Concurrent and Asynchronous Programming

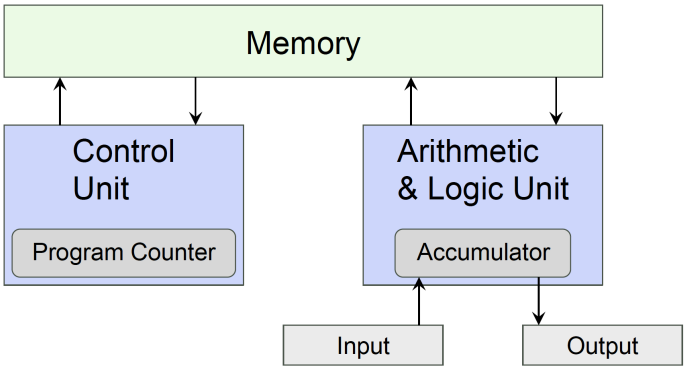
GURUTEAM
specialist ICT learning

Some Definitions

- Concurrent
  - more than one task logically proceeding within a given time interval
- Parallel
  - more than one task executing at the same instant
- Can be concurrent without being parallel
  - single CPU, multi-tasking OS
- Parallelism implies concurrency

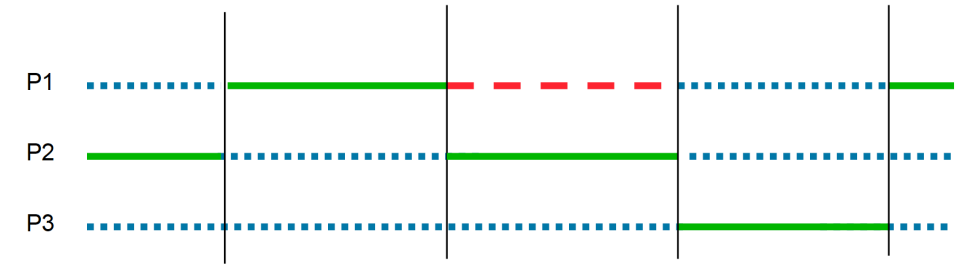
The Von Neumann Architecture

- Stored Program execution
  - Program stored in memory
  - Memory shared between program and data
  - Execution follows a sequential model



Process Based Concurrency

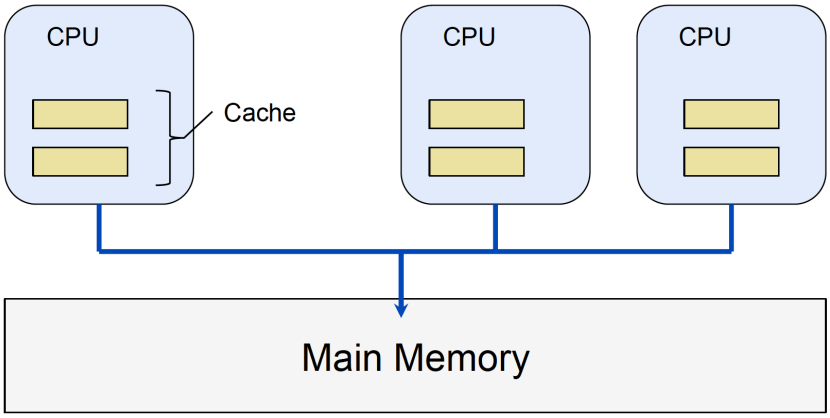
- Operating system schedules processes
  - concurrency achieved by sharing work across processes
  - can operate on single cpu core – no parallelism



...other processes...

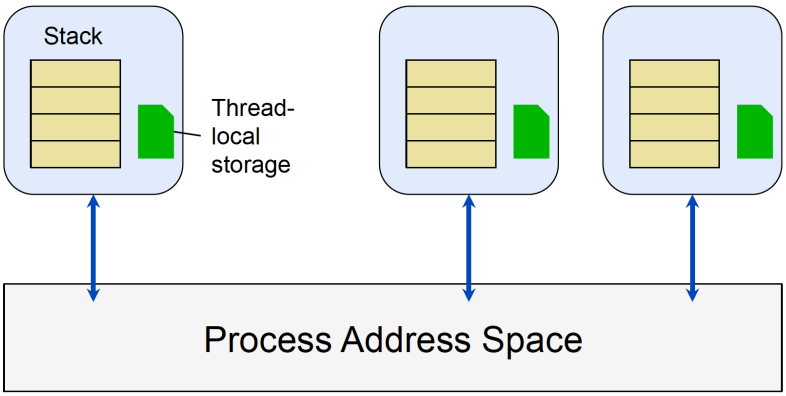
Multiprocessor/Multicore

- Multiple CPUs (cores) sharing memory



Traditional Threading Model

- Aim is to provide more lightweight concurrency model
- Multiple threads share the same address space

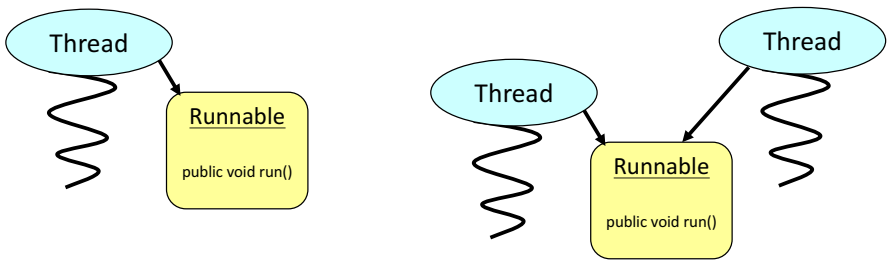


Threads and Processes

- Thread
  - a sequence of instructions that can execute independently (of other threads)
  - on multi-core CPUs threads can execute in parallel
  - on single-core CPUs threads are time-sliced
- Process
  - provides resources needed to execute a program
  - eE.g. address space, security context, environment
  - a process will contain at least one thread

JVM Threading: Threads and Runnable Objects

- Thread encapsulates a schedulable entity
- Runnable interface used to represent work for thread to do
- Scala provides access to these "primitive" features



Creating a Thread

- Instantiate Thread class
- Associate with Runnable object
- Start execution of thread
  - start() method invokes run() on the Runnable object

```
…
Runnable r = new RunnableImpl();
Thread t1 = new Thread( r );
Thread t2 = new Thread( r );
t1.start();
t2.start();
…
```

```
…
Thread t1 = new Thread( () -> { … } );
t1.start();
…
```


Creating a Thread

- `Thread` class implements Runnable
  - empty `run()` method
- Define subclass of `Thread`
  - override `run()` method with required action
- Create `Thread` object via subclass

```
public class SubThread
                extends Thread
{
  @Override
  public void run()
  {
    doSomething();
  }
}

…

SubThread s = new SubThread();
s.start();
```

Creating a Thread

- Creating `Thread` object doesn't create a thread
- The `start()` method creates the thread

```
Runnable r = () -> doSomething();
(new Thread(r)).start();
```

- Calls out to the operating system to create and register the thread

Thread Example

```
public class TickTock implements Runnable {
  private String word;
  private int delay;
  public TickTock(String w, int d) {
    word = w;
    delay = d;
  }

  public void run() {
    while (!Thread.interrupted()) { // More later
      try {
        System.out.print(word + " ");
        Thread.sleep(delay);
      } catch (InterruptedException ie) {
        Thread.currentThread().interrupt();
      }
    }
  }
}
```

```
public static void main(String[] args) {
  Thread t1 = new Thread(new TickTock("tick", 50));
  Thread t2 = new Thread(new TickTock("tock", 100));
  t1.start(); t2.start();
  Thread.sleep(5000); t1.interrupt(); t2.interrupt();
}
```

Thread Example

```
public class TickTock2 extends Thread {
  private String word;
  private int delay;
  public TickTock2(String w, int d) {
    word = w;
    delay = d;
  }

  public void run() {
    while (!Thread.interrupted()) {
      try {
        System.out.print(word + " ");
        Thread.sleep(delay);
      } catch (InterruptedException ie) {
        Thread.currentThread().interrupt();
      }
    }
  }
}
```

```
public static void main(String[] args) {
  TickTock2 tt1 = new TickTock2("tick", 50);
  TickTock2 tt2 = new TickTock2("tock", 100);
  tt1.start(); tt2.start();
  Thread.sleep(5000); tt1.interrupt(); tt2.interrupt();
 }
```


Thread Example

```
public class TickTock implements Runnable {
  private String word;
  private int delay;
  public TickTock(String w, int d) {
    word = w;
    delay = d;
  }

  public void run() {
    while (!Thread.interrupted())
      try {
        System.out.print(word + "
        Thread.sleep(delay);
      } catch (InterruptedExceptio
        Thread.currentThread().int
      }
    }
  }
}
```

```
import java.util.concurrent._;
…

  public static void main(String[] args) {
    Runnable r1 = new TickTock("tick", 50);
    Runnable r2 = new TickTock("tock", 100);

    Executor engine = Executors.newFixedThreadPool(2);

    engine.execute(r1);
    engine.execute(r2);

    Thread.sleep(5000);
    engine.shutdownNow();
  }
```

Problems

- Limited capabilities
  - run method returns Unit
- Scalability is limited
  - threads relatively heavyweight objects
  - limited number can be supported in VM
- Shared state difficult to protect
  - locks/synchronized blocks
  - introduces complexity to code
  - difficult to debug or reason about
  - blocking threads wastes resources

Problems

Why Threads Are A Bad Idea
(for most purposes)

John Ousterhout
Sun Microsystems Laboratories

john.ousterhout@eng.sun.com
http://www.sunlabs.com/~ouster

Problems

What's Wrong With Threads?

casual — all programmers — wizards

Visual Basic programmers

C programmers

C++ programmers

Threads programmers

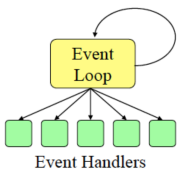
- Too hard for most programmers to use.
- Even for experts, development is painful.

Why Threads Are A Bad Idea *September 28, 1995, slide 5*

Problems

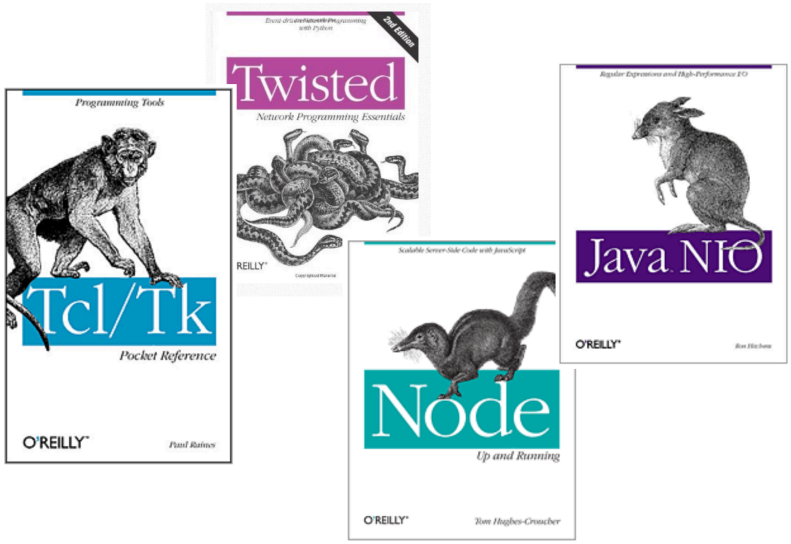
Event-Driven Programming

- One execution stream: no CPU concurrency.
- Register interest in events (callbacks).
- Event loop waits for events, invokes handlers.
- No preemption of event handlers.
- Handlers generally short-lived.



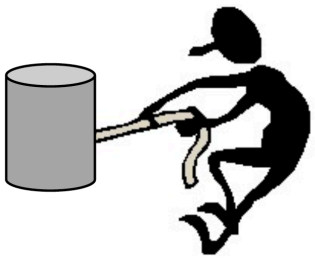
Why Threads Are A Bad Idea *September 28, 1995, slide 9*

Moving to a different model



Moving to a different model

- Conventional program ***pulls*** data from its sources
- Active polling or blocking can cause issues
- Event based programming is a solution
- Reactive Programming refines the approach further



Reactive?

- A developing "movement" in software architecture
  - programming and architecture

The Reactive Manifesto

`http://reactivemanifesto.org`

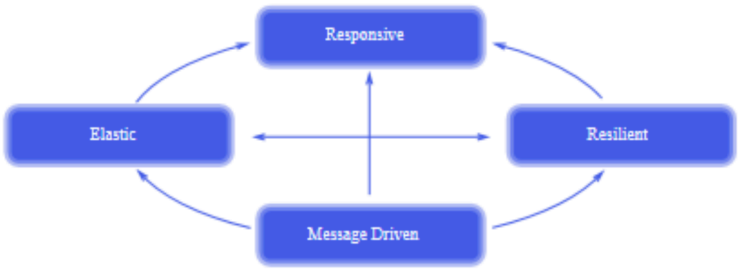
Published on September 16 2014. (v2.0)

Organisations working in disparate domains are independently discovering patterns for building software that look the same. These systems are more robust, more resilient, more flexible and better positioned to meet modern demands.

These changes are happening because application requirements have changed dramatically in recent years. Only a few years ago a large application had tens of servers, seconds of response time, hours of offline maintenance and gigabytes of data. Today applications are deployed on everything from mobile devices to cloud-based clusters running thousands of multi-core processors. Users expect millisecond response times and 100% uptime. Data is measured in Petabytes. Today's demands are simply not met by yesterday's software architectures.

Reactive?

- Reactive systems are
  - Responsive
  - Resilient
  - Elastic
  - Message driven (event driven)



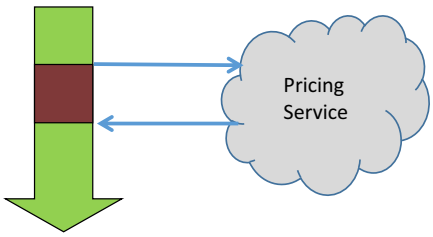
Functional?

- Reactive ideas often combined with functional programming
- Emphasis on immutable state
  - reduces the need for data synchronisation
- Declarative style abstracts away from implementation specifics
  - allows concurrency to be deployed where possible, without modifying application code

Asynchronous Programming

- A different approach
  - "do something" while calling thread continues
  - hand back a result when finished
- Higher level of abstraction

```
int theNumber = NumberService.fetchNum(…)
```



Asynchronous Programming

- A different approach
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int theNumber = NumberService.fetchNum(…)
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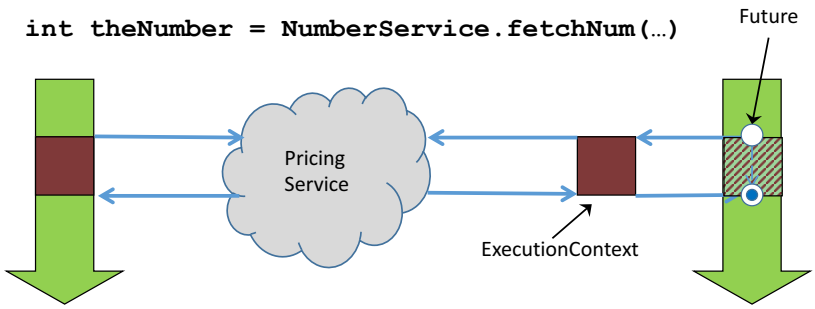


Fetching a Value

- Often a task is required to return a value
  - asynchronous calculation

```
public class NumberService {
 …
 public static int getNumber ( ) {
  delay();
  int theNum = random.nextInt() % 100;
  return theNum;
 }
}
```

```
Callable<Integer> fetchNum = new Callable<Integer> () {
 @Override
 public Integer call() {
  return NumberService.getNumber();
 }
};
```

```
Callable<Integer> fetchNum = () -> NumberService.getNumber();
```

Returning a Value

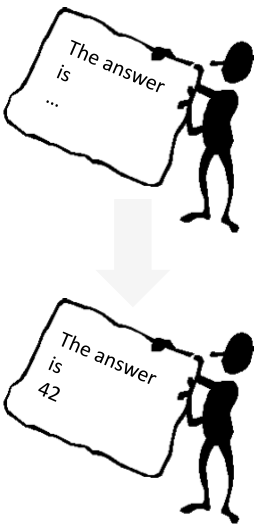
- Task submitted to `ExecutorService` using `submit()`
  - returns `Future<T>` to represent result

```
…
ExecutorService engine = Executors.newFixedThreadPool(2);
Future<Integer> numF = engine.submit(fetchNum);
```

```
…
Future<Integer> numF = engine.submit(
                              () -> NumberService.getNumber()
                       );
…
```


Working with `Future<T>`

- Operations:
  - fetch value, block thread if task not complete
  - check if task complete or cancelled
  - cancel task execution
- Operations throw exceptions to indicate failures
  - `ExecutionException` if task throws an exception
  - `CancellationException` if task was cancelled
  - `InterruptedException` if waiting thread is interrupted
  - `TimeoutException` if optional fetch timeout expires



Working with `Future<T>`

```
ExecutorService engine = Executors.newFixedThreadPool(2);
Future<Integer> numF = engine.submit(
                              () -> NumberService.getNumber() );
…
int theNum = 0;
try {
 while ( !numF.isDone() ) {
  System.out.print(".");
  Thread.sleep(200);
 }
 theNum = numF.get();
} catch ( InterruptedException ieIgnore ) {
} catch ( ExecutionException exIgnore ) {
} catch ( CancellationException ccIgnore ) {
}
System.out.println("Returned number: " + theNum);
```

```
Main thread id: 1
..........Returned number: -95
```


Limitations of Java Futures

- Not simple to trigger behavior once future completes
- Difficulty in combining results from futures
  - it is necessary to wait for the future value
- Slow operations may never return
  - which may cause the application to hang
- Futures can actually represent bottlenecks
  - where it is necessary to wait on a future operation
  - for example while waiting for a group of futures to complete

Completable Futures

- Promotes asynchronous, event-driven model
  - with asynchronous callback support
- Support for lambda expressions
  - for functional style
- Settable features
  - allowing any thread to set the value of the CompleteableFuture
- Ability to chain operations
  - allowing several asynchronous operations to be combined
  - see CompletionStage interface

`CompletableFuture<T>`

- Concrete implementation of `Future<T>`
- Created using static factory methods
  - supplyAsync(Supplier<U> supplier)
  - supplyAsync(Supplier<U> supplier, Executor executor)
  - runAsync(Runnable runnable)
  - runAsync(Runnable runnable, Executor executor)
- Supplier<T> interface
  - represents a supplier of results
  - functional interface
  - defines a single method T get()

```
CompletableFuture<String> future =
    CompletableFuture.supplyAsync(() -> {
        //...long running...
        return "Hello World";
    }, executor);
```

Using a CompletableFuture

- Create a Supplier and check for completion

```
ExecutorService executor = Executors.newFixedThreadPool(2);

System.out.println("Setting up Future");

CompletableFuture<String> future =
    CompletableFuture.supplyAsync(new Supplier<String>() {
        public String get() {
            try {
                Thread.sleep(500);
            } catch (InterruptedException e)){
                e.printStackTrace();
            }
            return "Hello Completable World!";
        }
    }, executor);
```


Using a CompletableFuture

- Create a Supplier and check for completion

```
System.out.println("Get value from CompletableFuture");

try {
    while (!future.isDone()) {
        System.out.println("Waiting ...");
        Thread.sleep(250);
    }
    String msg = future.get();
    System.out.println("Obtained result: " + msg);
} catch (Exception exp) {
    exp.printStackTrace();
}
```

```
Setting up Future
Get value form CompletableFuture
Waiting ...
Waiting ...
Obtained result: Hello Completable World!
```

Using a CompletableFuture

- Create a Supplier and check for completion
  - can supply a lambda expression
  - which can simplify the code

```
...
CompletableFuture<String> future =
    CompletableFuture.supplyAsync(() -> {
        try {
            Thread.sleep(500);
        } catch (InterruptedException e) {
            e.printStackTrace();
        }
        return "Hello Completable World!";
     }, executor);
```


Acting on Completion

- Can register an callback
  - to be invoked once future is completed
  - thenRun/thenRunAsync executes a Runnable
  - thenAccept/thenAcceptAsync invokes a Consumer passing in a value
  - typically the final stage in processing

```
System.out.println("Setting up Future");
CompletableFuture<String> future =
    CompletableFuture.supplyAsync(() -> {
        try {
            Thread.sleep(50);
        } catch (InterruptedException e) {
            e.printStackTrace();
        }
        return "Hello Completable World!";
 }, executor);
 future.thenAccept(System.out::println);
```

```
Setting up Future
Hello Completable World!
```

Combining Operations

- Can combine operations together
  - chain of operations to be invoked once future completes
  - thenApply/thenApplyAsync execute a Function
  - supports both synchronous and asynchronous invocations

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```
CompletableFuture<Integer> f1 =
    CompletableFuture.supplyAsync(() -> {
        try {
            Thread.sleep(50);
        } catch (InterruptedException e) {
           e.printStackTrace();
        }
        return 6;
    }, executor);
// Combine operations together
CompletableFuture<Integer> f2 = f1.thenApply(v -> v * 7);
CompletableFuture<String> f3 =
    f2.thenApply(v -> Integer.toString(v));
// Finally print result
f3.thenAccept(System.out::println);
```


Composing CompletableFutures

- `CompletableFutures` are composable
  - allows chaining of operations on the `Future`
  - `thenCompose / thenComposeAsync`

```
public static Future<Integer> compose() {
    CompletableFuture<Integer> cf =
        NumberService.getIntegerAsync();

    CompletableFuture<Integer> cf2 = cf1.thenCompose(
        v -> CompletableFuture.supplyAsync(
                    () -> NumberService.squareIt(v)));

    CompletableFuture<Integer> cf3 = cf2.thenCompose(
        v -> CompletableFuture.supplyAsync(
                    () -> NumberService.cubeIt(v)));

    return cf3;
}
```

Combining CompletableFutures together

- Can combine two independent futures
  - thenCombine / thenCombineAsync
  - results from two CompletableFutures combined

```
ExecutorService executor =
     Executors.newFixedThreadPool(3);

CompletableFuture<String> f1 =
    CompletableFuture.supplyAsync(() -> {
        return "Hello";
    } , executor);

CompletableFuture<String> f2 =
    CompletableFuture.supplyAsync(() -> {
        return "World";
} , executor);

CompletableFuture<String> f3 =
    f1.thenCombine(f2, (x, y) -> x + " " + y);

f3.thenAccept(System.out::println);
```

Hello World

Waiting for CompletableFutures to complete

- Can wait for two CompletableFutures to complete
  - thenAcceptBoth / runAfterBoth (and async versions)
- Can wait for first to finish
  - acceptEtiher / runAfterEither (and async versions)
  - applyToEither / applyToEitherAsync returns a future
  - anyOf / anyOfAync handles any number of futures
- Combining multiple CompletableFutures futures
  - can wait for arbitrary number of futures
  - allOf / allOfAsync

Error handling

- Can also handle exceptions asynchronously
  - exceptionally take a function
  - invoked asynchronously when future throws an error

```
System.out.println("Setting up Future");
CompletableFuture<String> future =
    CompletableFuture.supplyAsync(..., executor);

CompletableFuture<String> safe =
    future.exceptionally(
        ex -> "We have a problem: " + ex.getMessage());

safe.thenAccept(System.out::println);
```


Error handling

- Can handle exceptions when complete
  - `whenComplete` methods can all take an exception
  - can handle exception from anywhere in chain

```
CompletableFuture<String> f1 =
    CompletableFuture.supplyAsync(() -> {
       return "Hello";
    } , executor);
CompletableFuture<String> f2 = f1.thenApply(
    v -> {throw new RuntimeException("Noooo - " + v);});

f2.whenComplete((v, err) -> {
    if (v != null) {
        System.out.println(v);
    } else {
       System.err.println("Handling exception: " +
                          err.getMessage());
    }
});
```

```
Handling exception: java.lang.RuntimeException: Noooo - Hello
```

Explicit Completion

- CompletableFuture supports explicit completion
  - Success or failure
  - Allows for greater control over how tasks are executed

```
…
 public static Future<Integer> fetchIntCF ( ) {
  CompletableFuture<Integer> numF = new CompletableFuture<>();

  new Thread( () -> {
                     int num = NumberService.getNumber();
                     numF.complete(num);
                    } ).start();
  return numF;
 }

 public static Future<Integer> fetchIntAsync ( ) {
  return CompletableFuture.supplyAsync( () -> fetchInt() );
 }
…
```


Explicit Completion

- Task can complete but not successfully
  - boolean completeExceptionally(Throwable ex)
  - if not already completed, causes invocation of get and related methods to throw the given exception
  - return result indicates if future is now in completed state

```
boolean res = future.completeExceptionally(
                      new RuntimeException("Opps"));
```