Markov Chains

ECE 341: Random Processes

Lecture #20

note: All lecture notes, homework sets, and solutions are posted on www.BisonAcademy.com

A and B play a match

Problem 1: Two teams, A and B, are playing a match

- A has a 70% chance of winning any given game
- The first team to win 3 games wins the match.

This is a binomial distribution

Problem 2: Two teams, A and B, are playing a match

- A has a 70% chance of winning any given game
- The first team to win **by** 3 games wins the match.

This is a *totally* different problem.

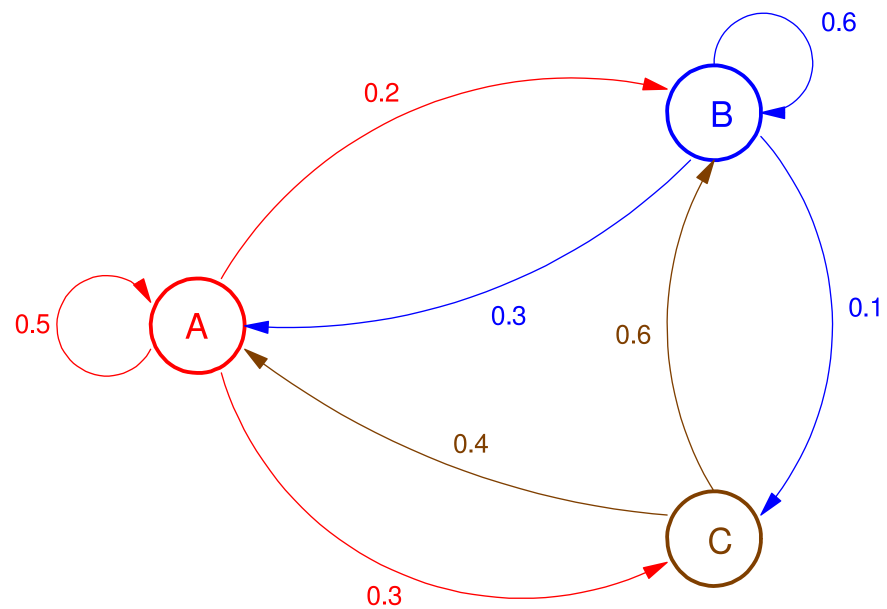
Problem #2 is an infinite sequence

- To solve, we need a different tool: Markov chains.

Markov Chain

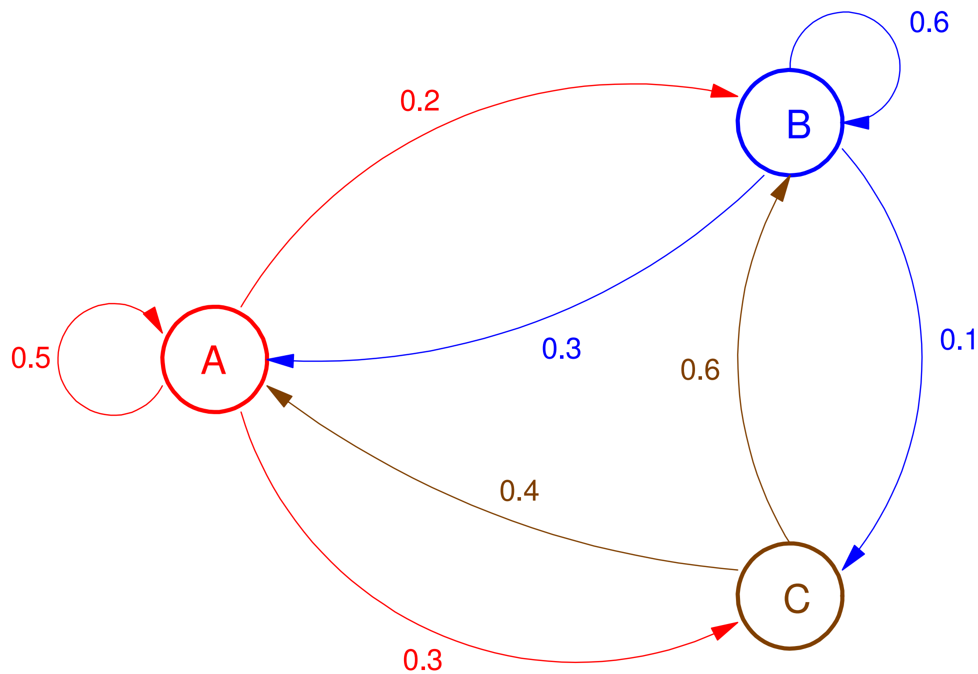
A Markov chain is a discrete-time probability function where

- X(k) is the state of the system at time k, and
- X(k+1) = A X(k)



Three people, A, B, and C, are playing ball. Every second they pass the ball at random:

- When A has the ball, he/she
  - Keeps the ball 50% of the time
  - Passes it to B 20% of the time, and
  - Passes it to C 30% of the time
- When B has the ball, he/she
  - Passes it to A 30% of the time
  - Keeps it 60% of the time, and
  - Passes it to C 10% of the time
- When C has the ball, he/she
  - Passes it to A 40% of the time, and
  - Passes it to B 60% of the time.



Assume at t=0, A has the ball.

- What is the probability that B will have the ball after k tosses?
- After infinite tosses?

This lecture covers three different methods to analyze problems of this sort:

- Matrix multiplication
- Eigenvalues and Eigenvectors, and
- z-Transforms.

Solution #1: Matrix Multiplication

Let X(k) be the probability that A, B, and C have the ball at time k:

$$x(k) = \begin{bmatrix} p(a) \\ p(b) \\ p(c) \end{bmatrix}$$

Then from the problem statement, X(k+1) is related to X(k) by a state-transition matrix:

$$x(k+1) = \begin{bmatrix} 0.5 & 0.3 & 0.4 \\ 0.2 & 0.6 & 0.6 \\ 0.3 & 0.1 & 0 \end{bmatrix} x(k) = A\, x(k) \qquad x(0) = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

Note that

- The columns are the probabilities in the above problem statement, and
- The columns must add up to 1.000 (all probabilities add to one)

The probability of each player having the ball after 1, 2, 3 tosses is (using Matlab)

```
A = [0.5,0.2,0.3 ; 0.3,0.6,0.1 ; 0.4,0.6,0]'

    0.5000    0.3000    0.4000
    0.2000    0.6000    0.6000
    0.3000    0.1000         0

X = [1;0;0]      % k = 0

    1.0000
    0.0000
    0.0000

X = A*X          % k = 1

    0.5000
    0.2000
    0.3000

X = A*X          % k = 2

    0.4300
    0.4000
    0.1700
```

```
X = A*X          % k = 3

     0.4030
     0.4280
     0.1690
```

time passes

```
X = A*X          % k = 100

     0.3953
     0.4419
     0.1628
```

Eventually X quits changing. This is the steady-state solution.

Steady-State Solution:

If you want to find the steady-state solution, you can simply raise A to a large number (like 100) and solve in one shot:

```
X0 = [1;0;0]

     1
     0
     0

X20 = A^100 * X0

    0.3953
    0.4419
    0.1628
```

You can also solve for the steady-state solution by finding x(k) such that

$$x(k+1) = x(k) = A\ x(k)$$

Solving:

$$(A - I)x(k) = 0$$

$$\left(\begin{bmatrix} 0.5 & 0.3 & 0.4 \\ 0.2 & 0.6 & 0.6 \\ 0.3 & 0.1 & 0 \end{bmatrix} - \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \right) \begin{bmatrix} a \\ b \\ c \end{bmatrix} = 0$$

$$\begin{bmatrix} -0.5 & 0.3 & 0.4 \\ 0.2 & -0.4 & 0.6 \\ 0.3 & 0.1 & -1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = 0$$

Assume c = 1

$$\begin{bmatrix} -0.5 & 0.3 \\ 0.2 & -0.4 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = -\begin{bmatrix} 0.4 \\ 0.6 \end{bmatrix}$$

```
ab = -inv([-0.5,0.3;0.2,-0.4])*[0.4;0.6]

    2.4286
    2.7143


X = [ab;1]                    X = X / sum(X)

    2.4286                    0.3953
    2.7143                    0.4419
    1.0000                    0.1268
```

which is the same answer we got before.

Solution #2: Eigenvalues and Eigenvectors

The problem we're trying to solve is

$$x(k+1) = A\ x(k) \qquad\qquad x(0) = X_0$$

This is actually an eigenvalue / eigenvector problem.

- Eigenvalues tell you how the system behaves,
- Eigenvectors tell you what behaves that way.

Since this system has three states, the generalized solution for x(k) will be:

$$x(k) = a_1 \Lambda_1 \lambda_1^k + a_2 \Lambda_2 \lambda_2^k + a_3 \Lambda_3 \lambda_3^k$$

where

- λ_i is the ith eigenvalue,
- Λ_i is the ith eigenvector, and
- a_i is a constant depending upon the initial condition.

At k = 0:

$$x(0) = \begin{bmatrix} \Lambda_1 & \Lambda_2 & \Lambda_3 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

The excitation of each eigenvector is then

```
X0 = [1;0;0]

     1
     0
     0

A123 = inv(M)*X0

    0.6149
    0.5482
    0.9354
```

meaning

$$x(k) = 0.6149\begin{bmatrix} 0.6430 \\ 0.7186 \\ 0.2468 \end{bmatrix}(1)^k + 0.5482\begin{bmatrix} 0.2222 \\ 0.5693 \\ -0.7915 \end{bmatrix}(-0.1562)^k + 0.9543\begin{bmatrix} 0.5151 \\ -0.8060 \\ 0.2989 \end{bmatrix}(0.2562)^k$$

or adding the scalars to the eigenvectors:

```
W = inv(M)*X0

    0.6149
    0.5482
    0.9354

M * diag(W)

    0.3953    0.1218    0.4828
    0.4419    0.3121   -0.7539
    0.1628   -0.4339    0.2711
```

$$x(k) = \begin{bmatrix} 0.3953 \\ 0.4419 \\ 0.1628 \end{bmatrix}(1)^k + \begin{bmatrix} 0.1218 \\ 0.3121 \\ -0.4339 \end{bmatrix}(-0.1562)^k + \begin{bmatrix} 0.4828 \\ -0.7539 \\ 0.2711 \end{bmatrix}(0.2562)^k$$

As k goes to infinity, the first eigenvector is all that remains.

Steady-State Solution using Eigenvectors

Note that the steady-state solution is simply the eigenvector associated with the eigenvalue of 1.000.

```
[M,V] = eig(A)

M =      eigenvectors

    0.6430    0.2222    0.5161
    0.7186    0.5693   -0.8060
    0.2648   -0.7915    0.2898


V =       eigenvelues

    1.0000         0         0
         0   -0.1562         0
         0         0    0.2562
```

Scale so the total is 1.0000

```
X = M(:,1);
X = X / sum(X)

    0.3953
    0.4419
    0.1628
```

Same answer as before.

Solution #3: z-Transforms

Again, the problem we are trying to solve is

$$x(k+1) = \begin{bmatrix} 0.5 & 0.3 & 0.4 \\ 0.2 & 0.6 & 0.6 \\ 0.3 & 0.1 & 0 \end{bmatrix} x(k) \qquad x(0) = X_0 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

This can be written as

$$x(k) = A\ x(k-1) + X_0\ \delta(k)$$

$$x(k+1) = A\ x(k) + X_0\ \delta(k+1)$$

Take the z-transform

$$zX = AX + zX_0$$

To determine the probability that B has the ball at time k, look at the second state

$$Y = CX = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} X$$

Solving for Y then gives the z-transform for b(k)

$$zX = AX + zX_0$$

$$(zI - A)X = zX_0$$

$$X = z(zI - A)^{-1} X_0$$

$$Y = CX = z\, C(zI - A)^{-1} X_0$$

$$Y = z\, C(zI - A)^{-1} X_0$$

For our 3x3 example,

$$Y(z) = z\begin{bmatrix} 0 & 1 & 0 \end{bmatrix}\left(\begin{bmatrix} z & 0 & 0 \\ 0 & z & 0 \\ 0 & 0 & z \end{bmatrix} - \begin{bmatrix} 0.5 & 0.3 & 0.4 \\ 0.2 & 0.6 & 0.6 \\ 0.3 & 0.1 & 0 \end{bmatrix}\right)^{-1}\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

C A B = X0

This is somewhat painful to compute by hand. Fortunately, there's Matlab to the rescue.

- G = ss(A, B, C, D, T) *input a dynamic system into matlab*
- Y = tf(G) *calculate and express the z-transform of Y in transfer function form*
- Y = zpk(G) *calculate and express the z-transform of Y in factored form*

In matlab:

```
A = [0.5,0.3,0.4;0.2,0.6,0.6;0.3,0.1,0]

    0.5000    0.3000    0.4000
    0.2000    0.6000    0.6000
    0.3000    0.1000         0

X0 = [1;0;0]

     1
     0
     0

C = [0,1,0]

     0     1     0

Bz = ss(A, X0, C, 0, 1);
```

```
tf(Bz)

       0.2 z + 0.18
-----------------------------
z^3 - 1.1 z^2 + 0.06 z + 0.04

Sampling time (seconds): 1

zpk(Bz)


        0.2 (z+0.9)
---------------------------
(z-1) (z-0.2562) (z+0.1562)

Sampling time (seconds): 1
```

(recall that you need to multuply by z)

Finding b(k):

$$B(z) = \left(\frac{0.2(z+0.9)z}{(z-1)(z-0.2562)(z-0.1562)} \right)$$

factor out a z and use partial fractions:

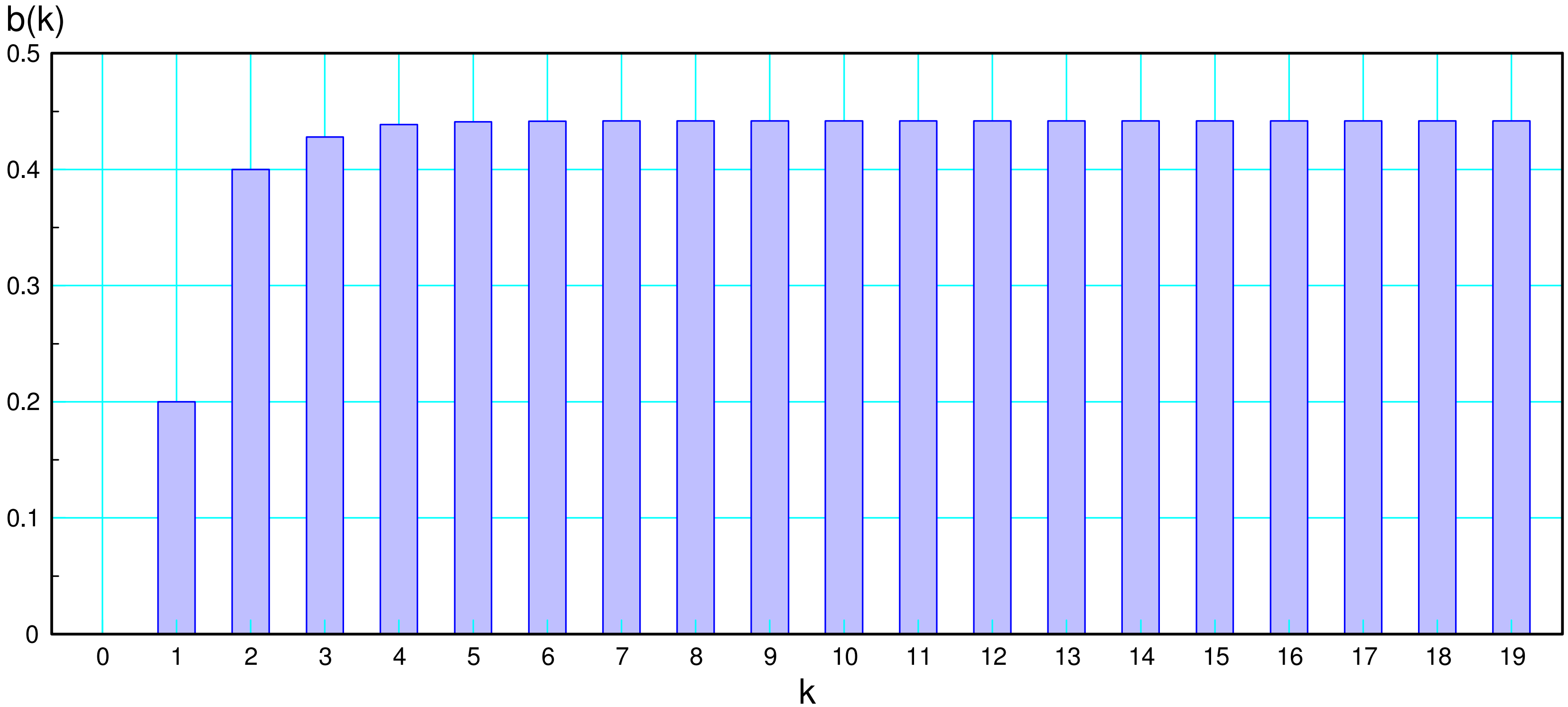
$$B(z) = \left(\left(\frac{0.6054}{z-1} \right) + \left(\frac{-3.1089}{z-0.2562} \right) + \left(\frac{2.5034}{z-0.1562} \right) \right) z$$

multiply by z

$$B = \left(\frac{0.6054z}{z-1} \right) + \left(\frac{-3.1089z}{z-0.2562} \right) + \left(\frac{2.5034z}{z-0.1562} \right)$$

Take the inverse z-transform

$$b(k) = \left(0.6054 - 3.1089(0.2562)^k + 2.5034(0.1562)^k \right) u(k)$$



Probability that player B has the ball after toss k

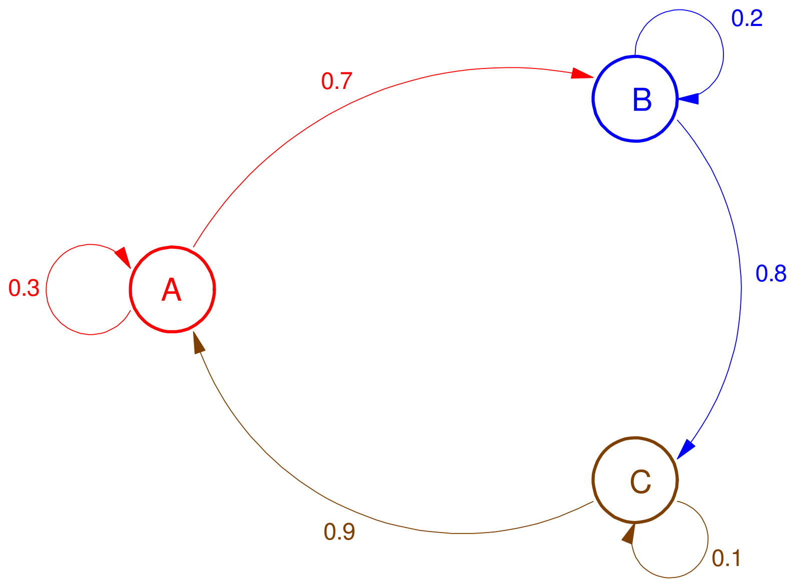
z-Transform with Complex Poles

You can get complex poles. If you do, use entry in the z-transform table:

$$\left(\frac{(a\angle\theta)z}{z-b\angle\phi}\right) + \left(\frac{(a\angle-\theta)z}{z-b\angle-\phi}\right) \rightarrow 2a\,b^k\ \cos\left(\phi k - \theta\right)\,u(k)$$

For example, suppose player A, B, and C toss the ball as:

- A keeps the ball 30% of the time and passes it to B 70% of the time
- B keeps the ball 20% of the time and passes it to C 80% of the time, and
- C keeps the ball 10% of the time and passes it to A 90% of the time



Suppose A starts with the ball at k = 0. Determine the probability that B has the ball after k tosses.

Solving using z-transforms: express in matrix form

$$zX = \begin{bmatrix} 0.3 & 0 & 0.9 \\ 0.7 & 0.2 & 0 \\ 0 & 0.8 & 0.1 \end{bmatrix} X \quad X(0) = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$Y = p(B) = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} X$$

Find B(z) using Matlab

```
A = [0.3,0,0.9;0.7,0.2,0;0,0.8,0.1]

    0.3000         0    0.9000
    0.7000    0.2000         0
         0    0.8000    0.1000

X0 = [1;0;0];
C = [0,1,0];
Bz = ss(A,X0,C,0,1);
zpk(Bz)

       0.7 (z-0.1)
-------------------------
(z-1) (z^2 + 0.4z + 0.51)


Sampling time (seconds): 1

(again - multiply by z to get B(z))
```

$$B(z) = \left(\frac{0.7(z-0.1)z}{(z-1)(z-0.7142\angle 106^0)(z-0.7142\angle -106^0)}\right)$$

Pull out a z and expand using partial fractions

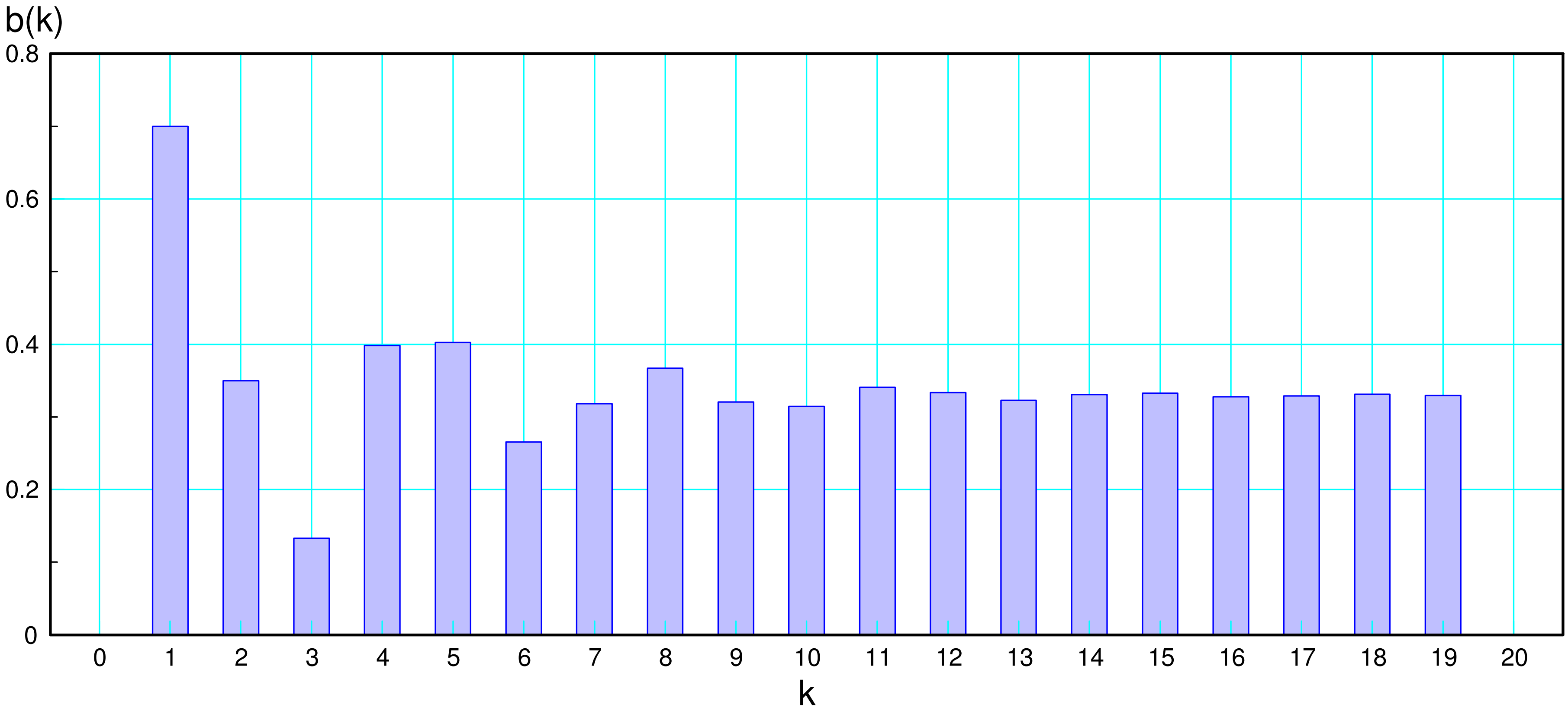
$$B(z) = \left(\left(\frac{0.3298}{(z-1)}\right) + \left(\frac{0.2764\angle -126.8^0}{(z-0.7142\angle 106^0)}\right) + \left(\frac{0.2764\angle 126.8^0}{(z-0.7142\angle -106^0)}\right)\right)z$$

Multiply both sides by z

$$B = \left(\frac{0.3298z}{(z-1)}\right) + \left(\frac{z0.2764\angle -126.8^0}{(z-0.7142\angle 106^0)}\right) + \left(\frac{z0.2764\angle 126.8^0}{(z-0.7142\angle -106^0)}\right)$$

Take the inverse z-transform

$$z\, b(k) = \left(0.3298 + 0.5527(0.7142)^k \cos\left(k \cdot 106^0 + 126.8^0\right)\right)u(k)$$



probability that player B has the ball after k tosses