

Notes for Recitation 3

1 State Machines

Recall from Lecture 3 (9/16) that an *invariant* is a property of a system (in lecture, that system was the 8-puzzle) that does not change, regardless of the system's behavior. Now we'll take a look at how we can make use of an important modeling tool — a state machine — to analyze systems. We'll see that finding invariants of state machines can often help us prove propositions.

A *state machine* is an abstract model of a step-by-step process. The model consists of a collection of *states* and *transitions* between those states. More formally, we can define a state machine as

- a set of states: Q
- a designated start state: $q_0 \in Q$
- a set of allowed transitions between states: $\delta \subseteq Q \times Q$.

1.1 Example: Bounded Counter

Take, for example, a bounded counter that counts from 0 to 99 and overflows at 100. A diagram representing the corresponding state machine was shown in recitation. Note that in this example, there is a finite number of states. However, in general, the set of states might be infinite.

1.2 Example: Unbounded Counter

An unbounded counter is similar to a bounded counter except that there is an infinite number of states and no overflow. See Figure 2.

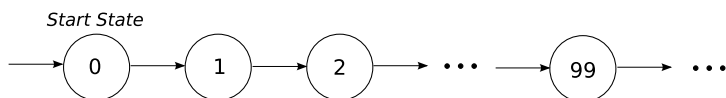


Figure 1: State machine for the unbounded counter

2 Problem: Breaking a chocolate bar

We are given a chocolate bar with $m \times n$ squares of chocolate, and our task is to divide it into mn individual squares. We are only allowed to split one piece of chocolate at a time using a vertical or a horizontal break.

For example, suppose that the chocolate bar is 2×2 . The first split makes two pieces, both 2×1 . Each of these pieces requires one more split to form single squares. This gives a total of three splits.

Prove that the number of times you split the bar does not depend on the sequence of splits you make.

Solution. As with the “stacking game” from class, we approach the problem with experimentation, strong induction and a strong hypothesis. First we guess what the number of splits needed is:

Theorem. *To divide up a chocolate bar with $m \times n$ squares, we need at most $mn - 1$ splits.*

This theorem does not immediately lend itself to an induction or strong induction proof, since there are *two* variables. In general, propositions involving several natural-valued variables can often be proved by using a sort of nested induction (make sure to try that).

However, in this case, we can get by with a single-variable induction and a trick.

Intuitively, to break up a big chocolate bar, we need one split to make two pieces, and then we can break up the two pieces recursively. This suggests a proof using strong induction on the *size* of the chocolate bar, where size is measured in chocolate squares. Now instead of a problem involving two variables (the two dimensions), we have a problem in one variable (the size). With this simplification, we can prove the theorem using strong induction.

Proof. The proof is by strong induction on the size of the chocolate bar. Let $P(k)$ be the proposition that a chocolate bar of size k requires at most $k - 1$ splits.

Base case, $k = 1$: $P(1)$ is true because there is only a single square of chocolate, and $1 - 1 = 0$ splits are required.

Induction step: We suppose $k \geq 1$ and any chocolate bar of size s , where $1 \leq s \leq k$, requires at most $s - 1$ splits. We must now show there is a way to split a chocolate bar of size $k + 1$ with at most k splits.

To do this, first break the chocolate bar of size $k + 1$ into two smaller pieces of size p and q where $p + q = k + 1$. This is certainly possible because the size of the bar is at least two. Now the pieces of sizes p and q are between one and k , so by strong induction, breaking these two pieces into single squares requires only $p - 1$ and $q - 1$ splits, respectively. The total number of splits required to break the bar of size $k + 1$ into single squares is therefore at most $1 + (p - 1) + (q - 1) = p + q - 1 = (k + 1) - 1 = k$.

This shows that $P(k)$ implies $P(k + 1)$, and the claim is proved by strong induction. □



3 Problem: The Temple of Forever

Each monk entering the Temple of Forever is given a bowl with 15 red beads and 12 green beads. Each time the Gong of Time rings, a monk must do one of two things:

1. *Exchange*: If he has at least 3 red beads in his bowl, then he may exchange 3 red beads for 2 green beads.
2. *Swap*: He may replace each green bead in his bowl with a red bead and replace each red bead in his bowl with a green bead. That is, if he starts with i red beads and j green beads, then after he performs this operation, he will have j red beads and i green beads.

A monk may leave the Temple of Forever only when he has exactly 5 red beads and 5 green beads in his bowl.

Let's look at how we can represent this problem as a state machine.

- What do the states of the machine look like?

Solution. We can use variables such as r to represent the number of red beads and g to represent the number of green beads. Then the states can be represented as pairs (r, g) for $r \geq 0, g \geq 0$. ■

- Use the notation you developed above to represent the allowable transitions in the state machine.

Solution. There are two possible transitions:

1. trade 3 red for 2 green (*exchange*): $(r, g) \rightarrow (r - 3, g + 2), r \geq 3$
2. swap red and green (*swap*): $(r, g) \rightarrow (g, r)$

- Expand the state machine diagram to the first three or four levels. Label the transitions according to the operation type (E for *exchange* or S for *swap*).

Solution. You can see the diagram in Figure 3. ■

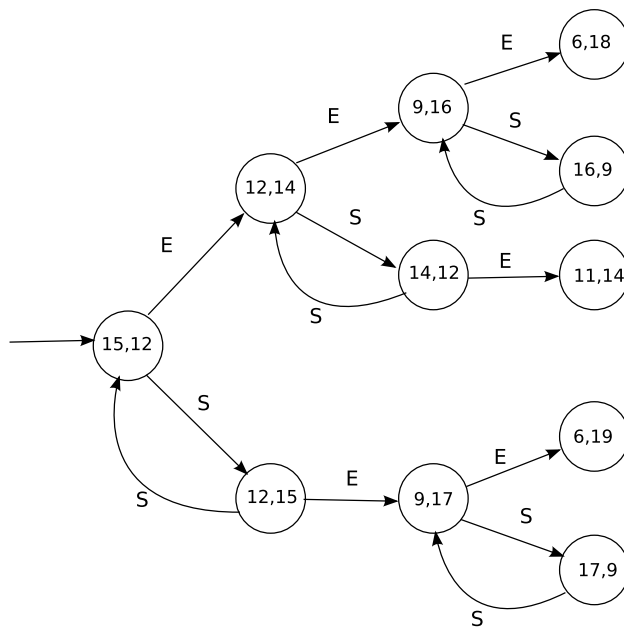


Figure 2: State machine diagram for first few levels

3.1 Invariants and State Machines

The Temple of Forever machine models every possible way of exchanging beads at each time step according to the rules. We would like to know whether the machine ever reaches the state $(5, 5)$. By starting at the start state and following the transition arrows through the state diagram, we can trace the possible paths, or *executions*, of the machine. So another way of stating our question is whether the state we are interested in appears in some execution of the machine. If so, then we can say that that state is *reachable*.

Definition 1. *A state is called reachable if there is a path to it starting from the start state, that is, if it appears in some execution.*

A useful technique for analyzing reachability is the identification of *invariants* of the machine. An invariant will hold for all reachable states of the machine. More formally,

Definition 2. *An invariant for a state machine is a predicate P on state machines such that $P(q_0)$ holds (where q_0 is the start state of the machine), and whenever $P(q)$ is true of a state q , and $q \rightarrow r$ for some state r , then $P(r)$ holds.*

Since, by definition, an invariant holds for the start state and for all transitions of the state machine, then we know (by induction) that the invariant must hold for all reachable states. Therefore, if we know some property to be an invariant, and we know that a certain state violates that property, then we can say that this state is unreachable.

Now we'll show that no monk can ever escape the Temple of Forever because the state $(5, 5)$ violates an invariant of the Temple of Forever machine.

Theorem 1. *No one ever leaves the Temple of Forever.*

Prove this theorem by induction. Begin by searching for an invariant that holds initially and is maintained by each operation, but would be violated by the condition required for departure.

Solution. *Proof.* We use induction on the number of gong rings. Let $P(n)$ be the proposition that after n rings, the number of red beads in the monk's bowl minus the number of green beads is equal to $5k + 2$ or $5k + 3$ for some integer k .

Base case: $P(0)$ is true because initially (after zero rings) the number of red beads minus the number of green beads is $15 - 12 = 5 \cdot 0 + 3$.

Inductive step: Now assume that $P(n)$ holds after n gong rings, where $n \geq 0$. Let r denote the number of red beads in the monk's bowl, and let g denote the number of green beads. In these terms, we are assuming that $r - g$ is equal to $5k + 2$ or $5k + 3$ for some integer k . After $n + 1$ gong rings, there are two cases to consider, depending on the monk's action:

1. If $r \geq 3$, then the monk may have exchanged 3 red beads for 2 green beads. Thus, the number of red beads minus the number of green becomes:

$$(r - 3) - (g + 2) = (r - g) - 5$$

This is equal to either $5(k - 1) + 2$ or $5(k - 1) + 3$, so $P(n + 1)$ is true.

2. Alternatively, the monk may have swapped every red bead for a green bead and vice versa. In this case, the number of reds minus the number of greens becomes $g - r$. If $r - g = 5k + 3$, then $g - r = 5(-k) - 3 = 5(-k - 1) + 2$. If $r - g = 5k + 2$, then $g - r = 5(-k) - 2 = 5(-k - 1) + 3$. Thus, $P(n + 1)$ is again true.

Therefore, $P(n)$ implies $P(n + 1)$ for all $n \geq 0$.

By the induction principle, $P(n)$ is true for all $n \geq 0$. Since the number of red beads minus the number of greens is always of the form $5k + 2$ or $5k + 3$ and the difference required to leave the temple does not match either form, no monk can ever leave the Temple of Forever. \square

■

Now let's take a look at a different property of the Temple of Forever machine.

Theorem 2. *There is a finite number of reachable states in the Temple of Forever machine.*

Prove this theorem. (Hint: First find an invariant that suggests an upper bound on the number of reachable states. Be sure to prove the invariant.)

Solution. We begin by noting that the Temple of Forever machine exhibits the following invariant:

Lemma 3. *For all reachable states, the total number of red beads and green beads in the monk's bowl — $r + g$ — is at most 27.*

Proof. We use induction on the number of gong rings. Let $P(n)$ be the proposition that after n gong rings, $r + g \leq 27$.

Base case: $P(0)$ is true because initially (after zero rings) the number of red beads plus the number of green beads is $15 + 12 = 27$.

Inductive step: Now assume that $P(n)$ holds after n gong rings, where $n \geq 0$. Let r denote the number of red beads in the monk's bowl, and let g denote the number of green beads. In these terms, we are assuming that $r + g$ is at most 27 after n gong rings. After $n + 1$ gong rings, there are two cases to consider, depending on the monk's action:

1. If $r \geq 3$, then the monk may have exchanged 3 red beads for 2 green beads. Thus, the number of red beads plus the number of green becomes:

$$(r - 3) + (g + 2) = (r + g) - 1$$

Since, by the inductive hypothesis, $r + g \leq 27$, it follows that $(r + g) - 1 \leq 27$, and so $P(n + 1)$ is true.

2. Alternatively, the monk may have swapped every red bead for a green bead and vice versa. In this case, the number of reds plus the number of greens becomes $g + r = r + g$. Thus, $P(n + 1)$ is again true by the inductive hypothesis.

□

We now prove the theorem by showing that there is a finite upper bound on the number of reachable states.

Proof. We give a direct argument. Lemma 3 tells us $r + g \leq 27$. This implies that there is an upper bound on the number of reachable states, since there can be at most 28 ways for r and g to sum to 27, 27 ways to sum to 26, and so on. Therefore, there can be at most $28 + 27 + \dots + 1 = \frac{29 \cdot 28}{2} = 406$ states in the Temple of Forever machine. Hence, there is a finite number of reachable states in the Temple of Forever machine. □

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Inside the Temple of Forever, the Gong of Time rings on. As you may well imagine, the monks begin to recognize that no matter how many ways they try to exchange or swap their beads, they always seem to end up in some state they've already been in before! For one or two monks, this realization is all they need to propel them instantly into a state of enlightenment. For the overwhelming majority, however, this knowledge does nothing but weaken their resolve. They just get depressed. Taking note of the mental state of this second group, the Keeper of the Temple makes an unannounced appearance and proclaims to the group, "From now on, any monk who is able to visit 108 (108 being the mystical number that encompasses all of existence¹) unique states will be allowed to leave the Temple of Forever."

Do the monks have any chance of leaving the Temple of Forever?

Theorem 4. *It is not possible to visit 108 unique states in the Temple of Forever machine.*

Prove this theorem. (Hint: Consider a proof by contradiction.)

Solution. *Proof.* The proof is by contradiction. Assume that it *is* possible for a monk to visit 108 unique states in some execution of the Temple of Forever machine, and consider the sequence of moves that the monk must have made to visit these states. Each move in the sequence must be either an *exchange* or a *swap*, since these are the only legal moves. Now, whenever the monk performs an *exchange* operation, the sum $r + g$ decreases by one:

$$(r - 3) + (g + 2) = (r + g) - 1$$

In contrast, swaps do not have any effect on the sum. Furthermore, we know that the sum $r + g$ must be at least 3 to perform an exchange operation. Therefore, there can be at most 25 exchange operations in the sequence.

Now consider swap operations: between each pair of exchanges in the sequence, there may be an unlimited number of swaps. However, only a single swap can take the monk to a new state: if at step k the monk is in state (r, g) , then at step $k + 2$, he will return to the same state. Therefore, an upper bound on the number of unique states in any execution of the

¹See <http://astrologyforthesoul.com/vp/mysticalnumber108.html>. Also consider: $42 + 24 + 42 = 108$.

machine is $25 + 26 + 1 = 52$ (if swaps are inserted at both the beginning and end of the sequence). But then this contradicts the assumption that the monk visits 108 unique states, so no monk ever leaves the Temple of Forever.

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What is the true maximal number of unique states a monk can visit in any execution of the Temple of Forever machine? How can this number be achieved?

Solution. The true maximum is 52. To achieve this number, the monk can perform sequential swaps and exchanges until he reaches the state $(5, 2)$ via an exchange. At this point, the longest path goes to $(2, 4)$, via an exchange, instead of $(2, 5)$, via a swap. This is because the path leading to $(2, 5)$ ends at $(2, 5)$, whereas the path leading to $(2, 4)$ continues with swaps and exchanges, with the final state being $(2, 0)$ (arrived at via a swap). However, the monk can reach 52 unique states if, at state $(5, 2)$, he performs two swap in a row to pick up state $(2, 5)$. Alternatively, the monk can perform two swaps at the start state, picking up state $(12, 15)$, and then continue with 25 pairs of sequential exchange, swap operations until he reaches $(2, 0)$. This also generates a path with 52 unique states.

■

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