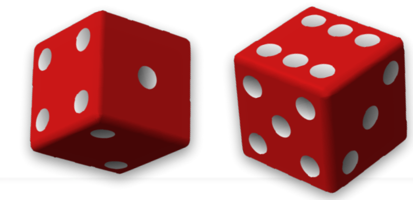
probabilistic algorithms

learning objectives

- algorithms
- your software
- system software
- hardware

- learn what randomized algorithms are
- learn what they are useful for
- learn about pseudo-randomness

determinism vs randomness



R. M. Karp. ***An introduction to randomized algorithms.*** Discrete Applied Mathematics, 34(1-3):165–201, November 1991.

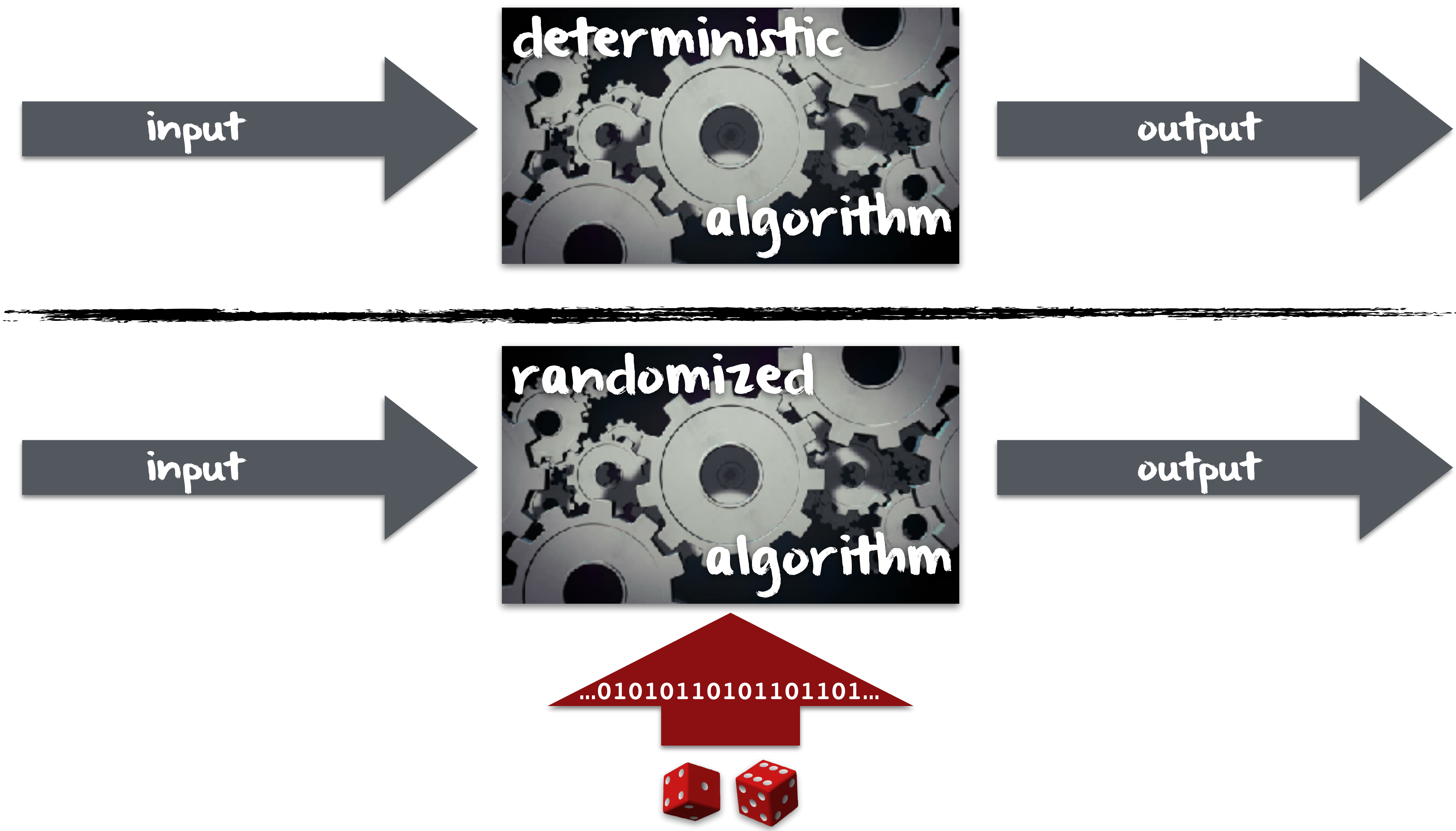
a computer is deterministic by design, so an algorithm executing on a computer is inherently deterministic

yet we can abstractly define the notion of probabilistic or randomized algorithm as follows:

a randomized algorithm is one that receives, in addition to its input data, a stream of random bits used to make random choices

so even for the same input, different executions of a randomized algorithm may give different outputs

deterministic algorithm vs randomized algorithm



why introduce randomness?

because randomized algorithms tend to be much **simpler** than their deterministic counterpart

because randomized algorithms tend to be **more efficient** than their deterministic counterpart*

*in execution time and memory space

but some randomized algorithms do **not always*** provide a **correct** answer (only probabilistically)

*always ⇔ deterministically

principles to construct randomized algorithms

abundance of witnesses

fingerprinting

random partitioning

random sampling

foiling the adversary

random ordering

Markov chains

abundance of witnesses

are these two polynomial of degree $d = 5$ identical?

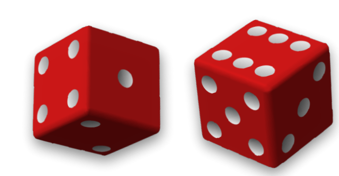
$$p(x) = (x-7)(x-3)(x-1)(x+2)(2\,x+5)$$

$$q(x) = 2\,x^5 - 13\,x^4 - 21\,x^3 + 127\,x^2 + 121\,x - 210$$

expanding $p(x)$ may take up to $O(d^2) = O(25)$ time*

*provided integer multiplication takes a unit of time

a randomized algorithm can take $O(d) = O(5)$ time



note that:

- computing $p(\dot{x})$ and $q(\dot{x})$ for a given value $\dot{x} \in \mathbb{Z}$ takes $O(d)$
- $p(\dot{x}) = q(\dot{x})$ is true if at least one of the following conditions is true
  1. we have the following polynomial equality $p(x) = q(x)$
  2. the value $\dot{x}$ is a root of polynomial $p(x) - q(x)$, i.e., if $p(\dot{x}) - q(\dot{x}) = 0$
- since $p(x) - q(x)$ is of degree $d = 5$, it has no more than 5 roots

abundance of witnesses

algorithm

- randomly choose $\dot{x}$ from a very large range of integer $R \subset \mathbb{Z}$
- compute $r = p(\dot{x}) - q(\dot{x})$
- if $r = 0$, then $p(x) = q(x)$ is true with probability $1 - \frac{d}{|R|}$

$\dot{x}$ is our potential witness that $p(x) \neq q(x)$

after n trials, the error probability is $\left(\frac{d}{|R|}\right)^n$

after $d + 1$ trial, the error probability drops to 0

this is a Monte Carlo algorithm

Monte Carlo & Las Vegas algorithms

a Monte Carlo algorithm computes in a deterministic time but only provides a correct answer probabilistically

a false-biased Monte Carlo algorithm is always correct when returning false

a true-biased Monte Carlo algorithm is always correct when returning true

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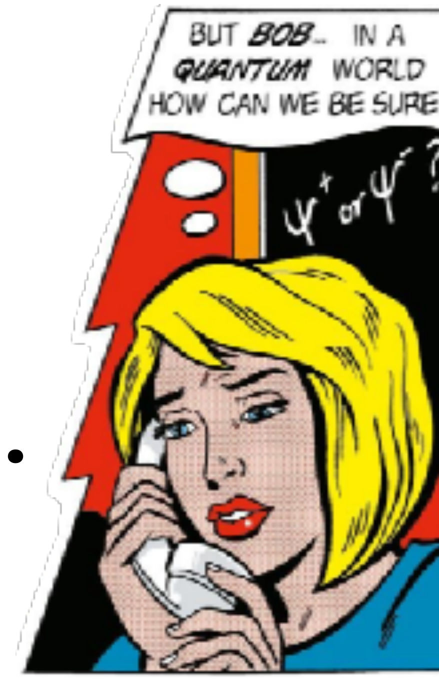
a Las Vegas algorithm computes in some random time but always* provides a correct answer

*always ⇔ deterministically

a Monte Carlo algorithm can be turned into a Las Vegas algorithm if we have a way to verify that the output is correct

fingerprinting

bob has x, a very long string of bits



...10100111000100101110101001010010100101...

they want to **check if** $x = y$ but their channel has limited bandwidth

alice has y, a very long string of bits

fingerprinting consist in computing **much shorter strings** of bits from x and y, so-called **fingerprints**, to then exchange them

a typical fingerprinting function is $h_p(s) = h(s) \; mod \; p$, where $h(s)$ is the integer corresponding to the string of bits s and p is a **prime number**

$h_p(s)$ is called a (high performance) **hash function**

algorithm

- bob randomly chooses a prime number p less than M
- bob sends p and $h_p(x)$ to alice
- alice checks whether $h_p(x) = h_p(y)$ and sends the results to bob

foiling the adversary via random ordering

we can see the execution of an algorithm as a zero-sum two-person game

the payoff is the execution time

chooses the input

long is good

short is good

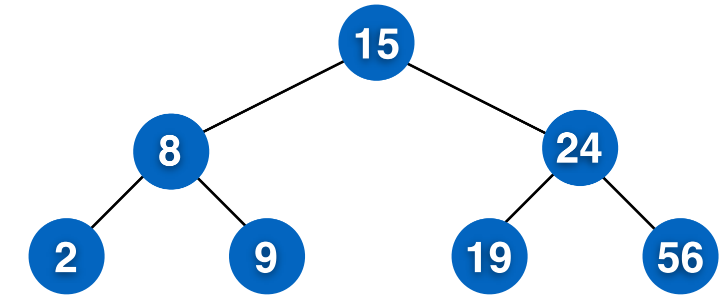
chooses the algorithm

a randomized algorithm can be seen as a probabilistic distribution over deterministic algorithms, i.e., as mixed strategy for the algorithm player

faced with a mixed strategy, the input player does not know what the algorithm player will do with the input

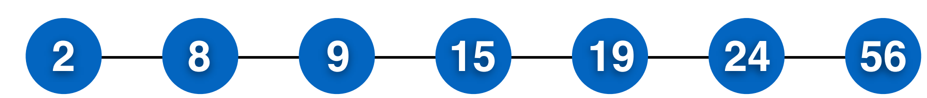
this uncertainty makes it difficult for the input player to choose an input that will slow down the execution time

foiling the adversary via random ordering



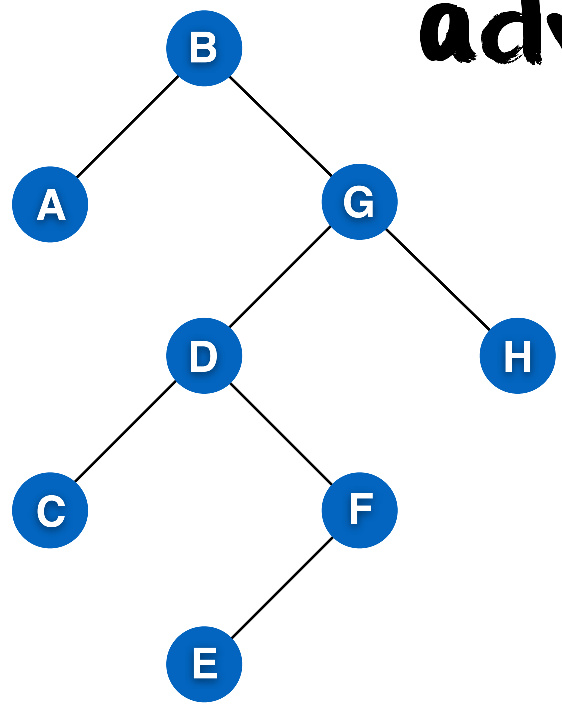
the performance of a binary search tree depends on its structure, which in turn depends on the order in which its elements were inserted

we cannot assume insertion are made in random order, so we can end up with a binary search tree with catastrophic performance

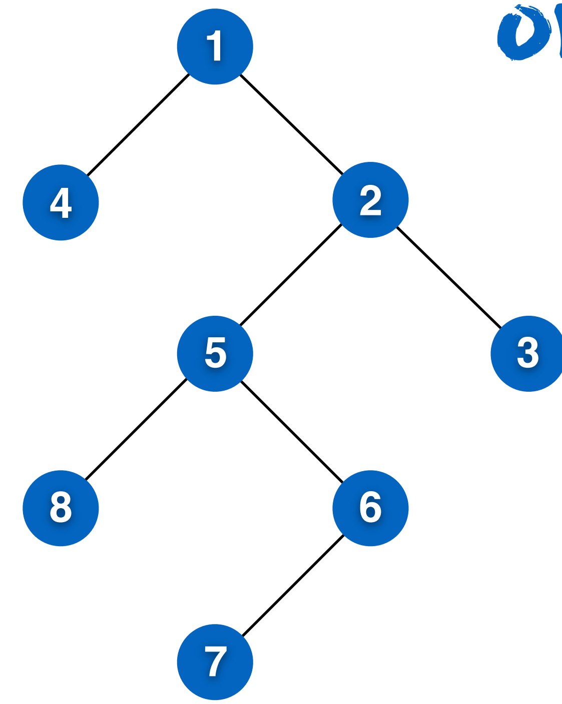


how can we get a binary search tree that looks like one resulting from insertions in random order whatever the execution?

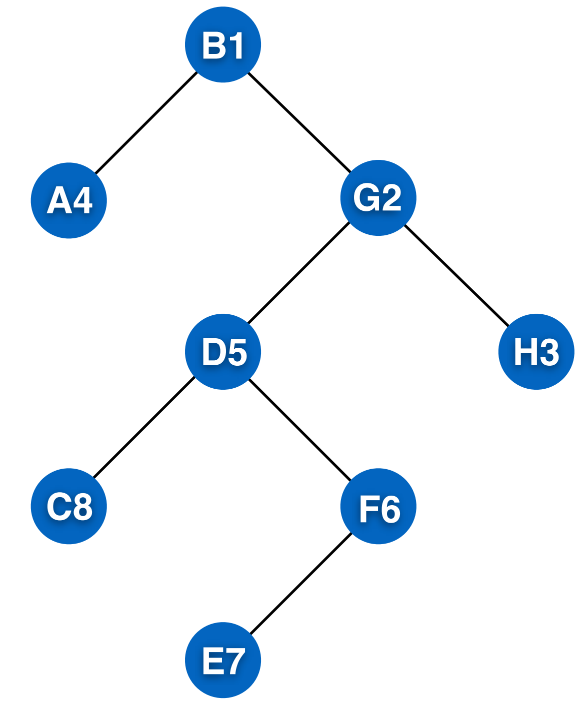
foiling the adversary via random ordering



binary search tree +



heap =



treap

a **heap** is a binary tree where the vertices on any path from the root to a leaf increase in value

a **treap** is a binary tree where each vertex v has two values, $v.key$ and $v.priority$ and which is a binary search tree with respect to key values and a heap with respect to $priority$ values

foiling the adversary via random ordering

given n items with associated keys and priorities, there exists a unique treap containing these n items

this unique treap has the same structure as a binary search tree where these n items would have been inserted in increasing order of priorities

algorithm for inserting key k

- draw a random priority p
- create new vertex v with $v.key = k$ and $v.priority = p$
- insert v in the treap

the random priority acts as a randomized timestamp

at any given time, we have a binary search tree obtained by random insertion

Markov chains

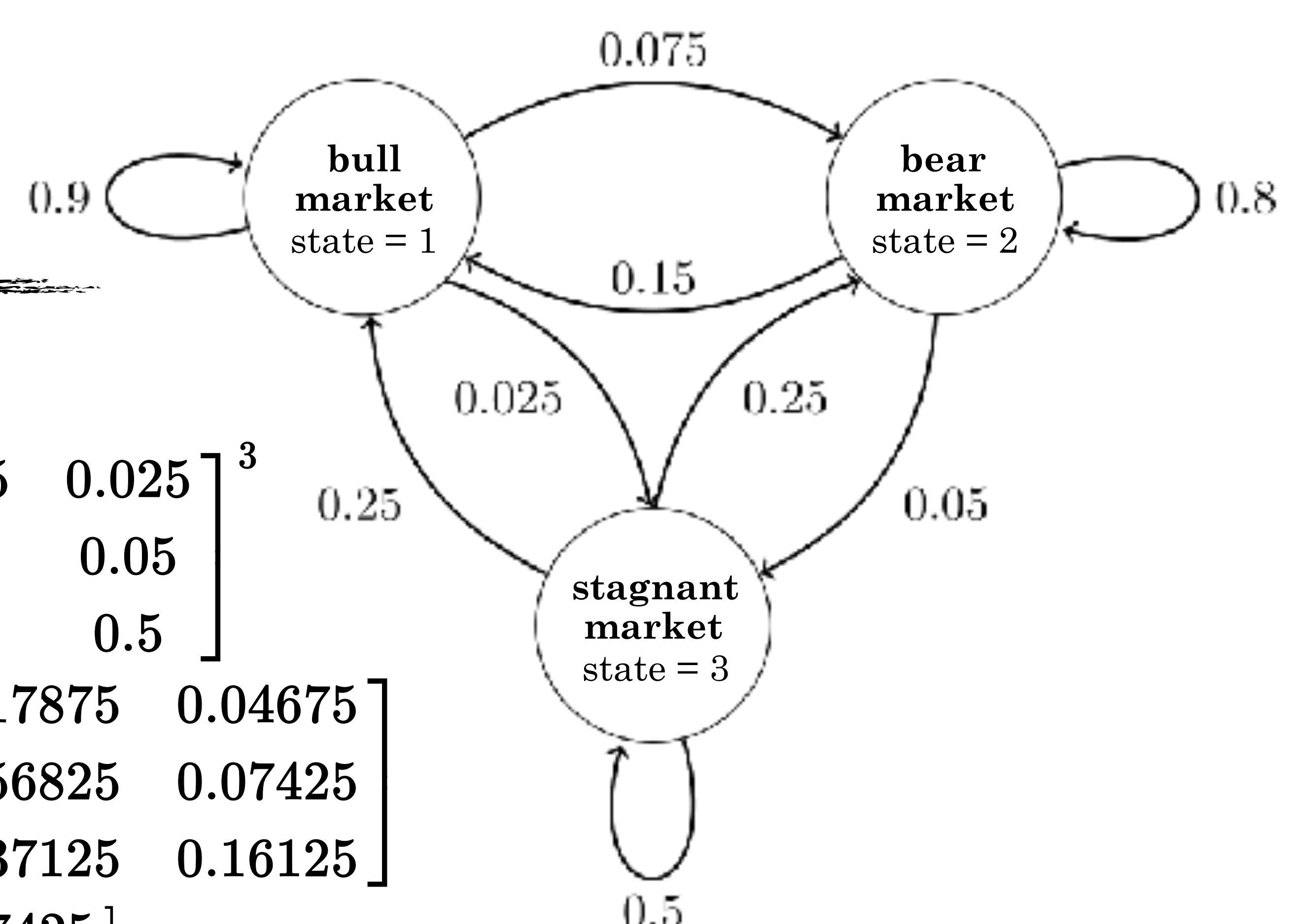
a Markov chain is a **stochastic* process** satisfying the **Markov property**, which states that the next state of the process only depends on its present state

*stochastic ⇔ probabilistic ⇔ non-deterministic

$$\Pr(X_{n+1} = x \mid X_1 = x_1, X_2 = x_2, \ldots, X_n = x_n) = \Pr(X_{n+1} = x \mid X_n = x_n)$$

transition matrix

$$\begin{bmatrix} 0.9 & 0.075 & 0.025 \\ 0.15 & 0.8 & 0.05 \\ 0.25 & 0.25 & 0.5 \end{bmatrix}$$



assume that at time t, $state = 2$ then at time $t+3$, we will have:

$$x^{(t+3)} = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0.9 & 0.075 & 0.025 \\ 0.15 & 0.8 & 0.05 \\ 0.25 & 0.25 & 0.5 \end{bmatrix}^3$$

$$= \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0.7745 & 0.17875 & 0.04675 \\ 0.3575 & 0.56825 & 0.07425 \\ 0.4675 & 0.37125 & 0.16125 \end{bmatrix}$$

$$= \begin{bmatrix} 0.3575 & 0.56825 & 0.07425 \end{bmatrix}.$$

how to generate randomness in a deterministic machine?

do computers have a real source of random bits?

true random number generator

augment computers with a intrinsically non-deterministic physical source

nuclear decay radiation, thermal noise from a resistor, etc...

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pseudo random number generator

a parameterized set of function $g = \{g_n\}$ such that each function $g_n : \langle 0,1 \rangle^n \rightarrow \langle 0,1 \rangle^{t(n)}$ takes a seed string of n bits and stretches to a longer string of length $t(n)$

not polynomial-time test can distinguish the output of g_n from a true random sequence of bits

how to generate randomness in a deterministic machine?

pseudo random number generator

```python
import random

random.seed(666)
f = random.random()
i = random.randint(2,9)
```

$0.0 \le f < 1.0$

$2 \le i \le 9$

```scala
import scala.util.Random

val rand = Random
random.setSeed(666)
val f = rand.nextFloat
val i = random.nextInt(9)
```

$0.0 \le f < 1.0$

$0 \le i < 9$

```swift
import Foundation

let i = arc4random()
let j = arc4random_uniform(9)
```

$0 \le i \le 2^{32} - 1$

$0 \le j < 9$