CS70: Jean Walrand: Lecture 25.

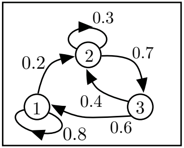
Markov Chains: Distributions

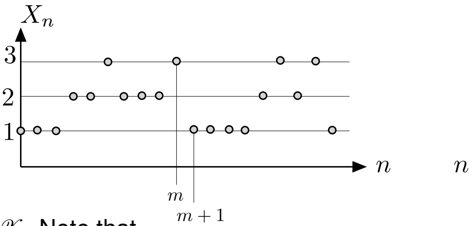
1. Review
2. Distribution
3. Irreducibility
4. Convergence

Review

- Markov Chain:
  - Finite set $\mathscr{X}$; π_0; $P = \{P(i,j), i,j \in \mathscr{X}\}$;
  - $Pr[X_0 = i] = \pi_0(i), i \in \mathscr{X}$
  - $Pr[X_{n+1} = j \mid X_0, \ldots, X_n = i] = P(i,j), i,j \in \mathscr{X}, n \geq 0$.
  - Note:
    $Pr[X_0 = i_0, X_1 = i_1, \ldots, X_n = i_n] = \pi_0(i_0)P(i_0,i_1) \cdots P(i_{n-1},i_n)$.
- First Passage Time:
  - $A \cap B = \emptyset; \beta(i) = E[T_A|X_0 = i]; \alpha(i) = P[T_A < T_B|X_0 = i]$
  - $\beta(i) = 1 + \sum_j P(i,j)\beta(j); \alpha(i) = \sum_j P(i,j)\alpha(j)$.

Distribution of X_n





Let $\pi_m(i) = Pr[X_m = i], i \in \mathscr{X}$. Note that

$$\begin{aligned} Pr[X_{m+1} = j] &= \sum_i Pr[X_{m+1} = j, X_m = i] \\ &= \sum_i Pr[X_m = i] Pr[X_{m+1} = j \mid X_m = i] \\ &= \sum_i \pi_m(i) P(i,j). \end{aligned}$$

Hence,

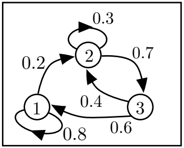
$$\pi_{m+1}(j) = \sum_i \pi_m(i) P(i,j), \forall j \in \mathscr{X}.$$

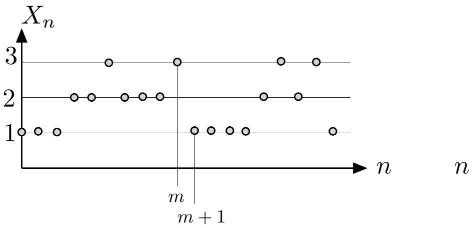
With π_m, π_{m+1} as a row vectors, these identities are written as $\pi_{m+1} = \pi_m P$.

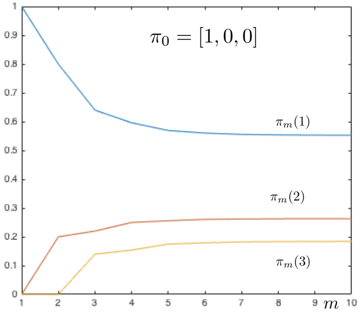
Thus, $\pi_1 = \pi_0 P$, $\pi_2 = \pi_1 P = \pi_0 PP = \pi_0 P^2, \ldots$. Hence,

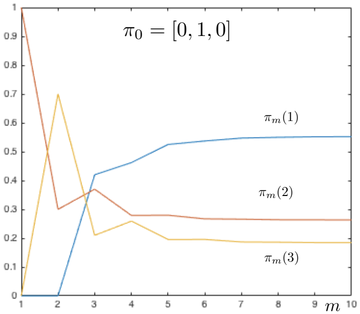
$$\pi_n = \pi_0 P^n, n \geq 0.$$

Distribution of X_n



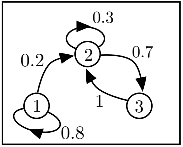


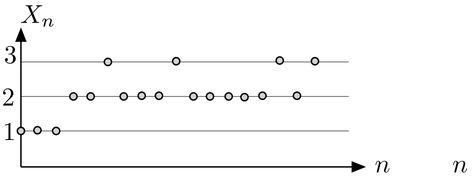


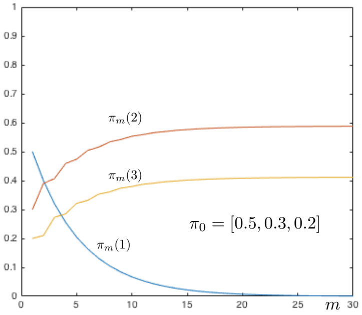


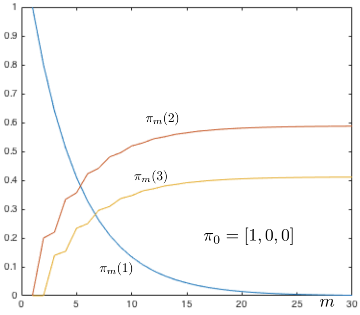
As m increases, π_m converges to a vector that does not depend on π_0.

Distribution of X_n









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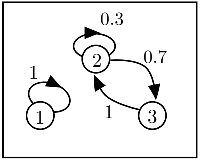
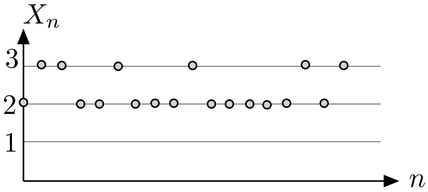
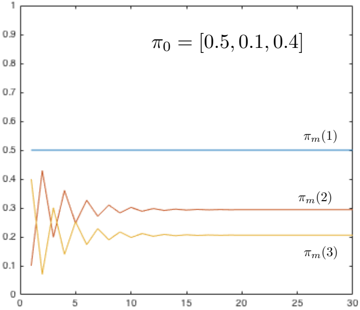
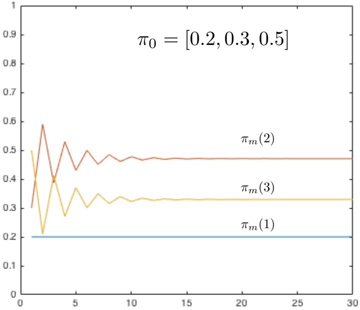
Distribution of X_n









As m increases, π_m converges to a vector that depends on π_0 (obviously, since $\pi_m(1) = \pi_0(1), \forall m$).

Balance Equations

Question: Is there some π_0 such that $\pi_m = \pi_0, \forall m$?

Definition A distribution π_0 such that $\pi_m = \pi_0, \forall m$ is said to be an invariant distribution.

Theorem A distribution π_0 is invariant iff $\pi_0 P = \pi_0$. These equations are called the balance equations.

Proof: $\pi_n = \pi_0 P^n$, so that $\pi_n = \pi_0, \forall n$ iff $\pi_0 P = \pi_0$. □

Thus, if π_0 is invariant, the distribution of X_n is always the same as that of X_0.

Of course, this does not mean that X_n does not move. It means that the probability that it leaves a state i is equal to the probability that it enters state i.

The balance equations say that $\sum_j \pi(j)P(j,i) = \pi(i)$.
That is,

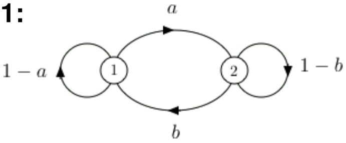
$$\sum_{j \neq i} \pi(j)P(j,i) = \pi(i)(1 - P(i,i)) = \pi(i)\sum_{j \neq i} P(i,j).$$

Thus, $Pr[\text{enter } i] = Pr[\text{leave } i]$.

Balance Equations

Theorem A distribution π_0 is invariant iff $\pi_0 P = \pi_0$. These equations are called the balance equations.

Example 1:



$$P = \begin{bmatrix} 1-a & a \\ b & 1-b \end{bmatrix}$$

$$\pi P = \pi \quad \Leftrightarrow \quad [\pi(1), \pi(2)] \begin{bmatrix} 1-a & a \\ b & 1-b \end{bmatrix} = [\pi(1), \pi(2)]$$

$$\Leftrightarrow \quad \pi(1)(1-a) + \pi(2)b = \pi(1) \text{ and } \pi(1)a + \pi(2)(1-b) = \pi(2)$$

$$\Leftrightarrow \quad \pi(1)a = \pi(2)b.$$

These equations are redundant! We have to add an equation: $\pi(1) + \pi(2) = 1$. Then we find

$$\pi = [\frac{b}{a+b}, \frac{a}{a+b}].$$

Balance Equations

Theorem A distribution π_0 is invariant iff $\pi_0 P = \pi_0$. These equations are called the balance equations.

Example 2:

$$P = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

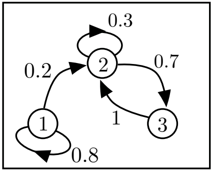
$$\pi P = \pi \Leftrightarrow [\pi(1), \pi(2)] \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = [\pi(1), \pi(2)] \Leftrightarrow \pi(1) = \pi(1) \text{ and } \pi(2) = \pi(2).$$

Every distribution is invariant for this Markov chain. This is obvious, since $X_n = X_0$ for all n. Hence, $Pr[X_n = i] = Pr[X_0 = i], \forall (i, n)$.

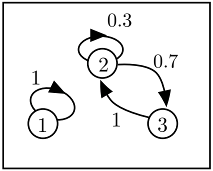
Irreducibility

Definition A Markov chain is irreducible if it can go from every state *i* to every state *j* (possibly in multiple steps).

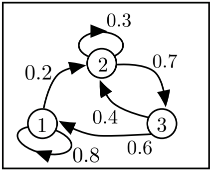
Examples:



[A]



[B]



[C]

[A] is not irreducible. It cannot go from (2) to (1).

[B] is not irreducible. It cannot go from (2) to (1).

[C] is irreducible. It can go from every *i* to every *j*.

If you consider the graph with arrows when $P(i,j) > 0$, irreducible means that there is a single connected component.

Existence and uniqueness of Invariant Distribution

Theorem A finite irreducible Markov chain has one and only one invariant distribution.

That is, there is a unique positive vector $\pi = [\pi(1), \ldots, \pi(K)]$ such that $\pi P = \pi$ and $\sum_k \pi(k) = 1$.

Proof: See EE126, or lecture note 24. (We will not expect you to understand this proof.)
Note: We know already that some irreducible Markov chains have multiple invariant distributions.

Fact: If a Markov chain has two different invariant distributions π and ν, then it has infinitely many invariant distributions. Indeed, $p\pi + (1-p)\nu$ is then invariant since

$$[p\pi + (1-p)\nu]P = p\pi P + (1-p)\nu P = p\pi + (1-p)\nu.$$

Long Term Fraction of Time in States

Theorem Let X_n be an irreducible Markov chain with invariant distribution π.

Then, for all i,

$$\frac{1}{n}\sum_{m=0}^{n-1} 1\{X_m = i\} \to \pi(i), \text{ as } n \to \infty.$$

The left-hand side is the fraction of time that $X_m = i$ during steps $0, 1, \ldots, n-1$. Thus, this fraction of time approaches $\pi(i)$.

Proof: See EE126. Lecture note 24 gives a plausibility argument.

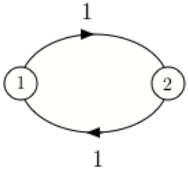
□

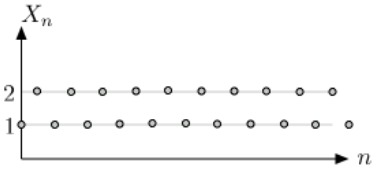
Long Term Fraction of Time in States

Theorem Let X_n be an irreducible Markov chain with invariant distribution π. Then, for all i, $\frac{1}{n}\sum_{m=0}^{n-1} 1\{X_m = i\} \to \pi(i)$, as $n \to \infty$.

Example 1:

$$P = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \qquad \pi P = \pi \Rightarrow \pi = [1/2, 1/2]$$





The fraction of time in state 1 converges to $1/2$, which is $\pi(1)$.

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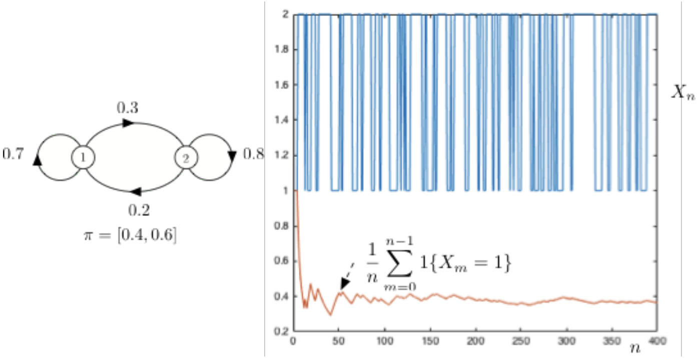
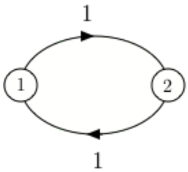


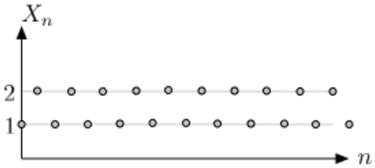
Convergence to Invariant Distribution

Question: Assume that the MC is irreducible. Does π_n approach the unique invariant distribution π?

Answer: Not necessarily. Here is an example:

$$P = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \qquad \pi P = \pi \Rightarrow \pi = [1/2, 1/2]$$





Assume $X_0 = 1$. Then $X_1 = 2, X_2 = 1, X_3 = 2, \ldots$.

Thus, if $\pi_0 = [1, 0]$, $\pi_1 = [0, 1], \pi_2 = [1, 0], \pi_3 = [0, 1]$, etc.

Hence, π_n does not converge to $\pi = [1/2, 1/2]$.

Periodicity

Theorem Assume that the MC is irreducible. Then

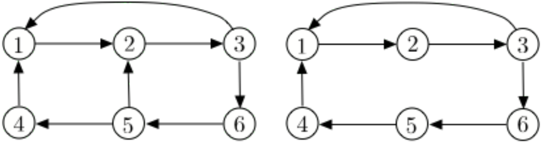
$$d(i) := \text{g.c.d.}\{n > 0 \mid Pr[X_n = i \mid X_0 = i] > 0\}$$

has the same value for all states i.

Proof: See Lecture notes 24. □

Definition If $d(i) = 1$, the Markov chain is said to be aperiodic. Otherwise, it is periodic with period $d(i)$.

Example



[A] [B]

[A]: $\{n > 0 \mid Pr[X_n = 1 | X_0 = 1] > 0\} = \{3, 6, 7, 9, 11, \ldots\} \Rightarrow d(1) = 1.$

$\{n > 0 \mid Pr[X_n = 2 | X_0 = 2] > 0\} = \{3, 4, \ldots\} \Rightarrow d(2) = 1.$

[B]: $\{n > 0 \mid Pr[X_n = 1 | X_0 = 1] > 0\} = \{3, 6, 9, \ldots\} \Rightarrow d(i) = 3.$

$\{n > 0 \mid Pr[X_n = 5 | X_0 = 5] > 0\} = \{6, 9, \ldots\} \Rightarrow d(5) = 3.$

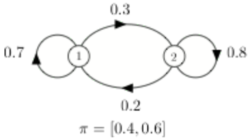
Convergence of π_n

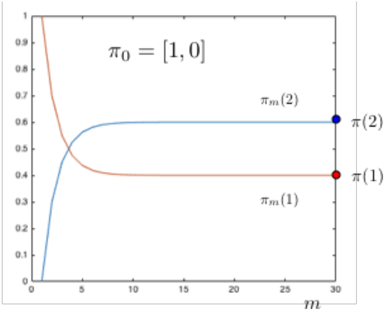
Theorem Let X_n be an irreducible and aperiodic Markov chain with invariant distribution π. Then, for all $i \in \mathscr{X}$,

$$\pi_n(i) \to \pi(i), \text{ as } n \to \infty.$$

Proof See EE126, or Lecture notes 24. □

Example





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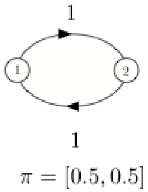

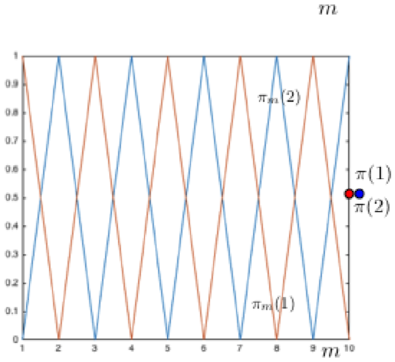

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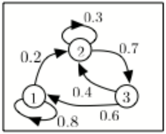
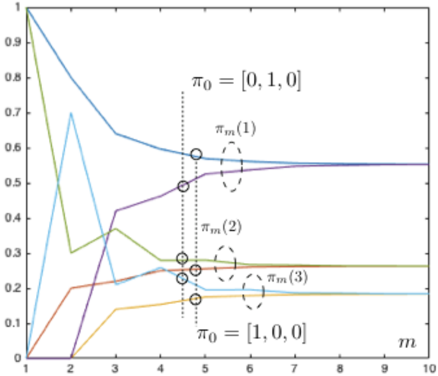
Example





Calculating π

Let P be irreducible. How do we find π?

Example: $P = \begin{bmatrix} 0.8 & 0.2 & 0 \\ 0 & 0.3 & 0.7 \\ 0.6 & 0.4 & 0 \end{bmatrix}$.

One has $\pi P = \pi$, i.e., $\pi[P - I] = \mathbf{0}$ where I is the identity matrix:

$$\pi \begin{bmatrix} 0.8-1 & 0.2 & 0 \\ 0 & 0.3-1 & 0.7 \\ 0.6 & 0.4 & 0-1 \end{bmatrix} = [0, 0, 0].$$

However, the sum of the columns of $P - I$ is $\mathbf{0}$. This shows that these equations are redundant: If all but the last one hold, so does the last one. Let us replace the last equation by $\pi\mathbf{1} = 1$, i.e., $\sum_j \pi(j) = 1$:

$$\pi \begin{bmatrix} 0.8-1 & 0.2 & 1 \\ 0 & 0.3-1 & 1 \\ 0.6 & 0.4 & 1 \end{bmatrix} = [0, 0, 1].$$

Hence,

$$\pi = [0, 0, 1] \begin{bmatrix} 0.8-1 & 0.2 & 1 \\ 0 & 0.3-1 & 1 \\ 0.6 & 0.4 & 1 \end{bmatrix}^{-1} \approx [0.55, 0.26, 0.19]$$

Summary

Markov Chains

- Markov Chain: $Pr[X_{n+1} = j | X_0, \ldots, X_n = i] = P(i,j)$
- FSE: $\beta(i) = 1 + \sum_j P(i,j)\beta(j); \alpha(i) = \sum_j P(i,j)\alpha(j)$.
- $\pi_n = \pi_0 P^n$
- π is invariant iff $\pi P = \pi$
- Irreducible $\Rightarrow$ one and only one invariant distribution π
- Irreducible $\Rightarrow$ fraction of time in state i approaches $\pi(i)$
- Irreducible + Aperiodic $\Rightarrow \pi_n \rightarrow \pi$.
- Calculating π: One finds $\pi = [0, 0 \ldots, 1] Q^{-1}$ where $Q = \cdots$.

How to Gamble, if You Must

Dubins and Savage, How to Gamble if You Must: Inequalities for Stochastic Processes. Dover Books on Mathematics. Paperback - July 23, 2014. (Original Edition, 1965.)

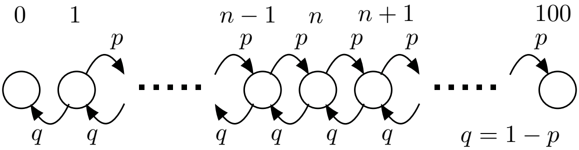
Recall the 'heads or tails game':
At each step, you win 1 w.p. p and loose 1 w.p. $q = 1 - p$.
You start with 10 and you want to maximize the probability of getting to 100 before you get to 0.

In their celebrated masterpiece, Dubins and Savage proved that the optimal strategy, if $p \leq 1/2$, is the bold one, always betting the maximum, and if $p \geq 1/2$, then an optimal strategy is the timid one, always betting the minimum.

There are relatively few problems for which one can prove such a clean result. However, there is a systematic approach to calculate the optimal strategy for many problems. We explain that approach next on this problem.

Original Strategy

Recall the original strategy: bet 1 each time. Then,



Let $\alpha(n)$ be the probability of reaching 100 before 0, starting from n, for $n = 0, 1, \ldots, 100$.

$$\alpha(0) = 0; \alpha(100) = 1.$$
$$\alpha(n) = p\alpha(n+1) + q\alpha(n-1), 0 < n < 100.$$

Solving, we find

$$\alpha(n) = \frac{1 - \rho^n}{1 - \rho^{100}} \text{ with } \rho = qp^{-1}.$$

For $p = 0.46$, we get $\alpha(10) \approx 3.5 \times 10^{-6}$.

Bold: Estimate

We can do better. Let us bet all we have. Then, with probability p^4 we have

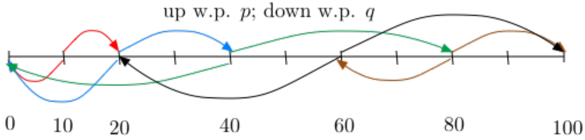
$$10 \to 20 \to 40 \to 80 \to 160.$$

With $p = 0.46$, we see that we get to 100, at least with probability $(0.46)^4 = 0.0448$. This is much better than 3.5×10^{-6}.

Thus, the probability of winning the game (i.e., getting to 100 before 0) is at least 0.0448 when playing bold.

Bold: Analysis

What is the exact probability of winning when playing bold? Here is the corresponding MC:



The FSE for $\alpha(n) = Pr[T_{100} < T_0 \mid X_0 = n]$ are

$$\alpha(10) = p\alpha(20) + q0; \alpha(20) = p\alpha(40) + q0; \alpha(40) = p\alpha(80) + q0$$
$$\alpha(80) = p1 + q\alpha(60); \alpha(60) = p1 + q\alpha(20)$$

To solve, let $\alpha(10) = x$. Then, we find

$$\alpha(20) = p^{-1}x; \alpha(40) = p^{-1}\alpha(20) = p^{-2}x$$
$$\alpha(80) = p^{-1}\alpha(40) = p^{-3}x; p^{-3}x = p + q\alpha(60); \alpha(60) = p + qp^{-1}x.$$

We solve the last two equations for x.
We find $x = p^2(1+q)/(p^{-2} - q^2) \approx 0.0735$.

Optimal Strategy

Note: The material on the remaining slides of this lecture will not be on the final.

We have seen that playing bold is much better than playing timid when $p = 0.46$.

Intuition suggests that this may be the best strategy. However, intuition is often misleading!

How do we calculate the optimal strategy?

Here is a systematic approach. Assume you can only play 0 time. Let $V(0,n)$ be you maximum probability of winning the game if you start with n. Clearly, $V(0,100) = 1$. Also, for $n = 0,\ldots,99$, one has $V(0,n) = 0$.

Let $V(k,n)$ be the maximum probability of winning the game if we can play k times and we start with n.

Then,

$$V(k+1,n) = \max\{pV(k,n+m) + qV(k,n-m) \mid m \leq n \text{ and } n+m \leq 100\}.$$

Also, the maximizing value of m is the best amount to bet when we have n and there are $k+1$ steps to go.

We can solve successively for $V(0,\cdot), V(1,\cdot), V(2,\cdot), \ldots$. In the limit, we find the the best strategy. The program shows that bold is optimal when $p < 0.5$. The finer result (Dubins and Savage) is to show this analytically.

Another Game

Consider the following game. One has a perfectly shuffled 52-card deck. The cards are turned over one at a time. You win if you can guess when the next card will be an ace. You can only guess once. What is the best strategy? Should you let a few cards go by, then decide that the next one will be an ace?

For $m \leq n$, let (n, m) mean that there are still n cards and m aces left in the deck. Let also $V(n, m)$ be the maximum probability of winning this game in that situation. Then,

$$V(n, m) = \max\{\frac{m}{n}, \frac{m}{n}V(n-1, m-1) + \frac{n-m}{n}V(n-1, m)\}.$$

The first term corresponds to stating 'the next card is an ace.' The second term corresponds to not deciding yet.

One boundary condition is $V(n, 0) = 0$. The maximum term determines the best decision in the situation (n, m).

Solving the equations, we find that $V(n, m) = m/n$ and that the two terms are equal as long as $m \geq 1$.

Conclusion: You might as well stop at the first card!.

Markov Decision Problems

The two games we discussed ('heads or tails', 'guess an ace') are examples of Markov Decision Problems.

The approach is to look at the maximum value of the game starting from a given state, with a number of steps to go. One then calculates that value with one more step. This technique is called Dynamic Programming. (Discovered by Richard Bellman in 1953.)

See EE126, CS188, EE223.