Practical Concurrent and Parallel Programming VI

Performance and Scalability

Raúl Pardo

Assignment 1 grading is completed

- Make sure you have a grade on assignment 1
    - **<u>If not, contact us!</u>**

- At the end of the semester, we will simply check that you got a 100 in at least 5 assignments

Oral feedback

- Remember that during oral feedback sessions you will need to explain your solutions
  - So please revisit your solutions before the oral feedback session so that you remember what you did

Exam answers

- For the exam, scarce answers may be considered insufficient
- Answers should be self-contained
  - Make sure that you include the context and all your assumptions are clearly stated

Agenda

- Performance versus scalability
- Scalability, speed-up and loss (of scalablity) classification
  Example: QuickSort
- Executors and Future
  Example: Dot Product
- Lock striping
  - A case study with Hash maps

Previously on PCPP…

Week 5

Speedup for quicksort:	3.6 using 8 threads
	2.9 using 4 threads
Speedup for counting primes:	3.9 using 8 threads
	2.3 using 4 threads

Performance versus scalability

Performance and scalability

Performance (of software)

- **Latency:** time till first result (response time)
- **Throughput**: results per second

Scalability (one way to improve performance)
Improve throughput/latency by adding more resources

One may sacrifice performance for scalability
Maybe OK to be slower on 1 core, if faster on 2 or 4 or ...

Goetz chapter 11

What limits performance?

Suggestions?

What limits performance?

CPU-bound
- Eg. counting prime numbers
- To speed up, add more CPUs (cores) (*exploitation*)

Input/output-bound
- Eg. reading from network
- To speed up, use more tasks (*inherent*)

Synchronization-bound
- Eg. Algorithm using shared data structure
- **To speed up, improve shared data structure**

(*Much of this lecture*)

Scalability, speed-up and loss classification
- Example: QuickSort

Quicksort

```
1 2 43 78 19 54 33 21 64 52 17 53
```

Quicksort

```
1 2 43 78 19 54 33 21 64 52 17 53
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```

Quicksort

```
1 2 43 78 19 54 33 21 64 52 17 53
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```

Quicksort

```
1 2 43 78 19 54 33 21 64 52 17 53
1 2 43 78 19 54 33 21 64 52 17 53
1 2 43 78 19 54 33 21 64 52 17 53
    ↑
```

Quicksort

```
1  2  43  78  19  54  33  21  64  52  17  53

1  2  43  78  19  54  33  21  64  52  17  53

1  2  43  78  19  54  33  21  64  52  17  53
      ↑                               ↑
```

Quicksort

```
1  2  43  78  19  54  33  21  64  52  17  53
1  2  43  78  19  54  33  21  64  52  17  53
1  2  43  78  19  54  33  21  64  52  17  53
      ↑                               ↑
1  2  17  78  19  54  33  21  64  52  43  53
      ↑                               ↑
```

Quicksort

```
1  2  43 78 19 54 33 21 64 52 17 53

1  2  43 78 19 54 33 21 64 52 17 53

1  2  43 78 19 54 33 21 64 52 17 53
      ↑                       ↑

1  2  17 78 19 54 33 21 64 52 43 53
      ↑                       ↑

1  2  17 78 19 54 33 21 64 52 43 53
         ↑           ↑
```

Quicksort

```
1  2  43 78 19 54 33 21 64 52 17 53

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1  2  43 78 19 54 33 21 64 52 17 53
      ↑                       ↑

1  2  17 78 19 54 33 21 64 52 43 53
      ↑                       ↑

1  2  17 78 19 54 33 21 64 52 43 53
         ↑           ↑

               ...
```

Quicksort

```
1  2  43  78  19  54  33  21  64  52  17  53

1  2  43  78  19  54  33  21  64  52  17  53

1  2  43  78  19  54  33  21  64  52  17  53
      ↑                               ↑

1  2  17  78  19  54  33  21  64  52  43  53
      ↑                               ↑

1  2  17  78  19  54  33  21  64  52  43  53
          ↑               ↑

                      ...

1  2  17  21  19  33  54  78  64  52  43  53
```

Quicksort

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      ↑                               ↑

1  2  17  78  19  54  33  21  64  52  43  53
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          ↑               ↑
                    ...
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      ↑                               ↑
1  2  17  78  19  54  33  21  64  52  43  53
      ↑                               ↑
1  2  17  78  19  54  33  21  64  52  43  53
          ↑               ↑
                    ...
1  2  17  21  19  33  54  78  64  52  43  53
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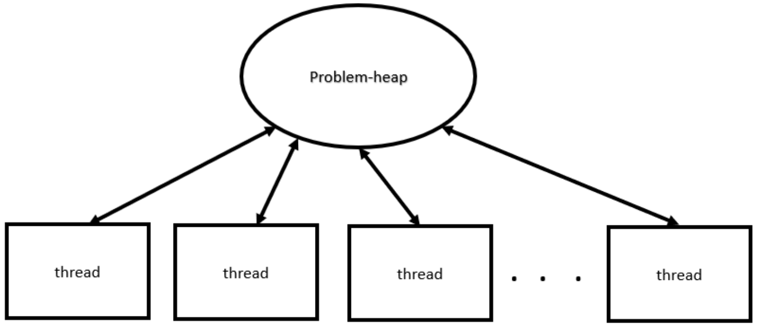
```

Two parts can be sorted independently

Multi-threaded version of Quicksort



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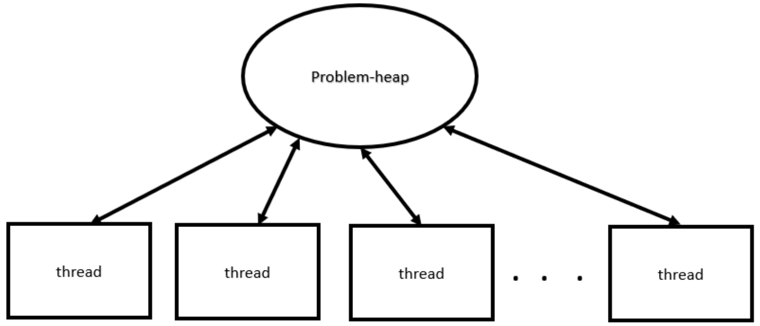
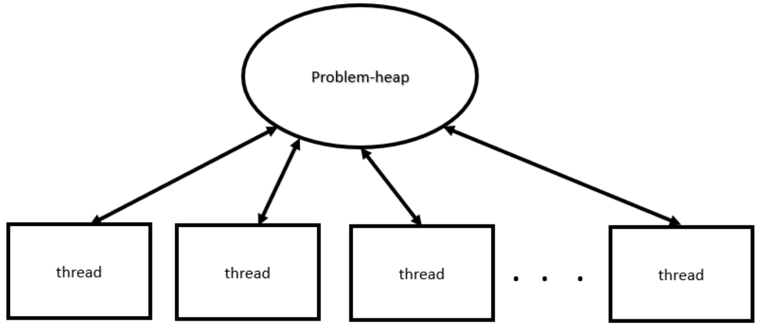


```
class Problem {
      public int[] arr;
      public int low, high;
      ...
      }
}

class ProblemHeap {
      list<Problem> heap= new List<Problem>;
      ...
}
```

Multi-threaded version of Quicksort



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      public int[] arr;
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      }
}

class ProblemHeap {
      list<Problem> heap= new List<Problem>;
      ...
}
```
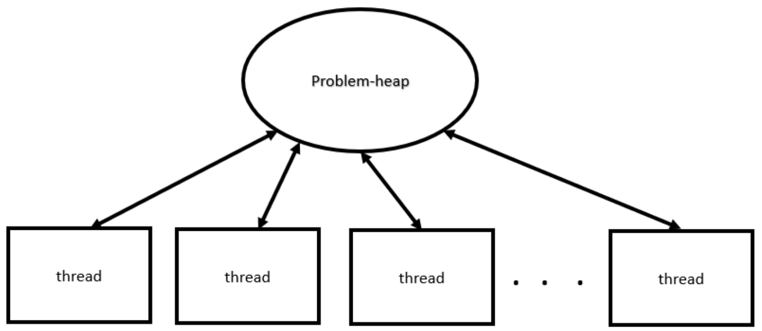

```
private static void qsort(Problem problem, ProblemHeap heap) {
  int[] arr= problem.arr;
  int a= problem.low;
  int b= problem.high;




}
```

Multi-threaded version of Quicksort



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        ...
        }
}

class ProblemHeap {
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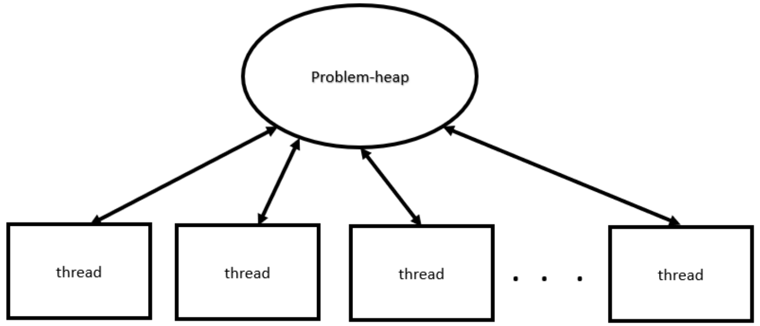
}
```

```
private static void qsort(Problem problem, ProblemHeap heap) {
  int[] arr= problem.arr;
  int a= problem.low;
  int b= problem.high;
  ... // solve a subtask of quicksort


}
```

Multi-threaded version of Quicksort



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class ProblemHeap {
      list<Problem> heap= new List<Problem>;
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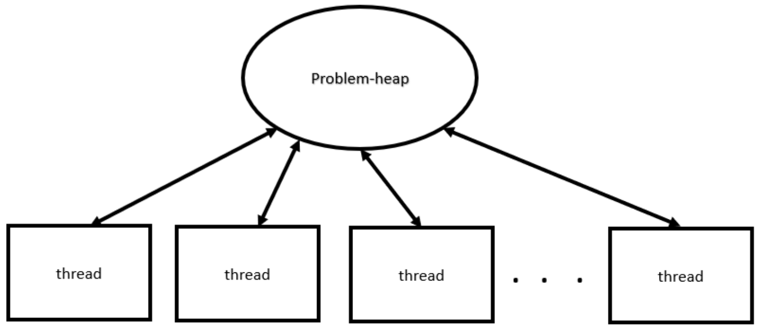
```
private static void qsort(Problem problem, ProblemHeap heap) {
   int[] arr= problem.arr;
   int a= problem.low;
   int b= problem.high;
   ... // solve a subtask of quicksort
   heap.add(new Problem(arr, a, j); //qsort(arr, a, j);

}
```

Multi-threaded version of Quicksort



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private static void qsort(Problem problem, ProblemHeap heap) {
    int[] arr= problem.arr;
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    ... // solve a subtask of quicksort
    heap.add(new Problem(arr, a, j); //qsort(arr, a, j);
    heap.add(new Problem(arr, i, b));//qsort(arr, i, b);
 }
```

Java code for Quicksort (1)

```
public static void problemHeapStart(int threadCount, int pSize, int[] intArray) {
 ProblemHeap heap= new ProblemHeap(threadCount);
 heap.add(new Problem(intArray, 0, pSize-1));

 for (int t=0; t<threadCount; t++) {









 }
}
```

Java code for Quicksort (1)

```
public static void problemHeapStart(int threadCount, int pSize, int[] intArray) {
 ProblemHeap heap= new ProblemHeap(threadCount);
 heap.add(new Problem(intArray, 0, pSize-1));

 for (int t=0; t<threadCount; t++) {


      while (newProblem != null) {  // when newProblem == null alg stops
        qsort(newProblem, heap);
        newProblem= heap.getProblem();
      }


 }
}
```

Java code for Quicksort (1)

```
public static void problemHeapStart(int threadCount, int pSize, int[] intArray) {
 ProblemHeap heap= new ProblemHeap(threadCount);
 heap.add(new Problem(intArray, 0, pSize-1));

 for (int t=0; t<threadCount; t++) {
   threads[t]= new Thread( () -> { try {
       Problem newProblem= heap.getProblem();
       while (newProblem != null) {  // when newProblem == null alg stops
         qsort(newProblem, heap);
         newProblem= heap.getProblem();
       }

   });
 }
}
```

Java code for Quicksort (1)

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   threads[t]= new Thread( () -> { try {
       Problem newProblem= heap.getProblem();
       while (newProblem != null) {  // when newProblem == null alg stops
         qsort(newProblem, heap);
         newProblem= heap.getProblem();
       }
       }catch (InterruptedException exn) { }  //needed because getProblem may wait
   });
 }
}
```

Java code for Quicksort (2)

“Measure, don’t guess”

Goetz p. 224

We use Mark8Setup to measure runtime

```
Benchmark.Mark8Setup("Problem heap quicksort",
        String.format("%2d", threadCount),
        new Benchmarkable() {








        }
    );
```

Java code for Quicksort (2)

“Measure, don’t guess”

Goetz p. 224

We use Mark8Setup to measure runtime

```
 Benchmark.Mark8Setup("Problem heap quicksort",
          String.format("%2d", threadCount),
          new Benchmarkable() {
            public void setup() {
               shuffle(intArray);
               problemHeapStart(threadCount, pSize, intArray);
            }



          }
    );
```

Java code for Quicksort (2)

“Measure, don’t guess”

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We use Mark8Setup to measure runtime

```
Benchmark.Mark8Setup("Problem heap quicksort",
         String.format("%2d", threadCount),
         new Benchmarkable() {
           public void setup() {
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              problemHeapStart(threadCount, pSize, intArray);
           }
           public double applyAsDouble(int i) {
              problemHeapFinish(threadCount, intArray); return 0.0;
           }
         }
    );
```

Java code for Quicksort (2)

“Measure, don’t guess”
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           }
         }
   );
```

Code in `ProblemHeapSortingBenchmarkable.java`

Java Executors (1)

Motivation

- Threads are expensive to start - executors reuse threads
- Problem heap - breaking a problem down to smaller problems (tasks)

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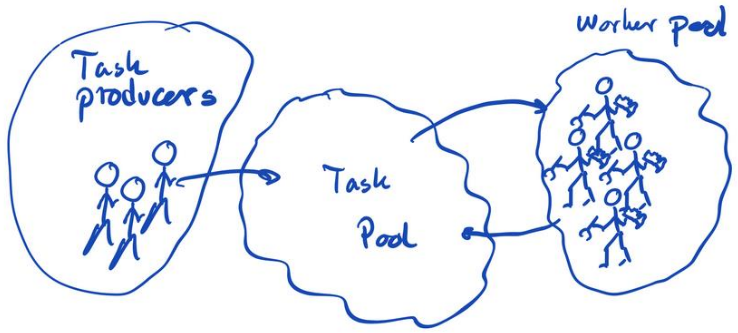

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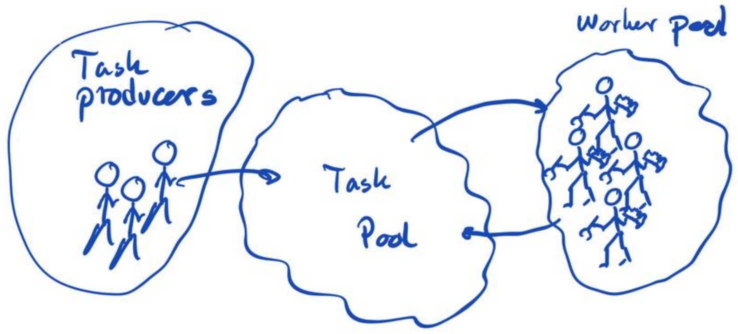

Task producers, and *Workers* are threads

Java Executors (1)

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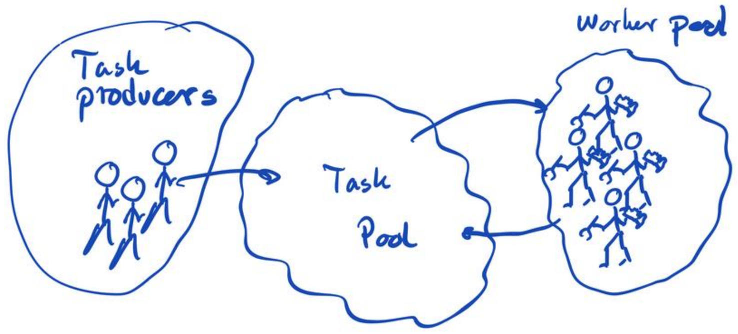

Task producers, and *Workers* are threads
Workers may themselves produce new tasks

Java Executors (1)

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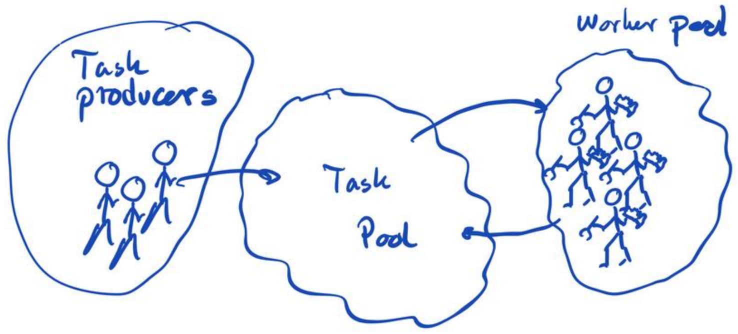

Task producers, and *Workers* are threads
Workers may themselves produce new tasks

The Task pool and Worker pool together is called an *Executor service*

Java Executors (2)

Goetz 6.2

```
new Thread(runnable1).start();
...
new Thread(runnable2).start();
...
new Thread(runnable3).start();
```

Threads are expensive !

```
ExecutorService pool;

pool.execute(runnable1);
...
pool.execute(runnable2);
...
pool.execute(runnable2);
```

Reuse of threads

https://howtodoinjava.com/java/multi-threading/java-fixed-size-thread-pool-executor-example/

Java Executors (3) - Tasks

- **Tasks** are a central concept for executors

- When designing a program using executors, first think about the tasks to be executed
  - Like for threads, tasks can be conveniently defined in their own class

- Ideally, tasks should be independent

Java Executors (3) - Tasks

- **Tasks** are a central concept for executors

- When designing a program using executors, first think about the tasks to be executed
  - Like for threads, tasks can be conveniently defined in their own class

- Ideally, tasks should be independent

Why?

Quicksort Task class

Quicksort Task class

```
class QuicksortTask implements Runnable {


















}
```

Quicksort Task class

```
class QuicksortTask implements Runnable {
 private Problem p;














}
```

Quicksort Task class

```
class QuicksortTask implements Runnable {
 private Problem p;
 private ExecutorService pool;










}
```

Quicksort Task class

```
class QuicksortTask implements Runnable {
 private Problem p;
 private ExecutorService pool;
 private static int threshold;


















}
```

Quicksort Task class

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class QuicksortTask implements Runnable {
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 ...









}
```

Quicksort Task class

```
class QuicksortTask implements Runnable {
 private Problem p;
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 ...

 @Override
 public void run() { qsort(p, pool, ... ); }









}
```

Quicksort Task class

```
class QuicksortTask implements Runnable {
 private Problem p;
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 @Override
 public void run() { qsort(p, pool, ... ); }

 public static void qsort(ExecutorService pool, ... ) {










 }
}
```

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 public void run() { qsort(p, pool, ... ); }

 public static void qsort(ExecutorService pool, ... ) {
  if (a < b) {










 }
}
```

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 @Override
 public void run() { qsort(p, pool, ... ); }

 public static void qsort(ExecutorService pool, ... ) {
  if (a < b) {

   ... // quicksort on Problem p





  }
  ... // subarray already ordered
 }
}
```

Quicksort Task class

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 private Problem p;
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 @Override
 public void run() { qsort(p, pool, ... ); }

 public static void qsort(ExecutorService pool, ... ) {
  if (a < b) {

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   if ((j-a)>=threshold) pool.execute(new QuicksortTask(new Problem(...), pool, ...));




  }
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```

Quicksort Task class

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class QuicksortTask implements Runnable {
 private Problem p;
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    if ((b-i)>= threshold) pool.execute(new QuicksortTask(new Problem(...), pool, ...));
    else qsort(new Problem(...), ...);
   }
   ... // subarray already ordered
  }
}
```

Quicksort Task class

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```

Are Quicksort tasks independent of each other?

Quicksort Task class

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```

Are Quicksort tasks independent of each other?

Code in `QuicksortTask.java`

Quicksort Executor class

- Kick-off class for the program
- It initializes the Executor service

```
class QuicksortExecutor {
     private ExecutorService pool;
     ...
    private static void setUpQS(int threadCount, int[] intArray, int threshold,...) {
     pool = Executors.newFixedThreadPool(threadCount);
     pool.execute( new QuicksortTask( new Problem(intArray, 0, intArray.length-1),
                          pool, threshold, ...) );
    }
}
```

Quicksort Executor class

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}
```

- There are several type of thread pools:
  - newFixedThreadPool
  - newCachedThreadPool (useful for testing)
  - newSingleThreadExecutor
  - …

Work stealing queues

- Instead of having a single task pool, each worker has its own task pool
    - This tasks pools are implemented as *queues*
- Workers add tasks to their own queues
    - Minimizes thread contention in a single thread resource
- If worker can work but its queue is empty, it *steals* a task from another worker task pool
    - From the end of the queue
    - To further minimize contention

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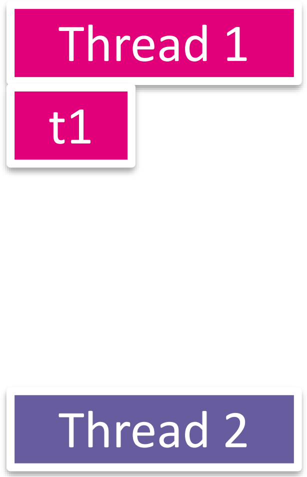

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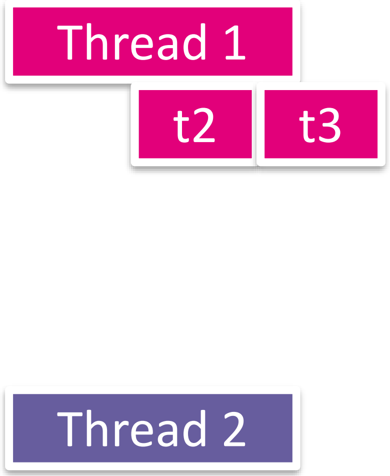

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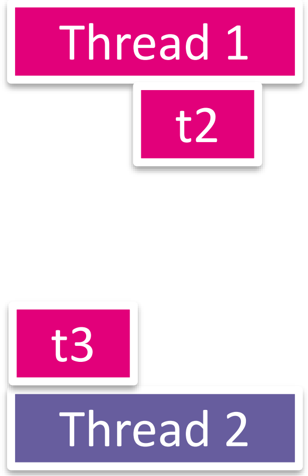

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- If worker can work but its queue is empty, it *steals* a task from another worker task pool
  - From the end of the queue
  - To further minimize contention

Work stealing queues

- Instead of having a single task pool, each worker has its own task pool
  - This tasks pools are implemented as *queues*
- Workers add tasks to their own queues
  - Minimizes thread contention in a single thread resource
- If worker can work but its queue is empty, it *steals* a task from another worker task pool
  - From the end of the queue
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Thread 1

Thread 2

In what type of algorithms may work stealing queues be useful?

Performance of Executor Quicksort

```
Executor quicksort  1     98003405.0 ns
Executor quicksort  2     53568593.9 ns
Executor quicksort  4     36397241.3 ns
Executor quicksort  8     21714103.7 ns
Executor quicksort 16     22237307.4 ns
Executor quicksort 32     22510681.9 ns
```

Speedup = 4.5

A bit better speed-up than using native Threads (slide 3)

Quicksort

```
1  2  43  78  19  54  33  21  64  52  17  53
1  2  43  78  19  54  33  21  64  52  17  53
1  2  43  78  19  54  33  21  64  52  17  53
      ↑                               ↑
1  2  17  78  19  54  33  21  64  52  43  53
      ↑                               ↑
1  2  17  78  19  54  33  21  64  52  43  53
          ↑               ↑
                    ...
1  2  17  21  19  54  33  78  64  52  43  53
1  2  17  21  19  33  54  78  64  52  43  53
```

Two parts can be sorted independently

What limits scalability?

What limits scalability?

Example: growing a crop

- 4 months growth + 1 month harvest if done by 1 person
- Growth (sequential) cannot be speeded up
- Using 30 people to harvest, takes 1/30 month = 1 day
- Speed-up using many harvesters: 5/(4+1/30) = 1.24 times faster

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- Speed-up using many harvesters: 5/(4+1/30) = 1.24 times faster

Amdahl's law (Goetz 11.2)

F = sequential fraction of problem = 4/5 = 0.8

N = number of threads (people) = 30

$$speed\ up \leq \frac{1}{F + \frac{(1-F)}{N}} = \frac{1}{0.8 + 0.2/30} = 1.24$$

Other types of "loss" of scalability

- Starvation loss
  - Minimize the time that the problem heap is empty

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Møller-Nielsen, P and Staunstrup, J, Problem-heap. A paradigm for multiprocessor algorithms. *Parallel Computing*, 4:63-74, 1987

Executors and Future

- Example: Dot Product

Termination in Executors

```
class QuicksortTask implements Runnable {

  public void run() { qsort(p, ...); }
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  //main (thread)
  setUpQS( … ) // Initializes pool, executes initial task
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How do we known when all tasks are finished?

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}
```

How do we known when all tasks are finished?

Need for a signal from the workers to the main thread!

Shut down

The ExecutorService has methods to shut down the pool.

```
 // Executor body
...
...

pool.shutdown();
```

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```
 // Executor body
...
...

pool.shutdown();
```

The challenge is *when to shut down*

In the Quicksort example, a counter is used to track the number of pending tasks. When there are no pending tasks we can shut down.

Solution 1: shared counter + barrier

```
// main thread
class public class QuicksortExecutor {
     ...
     final AtomicInteger count = new AtomicInteger(0);
     final CyclicBarrier done = new CyclicBarrier(2);

     private static void setUpQS(int threadCount, int[] intArray, int threshold,
                                CyclicBarrier done, AtomicInteger count) {
          pool = Executors.newFixedThreadPool(threadCount);
          count.set(1); // Initial task count
          pool.execute( new QuicksortTask(…, done, count) );
     }
     ...

}
```

Counts the number of pending tasks

It will be used to signal when to shutdown

Using the counter + barrier

```
public static void qsort(.., CyclicBarrier done, AtomicInteger count) {
if (a < b) {
  ...

  if ((j-a)>= threshold) count.incrementAndGet();
  if ((b-i)>= threshold) count.incrementAndGet();


  if ((j-a)>= threshold) {
    pool.execute(new QuicksortTask(new Problem(arr, a, j), pool, c) );
  } else qsort(...) // sequentially
  if ((b-i)>= threshold) {
    pool.execute(new solveProblem(new Problem(arr, i, b), pool, c) );
  } else qsort(...) // sequentially

  ...

  if (count.decrementAndGet() == 0) { done.await(); pool.shutdown(); }
}
```

Using the counter + barrier

```
public static void qsort(.., CyclicBarrier done, AtomicInteger count) {
if (a < b) {
   ...

   if ((j-a)>= threshold) count.incrementAndGet();
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   if ((j-a)>= threshold) {
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   ...

   if (count.decrementAndGet() == 0) { done.await(); pool.shutdown(); }
}
```

Why not incrementing in the branch creating the task?

Termination in Executors

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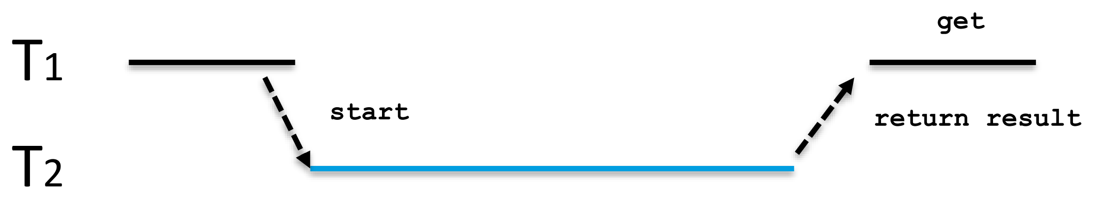
```
public class QuicksortExecutor {
  //main (thread)
  setUpQS( … ) // Initializes pool, executes initial task
  finishQS( … ) //wait for all tasks to be completed
}
```

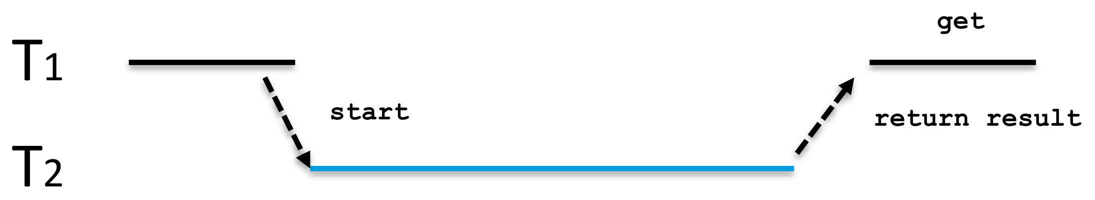
```
private static void finishQS(CyclicBarrier done) {
   try { done.await(); }
   catch (InterruptedException | BrokenBarrierException e) { ... ); }
}
```

Solution 2: Future



get() is a blocking call, so *watch out for deadlocks!*

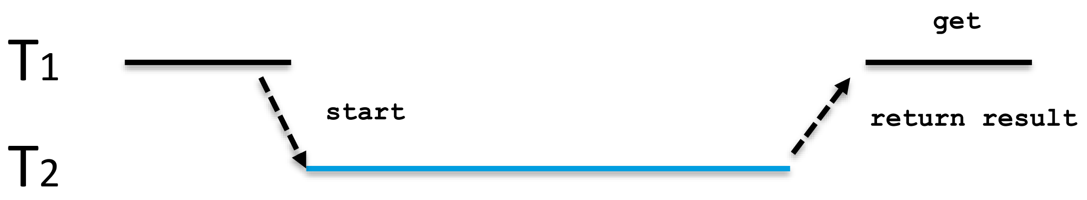
Solution 2: Future



```
T1:
  Future<Integer> future = T2.calculate(  );  // start
      ...
  future.get();
```

get() is a blocking call, so ***watch out for deadlocks!***

Solution 2: Future



```
T2:
  public Future<Integer> calculate(Integer input) {
    return executor.submit(() -> {
      ... // compute result
      return result;
    });
  }
}

T1:
  Future<Integer> future = T2.calculate(  );  // start
     ...
  future.get();
```

get() is a blocking call, so *watch out for deadlocks!*

Complete example

https://www.baeldung.com/java-future

```
private ExecutorService executor
      = Executors.newSingleThreadExecutor();

   public Future<Integer> calculate(Integer input) {
       return executor.submit(  //Callable
          () -> {...      return ... ;   }
      );
   }
```

Code in `futureExample.java`

Runnable vs. Callable

Both are used to specify the code of a thread.

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Futures are an example of message passing (coming weeks)

Runnable vs. Callable

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- Runnable cannot return a result
  - Overrides run()
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Could Callables use shared data as well?

As illustrated by the Quicksort example, Runnables may use shared data (e.g., to deliver a result)

Futures are an example of message passing (coming weeks)

dotProduct – Task class

Given two vectors *x, y* of equal size, their dot product equals $\sum_i x_i y_i$

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We use futures to multiple each vector position

dotProduct – Task class

Given two vectors *x, y* of equal size, their dot product equals $\sum_i x_i y_i$

```
public class DotProductTask implements Callable<Integer> {
     final int pos;
     final int[] x, y;

     public DotProductTask(int[] x, int[] y, int pos) {
          this.x   = x;
          this.y   = y;
          this.pos = pos;
     }

     @Override
     public Integer call() {
          return x[pos] * y[pos];
     }
}
```

We use futures to multiple each vector position

dotProduct – Future execution

Given two vectors x, y of equal size, their dot product equals $\sum_i x_i y_i$

```
...
List<DotProductTask> tasks = new ArrayList<DotProductTask>();

// Randomly initialize arrays ...









...
```

dotProduct – Future execution

Given two vectors x, y of equal size, their dot product equals $\sum_i x_i y_i$

```
...
List<DotProductTask> tasks = new ArrayList<DotProductTask>();

// Randomly initialize arrays ...

// Create the list of tasks (Futures) to execute
for (int i = 0; i < N; i++)
    tasks.add(new DotProductTask(x,y,i));









...
```

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// Add all futures to the execution pool at once
List<Future<Integer>> futures = pool.invokeAll(tasks);






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```

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// Add all futures to the execution pool at once
List<Future<Integer>> futures = pool.invokeAll(tasks);
for(Future<Integer> f : futures) {
     result += f.get(); // Wait for each future to be executed
                        // and add partial result



...
```

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Code in `FuturesDotProduct.java`

Lock striping

A case study with Hash maps

Scalability of Java Collections

A *collection* is simply an object that groups multiple elements into a single unit

Package: java.util

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Examples: ArrayList, HashMap, TreeSet, …

https://docs.oracle.com/javase/tutorial/collections/intro/index.html

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Methods: add, remove, size, contains, …

Many of the classes have synchronized/concurrent implementations

https://www.baeldung.com/java-synchronized-collections

Example: synchronized ArrayList

```
import java.util.*;
public class syncCollectionExample {
  public static void main(String[] args) {  new syncCollectionExample(); }











  public syncCollectionExample() {






  }
}
```

Goetz p. 80

Example: synchronized ArrayList

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import java.util.*;
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  public syncCollectionExample() {
    ArrayList<String> a= new ArrayList<String>();
    a.add("A");  ...



  }
}
```

Goetz p. 80

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  public syncCollectionExample() {
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    Collection<String> synColl = Collections.synchronizedCollection(a);
    ...
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Goetz p. 80

Example: synchronized ArrayList

```
import java.util.*;
public class syncCollectionExample {
  public static void main(String[] args) {  new syncCollectionExample(); }

  public String getLast(ArrayList<String> l) {
    int last= l.size()-1;
    return l.get(last);
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    int last= l.size()-1;
    l.remove(last);
  }

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    ...
  }
}
```

Goetz p. 80

Thread-safety (from week 3)

It is very important to note that for a program *p*:

p only accesses thread-safe <u>classes</u>

$\not\Rightarrow$

p is a thread-safe <u>program</u>

Making the synchronized ArrayList thread safe

```
import java.util.*;
public class syncCollectionExample {
  public static void main(String[] args) {  new syncCollectionExample(); }

  public String getLast(ArrayList<String> l) {
    synchronized(l) {
      int last= l.size()-1;
      return l.get(last);
    }
  }

  public static void delete(ArrayList<String> l) {
    synchronized(l) {
      int last= l.size()-1;
      l.remove(last);
    }
  }

  public syncCollectionExample() {
   ...
  }
}
```

Goetz p. 80

What if the data structure is huge?

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and used by many threads?

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for example:

a bank
Facebook updates
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What if the data structure is huge?

and used by many threads?

for example:

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What can we do?

Reduce locking !!

Example: A huge HashMap

Key value pairs: <k1, v1>, <k2, v2>, …

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Key	Value
Peter	20487612
Anna	51251218
Lena	34458318
Holger	89545010
Lisa	94959500

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Key	Value
Peter	20487612
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Lisa	94959500

```
class HashMap<K,V> {
  ...  // data structure
  public V get(K k) { ... }
  public V put(K k, V v) { ... }
  public boolean containsKey(K k) { ... }
  public int size() { return cachedSize; }
  public V remove(K k) { ... }
  ...
}
```

Example: A huge HashMap

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Peter	20487612
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  ...
}
```
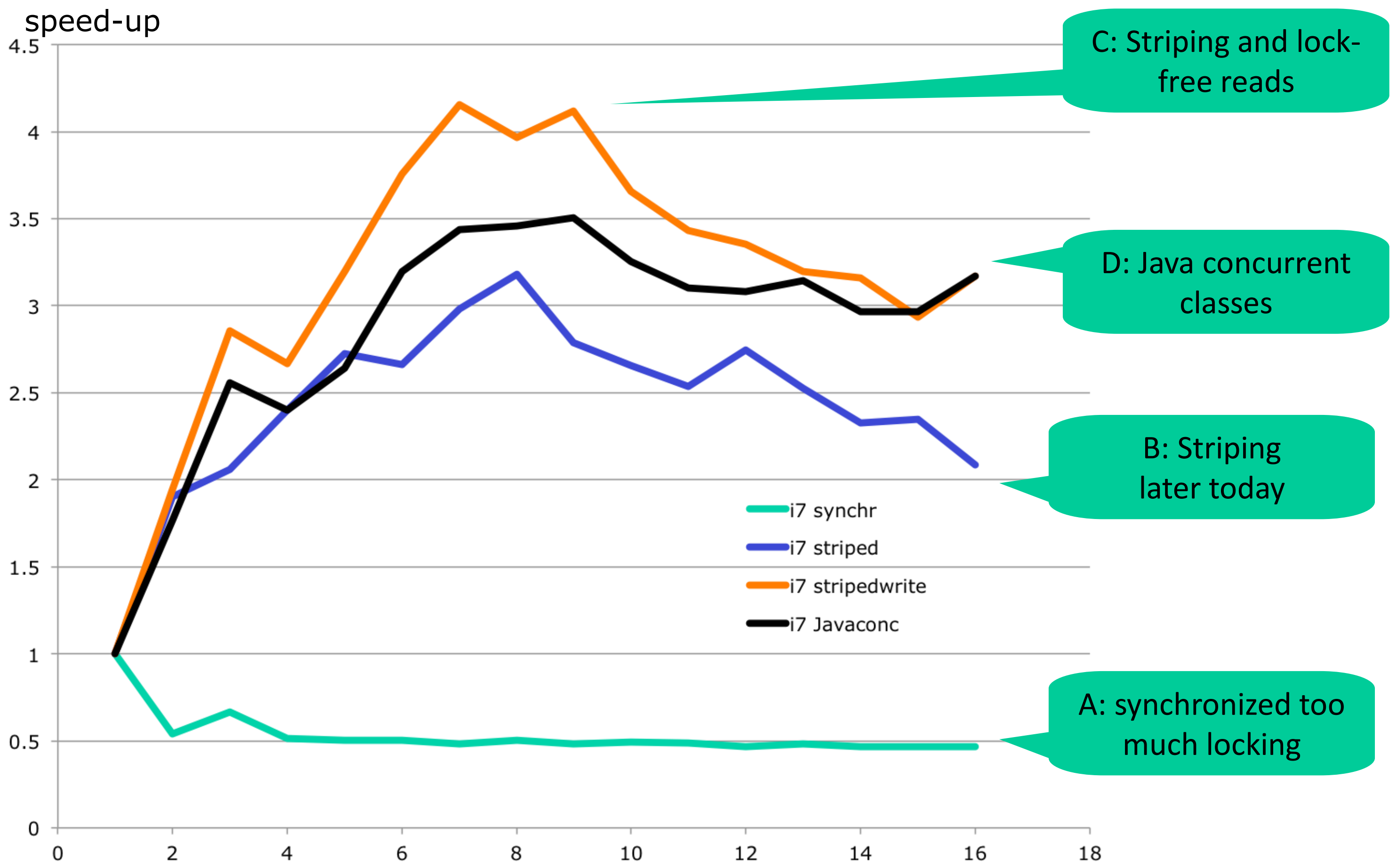

How to make it thread-safe?

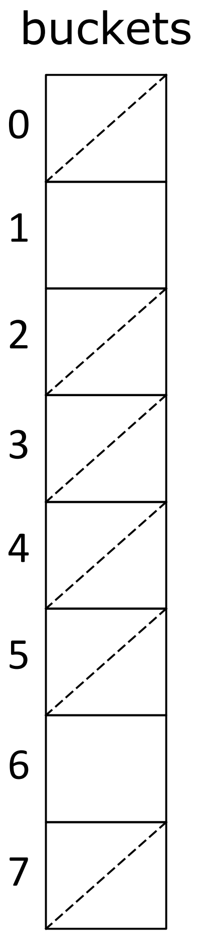
Scaling a HashMap

133



# threads

HashMap implementation



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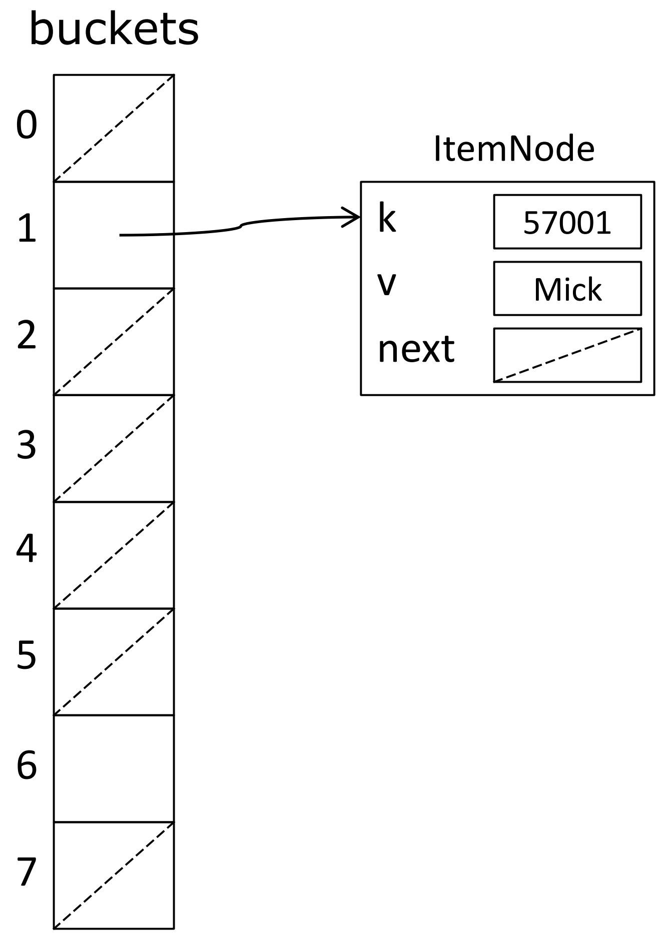

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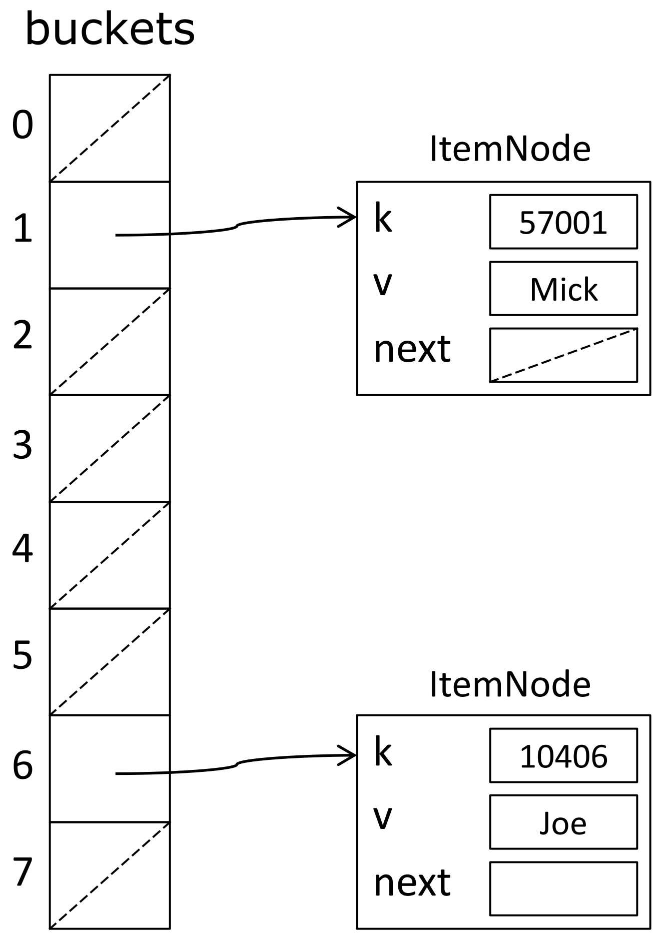

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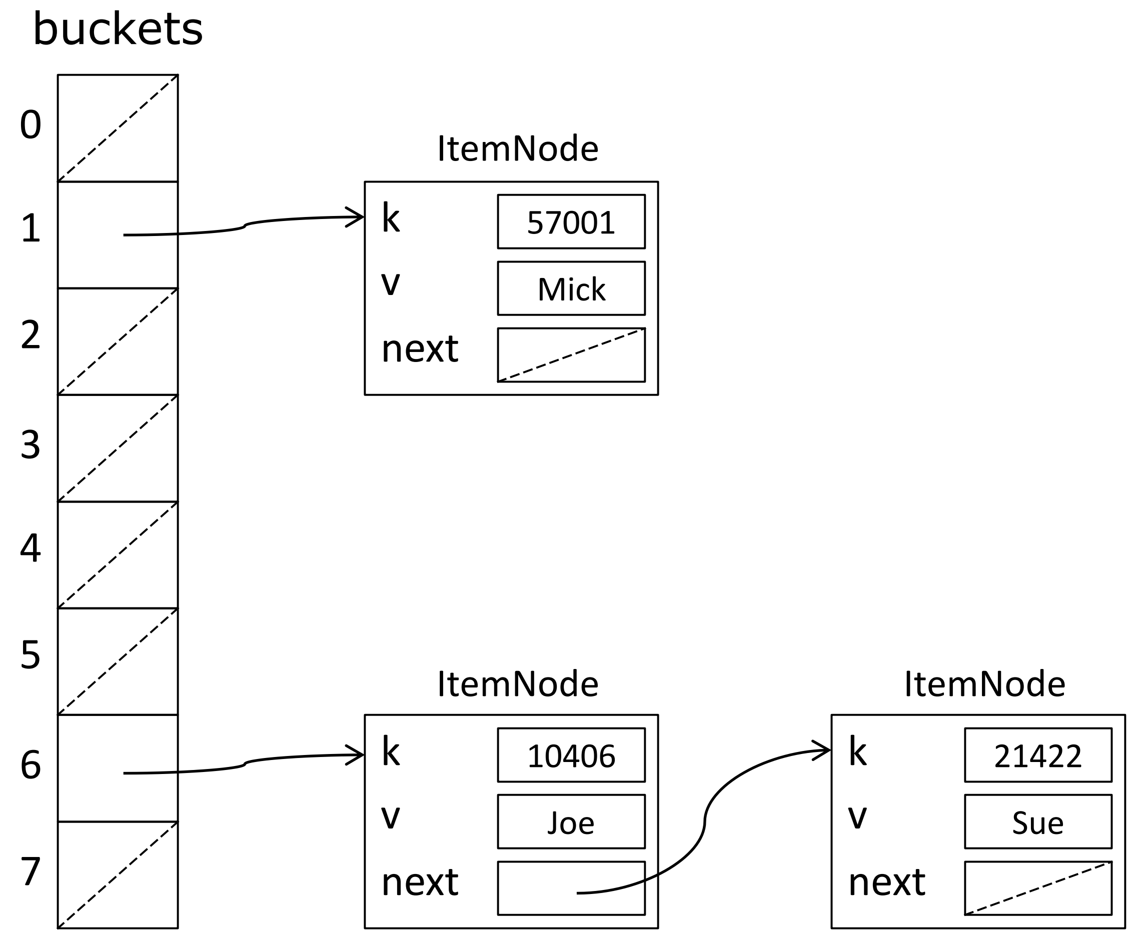

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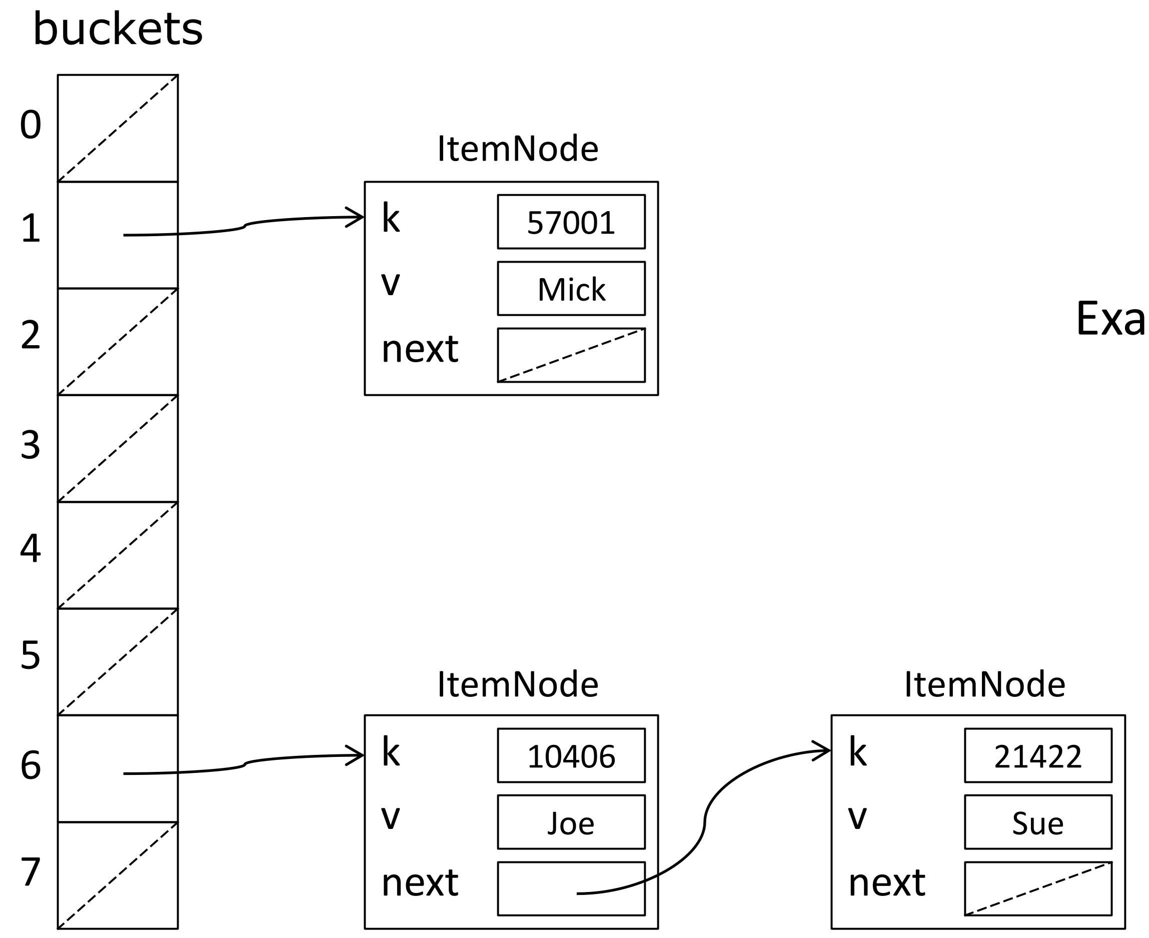
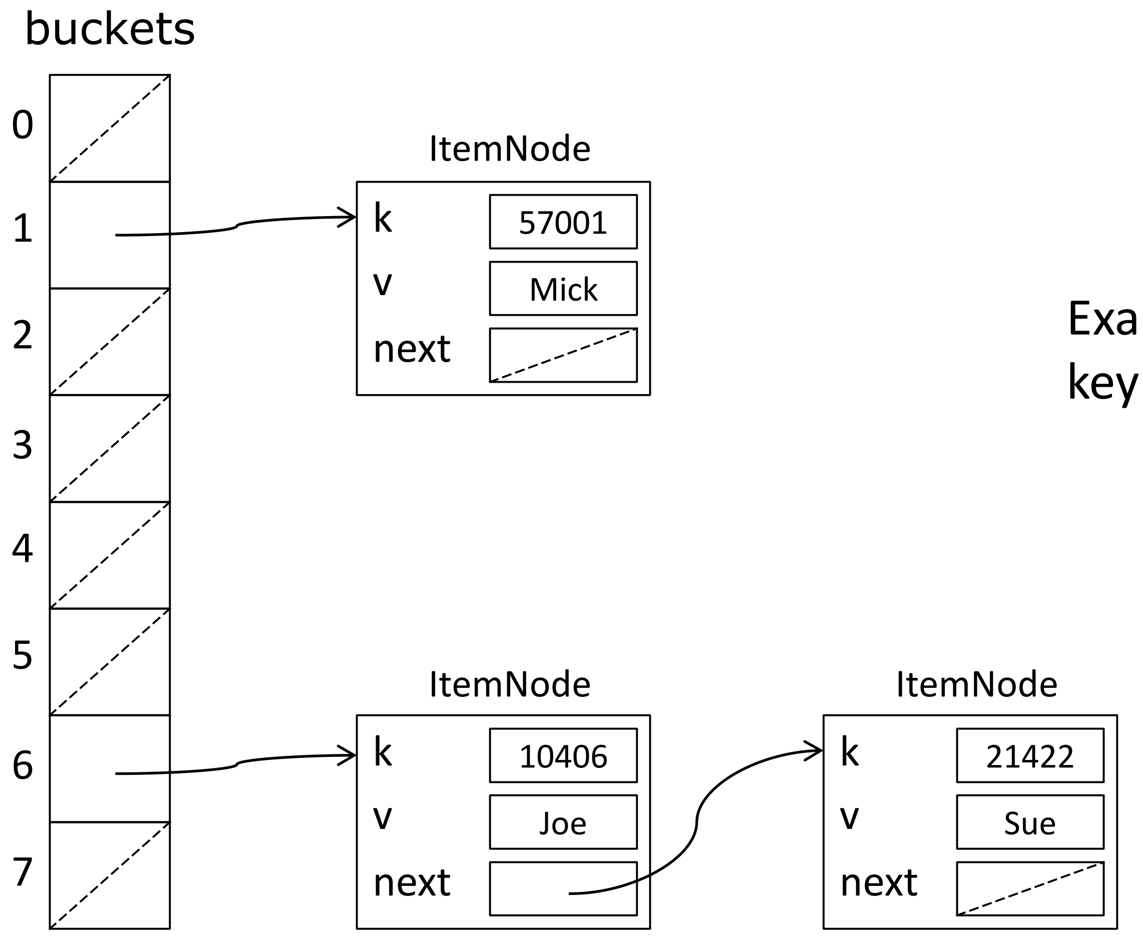


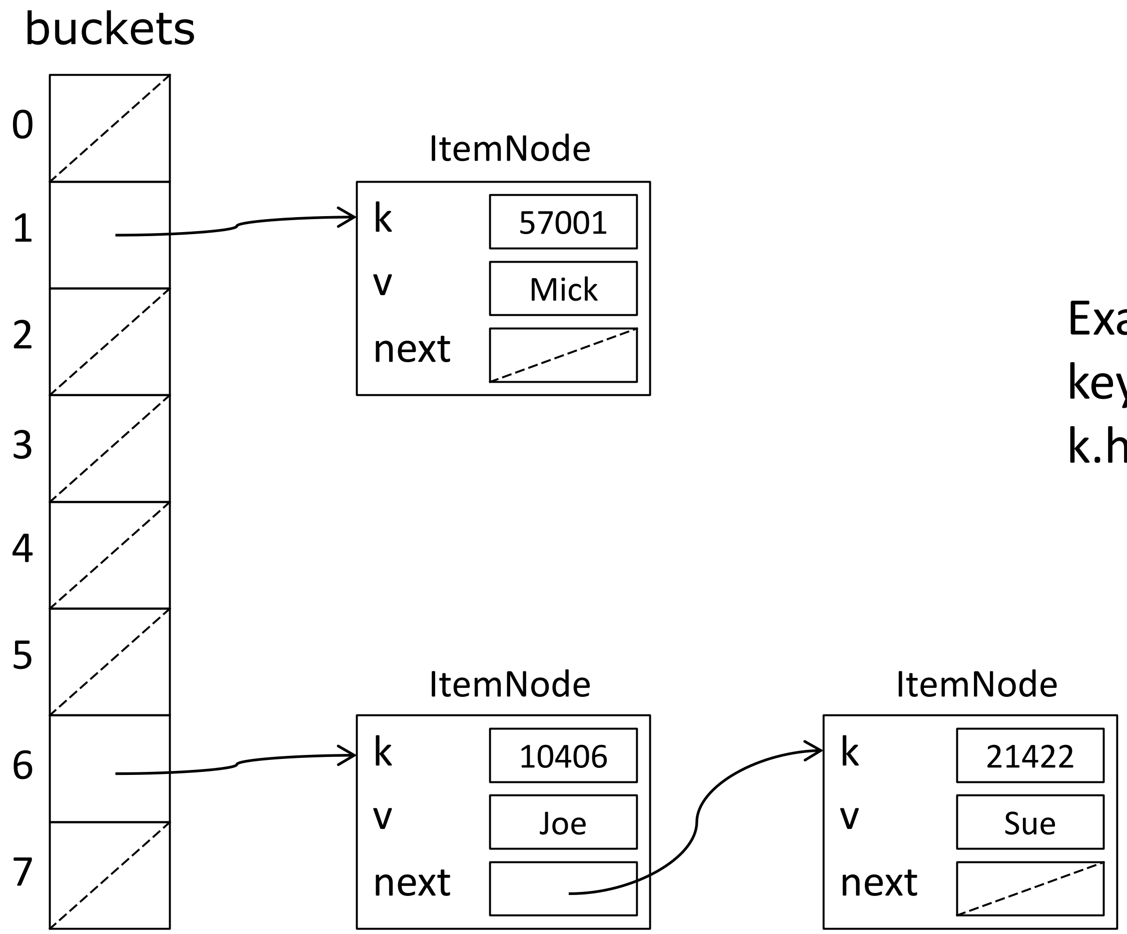
Example **get(10406)**

HashMap implementation



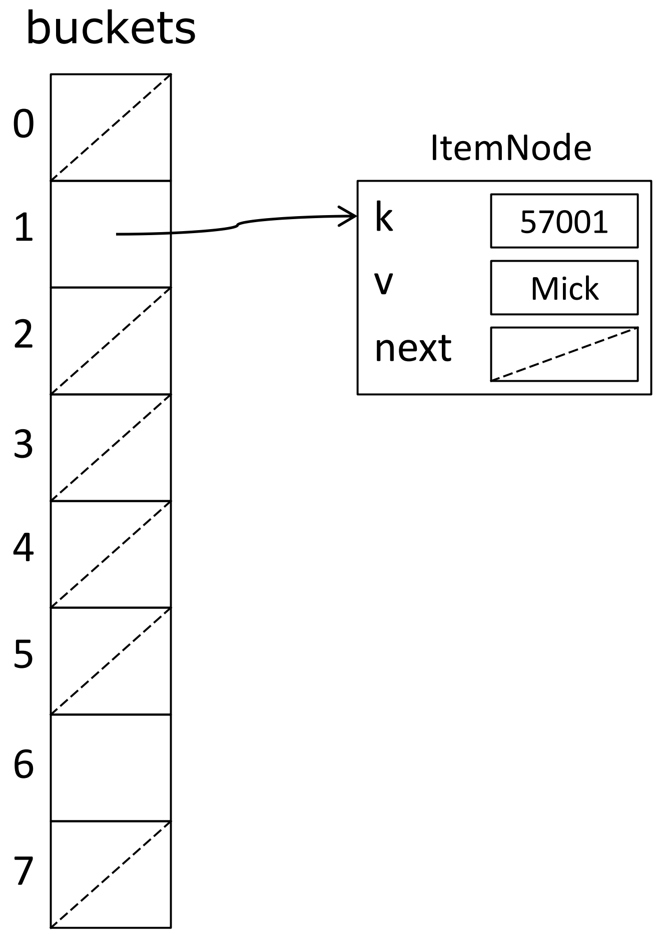
Example **get(10406)**
key k is 10406

HashMap implementation



Example **get(10406)**
key k is 10406
k.hashCode() is 6

HaspMap put



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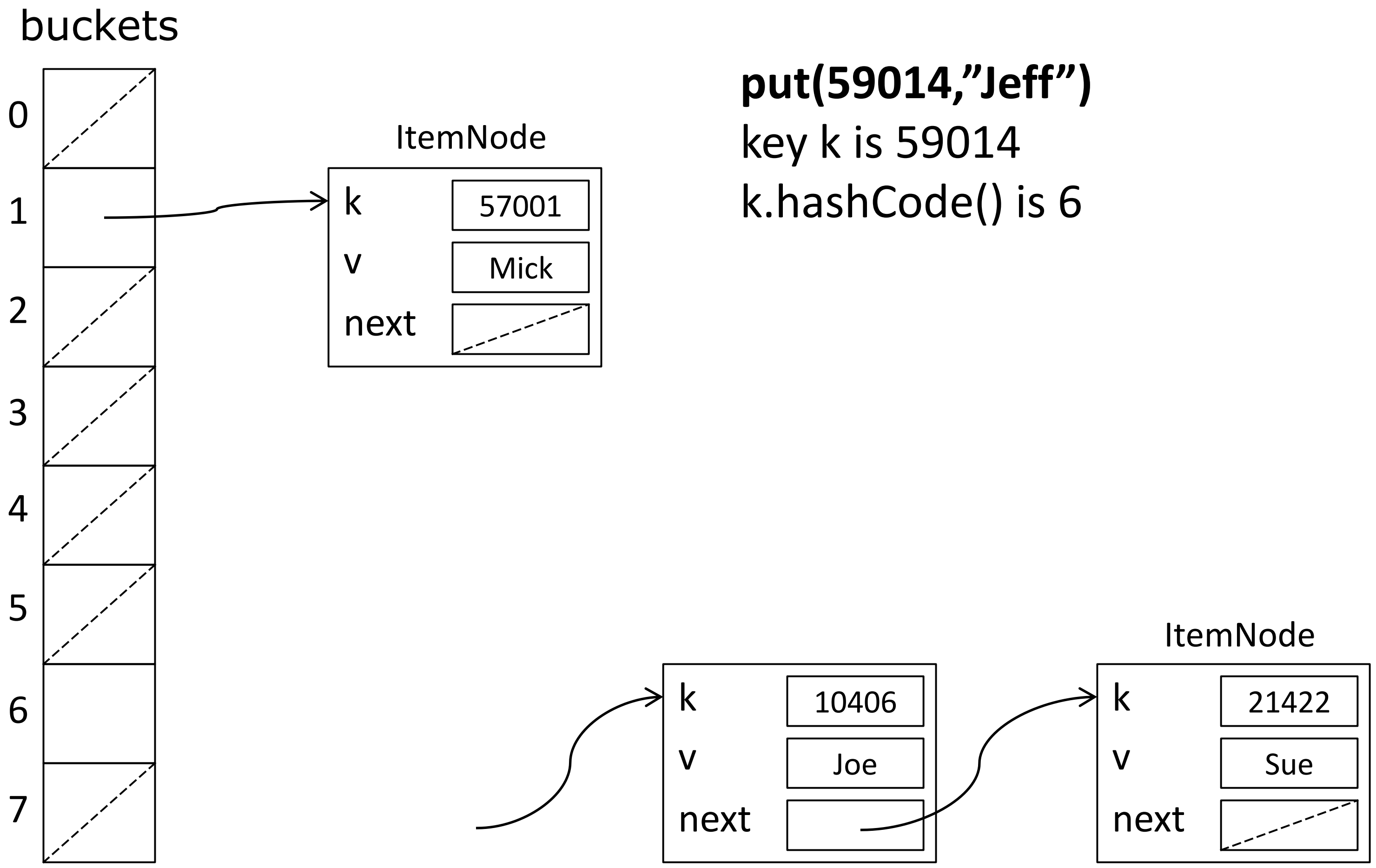
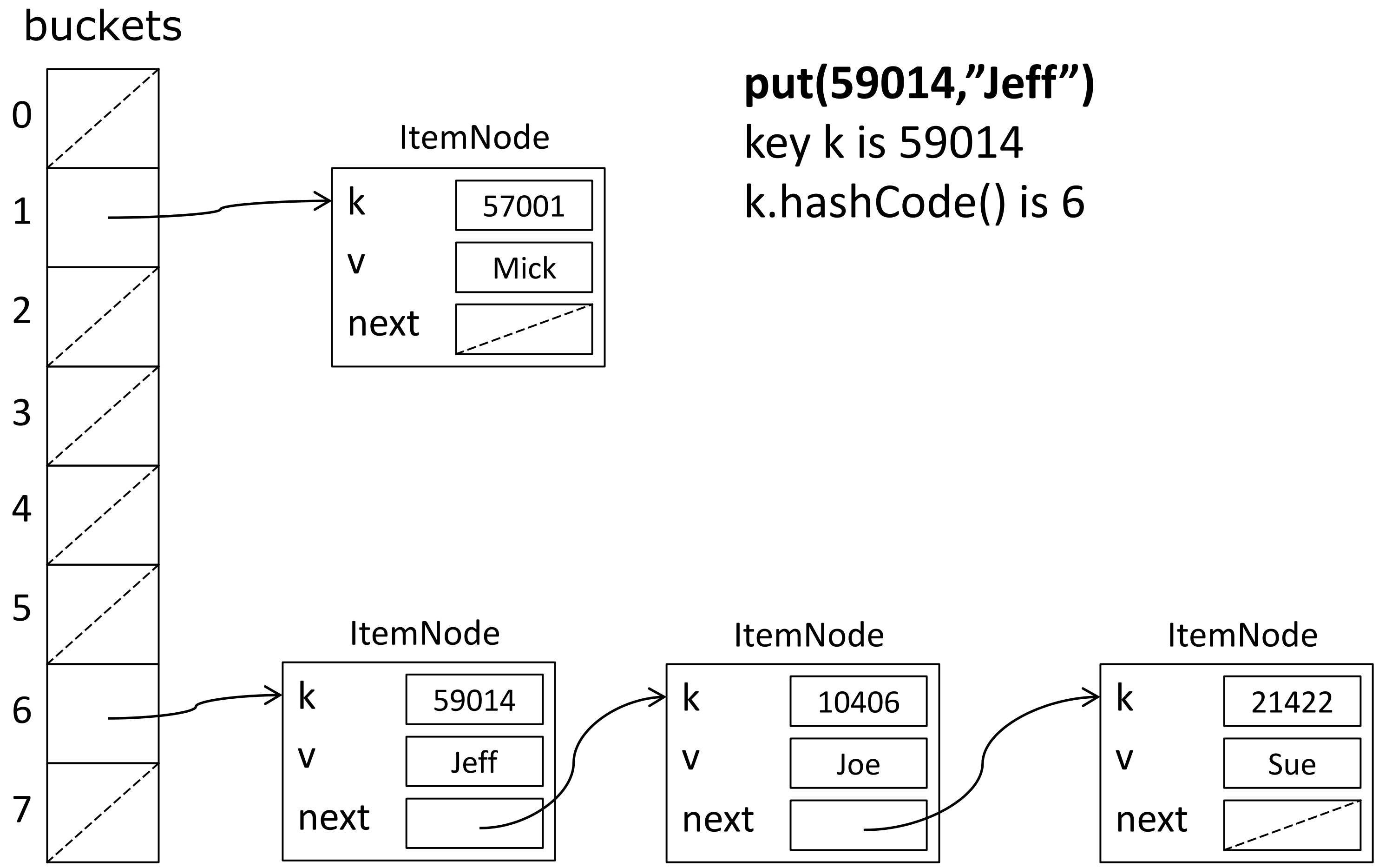


put(59014,”Jeff”)
key k is 59014
k.hashCode() is 6

HaspMap put



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Synchronized implementation

```
static class ItemNode<K,V> {
  private final K k;
  private V v;
  private ItemNode<K,V> next;
  public ItemNode(K k, V v, ItemNode<K,V> next) { ... }
}
```

```
class SynchronizedMap<K,V> {


  public synchronized V get(K k) { ... }
  public synchronized boolean containsKey(K k) { ... }
  public synchronized int size() { return cachedSize; }
  public synchronized V put(K k, V v) { ... }
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```
class SynchronizedMap<K,V> {
  private ItemNode<K,V>[] buckets;  // guarded by this
  private int cachedSize;           // guarded by this
  public synchronized V get(K k) { ... }
  public synchronized boolean containsKey(K k) { ... }
  public synchronized int size() { return cachedSize; }
  public synchronized V put(K k, V v) { ... }
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}
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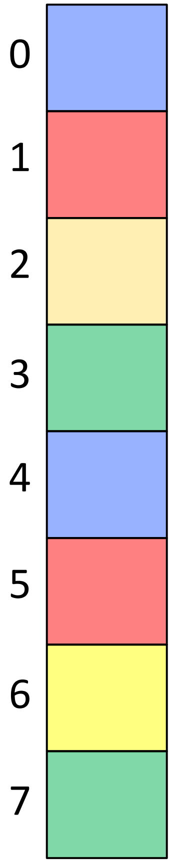

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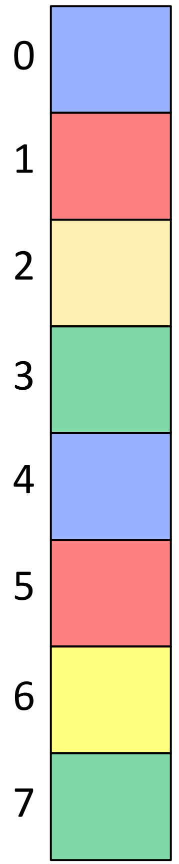

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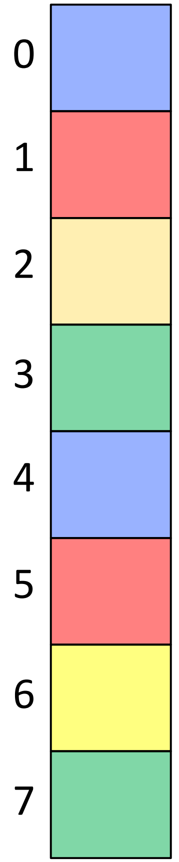

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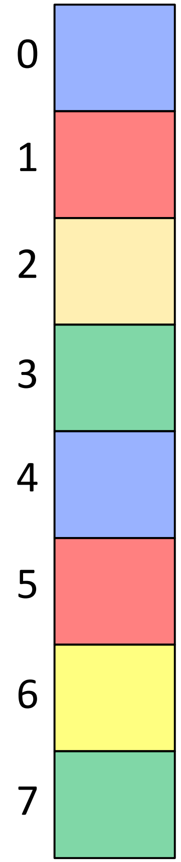

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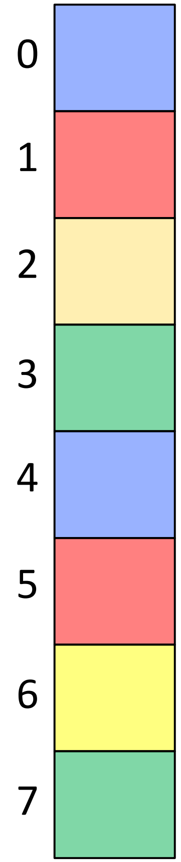
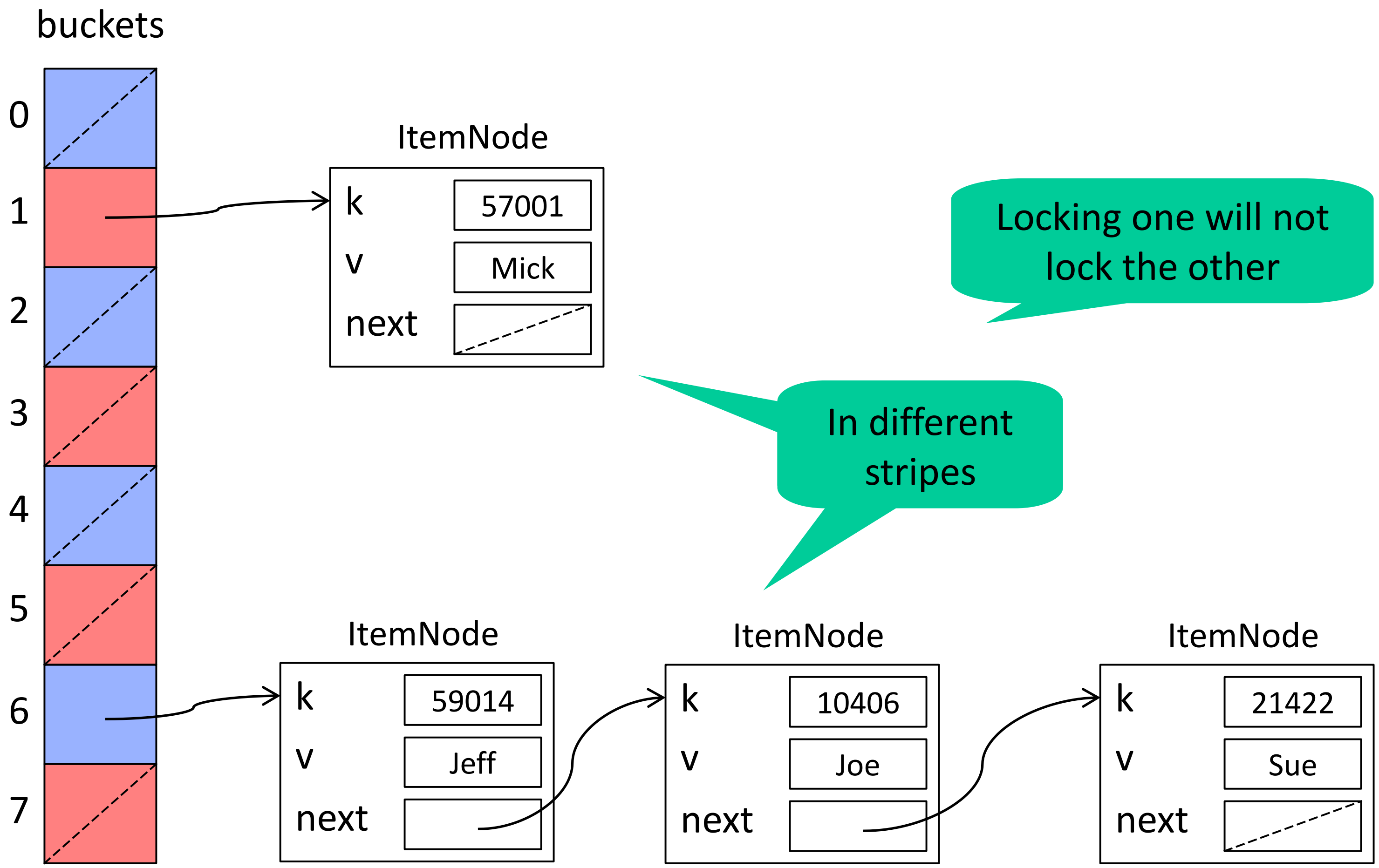
–hence will take different locks

- Less lock contention, better scalability



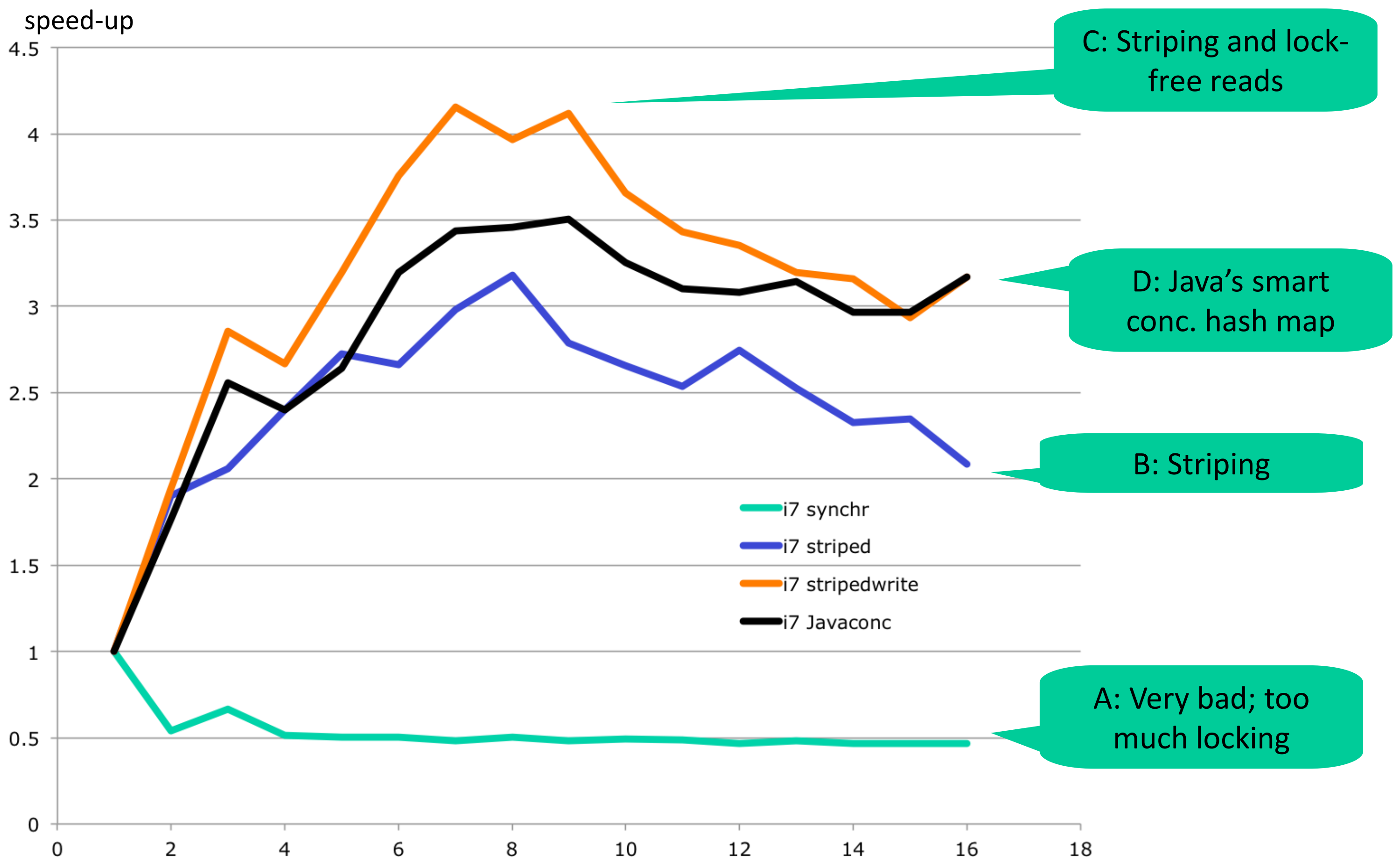
Bucket idea



Locking one will not lock the other

In different stripes

Reducing locking



Ultimate scalability

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but still maintain some sort of consistency

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Week 13