An Introduction to Reactive Programming (2)

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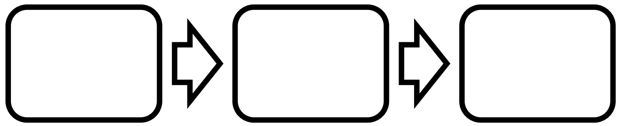
Outline

- Analysis of languages for reactive applications
- Details of reactive frameworks
- Advanced conversion functions
- Examples

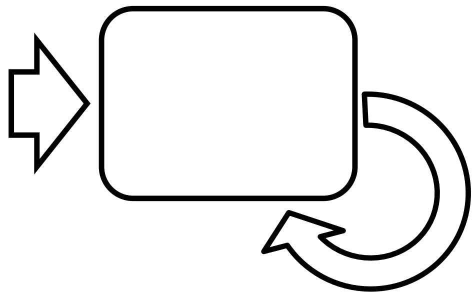
REACTIVE APPLICATIONS: ANALYSIS

Software Taxonomy

- A **transformational** systems
  - 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
  - Editors, Web apps, embedded software



Use of State

- Transformational systems:
  - Express transformations as incremental modifications of the internal data structures
  - Represent the state of iterations in loops

  Use of state is not essential

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

  State is essential to describe the system

How to implement Reactive Systems ?

- Observer Patter
  - The *traditional* way in OO languages

- Language-level events
  - In event-based languages

- Signals, vars, events and combinations of.
  - Reactive languages

OBSERVER PATTERN: ANALYSIS

The example

val c = a + b

val a = 3

val b = 7

a = 4

b = 8

The Example: Observer

```scala
trait Observable {
  val observers = scala.collection.mutable.Set[Observer]()
  def registerObserver(o: Observer) = { observers += o }
  def unregisterObserver(o: Observer) = { observers += o }
  def notifyObservers(a: Int,b: Int) = { observers.foreach(_.notify(a,b)) }
}
trait Observer {
  def notify(a: Int,b: Int)
}

class Sources extends Observable {
  var a = 3
  var b = 7
}
class Constraint(a: Int, b: Int) extends Observer {
  var c =  a + b
  def notify(a: Int,b: Int) = { c = a + b }
}
```

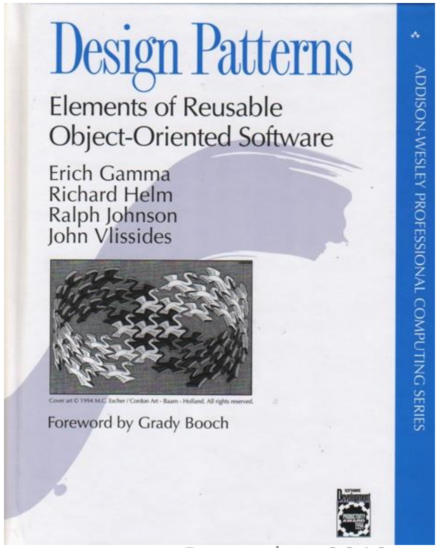
```scala
val s = new Sources()
val c = new Constraint(s.a,s.b)
s.registerObserver(c)
s.a = 4
s.notifyObservers(s.a,s.b)
s.b = 8
s.notifyObservers(s.a,s.b)
```

Observer for change propagation

- Main advantage:

Decouple the code that changes a value from the code that updates the values depending on it

  - “Sources” doesn’t know about “Constraint”



The (*good*? old) Observer Pattern

Long story of criticism…

- Inversion of *natural* dependency order
  - “Sources” updates “Constraint” but in the code “Constraint” calls “Sources” (to register itself)

- Boilerplate code

```
trait Observable {
  val observers = scala.collection.mutable.Set[Observer]()
  def registerObserver(o: Observer) = { observers += o }
  def unregisterObserver(o: Observer) = { observers += o }
….
```

The (*good*? old) Observer Pattern

- Reactions do not compose, return void
  - How to define new constraints based on the existing ones

```
class Constraint(a: Int, b: Int) … {
   var c =  a + b
   def notify(a: Int,b: Int) = {
      c = a + b
} }
```

+

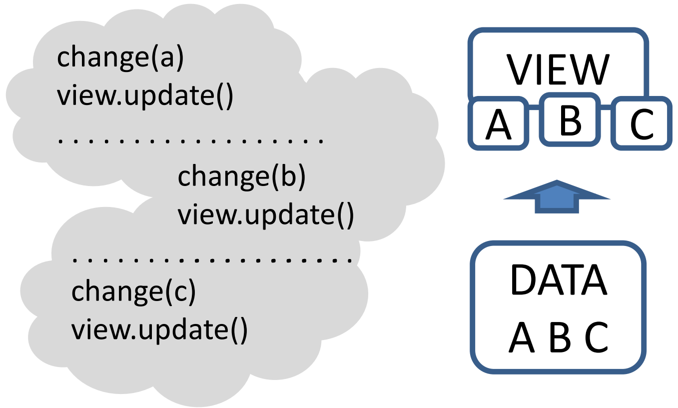
```
class Constraint2(d: Int) … {
   var d =  c * 7
   def notify(d: Int) = {
      d = c * 7
} }
```

= ??

The (*good*? old) Observer Pattern

- Scattering and tangling of triggering code
  - **Fail to update** all functionally dependent values.
  - Values are often update too much (**defensively**)

```
val s = new Sources()
val c = new Constraint(s.a,s.b)
s.registerObserver(c)
s.a = 4
s.notifyObservers(s.a,s.b)
s.b = 8
s.notifyObservers(s.a,s.b)
```



The (*good*? old) Observer Pattern

- Imperative updates of state

```
class Constraint(a: Int, b: Int) extends Observer {
   var c =  a + b
   def notify(a: Int,b: Int) = { c = a + b }
 }
```

- No separation of concerns

```
class Constraint(a: Int, b: Int) extends Observer {
   var c =  a + b
   def notify(a: Int,b: Int) = { c = a + b }
 }
```

Update logic
+
Constraint definition

EVENT-BASED LANGUAGES: ANALYSIS

Event-based Languages

- Language-level support for events
  - C#, Ptolemy, REScala, …

```
val e = new ImperativeEvent[Int]()
e += { println(_) }
e(10)
```

  - Imperative events

```
val update = new ImperativeEvent[Unit]()
```

  - Declarative events, ||, &&, dropParam, map, …

```
val changed[Unit] = resized || moved || afterExecSetColor
val invalidated[Rectangle] = changed.map( _ => getBounds() )
```

Event-based Languages

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

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

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

Event-based Languages

- More composable
  - Declarative events are composed by existing events
- Less boilerplate code
  - Applications are easier to understand

- Good integration with Objects and imperative style:
  - Imperative updates and side effects
  - Inheritance, polymorphism, …

Event-based Languages

- Dependencies still encoded manually
  - Handler registration
- Updates must be implemented explicitly
  - In the handlers
- Notifications are still error prone:
  - Too rarely / too often

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

REACTIVE LANGUAGES: ANALYSIS

Reactive Languages

- Functional-reactive programming (FRP) -- Haskell
  - **Time-changing values** as dedicated language abstractions.

    [Functional reactive animation, Elliott and Hudak. ICFP '97]

- More recently:
  - FrTime *[Embedding dynamic dataflow in a call-by-value language, Cooper and Krishnamurthi, ESOP'06]*
  - Flapjax *[Flapjax: a programming language for Ajax applications. Meyerovich et al. OOPSLA'09]*
  - Scala.React *[Imaier te al, Deprecating the Observer Pattern with Scala.React. Technical report, 2012]*

Reactive Languages and FRP

- Signals
  - Dedicated language abstractions for **time-changing** values

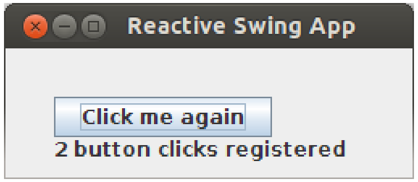
```
val a = Var(3)
val b = Var(7)
val c = Signal{ a() + b() }
println(c.getVal)
> 10
a()= 4
println(c.getVal)
> 11
```

- An alternative to the Observer pattern and inversion of control

```
/* 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"
}
```

```
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
}
```



Reactive Languages

- Easier to understand
  - Declarative style
  - Local reasoning
  - No need to follow the control flow to reverse engineer the constraints
- Dependent values are automatically consistent
  - No boilerplate code
  - No update errors (no updates/update defensively)
  - No scattering and tangling of update code
- Reactive behaviors are composable
  - In contrast to callbacks, which return void

NOW…

Signals allow a good design.
But they are *functional* (only).

```
val a = Var(3)
val b = Var(7)
val c = Signal{ a() + b() }
val d = Signal{ 2 * c() }
val e = Signal{ "Result: " + d() }
```

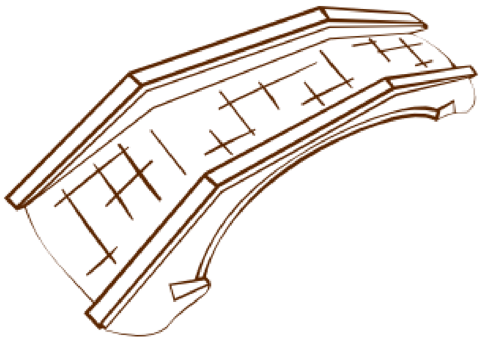
Functional programming is great! But…

The sad story:

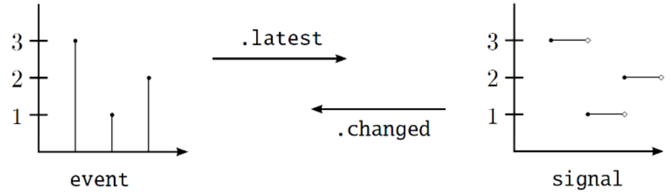
- The world is **event-based**, …
- Often **imperative, …**
- And mostly **Object-oriented**

Reactive Languages

- In practice, both are supported:
  - Signals (continuous)
  - Events (discrete)
- Conversion functions
  - Bridge signals and events
  - Allow interaction with objects state and imperative code



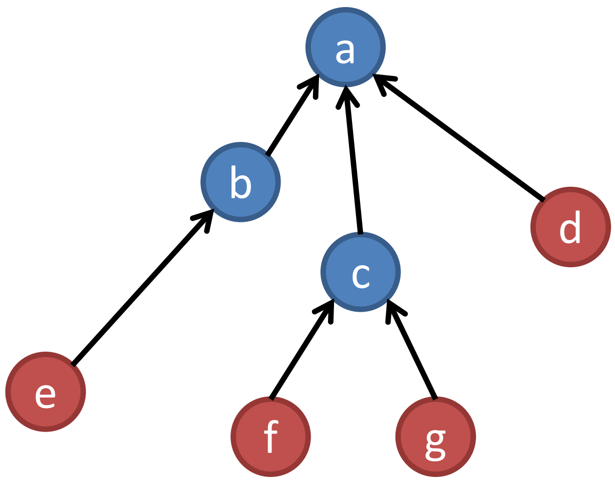
```
Changed :: Signal[T] -> Event[T]
Latest :: Event[T] -> Signal[T]
```



DETAILS ON THE REACTIVE MODEL

Implementation

- Change propagation model
  - Topologically ordered dependency graph
  - Push-driven evaluation
  - Track dynamic dependencies



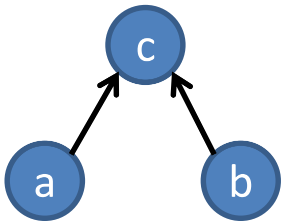

```
val e = Var(1)
val f = Var(2)
val g = Var(4)
val d = Var(true)

c = Signal { f() + g() }
b = Signal { e() * 100 }
a = Signal {
        if (d) c
        else b
    }
```

DSL implementation

Intuitively:

```
val a = Var(3)
val b = Var(4)
val c = Signal { a() + b() }
```

- Var(3) creates a leaf node
- Var(4) creates a leaf node
- The expression “a() + b()” is saved in a closure
  - To be evaluated later when a leaf changes
- Signal{…} creates another node
- The closure is evaluated
  - In the evaluation, the reactive values are detected.
  - The associated edges in the graph (i.e. the references from the leaves) are created
  - The result of the evaluation is assigned to the signal



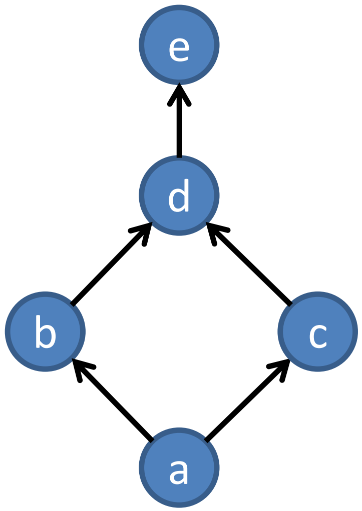
Glitches

- Glitch: a temporary *spurious* value due to the propagation order.

```
val a = Var(1)
val b = Signal{ a()*2 }
val c = Signal{ a()*3 }
val d = Signal{ b() + c() }
val e = d.changed
```

  - Consider the update order abdc
  - a()=2, b<-4, d<-7, c<-6, d<-10

  - d is redundantly evaluated 2 times
  - The first value of d has no meaning
  - E is erroneously fired two times
    the first one with the spurious value

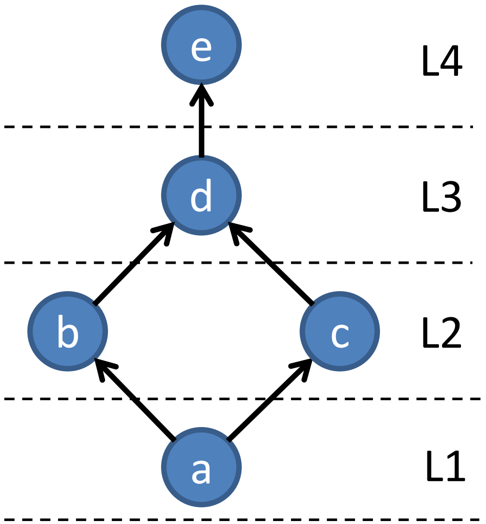


Glitch Freedom

- Ensured by updates *in topological order*
  - Nodes are assigned to levels **Ln** based on their position in the graph
  - Levels are updates in order

```
val a = Var(1)
val b = Signal{ a()*2 }
val c = Signal{ a()*3 }
val d = Signal{ b() + c() }
val e = d.changed
```

- In this case “abcde” or “acbde”



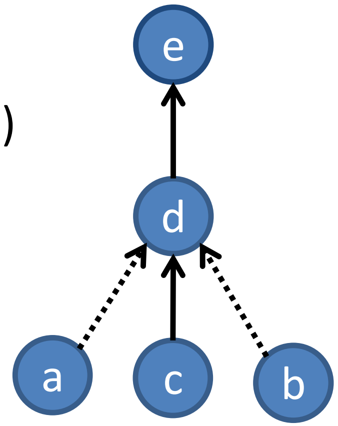
- In practice, levels are assigned and a priority queue keeps nodes to eval

Dynamic dependencies

- In some cases, dependencies are a consequence of a dynamic condition

  - When c==true, d must update if a changes but not if b changes
  - d depends on a or b based on the value of c
  - Reactive frameworks reroute the dependencies at runtime

```
val a = Var(3)
val b = Var(7)
val c = Var(false)
val d = Signal{
  if c()
    a()
  else
    b()
}
val e = Signal { 2 * c() }
```

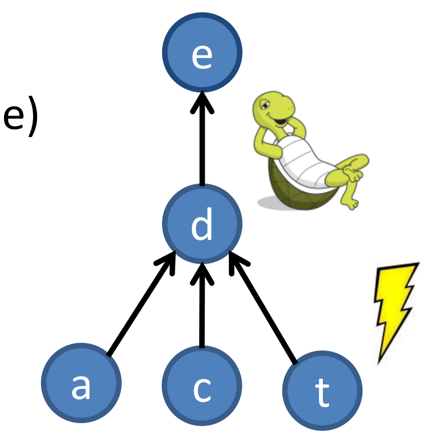


Dynamic dependencies

- What happens if dynamic dependencies are fix ?

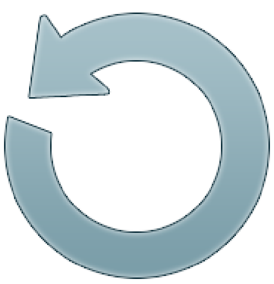
- Redundant evaluations
  - d is executed every time b is assigned even if the value of d does not change

```
val a = Var(3)
val t = Var(7)
val c = Var(true)
val d = Signal{
 if c()
   a()
 else
   t()
}
while(true){
 t()= … // system time
}
```



Loops

- Reject loops
  - The programmer has the responsibility (REScala, Flapjax)
  - Loops are rejected by the compiler
- Accept loops: which semantics ?
  - Delay to the next propagation round
  - Fix point semantics
    - Time consuming
    - Termination ?



ADVANCED INTERFACE FUNCTIONS

Fold

- Creates a signal by folding events with a function.
  - Initially the signal holds the **init** value.
- fold[T,A](e: Event[T], init: A)(f :(A,T)=>A): Signal[A]

```
val e = new ImperativeEvent[Int]()
val f = (x:Int,y:Int)=>(x+y)
val s: Signal[Int] = e.fold(10)(f)
assert(s.getValue == 10)
e(1)
e(2)
assert(s.getValue == 13)
```

Iterate

- Returns a signal holding value computed by **f** on the occurrence of an event.
  - No accumulator
- iterate[A](e: Event[_], init: A)(f: A=>A) :Signal[A]

```
var test: Int = 0
val e = new ImperativeEvent[Int]()
val f = (x:Int)=>{test=x; x+1}
val s: Signal[Int] = e.iterate(10)(f)
```

```
e(1)
assert(test == 10)
assert(s.getVal == 10)
e(2)
assert(test == 11)
assert(s.getVal == 10)
e(1)
assert(test == 12)
assert(s.getVal == 10)
```

LatestOption

- Variant of latest.
  - The Option type for the case the event did not fire yet.
  - Latest value of an event as Some(value) or None
- latestOption[T](e: Event[T]): Signal[Option[T]]

```
val e = new ImperativeEvent[Int]()
val s: Signal[Option[Int]] = e.latestOption(e)
assert(s.getVal == None)
e(1)
assert(s.getVal == Option(1))
e(2)
assert(s.getVal == Option(2))
e(1)
assert(s.getVal == Option(1))
```

Last

- Generalizes **latest**
  - Returns a signal which holds the last **n** events
  - Initially an empty list
- last[T](e: Event[T], n: Int): Signal[List[T]]

```
val e = new ImperativeEvent[Int]()
val s: Signal[List[Int]] = e.last(5)

assert(s.getVal == List())
e(1)
assert(s.getVal == List(1))
e(2)
assert(s.getVal == List(2,1))
```

```
e(3);e(4);e(5)
assert(s.getVal == List(5,4,3,2,1))
e(6)
assert(s.getVal == List(6,5,4,3,2))
```

List

- Collects the event values in a (ever growing) list.
- Use carefully…

- list[T](e: Event[T]): Signal[List[T]]

Count

- Returns a signal that counts the occurrences e
  - Initially, the signal holds 0.
  - The argument of the event is discarded.
- count(e: Event[_]): Signal[Int]

```
val e = new ImperativeEvent[Int]()
val s: Signal[Int] = e.count
assert(s.getValue == 0)
e(1)
e(3)
assert(s.getValue == 2)
```

Snapshot

- Returns a signal updated only when **e** fires.
  - Other changes of **s** are ignored.
  - The signal is updated to the current value of **s**.
- snapshot[V](e : Event[_], s: Signal[V]): Signal[V]

```
val e = new ImperativeEvent[Int]()
val v =  Var(1)
val s1 = Signal{ v1() + 1 }
val s = e.snapshot(s1)
```

```
assert(s.getValue == 2)
e(1)
assert(s.getValue == 2)
v.setVal(2)
assert(s.getValue == 2)
e(1)
assert(s.getValue == 3)
```

Change

- Similar to changed
  - Provides both the old and the new value in a tuple
  - change[U >: T]: Event[(U, U)]

```
val s = Signal{ ... }
val e: Event[(Int,Int)] = s.change
e += (x: (Int,Int)=> {
   ...
})
```

ChangedTo

- Similar to changed
  - The event is fired only if the signal holds the given value
  - The value of e is discarded
- changedTo[V](value: V): Event[Unit]

```
var test = 0
val v =  Var(1)
val s = Signal{ v() + 1 }
val e: Event[Unit] = s.changedTo(3)
e += ((x:Unit)=>{test+=1})
```

```
assert(test == 0)
v setVal 2
assert(test == 1)
v setVal 3
assert(test == 1)
```

Reset

- Factory uses the event value to build the new signal.
- Initially, the init value is used

reset[T,A](e: Event[T], init: T)(factory: (T)=>Signal[A]): Signal[A]

```
val e = new ImperativeEvent[Int]()
val v1 =  Var(0)
val v2 =  Var(10)
val s1 = Signal{ v1() + 1 }
val s2 = Signal{ v2() + 1 }

def factory(x: Int) = x%2 match {
  case 0 => s1
  case 1 => s2
}
```

```
val s3 = e.reset(100)(factory)

assert(s3.getVal == 1)
v1.setVal(1)
assert(s3.getVal == 2)
e(101)
assert(s3.getVal == 11)
v2.setVal(11)
assert(s3.getVal == 12)
```

Toggle

- Switches between signals on the occurrence of e.
  - The value attached to the event is discarded
  - toggle[T](e : Event[_], a: Signal[T], b: Signal[T]): Signal[T]

```
val e = new ImperativeEvent[Int]()
val v1 =  Var(1)
val s1 = Signal{ v1() + 1 }
val v2 =  Var(11)
val s2 = Signal{ v2() + 1 }
val s = e.toggle(s1,s2)
```

```
assert(s.getValue == 2)
e(1)
assert(s.getValue == 12)
v2.setVal(12)
assert(s.getValue == 13)
v1.setVal(2)
assert(s.getValue == 13)
e(1)
v1.setVal(3)
assert(s.getValue == 4)
v2.setVal(13)
assert(s.getValue == 4)
```

switchTo

- Switches the signal on the occurrence of the event e.
  - The result is a constant signal
  - The value of the retuned signal is carried by the event e.
- switchTo[T](e : Event[T], original: Signal[T]): Signal[T]

```
val e = new ImperativeEvent[Int]()
val v =  Var(1)
val s1 = Signal{ v() + 1 }
val s2 = s1.switchTo(e)
```

```
assert(s2.getVal == 2)
e(1)
assert(s2.getVal == 1)
e(100)
assert(s2.getVal == 100)
v.setVal(2)
assert(s2.getVal == 100)
```

switchOnce

- Switches to a new signal provided as a parameter once, on the occurrence of e

switchOnce[T]

(e: Event[_], original: Signal[T], newSignal: Signal[T]): Signal[T]

```
val e = new ImperativeEvent[Int]()
val v1 =  Var(0)
val v2 =  Var(10)
val s1 = Signal{ v1() + 1 }
val s2 = Signal{ v2() + 1 }
val s3 = s1.switchOnce(e,s2)
```

```
assert(s3.getVal == 1)
v1.setVal(1)
assert(s3.getVal == 2)
e(1)
assert(s3.getVal == 11)
e(2)
v2.setVal(11)
assert(s3.getVal == 12)
```

Note on the interface

- We showed the "non OO" signature for most interface functions
  - In practice the signature is in OO style
  - One of the parameters is the receiver of the method

- For example

```
Ifunctions.snapshot(e,s)    // snapshot[V](e : Event[_], s: Signal[V]): Signal[V]
```

  - Can be called as:

```
e.snapshot(s)    // e.snapshot[V](s: Signal[V]): Signal[V]
s.snapshot(e)    // s.snapshot[V](e : Event[_]): Signal[V]
```

Mean Over Window

- Events collect Double values from a sensor
- Mean over a shifting window of the last n events
- Print the mean only when it changes

e(2) e(1) e(3) e(2) e(1) e(3) e(4) e(1) e(3) e(4)

MEAN

Mean Over Window

```
val e = new ImperativeEvent[Double]

val window = e.last(5)
val mean = Signal {
  window().sum /
  window().length
}
mean.changed += {println(_)}


e(2); e(1); e(3); e(4); e(1); e(1)
```

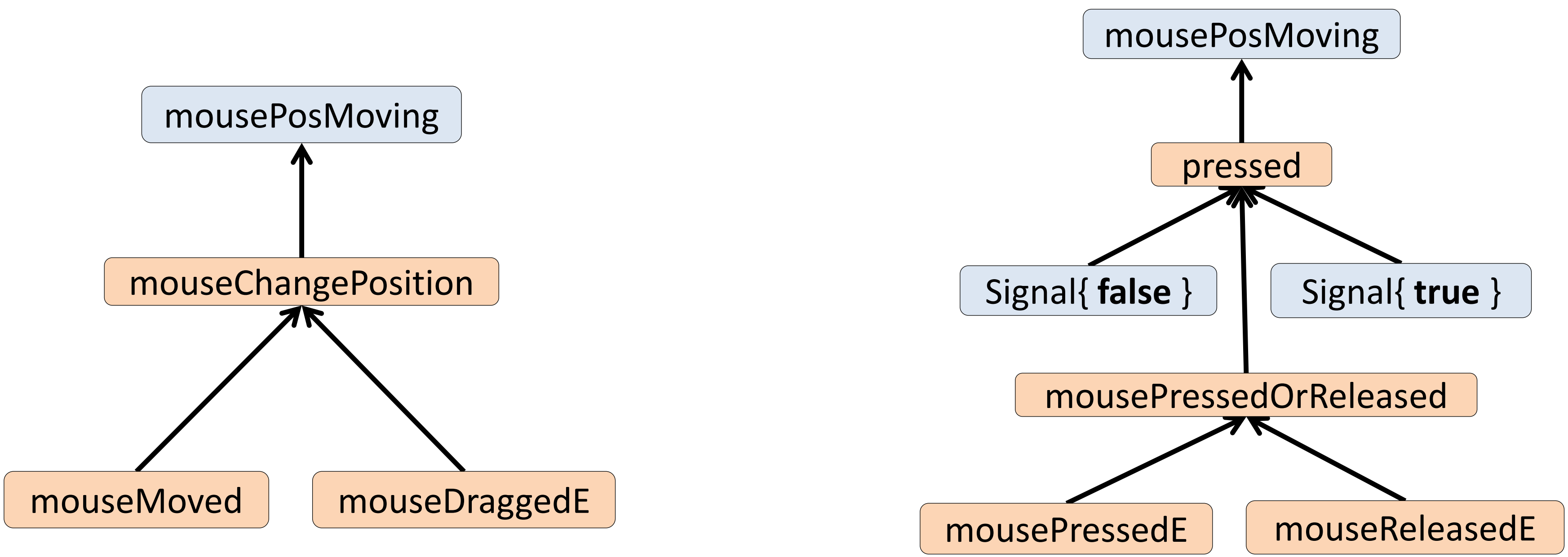
```
2.0
1.5
2.0
2.5
2.2
2.0
```

Example: Interface Functions

```
/* Compose reactive values */
val mouseChangePosition = mouseMovedE || mouseDraggedE
val mousePressedOrReleased = mousePressedE || mouseReleasedE
val mousePosMoving: Signal[Point] = mouseChangePosition.latest( new Point(0, 0) )
val pressed: Signal[Boolean] = mousePressedOrReleased.toggle( Signal{ false }, Signal{ true } )
```

Dependency Graph

```
/* Compose reactive values */
val mouseChangePosition = mouseMovedE || mouseDraggedE
val mousePressedOrReleased = mousePressedE || mouseReleasedE
val mousePosMoving: Signal[Point] = mouseChangePosition.latest( new Point(0, 0) )
val pressed: Signal[Boolean] = mousePressedOrReleased.toggle( Signal{ false }, Signal{ true } )
```



Example: Time Elapsing

- We want to show the elapsing time on a display
- (second,minute,hour,day)

(0,0,0,0)	(1,2,0,0)
(1,0,0,0)	…
(2,0,0,0)	(59,59,0,0)
…	(0,0,1,0)
(59,0,0,0)	…
(0,1,0,0)	(59,59,23,0)
(1,1,0,0)	(0,0,0,1)
(2,1,0,0)	….
…	
(59,1,0,0)	
(0,2,0,0)	

Time Elapsing: First Attempt

```
object TimeElapsing extends App {

  println("start!")

  val tick = Var(0)
  val second = Signal{ tick() % 60 }
  val minute = Signal{ tick()/60 % 60 }
  val hour = Signal{ tick()/(60*60) % (60*60) }
  val day = Signal{ tick()/(60*60*24) % (60*60*24) }

  while(true){
    Thread.sleep(0)
    println((second.getVal, minute.getVal, hour.getVal, day.getVal))
    tick.setVal(tick.getVal + 1)
  }
}
```

But day is still circular.
At some point day==0 again

Also, conceptually hard to follow

Time Elapsing

```
object AdvancedTimeElapsing extends App {
 println("start!")
 val tick = new ImperativeEvent[Unit]()

 val numTics = tick.count
 val seconds = Signal{ numTics() % 60 }
 val minutes = Signal{ seconds.changedTo(0).count() % 60 }
 val hours = Signal{ minutes.changedTo(0).count() % 24 }
 val days = hours.changedTo(0).count

 while(true){
  Thread.sleep(0)
  println((seconds.getVal, minutes.getVal, hours.getVal, days.getVal))
  tick()
 }
}
```

Use

s.changedTo(v)

- Fires and event if s holds v

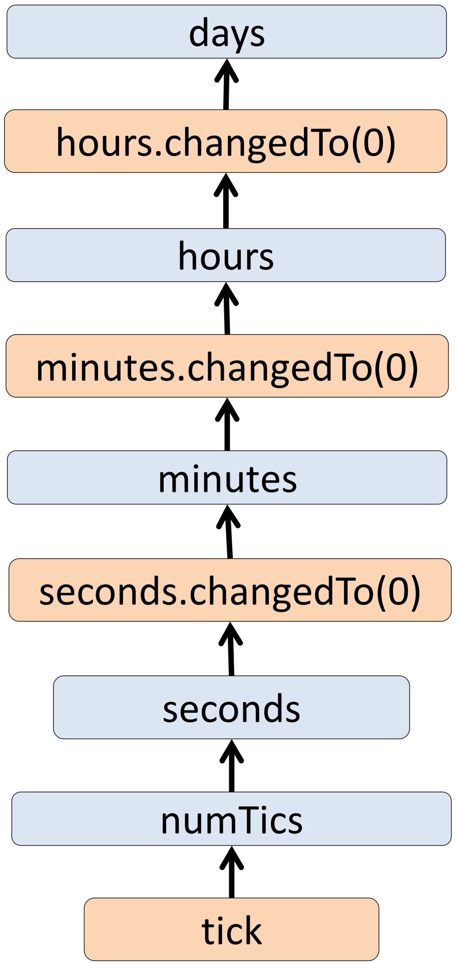
e.count

- Counts the occurrences of e

Exercise: draw dependency graph

```
val tick = new ImperativeEvent[Unit]()
val numTics = tick.count
val seconds = Signal{ numTics() % 60 }
val minutes = Signal{ seconds.changedTo(0).count() % 60 }
val hours = Signal{ minutes.changedTo(0).count() % 24 }
val days = hours.changedTo(0).count
```

- Which variables are affected by a change to tick ?



TRUBLESHOOTING

Common pitfalls

- Establishing dependencies
  - () creates a dependency.
    Only in signal expressions
  - getVal returns the current value

```scala
val s = Signal{ a.getVal + 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.getVal)
```

- 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
}
// s.getVal == 11
foo.x = 2
// s.getVal == 11
```

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

val varFoo = Var(foo)
val s = Signal{
  varFoo().x + 10
}
// s.getVal == 11
varFoo()= newFoo(2)
// s.getVal == 12
```

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

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

QUESTIONS?