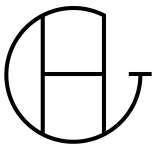

HoGent

Faculteit Bedrijf en Organisatie

# Research of caching strategies in mobile native applications using external data services

Bijlagen

Frederik De Smedt

Scriptie voorgedragen tot het bekomen van de graad van
Bachelor in de toegepaste informatica

Promotor:
Joeri Van Herreweghe
Co-promotor:
Jens Buysse

Instelling: —

Academiejaar: 2015-2016

Tweede examenperiode

Faculteit Bedrijf en Organisatie

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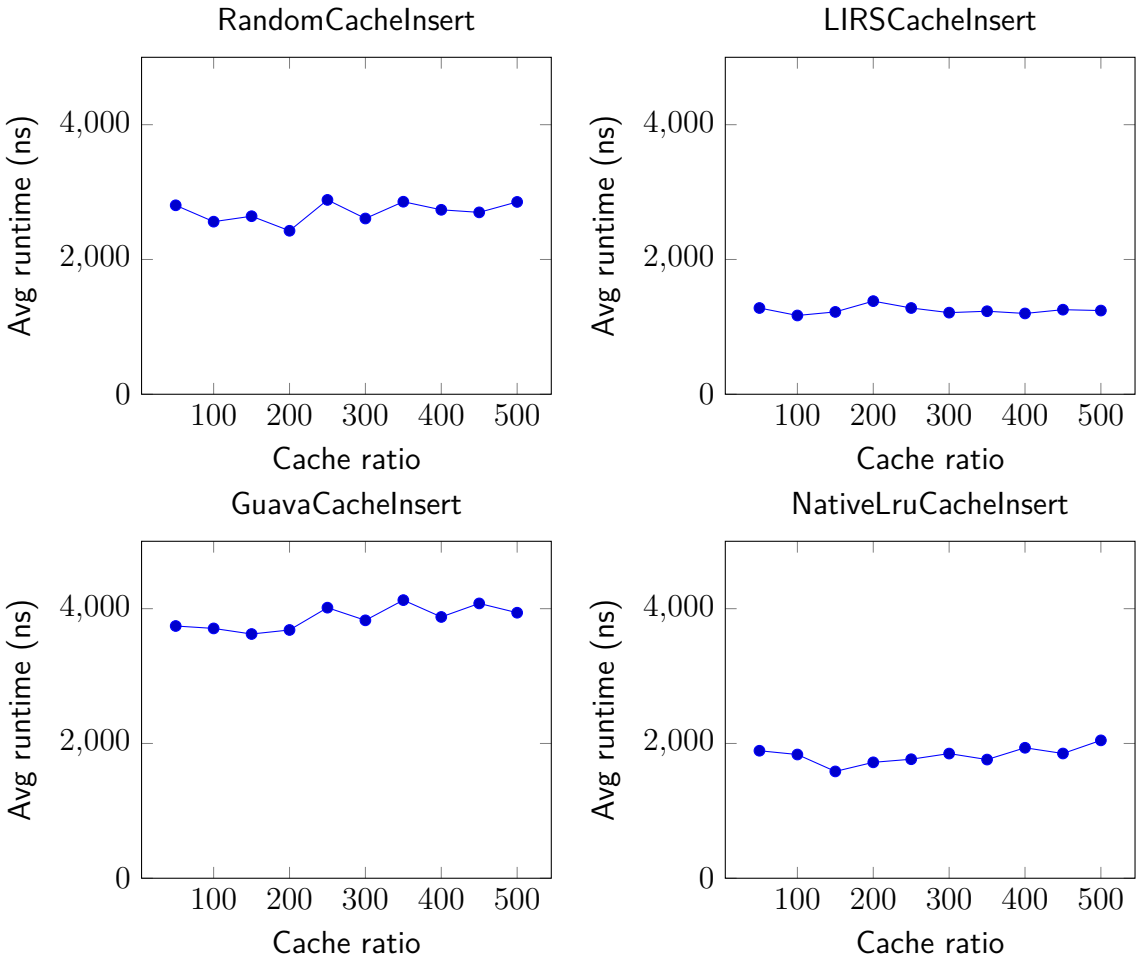
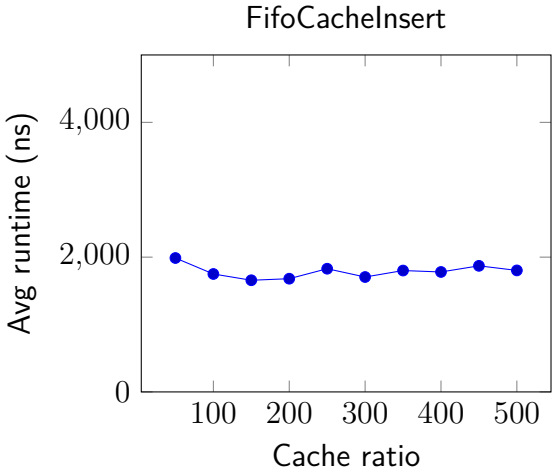
# Contents

# Appendices

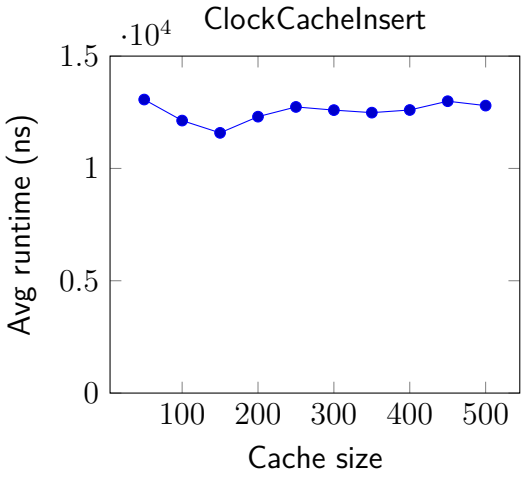
# Appendix A

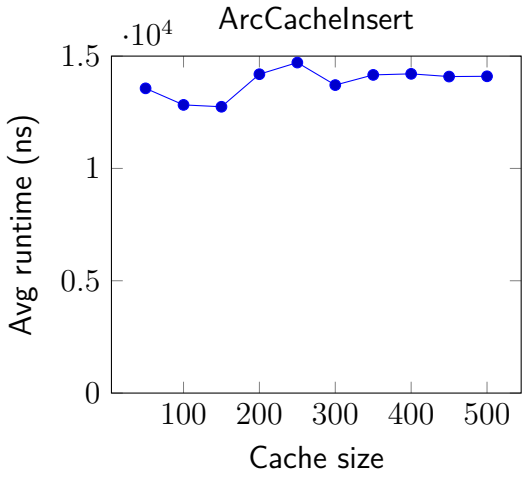
# Insert benchmarks





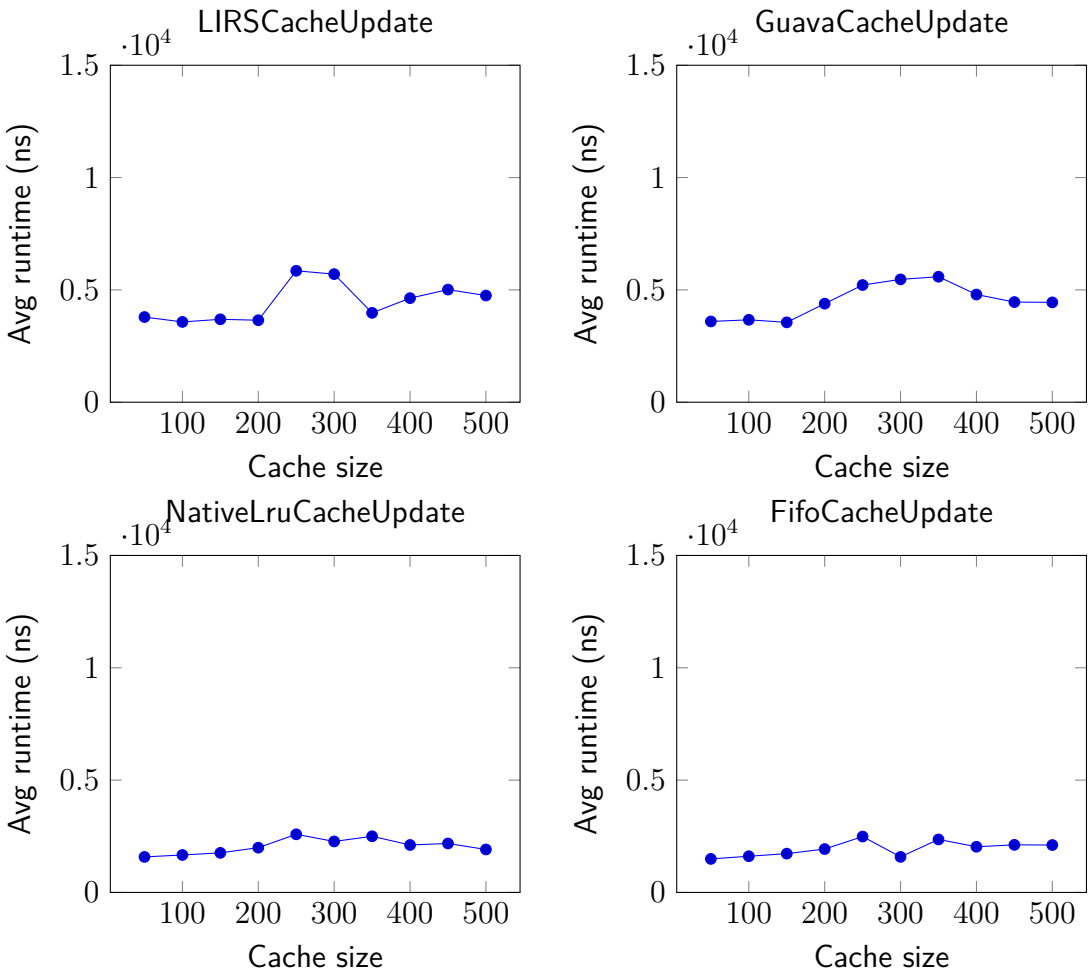

These benchmarks have an average execution time above 5000 ns. Due to the scale difference they are placed separately.

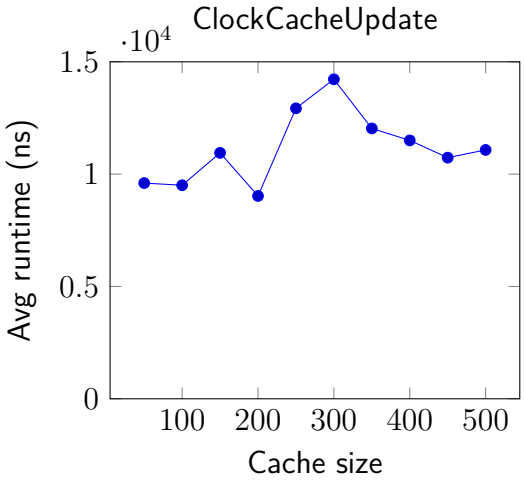


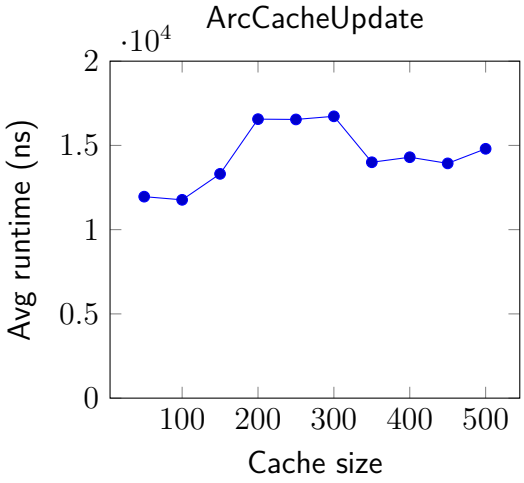
# Appendix B

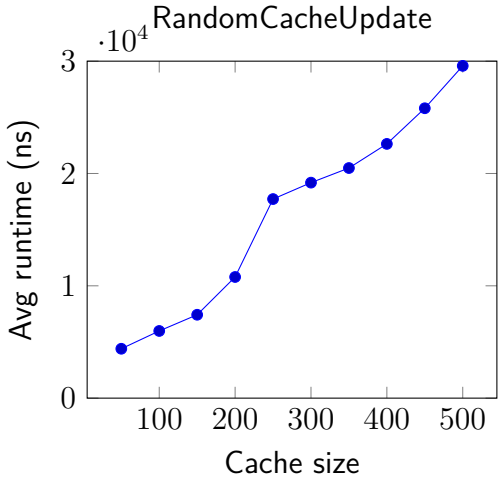
# Update benchmarks





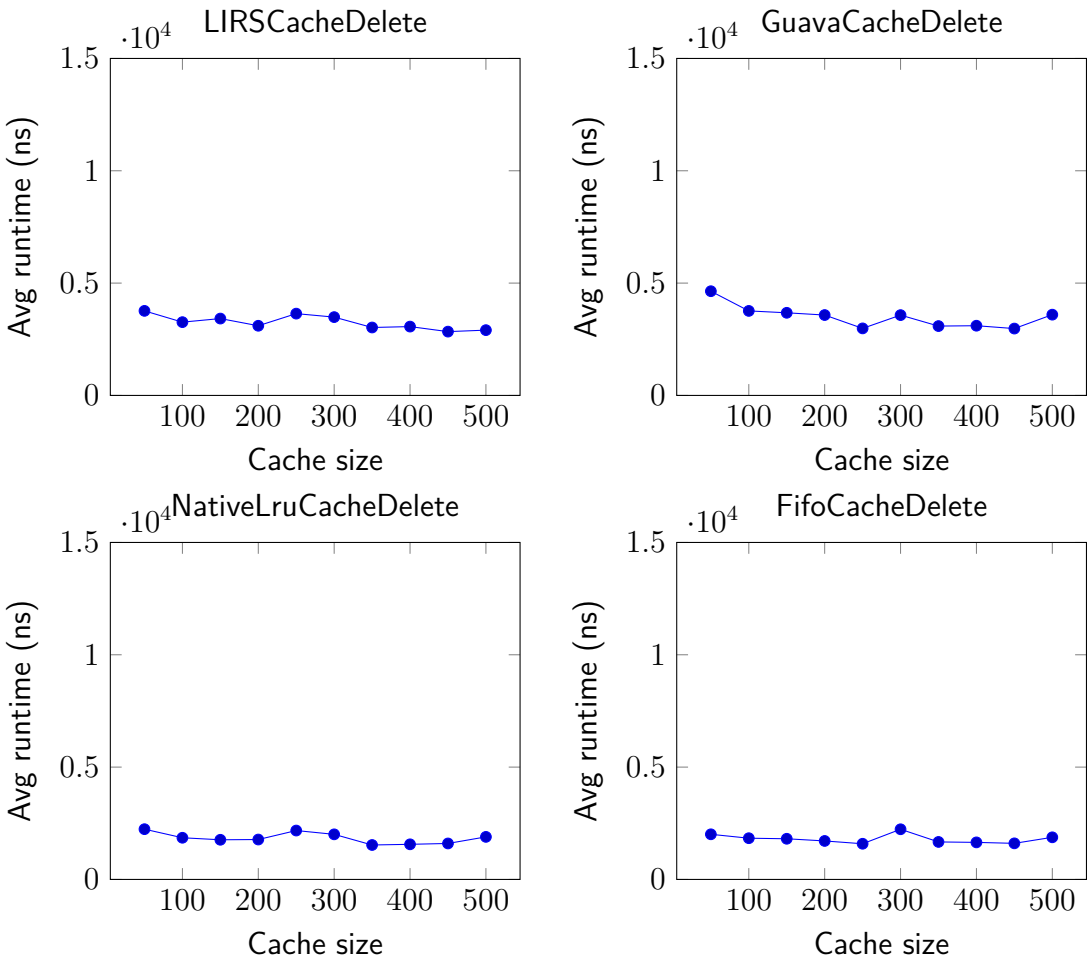

Due to high average runtimes of ARC and random cache, they are placed separately and each have a different scale.

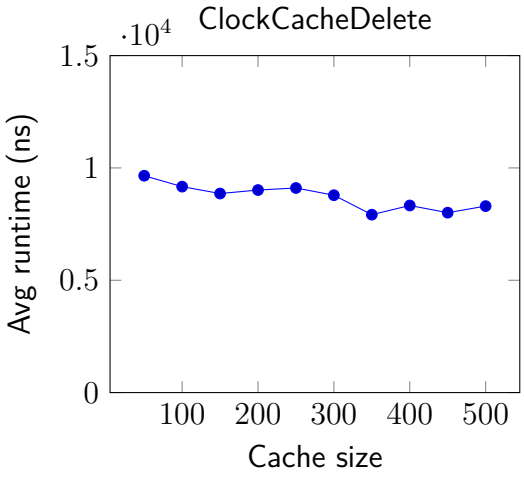


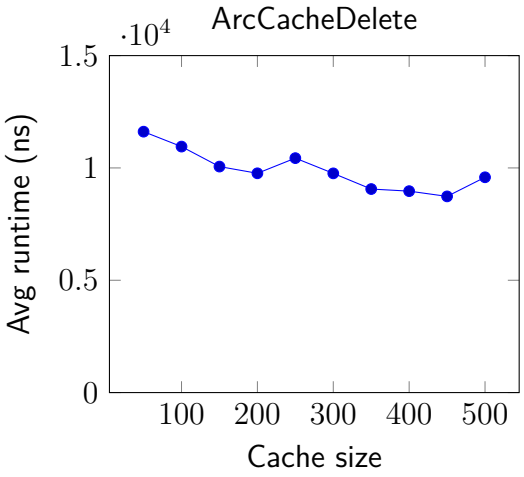



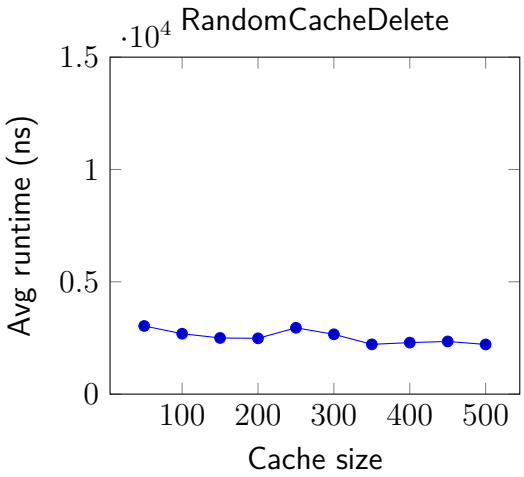
# Appendix C

# Delete benchmarks



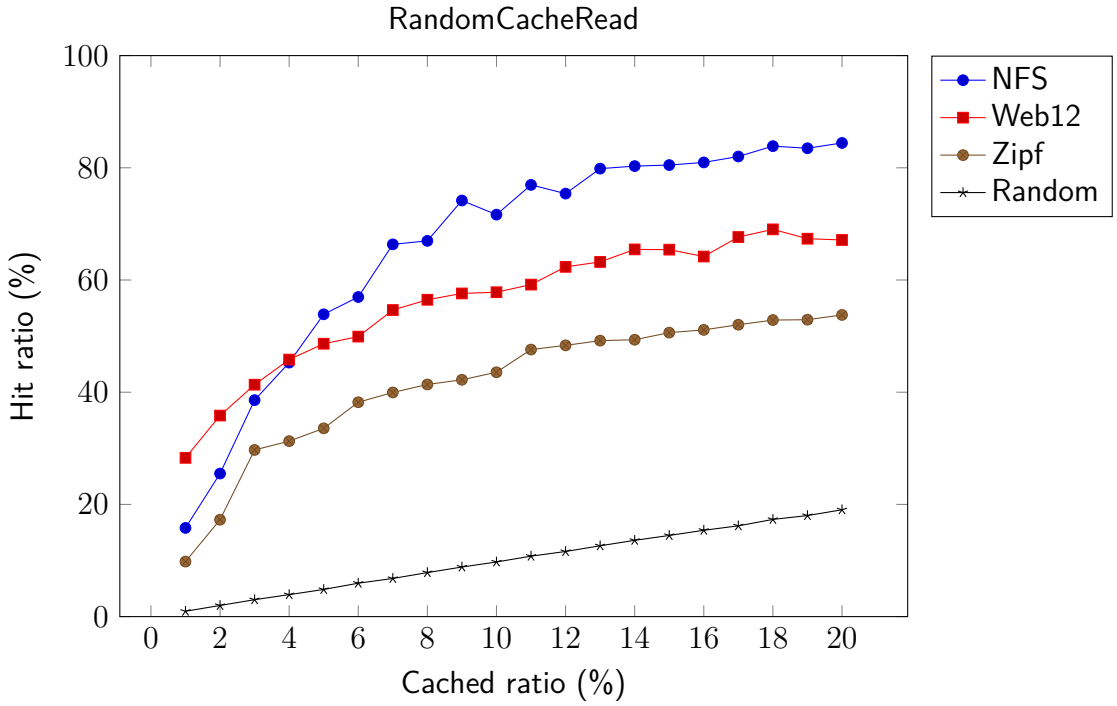

ClockCacheDelete
$\cdot 10^4$
1.5
1
0.5
0
Avg runtime (ns)
100
200
300
400
500
Cache size

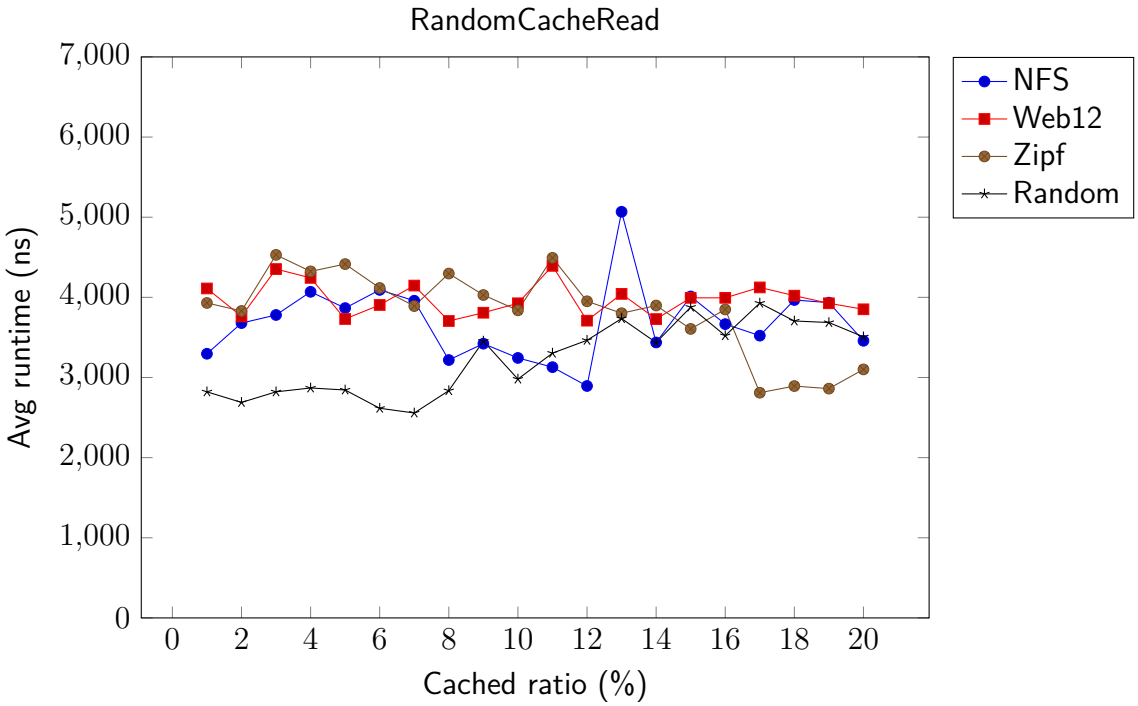

ArcCacheDelete
$\cdot 10^4$
1.5
1
0.5
0
Avg runtime (ns)
100
200
300
400
500
Cache size

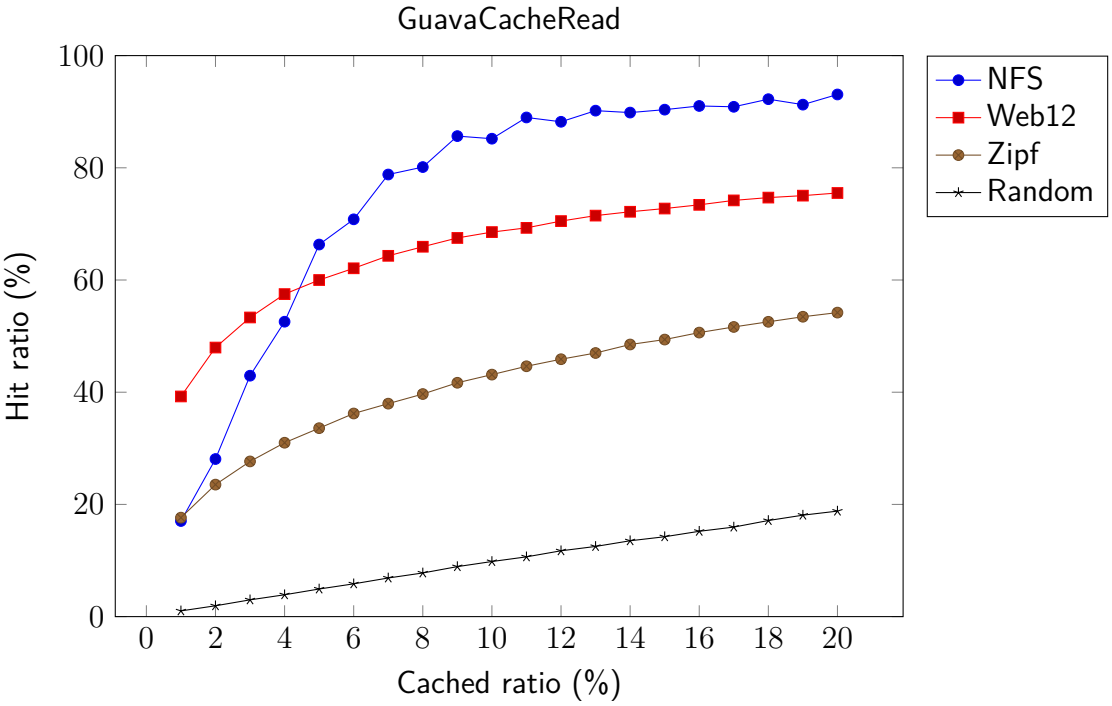

RandomCacheDelete
$\cdot 10^4$
1.5
1
0.5
0
Avg runtime (ns)
100
200
300
400
500
Cache size

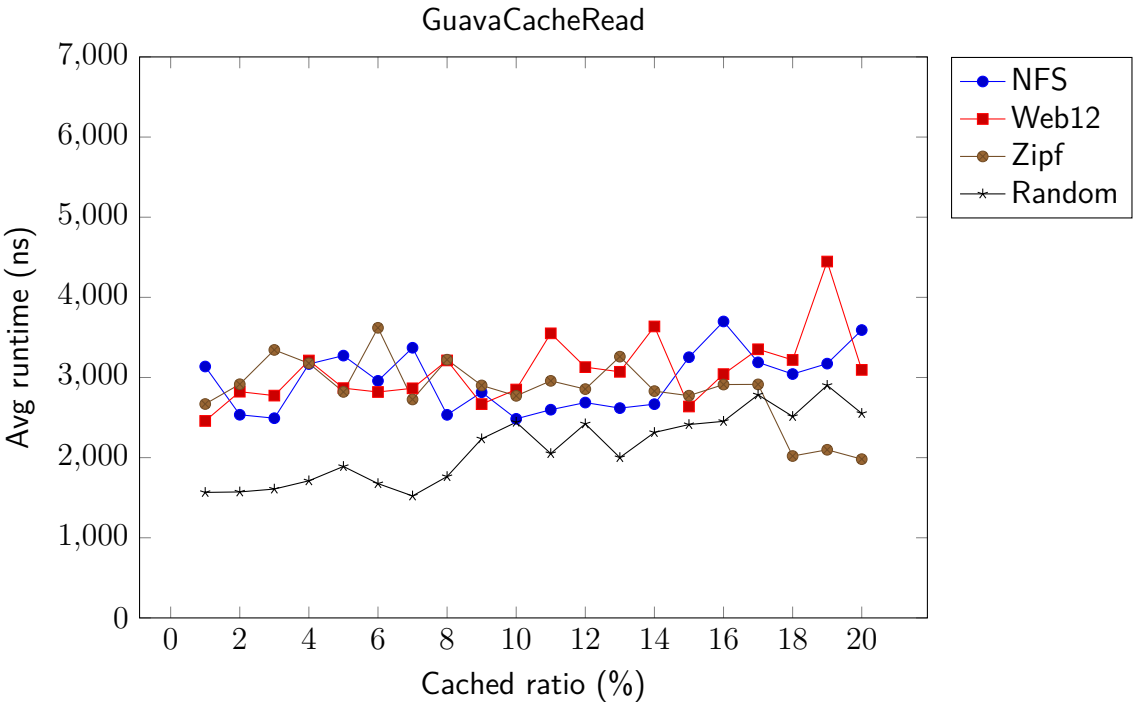
# Appendix D

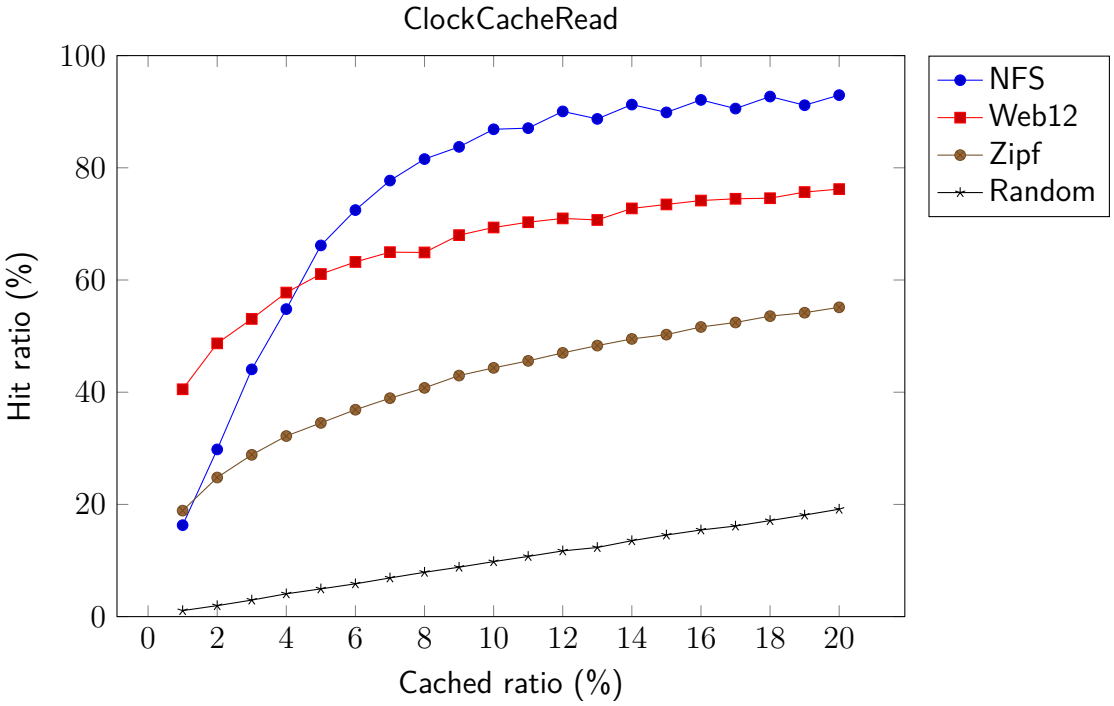
# Read benchmarks

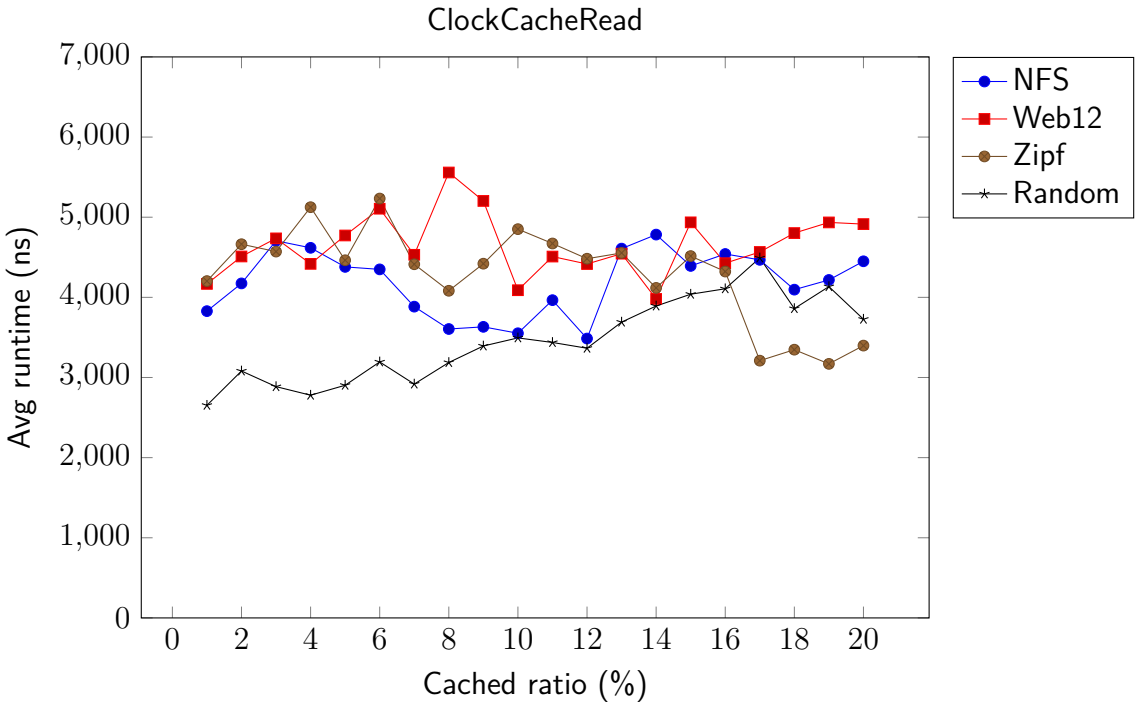

RandomCacheRead
Hit ratio (%)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20

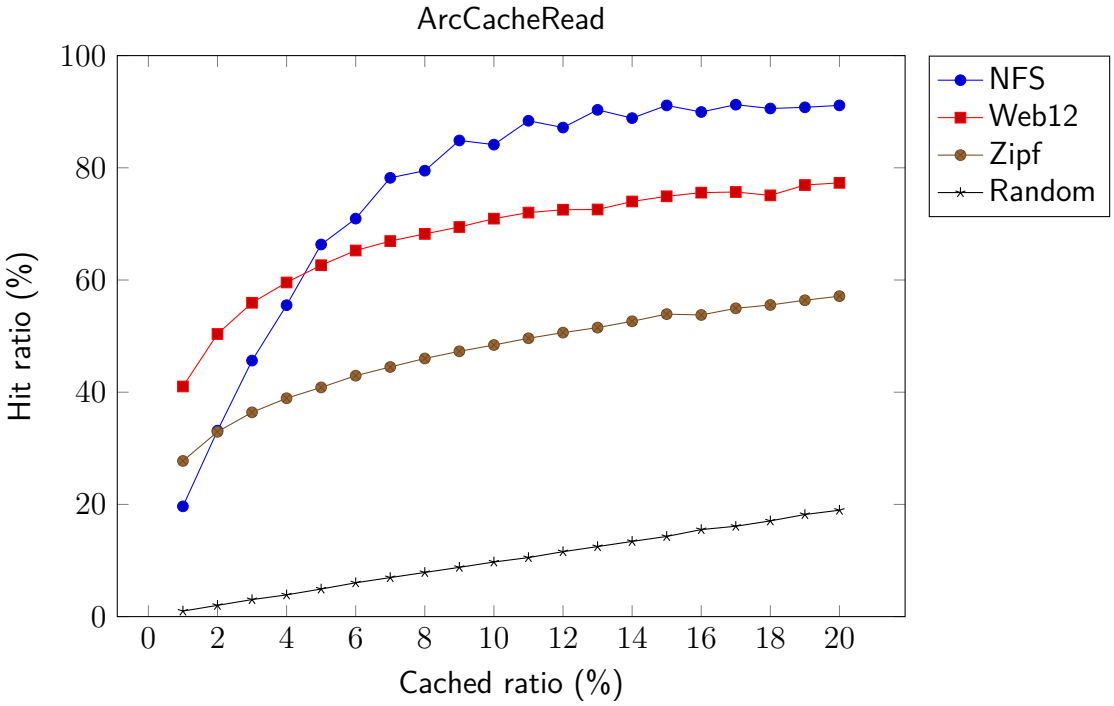

RandomCacheRead
Avg runtime (ns)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
0
2
4
6
8
10
12
14
16
18
20

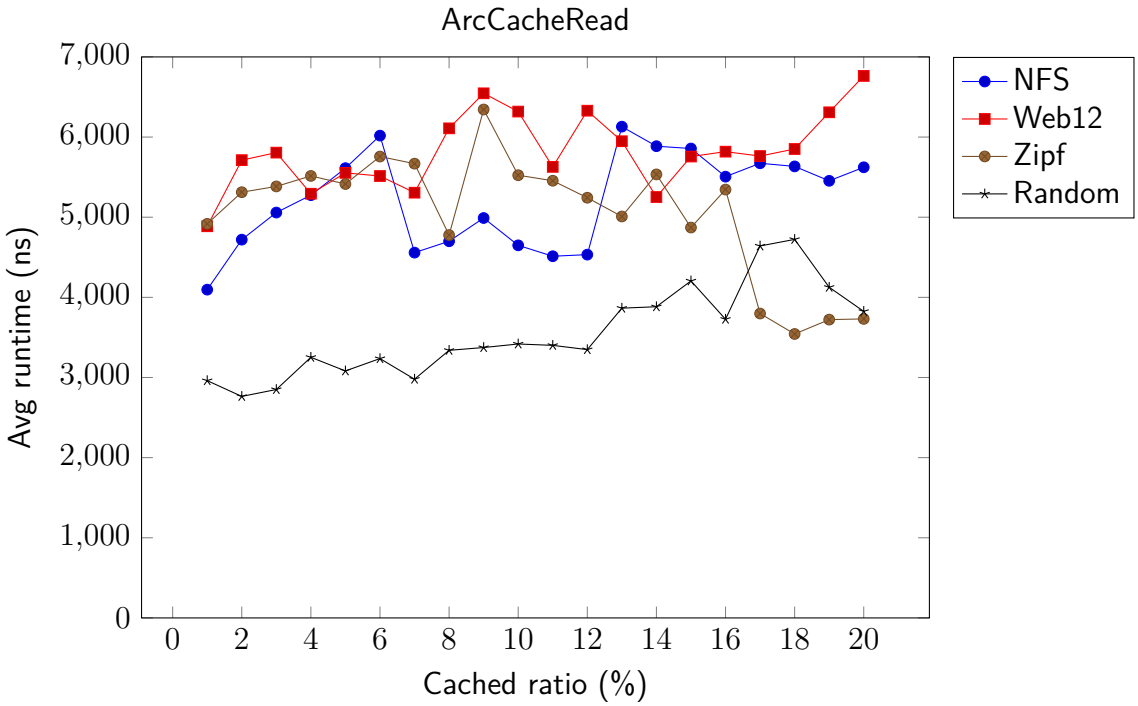

GuavaCacheRead
Hit ratio (%)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20

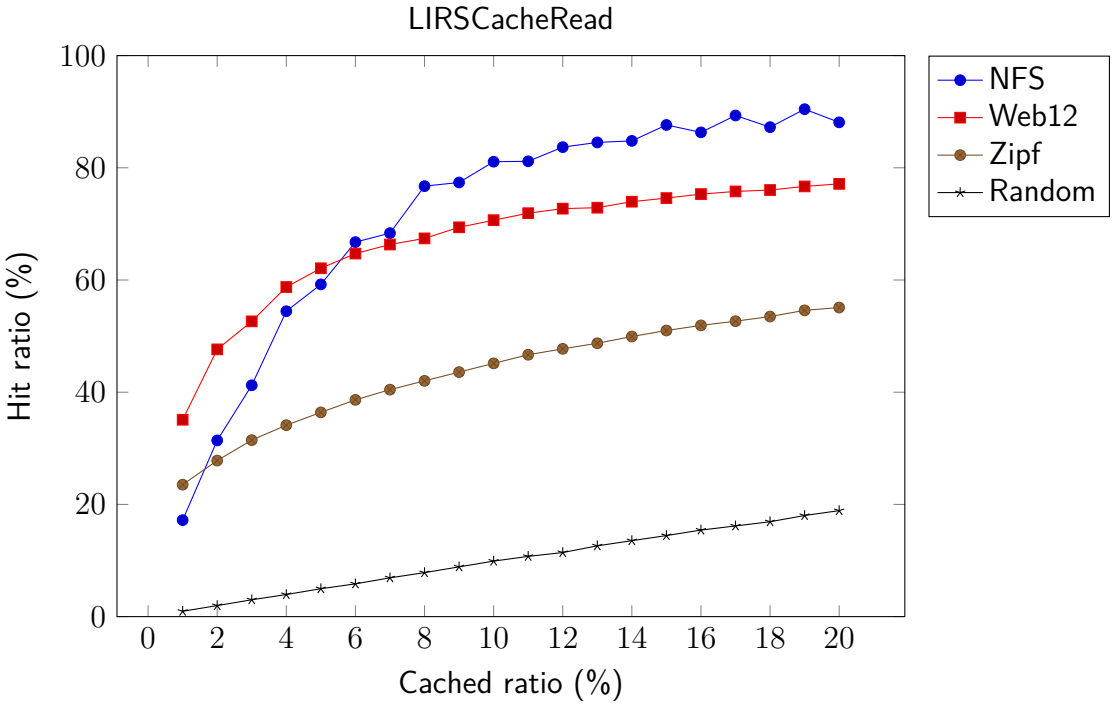

GuavaCacheRead
Avg runtime (ns)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
0
2
4
6
8
10
12
14
16
18
20

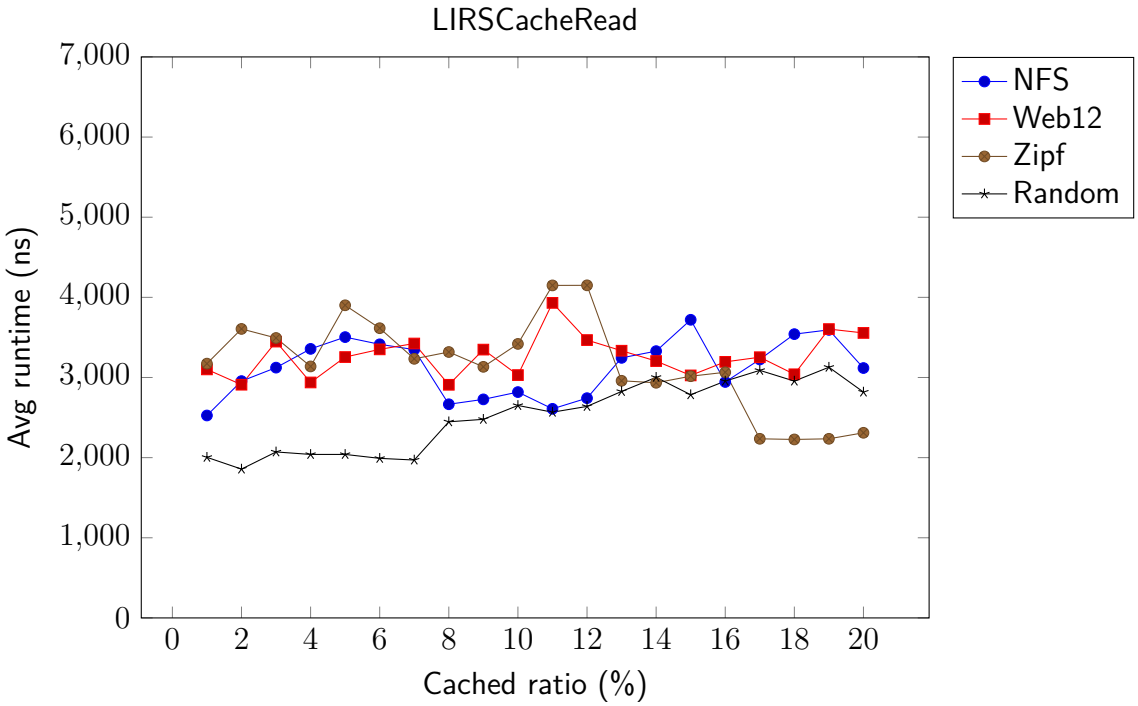

ClockCacheRead
Hit ratio (%)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20

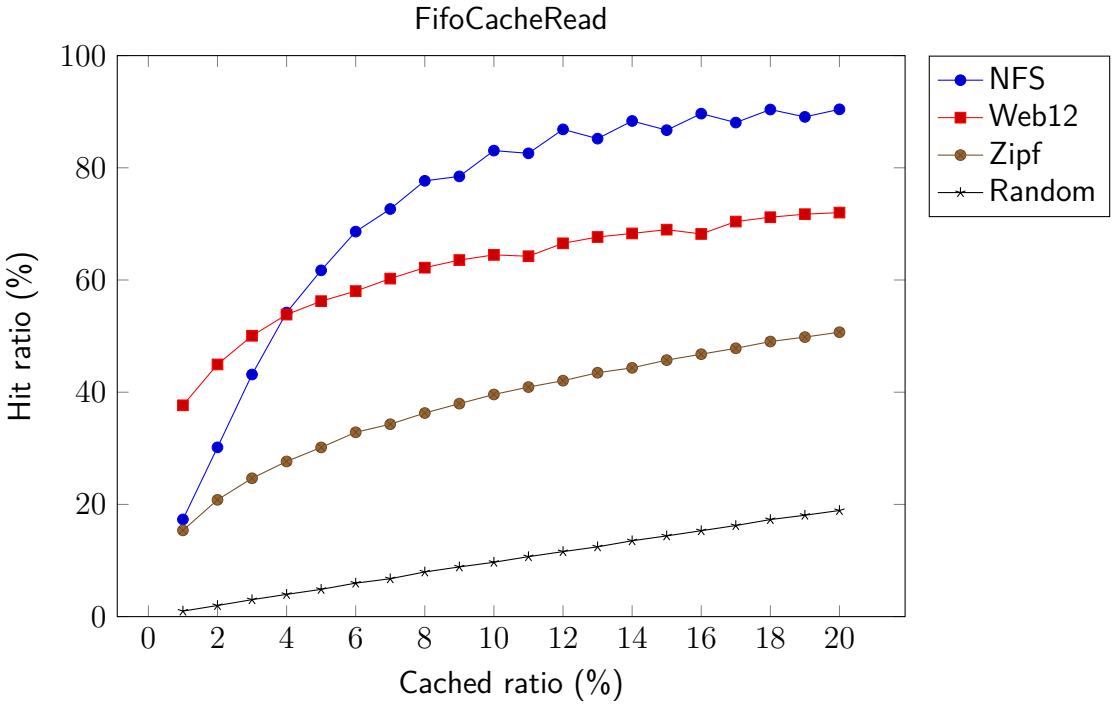

ClockCacheRead
Avg runtime (ns)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
0
2
4
6
8
10
12
14
16
18
20

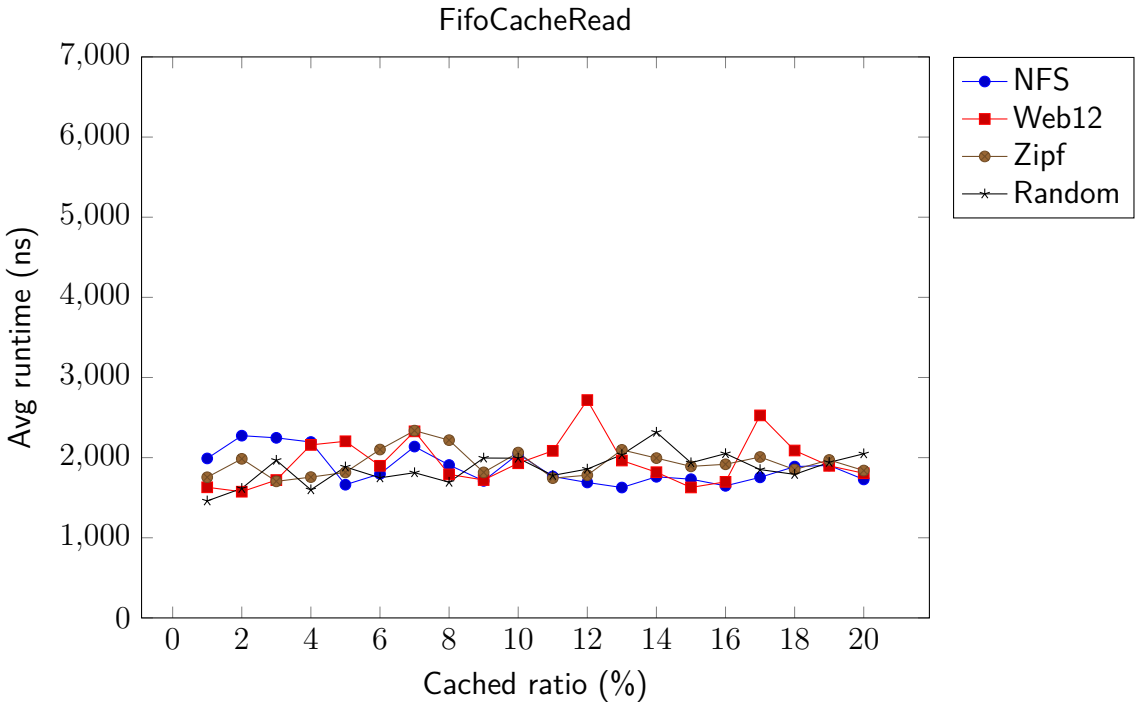

ArcCacheRead
Hit ratio (%)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20

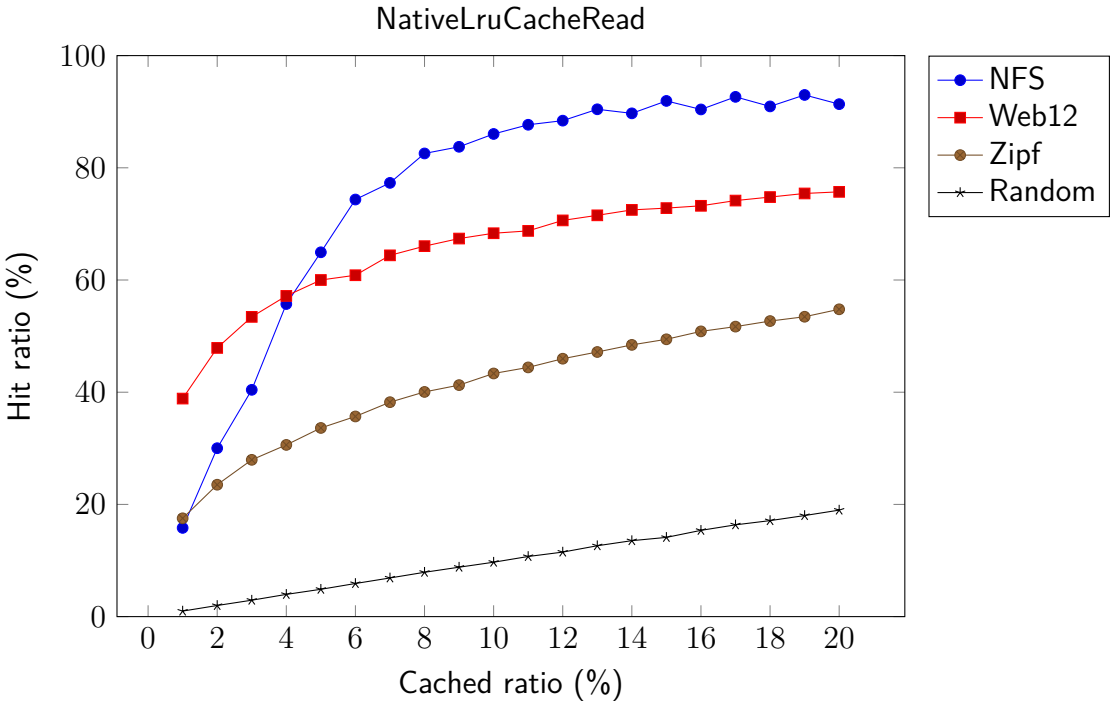

ArcCacheRead
Avg runtime (ns)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
0
2
4
6
8
10
12
14
16
18
20

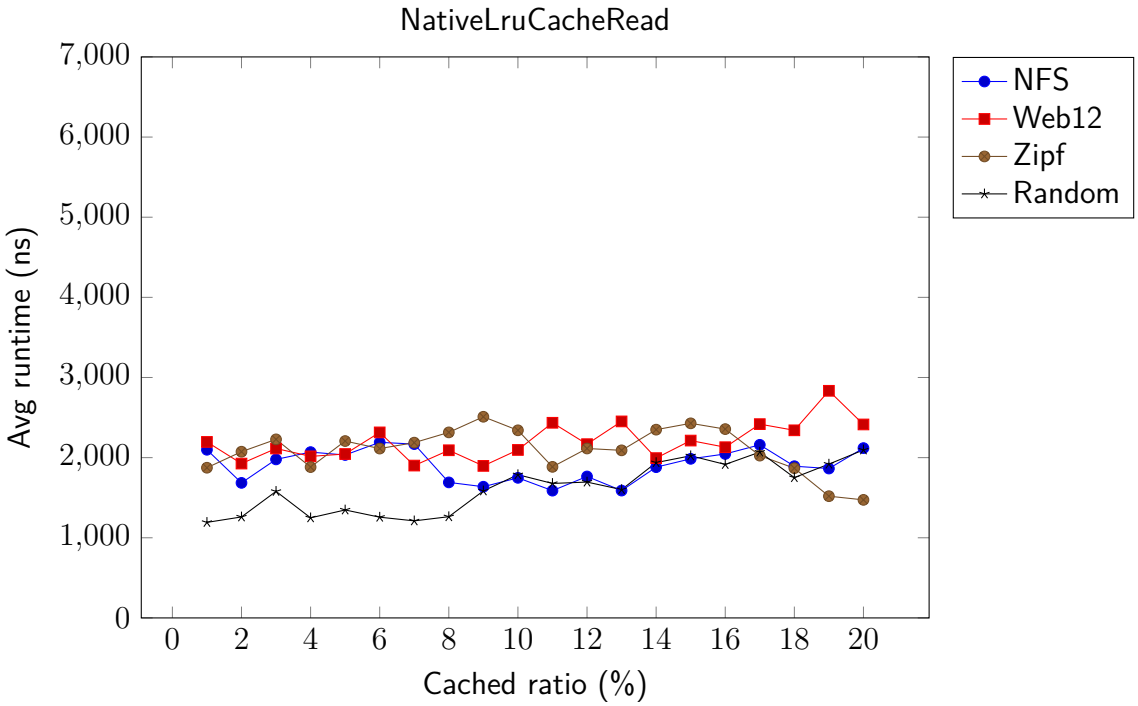

LIRSCacheRead
Hit ratio (%)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20

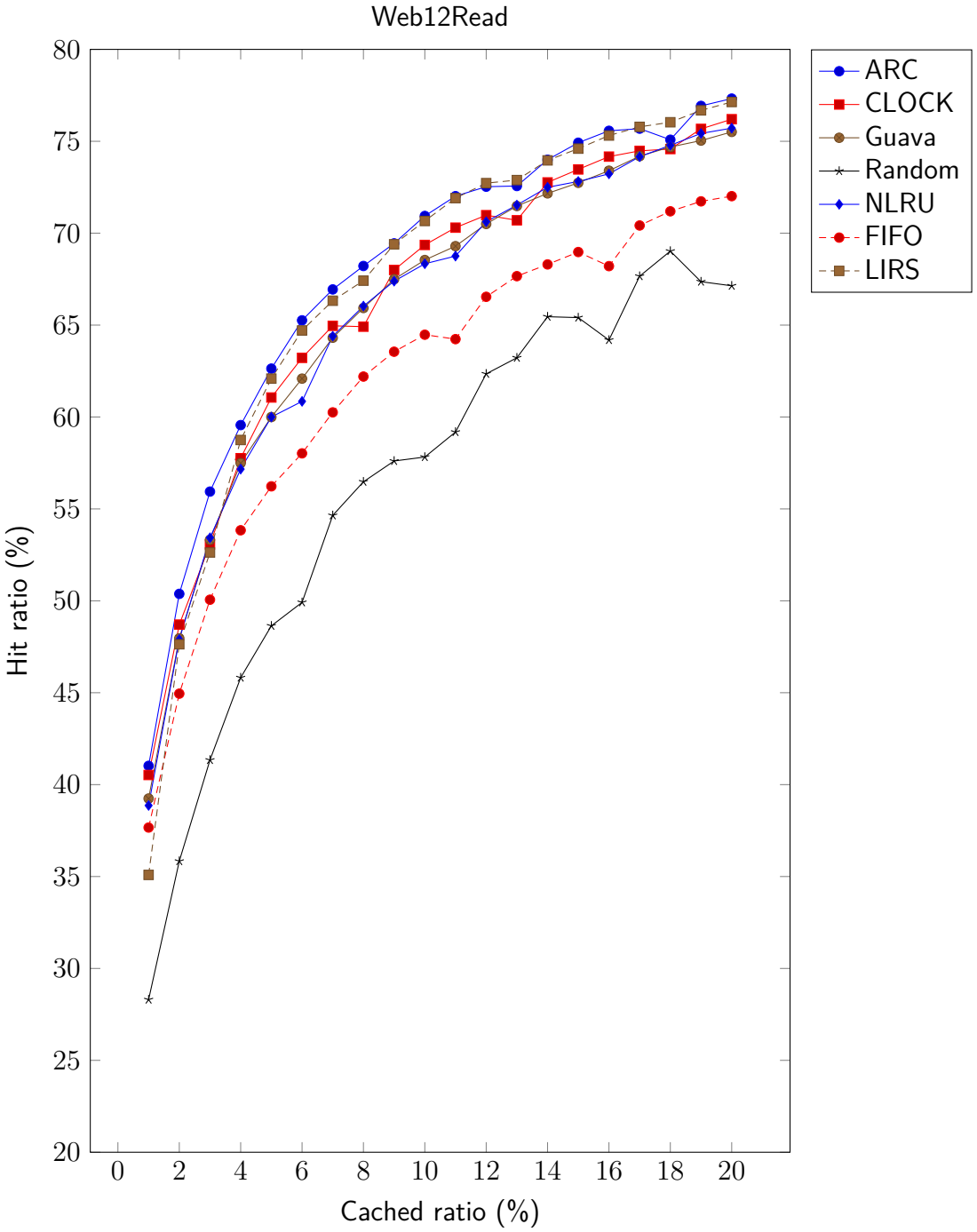

LIRSCacheRead
Avg runtime (ns)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
0
2
4
6
8
10
12
14
16
18
20

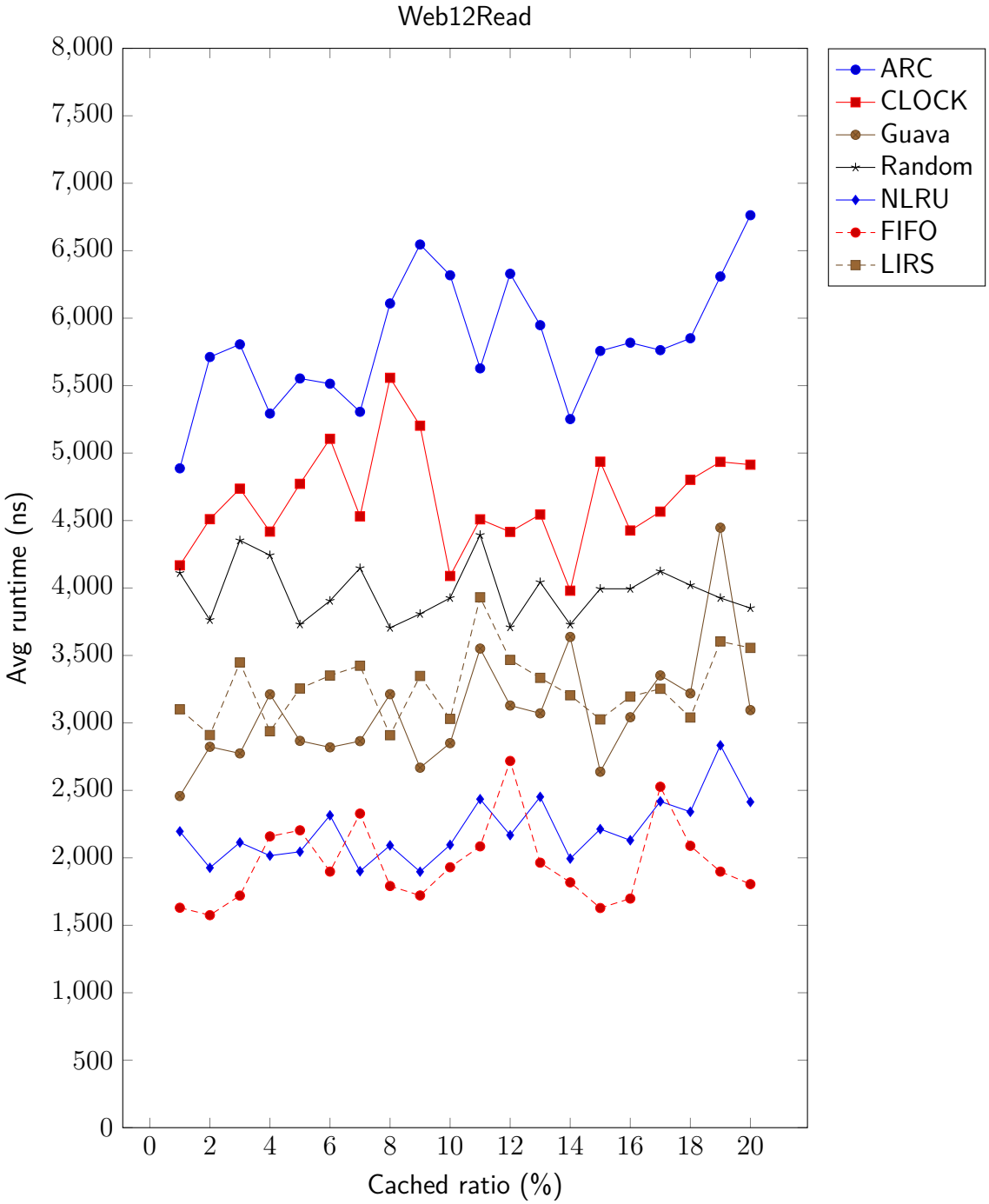

FifoCacheRead
Hit ratio (%)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20

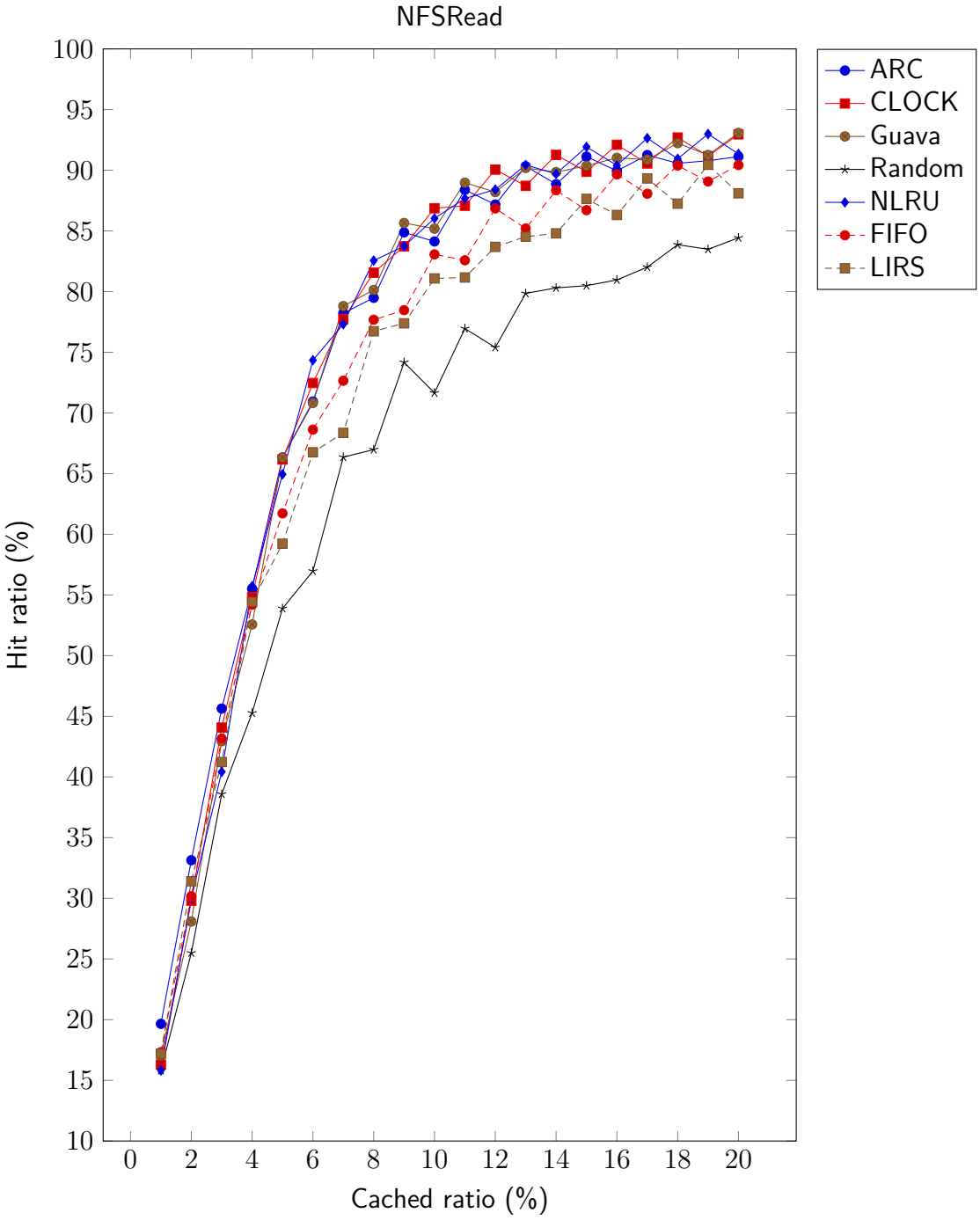

FifoCacheRead
Avg runtime (ns)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
0
2
4
6
8
10
12
14
16
18
20

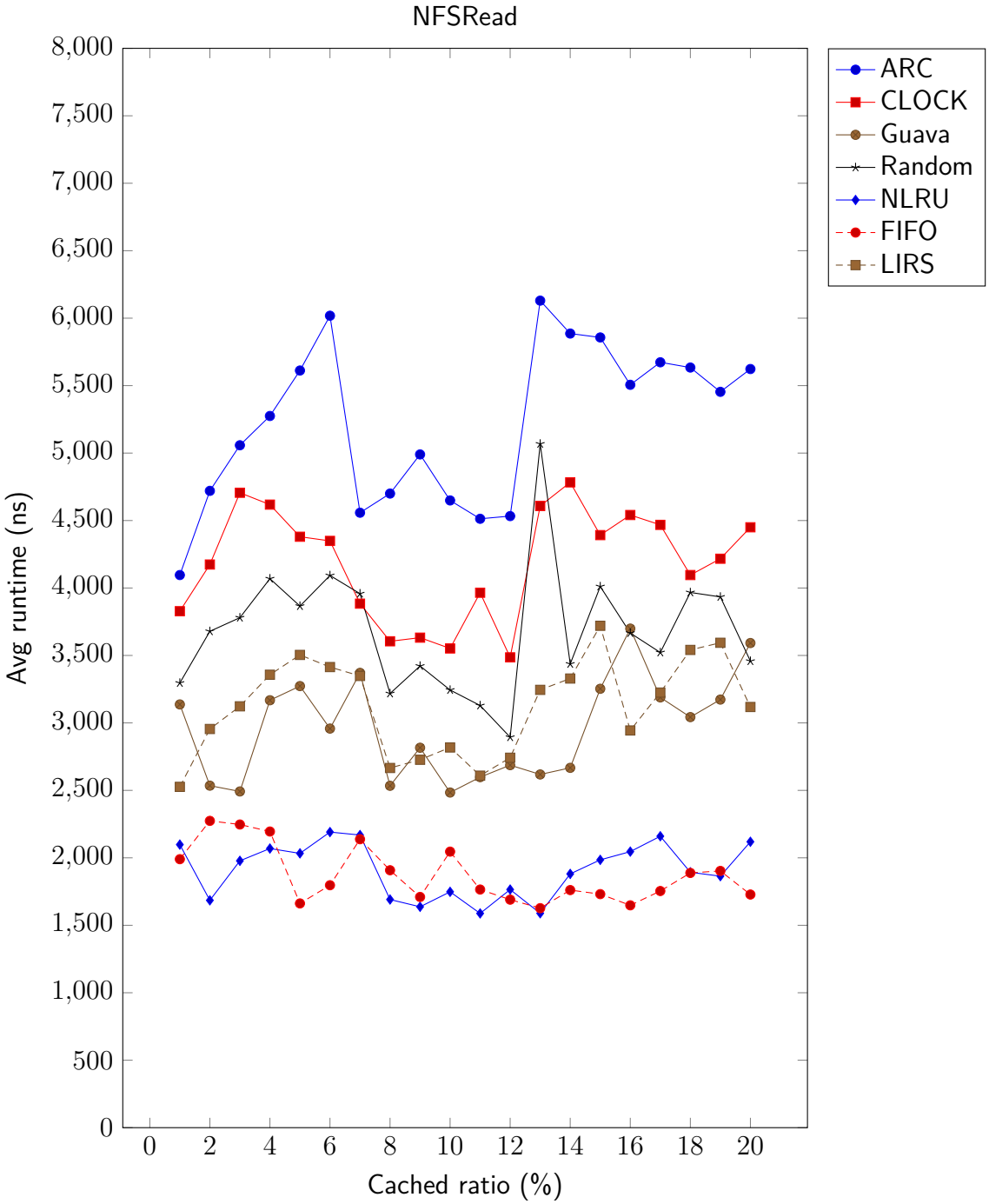

NativeLruCacheRead
Hit ratio (%)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20

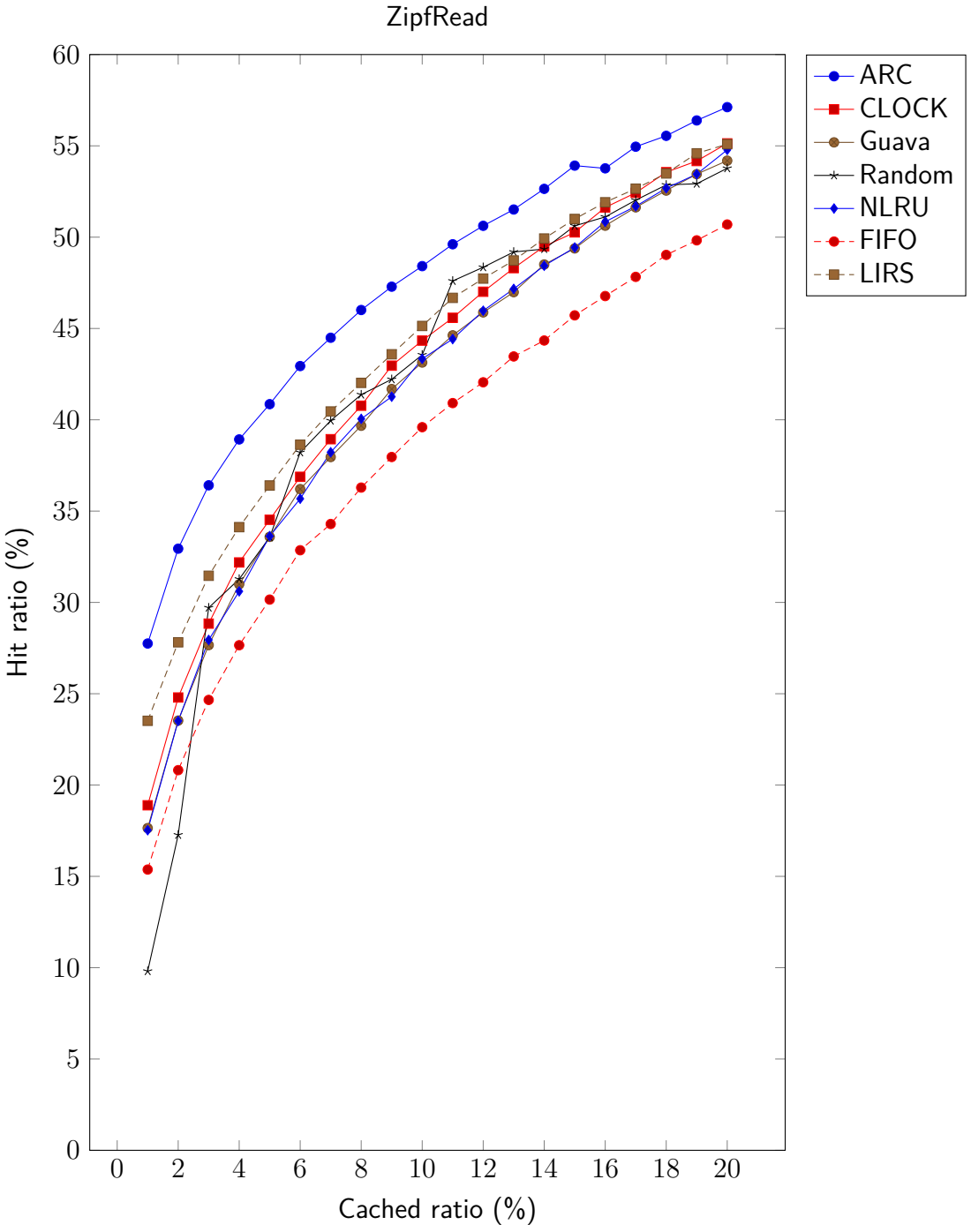

NativeLruCacheRead
Avg runtime (ns)
Cached ratio (%)
NFS
Web12
Zipf
Random
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
0
2
4
6
8
10
12
14
16
18
20

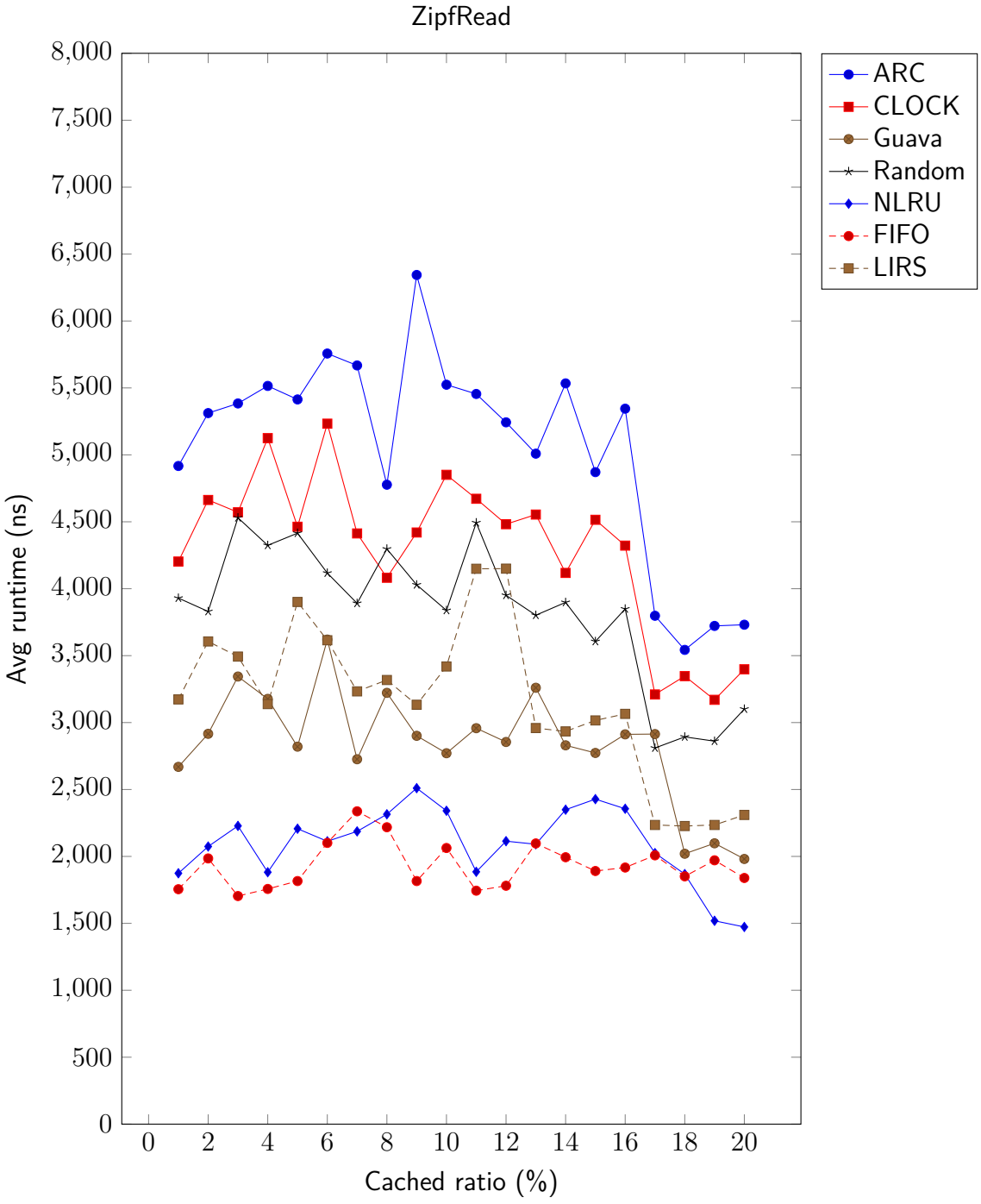

Web12Read
Hit ratio (%)
Cached ratio (%)
80
75
70
65
60
55
50
45
40
35
30
25
20
0
2
4
6
8
10
12
14
16
18
20
ARC
CLOCK
Guava
Random
NLRU
FIFO
LIRS

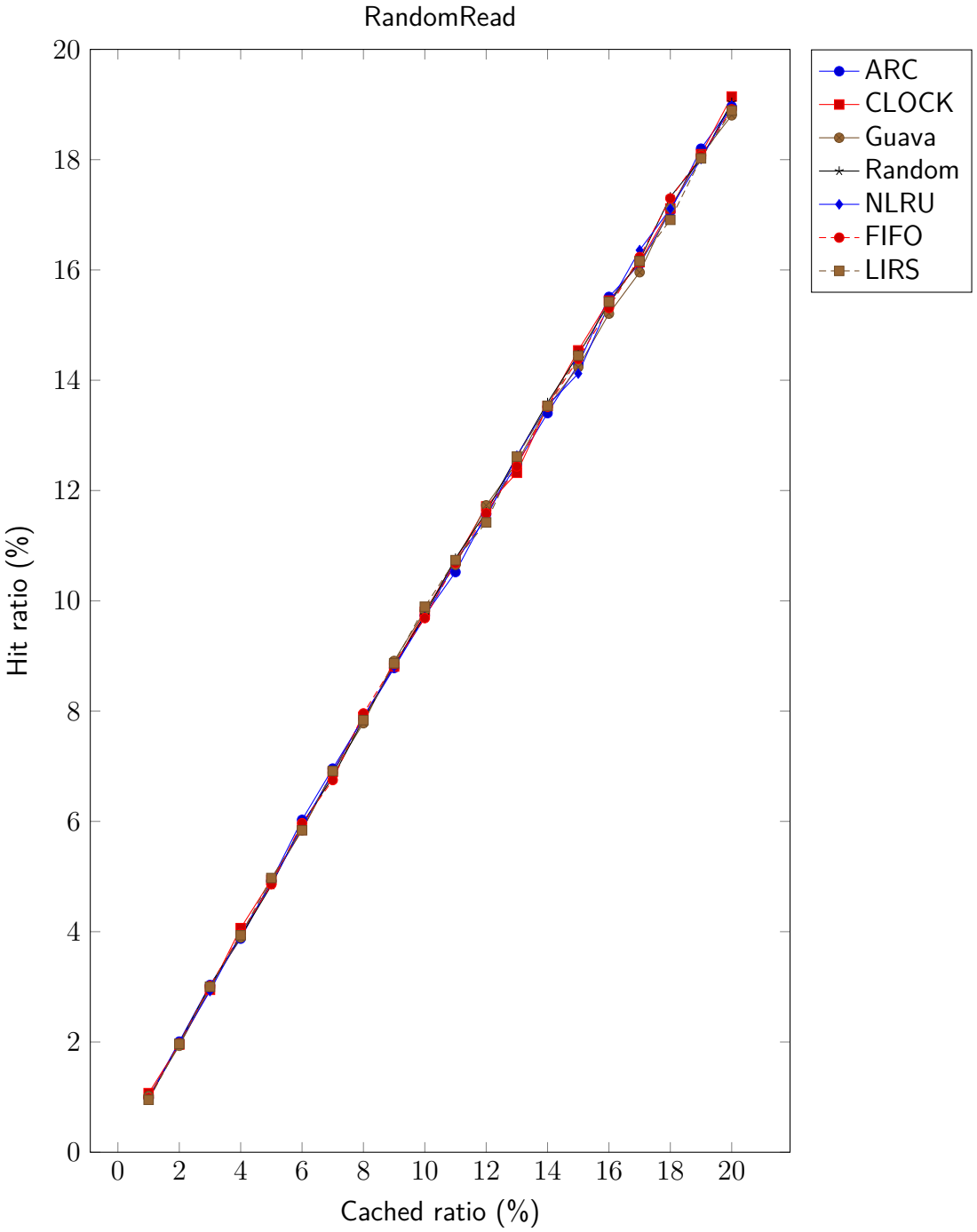

Web12Read
Avg runtime (ns)
Cached ratio (%)
8,000
7,500
7,000
6,500
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
2
4
6
8
10
12
14
16
18
20
ARC
CLOCK
Guava
Random
NLRU
FIFO
LIRS

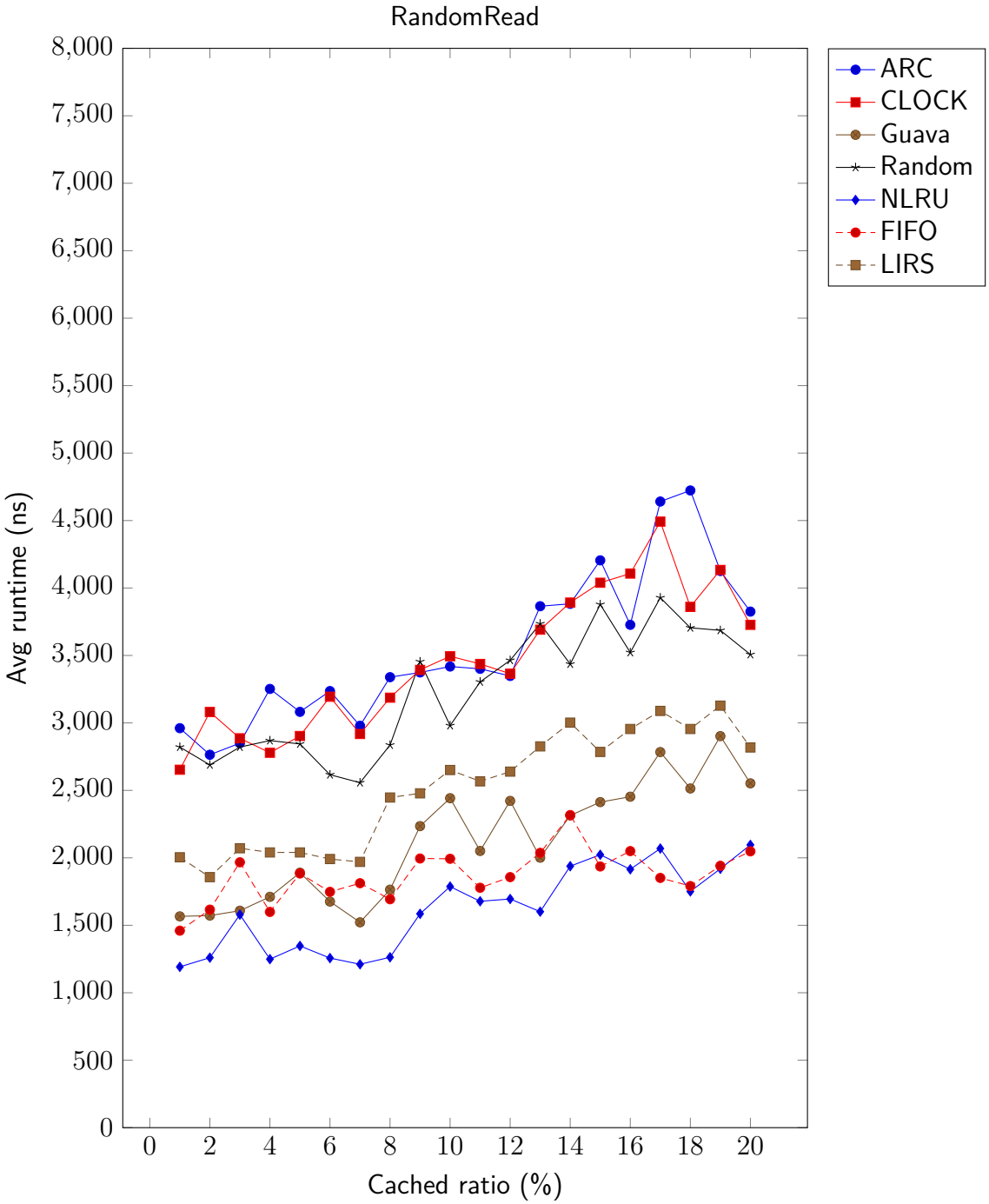

NFSRead
Hit ratio (%)
Cached ratio (%)
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
0
2
4
6
8
10
12
14
16
18
20
ARC
CLOCK
Guava
Random
NLRU
FIFO
LIRS


NFSRead
Avg runtime (ns)
Cached ratio (%)
8,000
7,500
7,000
6,500
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
2
4
6
8
10
12
14
16
18
20
ARC
CLOCK
Guava
Random
NLRU
FIFO
LIRS


ZipfRead
Hit ratio (%)
Cached ratio (%)
0
5
10
15
20
25
30
35
40
45
50
55
60
0
2
4
6
8
10
12
14
16
18
20
ARC
CLOCK
Guava
Random
NLRU
FIFO
LIRS


ZipfRead
Avg runtime (ns)
Cached ratio (%)
8,000
7,500
7,000
6,500
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
2
4
6
8
10
12
14
16
18
20
ARC
CLOCK
Guava
Random
NLRU
FIFO
LIRS


RandomRead
Hit ratio (%)
Cached ratio (%)
0
2
4
6
8
10
12
14
16
18
20
ARC
CLOCK
Guava
Random
NLRU
FIFO
LIRS


RandomRead
Avg runtime (ns)
Cached ratio (%)
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
5,500
6,000
6,500
7,000
7,500
8,000
0
2
4
6
8
10
12
14
16
18
20
ARC
CLOCK
Guava
Random
NLRU
FIFO
LIRS

# Appendix E

# Code

## E.1 Package cachebenchmarking

Listing E.1: app.src.main.java.desmedt.frederik.cachebenchmarking.BenchmarkRunner

```
package desmedt.frederik.cachebenchmarking;

import android.util.Log;
import android.util.Pair;

import java.io.IOException;
import java.lang.ref.PhantomReference;
import java.lang.ref.ReferenceQueue;
import java.lang.ref.SoftReference;
import java.util.ArrayList;
import java.util.Arrays;
import java.util.HashMap;
import java.util.LinkedList;
import java.util.List;
import java.util.Map;
import java.util.Queue;
import java.util.concurrent.ExecutorService;
import java.util.concurrent.Executors;

import desmedt.frederik.cachebenchmarking.benchmark.BaseBenchmark;
import desmedt.frederik.cachebenchmarking.benchmark.Cache2KBenchmark;
import desmedt.frederik.cachebenchmarking.benchmark.CustomBenchmark;
import desmedt.frederik.cachebenchmarking.benchmark.GuavaBenchmarks;
import desmedt.frederik.cachebenchmarking.benchmark.JackRabbitLIRSBenchmark;
import desmedt.frederik.cachebenchmarking.benchmark.NativeLruBenchmarks;
import desmedt.frederik.cachebenchmarking.cache.Cache;
import desmedt.frederik.cachebenchmarking.cache.FIFOCache;
import desmedt.frederik.cachebenchmarking.cache.RandomCache;
import desmedt.frederik.cachebenchmarking.generator.Generator;
import desmedt.frederik.cachebenchmarking.generator.NfsGenerator;
import desmedt.frederik.cachebenchmarking.generator.RandomGenerator;
import desmedt.frederik.cachebenchmarking.generator.SearchEngineGenerator;
import desmedt.frederik.cachebenchmarking.generator.Web12Generator;
import desmedt.frederik.cachebenchmarking.generator.ZipfGenerator;

/**
```

```
 * Responsible for running all {@link CacheBenchmarkConfiguration}s.
 */
public class BenchmarkRunner {

    private static final String TAG = BenchmarkRunner.class.getSimpleName();

    private Map<String, List<CacheBenchmarkConfiguration.CacheStats>>
        benchmarkResults = new HashMap<>();

    /**
     * ExecutorService executing every benchmark in a serializable fashion.
         Meaning none of them will
     * run parallel to another benchmark. This is way more reliable than parallel
         execution as in
     * parallel scenario's different benchmarks are both competing for the same
         resources and locks.
     */
    private ExecutorService benchmarkRunnerService = Executors.
        newSingleThreadExecutor();

    private Generator<Cache<Integer, Integer>> generateRandomCache(final int
        cacheSize) {
        return new Generator<Cache<Integer, Integer>>() {
            @Override
            public Cache<Integer, Integer> next() {
                return new RandomCache<>(cacheSize);
            }
        };
    }

    private Generator<Cache<Integer, Integer>> generateFifoCache(final int
        cacheSize) {
        return new Generator<Cache<Integer, Integer>>() {
            @Override
            public Cache<Integer, Integer> next() {
                return new FIFOCache<>(cacheSize);
            }
        };
    }

    public void runBenchmarks() {
        NfsGenerator nfsGenerator = new NfsGenerator();
        for (int i = 1; i <= 20; i++) {
            submitCountedReadBenchmarks(NfsGenerator.getLowerBound(), NfsGenerator
                .getUpperBound(), (double) i / 100, NfsGenerator.TRACE_TAG,
                nfsGenerator, 1000, NfsGenerator.getUpperBound() * 50);
        }
        nfsGenerator = null; // remove strong reference

        SearchEngineGenerator searchEngineGenerator = new SearchEngineGenerator();
        for (int i = 1; i <= 10; i++) {
            submitCountedReadBenchmarks(SearchEngineGenerator.getLowerBound(),
                SearchEngineGenerator.getUpperBound(), (double) i / 1000,
                SearchEngineGenerator.TRACE_TAG, searchEngineGenerator, 1000, 10
                _000);
        }
        searchEngineGenerator = null; // remove strong reference

        Web12Generator web12Generator = new Web12Generator();
        for (int i = 1; i <= 20; i++) {
            submitCountedReadBenchmarks(0, Web12Generator.getUpperBound(), (double
                ) i / 100, Web12Generator.TRACE_TAG, web12Generator, 1000, 100_000
```

```
            );
        }
        web12Generator = null;

        ZipfGenerator zipfGenerator = new ZipfGenerator(0, 50000);
        for (int i = 1; i <= 20; i++) {
            submitCountedReadBenchmarks(0, 50000, (double) i / 100, ZipfGenerator.
                TRACE_TAG, zipfGenerator, 1000, 100_000);
        }
        zipfGenerator = null;

        RandomGenerator randomGenerator = new RandomGenerator(0, 50000);
        for (int i = 1; i <= 20; i++) {
            submitCountedReadBenchmarks(0, 50000, (double) i / 100,
                RandomGenerator.TRACE_TAG, randomGenerator, 1000, 100_000);
        }
        randomGenerator = null;

        /* Insert benchmarks */

        for (int i = 1; i <= 10; i++) {
            final int upperBound = 500;
            double cacheRatio = (double) i / 10;
            final int cacheSize = Math.round(upperBound * ((float) i / 10));

            submitCountedBenchmark(new GuavaBenchmarks.Insert(cacheRatio, 0,
                upperBound));
            submitCountedBenchmark(new NativeLruBenchmarks.Insert(cacheRatio, 0,
                upperBound));
            submitCountedBenchmark(new CustomBenchmark.Insert("FifoCache",
                cacheRatio, 0, upperBound, generateFifoCache(cacheSize)));
            submitCountedBenchmark(new CustomBenchmark.Insert("RandomCache",
                cacheRatio, 0, upperBound, generateRandomCache(cacheSize)));
            submitCountedBenchmark(new JackRabbitLIRSBenchmark.Insert(cacheRatio,
                0, upperBound));
            submitCountedBenchmark(new Cache2KBenchmark.Insert(Cache2KBenchmark.
                CLOCK_CACHE, cacheRatio, 0, upperBound));
            submitCountedBenchmark(new Cache2KBenchmark.Insert(Cache2KBenchmark.
                ARC_CACHE, cacheRatio, 0, upperBound));
        }

        /* Update benchmarks */

        for (int i = 1; i <= 10; i++) {
            final int upperBound = 500;
            double cacheRatio = (double) i / 10;
            final int cacheSize = (int) Math.round(upperBound * cacheRatio);

            submitCountedBenchmark(new GuavaBenchmarks.Update(cacheRatio, 0,
                upperBound));
            submitCountedBenchmark(new NativeLruBenchmarks.Update(cacheRatio, 0,
                upperBound));
            submitCountedBenchmark(new CustomBenchmark.Update("FifoCache",
                cacheRatio, 0, upperBound, generateFifoCache(cacheSize)));
            submitCountedBenchmark(new CustomBenchmark.Update("RandomCache",
                cacheRatio, 0, upperBound, generateRandomCache(cacheSize)));
            submitCountedBenchmark(new JackRabbitLIRSBenchmark.Update(cacheRatio,
                0, upperBound));
            submitCountedBenchmark(new Cache2KBenchmark.Update(Cache2KBenchmark.
                CLOCK_CACHE, cacheRatio, 0, upperBound));
            submitCountedBenchmark(new Cache2KBenchmark.Update(Cache2KBenchmark.
                ARC_CACHE, cacheRatio, 0, upperBound));
```

```
        }

        /* Delete benchmarks */

        for (int i = 1; i <= 10; i++) {
            final int upperBound = 500;
            double cacheRatio = (double) i / 10;
            final int cacheSize = Math.round(upperBound * ((float) i / 10));

            submitCountedBenchmark(new GuavaBenchmarks.Delete(cacheRatio, 0,
                upperBound));
            submitCountedBenchmark(new NativeLruBenchmarks.Delete(cacheRatio, 0,
                upperBound));
            submitCountedBenchmark(new CustomBenchmark.Delete("FifoCache",
                cacheRatio, 0, upperBound, generateFifoCache(cacheSize)));
            submitCountedBenchmark(new CustomBenchmark.Delete("RandomCache",
                cacheRatio, 0, upperBound, generateRandomCache(cacheSize)));
            submitCountedBenchmark(new JackRabbitLIRSBenchmark.Delete(cacheRatio,
                0, upperBound));
            submitCountedBenchmark(new Cache2KBenchmark.Delete(Cache2KBenchmark.
                CLOCK_CACHE, cacheRatio, 0, upperBound));
            submitCountedBenchmark(new Cache2KBenchmark.Delete(Cache2KBenchmark.
                ARC_CACHE, cacheRatio, 0, upperBound));
        }

        benchmarkRunnerService.submit(new Runnable() {
            @Override
            public void run() {
                logBenchmarkResults();
            }
        });

        benchmarkRunnerService.shutdown();
    }

    public void resetEnvironment() {
        gc();
    }

    public void logBenchmarkResults() {
        for (Map.Entry<String, List<CacheBenchmarkConfiguration.CacheStats>> entry
             : benchmarkResults.entrySet()) {
            Log.i(TAG, TableFormatter.generateHitRatioTable(entry.getKey(), entry.
                getValue()));
            Log.i(TAG, TableFormatter.generateAvgReadRuntimeTable(entry.getKey(),
                entry.getValue()));
            Log.i(TAG, TableFormatter.generateAvgRuntimeTable(
                CacheBenchmarkConfiguration.StatType.INSERT, entry.getKey(), entry
                .getValue()));
            Log.i(TAG, TableFormatter.generateAvgRuntimeTable(
                CacheBenchmarkConfiguration.StatType.UPDATE, entry.getKey(), entry
                .getValue()));
            Log.i(TAG, TableFormatter.generateAvgRuntimeTable(
                CacheBenchmarkConfiguration.StatType.DELETE, entry.getKey(), entry
                .getValue()));
        }

//          TableFormatter hitRatioFormatter = new TableFormatter(String.format("%35
    s", "Benchmark name"), "Min hitrate", "Max hitrate");
//          int i = 0;
//          for (String benchmark : benchmarks) {
```

```
//            hitRatioFormatter.addRow(benchmark, String.format("%.4f",
    minHitrateList.get(i)), String.format("%.4f", maxHitrateList.get(i++)));
//        }
//        Log.i(TAG, hitRatioFormatter.toString());
    }

    public ExecutorService getBenchmarkRunnerService() {
        return benchmarkRunnerService;
    }

    private void submitCountedBenchmark(final CacheBenchmarkConfiguration
        benchmarkConfiguration) {
        submitCountedBenchmark(benchmarkConfiguration, 100, 1_000_000);
    }

    private void submitCountedBenchmark(final CacheBenchmarkConfiguration
        benchmarkConfiguration, final long warmupIterations, final long
        runIterations) {
        benchmarkRunnerService.submit(new Runnable() {

            @Override
            public void run() {
                benchmarkConfiguration.runMany(warmupIterations, runIterations);
                CacheBenchmarkConfiguration.CacheStats stats =
                    benchmarkConfiguration.getStats();

                if (benchmarkResults.containsKey(stats.getPolicyTag())) {
                    benchmarkResults.get(stats.getPolicyTag()).add(stats);
                } else {
                    benchmarkResults.put(stats.getPolicyTag(), new LinkedList<>(
                        Arrays.asList(stats)));
                }

                Log.i(TAG, benchmarkConfiguration.getStats().toString());
                resetEnvironment();
            }
        });
    }

    private void submitCountedReadBenchmarks(int lowerBound, int upperBound,
        double cachedRatio, String traceTag, Generator<Integer> generator, int
        warmupIterations, int runIterations) {
        final int cacheSize = (int) Math.round((upperBound - lowerBound) *
            cachedRatio);
        submitCountedBenchmark(new GuavaBenchmarks.Read(traceTag, generator,
            cachedRatio, lowerBound, upperBound), warmupIterations, runIterations)
            ;
        submitCountedBenchmark(new NativeLruBenchmarks.Read(traceTag, generator,
            cachedRatio, lowerBound, upperBound), warmupIterations, runIterations)
            ;
        submitCountedBenchmark(new CustomBenchmark.Read(FIFOCache.CACHE_TAG,
            traceTag, generator, cachedRatio, lowerBound, upperBound,
            generateFifoCache(cacheSize)), warmupIterations, runIterations);
        submitCountedBenchmark(new Cache2KBenchmark.Read(Cache2KBenchmark.
            RANDOM_CACHE, traceTag, generator, cachedRatio, lowerBound, upperBound
            ), warmupIterations, runIterations);
        submitCountedBenchmark(new JackRabbitLIRSBenchmark.Read(traceTag,
            generator, cachedRatio, lowerBound, upperBound), warmupIterations,
            runIterations);
        submitCountedBenchmark(new Cache2KBenchmark.Read(Cache2KBenchmark.
            CLOCK_CACHE, traceTag, generator, cachedRatio, lowerBound, upperBound)
            , warmupIterations, runIterations);
```

```
        submitCountedBenchmark(new Cache2KBenchmark.Read(Cache2KBenchmark.
            ARC_CACHE, traceTag, generator, cachedRatio, lowerBound, upperBound),
            warmupIterations, runIterations);
    }

    /**
     * Force the garbage collection to run, rather than suggesting it. This will
         make sure that every
     * benchmark will be run in a "fresh" memory environment, without the garbage
         collector kicking in
     * clearing objects of previous benchmarks during recording.
     */
    private void gc() {
        Log.v(TAG, "Running garbage collector");
        Object obj = new Object();
        ReferenceQueue queue = new ReferenceQueue();
        PhantomReference ref = new PhantomReference<>(obj, queue);
        obj = null;

        long end = System.currentTimeMillis() + 2_000;
        while (!ref.isEnqueued()) {
            System.gc();
            if (System.currentTimeMillis() > end) {
                Log.v(TAG, "No garbage collection needed!");
                return;
            }
        }

        Log.v(TAG, "Memory is garbage collected");
    }
}
```

Listing E.2: app.src.main.java.desmedt.frederik.cachebenchmarking.CacheBenchmarkConfiguration

```
package desmedt.frederik.cachebenchmarking;

import android.util.Log;
import android.util.Pair;

/**
 * A benchmark configuration ran by the {@link BenchmarkRunner}.
 * <p/>
 * Note how this class is immutable, this is to enforce a reliable never-changing
     configuration
 * that maintains the integrity of the end results.
 * After the benchmark is run {@link CacheStats} are generated that can be
     retrieved.
 * <p/>
 * Every cache benchmark configuration handles keys and values, where the key is {
     @link Comparable}.
 */
public abstract class CacheBenchmarkConfiguration<K extends Comparable, V> {

    /**
     * How many times should the configuration log updates in a complete
         configuration run
     * ({@link CacheBenchmarkConfiguration#runMany(long, long)} or {@link
         CacheBenchmarkConfiguration#runTimed(long, long)}.
     */
    private static final int CONFIGURATION_RUN_LOG_POINT_COUNT = 5;
```

```
    public final String TAG;
    private final String name;
    private final String policyTag;
    private final String traceTag;
    private final double cacheRatio;

    private K lowerKeyBound;
    private K upperKeyBound;

    private CacheStats stats;
    private long totalTimeNanos;

    public CacheBenchmarkConfiguration(String policyTag, String traceTag, double
        cacheRatio, K lowerBound, K upperBound) {
        this.name = policyTag + traceTag + "␣(" + String.format("%.1f%%",
            cacheRatio * 100) + ")";
        this.policyTag = policyTag;
        this.traceTag = traceTag;
        this.cacheRatio = cacheRatio;
        TAG = CacheBenchmarkConfiguration.class.getSimpleName() + "␣-␣" + name;
        this.lowerKeyBound = lowerBound;
        this.upperKeyBound = upperBound;
    }

    public K getLowerKeyBound() {
        return lowerKeyBound;
    }

    public K getUpperKeyBound() {
        return upperKeyBound;
    }

    public String getName() {
        return name;
    }

    public double getCacheRatio() {
        return cacheRatio;
    }

    public String getPolicyTag() {
        return policyTag;
    }

    public String getTraceTag() {
        return traceTag;
    }

    /**
     * Run the operation the benchmark is supposed to evaluate exactly once. The
         behaviour,
     * such as the speed, of this method is recorded and used to generate the
         final result of the
     * configuration. Therefore it is essential that this is as high performance
         as it can be, e.g.
     * you shouldn't log non-essential information or have an entire try-catch
         block unless if this
     * is absolutely necessary.
     *
     * @param key   The key used in the operation, can be null if it is not used
         in some specific
     *              implementation. The key will always be within the lower and
```

```
     upper bounds.
 * @param value The value used in the operation, can be null if it is not used
     in some specific
 *              implementation.
 * @return true if the run succeeded, say by a cache success, false if the run
     did not succeed,
 * say by a cache miss
 */
protected abstract boolean run(K key, V value);

/**
 * Generates a possible input for the next run. If the input to {@link
     CacheBenchmarkConfiguration#run(Comparable, Object)}
 * is irrelevant this could return <code>null</code>. Note how this can have
     an arbitrary
 * probability distribution when picking a value from the input space. In
     other words, you could
 * always return the same value from the input space (the obvious one being <
     code>null</code>),
 * or you could have a perfectly random distribution. This method is not
     recorded/timed.
 *
 * @return A key-value pair used as a possible input for a single run
 */
protected abstract Pair<K, V> generateInput();

/**
 * Generates statistics regarding the cache that is being benchmarked. Based
     on the type of benchmark
 * some of the properties of the returned stats are allowed to be null.
 * <p/>
 * This method should not be used when trying to get an overview of benchmark
     statistics,
 * {@link CacheBenchmarkConfiguration#getStats()} should be used instead.
 *
 * @return Statistics relating to the cache
 * @see CacheStats
 */
protected abstract CacheStats generateStats();

/**
 * Optional step performed after initialization and before the benchmark run.
 * Here the benchmark configuration has the chance of performing operations
     that should be run a
 * single time before the benchmark is started, like initializing the cache.
 * This method is not recorded/timed.
 */
protected void setup() {
}

/**
 * Optional step performed after the complete benchmark run with
 * {@link CacheBenchmarkConfiguration#runMany(long, long)} and
 * {@link CacheBenchmarkConfiguration#runTimed(long, long)}. Here the
     benchmark configuration has
 * the chance of performing operations that should be run a single time after
     the benchmark run,
 * like purging the cache. This method is not recorded/timed.
 */
protected void tearDown() {
}
```

```
/**
 * Optional intermediary step performed before each single run. Here the
     benchmark configuration has
 * the chance of performing dependent operations that are required in the run,
     yet should not be
 * recorded. Therefore this method is not recorded/timed.
 */
protected void prepare() {
}

/**
 * Optional intermediary step performed after each single run. Here the
     benchmark configuration has the
 * chance of cleaning everything up to maintain reliable runs. This method is
     not recorded/timed.
 *
 * @param key       The key of the last run
 * @param value     The value of the last run
 * @param succeeded Whether the last run succeeded or not
 */
protected void cleanup(K key, V value, boolean succeeded) {
}

/**
 * Generates a legal key-value pair to be used as an input for a single run by
     using
 * {@link CacheBenchmarkConfiguration#generateInput()} and then checking the
     lower and upper bounds.
 *
 * @return A legal input key-value pair
 */
private Pair<K, V> generateLegalInput() {
    final Pair<K, V> input = generateInput();

    if (input != null && (input.first.compareTo(lowerKeyBound) < 0 || input.
        first.compareTo(upperKeyBound) > 0)) {
        throw new IllegalArgumentException("Generated an input " + input.
            toString() + " that is either lower or higher than the lower or
            upper bound!");
    }

    return input;
}

/**
 * Runs the configuration <code>warmupIterations + runIterations</code> times,
     using
 * {@link CacheBenchmarkConfiguration#run(Comparable, Object)} to execute the
     operation and
 * {@link CacheBenchmarkConfiguration#generateInput()} to generate a random
     input. These results will
 * then be collected and returned.
 *
 * @param warmupIterations How many iterations the configuration should be run
     before recording
 *                         the results
 * @param runIterations    How many iterations the configuration should be run
     and recorded
 * @returns The final result after completing all iterations
 */
public final void runMany(long warmupIterations, long runIterations) {
    setup();
```

```
        final long logPoint = runIterations / CONFIGURATION_RUN_LOG_POINT_COUNT;

        Log.v(TAG, "Starting warmup");
        for (int i = 0; i < warmupIterations; i++) {
            runAndRecord();
        }

        Log.v(TAG, "Completed warmup, starting run");

        for (int i = 0; i < runIterations; i++) {
            runAndRecord();
            if (i % logPoint == 0 && i != 0) {
                Log.v(TAG, String.format("Reached %d iterations after %d millis",
                    i, totalTimeNanos / 1_000_000));
            }
        }

        stats = generateStats();
        stats.benchmarkName = getName();
        stats.policyTag = policyTag;
        stats.traceTag = traceTag;
        stats.cacheRatio = cacheRatio;
        stats.averageRunTime = totalTimeNanos / runIterations;
        tearDown();
        Log.v(TAG, "Completed run");
    }

    /**
     * Runs the configuration for <code>millis</code> milliseconds, using
     * {@link CacheBenchmarkConfiguration#run(Comparable, Object)} to execute the
        operation and
     * {@link CacheBenchmarkConfiguration#generateInput()} to generate a random
        input. These results will
     * then be collected and returned.
     *
     * @param warmupMillis How long the warmup run should be in milliseconds
     * @param runMillis    How long the actual recorded run should be in
        milliseconds
     * @returns The final result after completing all iterations fitting in <code>
        runMillis</code> milliseconds
     */
    public final void runTimed(long warmupMillis, long runMillis) {
        setup();
        long nextLogPoint = runMillis / CONFIGURATION_RUN_LOG_POINT_COUNT;

        Log.i(TAG, "Starting warmup");
        while (totalTimeNanos < warmupMillis) {
            runAndRecord();
        }

        Log.i(TAG, "Completed warmup, starting run");

        totalTimeNanos = 0;
        int totalIterations = 0;
        while (totalTimeNanos < runMillis) {
            totalIterations++;
            runAndRecord();
            if (totalTimeNanos / 1_000_000 >= runMillis) {
                // Stop the loop as the recording passed the specified run time
                // Repeating the run until there is a recording that fits in the
                    specified run time
                // is both indeterministic and unfair.
```

```
                break;
            }

            if (totalTimeNanos >= nextLogPoint) {
                Log.v(TAG, String.format("Reached␣%d␣iterations␣after␣%d␣millis",
                    totalIterations,
                        totalTimeNanos / 1_000_000));
                nextLogPoint = nextLogPoint + runMillis /
                    CONFIGURATION_RUN_LOG_POINT_COUNT;
            }
        }

        stats = generateStats();
        stats.benchmarkName = getName();
        stats.policyTag = policyTag;
        stats.traceTag = traceTag;
        stats.cacheRatio = cacheRatio;
        stats.averageRunTime = totalTimeNanos / totalIterations;
        tearDown();
        Log.i(TAG, "Completed␣run");
    }

    private void runAndRecord() {
        prepare();
        final Pair<K, V> input = generateLegalInput();
        long before = 0;
        long after = 0;
        boolean succeeded;

        if (input == null) {
            before = System.nanoTime();
            succeeded = run(null, null);
            after = System.nanoTime();
        } else {
            before = System.nanoTime();
            succeeded = run(input.first, input.second);
            after = System.nanoTime();
        }

        cleanup(input.first, input.second, succeeded);
        totalTimeNanos += after - before;
    }

    /**
     * Get stats of the benchmark configuration, consisting of a combination of
         statistics generated
     * by the base {@link CacheBenchmarkConfiguration} and statistics generated by
          the cache itself.
     * <p/>
     * When the benchmark configuration is has not been run or is not yet finished
         , this will return
     * null.
     *
     * @return Reliable cache statistics
     */
    public CacheStats getStats() {
        return stats;
    }

    /**
     * Represents statistics of the cache used in the cache benchmark. Several
         statistics might be null
```

```
     * based on the use case.
     */
    public static class CacheStats {

        private Integer successCount;
        private Integer failureCount;
        private Integer maxCacheSize;
        private Integer cacheEntryCount;

        private String benchmarkName;
        private double averageRunTime;

        private String policyTag;
        private String traceTag;
        private double cacheRatio;

        private final StatType type;

        private CacheStats(StatType type) {
            this.type = type;
        }

        /**
         * A Simple Factory used for creating {@link CacheStats} of a cache
             benchmark where reading
         * a cache is recorded.
         *
         * @param successCount     The amount of successful reads that have
             occurred in the current benchmark
         *                         configuration
         * @param failureCount     The amount of failed reads that have occurred in
              the current benchmark
         *                         configuration
         * @param cacheSize        The cache size of the cache used in the
             benchmark configuration (in entries), with
         *                         a dynamically sized cache this is the maximum
             amount of entries
         * @param cacheEntryCount The amount of cache entries in the cache used in
              the benchmark configuration
         * @return A {@link CacheStats} object containing the specified data
         */
        public static CacheStats read(int successCount, int failureCount, int
            cacheSize, int cacheEntryCount) {
            CacheStats metrics = new CacheStats(StatType.READ);
            metrics.successCount = successCount;
            metrics.failureCount = failureCount;
            metrics.maxCacheSize = cacheSize;
            metrics.cacheEntryCount = cacheEntryCount;
            return metrics;
        }

        /**
         * A Simple Factory used for creating {@link CacheStats} of a cache
             benchmark where
         * inserting, updating or deleting a cache is recorded.
         *
         * @param maxCacheSize     The cache size of the cache used in the
             benchmark configuration (in entries), with
         *                         a dynamically sized cache this is the maximum
             amount of entries
         * @param cacheEntryCount The amount of cache entries in the cache used in
              the benchmark configuration
```

```
     * @return A {@link CacheStats} object containing the specified data
     */
    public static CacheStats nonRead(StatType type, int maxCacheSize, int
        cacheEntryCount) {
        CacheStats metrics = new CacheStats(type);
        metrics.maxCacheSize = maxCacheSize;
        metrics.cacheEntryCount = cacheEntryCount;
        return metrics;
    }

    /**
     * @return The amount of successful reads that have occurred in the
         current benchmark
     * configuration. Null if the benchmark configuration is not a reading
         benchmark.
     */
    public Integer getSuccessCount() {
        return successCount;
    }

    /**
     * @return The amount of failed reads that have occurred in the current
         benchmark
     * configuration. Null if the benchmark configuration is not a reading
         benchmark.
     */
    public Integer getFailureCount() {
        return failureCount;
    }

    /**
     * @return The cache size of the cache used in the benchmark configuration
         (in entries), with
     * a dynamically sized cache this is the maximum amount of entries.
     */
    public Integer getMaxCacheSize() {
        return maxCacheSize;
    }

    /**
     * @return The amount of cache entries in the cache used in the benchmark
         configuration.
     * Null if this does not make sense in the current benchmark configuration
         , e.g. a delete
     * benchmark that should always have 0 cache entries after each run.
     */
    public Integer getCacheEntryCount() {
        return cacheEntryCount;
    }

    private void setBenchmarkName(String benchmarkName) {
        this.benchmarkName = benchmarkName;
    }

    private void setCacheRatio(double cacheRatio) {
        this.cacheRatio = cacheRatio;
    }

    private void setPolicyTag(String policyTag) {
        this.policyTag = policyTag;
    }
```

```
    private void setTraceTag(String traceTag) {
        this.traceTag = traceTag;
    }

    /**
     * Sets the average runtime, should only be set by the base {@link
         CacheBenchmarkConfiguration}.
     *
     * @param averageRunTime The average runtime in nanoseconds
     */
    private void setAverageRunTime(double averageRunTime) {
        this.averageRunTime = averageRunTime;
    }

    public double getAverageRunTime() {
        return averageRunTime;
    }

    public String getBenchmarkName() {
        return benchmarkName;
    }

    /**
     * @return The average hitrate of the run, which is a number where {@code
         0 <= val <= 100}
     */
    public double getHitrate() {
        return (double) successCount / (successCount + failureCount) * 100;
    }

    public String getPolicyTag() {
        return policyTag;
    }

    public String getTraceTag() {
        return traceTag;
    }

    public double getCacheRatio() {
        return cacheRatio;
    }

    public String getPolicyWithCacheRatio() {
        return policyTag + "␣(" + String.format("%.3f)", cacheRatio);
    }

    public StatType getStatType() {
        return type;
    }

    @Override
    public String toString() {
        final StringBuilder builder = new StringBuilder(String.format("%-25s␣"
            , benchmarkName));

        builder.append(String.format("Cache␣size:␣%-5d␣", maxCacheSize));

        if (getStatType() == StatType.READ) {
            builder.append(String.format("Hit␣ratio:␣%-5.3f%%␣␣␣␣␣", (double)
                successCount / (successCount + failureCount) * 100));
        }
```

```
            builder.append(String.format("Average␣(ns):␣%-7.1f␣␣␣␣␣",
                averageRunTime));

            if (successCount != null) {
                builder.append(String.format("Successes:␣%-8d␣␣␣␣␣", successCount)
                    );
            }

            if (failureCount != null) {
                builder.append(String.format("Failures:␣%-8d␣␣␣␣␣", failureCount))
                    ;
            }

            if (cacheEntryCount != null) {
                builder.append(String.format("Cache␣entries:␣%-5d",
                    cacheEntryCount));
            }

            return builder.toString();
        }
    }

    public enum StatType {
        READ, INSERT, UPDATE, DELETE
    }
}
```

Listing E.3: app.src.main.java.desmedt.frederik.cachebenchmarking.TableFormatter

```
package desmedt.frederik.cachebenchmarking;

import java.util.ArrayList;
import java.util.Arrays;
import java.util.Collection;
import java.util.Collections;
import java.util.Comparator;
import java.util.HashMap;
import java.util.LinkedList;
import java.util.List;
import java.util.Map;
import java.util.StringTokenizer;

/**
 * Create a {@link String}-based table based on columns and multiple rows
 */
public class TableFormatter {

    private List<String> columnNames = new ArrayList<>();
    private List<List<?>> rows = new ArrayList<>();

    public TableFormatter() {
    }

    public TableFormatter(String... columns) {
        this(Arrays.asList(columns));
    }

    public TableFormatter(Collection<String> columns) {
        for (String column : columns) {
            addColumn(column);
        }
```

```
    }

    public TableFormatter addColumn(String column) {
        columnNames.add(column);
        return this;
    }

    public TableFormatter addRow(Object... columnValues) {
        return addRow(Arrays.asList(columnValues));
    }

    public TableFormatter addRow(Collection<?> columnValues) {
        rows.add(new LinkedList<>(columnValues));
        return this;
    }

    public TableFormatter addRow(RowBuilder rowBuilder) {
        rows.add(rowBuilder.values);
        return this;
    }

    /**
     * Sort all rows currently received by the values in the column at index {
         @code columnIndex}.
     *
     * @param columnIndex the column index on which should be sorted
     */
    public TableFormatter sort(int columnIndex) {
        Collections.sort(rows, new SingleColumnRowComparator(columnIndex));
        return this;
    }

    @Override
    public String toString() {
        final List<Integer> columnWidths = new ArrayList<>();
        final StringBuilder builder = new StringBuilder();

        for (List<?> row : rows) {
            for (int i = 0; i < row.size(); i++) {
                if (i < columnWidths.size()) {
                    final int columnWidth = row.get(i).toString().length();
                    if (columnWidths.get(i) < columnWidth) {
                        columnWidths.set(i, columnWidth);
                    }
                } else {
                    columnWidths.add(row.get(i).toString().length());
                }
            }
        }

        for (int i = 0; i < columnNames.size(); i++) {
            if (i < columnWidths.size()) {
                final String column = columnNames.get(i);
                final int columnWidth = column.toString().length();
                if (columnWidths.get(i) < columnWidth) {
                    columnWidths.set(i, columnWidth);
                }

                builder.append(String.format("␣%" + columnWidths.get(i) + "s␣",
                    column));
            }
        }
```

```
        builder.append(String.format("%n"));
        for (Collection<?> row : rows) {
            int i = 0;
            for (Object value : row) {
                builder.append(String.format("␣%" + columnWidths.get(i++) + "s␣",
                    value.toString()));
            }

            builder.append(String.format("%n"));
        }

        return builder.toString();
    }

    public static String formatRow(String... values) {
        StringBuilder builder = new StringBuilder();
        for (String value : values) {
            builder.append(value);
        }

        return builder.toString();
    }

    public static String generateHitRatioTable(String policyTag, Collection<
        CacheBenchmarkConfiguration.CacheStats> stats) {
        TableFormatter table = new TableFormatter("Cache␣size");
        Map<Double, RowBuilder> cacheRatioRowMap = new HashMap<>();
        List<String> tagIndexer = new ArrayList<>(stats.size() + 1);
        tagIndexer.add("");
        for (CacheBenchmarkConfiguration.CacheStats stat : stats) {
            if (stat.getStatType() == CacheBenchmarkConfiguration.StatType.READ) {
                if (!tagIndexer.contains(stat.getTraceTag())) {
                    tagIndexer.add(stat.getTraceTag());
                    table.addColumn(stat.getTraceTag());
                }

                if (!cacheRatioRowMap.containsKey(stat.getCacheRatio())) {
                    cacheRatioRowMap.put(stat.getCacheRatio(), new RowBuilder(
                        String.format("%.2f%%", stat.getCacheRatio() * 100)));
                }

                cacheRatioRowMap.get(stat.getCacheRatio()).insertValue(tagIndexer.
                    indexOf(stat.getTraceTag()), String.format("%.3f%%", stat.
                    getHitrate()));
            }
        }

        for (RowBuilder builder : cacheRatioRowMap.values()) {
            table.addRow(builder);
        }

        return table.rows.isEmpty() ? "" : new StringBuilder(String.format("%s␣-␣%
            s␣-␣Hit␣ratios%n", policyTag, CacheBenchmarkConfiguration.StatType.
            READ.toString())).append(table.sort(0).toString()).toString();
    }

    public static String generateAvgReadRuntimeTable(String policyTag, Collection<
        CacheBenchmarkConfiguration.CacheStats> stats) {
        TableFormatter table = new TableFormatter("Cache␣size");
        Map<Double, RowBuilder> avgReadRowMap = new HashMap<>();
        List<String> tagIndexer = new ArrayList<>(stats.size() + 1);
```

```
        tagIndexer.add("");
        for (CacheBenchmarkConfiguration.CacheStats stat : stats) {
            if (stat.getStatType() == CacheBenchmarkConfiguration.StatType.READ) {
                if (!tagIndexer.contains(stat.getTraceTag())) {
                    tagIndexer.add(stat.getTraceTag());
                    table.addColumn(stat.getTraceTag());
                }

                if (!avgReadRowMap.containsKey(stat.getCacheRatio())) {
                    avgReadRowMap.put(stat.getCacheRatio(), new RowBuilder(String.
                        format("%.2f%%", stat.getCacheRatio() * 100)));
                }

                avgReadRowMap.get(stat.getCacheRatio()).insertValue(tagIndexer.
                    indexOf(stat.getTraceTag()), String.format("%.1f", stat.
                    getAverageRunTime()));
            }
        }

        for (RowBuilder builder : avgReadRowMap.values()) {
            table.addRow(builder);
        }

        return table.rows.isEmpty() ? "" : new StringBuilder(String.format("%s - %
            s - Average execution time (ns)%n", policyTag,
            CacheBenchmarkConfiguration.StatType.READ)).append(table.sort(0).
            toString()).toString();
    }

    public static String generateAvgRuntimeTable(CacheBenchmarkConfiguration.
        StatType statType, String policyTag, Collection<
        CacheBenchmarkConfiguration.CacheStats> stats) {
        if (statType == CacheBenchmarkConfiguration.StatType.READ) {
            return generateAvgReadRuntimeTable(policyTag, stats);
        }

        TableFormatter table = new TableFormatter("Cache ratio", "Cache size", "
            Avg runtime (ns)");
        Map<Double, RowBuilder> avgReadRowMap = new HashMap<>();
        for (CacheBenchmarkConfiguration.CacheStats stat : stats) {
            if (stat.getStatType() == statType) {
                if (!avgReadRowMap.containsKey(stat.getCacheRatio())) {
                    avgReadRowMap.put(stat.getCacheRatio(), new RowBuilder(String.
                        format("%.2f%%", stat.getCacheRatio() * 100), stat.
                        getMaxCacheSize().toString(), String.format("%.1f", stat.
                        getAverageRunTime())));
                }
            }
        }

        for (RowBuilder builder : avgReadRowMap.values()) {
            table.addRow(builder);
        }

        return table.rows.isEmpty() ? "" : new StringBuilder(String.format("%s - %
            s - Average execution time (ns)%n", policyTag, statType.toString())).
            append(table.sort(0).toString()).toString();
    }

    public static class RowBuilder {

        private List<String> values;
```

```
        public RowBuilder() {
            values = new LinkedList<>();
        }

        public RowBuilder(String... values) {
            this(new LinkedList<>(Arrays.asList(values)));
        }

        public RowBuilder(Collection<String> values) {
            this.values = new LinkedList<>(values);
        }

        public RowBuilder addValue(String value) {
            values.add(value);
            return this;
        }

        public RowBuilder insertValue(int index, String value) {
            if (index >= values.size()) {
                for (int i = 0; values.size() < index; i++) {
                    values.add("");
                }

                values.add(value);
            } else {
                values.add(index, value);
            }

            return this;
        }

        public List<String> build() {
            return values;
        }

    }

    private static class SingleColumnRowComparator implements Comparator<List<?>>
        {

        private int columnIndex;

        public SingleColumnRowComparator(int columnIndex) {
            this.columnIndex = columnIndex;
        }

        @Override
        public int compare(List<?> lhs, List<?> rhs) {
            if (lhs.size() <= columnIndex) {
                return 1;
            }

            if (rhs.size() <= columnIndex) {
                return -1;
            }

            Object left = lhs.get(columnIndex);
            Object right = rhs.get(columnIndex);

            try {
                double leftValue;
```

```
                if (left.toString().endsWith("%")) {
                    leftValue = Double.parseDouble(left.toString().substring(0,
                        left.toString().length() - 1));
                } else {
                    leftValue = Double.parseDouble(left.toString());
                }

                double rightValue;
                if (right.toString().endsWith("%")) {
                    rightValue = Double.parseDouble(right.toString().substring(0,
                        right.toString().length() - 1));
                } else {
                    rightValue = Double.parseDouble(right.toString());
                }

                return leftValue < rightValue ? -1 : 1;
            } catch (NumberFormatException nfex) {
                return left.toString().compareTo(right.toString());
            }
        }
    }
}
```

## E.2 Package cachebenchmarking.benchmark

Listing E.4: app.src.main.java.desmedt.frederik.cachebenchmarking.benchmark.BaseBenchmark

```
package desmedt.frederik.cachebenchmarking.benchmark;

import android.util.Pair;

import java.util.Random;

import desmedt.frederik.cachebenchmarking.CacheBenchmarkConfiguration;
import desmedt.frederik.cachebenchmarking.generator.Generator;
import desmedt.frederik.cachebenchmarking.generator.RandomGenerator;
import desmedt.frederik.cachebenchmarking.generator.ZipfGenerator;

/**
 * A collection of basic {@link desmedt.frederik.cachebenchmarking.
     CacheBenchmarkConfiguration} that
 * implement common code while remaining cache independent.
 */
public class BaseBenchmark {

    public static final String INSERT_TAG = "Insert";
    public static final String DELETE_TAG = "Delete";
    public static final String UPDATE_TAG = "Update";

    /**
     * Base benchmark configuration used by all static classes in {@link
         BaseBenchmark}.
     * It contains all common functionalities of its subclasses as well as
         management of benchmark
     * {@link CacheBenchmarkConfiguration#setup()} and {@link
         CacheBenchmarkConfiguration#tearDown()}.
     * <p/>
```

```
     * It expects the cache to be based on {@link Integer} keys.
     *
     * @param <V> The type of values that will be stored in the cache
     */
    public static abstract class BaseBenchmarkConfiguration<V> extends
        CacheBenchmarkConfiguration<Integer, V> {

        private int cacheSize;

        public BaseBenchmarkConfiguration(String policyTag, String traceTag,
            double cachedRatio, Integer lowerBound, Integer upperBound) {
            super(policyTag, traceTag, cachedRatio, lowerBound, upperBound);
            cacheSize = (int) Math.round((upperBound - lowerBound) * cachedRatio);
        }

        @Override
        protected void setup() {
            createCache(cacheSize);
        }

        @Override
        protected void tearDown() {
            clearCache();
        }

        /**
         * Generate a random value to be used as a value in a run.
         *
         * @return A random value
         */
        protected abstract V generateValue();

        /**
         * Create the cache that is used for benchmarking of size {@code cacheSize
             }. This method is
         * called only once before the benchmark run and is not timed.
         *
         * @param cacheSize The maximum amount of entries the cache should have
         */
        protected abstract void createCache(int cacheSize);

        /**
         * Completely clear the cache used for benchmarking. This means cleaning
             as much as possible
         * and possibly even removing the cache reference for the garbage
             collector in case there are
         * lots of strong references that are maintained. This method is called
             only after the complete
         * benchmark run and is not timed.
         */
        protected abstract void clearCache();

        public int getCacheSize() {
            return cacheSize;
        }
    }

    public static abstract class Read<V> extends BaseBenchmarkConfiguration<V> {

        private Generator<Integer> randomGenerator;

        /**
```

```
         *
         * @param name The name of the cache policy used
         * @param traceTag The name of trace used
         * @param traceGenerator A generator representing some trace
         * @param cachedRatio How much of the total key space should be available
             in the cache, {@code 0 <= cachedRatio <= 1}
         * @param lowerBound The lower bound of the key space
         * @param upperBound The upper bound of the key space
         */
        public Read(String name, String traceTag, Generator<Integer>
            traceGenerator, double cachedRatio, Integer lowerBound, Integer
            upperBound) {
            super(name + "Read", traceTag, cachedRatio, lowerBound, upperBound);
            randomGenerator = traceGenerator;
        }

        protected abstract void addToCache(Integer key, V value);

        @Override
        protected void cleanup(Integer key, V value, boolean succeeded) {
            if (!succeeded) {
                addToCache(key, value);
            }
        }

        @Override
        protected Pair<Integer, V> generateInput() {
            return new Pair<>(randomGenerator.next(), generateValue());
        }
    }

    /**
     * A default benchmark configuration for reading a cache. It simulates random
         cache access by
     * continuously generating random values before each individual run.
     * <p/>
     * It expects the cache to be based on {@link Integer} keys.
     *
     * @param <V> The type of the values that will be stored in the cache
     */
    public static abstract class RandomRead<V> extends BaseBenchmark.Read<V> {

        public RandomRead(String name, double cachedRatio, Integer lowerBound,
            Integer upperBound) {
            super(name, RandomGenerator.TRACE_TAG, new RandomGenerator(lowerBound,
                upperBound), cachedRatio, lowerBound, upperBound);
        }
    }

    /**
     * A default benchmark configuration for reading a cache. It simulates GET
         HTTP requests that
     * pass by the cache by continuously generating random values according to a
         Zipf probability
     * distribution ({@link ZipfGenerator}) before each individual run.
     * <p/>
     * It expects the cache to be based on {@link Integer} keys.
     *
     * @param <V> The type of the values that will be stored in the cache
     */
    public static abstract class ZipfRead<V> extends BaseBenchmark.Read<V> {
```

```
        public ZipfRead(String name, double cachedRatio, Integer lowerBound,
            Integer upperBound) {
            super(name, ZipfGenerator.TRACE_TAG, new ZipfGenerator(lowerBound,
                upperBound), cachedRatio, lowerBound, upperBound);
        }
    }

    /**
     * A default insert benchmark, that is used to monitor the performance of
         inserting key-value pairs
     * in a cache. The key passed to the run will always be a key of an entry that
         is not currently
     * stored in the cache. Therefore it will always be a pure insert run and will
         never be updating
     * an existing entry.
     * <p/>
     * It expects the cache to be based on {@link Integer} keys.
     * The keys that are used are completely random.
     *
     * @param <V> The type of the values that will be stored in the cache
     */
    public static abstract class Insert<V> extends BaseBenchmarkConfiguration<V> {

        private Generator<Integer> generator;
        private int nextKey;

        public Insert(String name, double cachedRatio, Integer lowerBound, Integer
             upperBound) {
            super(name + INSERT_TAG, RandomGenerator.TRACE_TAG, cachedRatio,
                lowerBound, upperBound);
            generator = new RandomGenerator(lowerBound, upperBound);
        }

        protected abstract void removeElement(Integer key);

        protected abstract V generateValue();

        @Override
        protected void cleanup(Integer key, V value, boolean succeeded) {
            nextKey = generator.next();
            removeElement(key);
        }

        @Override
        protected Pair<Integer, V> generateInput() {
            return new Pair<>(nextKey, generateValue());
        }
    }

    /**
     * A default benchmark configuration for deleting an entry from a cache.
     * The key passed to the run will always be a key of an existing entry in the
         cache. Therefore
     * the run is never told to try and remove the entry bound to the key that is
         not in the cache.
     * <p/>
     * It expects the cache to be based on {@link Integer} keys.
     * The keys generated are completely random.
     *
     * @param <V> The type of the values that will be stored in the cache
     */
```

```
public static abstract class Delete<V> extends BaseBenchmarkConfiguration<V> {

    private Generator<Integer> generator;
    private int nextKey;

    public Delete(String name, double cachedRatio, Integer lowerBound, Integer
         upperBound) {
        super(name + DELETE_TAG, RandomGenerator.TRACE_TAG, cachedRatio,
            lowerBound, upperBound);
        generator = new RandomGenerator(lowerBound, upperBound);
    }

    public abstract void addToCache(int key, V value);

    protected abstract V generateValue();

    @Override
    protected void setup() {
        super.setup();
        for (int i = 0; i < getCacheSize(); i++) {
            prepare();
        }
    }

    @Override
    protected void prepare() {
        nextKey = generator.next();
        addToCache(nextKey, generateValue());
    }

    @Override
    protected Pair<Integer, V> generateInput() {
        return new Pair<>(nextKey, generateValue());
    }
}

/**
 * A default benchmark configuration for updating entries in a cache.
 * The key passed to the run might be bound to an already existing entry in
     the cache, yet this
 * is not enforced. Considering that a cache update is almost always used with
      a
 * "update or add if non existent" semantics.
 * <p/>
 * It expects the cache to be based on {@link Integer} keys.
 * The keys generated are completely random.
 *
 * @param <V> The type of the values that will be stored in the cache
 */
public static abstract class Update<V> extends BaseBenchmarkConfiguration<V> {

    private Generator<Integer> generator;
    private int nextKey;

    public Update(String name, double cachedRatio, Integer lowerBound, Integer
         upperBound) {
        super(name + UPDATE_TAG, RandomGenerator.TRACE_TAG, cachedRatio,
            lowerBound, upperBound);
        generator = new RandomGenerator(lowerBound, upperBound);
    }

    protected abstract void addToCache(int key, V value);
```

```
        protected abstract V generateValue();

        @Override
        protected void prepare() {
            nextKey = generator.next();
            addToCache(nextKey, generateValue());
        }

        @Override
        protected Pair<Integer, V> generateInput() {
            return new Pair<>(nextKey, generateValue());
        }
    }
}
```

Listing E.5: app.src.main.java.desmedt.frederik.cachebenchmarking.benchmark.Cache2KBenchmark

```
package desmedt.frederik.cachebenchmarking.benchmark;

import org.cache2k.Cache;
import org.cache2k.CacheBuilder;
import org.cache2k.impl.ArcCache;
import org.cache2k.impl.BaseCache;
import org.cache2k.impl.ClockCache;
import org.cache2k.impl.RandomCache;

import java.util.Random;
import java.util.UUID;

import desmedt.frederik.cachebenchmarking.CacheBenchmarkConfiguration;
import desmedt.frederik.cachebenchmarking.generator.Generator;

/**
 * Contains a collection of Clock benchmarks (by Cache2K) as inner classes.
 */
public class Cache2KBenchmark {

    public static final Class<ClockCache> CLOCK_CACHE = ClockCache.class;
    public static final Class<ArcCache> ARC_CACHE = ArcCache.class;
    public static final Class<RandomCache> RANDOM_CACHE = RandomCache.class;

    private static Cache<Integer, Integer> createCache(Class<? extends BaseCache>
        cacheImplementation, int maxSize) {
        return CacheBuilder.newCache(Integer.class, Integer.class).name(UUID.
            randomUUID().toString())
                .eternal(true)
                .maxSize(maxSize)
                .keepDataAfterExpired(false)
                .implementation(cacheImplementation)
                .build();
    }

    public static class Read extends BaseBenchmark.Read<Integer> {

        private Cache<Integer, Integer> cache;
        private final Random random = new Random();
        private final Class<? extends BaseCache> cacheClass;

        // Certain Cache2K cache implementations automatically generate statistics
            , yet the base
```

```
        // cache does not, therefore record them here so that the implementation
            is irrelevant.
        private int successes;
        private int failures;

        public Read(Class<? extends BaseCache> cacheClass, String traceTag,
            Generator<Integer> traceGenerator, double cachedRatio, Integer
            lowerBound, Integer upperBound) {
            super(cacheClass.getSimpleName(), traceTag, traceGenerator,
                cachedRatio, lowerBound, upperBound);
            this.cacheClass = cacheClass;
        }

        @Override
        protected void addToCache(Integer key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = Cache2KBenchmark.createCache(cacheClass, cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.close();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            return cache.peek(key) != null;
        }

        @Override
        protected void cleanup(Integer key, Integer value, boolean succeeded) {
            super.cleanup(key, value, succeeded);
            if (succeeded) {
                successes++;
            } else {
                failures++;
            }
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.read(successes, failures, getCacheSize(), cache.
                getTotalEntryCount());
        }
    }

    public static class Insert extends BaseBenchmark.Insert<Integer> {

        private Cache<Integer, Integer> cache;
        private final Random random = new Random();
        private final Class<? extends BaseCache> cacheClass;
```

```
        public Insert(Class<? extends BaseCache> cacheClass, double cachedRatio,
            Integer lowerBound, Integer upperBound) {
            super(cacheClass.getSimpleName(), cachedRatio, lowerBound, upperBound)
                ;
            this.cacheClass = cacheClass;
        }

        @Override
        protected void removeElement(Integer key) {
            cache.remove(key);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = Cache2KBenchmark.createCache(cacheClass, cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.close();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            cache.put(key, value);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.INSERT, getCacheSize(), cache.
                getTotalEntryCount());
        }
    }

    public static class Update extends BaseBenchmark.Update<Integer> {

        private Cache<Integer, Integer> cache;
        private final Random random = new Random();
        private final Class<? extends BaseCache> cacheClass;


        public Update(Class<? extends BaseCache> cacheClass, double cachedRatio,
            Integer lowerBound, Integer upperBound) {
            super(cacheClass.getSimpleName(), cachedRatio, lowerBound, upperBound)
                ;
            this.cacheClass = cacheClass;
        }

        @Override
        protected void addToCache(int key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
```

```
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = Cache2KBenchmark.createCache(cacheClass, cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.close();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            cache.put(key, value);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.UPDATE, getCacheSize(), cache.
                getTotalEntryCount());
        }
    }

    public static class Delete extends BaseBenchmark.Delete<Integer> {

        private Cache<Integer, Integer> cache;
        private final Random random = new Random();
        private final Class<? extends BaseCache> cacheClass;


        public Delete(Class<? extends BaseCache> cacheClass, double cachedRatio,
            Integer lowerBound, Integer upperBound) {
            super(cacheClass.getSimpleName(), cachedRatio, lowerBound, upperBound)
                ;
            this.cacheClass = cacheClass;
        }


        @Override
        public void addToCache(int key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = Cache2KBenchmark.createCache(cacheClass, cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.close();
            cache = null;
        }
```

```
        @Override
        protected boolean run(Integer key, Integer value) {
            cache.remove(key);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.DELETE, getCacheSize(), cache.
                getTotalEntryCount());
        }
    }
}
```

Listing E.6: app.src.main.java.desmedt.frederik.cachebenchmarking.benchmark.CustomBenchmark

```
package desmedt.frederik.cachebenchmarking.benchmark;

import android.util.Pair;

import java.util.Random;

import desmedt.frederik.cachebenchmarking.CacheBenchmarkConfiguration;
import desmedt.frederik.cachebenchmarking.benchmark.BaseBenchmark.Read;
import desmedt.frederik.cachebenchmarking.cache.Cache;
import desmedt.frederik.cachebenchmarking.generator.Generator;
import desmedt.frederik.cachebenchmarking.generator.RandomGenerator;
import desmedt.frederik.cachebenchmarking.generator.ZipfGenerator;

/**
 * A collection of cache benchmark configurations for every custom cache
     implemented.
 */
public class CustomBenchmark {

    public static class Insert extends BaseBenchmark.Insert<Integer> {

        private Cache<Integer, Integer> cache;
        private final Random random = new Random();
        private final Generator<Cache<Integer, Integer>> cacheGenerator;

        public Insert(String name, double cachedRatio, Integer lowerBound, Integer
             upperBound, Generator<Cache<Integer, Integer>> generator) {
            super(name, cachedRatio, lowerBound, upperBound);
            this.cacheGenerator = generator;
        }

        @Override
        protected void removeElement(Integer key) {
            cache.remove(key);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = cacheGenerator.next();
```

```
        }

        @Override
        protected void clearCache() {
            cache.removeAll();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            cache.put(key, value);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.INSERT, cache.maxSize(), cache.size
                ());
        }
    }

    public static class Read extends BaseBenchmark.Read<Integer> {

        private Cache<Integer, Integer> cache;
        private final Random random = new Random();
        private final Generator<Cache<Integer, Integer>> cacheGenerator;

        private int succeses = 0;
        private int failures = 0;

        public Read(String name, String traceTag, Generator<Integer>
            traceGenerator, double cachedRatio, Integer lowerBound, Integer
            upperBound, Generator<Cache<Integer, Integer>> generator) {
            super(name, traceTag, traceGenerator, cachedRatio, lowerBound,
                upperBound);
            this.cacheGenerator = generator;
        }

        @Override
        protected void addToCache(Integer key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = cacheGenerator.next();
        }

        @Override
        protected void clearCache() {
            cache.removeAll();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            return cache.get(key) != null;
```

```
        }

        @Override
        protected void cleanup(Integer key, Integer value, boolean succeeded) {
            super.cleanup(key, value, succeeded);
            if (succeeded) {
                succeses++;
            } else {
                failures++;
            }
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.read(succeses, failures, cache.maxSize(), cache.size
                ());
        }
    }

    public static class Update extends BaseBenchmark.Update<Integer> {

        private Cache<Integer, Integer> cache;
        private final Random random = new Random();
        private final Generator<Cache<Integer, Integer>> cacheGenerator;

        public Update(String name, double cachedRatio, Integer lowerBound, Integer
             upperBound, Generator<Cache<Integer, Integer>> generator) {
            super(name, cachedRatio, lowerBound, upperBound);
            this.cacheGenerator = generator;
        }

        @Override
        protected void addToCache(int key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = cacheGenerator.next();
        }

        @Override
        protected void clearCache() {
            cache.removeAll();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            cache.put(key, value);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.UPDATE, cache.maxSize(), cache.size
                ());
```

```
        }
    }

    public static class Delete extends BaseBenchmark.Delete<Integer> {

        private Cache<Integer, Integer> cache;
        private final Random random = new Random();
        private final Generator<Cache<Integer, Integer>> cacheGenerator;

        public Delete(String name, double cachedRatio, Integer lowerBound, Integer
             upperBound, Generator<Cache<Integer, Integer>> generator) {
            super(name, cachedRatio, lowerBound, upperBound);
            this.cacheGenerator = generator;
        }

        @Override
        public void addToCache(int key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = cacheGenerator.next();
        }

        @Override
        protected void clearCache() {
            cache.removeAll();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            cache.remove(key);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.DELETE, cache.maxSize(), cache.size
                ());
        }
    }
}
```

Listing E.7: app.src.main.java.desmedt.frederik.cachebenchmarking.benchmark.GuavaBenchmarks

```
package desmedt.frederik.cachebenchmarking.benchmark;

import com.google.common.cache.Cache;
import com.google.common.cache.CacheBuilder;

import java.util.Random;

import desmedt.frederik.cachebenchmarking.CacheBenchmarkConfiguration;
import desmedt.frederik.cachebenchmarking.benchmark.BaseBenchmark.Read;
```

```java
import desmedt.frederik.cachebenchmarking.generator.Generator;

/**
 * Contains a collection of Guava benchmarks as inner classes.
 */
public class GuavaBenchmarks {

    public static final String CACHE_TAG = "Guava";

    private static Cache<Integer, Integer> createCache(int cacheSize) {
        return CacheBuilder.newBuilder()
                .maximumSize(cacheSize)
                .recordStats()
                .build();
    }

    public static class Read extends BaseBenchmark.Read<Integer> {

        private Cache<Integer, Integer> cache;
        private Random random = new Random();

        public Read(String traceTag, Generator<Integer> traceGenerator, double
            cacheRatio, Integer lowerBound, Integer upperBound) {
            super("Guava", traceTag, traceGenerator, cacheRatio, lowerBound,
                upperBound);
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            return cache.getIfPresent(key) != null;
        }

        @Override
        protected void addToCache(Integer key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = GuavaBenchmarks.createCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.invalidateAll();
            cache = null;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.read((int) cache.stats().hitCount(), (int) cache.
                stats().missCount(), getCacheSize(), (int) cache.size());
        }
    }

    public static class Insert extends BaseBenchmark.Insert<Integer> {
```

```
        private final Random random = new Random();
        private Cache<Integer, Integer> cache;

        private int nextKey = 0;

        public Insert(double cacheRatio, int lowerBound, int upperBound) {
            super(CACHE_TAG, cacheRatio, lowerBound, upperBound);
        }

        @Override
        protected void removeElement(Integer key) {
            cache.invalidate(key);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = GuavaBenchmarks.createCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.invalidateAll();
            cache = null;
        }

        @Override
        public boolean run(Integer key, Integer value) {
            cache.put(key, value);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.INSERT, getCacheSize(), (int) cache
                .size());
        }
    }

    public static class Delete extends BaseBenchmark.Delete<Integer> {

        private Cache<Integer, Integer> cache;
        private Random random = new Random();

        public Delete(double cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, cacheRatio, lowerBound, upperBound);
        }

        @Override
        public void addToCache(int key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }
```

```
        @Override
        protected void createCache(int cacheSize) {
            cache = GuavaBenchmarks.createCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.invalidateAll();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            cache.invalidate(key);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.DELETE, getCacheSize(), (int) cache
                .size());
        }
    }

    public static class Update extends BaseBenchmark.Update<Integer> {

        private Random random = new Random();
        private Cache<Integer, Integer> cache;

        public Update(double cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, cacheRatio, lowerBound, upperBound);
        }

        @Override
        protected void addToCache(int key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = GuavaBenchmarks.createCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.invalidateAll();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            cache.put(key, value);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
```

```
            return CacheStats.nonRead(StatType.UPDATE, getCacheSize(), (int) cache
                .size());
        }
    }
}
```

Listing E.8: app.src.main.java.desmedt.frederik.cachebenchmarking.benchmark.JackRabbitLIRSBenchmark

```
package desmedt.frederik.cachebenchmarking.benchmark;

import com.google.common.cache.Cache;

import java.util.Random;

import desmedt.frederik.cachebenchmarking.CacheBenchmarkConfiguration;
import desmedt.frederik.cachebenchmarking.cache.CacheLIRS;
import desmedt.frederik.cachebenchmarking.generator.Generator;

/**
 * Contains a collection of LIRS cache benchmarks, by JackRabbit, as inner classes
     .
 */
public class JackRabbitLIRSBenchmark {

    private static final String CACHE_TAG = "LIRS";

    private static Cache<Integer, Integer> createCache(int maxSize) {
        return new CacheLIRS<>(maxSize);
    }

    public static class RandomRead extends BaseBenchmark.RandomRead<Integer> {

        private Random random = new Random();
        private Cache<Integer, Integer> lirsCache;

        public RandomRead(int cacheSize, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, cacheSize, lowerBound, upperBound);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            lirsCache = JackRabbitLIRSBenchmark.createCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            lirsCache.invalidateAll();
            lirsCache = null;
        }

        @Override
        protected void addToCache(Integer key, Integer value) {
            lirsCache.put(key, value);
        }

        @Override
```

```
        protected boolean run(Integer key, Integer value) {
            return lirsCache.getIfPresent(key) != null;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.read((int) lirsCache.stats().hitCount(), (int)
                lirsCache.stats().missCount(), getCacheSize(), (int) lirsCache.
                size());
        }
    }

    public static class Read extends BaseBenchmark.Read<Integer> {

        private Random random = new Random();
        private Cache<Integer, Integer> lirsCache;

        public Read(String traceTag, Generator<Integer> traceGenerator, double
            cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, traceTag, traceGenerator, cacheRatio, lowerBound,
                upperBound);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            lirsCache = JackRabbitLIRSBenchmark.createCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            lirsCache.invalidateAll();
            lirsCache = null;
        }

        @Override
        protected void addToCache(Integer key, Integer value) {
            lirsCache.put(key, value);
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            Integer result = lirsCache.getIfPresent(key);
            boolean present = result != null;
            return present;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.read((int) lirsCache.stats().hitCount(), (int)
                lirsCache.stats().missCount(), getCacheSize(), (int) lirsCache.
                size());
        }
    }

    public static class Insert extends BaseBenchmark.Insert<Integer> {

        private Cache<Integer, Integer> lirsCache;
```

```
        private Random random = new Random();

        public Insert(double cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, cacheRatio, lowerBound, upperBound);
        }

        @Override
        protected void removeElement(Integer key) {
            lirsCache.invalidate(key);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            lirsCache = JackRabbitLIRSBenchmark.createCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            lirsCache.invalidateAll();
            lirsCache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            return false;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.INSERT, getCacheSize(), (int)
                lirsCache.size());
        }
    }

    public static class Delete extends BaseBenchmark.Delete<Integer> {

        private Cache<Integer, Integer> lirsCache;
        private Random random = new Random();

        public Delete(double cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, cacheRatio, lowerBound, upperBound);
        }

        @Override
        public void addToCache(int key, Integer value) {
            lirsCache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            lirsCache = JackRabbitLIRSBenchmark.createCache(cacheSize);
        }
```

```
        @Override
        protected void clearCache() {
            lirsCache.invalidateAll();
            lirsCache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            lirsCache.invalidate(key);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.DELETE, getCacheSize(), (int)
                lirsCache.size());
        }
    }

    public static class Update extends BaseBenchmark.Update<Integer> {

        private Cache<Integer, Integer> lirsCache;
        private Random random = new Random();

        public Update(double cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, cacheRatio, lowerBound, upperBound);
        }

        @Override
        protected void addToCache(int key, Integer value) {
            lirsCache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            lirsCache = JackRabbitLIRSBenchmark.createCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            lirsCache.invalidateAll();
            lirsCache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            lirsCache.put(key, value);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.UPDATE, getCacheSize(), (int)
                lirsCache.size());
        }
    }
```

```
}
```

Listing E.9: app.src.main.java.desmedt.frederik.cachebenchmarking.benchmark.NativeLruBenchmarks

```
package desmedt.frederik.cachebenchmarking.benchmark;

import android.support.v4.util.LruCache;
import android.util.Pair;

import java.util.Random;
import java.util.StringTokenizer;

import desmedt.frederik.cachebenchmarking.CacheBenchmarkConfiguration;
import desmedt.frederik.cachebenchmarking.generator.Generator;
import desmedt.frederik.cachebenchmarking.generator.RandomGenerator;
import desmedt.frederik.cachebenchmarking.generator.ZipfGenerator;

/**
 * Contains a collection of native LRU benchmarks as inner classes.
 */
public class NativeLruBenchmarks {

    public static final String CACHE_TAG = "NativeLru";

    public static class Update extends BaseBenchmark.Update<Integer> {

        private LruCache cache;
        private final Random random = new Random();

        public Update(double cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, cacheRatio, lowerBound, upperBound);
        }

        @Override
        protected void addToCache(int key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = new LruCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.evictAll();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            cache.put(key, value);
            return true;
        }

        @Override
```

```
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.UPDATE, cache.size(), cache.maxSize
                ());
        }
    }

    public static class Read extends BaseBenchmark.Read<Integer> {

        private LruCache cache;
        private final Random random = new Random();

        public Read(String traceTag, Generator<Integer> traceGenerator, double
            cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, traceTag, traceGenerator, cacheRatio, lowerBound,
                upperBound);
        }

        @Override
        protected void addToCache(Integer key, Integer value) {
            cache.put(key, value);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = new LruCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.evictAll();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            return cache.get(key) != null;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.read(cache.hitCount(), cache.missCount(), cache.
                maxSize(), cache.size());
        }
    }

    public static class Delete extends BaseBenchmark.Delete<Integer> {

        private LruCache cache;
        private final Random random = new Random();

        public Delete(double cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, cacheRatio, lowerBound, upperBound);
        }

        @Override
        public void addToCache(int key, Integer value) {
            cache.put(key, value);
```

```
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = new LruCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.evictAll();
            cache = null;
        }

        @Override
        protected boolean run(Integer key, Integer value) {
            cache.remove(key);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.DELETE, cache.maxSize(), cache.size
                ());
        }
    }

    public static class Insert extends BaseBenchmark.Insert<Integer> {

        private LruCache cache;
        private final Random random = new Random();

        public Insert(double cacheRatio, Integer lowerBound, Integer upperBound) {
            super(CACHE_TAG, cacheRatio, lowerBound, upperBound);
        }

        @Override
        protected void removeElement(Integer key) {
            cache.remove(key);
        }

        @Override
        protected Integer generateValue() {
            return random.nextInt();
        }

        @Override
        protected void createCache(int cacheSize) {
            cache = new LruCache(cacheSize);
        }

        @Override
        protected void clearCache() {
            cache.evictAll();
            cache = null;
        }

        @Override
```

```
        protected boolean run(Integer key, Integer value) {
            cache.put(key, value);
            return true;
        }

        @Override
        protected CacheStats generateStats() {
            return CacheStats.nonRead(StatType.INSERT, cache.maxSize(), cache.size
                ());
        }
    }
}
```

## E.3 Package cachebenchmarking.cache

Listing E.10: app.src.main.java.desmedt.frederik.cachebenchmarking.cache.Cache

```
package desmedt.frederik.cachebenchmarking.cache;

/**
 * Interface for every custom cache implementation.
 */
public interface Cache<K extends Comparable<K>, V> {

    /**
     * Get the value of the entry associated with the key or null if there is no
         entry in the cache
     * linked to the key.
     *
     * @param key The key associated with the entry
     * @return The value if the key exists in the cache, false otherwise
     */
    V get(K key);

    /**
     * Put a new entry in the cache with a key and a value.
     *
     * @param key   The key of the entry
     * @param value The value of the entry
     */
    void put(K key, V value);

    /**
     * Removes a single entry from the cache, or does nothing if the key is not
         present.
     *
     * @param key The key of the entry that should be removed
     */
    void remove(K key);

    /**
     * Removes all elements from the cache.
     */
    void removeAll();

    /**
     * @return The maximum amount of entries present in the cache at any given
         time
```

```
     */
    int maxSize();

    /**
     * @return The current amount of entries present in the cache
     */
    int size();

    class Element<K extends Comparable<K>, V> implements Comparable<K> {

        private K key;
        private V value;

        public Element(K key, V value) {
            this.key = key;
            this.value = value;
        }

        public K getKey() {
            return key;
        }

        public void setKey(K key) {
            this.key = key;
        }

        public V getValue() {
            return value;
        }

        public void setValue(V value) {
            this.value = value;
        }

        @Override
        public boolean equals(Object o) {
            if (o instanceof Element) {
                return key.equals(((Element) o).getKey()) && value.equals(((
                    Element) o).getValue());
            } else {
                return key.equals(o);
            }
        }

        @Override
        public int compareTo(K key) {
            return getKey().compareTo(key);
        }
    }
}
```

Listing E.11: app.src.main.java.desmedt.frederik.cachebenchmarking.cache.FIFOCache

```
package desmedt.frederik.cachebenchmarking.cache;

import java.util.LinkedHashMap;
import java.util.ListIterator;
import java.util.Map;

/**
 * A simple FIFO cache replacement policy implementation. Uses the FIFO mode of {
```

```
     @link LinkedHashMap}
 * to store, retrieve and remove its elements.
 */
public class FIFOCache<K extends Comparable<K>, V> implements Cache<K, V> {

    public static final String CACHE_TAG = "FifoCache";

    private LinkedHashMap<K, V> heap = new LinkedHashMap<>();
    private int maxSize = 0;

    public FIFOCache(int maxSize) {
        this.maxSize = maxSize;
    }

    @Override
    public V get(K key) {
        return heap.get(key);
    }

    @Override
    public void put(K key, V value) {
        heap.put(key, value);

        if (maxSize < heap.size()) {
            removeElement();
        }
    }

    private void removeElement() {
        K key = heap.keySet().iterator().next();
        heap.remove(key);
    }

    @Override
    public void remove(K key) {
        heap.remove(key);
    }

    @Override
    public void removeAll() {
        heap.clear();
    }

    @Override
    public int maxSize() {
        return maxSize;
    }

    @Override
    public int size() {
        return heap.size();
    }
}
```

Listing E.12: app.src.main.java.desmedt.frederik.cachebenchmarking.cache.RandomCache

```
package desmedt.frederik.cachebenchmarking.cache;

import java.util.Arrays;
import java.util.Collections;
import java.util.LinkedList;
```

```java
import java.util.Random;
import java.util.StringTokenizer;

import desmedt.frederik.cachebenchmarking.cache.Cache;

/**
 * A simple random cache replacement policy implementation.
 */
public class RandomCache<K extends Comparable<K>, V> implements Cache<K, V> {

    public static final String CACHE_TAG = "RandomCache";

    private int maxSize;
    private LinkedList<Element<K, V>> heap = new LinkedList<>();
    private Random random = new Random();

    public RandomCache(int maxSize) {
        this.maxSize = maxSize;
    }

    @Override
    public V get(K key) {
        final int index = Collections.binarySearch(heap, key);
        return index < 0 ? null : heap.get(index).getValue();
    }

    @Override
    public void put(K key, V value) {
        int index = Collections.binarySearch(heap, key);
        if (index < 0) {
            if (maxSize < heap.size() + 1) {
                removeElement();
            }

            int insertIndex = -(index + 1);
            if (insertIndex == heap.size() + 1) {
                heap.add(new Element<K, V>(key, value));
            } else {
                heap.add(insertIndex, new Element<>(key, value));
            }
        } else {
            heap.get(index).setValue(value);
        }
    }

    @Override
    public void remove(K key) {
        int index = Collections.binarySearch(heap, key);
        if (index > 0) {
            heap.remove(index);
        }
    }

    @Override
    public void removeAll() {
        heap.clear();
    }

    private void removeElement() {
        final int index = random.nextInt(maxSize);
        heap.remove(index);
    }
```

```
    @Override
    public int maxSize() {
        return maxSize;
    }

    @Override
    public int size() {
        return heap.size();
    }
}
```

## E.4 Package cachebenchmarking.generator

Listing E.13: app.src.main.java.desmedt.frederik.cachebenchmarking.generator.Generator

```
package desmedt.frederik.cachebenchmarking.generator;

/**
 * Something that can generate values of type {@code E}. This interface is used
     with arbitrary
 * semantics, be it as a random instance generator or a one-time single instance
     generator.
 */
public interface Generator<E> {

    E next();
}
```

Listing E.14: app.src.main.java.desmedt.frederik.cachebenchmarking.generator.LoopingAccessPattern

```
package desmedt.frederik.cachebenchmarking.generator;

import org.cache2k.benchmark.util.AccessPattern;
import org.cache2k.benchmark.util.AccessTrace;

/**
 * An {@link AccessPattern} looping over a given eternal {@link org.cache2k.
     benchmark.util.AccessTrace},
 * essentially making it eternal.
 */
public class LoopingAccessPattern extends AccessPattern {

    private AccessTrace trace;
    private int index = 0;
    private int[] traceArray;

    /**
     * @param trace The trace that should be looped
     */
    public LoopingAccessPattern(AccessTrace trace) {
        this.trace = trace;
        traceArray = trace.getTrace();
    }

    @Override
    public boolean isEternal() {
```

```
        return true;
    }

    @Override
    public boolean hasNext() throws Exception {
        return true;
    }

    @Override
    public int next() throws Exception {
        int result = traceArray[index];
        index = (index + 1) % traceArray.length;
        return result;
    }
}
```

Listing E.15: app.src.main.java.desmedt.frederik.cachebenchmarking.generator.NfsGenerator

```
package desmedt.frederik.cachebenchmarking.generator;

import android.util.Log;

import org.cache2k.benchmark.traces.CacheAccessTraceSprite;
import org.cache2k.benchmark.traces.CacheAccessTraceUmassWebSearch1;
import org.cache2k.benchmark.util.AccessPattern;
import org.cache2k.benchmark.util.AccessTrace;

/**
 * A generator generating values based on access requests on the Sprite network
     file system.
 */
public class NfsGenerator implements Generator<Integer> {

    public static final String TRACE_TAG = "NFS";

    private static final String TAG = NfsGenerator.class.getSimpleName();
    private AccessTrace trace = CacheAccessTraceSprite.getInstance();
    private AccessPattern pattern = new LoopingAccessPattern(trace);

    @Override
    public Integer next() {
        int next = Integer.MIN_VALUE;

        while (next < 0) {
            try {
                next = pattern.next();
            } catch (Exception e) {
                Log.e(TAG, "Couldn't generate next value in trace", e);
                return null;
            }
        }

        return next;
    }

    public static int getLowerBound() {
        return 0;
    }

    public static int getUpperBound() {
        // Call getInstance() instead of static field to not cause a strong
```

```
            reference
        return CacheAccessTraceSprite.getInstance().getHighValue();
    }
}
```

Listing E.16: app.src.main.java.desmedt.frederik.cachebenchmarking.generator.RandomGenerator

```
package desmedt.frederik.cachebenchmarking.generator;

import java.util.Random;

/**
 * A generator generating random numbers between some lower and upper bound.
 */
public class RandomGenerator implements Generator<Integer> {

    public static final String TRACE_TAG = "Random";

    private Random random = new Random();

    private int lower;
    private int upper;

    public RandomGenerator(int lower, int upper) {
        this.lower = lower;
        this.upper = upper;
    }

    public Integer next() {
        return lower + random.nextInt(upper);
    }
}
```

Listing E.17: app.src.main.java.desmedt.frederik.cachebenchmarking.generator.SearchEngineGenerato

```
package desmedt.frederik.cachebenchmarking.generator;

import android.util.Log;

import org.cache2k.benchmark.traces.CacheAccessTraceSprite;
import org.cache2k.benchmark.traces.CacheAccessTraceUmassWebSearch1;
import org.cache2k.benchmark.traces.CacheAccessTraceWeb12;
import org.cache2k.benchmark.util.AccessPattern;
import org.cache2k.benchmark.util.AccessTrace;

/**
 * A generator generating values based on search requests of an unnamed popular
     search engine.
 */
public class SearchEngineGenerator implements Generator<Integer> {

    public static final String TRACE_TAG = "SearchEngine";

    private static final String TAG = SearchEngineGenerator.class.getSimpleName();
    private AccessTrace trace = CacheAccessTraceUmassWebSearch1.getInstance();
    private AccessPattern pattern = new LoopingAccessPattern(trace);

    @Override
    public Integer next() {
        int next = Integer.MIN_VALUE;
```

```
        while (next < 0) {
            try {
                next = pattern.next();
            } catch (Exception e) {
                Log.e(TAG, "Couldn't generate next value in trace", e);
                return null;
            }
        }

        return next;
    }

    public static int getLowerBound() {
        return 0;
    }

    public static int getUpperBound() {
        // Call getInstance() instead of static field to not cause a strong
            reference
        return CacheAccessTraceUmassWebSearch1.getInstance().getHighValue();
    }
}
```

Listing E.18: app.src.main.java.desmedt.frederik.cachebenchmarking.generator.Web12Generator

```
package desmedt.frederik.cachebenchmarking.generator;

import android.util.Log;

import org.cache2k.benchmark.traces.CacheAccessTraceWeb12;
import org.cache2k.benchmark.util.AccessPattern;
import org.cache2k.benchmark.util.AccessTrace;

/**
 * A generator generating values based on HTTP GET requests of a product detail
     website.
 */
public class Web12Generator implements Generator<Integer> {

    public static final String TRACE_TAG = "Web12";

    private static final String TAG = Web12Generator.class.getSimpleName();
    private AccessTrace trace = CacheAccessTraceWeb12.getInstance();
    private AccessPattern pattern = new LoopingAccessPattern(trace);

    @Override
    public Integer next() {
        int next = Integer.MIN_VALUE;

        while (next < 0) {
            try {
                next = pattern.next();
            } catch (Exception e) {
                Log.e(TAG, "Couldn't generate next value in trace", e);
                return null;
            }
        }

        return next;
    }
```

```
    public static int getLowerBound() {
        return 0;
    }

    public static int getUpperBound() {
        // Call getInstance() instead of static field to not cause a strong
            reference
        return CacheAccessTraceWeb12.getInstance().getHighValue();
    }
}
```

Listing E.19: app.src.main.java.desmedt.frederik.cachebenchmarking.generator.ZipfGenerator

```
package desmedt.frederik.cachebenchmarking.generator;

import org.cache2k.benchmark.util.ZipfianPattern;

/**
 * A generator generating random numbers between some lower and upper bound
     following a zipf-like
 * pattern.
 */
public class ZipfGenerator implements Generator<Integer> {

    public static final String TRACE_TAG = "Zipf";

    private final ZipfianPattern pattern;

    // UPisa trace
    private double UPISA = 0.78;

    public ZipfGenerator(int lowerBound, int upperBound) {
        pattern = new ZipfianPattern((long) lowerBound, (long) upperBound, UPISA);
    }

    @Override
    public Integer next() {
        int next = pattern.next();
        return next;
    }
}
```

## E.5 Package cachebenchmarking.ui

Listing E.20: app.src.main.java.desmedt.frederik.cachebenchmarking.ui.BenchmarkActivity

```
package desmedt.frederik.cachebenchmarking.ui;

import android.os.AsyncTask;
import android.support.v4.os.TraceCompat;
import android.support.v7.app.AppCompatActivity;
import android.os.Bundle;
import android.view.View;
import android.widget.CheckedTextView;
import android.widget.ImageView;
import android.widget.ProgressBar;
```

```
import android.widget.TextView;

import org.cache2k.benchmark.traces.TraceCache;

import java.util.concurrent.TimeUnit;

import desmedt.frederik.cachebenchmarking.BenchmarkRunner;
import desmedt.frederik.cachebenchmarking.R;

public class BenchmarkActivity extends AppCompatActivity {

    private BenchmarkRunner runner;

    private ProgressBar benchmarkProgressBar;
    private TextView textCompleted;
    private ImageView checkCompleted;

    @Override
    protected void onCreate(Bundle savedInstanceState) {
        super.onCreate(savedInstanceState);
        setContentView(R.layout.activity_benchmark);
    }

    @Override
    @SuppressWarnings("unchecked")
    protected void onStart() {
        super.onStart();

        TraceCache.applicationContext = getApplicationContext();
        benchmarkProgressBar = (ProgressBar) findViewById(R.id.
            benchmarkProgressBar);
        textCompleted = (TextView) findViewById(R.id.textCompleted);
        checkCompleted = (ImageView) findViewById(R.id.checkCompleted);

        new AsyncTask() {
            @Override
            protected Object doInBackground(Object[] params) {
                runner = new BenchmarkRunner();
                runner.runBenchmarks();

                try {
                    return runner.getBenchmarkRunnerService().awaitTermination(1,
                        TimeUnit.DAYS);
                } catch (InterruptedException iex) {
                    return false;
                }
            }

            @Override
            protected void onPostExecute(Object o) {
                super.onPostExecute(o);
                benchmarkProgressBar.setVisibility(View.INVISIBLE);
                checkCompleted.setVisibility(View.VISIBLE);
                textCompleted.setVisibility(View.VISIBLE);
            }
        }.execute();
    }
}
```