Quantum Computing Modeling in Scala

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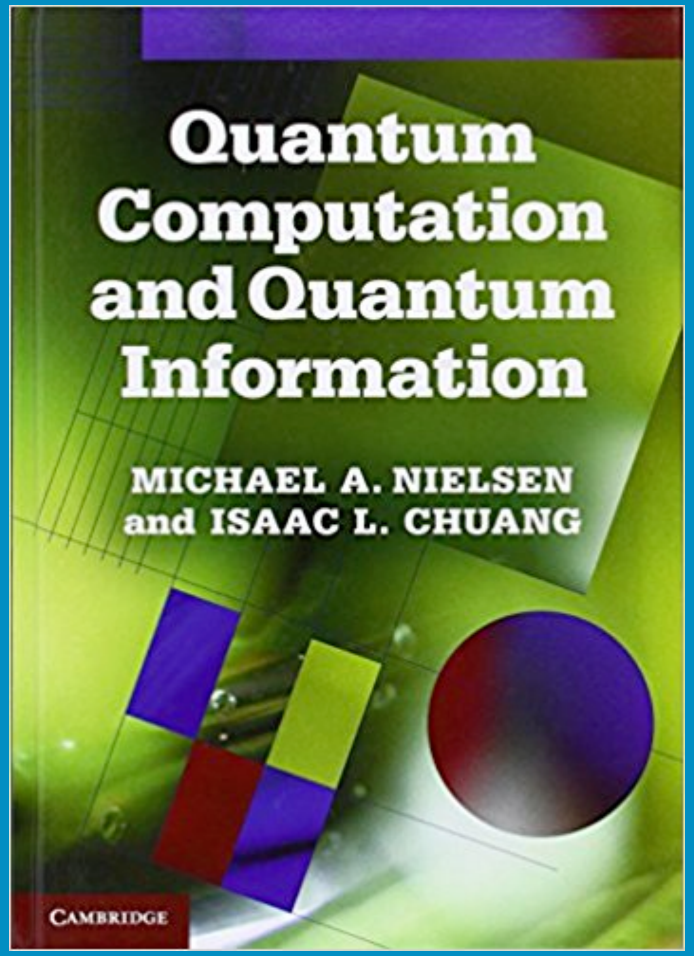
Scale By the Bay, November 2018

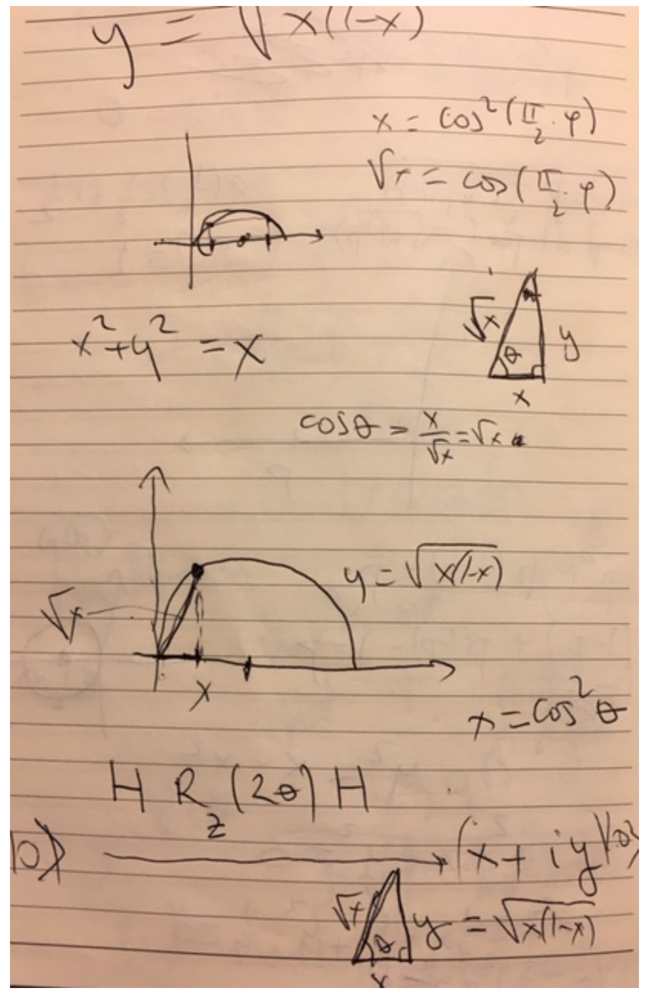


“

The postulates of quantum mechanics were derived after a long process of trial and (mostly) error, which involved a considerable amount of guessing and fumbling by the originators of the theory.

Why Scala?

Higher To Lower Abstraction



Math

↔

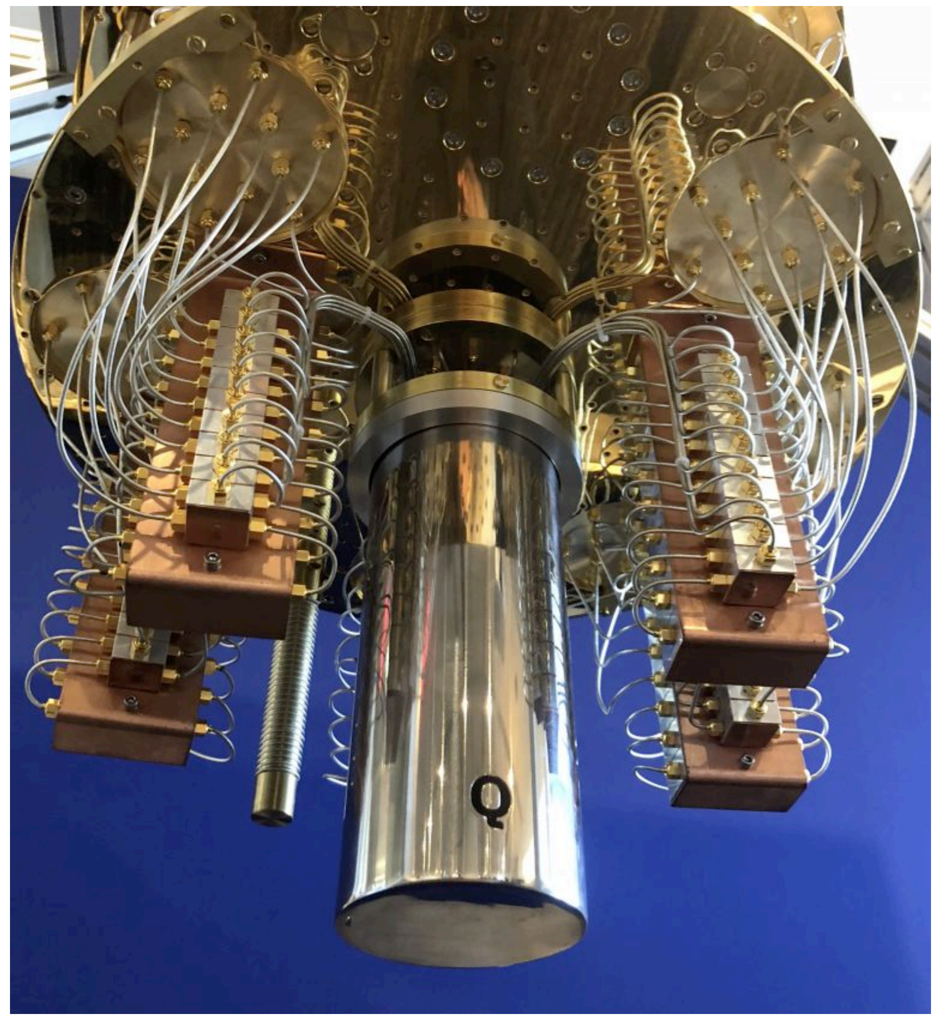
Scala Simulator

→

QISKit
Quantum Information Software Kit

Python Simulator

→



Quantum Computer

Quantum Postulates

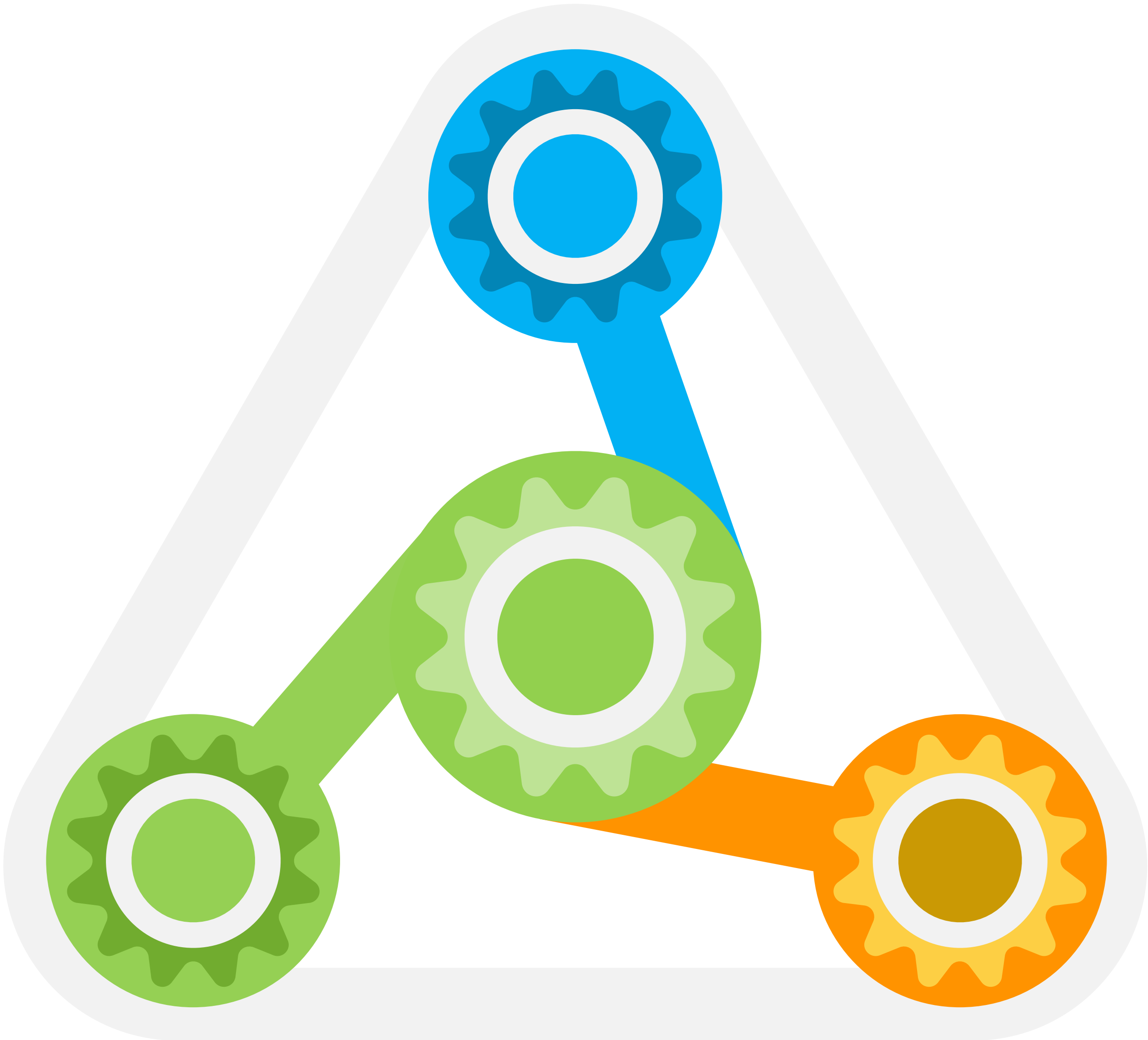
What quantum state is, how it changes, how it is measured and composed

State Space

A quantum system is completely described by its state vector

Measurement

Only certain outcomes may occur in an experiment



Evolution

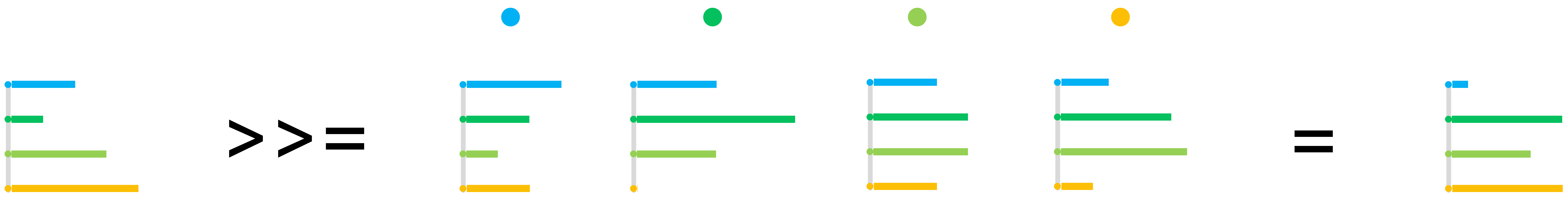
States at two different times are related by a unitary operator

Composition

The state space of a composite system is the tensor product of component states

Monadic State Evolution

The system state is defined by labeled values (allocations)



State: `List[(B, V)]`

Change: `B => List[(B, V)]`

State: `List[(B, V)]`

Examples: resource allocation, accounting systems, probabilistic systems, quantum systems

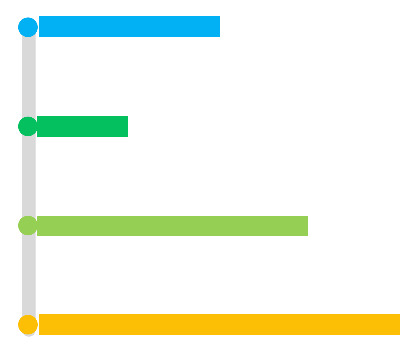
Compare with typical monads:

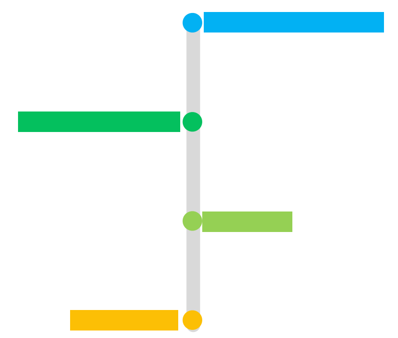
Container: M[A] >>= Change: A => M[A] = Container: M[A]

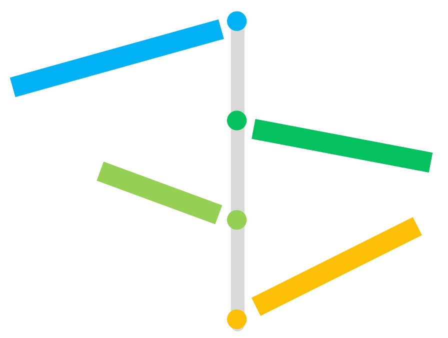
State Representation and Evolution

Unified monadic approach to classical, probabilistic and quantum state

```scala
trait UState[+This <: UState[This, B, V], B, V] {
  protected val bins: List[(B, V)]
  protected val m: Monoid[V]

  protected val normalizeStateRule: List[(B, V)] => List[(B, V)] = identity

  protected val combineBinsRule: List[(B, V)] => List[(B, V)] = { bvs =>
    bvs.groupBy(_._1).toList.map {
      case (b, vs) => (b, vs.map(_._2).foldLeft(m.empty)(m.combine))
    }
  }
  protected val distributionRule: ((B, V), List[(B, V)]) => List[(B, V)]

  def create(bins: List[(B, V)]): This

  def normalize(): This = create(normalizeStateRule(bins))

  def flatMap(f: B => List[(B, V)]): This = {
    val updates: List[(B, V)] = bins.flatMap({ case (b, v) => distributionRule((b, v), f(b)) })
    create(normalizeStateRule(combineBinsRule(updates)))
  }

  def >>=(f: B => List[(B, V)]): This = flatMap(f)
}
```







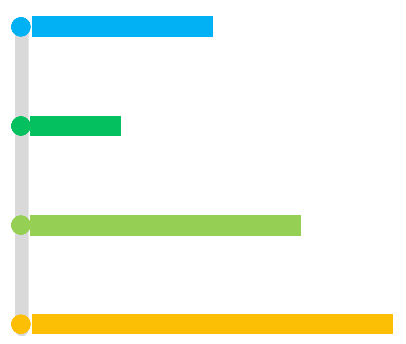
State: `List[(B, V)]`

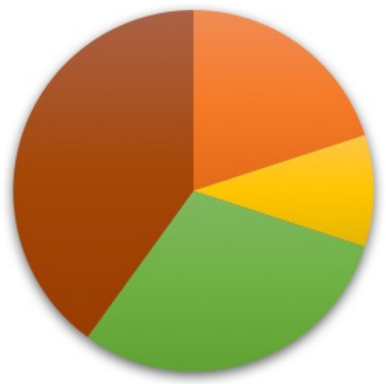
Change: `B => List[(B, V)]`

Portfolio Balancing

Percentage based resource allocation

```scala
val bins: List[(String, Double)] = List("a" -> .2, "b" -> .1, "c" -> .3, "d" -> .4)

val m = RState[String](bins)
val changeA = List("a" -> .25, "b" -> .5, "c" -> .25)
val changeB = List("b" -> 1.0)
val changeC = List("c" -> 1.0)
val changeD = List("d" -> 1.0)

val state = m >>= Map("a" -> changeA, "b" -> changeB, "c" -> changeC, "d" -> changeD)

assert(state.bins.toSet == Set("a" -> .05, "b" -> .2, "c" -> .35, "d" -> .4))
```





Implementation

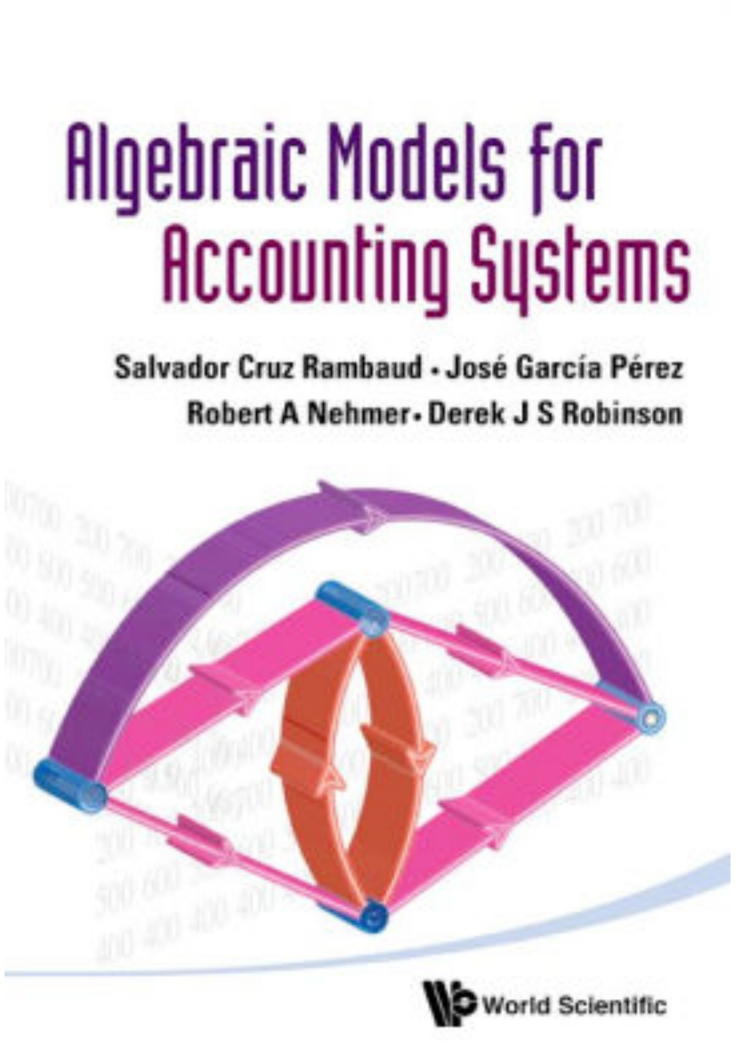
```scala
case class RState[B](bins: List[(B, Double)]) extends UState[RState[B], B, Double] {
  val m = new Monoid[Double] {
    override val empty: Double = 0.0
    override val combine: (Double, Double) => Double = _ + _
  }

  override val distributionRule: ((B, Double), List[(B, Double)]) => List[(B, Double)] = {
    case ((b, v), cs) => cs.map { case (c, u) => (c, u * v) }
  }

  override def create(bins: List[(B, Double)]) = RState(bins)
}
```

Invariant: sum = 1

Account Balances

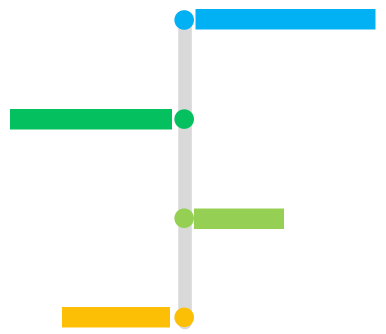
State of a closed accounting system

```scala
val bins: List[(String, Double)] = List("a" -> 2, "b" -> 3, "c" -> 5, "d" -> -8, "e" -> -2)

val z = ZState[String](bins)
val changeA = List("a" -> -1.0, "b" -> 1.0)
val changeB = List("b" -> -2.0, "c" -> 1.0, "d" -> 1.0)

val state = z >>= Map("a" -> changeA, "b" -> changeB, "c" -> Nil, "d" -> Nil, "e" -> Nil)

assert(state.bins.toSet == Set("a" -> 1.0, "b" -> 2.0, "c" -> 6.0, "d" -> -7.0, "e" -> -2.0))
```



Implementation

```scala
case class ZState[B](bins: List[(B, Double)]) extends UState[ZState[B], B, Double] {
  val m = new Monoid[Double] {
    override val empty: Double = 0.0
    override val combine: (Double, Double) => Double = _ + _
  }
  override val distributionRule: ((B, Double), List[(B, Double)]) => List[(B, Double)] = {
    case ((b, v), cs) => List((b -> v)) ++ cs
  }

  override def create(bins: List[(B, Double)]) = ZState(bins)
}
```

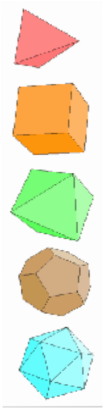


Invariant: sum = 0

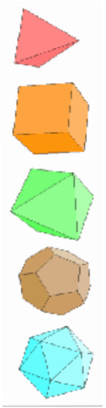
Probabilistic State

Each possible outcome is assigned a probability

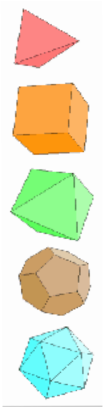
Repeatedly rolling one of the 5 platonic solid dice yields the following sequence: 6, 6, 8, 7, 7, 5, 4.
Guess which die was used?



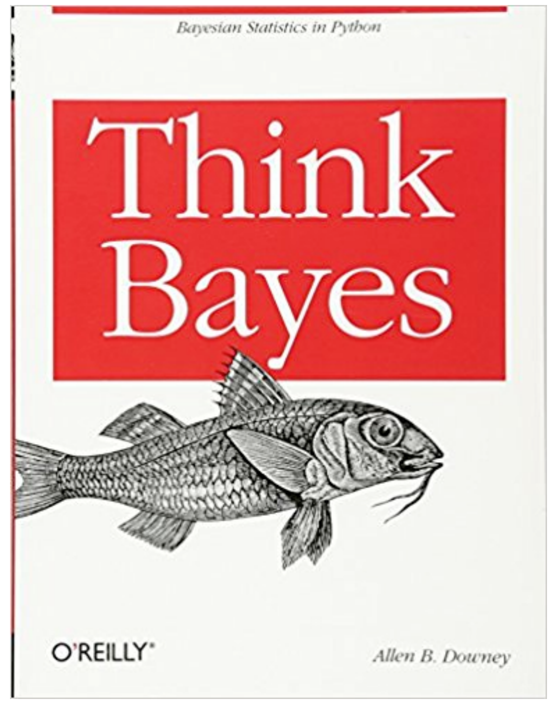
```
Priors:
4   0.2    ##########
6   0.2    ##########
8   0.2    ##########
12  0.2    ##########
20  0.2    ##########
```



```
After a 6 is rolled:
4   0.0
6   0.3921 ###################
8   0.2941 ##############
12  0.1960 #########
20  0.1176 #####
```

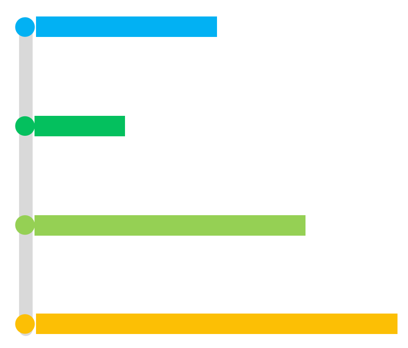


```
After 6, 8, 7, 7, 5, 4 are rolled after the first 6:
4   0.0
6   0.0
8   0.9432 ###############################################
12  0.0552 ##
20  0.0015
```



Probabilistic State

Bayes Theorem



```
case class PState[B](bins: List[(B, Double)]) extends UState[PState[B], B, Double] {
  val m = new Monoid[Double] {
    override val empty: Double = 1.0
    override val combine: (Double, Double) => Double = _ * _
  }

  override val distributionRule: ((B, Double), List[(B, Double)]) => List[(B, Double)] = {
    case ((b, v), cs) => cs.map { case (c, u) => (c, u * v) }
    //case ((b, v), cs) => List((b -> v)) ++ cs  // both work
  }

  override val normalizeStateRule = { bvs: List[(B, Double)] =>
    val sum = bvs.map(_._2).foldLeft(0.0)(_ + _)
    if (sum == 1.0) bins else bvs.map {
      case (b, v) => (b, v / sum)

    }
  }

  override def create(bins: List[(B, Double)]) = PState(bins)
}
```

Invariant: normalized sum = 1

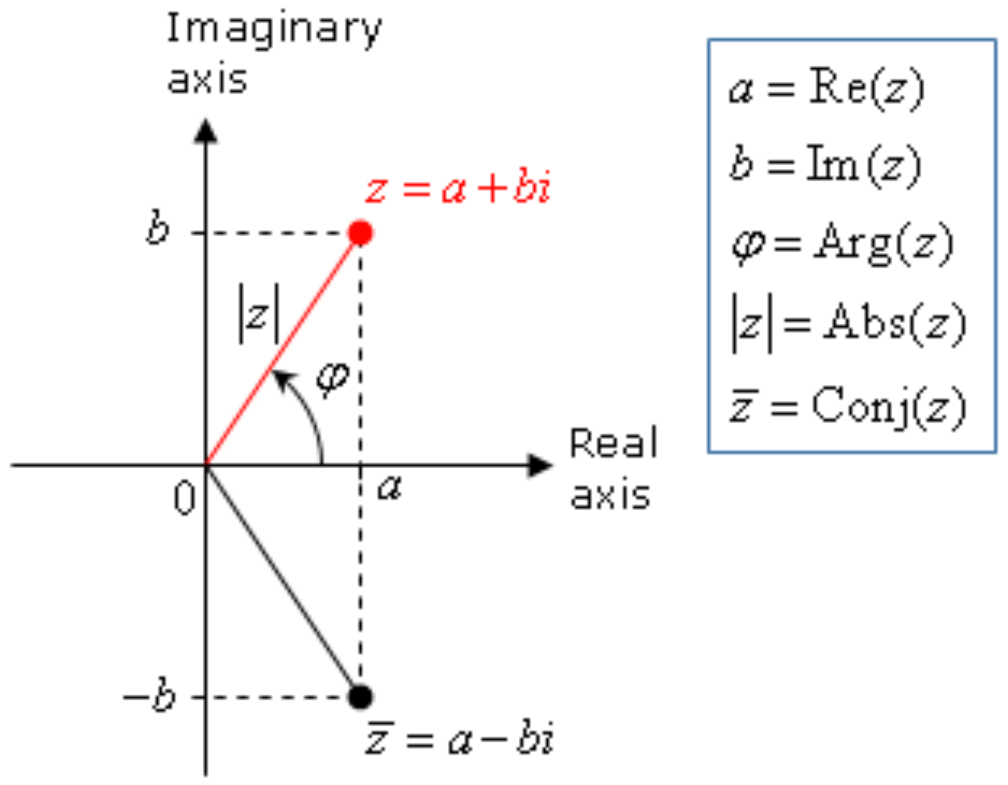
Change: data point likelihoods

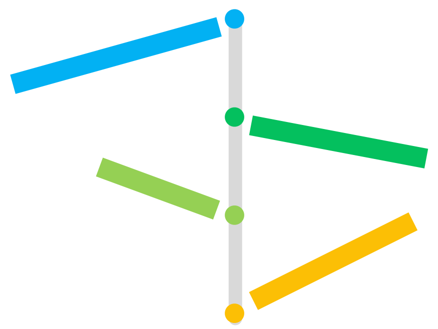
```
val change = Map(
  "a" -> List("a" -> 0.2),
  "b" -> List("b" -> 0.7),
  "c" -> List("c" -> 0.0))
```

Quantum State

Complex numbers (2 -dimensional vectors) as values

```
case class QState[B](bins: List[(B, Complex)]) extends UState[QState[B], B, Complex] {
  val m = new Monoid[Complex] {
    override val empty: Complex = Complex.zero
    override val combine: (Complex, Complex) => Complex = Complex.plus
  }

  override val distributionRule: ((B, Complex), List[(B, Complex)]) => List[(B, Complex)] = {
    case ((b, v), cs) => cs.map { case (c, u) => (c, u * v) }
  }

  override def create(bins: List[(B, Complex)]) = QState(bins)
}
```

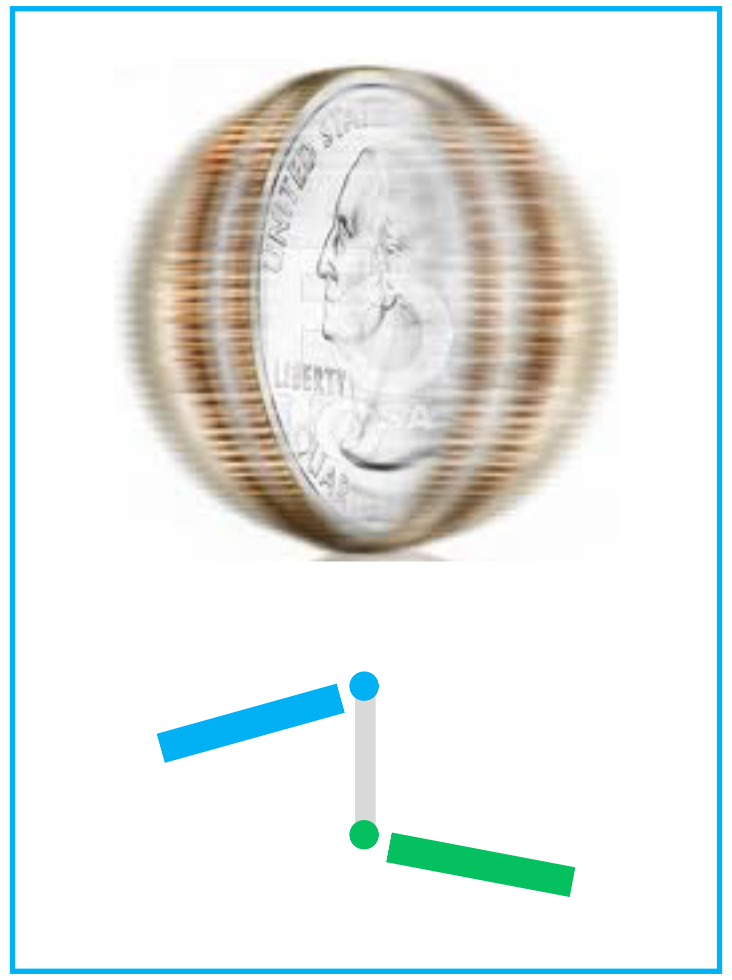




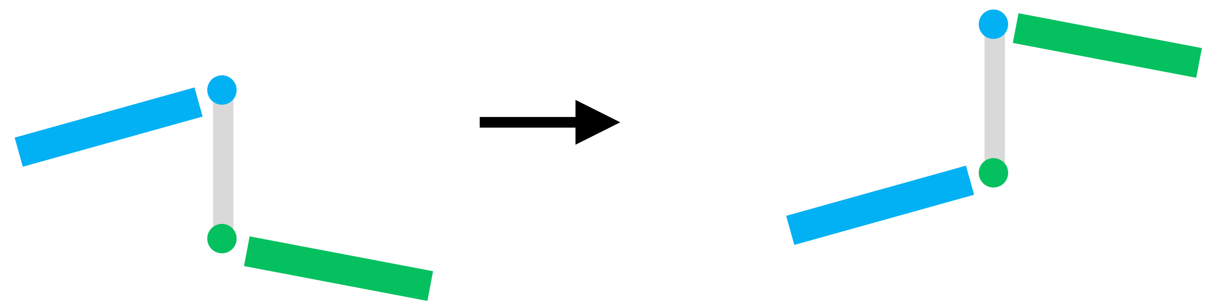
Invariant:
sum of squared magnitudes
= 1

Quantum State Transformations

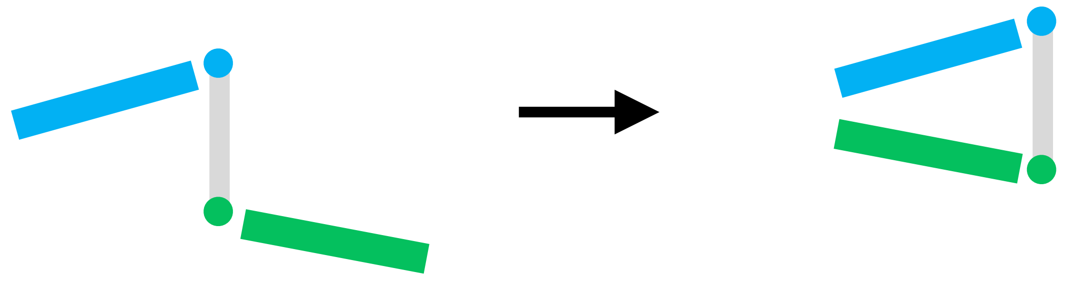
Standard single qubit transformations



X transformation

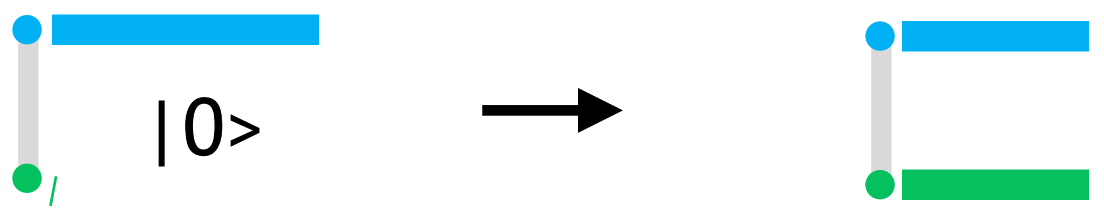


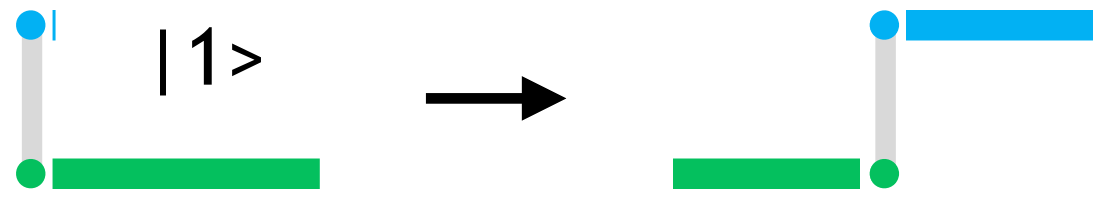
Z transformation



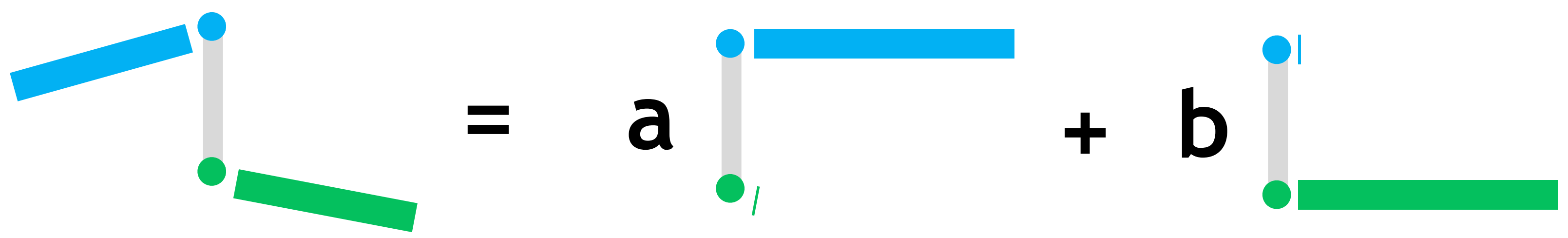
Hadamard transformation

```scala
val sq = toComplex(1 / math.sqrt(2))
val H = Map(
  "|0>" -> List("|0>" -> sq, "|1>" -> sq),
  "|1>" -> List("|0>" -> sq, "|1>" -> -sq)
)
```





Basis:



Quantum Postulates

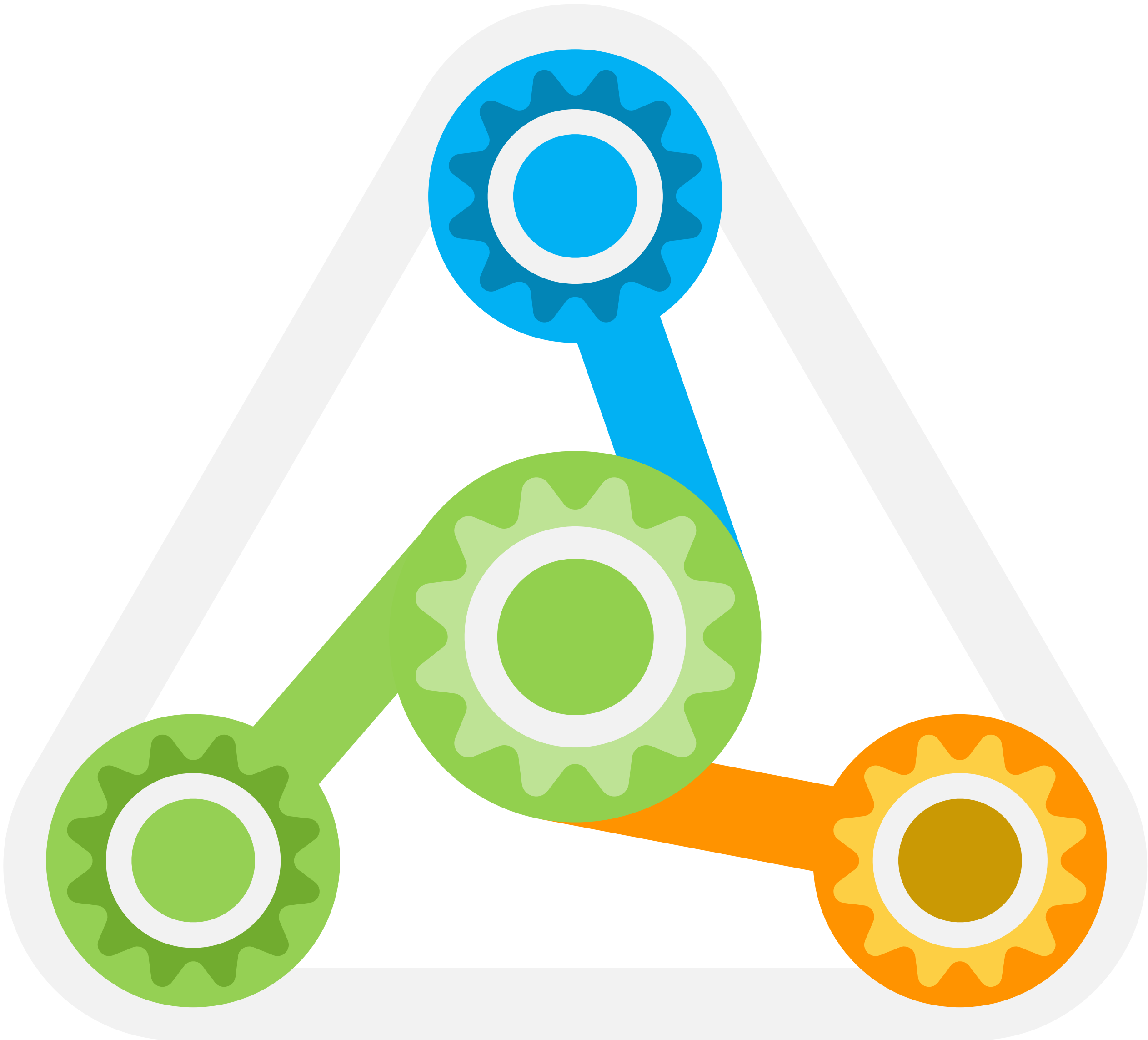
What quantum state is, how it changes, how it is measured and composed

State Space

A quantum system is completely described by its state vector

Measurement

Only certain outcomes may occur in an experiment



Evolution

States at two different times are related by a unitary operator

Composition

The state space of a composite system is the tensor product of component states

Composition and Measurement

Qubits, superposition, entanglement

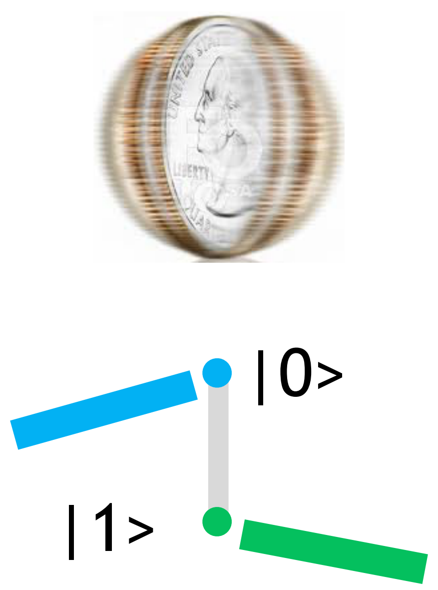
Qubits

Quantum State

One amplitude for each possible outcome

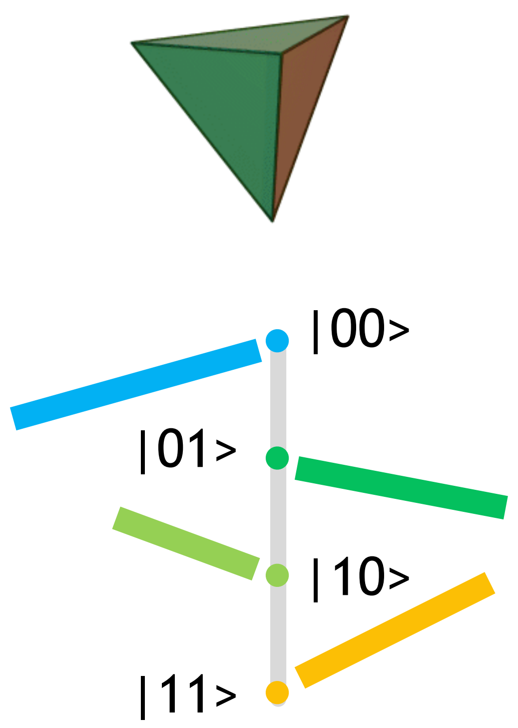
Measurement Outcomes

The probability of an outcome is the squared magnitude of its associated amplitude



$|0\rangle$

$|1\rangle$



$|00\rangle$

$|01\rangle$

$|10\rangle$

$|11\rangle$

Calculating Fibonacci Numbers

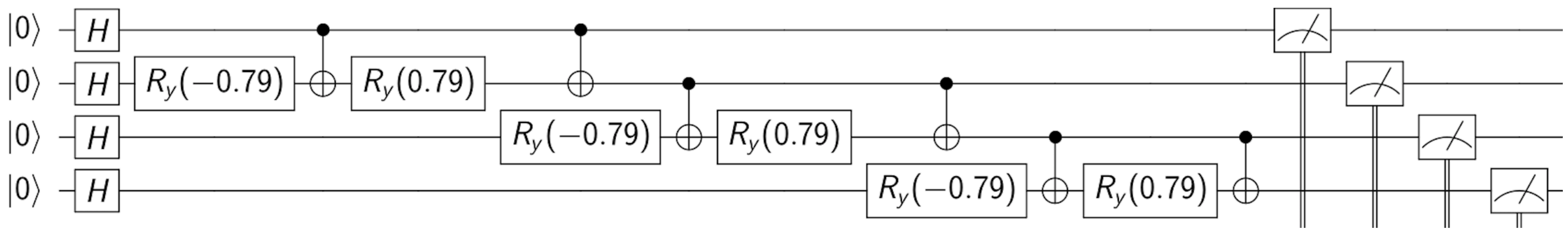
Counting binary words with no consecutive ones

```
def fib(n: Int): QState = {
  var state = pure(Word.fromInt(0, n))
  for (i <- 0 until n) state = state >>= wire(i, H)
  for (i <- 0 until n - 1)  state = state >>= controlled(i, i + 1, ZERO)
  state
}
```

```
F(1) = 2
F(2) = 3
F(3) = 5
F(4) = 8
F(5) = 13
F(6) = 21
F(7) = 34
F(8) = 55
F(9) = 89
F(10) = 144
F(11) = 233
F(12) = 377
F(13) = 610
F(14) = 987
F(15) = 1597
```

Circuit implementation:

```
for (i <- 0 until n - 1)  state = state >>= wire(i + 1, Ry(-math.Pi/4)) >>=
  controlled(i, i + 1, X) >>= wire(i + 1, Ry(math.Pi/4)) >>= controlled(i, i + 1, X)
```



Thank You

Code

https://github.com/logicalguess/quantum-scale

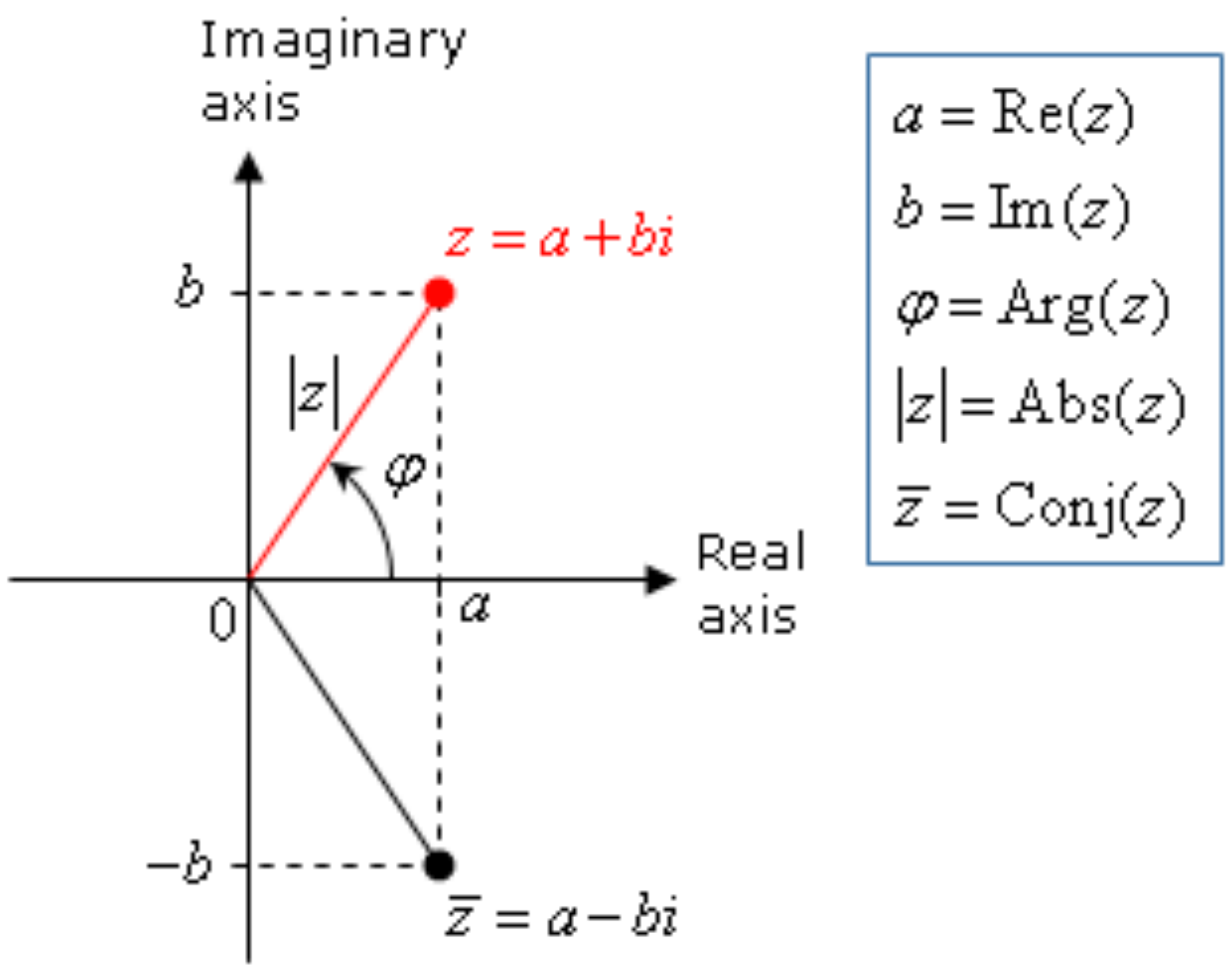
Credits

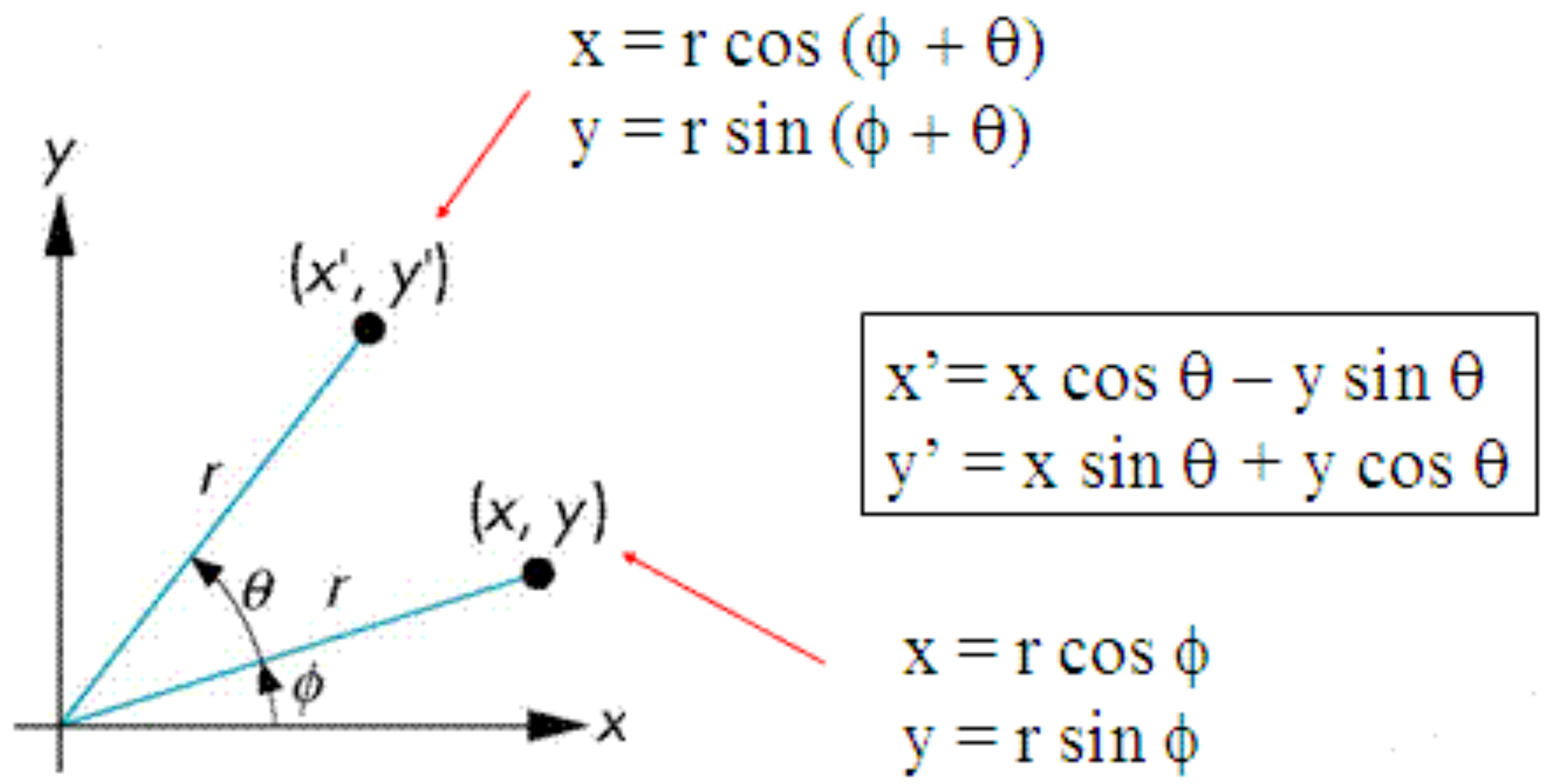
https://github.com/jliszka/quantum-probability-monad
https://sigfpe.wordpress.com/2007/03/04/monads-vector-spaces-and-quantum-mechanics-pt-ii/

Appendix

Complex Numbers

Complex numbers (2 -dimensional vectors) as values





http://www.thefouriertransform.com/math/complexmath.php

Elementary Gates

Elementary Gates

```
"X" should "swap the amplitudes of |0> and |1>" in forAll { s: QState =>
  val t: QState = X(s)

  assert(t(S0) == s(S1))
  assert(t(S1) == s(S0))
}

"Y" should "swap the amplitudes of |0> and |1>, multiply each amplitude by i, and negate the amplitude of |1>" in forAll { s: QState =>
  val t: QState = Y(s)

  assert(t(S0) == - s(S1) * Complex.i)
  assert(t(S1) == s(S0) * Complex.i)
}

"Z" should "negate the amplitude of |1>, leaving the amplitude of |0> unchanged" in forAll { s: QState =>
  val t: QState = Z(s)

  assert(t(S0) == s(S0))
  assert(t(S1) == -s(S1))
}
```

Rotations

Rotations around the Y axis

```
"Ry(theta)" should "mix the amplitudes of |0> and |1> (like vector rotation)" in
forAll { ts: (Double, QState) =>
  val theta = ts._1
  val state = ts._2

  val y: QState = Ry(theta)(state)

  // same formula as 2-dimensional vector rotation (but with half angle)
  val t0 = state(S0) * math.cos(theta/2) - state(S1) * math.sin(theta/2)
  val t1 = state(S0) * math.sin(theta/2) + state(S1) * math.cos(theta/2)

  assert(y(S0) == t0)
  assert(y(S1) == t1)
}
```

```
"Ry(pi/2)" should "equal HZ" in forAll { state:  QState =>

  val y: QState = state >>= Ry(math.Pi/2)
  val h: QState = state >>= Z >>= H

  assert(y(S0).toString == h(S0).toString)
  assert(y(S1).toString == h(S1).toString)
}
```

```
"Ry(theta)" should "be a weighted average of I and Ry(pi)" in
forAll { ts: (Double, QState) =>
  val theta = ts._1
  val state = ts._2

  val A: Gate = I * math.cos(theta / 2) + Ry(math.Pi) *
math.sin(theta / 2)

  val z: QState = Ry(theta)(state)
  val a: QState = A(state)

  assert(z(S0).toString == a(S0).toString)
  assert(z(S1).toString == a(S1).toString)
}
```