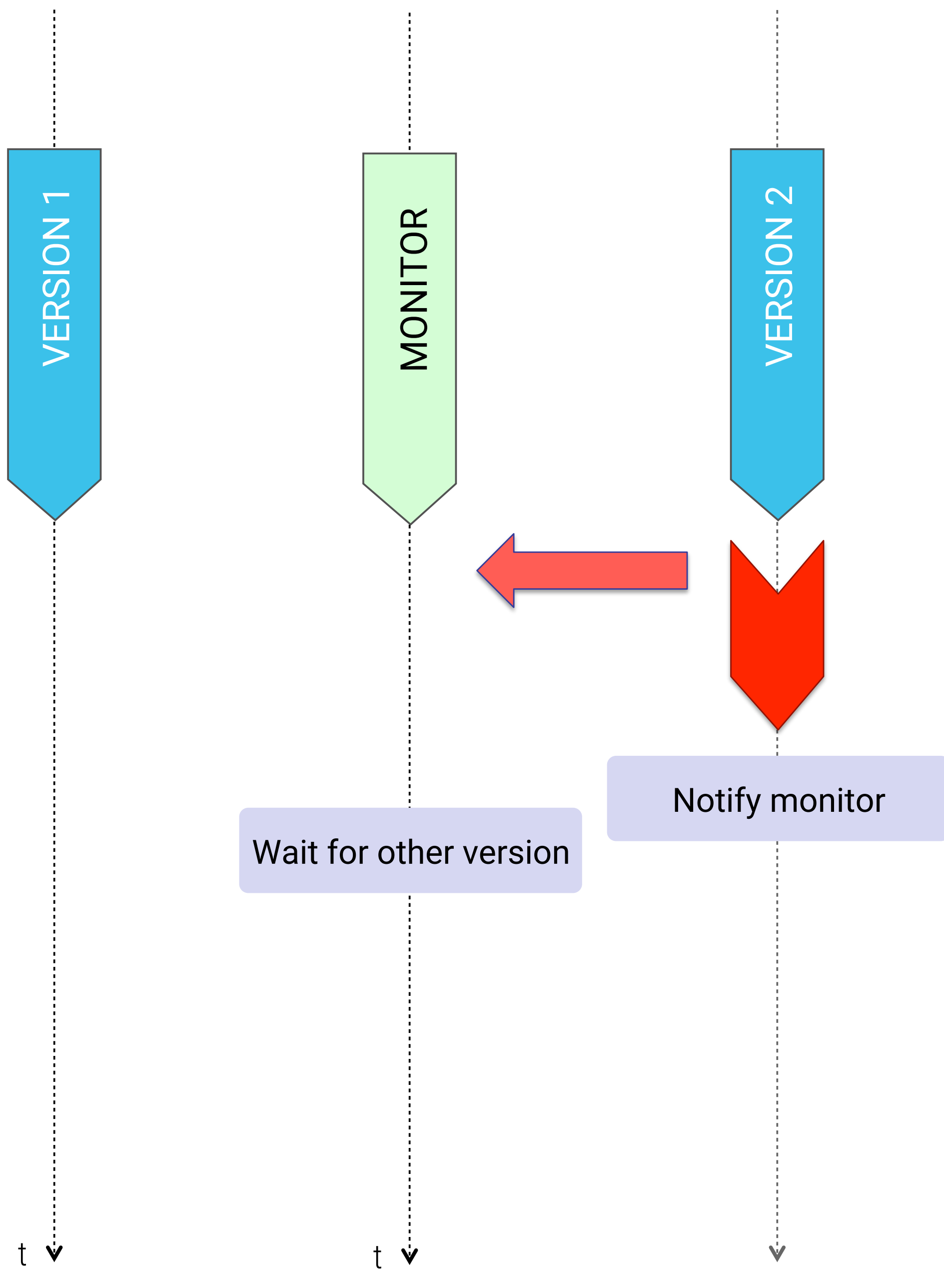
External Behavior Evolves Sporadically

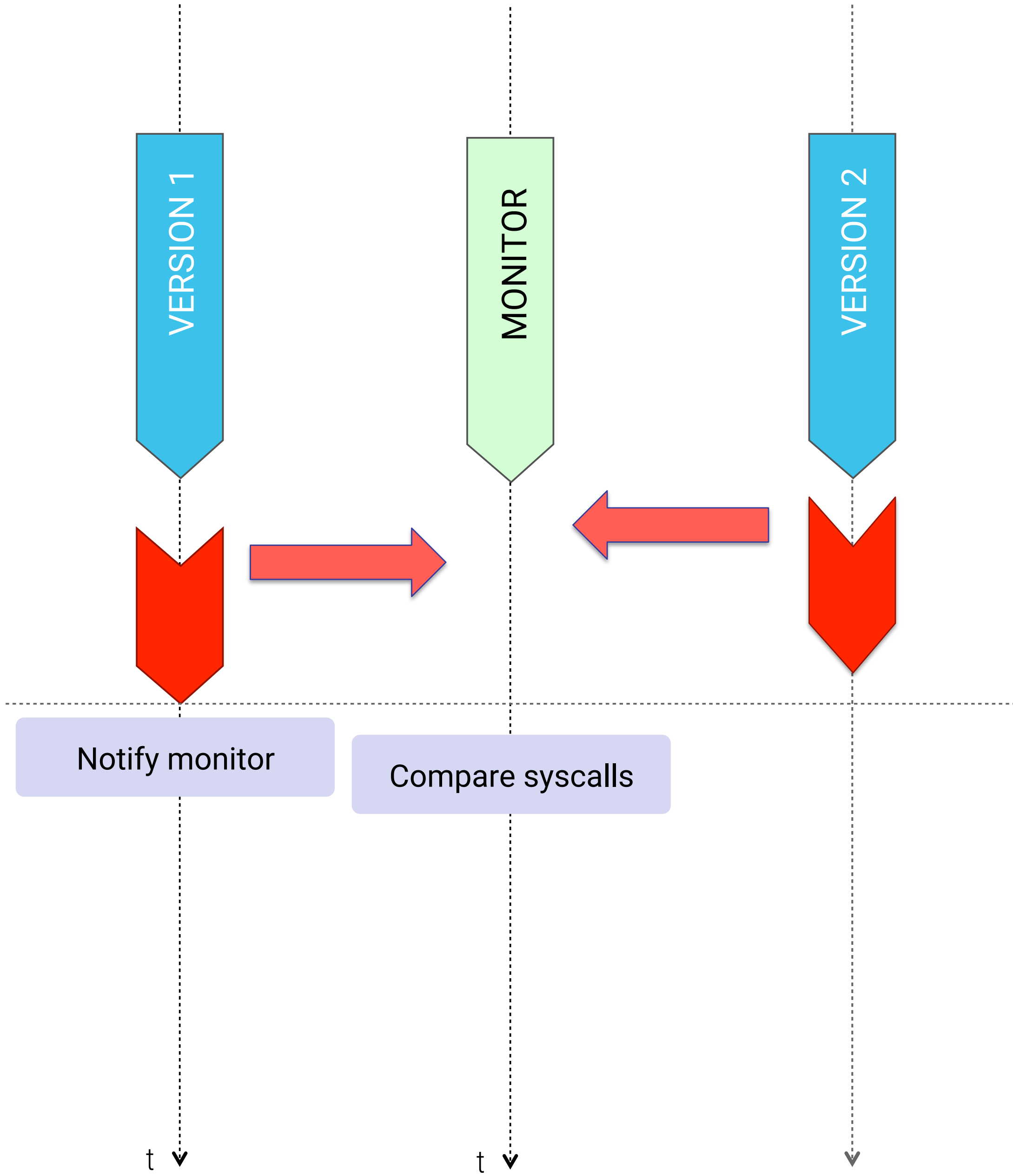


95% of lighttpd revisions introduce *no change**

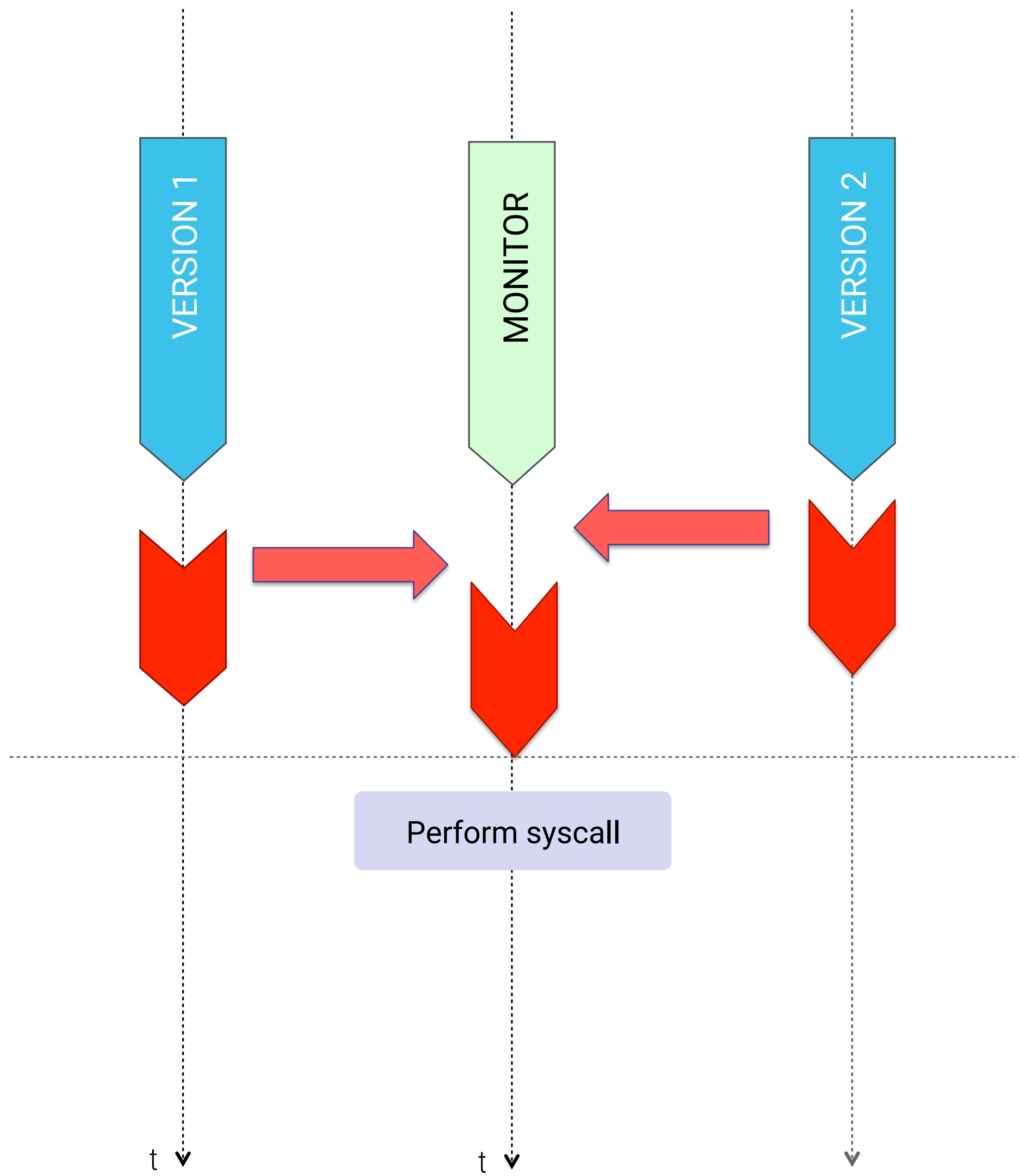
Measured using lighttpd regression suite on 164 revisions (~10 months)

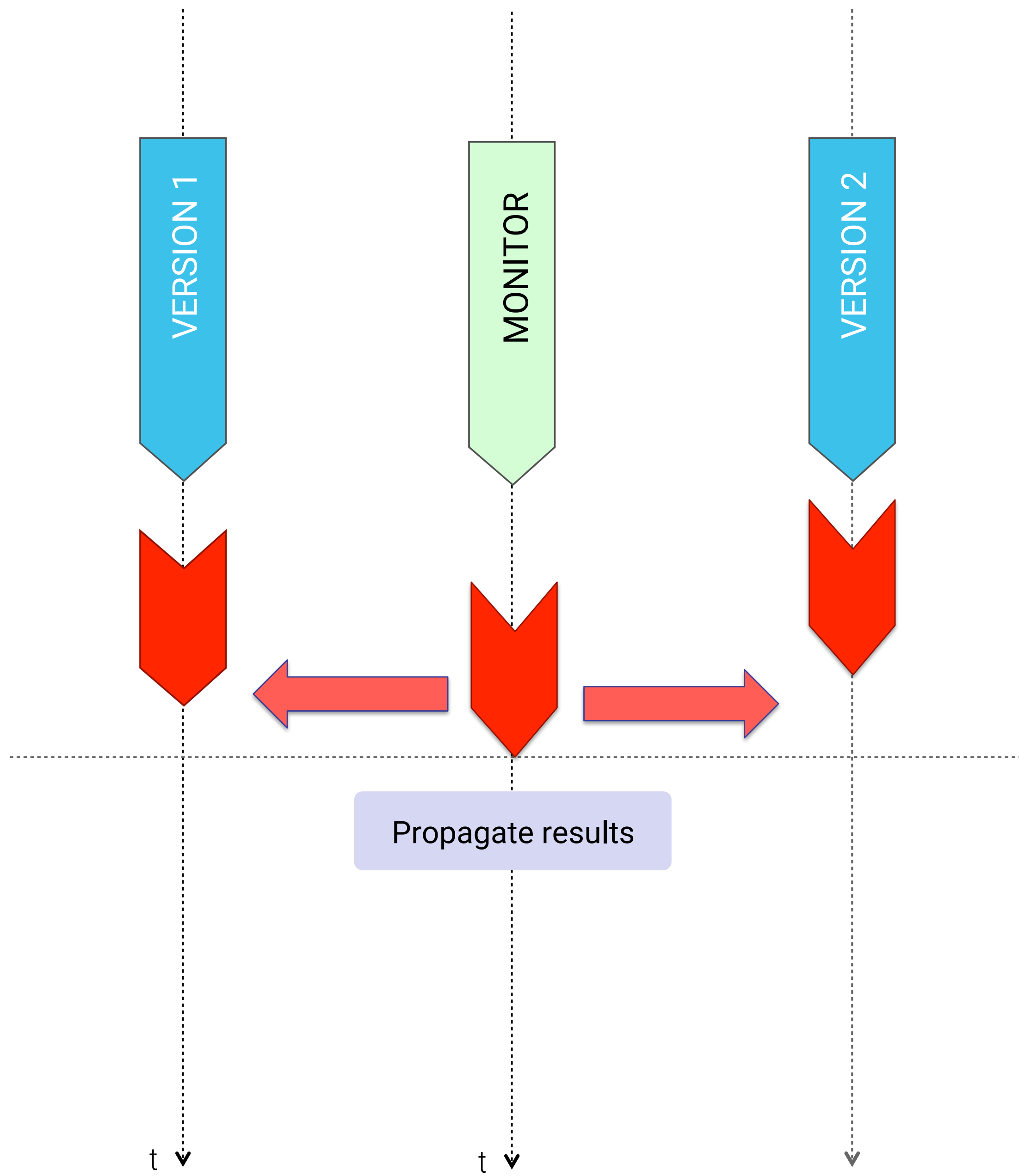
*Taken on Linux kernel 2.6.40 and glibc 2.14 using strace tool and custom post-processing (details in [ICSE'13])

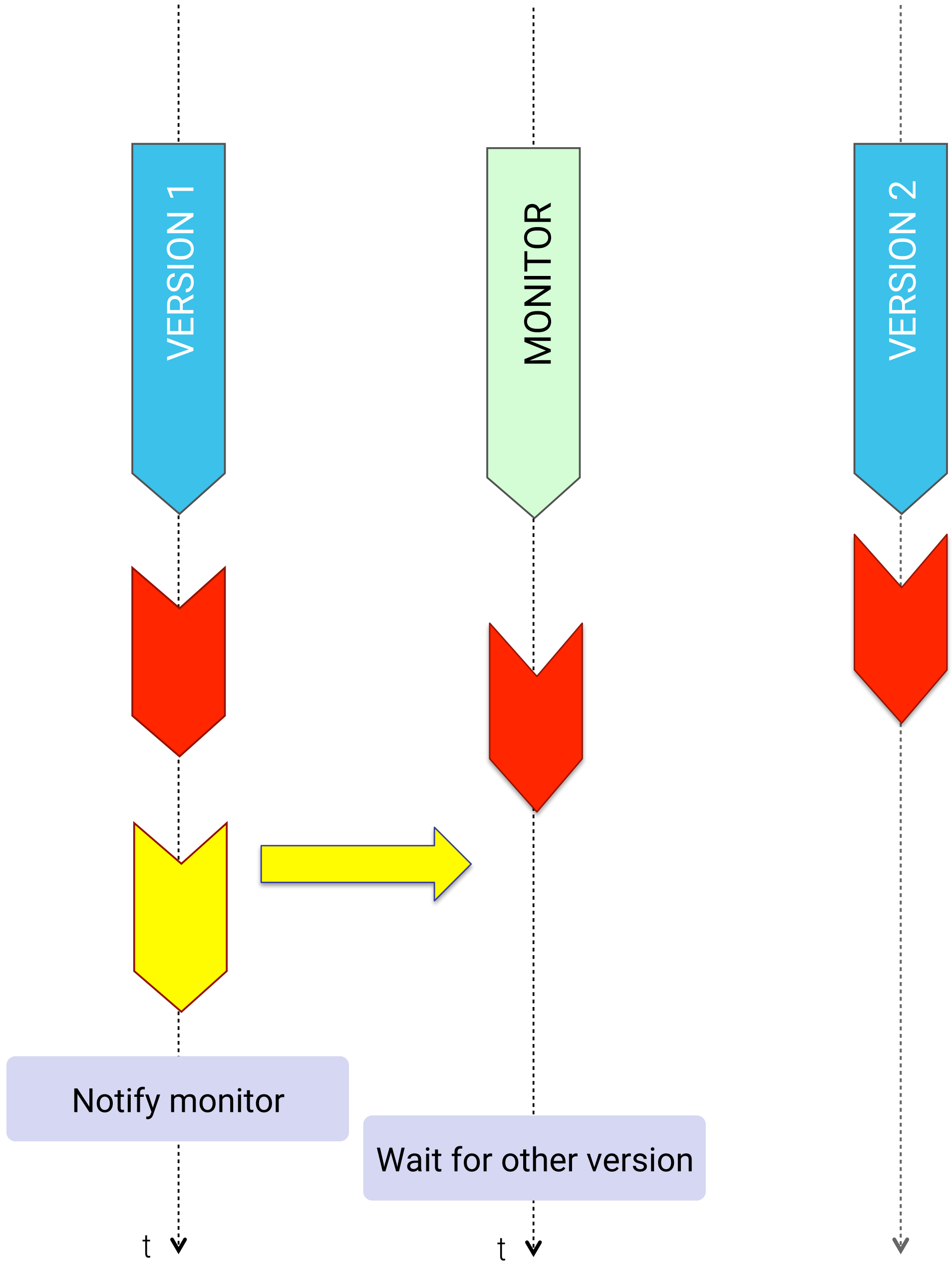

VERSION 1
MONITOR
VERSION 2
Notify monitor
Wait for other version
t
t

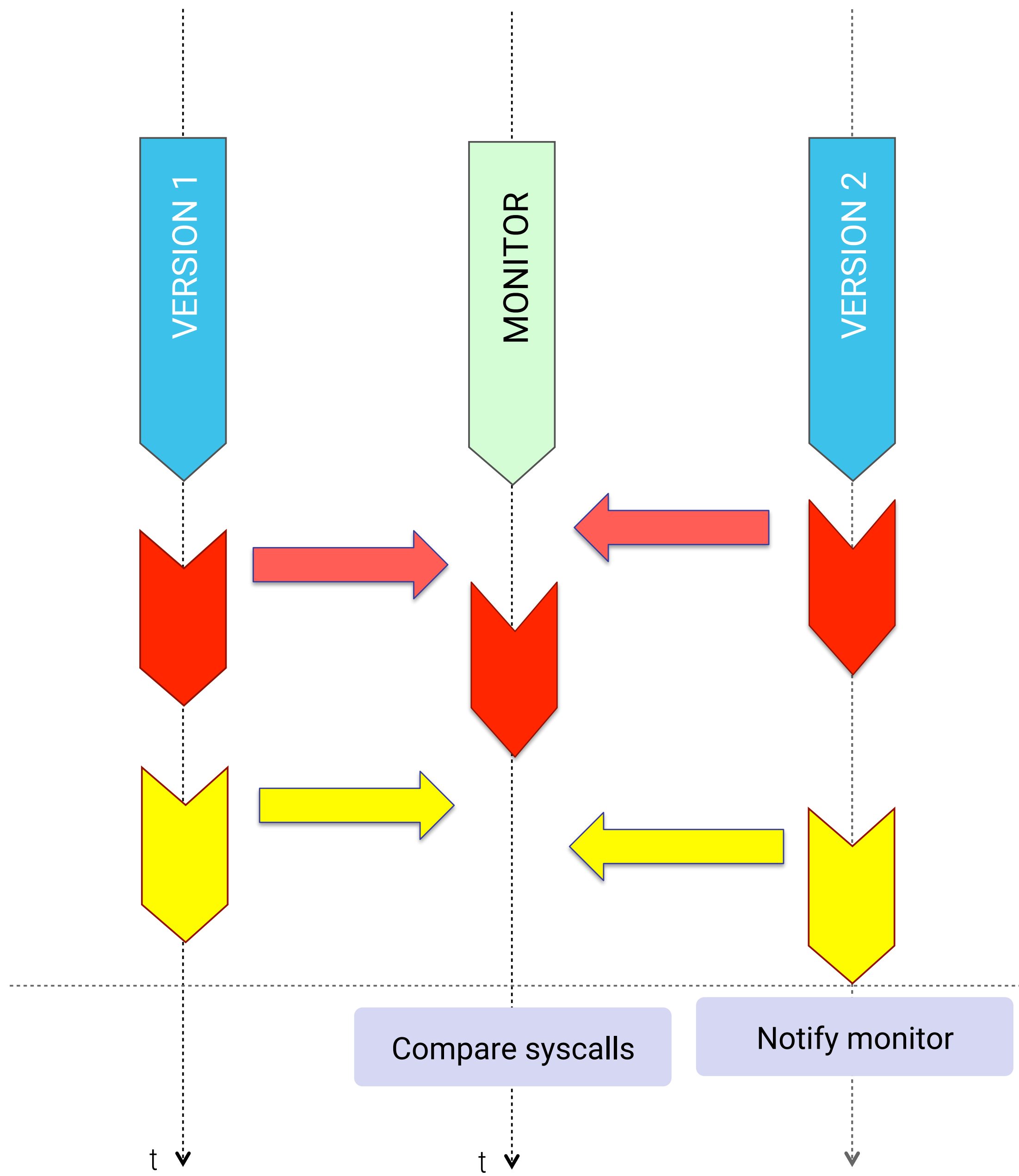


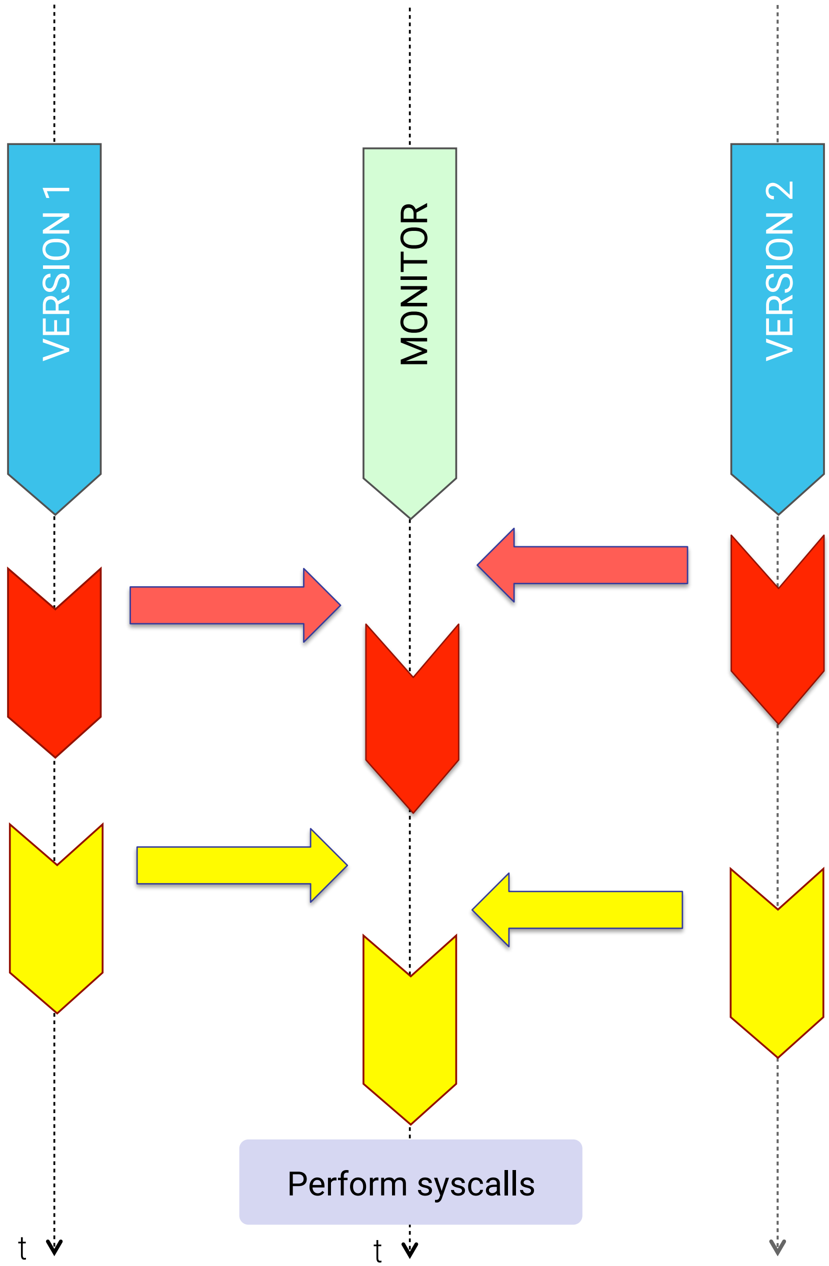
VERSION 1
MONITOR
VERSION 2
Notify monitor
Compare syscalls
t
t

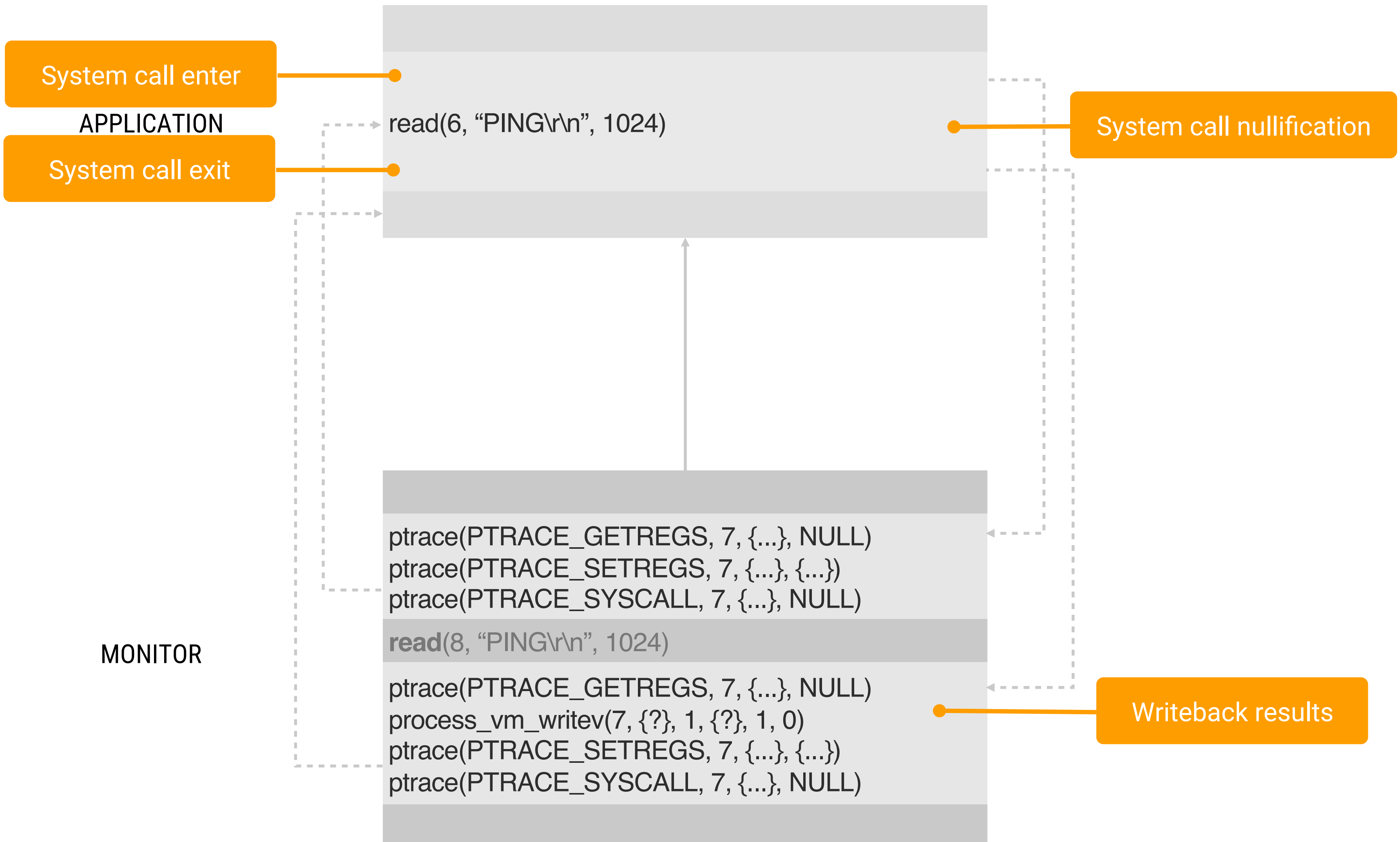

VERSION 1
MONITOR
VERSION 2
Perform syscall
t
t


VERSION 1
MONITOR
VERSION 2
Propagate results
t
t


VERSION 1
MONITOR
VERSION 2
Notify monitor
Wait for other version
t
t


VERSION 1
MONITOR
VERSION 2
Compare syscalls
Notify monitor
t
t


VERSION 1
MONITOR
VERSION 2
Perform syscalls
t
t


System call enter
APPLICATION
System call exit
read(6, “PING\r\n”, 1024)
System call nullification
MONITOR
ptrace(PTRACE_GETREGS, 7, {...}, NULL)
ptrace(PTRACE_SETREGS, 7, {...}, {...})
ptrace(PTRACE_SYSCALL, 7, {...}, NULL)
read(8, “PING\r\n”, 1024)
ptrace(PTRACE_GETREGS, 7, {...}, NULL)
process_vm_writev(7, {?}, 1, {?}, 1, 0)
ptrace(PTRACE_SETREGS, 7, {...}, {...})
ptrace(PTRACE_SYSCALL, 7, {...}, NULL)
Writeback results

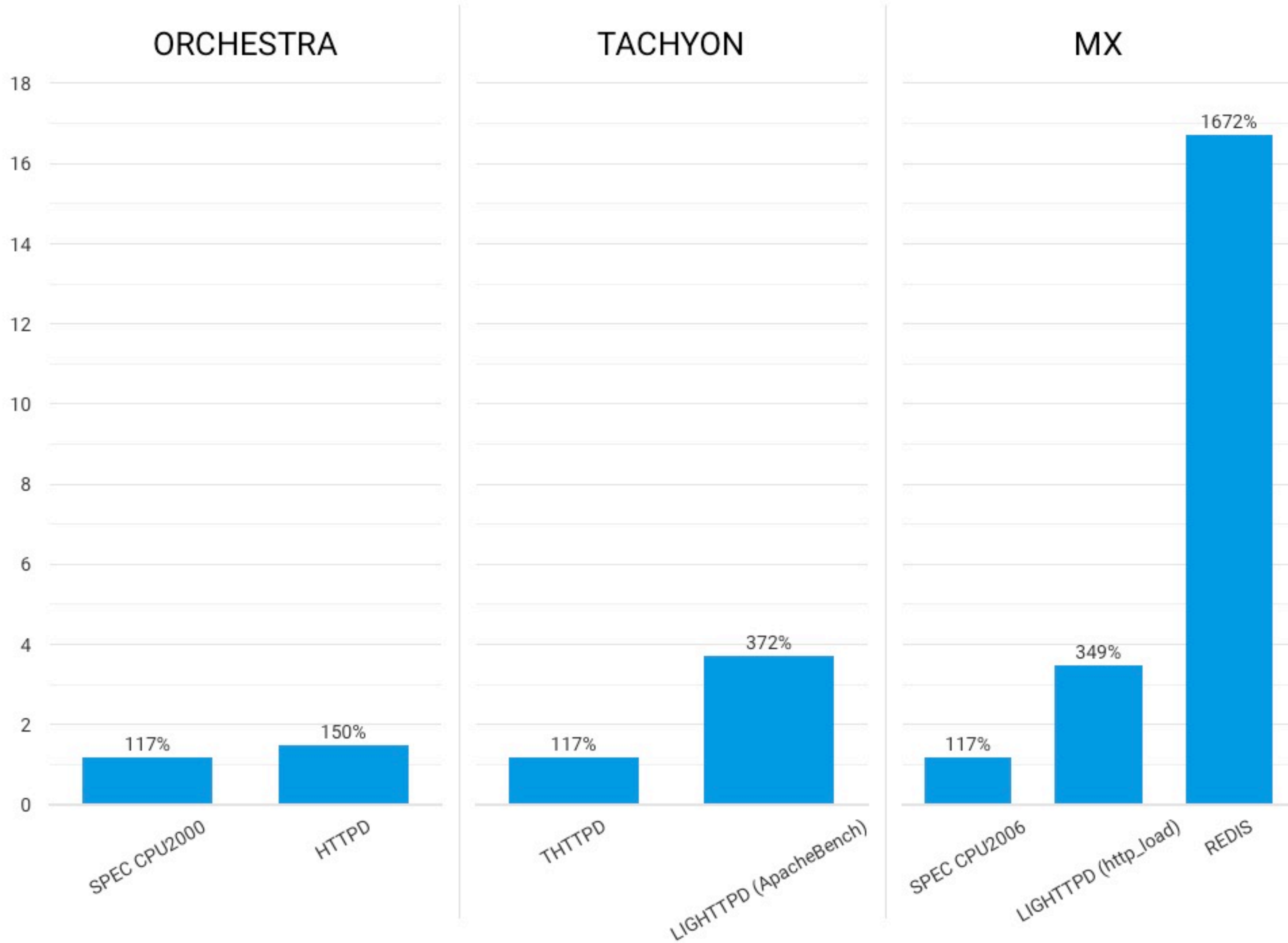
Disadvantages of ptrace

Slow

- For each system call run by each version, the monitor runs several system calls (and traps)
- Does not scale well to large number of versions
- Multi-version execution runs no faster than the slowest version

Inflexible

- Lockstep execution requires the same sequence of system calls


ORCHESTRA
TACHYON
MX
18
16
14
12
10
8
6
4
2
0
117%
150%
117%
372%
117%
349%
1672%
SPEC CPU2000
HTTPD
THTTPD
LIGHTTPD (ApacheBench)
SPEC CPU2006
LIGHTTPD (http_load)
REDIS

Varan

Distributed Highly-Concurrent Multi-Version Monitor

http://godzilla.wikia.com/wiki/Varan

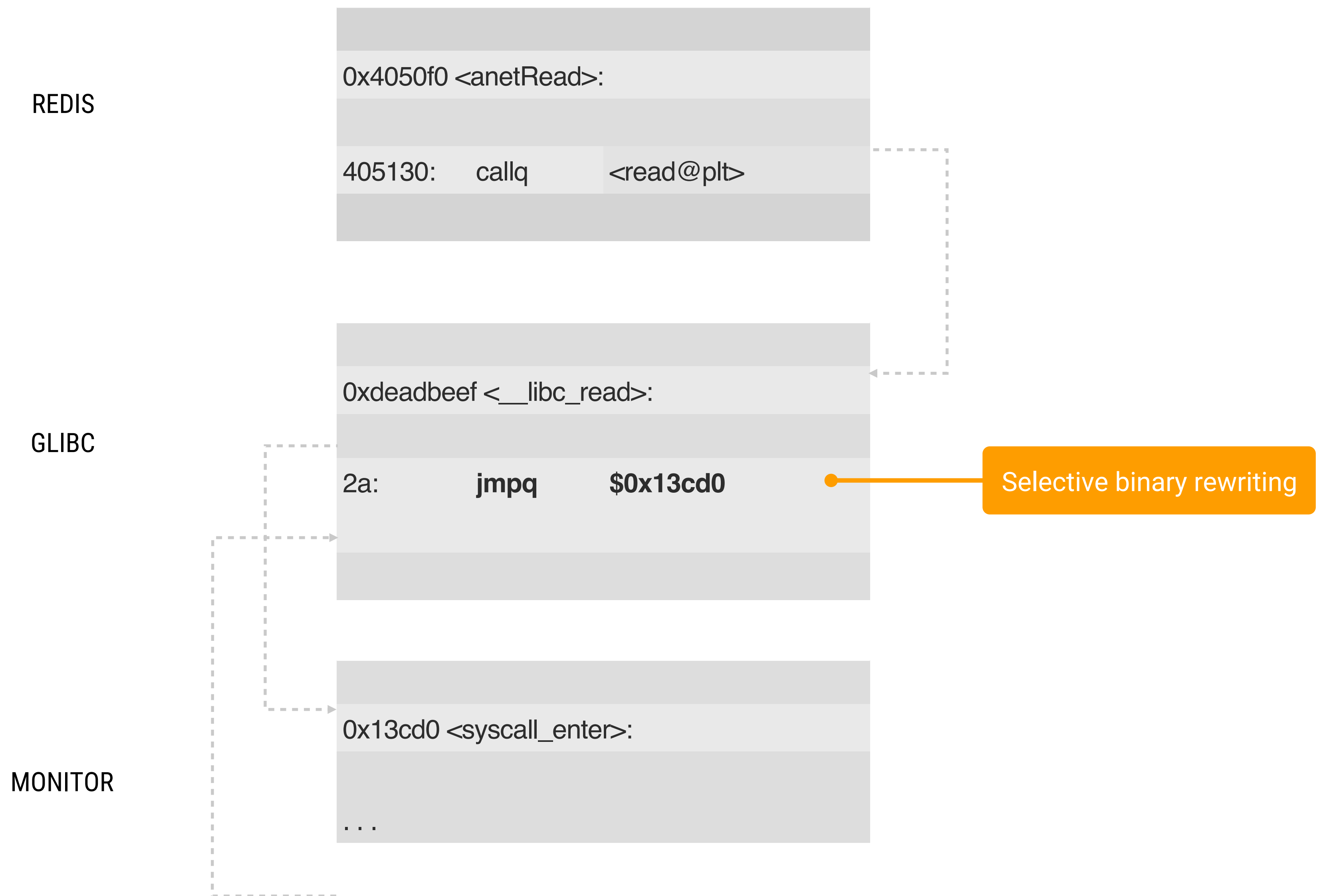
Varan

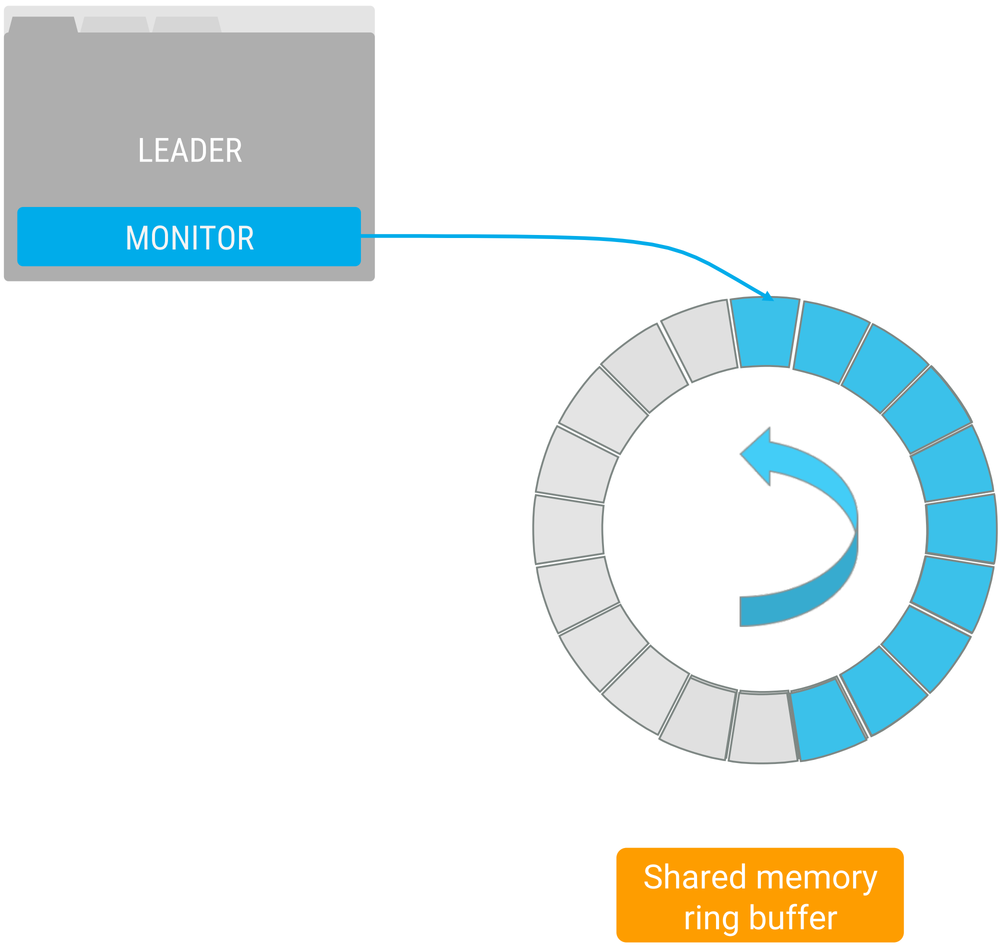
Performance

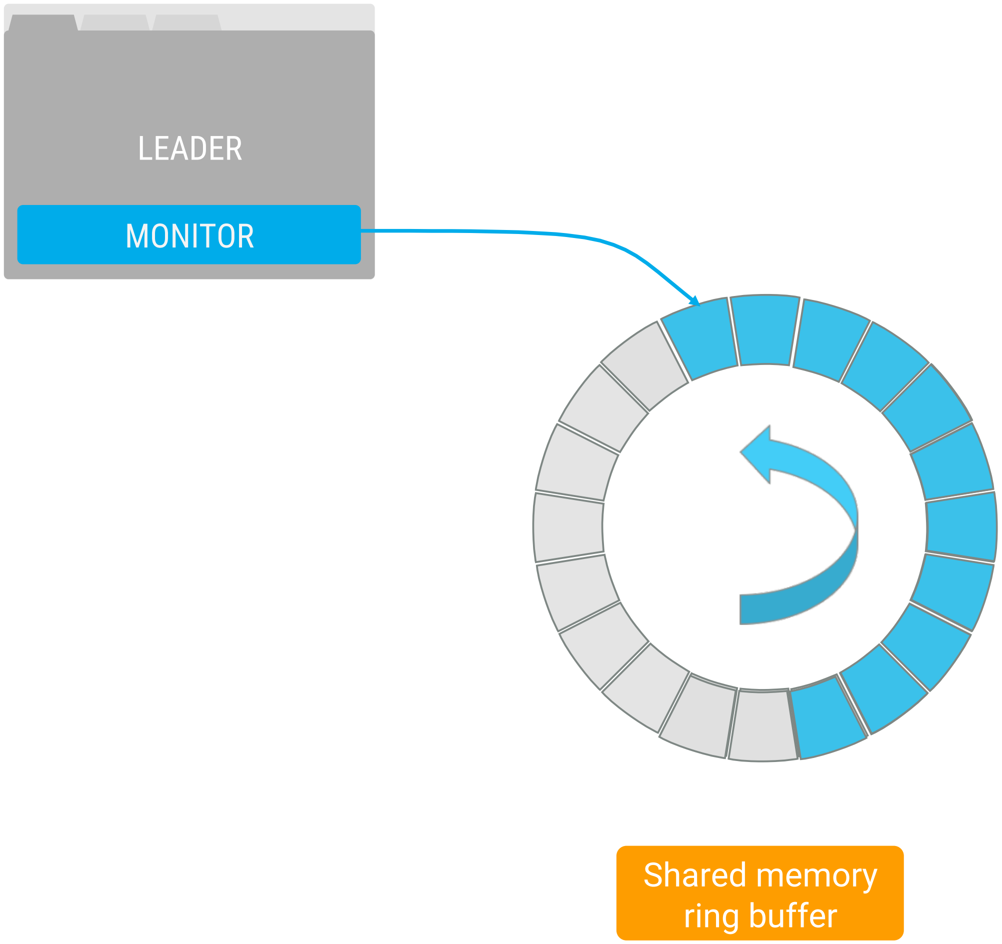
- Low performance overhead
- Scales to large number of versions

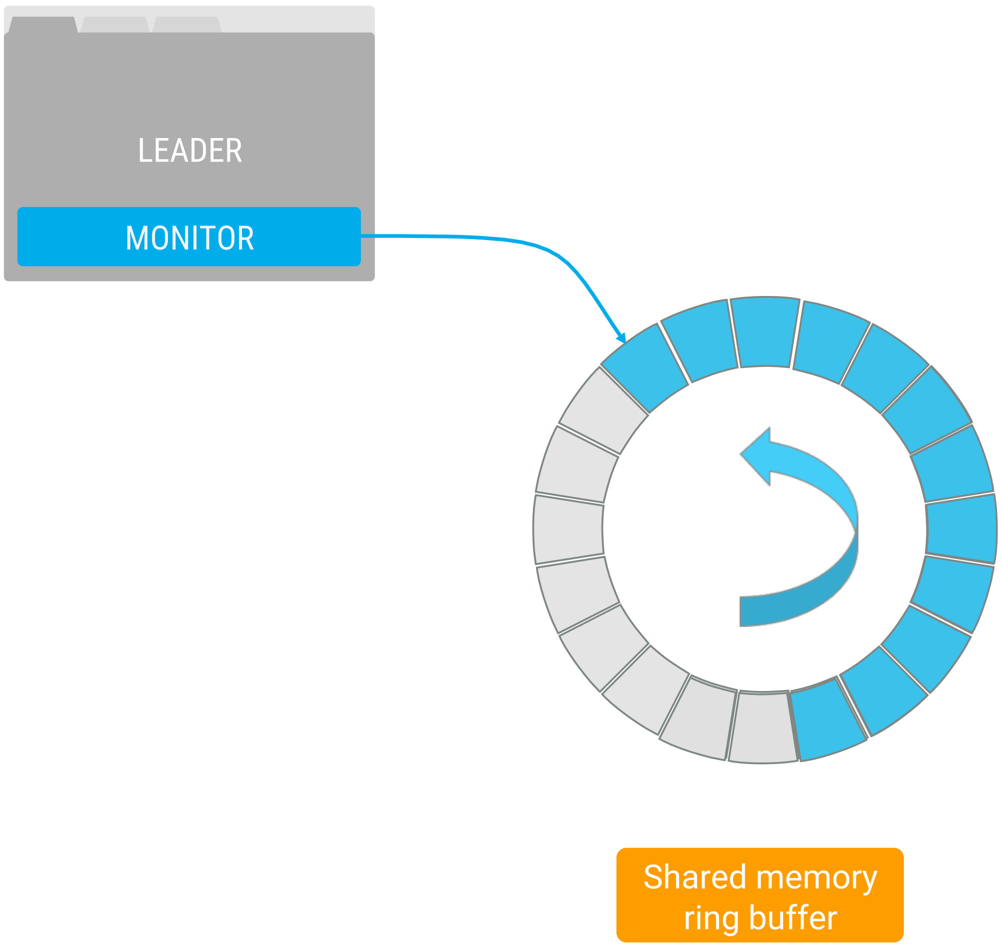
Flexibility

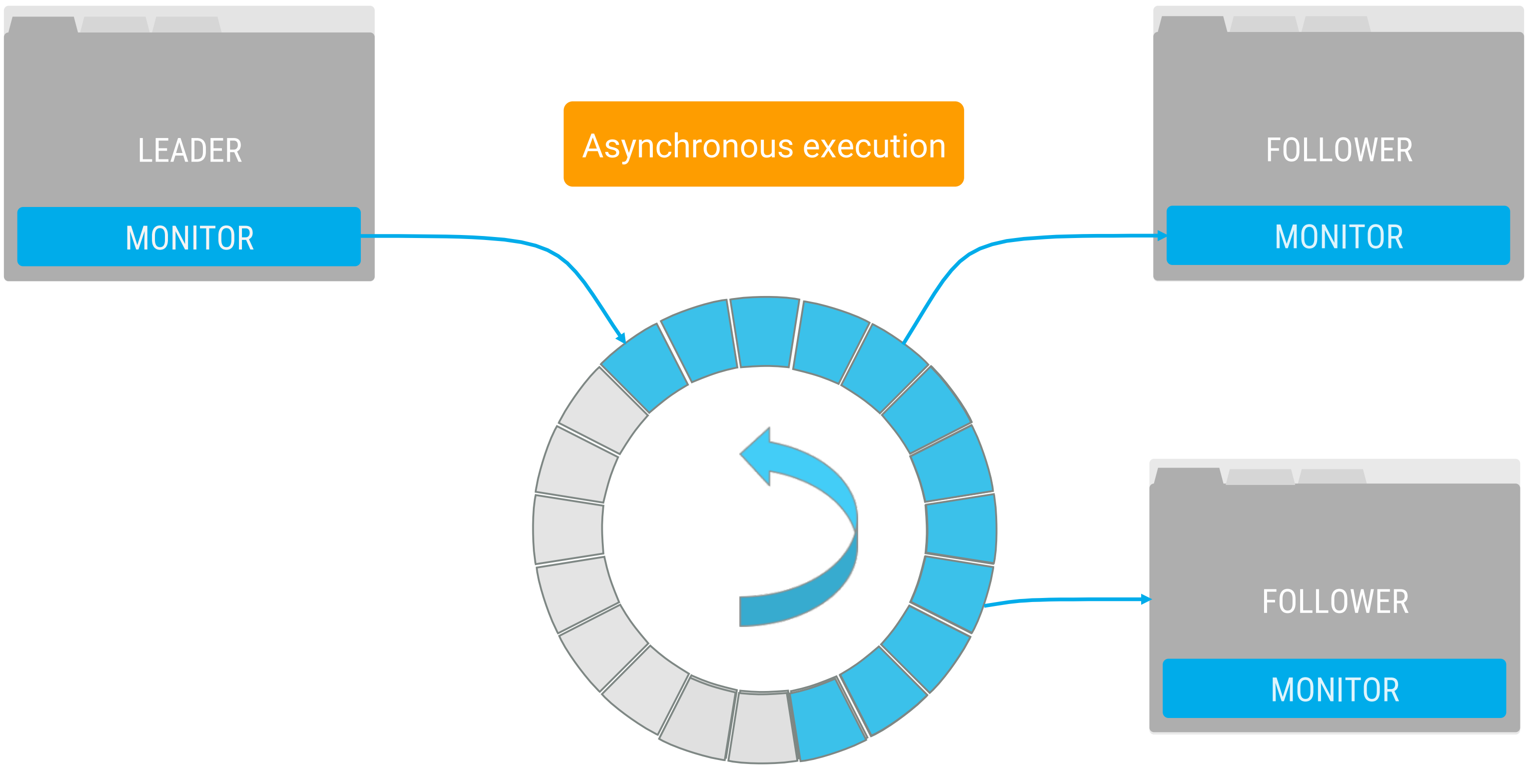
- Does not require lockstep execution
  - Tolerance to minor differences
  - Enables novel applications


REDIS
0x4050f0 <anetRead>:
405130: callq <read@plt>
GLIBC
0xdeadbeef <__libc_read>:
2a: jmpq $0x13cd0
Selective binary rewriting
MONITOR
0x13cd0 <syscall_enter>:
. . .

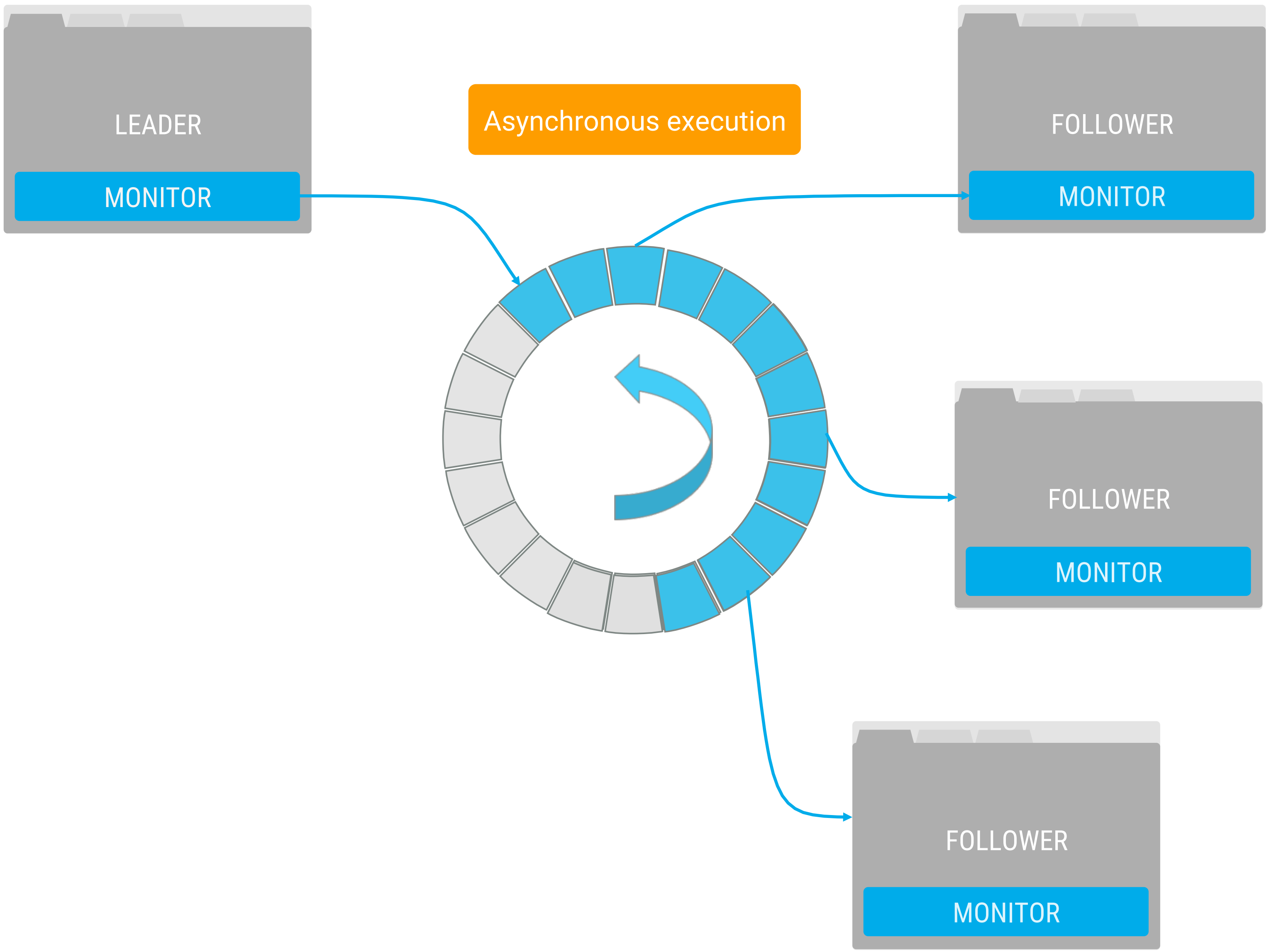

LEADER
MONITOR
Shared memory
ring buffer

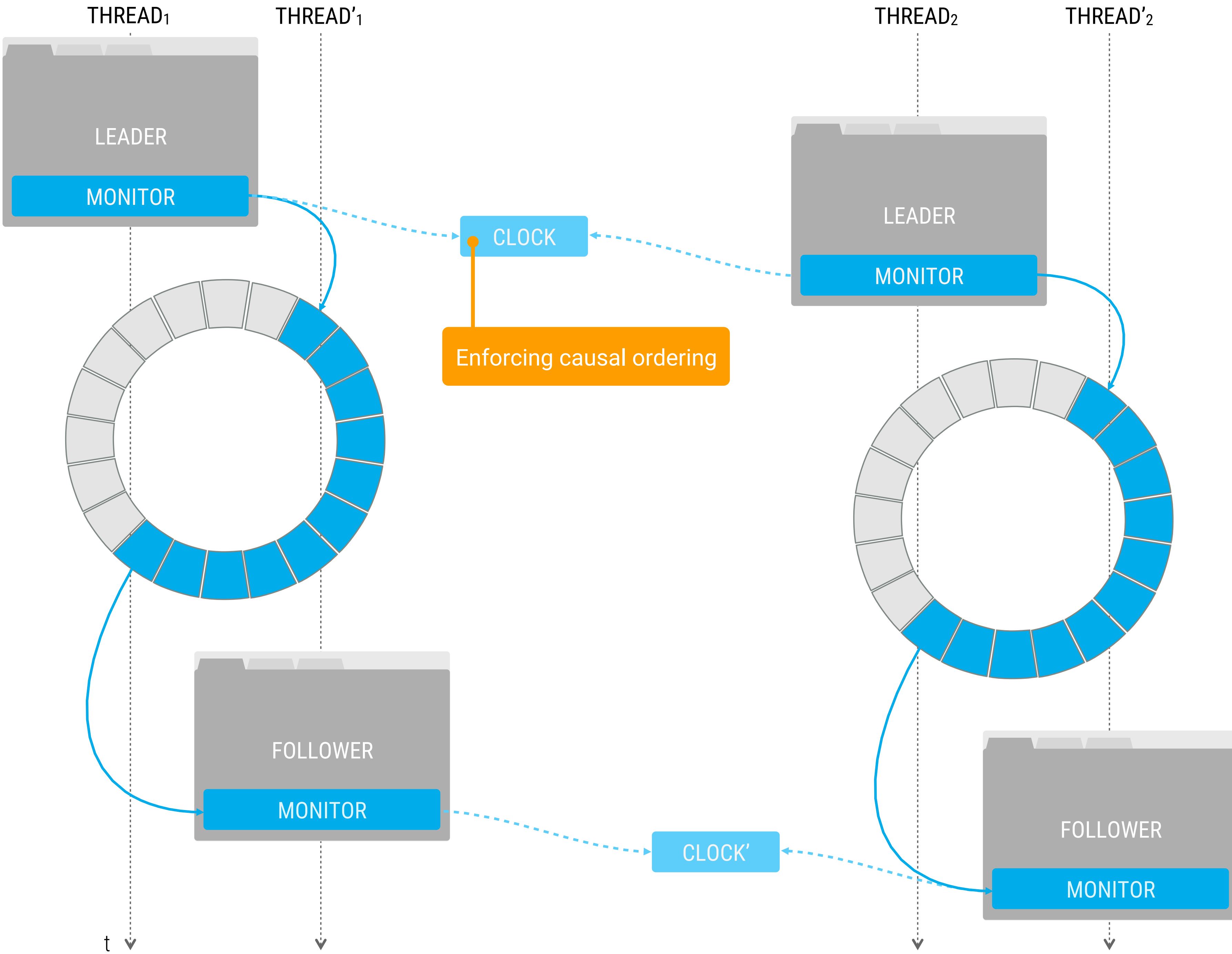

LEADER
MONITOR
Shared memory
ring buffer


LEADER
MONITOR
Shared memory
ring buffer



LEADER
MONITOR
Asynchronous execution
FOLLOWER
MONITOR
FOLLOWER
MONITOR


LEADER
MONITOR
Asynchronous execution
FOLLOWER
MONITOR
FOLLOWER
MONITOR
FOLLOWER
MONITOR

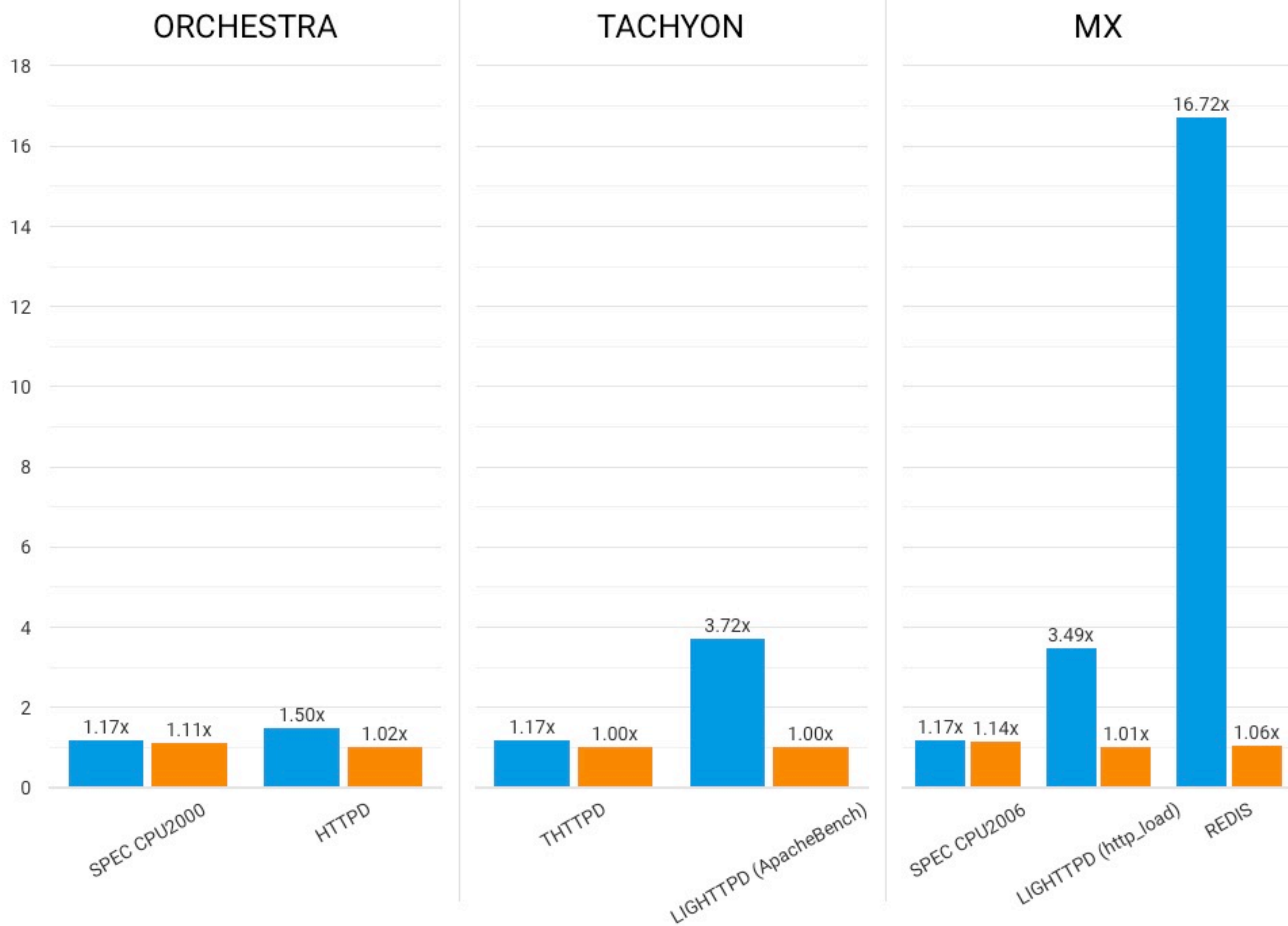

THREAD$_1$
THREAD'$_1$
THREAD$_2$
THREAD'$_2$
LEADER
MONITOR
CLOCK
Enforcing causal ordering
LEADER
MONITOR
FOLLOWER
MONITOR
CLOCK'
FOLLOWER
MONITOR
t

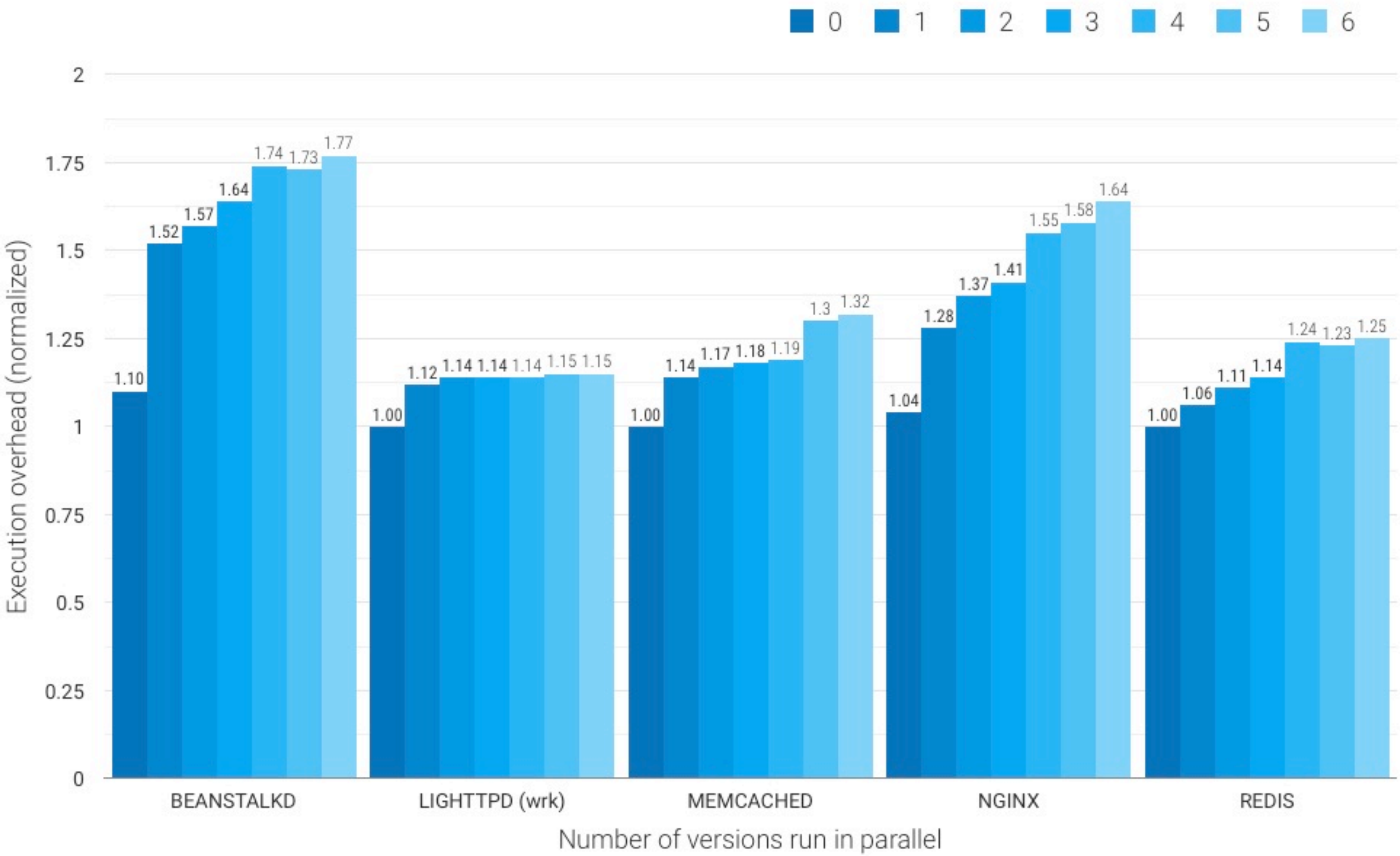
VARAN: Performance Evaluation

Varan

Performance

- **Low performance overhead**
- **Does not require lockstep execution**
- **Scales to large number of versions**

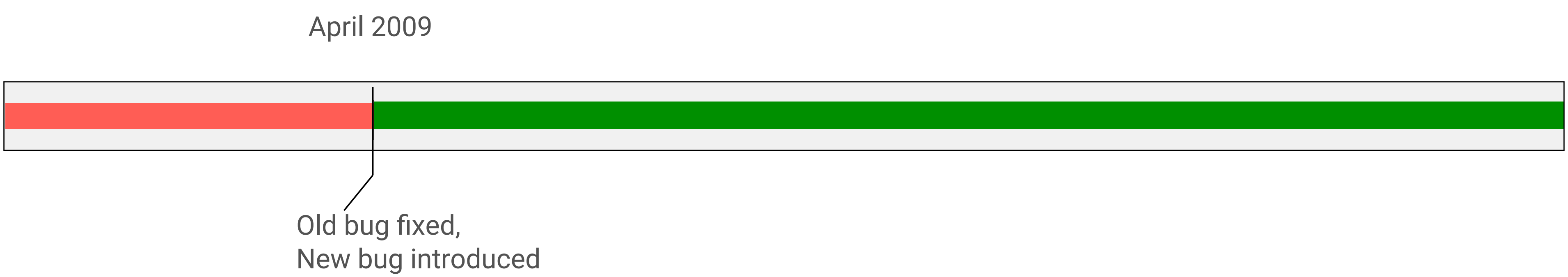

ORCHESTRA
TACHYON
MX
18
16
14
12
10
8
6
4
2
0
1.17x
1.11x
1.50x
1.02x
1.17x
1.00x
3.72x
1.00x
1.17x
1.14x
3.49x
1.01x
16.72x
1.06x
SPEC CPU2000
HTTPD
THTTPD
LIGHTTPD (ApacheBench)
SPEC CPU2006
LIGHTTPD (http_load)
REDIS



Taken on 3.40 GHz Intel Core i7-2600 with 8 GB of RAM, Linux kernel 3.11.0

Safe updates via multi-version execution

Handling crashes in some of the versions

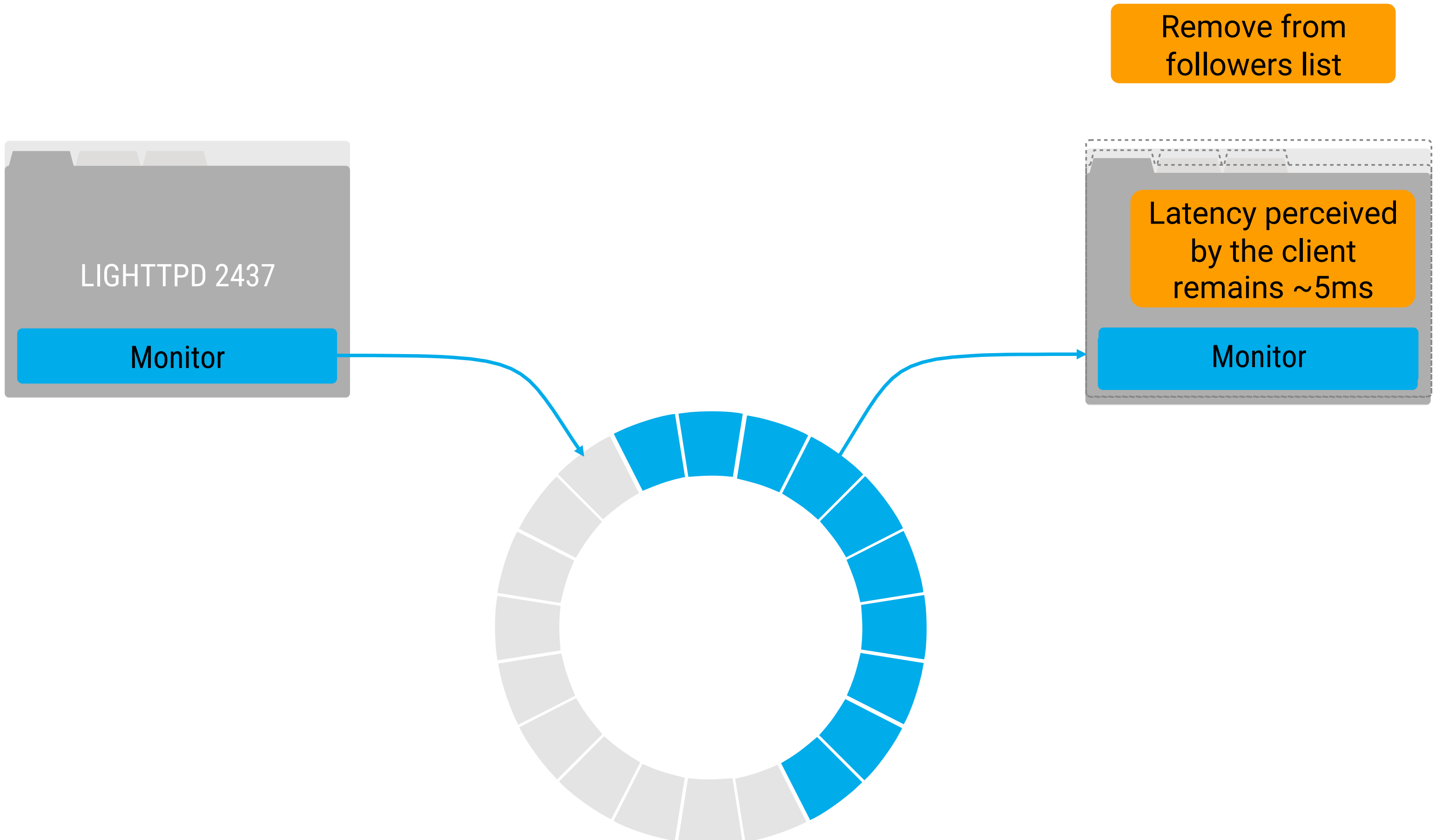


HTTP ETag hash value computation in etag_mutate

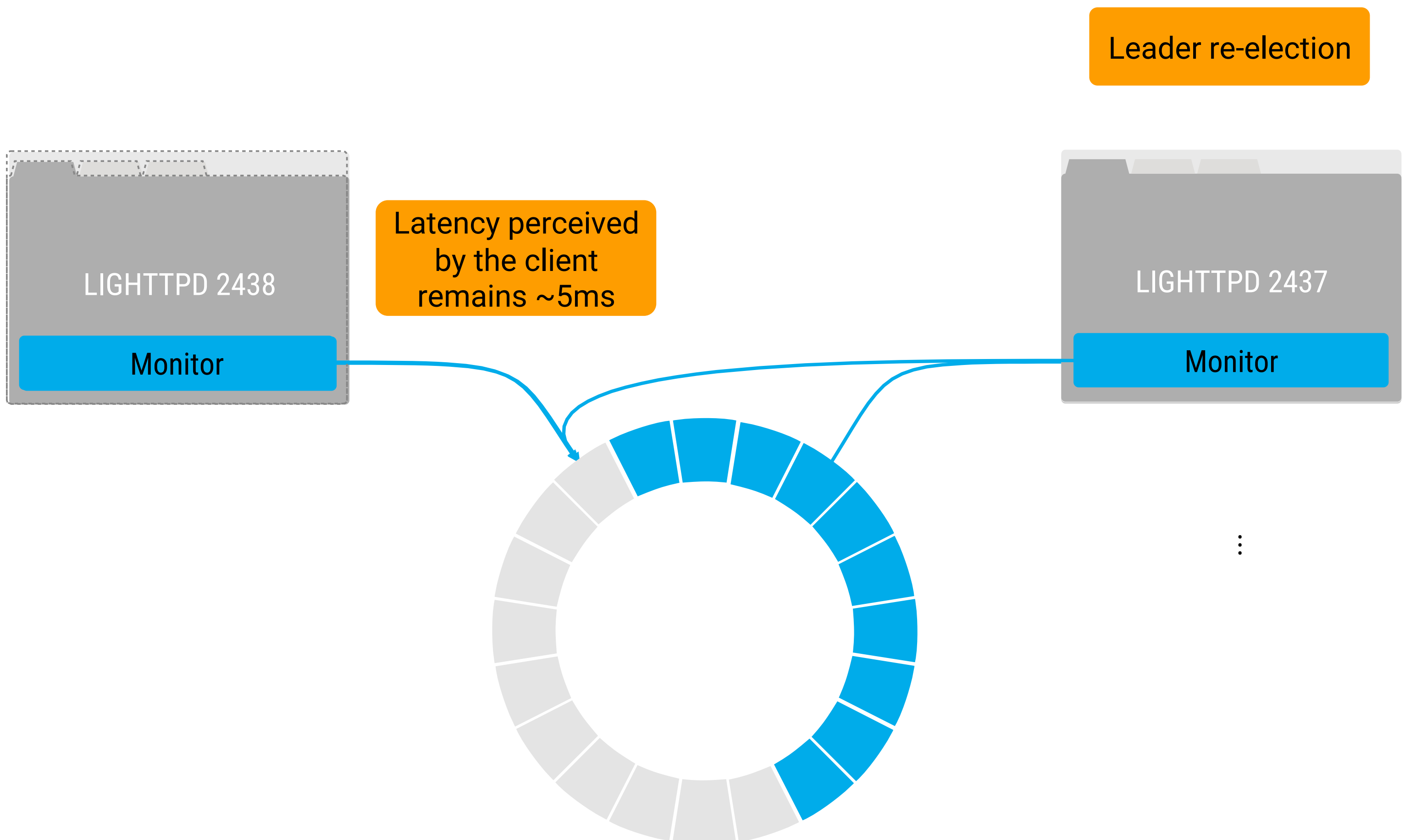
```
for (h = 0, i = 0; i < etag->used - 1; ++i)
     h = (h << 5) ^ (h >> 27) ^ (etag->ptr[i]);
```

File (re)compression in mod_compress_physical

```
if (use_etag)
    etag_mutate(con->physical.etag, srv->tmp_buf);
}
```



Case 1: Follower crashes



Case 2: Leader crashes

redis

Advanced key-value store server

Powers several popular services such as GitHub and Flickr

redis

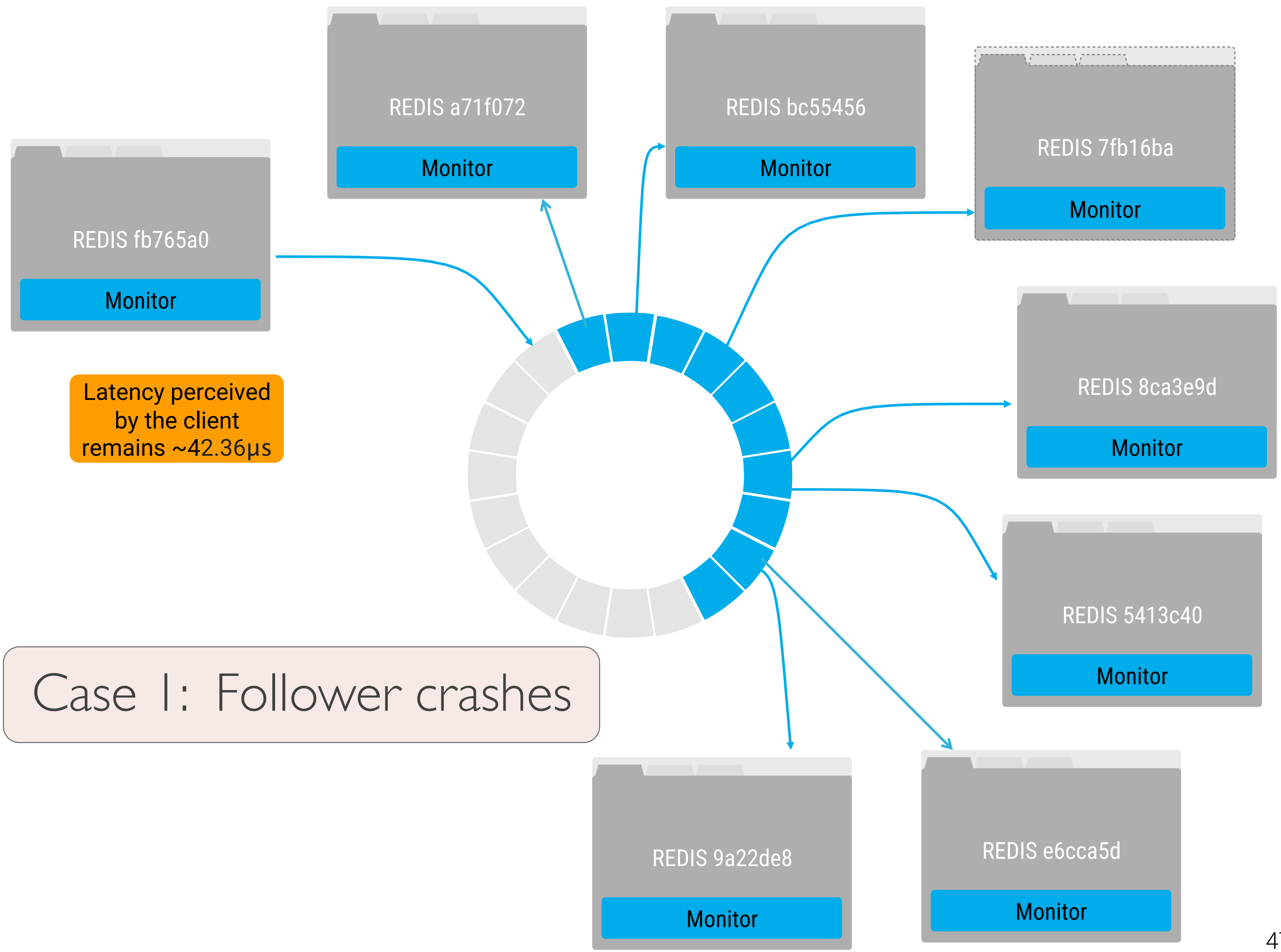
HMGET command hmgetCommand function

```
robj *o = lookupKeyRead(c->db, c->argv[1]);
if (o == NULL) {
    addReplySds(c,sdscatprintf(sdsempty(),
                "*%d\r\n",c->argc-2));
    for (i = 2; i < c->argc; i++) {
        addReply(c,shared.nullbulk);
    }
    return;
} else {
    if (o->type != REDIS_HASH) {
        addReply(c,shared.wrongtypeerr);
        return;
    }
}
addReplySds(c,sdscatprintf(sdsempty(),
            "*%d\r\n",c->argc-2));
```

```
robj *o, *value;
o = lookupKeyRead(c->db,c->argv[1]);
if (o != NULL && o->type != REDIS_HASH) {
    addReply(c,shared.wrongtypeerr);
    return; <- missing return
}
addReplySds(c,sdscatprintf(sdsempty(),
            "*%d\r\n",c->argc-2));
for (i = 2; i < c->argc; i++) {
    if (o != NULL && (value = hashGet(o,c-
>argv[i])) != NULL) {
        addReplyBulk(c,value);
        decrRefCount(value);
    } else {
        addReply(c,shared.nullbulk);
    }
}
```

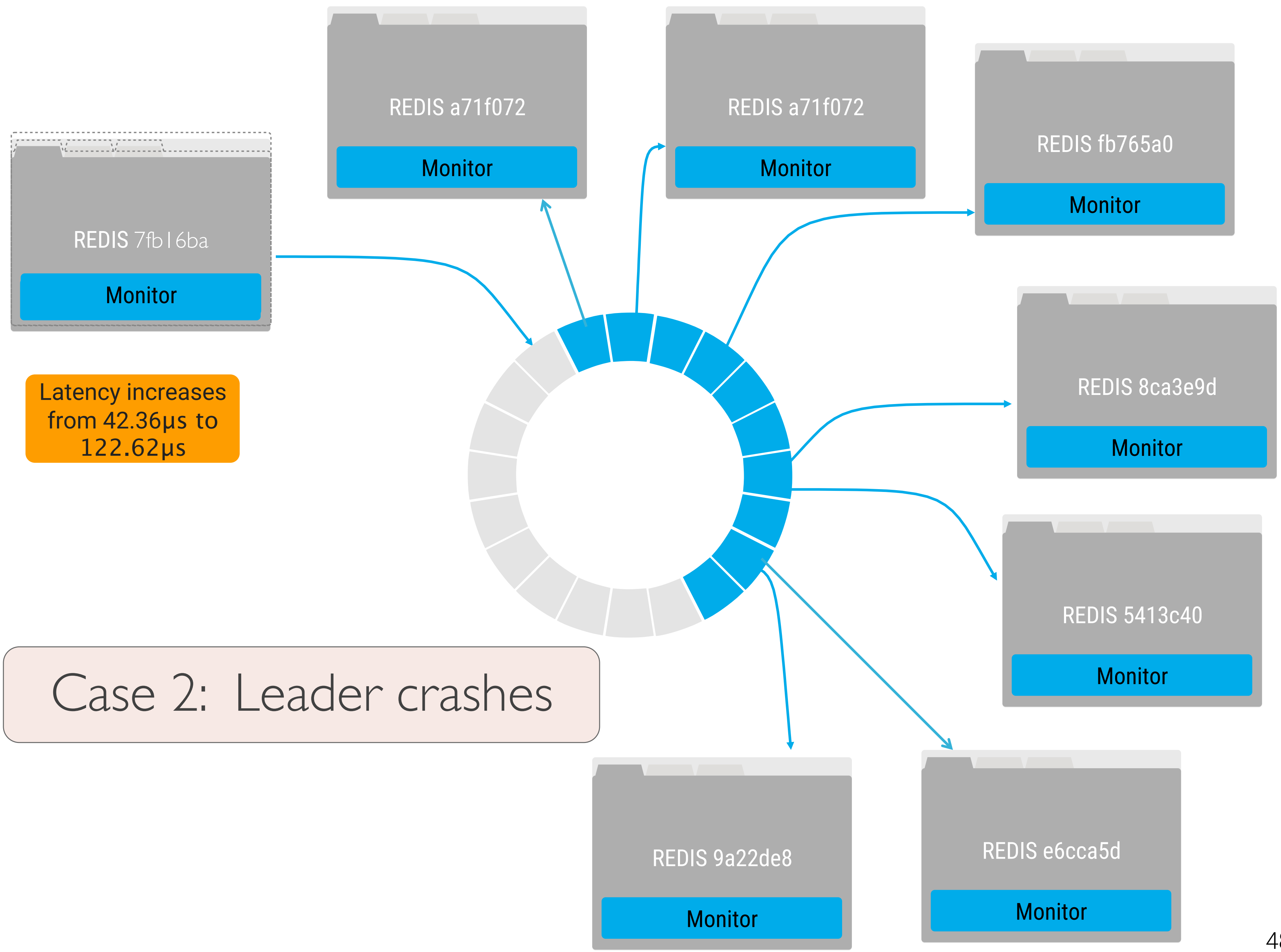
Refactor

Bug may result in loosing some or even all of the stored data



Case 1: Follower crashes

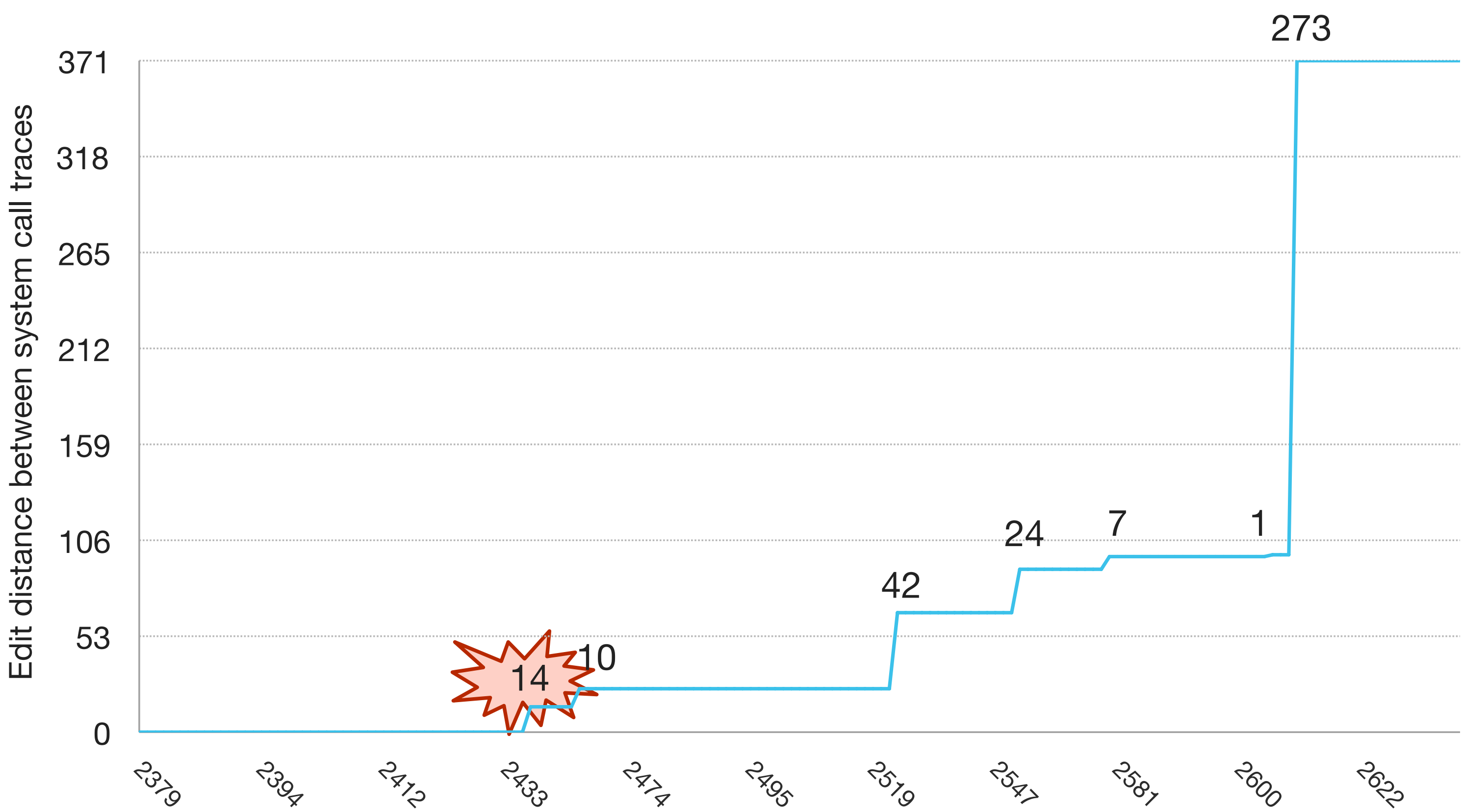
Case 2: Leader crashes



Handling divergences between versions

Using rewrite rules

External Behavior Evolves Sporadically



95% of lighttpd revisions introduce *no change**

Measured using lighttpd regression suite on 164 revisions (~10 months)

*Taken on Linux kernel 2.6.40 and glibc 2.14 using strace tool and custom post-processing (details in [ICSE'13])

LIGHTTPD
fly light.

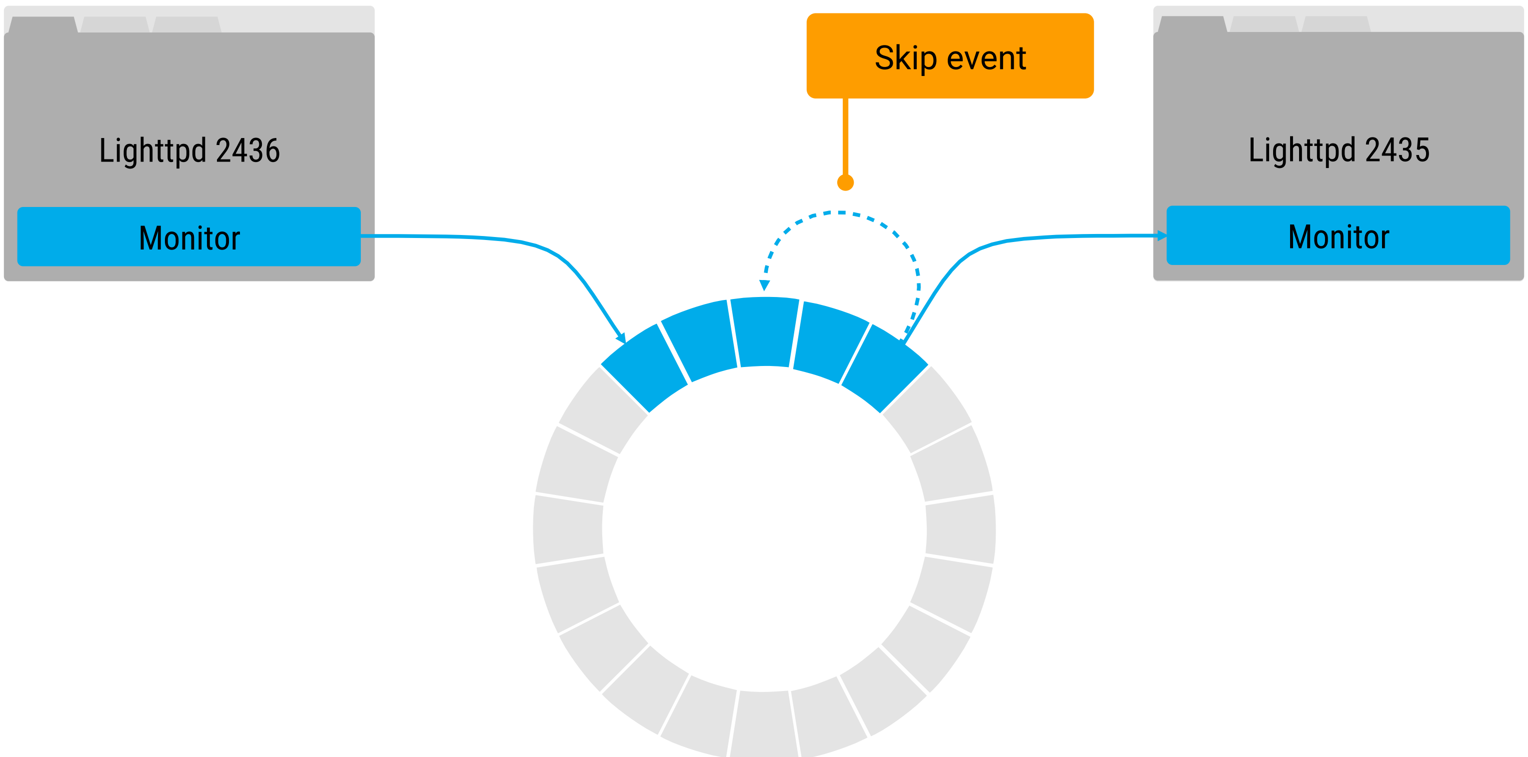
```
if (!i_am_root &&
    (geteuid() == 0 || getegid() == 0)) {
```

LIGHTTPD 2435

```
#ifdef HAVE_GETUID
# ifndef HAVE_ISSETUGID

static int l_issetugid() {
   return (geteuid() != getuid() ||
           getegid() != getgid());
}

#  define issetugid l_issetugid
# endif
#endif

if (!i_am_root && issetugid()) {
```

Extra system calls

LIGHTTPD 2436



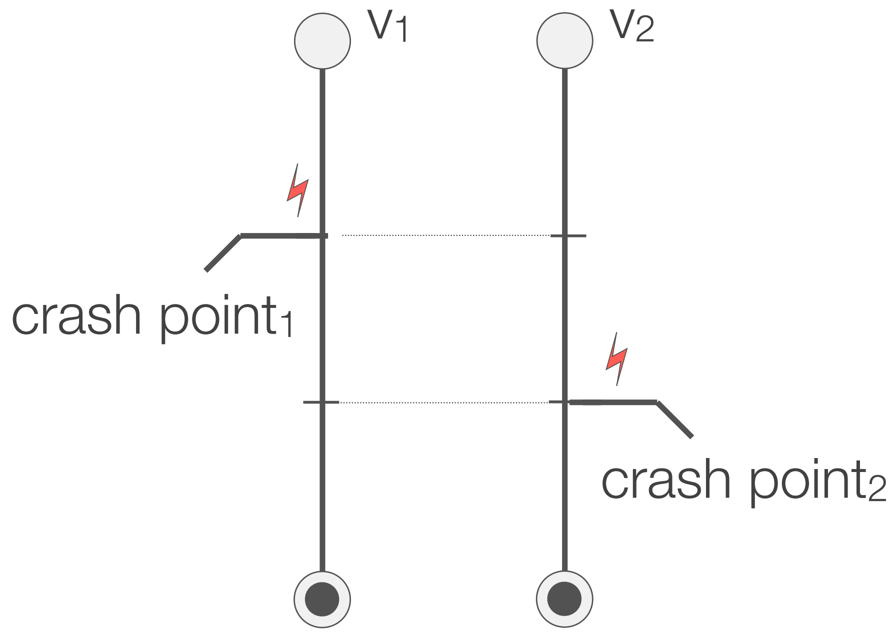
BPF filter

```
ld event[0]
jeq #108, getegid       /* __NR_getegid */
jeq #2, open            /* __NR_open */
jmp bad
getegid:
ld [0]                  /* offsetof(struct event_data, nr) */
jeq #102, good          /* __NR_getuid */
open:
ld [0]                  /* offsetof(struct event_data, nr) */
jeq #104, good          /* __NR_getgid */
bad: ret #0             /* SECCOMP_RET_KILL */
good: ret #0x7fff0000   /* SECCOMP_RET_ALLOW */
```

Handling different crashes in multiple versions

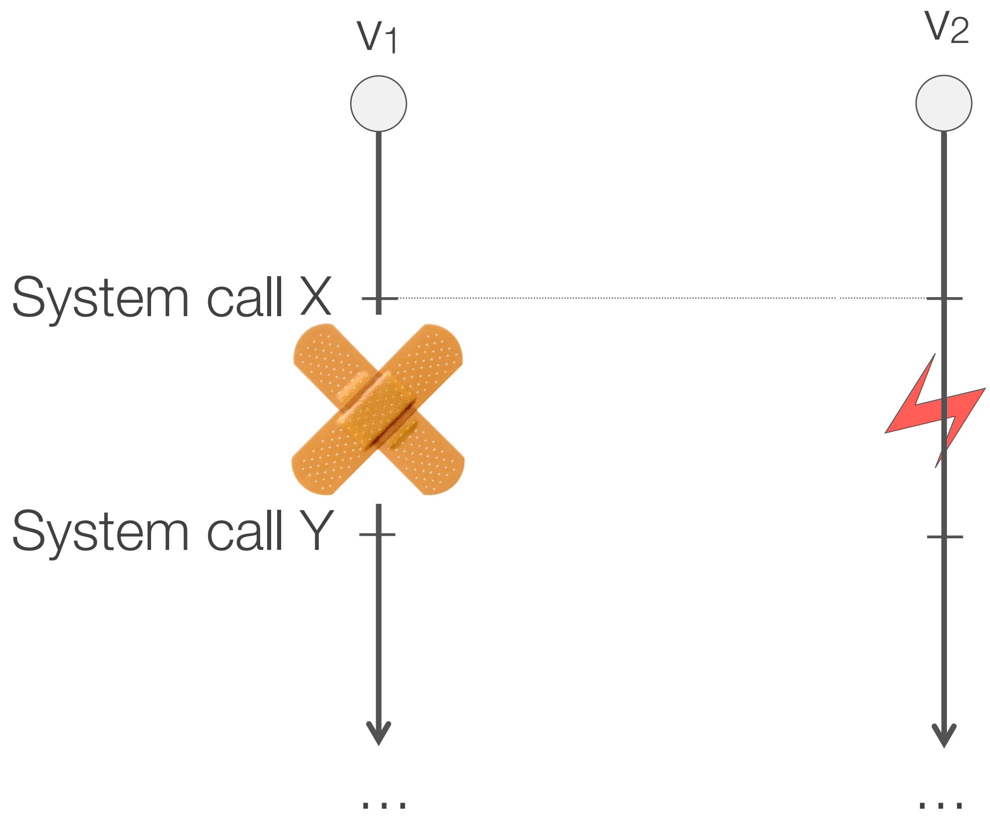
Via failure recovery

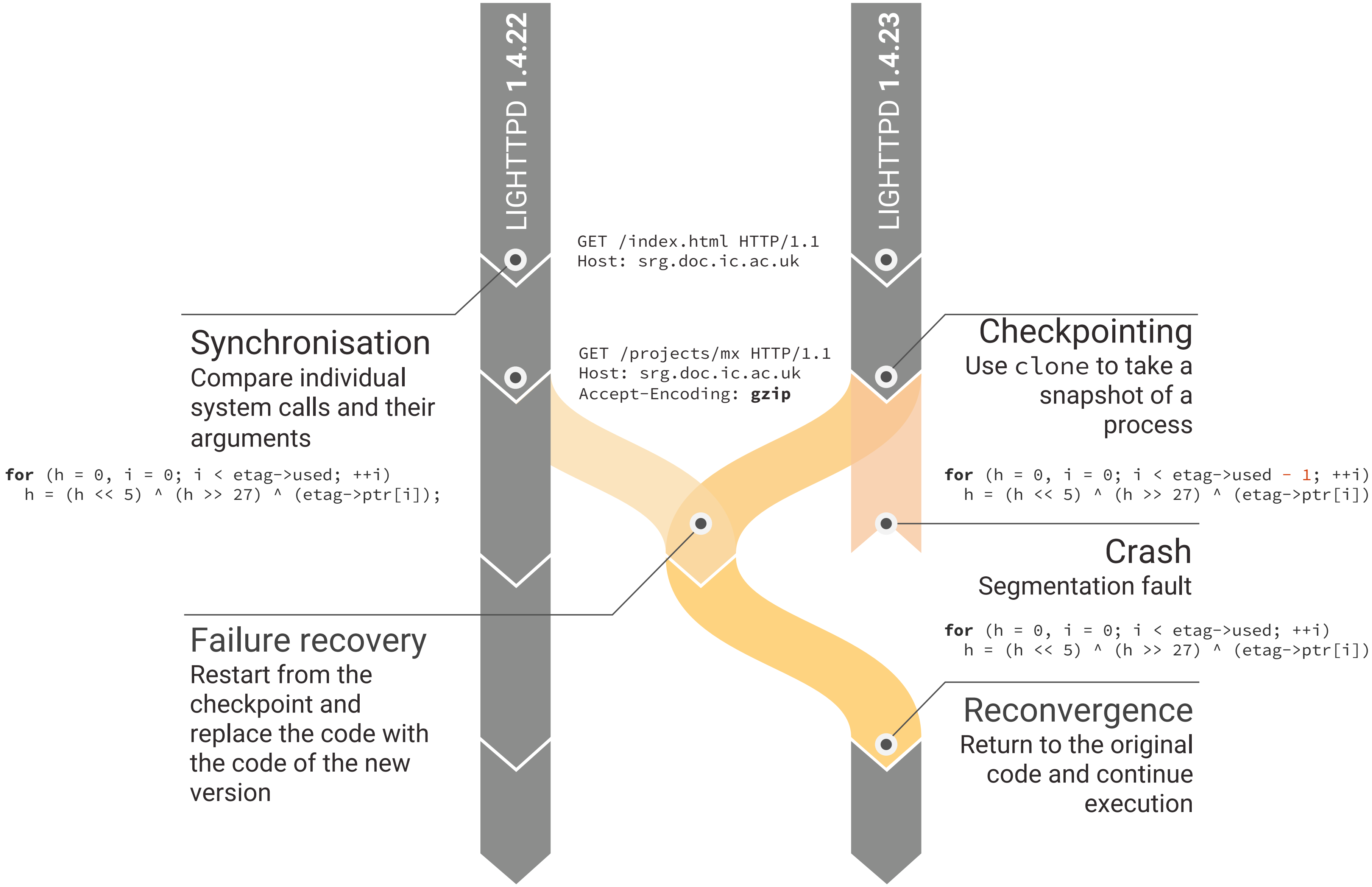
Scope: Surviving crash errors occurring at different times



Current limitation: implemented in a ptrace-based system, with lockstep execution

Failure Recovery: Runtime Code Patching





Synchronisation and failure recovery mechanism

Failure Recovery: Suitable Scenarios

Errors with a small propagation distance

“Localized” around a small portion of code

Applications which provide “natural” synchronization points

E.g., servers structured around a main dispatch loop

Changes which do not affect memory layout

E.g., refactorings, security patches

Failure Recovery: Guarantees?

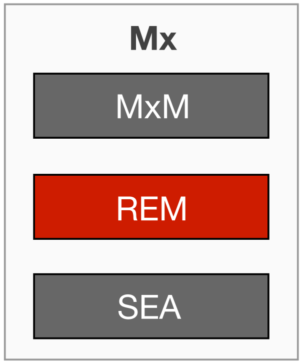
Assumes that recovery is successful if versions exhibit the same external behavior after recovery

- If unrecoverable, drops the crashed version
- (By design, Mx does not attempt to survive errors it cannot handle)

Failure Recovery – Details

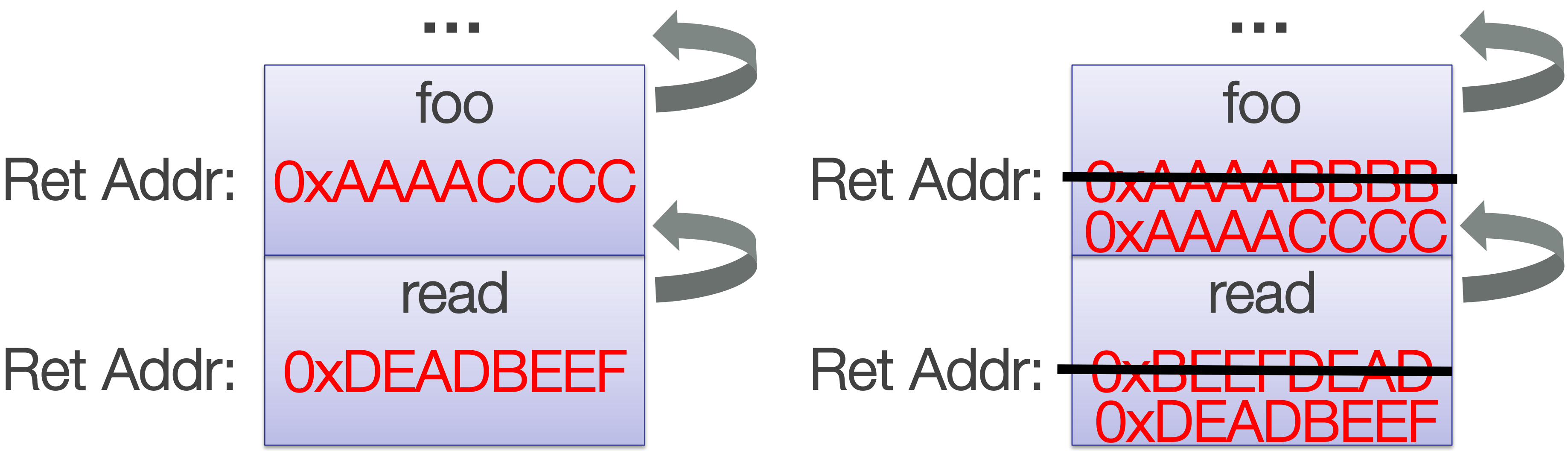
Runtime code patching and fault recovery

- OS-level checkpointing (using clone syscall)
- Code segment replacement*
- Runtime stack manipulation
- Breakpoint insertion and handling (for indirect fun calls)



*Currently with compiler support

Stack Patching



Version 1

0xDEADBEEF:

```
void foo() {
    ...
    read(1, buf, 3);
    ...
}
```

Version 2 (patched)

0xBEEFDEAD:

```
void foo() {
    ...
    read(1, buf, 3);
    ...
}
```

Indirect Calls

Version 1

0x012345678:

```
fptr = bar;
...

void bar(int x) {
    ...
}

void foo() {
    ...
    fptr(1);
    ...
}
```

Memory

fptr: 0x12345678

Version 2 (patched)

0x87654321:

```
fptr = bar;
...

void bar(int x) {
    INT 3
    ...
}

void foo() {
    INT 3
    ...
    fptr(1);
    ...
}
```

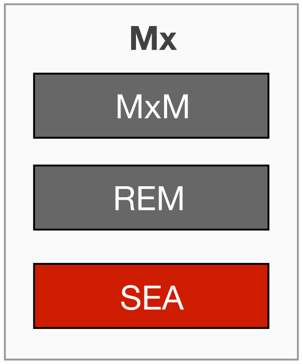
Memory

fptr: 0x876543210

Static Binary Analyzer

Create various mappings between the two version binaries

- Static analysis of binary executables
- Extracting function symbols from binaries (libbfd)
- Machine code disassembling and analysis (libopcodes)
- Binary call graph reconstruction and matching



Evaluation: survived several crash bugs

	Application	Bug
UTILITIES	md5sum sha1sum	Buffer overflow
	mkdir mkfifo mknod	NULL-ptr dereference
	cut	Buffer overflow
SERVERS	lighttpd #1	Loop index underflow
	lighttpd #2	Off-by-one error
	redis	Missing return

Mx and Varan

Promising new approach for improving software updates

Based on multi-version execution

Our prototypes can survive crash bugs in real software updates

Varan's novel architecture incurs a low performance overhead and can handle system call divergences

Many opportunities for future work

Support for more complex code changes in Mx & more complex divergences in Varan

Improve memory consumption

Explore new other applications, e.g., live sanitization

Can multiple software versions be effectively combined to increase software reliability and security?

Imperial College London

Mx and Varan: Safe Software Updates via Multi-version Execution

[ASPLOS 2015] Hosek and Cadar, VARAN the Unbelievable An Efficient N-version Execution Framework

[ICSE 2013] Hosek and Cadar, Safe Software Updates via Multi-version Execution

[HotSwUp 2012] Cadar and Hosek, Multi-version software updates