An Introduction to Reactive Programming

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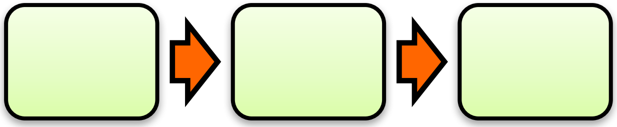
Outline

- Intro to reactive applications
- The Observer pattern
- Event-based languages
- Reactive languages

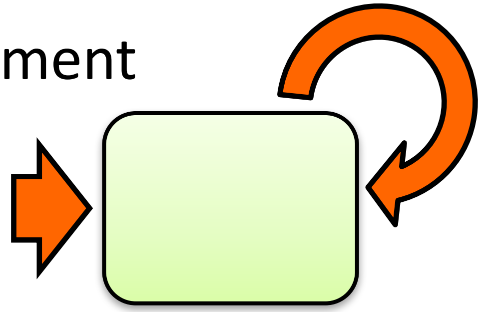
INTRO TO REACTIVE APPLICATIONS

Software Taxonomy

- A **transformational** system
  - Accepts input, performs computation on it, produces output, and terminates
  - Compilers, shell tools, scientific computations



- A **reactive** system
  - Continuously interacts with the environment
  - Updates its state



Use of State

- Transformational systems:
  - Express transformations as incremental modifications of the internal data structures

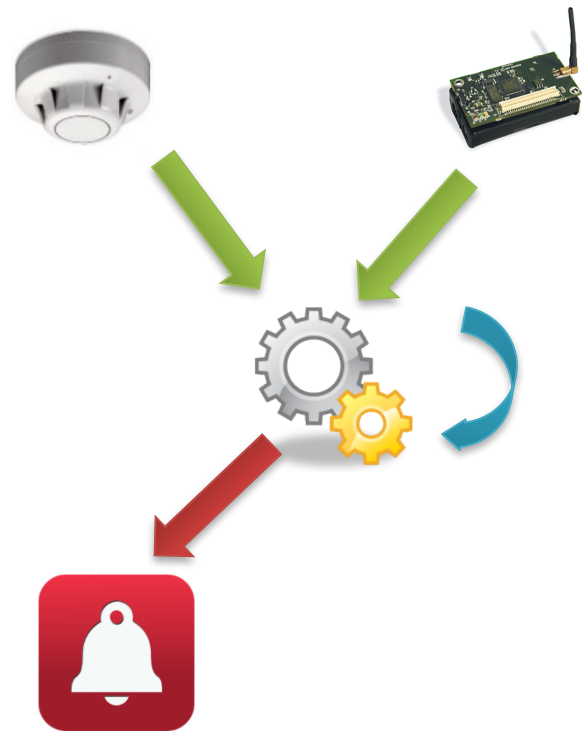
State is not necessary to describe the system

- Reactive systems:
  - Represent the current state of interaction
  - Reflect changes of the external world during interaction

State is essential to describe the system

Reactive Applications

Interactive Applications
UI



Monitoring / Control
Systems

Reactive Applications

- Many other examples
  - Web applications
  - Mobile apps
  - Distributed computations
    - Cloud
  - …
- Typical operations
  - Detect events/notifications and react
  - Combine reactions
  - Propagate updates/changes

Reactive Applications
Why should we care?

- Event handling:
  - 30% of code in desktop applications
  - 50% of bugs reported during production cycle

Reactive Programming

Now…

- Reactive applications are extremely common
- Can we design new language features to specifically address this issue ?

- Think about the problems solved by exceptions, visibility modifiers, inheritance, …

REACTIVE PROGRAMMING

Reactive Programming

Definition… ?

"Programming language abstractions
(techniques and patterns)
to develop reactive applications"

For example, abstractions to:

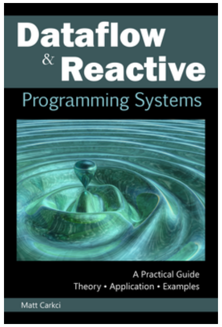
- Represent event streams
- Automatically propagate changes in the state
- Combine events
- …

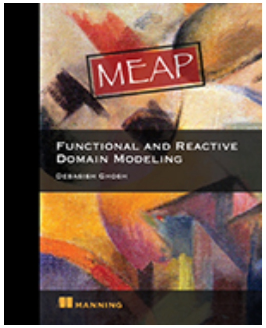
Reactive Programming

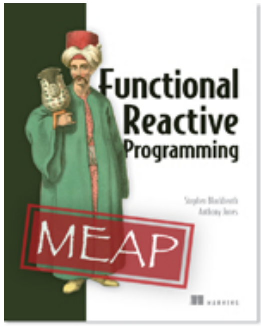
- Haskell: Fran, Yampa
- FrTime, Flapjax, REScala, Scala.react, …

- Angular.js, Bacon.js, Reactive.js, …
- Microsoft Reactive Extensions (Rx)

- Books 2014-16

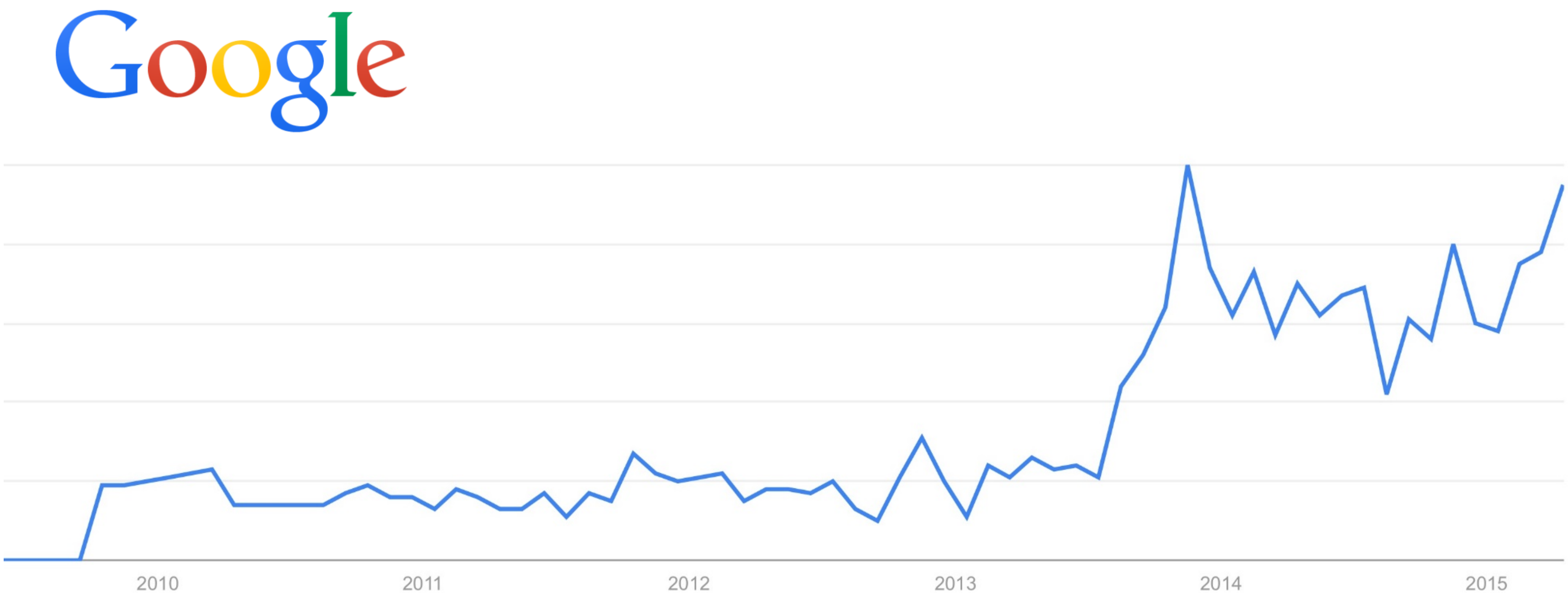






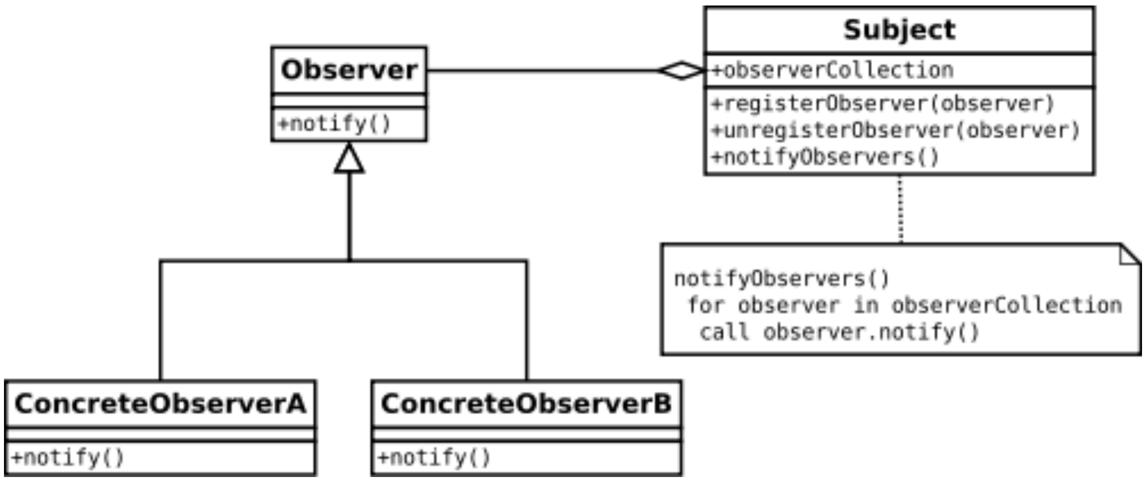
Reactive Programming

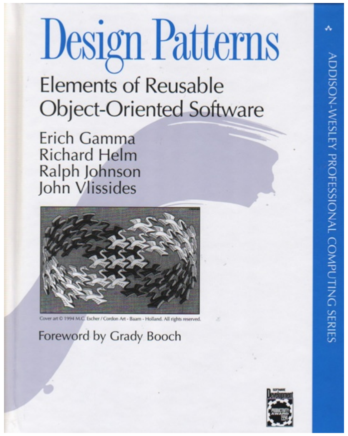
Reactive Programming



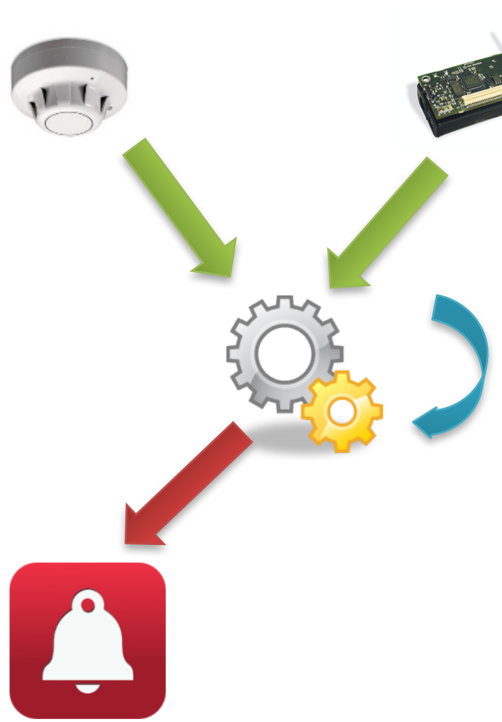
THE OBSERVER PATTERN

The (*good*? old) Observer Pattern





The (*good*? old) Observer Pattern



```
boolean highTemp;
boolean smoke;

void Init() {
        tempSensor.register(this);
        smokeSensor.register(this);
}

void notifyTempReading(TempEvent e ) {
        highTemp = e.getValue() > 45;
        if (highTemp && smoke) {
                alert.start();
        }
}

void notifySmokeReading(SmokeEvent e) {
        smoke = e.getIntensity() > 0.5;
        if (highTemp && smoke) {
                alert.start();
        }
}
```

State

Registration

Callback functions

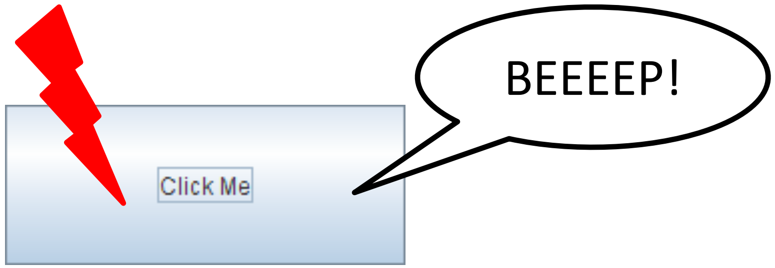
Control statements

Callback functions

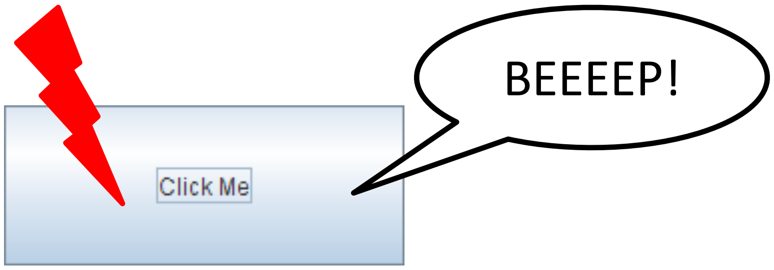
Control statements

The Observer Pattern

- What about Java Swing ?
  - javax.swing



```java
public class Beeper extends JPanel  implements ActionListener {
  JButton button;

  public Beeper() {
     super(new BorderLayout());
     button = new JButton("Click Me");
     button.setPreferredSize(new Dimension(200, 80));
     add(button, BorderLayout.CENTER);
     button.addActionListener(this);
  }
  public void actionPerformed(ActionEvent e) {
     Toolkit.getDefaultToolkit().beep();
  }
  private static void createAndShowGUI() { // Create the GUI and show it.
     JFrame frame = new JFrame("Beeper");        //Create and set up the window.
     frame.setDefaultCloseOperation(JFrame.EXIT_ON_CLOSE);
     JComponent newContentPane = new Beeper();  //Create and set up the content pane.
     newContentPane.setOpaque(true);
     frame.setContentPane(newContentPane);
     frame.pack();        //Display the window.
     frame.setVisible(true);
  }
  public static void main(String[] args) {
     javax.swing.SwingUtilities.invokeLater( new Runnable() { public void run() {createAndShowGUI();}});
  }
}
```



EVENT-BASED LANGUAGES

Event-based Languages

Language-level support for events

- Events as object attributes
  - Describe changes of the object's state
  - Part of the interface
- Event-based languages are *better*!
  - More concise, clear programming intention, …
  - C#, Ptolemy, EScala, EventJava, …

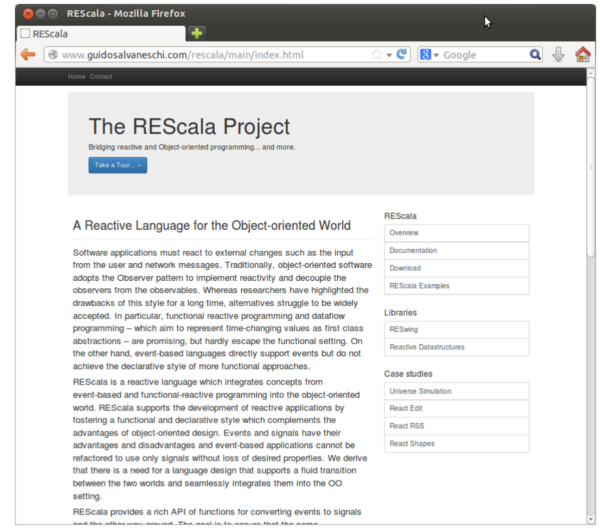
Example in C#

```
public class Drawing {
   Collection<Figure> figures;
   public event NoArgs Changed();
   public virtual void Add(Figure figure) {
      figures.Add(figure);
      figure.Changed += OnChanged;
      OnChanged();
   }
   public virtual void Remove(Figure figure) {
      figures.Remove(figure);
      figure.Changed -= OnChanged;
      OnChanged();
   }
   protected virtual void OnChanged() {
      if (Changed != null) { Changed(); }
   }
  ...
}
```

EVENTS IN SCALA

REScala

- ***www.rescala-lang.com***
  - An advanced event-based system
  - Abstractions for time-changing values
  - Bridging between them



- **Philosophy**: foster a more declarative and functional style without sacrificing the power of OO design
- Pure Scala

Adding Events to Scala

- C# events are recognized by the compiler
  - Scala does not support events by itself, but…
- Can we introduce events using the powerful Scala support for DSLs?
- Can we do even better than C# ?
  - E.g., event composition ?

REScala events: Summary

- Different types of events: Imperative, declarative, …
- Events carry a value
  - Bound to the event when the event is fired
  - Received by all the handlers
- Events are parametric types.
  - Event[T], Evt[T]
- All events are subtype of Event[T]

Imperative Events

- Valid event declarations

```
val e1 = Evt[Unit]()
val e2 = Evt[Int]()
val e3 = Evt[String]()
val e4 = Evt[Boolean]()

val e5: Event[Int] = Evt[Int]()

class Foo
val e6 = Evt[Foo]()
```

Imperative Events

- Multiple values for the same event are expressed using tuples

```
val e1 = Evt[(Int,Int)]()
val e2 = Evt[(String,String)]()
val e3 = Evt[(String,Int)]()

val e4 = Evt[(Boolean,String,Int)]()

val e5: Evt[(Int,Int)] = Evt[(Int,Int)]()
```

Handlers

- Handlers are executed when the event is fired
  - The += operator registers the handler.
- The handler is a first class function
  - The attached value is the function parameter.

```
var state = 0
val e = Evt[Int]()
e += { println(_) }
e += (x => println(x))
e += ((x: Int) => println(x))
e += (x => {  // Multiple statements in the handler
  state = x
  println(x)
})
```

Handlers

- The signature of the handler must conform the event
  - E.g., Event[(Int,Int)] requires (Int,Int) =>Unit
  - The handler:
    - receives the attached value
    - performs side effects.

```
val e = Evt[(Int,String)]()
e += (x => {
  println(x._1)
  println(x._2)
})
e += (x: (Int,String) => {
  println(x)
})
```

Handlers

- Events without arguments still need a Unit argument in the handler.

```
val e = Evt[Unit]()
e += { x => println("Fired!") }
e += { (x: Unit) => println("Fired!") }
```

Methods as Handlers

- Methods can be used as handlers.
  - *Partially applied functions* syntax
  - Types must be correct

```
def m1(x: Int) = {
  val y = x + 1
  println(y)
}

val e = Evt[Int]
e += m1 _
e(10)
```

Firing Events

- Method call syntax
- The value is bound to the event occurrence

```
val e1 = Evt[Int]()
val e2 = Evt[Boolean]()
val e3 = Evt[(Int,String)]()

e1(10)
e2(false)
e3((10,"Hallo"))
```

Firing Events

- Registered handlers are executed every time the event is fired.
  - The actual parameter is provided to the handler

```
val e = Evt[Int]()
e += { x => println(x) }
e(10)
e(11)

-- output ----
10
11
```

Firing Events

- All registered handlers are executed
  - The execution order is non deterministic

```
val e = Evt[Int]()
e += { x => println(x) }
e += { x => println("n: " + x)}
e(10)
e(11)

-- output ----
10
n: 10
11
n: 11
```

Firing Events

- The .remove operator unregisters a *handler* via its *handle*
- The += operator also returns the handle that will be used for unregistration

```
val e = Evt[Int]()
val handler1 = { x: Int => println(x) }
val handler2 = { x: Int => println("n: " + x) }

val h1 = e += handler1
val h2 = e += handler2
e(10)
h1.remove
e(10)
h2.remove
e(10)

-- output ----
10
n: 10
n: 10
```

Imperative Events

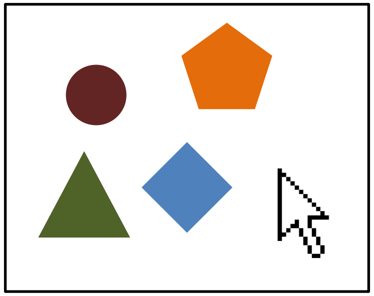
- Events can be referred to generically

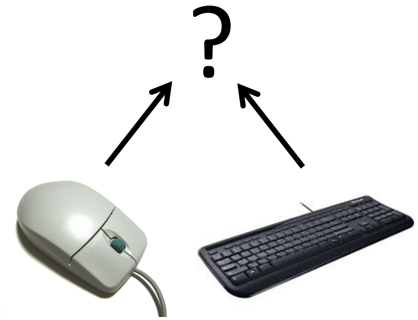
```
val e1: Event[Int] = Evt[Int]()
```

DECLARATIVE EVENTS

The Problem

- Imperative events are fired by the programmer
- Conceptually, certain events depend on other events





- Examples:
  - mouseClickE -> museClickOnShape
  - mouseClose, keyboardClose -> closeWindow
- Can we solve this problem enhancing the language?

Declarative Events

- Declarative events are defined by a combination of other events.

- Some valid declarations:

```
val e1 = Evt[Int]()
val e2 = Evt[Int]()

val e3 = e1 || e2
val e4 = e1 && ((x: Int)=> x>10)
val e5 = e1 map ((x: Int)=> x.toString)
```

OR events

- The event e1 || e2 is fired upon the occurrence of one among e1 or e2.
  - The events in the event expression have the same parameter type

```
val e1 = Evt[Int]()
val e2 = Evt[Int]()
val e1_OR_e2 = e1 || e2
e1_OR_e2 += ((x: Int) => println(x))
e1(10)
e2(10)

-- output ----
10
10
```

Predicate Events

- The event e && p is fired if e occurs and the predicate p is satisfied.
  - The predicate is a function that accepts the event parameter as a formal and returns Boolean.
  - && filters events using a parameter and a predicate.

```
val e = Evt[Int]()
val e_AND: Event[Int] = e && ((x: Int) => x>10)
e_AND += ((x: Int) => println(x))
e(5)
e(15)
-- output ----
15
```

Map Events

- The event e map f is obtained by applying f to the value carried by e.
  - The map function takes the event parameter as a formal.
  - The return type of map is the type parameter of the resulting event.

```
val e = Evt[Int]()
val e_MAP: Event[String] = e map ((x: Int) => x.toString)
e_MAP += ((x: String) => println("Here: " + x))
e(5)
e(15)
-- output ----
Here: 5
Here: 15
```

EXAMPLES OF RESCALA EVENTS

Example: Figures

```
abstract class Figure {
   val moved[Unit] = afterExecMoveBy
   val resized[Unit]
   val changed[Unit] = resized || moved || afterExecSetColor
   val invalidated[Rectangle] = changed.map( _ => getBounds() )
  ...
   val afterExecMoveBy = new Evt[Unit]
   val afterExecSetColor = new Evt[Unit]
  ...
   def moveBy(dx: Int, dy: Int) { position.move(dx, dy); afterExecMoveBy() }
   def resize(s: Size) { size = s }
   def setColor(col: Color) { color = col; afterExecSetColor() }
   def getBounds(): Rectangle
...
}
```

Example: Figures

```
class Connector(val start: Figure, val end: Figure) {
   val h1 = start.changed += updateStart _
   val h2 = end.changed += updateEnd _
  ...
   def updateStart() { ... }
   def updateEnd() { ... }
  ...
   def dispose {
      h1.remove
      h2.remove
   }
}
```

Example: Figures

- Inherited events
  - May be overridden
  - Are late bound

```
abstract class Figure {
   val moved[Unit] = afterExecMoveBy
   val resized[Unit]
  ...
}
```

```
class RectangleFigure extends Figure {
   val resized = afterExecResize || afterExecSetBounds
   override val moved = super.moved || afterExecSetBounds
  ...
   val afterExecResize = new Evt[Unit]
   val afterExecSetBounds = new Evt[Unit]
  ...
   def resize(s: Size) { ... ; afterExecResize() }
   def setBounds(x1: Int, y1: Int, x2: Int, y2: Int) { ... ; afterExecSetBounds }
  ...
}
```

Example: Temperature Sensor

```
class TemperatureSensor {
    val tempChanged[Int] = new Evt[Int]

   ...
    def run {
        var currentTemp = measureTemp()
        while(!stop) {
            val newTemp = measureTemp()
            if (newTemp != currentTemp) {
                tempChanged(newTemp)
                currentTemp = newTemp
            }
            sleep(100)
        }
    }
}
```

REACTIVE LANGUAGES

Events and Functional Dependencies

Events are often used for functional dependencies

boolean highTemp := (temp.value > 45);

```
var a = 3
var b = 7
val c = a + b

a = 4
b = 8
```

```
val update = Evt[Unit]()
var a = 3
var b = 7
var c = a + b  // Functional dependency

update += ( _ =>{
  c = a + b
})

a = 4
update()
b = 8
update()
```

Constraints

- What about expressing functional dependencies as constraints ?

```
val a = 3
val b = 7
val c = a + b // Statement
println(c)
> 10
a= 4
println(c)
> 10
```

```
val a = 3
val b = 7
val c := a + b // Constraint
println(c)
> 10
a= 4
println(c)
> 11
```

EMBEDDING REACTIVE PROGRAMMING IN SCALA

Reactive Values

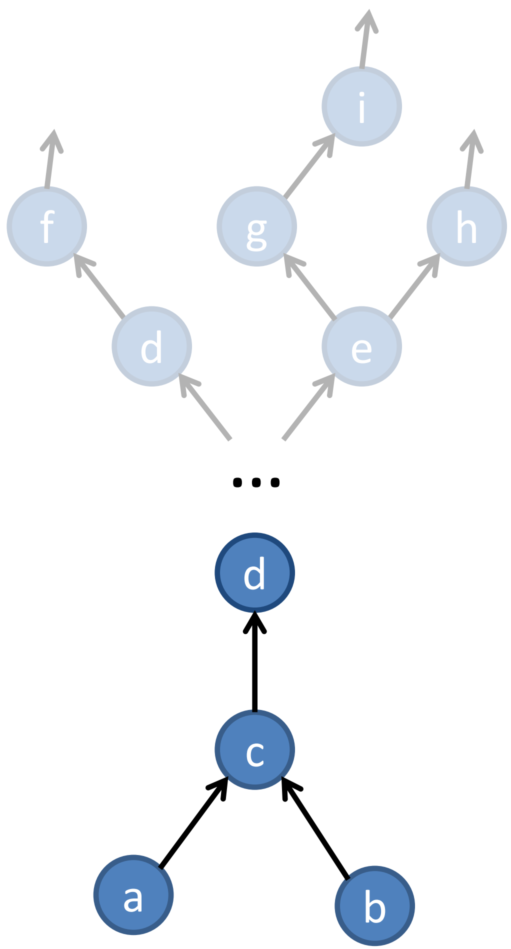
- **Vars**: primitive reactive values
  - Updated “manually”
- **Signals**: reactive expressions
  - The constraints “automatically” enforced

```
val a = Var(3)
val b = Var(7)
val c = Signal{ a() + b() }
println(c.now)
> 10
a()= 4
println(c.now)
> 11
```

Reference Model

- Change propagation model
  - Dependency graph
  - Push-driven evaluation

```
val a = Var(3)
val b = Var(7)
val c = Signal{ a() + b() }
val d = Signal { 2 * c() }
…
```



SIGNALS AND VARS

Vars

- Vars wrap *normal* Scala values
- Var[T] is a parametric type.
  - The parameter T is the type the var wraps around
  - Vars are assigned by the “()=“ operator

```
val a = Var(0)
val b = Var("Hello World")
val c = Var(false)
val d: Var[Int] = Var(30)
val e: Var[String] = Var("REScala")
val f: Var[Boolean] = Var(false)


a()= 3
b()=“New World”
c()=true
```

Signals

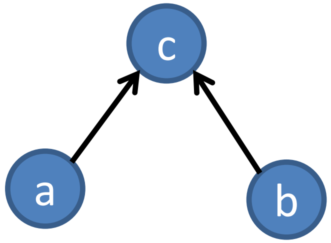
- Syntax: Signal{sigexpr}
  - Sigexpr should be **side-effect free**

- Signals are parametric types.
  - A signal Signal[T] carries a value of type T

Signals: Collecting Dependencies

- A **Var** or a **Signal** called with () in a signal expression is added to the dependencies of the defined signal

```
// Multiple vars
// in a signal expression
val a = Var(0)
val b = Var(0)
val s = Signal{ a() + b() }
```



Signals: Examples

```
val a = Var(0)
val b = Var(0)
val c = Var(0)

val r: Signal[Int] = Signal{ a() + 1 }   // Explicit type in var decl

val s = Signal{ a() + b() }              // Multiple vars is a signal expression

val t = Signal{ s() * c() + 10 }         // Mix signals and vars in signal expressions

val u = Signal{ s() * t() }              // A signal that depends on other signals
```

Signals: Examples

```
val a = Var(0)
val b = Var(2)
val c = Var(true)
val s = Signal{ if (c()) a() else b() }
```

```
def factorial(n: Int) = ...
val a = Var(0)

val s: Signal[Int] = Signal{    // A signal expression can be any code block
  val tmp = a() * 2
  val k = factorial(tmp)
  k + 2      // Returns an Int
}
```

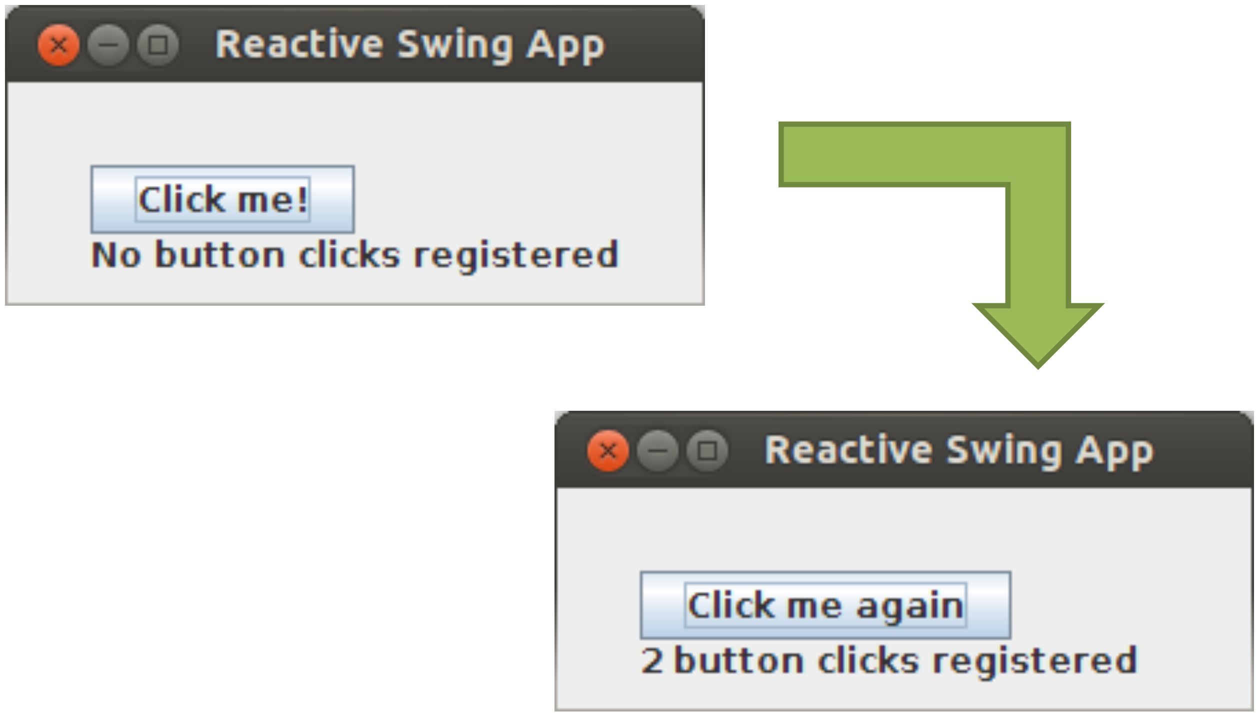
Signals

- Accessing reactive values: now
  - Often used to return to a *traditional* computation

```
val a = Var(0)
val b = Var(2)
val c = Var(true)
val s: Signal[Int] = Signal{ a() + b() }
val t: Signal[Boolean] = Signal{ !c() }

val x: Int = a.now
val y: Int = s.now

val z: Boolean = t.now
println(z)
```

EXAMPLES OF SIGNALS

Example


Reactive Swing App
Click me!
No button clicks registered
Reactive Swing App
Click me again
2 button clicks registered

Example: Observer


```
/* Create the graphics */
title = "Reactive Swing App"
val button = new Button {
  text = "Click me!"
}
val label = new Label {
  text = "No button clicks registered"
}
contents = new BoxPanel(Orientation.Vertical) {
  contents += button
  contents += label
}
```

```
/* The logic */
listenTo(button)
var nClicks = 0
reactions += {
  case ButtonClicked(b) =>
    nClicks += 1
    label.text = "Number of button clicks: " + nClicks
    if (nClicks > 0)
      button.text = "Click me again"
}
```

Example: Signals


```
title = "Reactive Swing App"
val label = new ReactiveLabel
val button = new ReactiveButton

val nClicks = button.clicked.fold(0) {(x, _) => x + 1}

label.text = Signal { ( if (nClicks() == 0) "No" else nClicks() ) + " button clicks registered" }

button.text = Signal { "Click me" + (if (nClicks() == 0) "!" else " again " )}

contents = new BoxPanel(Orientation.Vertical) {
   contents += button
   contents += label
}
```

Example: Smashing Particles

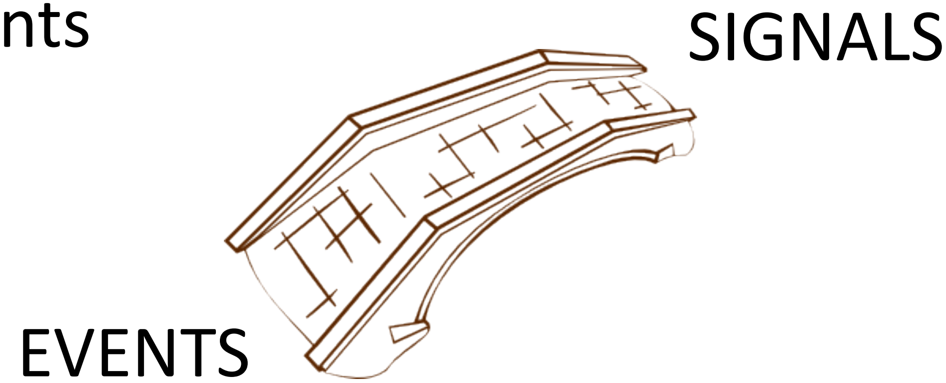
```
class Oval(center: Signal[Point], radius: Signal[Int]) { … }

val base = Var(0)  // Increases indefinitely
val linearTime = base()
val cyclicTime = Signal{linearTime() % 200}

val point1 = Signal{ new Point(20+ cyclicTime (), 20+ cyclicTime ()) }
new Oval(point1, cyclicTime )
 … // 4 times
```

BASIC CONVERSION FUNCTIONS

REScala design principles

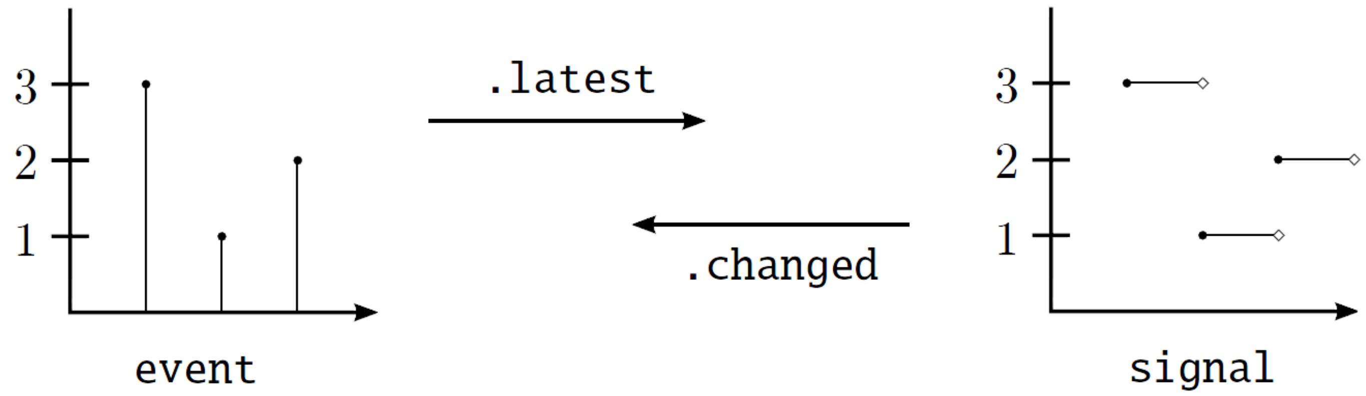
- Signals (and events) are objects fields
  - Inheritance, late binding, visibility modifiers, …

- Conversion functions
  bridge signals and events



Basic Conversion Functions

- **`Changed :: Signal[T] -> Event[T]`**
- **`Latest :: Event[T] -> Signal[T]`**



Example: Changed

```
val SPEED = 10
val time = Var(0)
val space = Signal{ SPEED * time() }

while (true) {
  Thread sleep 20
  time() = time.now + 1
}

space.changed += ((x: Int) => println(x))

-- output --
10
20
30
40
 ...
```

Example: Latest

```
val senseTmp = Evt[Int]() // Fahrenheit
val threshold = 40

val fahrenheitTmp = senseTmp.latest(0)
val celsiusTmp = Signal{ (fahrenheitTmp() – 32) / 1.8 }

val alert = Signal{ if (celsiusTmp() > threshold ) “Warning ” else “OK”  }
```

Quiz 1

```
val v1 =  Var(4)
val v2 =  Var(2)
val s1 = Signal{ v1() + v2() }
val s2 = Signal{ s1() / 3 }

assert(s2.now == 2)
v1()=1
assert(s2.now == 1)
```

Quiz 2

```
var test = 0
 val v1 =  Var(4)
 val v2 =  Var(2)
 val s1 = Signal{ v1() + v2() }
 s1.changed += ((x: Int)=>{test+=1})

 assert(test == 0)
 v1()=1
 assert(test == 1)
```

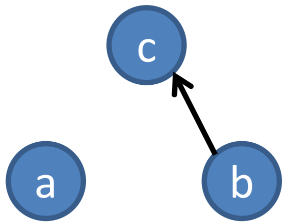
Quiz 3

```
val e = Evt[Int]()
val v1 =  Var(4)
val v2 =  Var(2)
val s1 =  e.latest(0)
val s2 = Signal{ v1() + v2() + s1() }

assert(s2.now == 6)
e(2)
assert(s2.now == 8)
e(1)
assert(s2.now == 7)
```

TRUBLESHOOTING

Common pitfalls

- Establishing dependencies
  - () creates a dependency.
    Use only in signal expressions
  - **now** returns the current value




```
val a = Var(2)
val b = Var(3)
val c = Signal{ a.now + b() }
```

- Signals are **not** assignable.
  - Depend on other signals and vars
  - Are automatically updated

Common pitfalls

- Avoid side effects in signal expressions

WRONG!

```
var c = 0
val s = Signal{
  val sum = a() + b();
  c = sum * 2
}
 ...
foo(c)
```

```
val c = Signal{
  val sum = a() + b();
  sum * 2
}
 ...
foo(c.now)
```

- Avoid cyclic dependencies

WRONG!

```
val a = Var(0)
val s = Signal{ a() + t() }
val t = Signal{ a() + s() + 1 }
```

Reactive Abstractions and Mutability

- Signals and vars hold references to objects, not the objects themselves.

```
class Foo(init: Int){
  var x = init
}
val foo = new Foo(1)

val varFoo = Var(foo)
val s = Signal{
  varFoo().x + 10
}
assert(s. now== 11)
foo.x = 2
assert(s.now == 11)
```

```
class Foo(init: Int){
  var x = init
}
val foo = new Foo(1)

val varFoo = Var(foo)
val s = Signal{
  varFoo().x + 10
}
assert(s.now == 11)
foo.x = 2
varFoo()=foo
assert(s.now == 11)
```

```
class Foo(x: Int)  //Immutable
val foo = new Foo(1)

val varFoo = Var(foo)
val s = Signal{
  varFoo().x + 10
}
assert(s.now == 11)
varFoo()= new Foo(2)
assert(s.now == 12)
```

QUESTIONS?