CSC 533: Programming Languages

Spring 2018

Concurrency

- levels of concurrency
- synchronization
  competition vs. cooperation, race conditions
- synchronization mechanisms
  semaphores, monitors, message passing
- concurrency in Java
  threads, Thread/Runnable, synchronize

Concurrency

many modern computers utilize multiple processors or multicores

- can speed up processing by executing statements/programs concurrently
- e.g., a Web server may have multiple processors to handle requests
- e.g., a Web browser might download/request/render concurrently

concurrency can occur at four levels

- machine instruction level –handled at hardware level
- *high-level language statement level*
- *unit (subprogram) level*
- program level – handled at OS level

concurrency can be

- *physical* - multiple independent processors (multiple threads of control)
- *logical* – even with one processor, can time-share to (e.g., browser tasks)

Subprogram-level concurrency

a *task* or *process* or *thread* is a program unit that can be in concurrent execution with other program units

tasks differ from ordinary subprograms in that:

- a task may be implicitly started
- when a program unit starts the execution of a task, it is not necessarily suspended
- when a task's execution is completed, control may not return to the caller

tasks can be:

- *heavyweight* – each executes in its own address space
- lightweight – all tasks execute in the same address space (more efficient)

since tasks are rarely disjoint, there must be mechanisms for coordinating or *synchronizing* tasks

Cooperation synchronization

sometimes, tasks must cooperate

- task A must wait for task B to complete some activity before it can begin or continue its execution
- e.g., producer/consumer relationship

  task A constantly monitors the keyboard, reading each new input and storing in a buffer

  – can't store if the buffer is full

  task B constantly monitors the buffer, accesses each new input and removes from the buffer

  – can't access if the buffer is empty

Competition synchronization

sometimes tasks compete for resources

- tasks A and B both require access to a non-shareable resource – must prevent simultaneous access to preserve integrity

- e.g., suppose tasks A & B access a shared variable `TOTAL`

A executes `TOTAL += 1;`   B executes `TOTAL *= 2;`

at the machine-language level, each assignment involves 3 steps:

1. fetch the value of `TOTAL`
2. perform the operation
3. store the result in `TOTAL`

Race condition

if the shared variable can be accessed "simultaneously," the interleaving of steps can produce different results

1. B fetches `TOTAL` (3)
2. A fetches `TOTAL` (3)
3. B performs operation (6)
4. A performs operation (4)
5. B stores `TOTAL` (6)
6. A stores `TOTAL` (4)

1. B fetches `TOTAL` (3)
2. B performs operation (6)
3. B stores `TOTAL` (6)
4. A fetches `TOTAL` (6)
5. A performs operation (7)
6. A stores `TOTAL` (7)

are other results possible?

1. A fetches `TOTAL` (3)
2. B fetches `TOTAL` (3)
3. A performs operation (4)
4. B performs operation (6)
5. A stores `TOTAL` (4)
6. B stores `TOTAL` (6)

1. A fetches `TOTAL` (3)
2. A performs operation (4)
3. A stores `TOTAL` (4)
4. B fetches `TOTAL` (4)
5. B performs operation (8)
6. B stores `TOTAL` (8)

Synchronization mechanisms

3 methods for providing mutually exclusive access to a resource

1. semaphores
   – early, simple approach (Dijkstra, 1965)

2. monitors
   – incorporates data abstraction (Brinch Hansen, 1973)

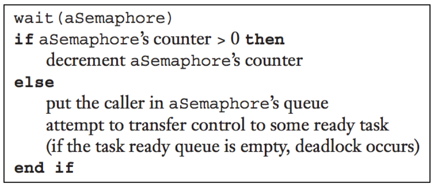
3. message passing
   – utilizes rendezvous messages (Brinch Hansen and Hoare, 1978)
   (see text for examples - will not discuss here)

Semaphores

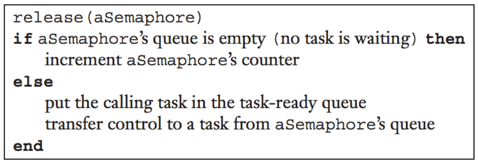
a *semaphore* is a data structure consisting of a counter and a queue for storing task descriptors

- counter represents a number of available resources (initially some N)
- queue represents tasks waiting for resources (initially empty)

- *wait operation:* allocate resource if available, else enqueue the task
- *release:* deallocate the resource, reassign to a task if waiting

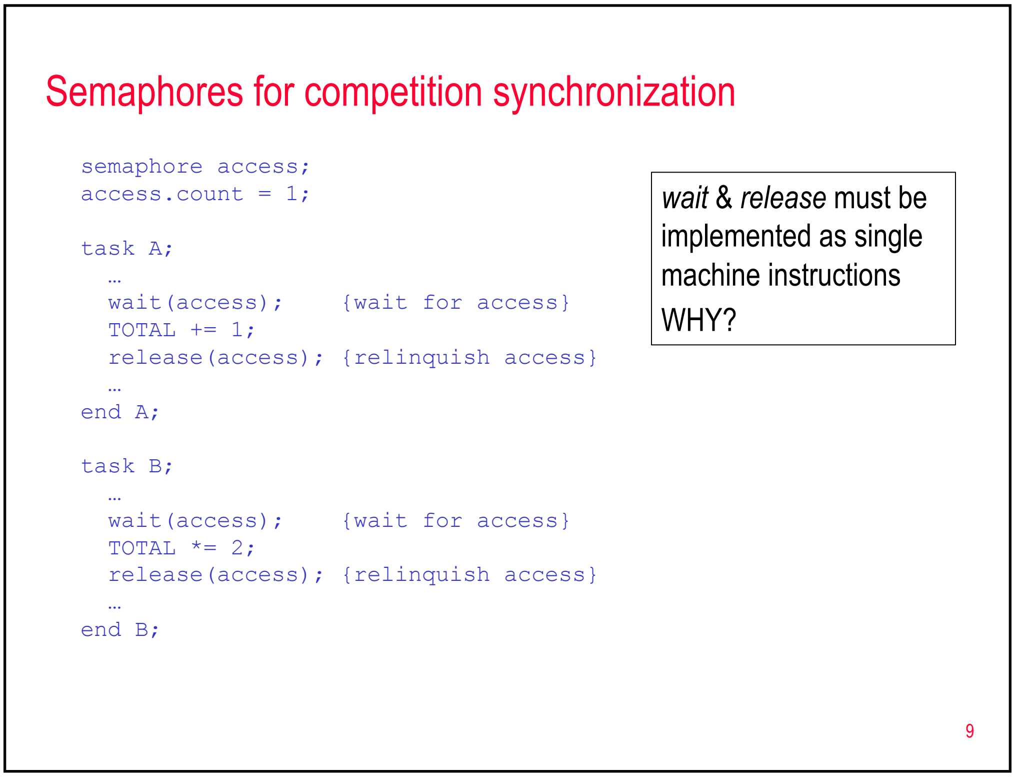


```
wait(aSemaphore)
if aSemaphore's counter > 0 then
    decrement aSemaphore's counter
else
    put the caller in aSemaphore's queue
    attempt to transfer control to some ready task
    (if the task ready queue is empty, deadlock occurs)
end if
```



```
release(aSemaphore)
if aSemaphore's queue is empty (no task is waiting) then
    increment aSemaphore's counter
else
    put the calling task in the task-ready queue
    transfer control to a task from aSemaphore's queue
end
```

- can be used for both competition and cooperation synchronization

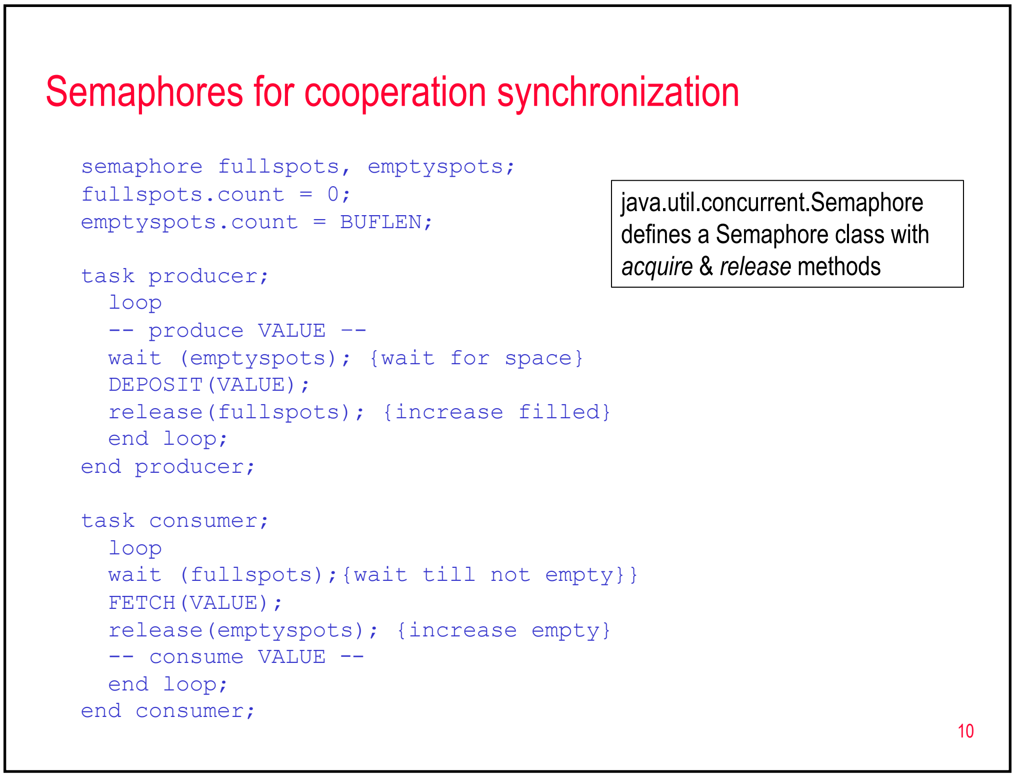


Semaphores for competition synchronization

```
semaphore access;
access.count = 1;

task A;
  …
  wait(access);     {wait for access}
  TOTAL += 1;
  release(access); {relinquish access}
  …
end A;

task B;
  …
  wait(access);     {wait for access}
  TOTAL *= 2;
  release(access); {relinquish access}
  …
end B;
```

wait & *release* must be implemented as single machine instructions

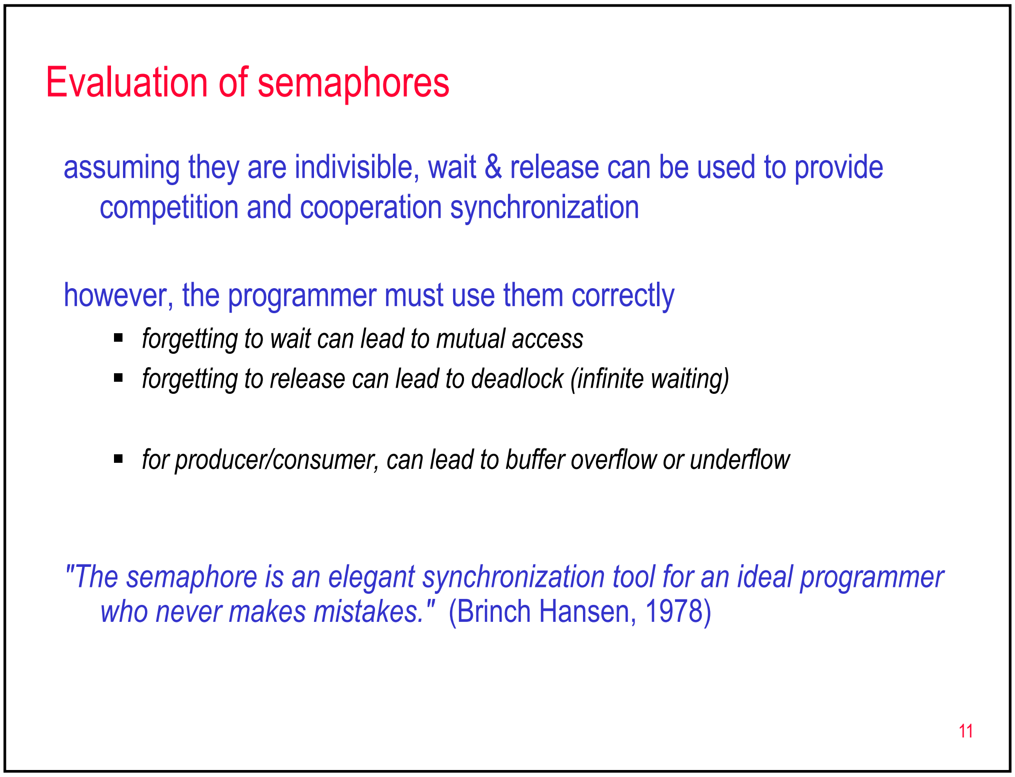
WHY?



Semaphores for cooperation synchronization

```
semaphore fullspots, emptyspots;
fullspots.count = 0;
emptyspots.count = BUFLEN;

task producer;
  loop
  -- produce VALUE --
  wait (emptyspots); {wait for space}
  DEPOSIT(VALUE);
  release(fullspots); {increase filled}
  end loop;
end producer;

task consumer;
  loop
  wait (fullspots);{wait till not empty}}
  FETCH(VALUE);
  release(emptyspots); {increase empty}
  -- consume VALUE --
  end loop;
end consumer;
```

java.util.concurrent.Semaphore defines a Semaphore class with *acquire* & *release* methods



Evaluation of semaphores

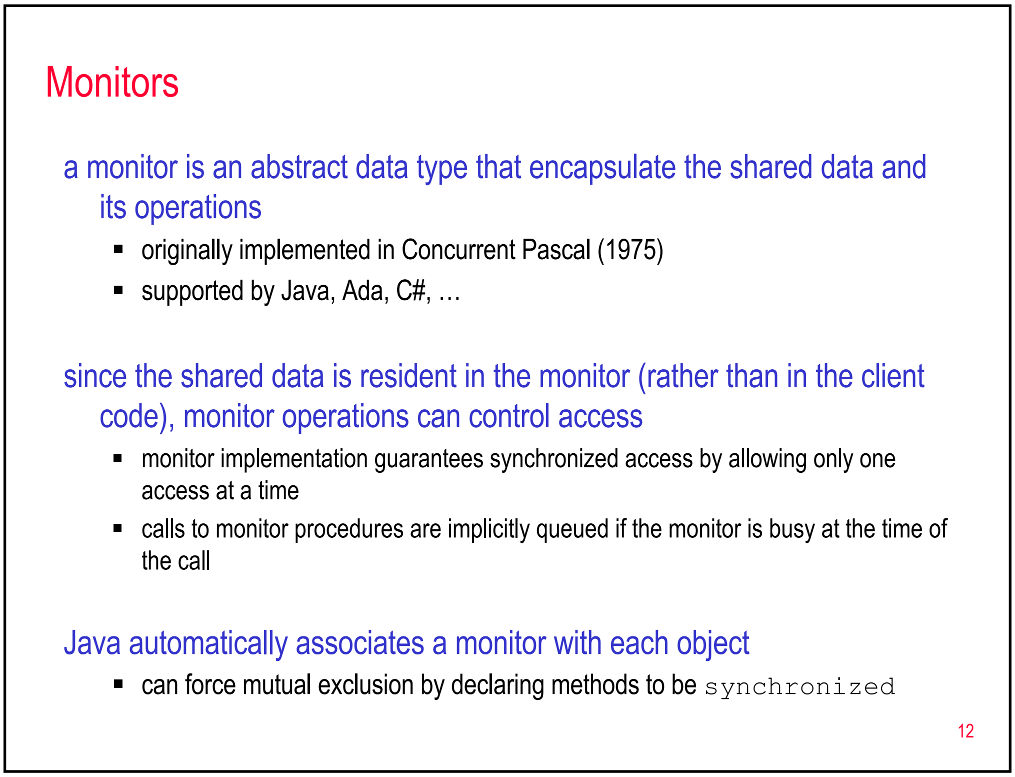
assuming they are indivisible, wait & release can be used to provide competition and cooperation synchronization

however, the programmer must use them correctly

- *forgetting to wait can lead to mutual access*
- *forgetting to release can lead to deadlock (infinite waiting)*

- *for producer/consumer, can lead to buffer overflow or underflow*

"The semaphore is an elegant synchronization tool for an ideal programmer who never makes mistakes." (Brinch Hansen, 1978)



Monitors

a monitor is an abstract data type that encapsulate the shared data and its operations

- originally implemented in Concurrent Pascal (1975)
- supported by Java, Ada, C#, …

since the shared data is resident in the monitor (rather than in the client code), monitor operations can control access

- monitor implementation guarantees synchronized access by allowing only one access at a time
- calls to monitor procedures are implicitly queued if the monitor is busy at the time of the call

Java automatically associates a monitor with each object

- can force mutual exclusion by declaring methods to be `synchronized`

Example: producer/consumer in Java

Java supports concurrency via threads (lightweight processes)

- `public static void main` automatically spawns a thread
- users can create additional threads by extending the `Thread` class (or by implementing the `Runnable` interface)
- a `Thread` class must override `run()`, which specifies the action of that thread

```
class Producer extends Thread {
  private Buffer buffer;

  Producer(Buffer b) {
    this.buffer = b;
  }

  public void run() {
    for (int t = 1; t <= 10; t++) {
      System.out.println("Produced task " +
t);
      this.buffer.put(t);
    }
  }
}
```

```
class Consumer extends Thread {
  private Buffer buffer;

  Consumer(Buffer b) {
    this.buffer = b;
  }

  public void run() {
    for (int i = 1; i <= 10; i++) {
      int t = this.buffer.get();
      System.out.println("Consuming task " + t);
    }
  }
}
```

```
public class Buffer {
  private int [] buffer;
  private int numStored, putIndex, getIndex;

  public Buffer(int size) {
    this.buffer = new int[size];
  }

  public synchronized void put(int task) {
    while(this.numStored == this.buffer.length) {
      try { wait(); }
      catch (InterruptedException e) { }
    }
    this.buffer[this.putIndex] = task;
    this.putIndex =
        (this.putIndex + 1) % this.buffer.length;
    this.numStored++;
    notify();
  }

  public synchronized int get() {
    while (this.numStored == 0) {
      try { wait(); }
      catch (InterruptedException e) { }
    }
    int task = this.buffer[this.getIndex];
    this.getIndex =
        (this.getIndex + 1) % this.buffer.length;
    this.numStored--;
    notify();
    return task;
  }
```

here, Buffer contains an array of ints

- will treat as a circular queue
- `putIndex` will keep track of next place to put a value (wraps around)
- `getIndex` will keep track of next place to get a value (wraps around)
- `numStored` keeps track of number currently stored

useful `Thread` methods

- `start()` spawns the thread (i.e., calls its `run` method)
- `wait()` suspends the current thread (and releases the monitor)
- `notify()` wakes up a thread waiting for the monitor

```
  public static void main(String [] args)
{
    Buffer b = new Buffer(4);
    Producer p = new Producer(b);
    Consumer c = new Consumer(b);

    p.start();
    c.start();
  }
}
```

Example: summing an array

consider the task of summing all of the numbers in an array

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
nums	22	18	12	-4	27	30	36	50	7	68	91	56	2	85	42	98

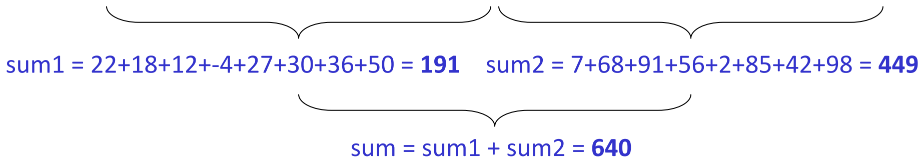
```
public static int sum(int[] nums) {
    int total = 0;
    for (int i = 0; i < nums.length; i++) {
        total += nums[i];
    }
    return total;
}
```

- brute force algorithm is O(N), so doubling the size doubles the time

Example: summing an array

if we had 2 CPUs/cores, could sum each half separately, then combine

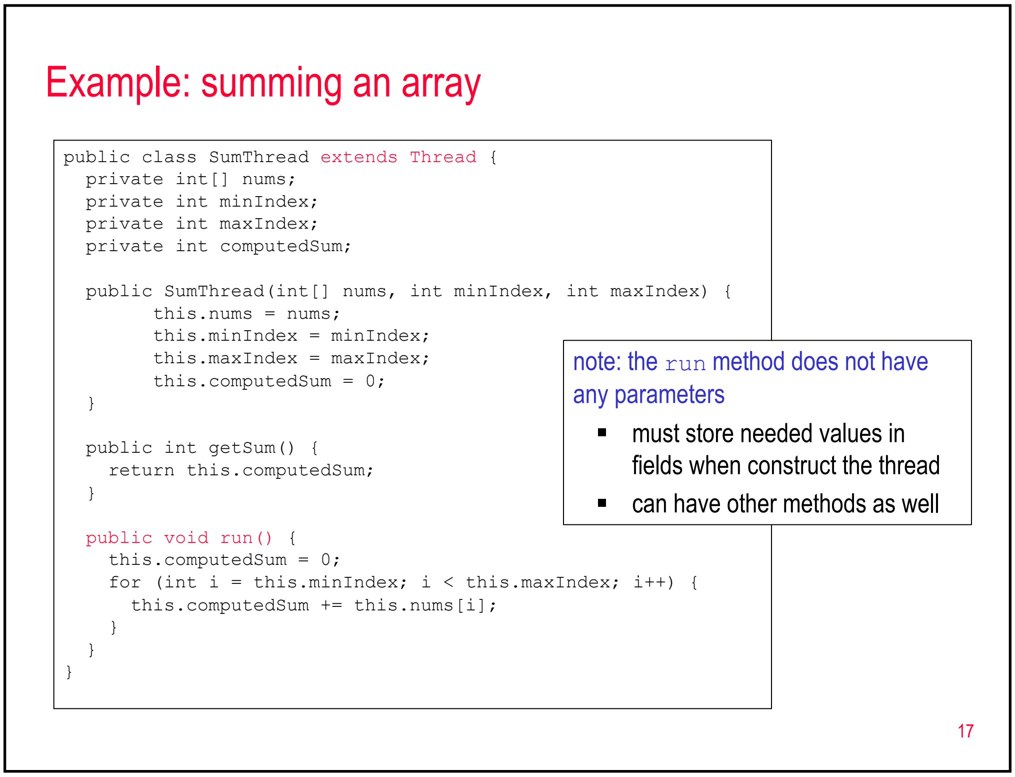
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
nums	22	18	12	-4	27	30	36	50	7	68	91	56	2	85	42	98



sum1 = 22+18+12+-4+27+30+36+50 = **191**   sum2 = 7+68+91+56+2+85+42+98 = **449**

sum = sum1 + sum2 = **640**

- note: still O(N), but reduces the constant BY HOW MUCH?

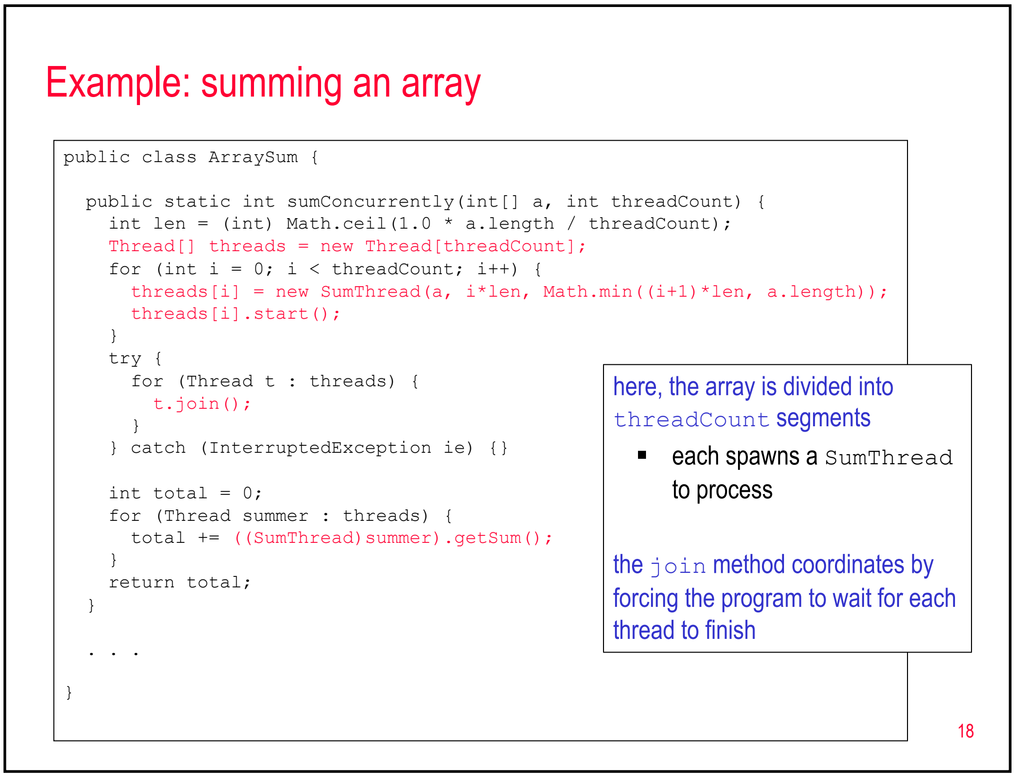


Example: summing an array

```
public class SumThread extends Thread {
  private int[] nums;
  private int minIndex;
  private int maxIndex;
  private int computedSum;

  public SumThread(int[] nums, int minIndex, int maxIndex) {
        this.nums = nums;
        this.minIndex = minIndex;
        this.maxIndex = maxIndex;
        this.computedSum = 0;
  }

  public int getSum() {
    return this.computedSum;
  }

  public void run() {
    this.computedSum = 0;
    for (int i = this.minIndex; i < this.maxIndex; i++) {
      this.computedSum += this.nums[i];
    }
  }
}
```

note: the `run` method does not have any parameters

- must store needed values in fields when construct the thread
- can have other methods as well



Example: summing an array

```
public class ArraySum {

  public static int sumConcurrently(int[] a, int threadCount) {
    int len = (int) Math.ceil(1.0 * a.length / threadCount);
    Thread[] threads = new Thread[threadCount];
    for (int i = 0; i < threadCount; i++) {
      threads[i] = new SumThread(a, i*len, Math.min((i+1)*len, a.length));
      threads[i].start();
    }
    try {
      for (Thread t : threads) {
        t.join();
      }
    } catch (InterruptedException ie) {}

    int total = 0;
    for (Thread summer : threads) {
      total += ((SumThread)summer).getSum();
    }
    return total;
  }

  . . .

}
```

here, the array is divided into `threadCount` segments

- each spawns a `SumThread` to process

the `join` method coordinates by forcing the program to wait for each thread to finish

Example: summing an array

```
public static void main(String[] args) {
  Random randy = new Random();
  int size = 1000;

  System.out.println("Enter number of threads: ");
  Scanner input = new Scanner(System.in);
  int numThreads = input.nextInt();
  input.close();

  while (true) {
    int[] nums = new int[size];
    for (int j = 0; j < size; j++) {
      nums[j] = randy.nextInt();
    }

    long start = System.currentTimeMillis();
    int total = 0;
    for (int j = 1; j <= 1000; j++) {
      total = sumConcurrently(nums, numThreads);
    }
    long end = System.currentTimeMillis();

    System.out.printf("%10d elements => %6d microsec\n", size, end-start);
    size *= 2;
  }
}
```

driver program prompts for the number of threads

since timings are so fast, actually performs 1000 sums

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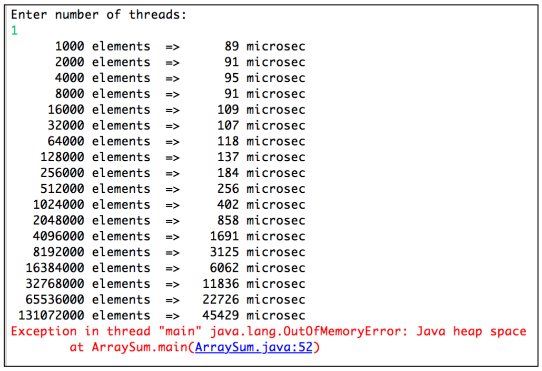
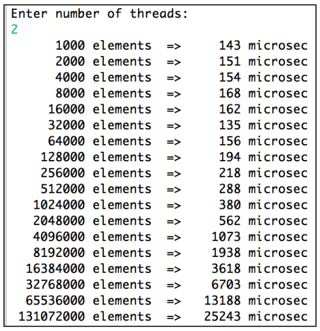
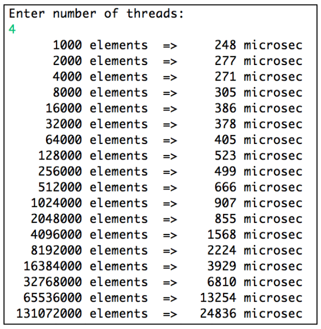


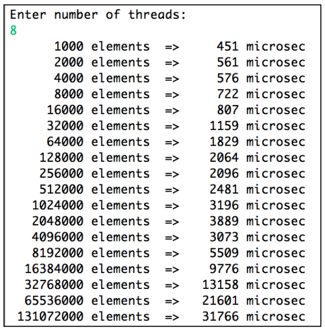
```
Enter number of threads:
1
      1000 elements  =>      89 microsec
      2000 elements  =>      91 microsec
      4000 elements  =>      95 microsec
      8000 elements  =>      91 microsec
     16000 elements  =>     109 microsec
     32000 elements  =>     107 microsec
     64000 elements  =>     118 microsec
    128000 elements  =>     137 microsec
    256000 elements  =>     184 microsec
    512000 elements  =>     256 microsec
   1024000 elements  =>     402 microsec
   2048000 elements  =>     858 microsec
   4096000 elements  =>    1691 microsec
   8192000 elements  =>    3125 microsec
  16384000 elements  =>    6062 microsec
  32768000 elements  =>   11836 microsec
  65536000 elements  =>   22726 microsec
 131072000 elements  =>   45429 microsec
Exception in thread "main" java.lang.OutOfMemoryError: Java heap space
        at ArraySum.main(ArraySum.java:52)
```



```
Enter number of threads:
2
      1000 elements  =>     143 microsec
      2000 elements  =>     151 microsec
      4000 elements  =>     154 microsec
      8000 elements  =>     168 microsec
     16000 elements  =>     162 microsec
     32000 elements  =>     135 microsec
     64000 elements  =>     156 microsec
    128000 elements  =>     194 microsec
    256000 elements  =>     218 microsec
    512000 elements  =>     288 microsec
   1024000 elements  =>     380 microsec
   2048000 elements  =>     562 microsec
   4096000 elements  =>    1073 microsec
   8192000 elements  =>    1938 microsec
  16384000 elements  =>    3618 microsec
  32768000 elements  =>    6703 microsec
  65536000 elements  =>   13188 microsec
 131072000 elements  =>   25243 microsec
```



```
Enter number of threads:
4
      1000 elements  =>     248 microsec
      2000 elements  =>     277 microsec
      4000 elements  =>     271 microsec
      8000 elements  =>     305 microsec
     16000 elements  =>     386 microsec
     32000 elements  =>     378 microsec
     64000 elements  =>     405 microsec
    128000 elements  =>     523 microsec
    256000 elements  =>     499 microsec
    512000 elements  =>     666 microsec
   1024000 elements  =>     907 microsec
   2048000 elements  =>     855 microsec
   4096000 elements  =>    1568 microsec
   8192000 elements  =>    2224 microsec
  16384000 elements  =>    3929 microsec
  32768000 elements  =>    6810 microsec
  65536000 elements  =>   13254 microsec
 131072000 elements  =>   24836 microsec
```



```
Enter number of threads:
8
      1000 elements  =>     451 microsec
      2000 elements  =>     561 microsec
      4000 elements  =>     576 microsec
      8000 elements  =>     722 microsec
     16000 elements  =>     807 microsec
     32000 elements  =>    1159 microsec
     64000 elements  =>    1829 microsec
    128000 elements  =>    2064 microsec
    256000 elements  =>    2096 microsec
    512000 elements  =>    2481 microsec
   1024000 elements  =>    3196 microsec
   2048000 elements  =>    3889 microsec
   4096000 elements  =>    3073 microsec
   8192000 elements  =>    5509 microsec
  16384000 elements  =>    9776 microsec
  32768000 elements  =>   13158 microsec
  65536000 elements  =>   21601 microsec
 131072000 elements  =>   31766 microsec
```

How many threads?

you can find out how many CPUs/cores your machine has

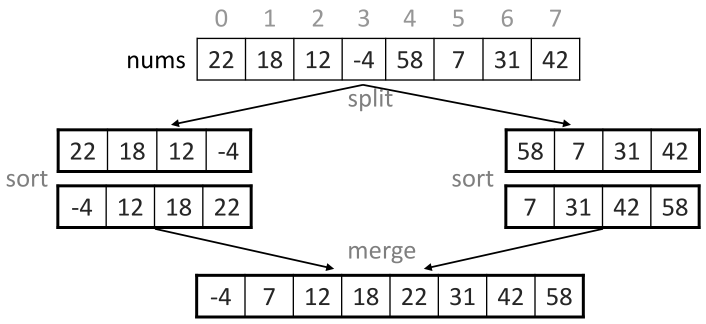
```
int cores = Runtime.getRuntime().availableProcessors();
```

- timings on previous slide were on a computer with 8 cores
- note that a user program may not have access to all cores
  - in previous timings, 8 threads actually degraded performance
- there is overhead associated with creating and managing threads
  - 1 thread was faster than 2 threads up to 1M numbers
  - 2 threads was faster than 4 threads up to 1B numbers

Example: parallel mergeSort

suppose we want to take advantage of multicores when sorting

- have separate threads sort the left and right halves, then merge



	0	1	2	3	4	5	6	7
nums	22	18	12	-4	58	7	31	42

22	18	12	-4
-4	12	18	22

58	7	31	42
7	31	42	58

-4	7	12	18	22	31	42	58

- each of the threads can spawn new threads, *up to some limit*

Example: parallel mergeSort

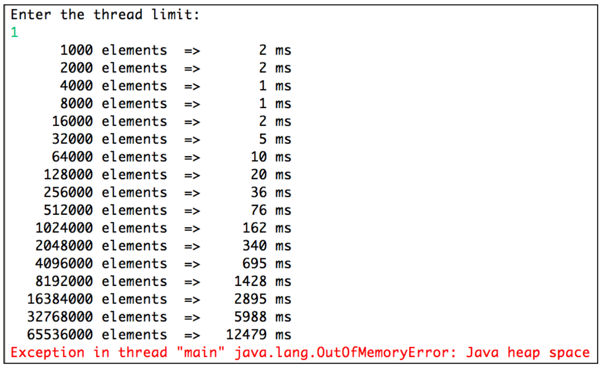
```
public class SortThread extends Thread {
  private int[] nums;
  private int minIndex;
  private int maxIndex;
  private int threadCount;

  public SortThread(int[] nums, int minIndex, int maxIndex, int threadCount) {
    this.nums = nums;
    this.minIndex = minIndex;
    this.maxIndex = maxIndex;
    this.threadCount = threadCount;
  }

  public void run() {
    MergeSort.mergeSortConcurrently(this.nums, this.minIndex,
                                     this.maxIndex, this.threadCount);
  }
}
```

Example: parallel mergeSort

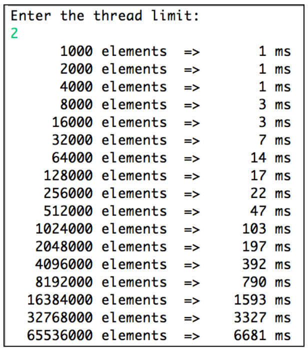
```
public class MergeSort {
  public static void mergeSortConcurrently(int[] a, int threadCount) {
    MergeSort.mergeSortConcurrently(a, 0, a.length-1, threadCount);
  }

  public static void mergeSortConcurrently(int[] a, int minIndex, int maxIndex,
                                         int threadCount) {
    if (minIndex < maxIndex) {
      int mid = (minIndex+maxIndex)/2;
      if (threadCount > 1) {
        Thread leftThread = new SortThread(a, minIndex, mid, threadCount/2);
        Thread rightThread = new SortThread(a, mid+1, maxIndex, threadCount/2);
        leftThread.start();
        rightThread.start();

        try {
          leftThread.join();
          rightThread.join();
        } catch (InterruptedException ie) {}
      }
      else {
        MergeSort.mergeSortConcurrently(a, minIndex, mid, threadCount/2);
        MergeSort.mergeSortConcurrently(a,  mid+1, maxIndex, threadCount/2);
      }
      MergeSort.merge(a, minIndex, maxIndex);
    }
  }
```

Example: parallel mergeSort

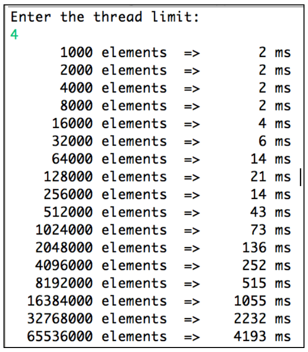
```
public static void main(String[] args) {
  Random randy = new Random();
  int size = 1000;

  System.out.println("Enter the thread limit: ");
  Scanner input = new Scanner(System.in);
  int numThreads = input.nextInt();
  input.close();

  while (true) {
   int[] nums = new int[size];
   for (int j = 0; j < size; j++) {
    nums[j] = randy.nextInt();
   }

   long start = System.currentTimeMillis();
   MergeSort.mergeSortConcurrently(nums, numThreads);
   long end = System.currentTimeMillis();

   System.out.printf("%10d elements  =>  %6d ms \n", size, end-start);
   size *= 2;
  }
 }
```



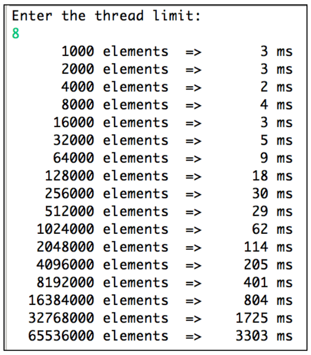
```
Enter the thread limit:
1
      1000 elements  =>       2 ms
      2000 elements  =>       2 ms
      4000 elements  =>       1 ms
      8000 elements  =>       1 ms
     16000 elements  =>       2 ms
     32000 elements  =>       5 ms
     64000 elements  =>      10 ms
    128000 elements  =>      20 ms
    256000 elements  =>      36 ms
    512000 elements  =>      76 ms
   1024000 elements  =>     162 ms
   2048000 elements  =>     340 ms
   4096000 elements  =>     695 ms
   8192000 elements  =>    1428 ms
  16384000 elements  =>    2895 ms
  32768000 elements  =>    5988 ms
  65536000 elements  =>   12479 ms
Exception in thread "main" java.lang.OutOfMemoryError: Java heap space
```



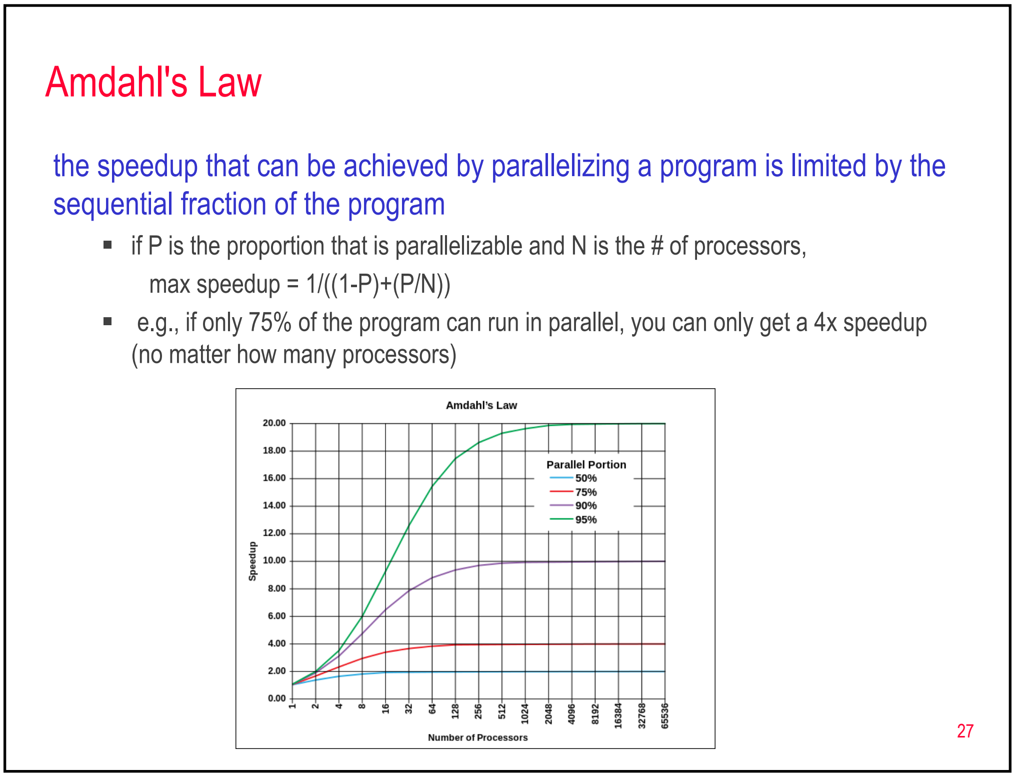
```
Enter the thread limit:
2
      1000 elements  =>       1 ms
      2000 elements  =>       1 ms
      4000 elements  =>       1 ms
      8000 elements  =>       3 ms
     16000 elements  =>       3 ms
     32000 elements  =>       7 ms
     64000 elements  =>      14 ms
    128000 elements  =>      17 ms
    256000 elements  =>      22 ms
    512000 elements  =>      47 ms
   1024000 elements  =>     103 ms
   2048000 elements  =>     197 ms
   4096000 elements  =>     392 ms
   8192000 elements  =>     790 ms
  16384000 elements  =>    1593 ms
  32768000 elements  =>    3327 ms
  65536000 elements  =>    6681 ms
```



```
Enter the thread limit:
4
      1000 elements  =>       2 ms
      2000 elements  =>       2 ms
      4000 elements  =>       2 ms
      8000 elements  =>       2 ms
     16000 elements  =>       4 ms
     32000 elements  =>       6 ms
     64000 elements  =>      14 ms
    128000 elements  =>      21 ms
    256000 elements  =>      14 ms
    512000 elements  =>      43 ms
   1024000 elements  =>      73 ms
   2048000 elements  =>     136 ms
   4096000 elements  =>     252 ms
   8192000 elements  =>     515 ms
  16384000 elements  =>    1055 ms
  32768000 elements  =>    2232 ms
  65536000 elements  =>    4193 ms
```



```
Enter the thread limit:
8
      1000 elements  =>       3 ms
      2000 elements  =>       3 ms
      4000 elements  =>       2 ms
      8000 elements  =>       4 ms
     16000 elements  =>       3 ms
     32000 elements  =>       5 ms
     64000 elements  =>       9 ms
    128000 elements  =>      18 ms
    256000 elements  =>      30 ms
    512000 elements  =>      29 ms
   1024000 elements  =>      62 ms
   2048000 elements  =>     114 ms
   4096000 elements  =>     205 ms
   8192000 elements  =>     401 ms
  16384000 elements  =>     804 ms
  32768000 elements  =>    1725 ms
  65536000 elements  =>    3303 ms
```



Amdahl's Law

the speedup that can be achieved by parallelizing a program is limited by the sequential fraction of the program

- if P is the proportion that is parallelizable and N is the # of processors,

  max speedup = 1/((1-P)+(P/N))

- e.g., if only 75% of the program can run in parallel, you can only get a 4x speedup (no matter how many processors)