MATH 579 Fall 2018 Supplement: Recurrences

A recurrence is a sequence of numbers, defined by some positional relationship. This positional relationship is called a recurrence relation. That is, the \( n^{\text{th}} \) number is a function of the previous numbers. Some examples of recurrence relations are 
\[
a_n = 2a_{n-1}, \quad b_n = b_{n-2} + 2, \\
c_n = c_{n-1} + c_{n-2} \quad \text{(Fibonacci numbers if } c_1 = c_2 = 1), \\
d_{n+1} = n(d_{n-1} + d_n) \quad \text{(derangements if } d_1 = 0, d_2 = 1).
\]

To fully specify the sequence, ‘enough’ initial conditions are necessary. For example, \( \{a_n\} \) requires one initial condition (e.g. \( a_1 = 3 \)). \( \{b_n\} \) requires two; \( b_1 = 3 \) is enough to specify all the odd terms in the sequence, but to specify the even terms we need \( b_2 = 4 \).

To solve a recurrence means to find a closed-form expression for the sequence, that does not depend on previous terms. Assuming you have psychic powers, the best way to solve recurrences is by guessing. A recurrence is completely specified by its initial conditions and recurrence. If you can guess the answer and show that your guess satisfies the recurrence and satisfies the initial conditions – this is enough to prove your answer.

**Example 1a**: \( a_1 = 1, a_n = 2a_{n-1} \quad (n \geq 2) \)

Guess \( a_n = 2^{n-1} \). Check that \( 2^{1-1} = 1 \), so the initial condition is satisfied. Also, \( 2^{n-1} = 2 \times 2^{(n-1)-1} \), so the recurrence relation is satisfied.

Much as with differential equations, recurrences fall into many types, with many different strategies for solution. A linear recurrence relation of order \( k \) may be written as 
\[
a_n = c_n a_{n-1} + c_{n-2} a_{n-2} + \cdots + c_{n-k} a_{n-k} + *, \quad \text{where each } * \text{ is some function of } n.
\]
If each \( * \) is, in fact, a constant, we say that the recurrence has **constant coefficients**. In this section, we will only consider linear recurrences. Further, we will assume that all the coefficients (except possibly the final \( * \)) are constants. If the final \( * \) is identically zero (i.e. \( a_n = c_{n-1} a_{n-1} + c_{n-2} a_{n-2} + \cdots + c_{n-k} a_{n-k} \)) we call the relation **homogeneous**; otherwise we call it **nonhomogeneous**.

In the above examples, \( a_n = 2a_{n-1} \) is first-order homogeneous with constant coefficients, \( b_n = b_{n-2} + 2 \) is second-order nonhomogeneous with constant coefficients, \( c_n = c_{n-1} + c_{n-2} \) is second-order homogeneous with constant coefficients, and \( d_{n+1} = n(d_{n-1} + d_n) \) is second-order homogeneous with nonconstant coefficients.

**Homogeneous Linear Recurrence Relations with Constant Coefficients**

We consider the recurrence relation 
\[
a_n = c_{n-1} a_{n-1} + c_{n-2} a_{n-2} + \cdots + c_{n-k} a_{n-k}.
\]
Because this is homogeneous, we may multiply a solution by any constant and it will be a solution. We may also add two solutions and get a solution. In short, the set of solutions forms a linear space. This space is of dimension \( k \), because the relation is of order \( k \) and requires \( k \) initial conditions to fully specify the recurrence. Hence, to find the general solution, we may find \( k \) linearly independent solutions, and take all their linear combinations. Caution: be sure that the \( k \) specific solutions are linearly independent.

Let’s guess that \( a_n = x^n \) is a solution. We substitute into the recurrence to get \( x^n = \)
Dividing by \( x^{n-k} \) gives us
\[
x^k = c_{n-1} x^{k-1} + c_{n-2} x^{k-2} + \cdots + c_{n-k}.
\]
This is known as the \textit{characteristic equation} of the recurrence relation. It is a polynomial of degree \( k \), and therefore by the Fundamental Theorem of Algebra has \( k \) complex roots, counted by multiplicity.

If the \( k \) roots \( r_1, r_2, \ldots, r_k \) are all distinct, then \( a_n = r_1^n, a_n = r_2^n, \ldots, a_n = r_k^n \) are \( k \) linearly independent solutions, and therefore span the solution space. The general solution is therefore \( a_n = \alpha_1 r_1^n + \alpha_2 r_2^n + \cdots + \alpha_k r_k^n \). The \( k \) initial conditions allow us to determine the unknown \( \alpha_1, \alpha_2, \ldots, \alpha_k \) for a particular solution.

If, on the other hand, a root is repeated (i.e. \( r_1 = r_2 \)), then \( a_n = r_1^n, a_n = r_2^n, \ldots, a_n = r_k^n \) are \textit{NOT} \( k \) linearly independent solutions. \( \alpha_1 r_1^n + \alpha_2 r_2^n \) is a one-dimensional subspace, being equal to \( \alpha_1 r_1^n \) alone, because \( r_1 = r_2 \). Fortunately, if a root is repeated, we have available to us additional solutions, that are linearly independent. If root \( r_1 \) has multiplicity 4, then \( r_1^n, nr_1^n, n^2 r_1^n, n^3 r_1^n \) are four linearly independent solutions (this fact will not be proved). In this manner we again get \( k \) linearly independent solutions, and therefore the general solution via linear combinations.

\textbf{Example 1b:} \( a_1 = 1, a_n = 2a_{n-1} (n \geq 2) \)

This has characteristic equation \( x = 2 \); hence the general solution is \( a_n = \alpha 2^n \). Substituting \( n = 1 \) and using the initial conditions, we have \( 1 = a_1 = \alpha 2^1 \). We solve to find \( \alpha = 1/2 \); hence the specific solution is \( a_n = (1/2)2^n = 2^{n-1} \).

\textbf{Example 2:} \( a_1 = a_2 = 1, a_n = a_{n-1} + a_{n-2} (n \geq 3) \) (Fibonacci numbers)

This has characteristic equation \( x^2 = x + 1 \), which has roots (using the quadratic formula) \( r_1 = (1 + \sqrt{5})/2 \) and \( r_2 = (1 - \sqrt{5})/2 \). Hence the general solution is \( a_n = \alpha_1 r_1^n + \alpha_2 r_2^n \). We have two initial conditions: \( 1 = a_1 = \alpha_1 r_1 + \alpha_2 r_2 \), \( 1 = a_2 = \alpha_1 r_1^2 + \alpha_2 r_2^2 \). This is a \( 2 \times 2 \) linear system in the unknowns \( \alpha_1, \alpha_2 \), with solution \( \alpha_1 = \frac{1}{\sqrt{5}}, \alpha_2 = \frac{-1}{\sqrt{5}} \). Hence the specific solution is \( a_n = (r_1^n - r_2^n)/\sqrt{5} \).

\textbf{Example 3:} \( a_0 = a_2 = 1, a_1 = 0, a_3 = 2, a_n = -a_{n-1} + 3a_{n-2} + 5a_{n-3} + 2a_{n-4} (n \geq 4) \)

This has characteristic equation \( x^4 + x^3 - 3x^2 - 5x - 2 = 0 \). We find the roots by guessing small integers (the rational root theorem helps too); if we successfully guess a root \( r \), we divide by \( x - r \) using long division and continue. In this manner, we find roots \(-1 \) (multiplicity 3), and 2. Hence, the general solution is \( a_n = \alpha_1(-1)^n + \alpha_2 n(-1)^n + \alpha_3 n^2(-1)^n + \alpha_4 2^n \). We now apply our initial conditions to get:

\[
\begin{align*}
(n = 0): & \quad 1 = a_0 = \alpha_1 + \alpha_4 \\
(n = 1): & \quad 0 = a_1 = \alpha_1(-1) + \alpha_2(-1) + \alpha_3(-1) + \alpha_4 2 \\
(n = 2): & \quad 1 = a_2 = \alpha_1 + \alpha_2 + \alpha_3 4 + \alpha_4 4 \\
(n = 3): & \quad 2 = a_3 = \alpha_1(-1) + \alpha_2(-3) + \alpha_3(-9) + \alpha_4 8
\end{align*}
\]

This is a \( 4 \times 4 \) linear system, with solution \( \alpha_1 = 7/9, \alpha_2 = -3/9, \alpha_3 = 0, \alpha_4 = 2/9 \). Therefore, the specific solution is \( a_n = (7/9)(-1)^n - (3n/9)(-1)^n + (2/9)2^n \).
Example 4 (Gambler’s ruin): A gambler repeatedly plays a game against a casino, until one of them runs out of money. Each time the gambler has probability $p$ of winning $1$, and probability $q = 1 - p$ of losing $1$. The gambler starts with $n$ dollars, and the casino with $m - n$ dollars (there are $m$ total dollars to be won). What is the probability that the gambler will run out of money before the casino?

Let $a_n$ denote the desired probability, that the gambler is successful starting with $n$ dollars. For the gambler to win, either (1) gambler wins first bet, and then is successful starting with $n + 1$ dollars, or (2) gambler loses first bet, and then is successful starting with $n - 1$ dollars. Therefore, this sequence satisfies the recurrence relation $a_n = pa_{n+1} + qa_{n-1} (0 < n < m)$, with boundary conditions $a_0 = 1, a_m = 0$. This has characteristic equation $px^2 - x + q = 0$, with roots $r_1 = 1, r_2 = q/p$. Hence the problem breaks into two cases, depending on whether $p = q$ or not.

($p \neq q$): The general solution is $a_n = \alpha 1^n + \beta r_2^n = \alpha + \beta r_2^n$. We apply the boundary conditions, to get $(n = 0) : 1 = a_0 = \alpha + \beta, \quad (n = m) : 0 = a_m = \alpha + \beta r_2^m$. This has solution $\alpha = -r_2^m/(1 - r_2^m), \beta = 1/(1 - r_2^m)$. Hence, the specific solution is $(-r_2^m + r_2^n)/(1 - r_2^m) = 1 - \frac{1 - r_2^n}{1 - r_2^m}$.

($p = q = 1/2$): The general solution is $a_n = \alpha 1^n + \beta n 1^n = \alpha + \beta n$. We apply the boundary conditions, to get $(n = 0) : 1 = a_0 = \alpha, \quad (n = m) : 0 = a_m = \alpha + \beta m$. This has solution $\alpha = 1, \beta = -1/m$. Hence, the specific solution is $1 - (n/m)$.

Nonhomogeneous Linear Recurrence Relations

We want to solve the nonhomogeneous recurrence relation $a_n = c_{n-1}a_{n-1} + c_{n-2}a_{n-2} + \cdots + c_{n-k}a_{n-k} + b(n)$, where $b(n)$ is a function of $n$. The technique to find the general solution is in two parts. First, drop the $b(n)$ term and find the general solution to the homogeneous recurrence relation. Then, find any single solution to the nonhomogeneous recurrence (under any initial/boundary conditions). The general solution to the nonhomogeneous recurrence is the sum of these two – a $k$-dimensional term from the homogeneous part, and a single term with no constants from the nonhomogeneous part.

Finding a particular solution is, at times, an art form. The only good way to find them is to guess and check – guess a particular solution, and see if it fits the nonhomogeneous relation. If $b(n)$ is a polynomial, it’s a good idea to try guessing a polynomial of the same degree; however, if the homogeneous solution has overlap with this, then increase the degree of your guess. If $b(n)$ is an exponential, it’s a good idea to try a multiple of the same exponential.

Example 5: $a_0 = 2, a_n = 2a_{n-1} + 3^n \ (n \geq 1)$

Homogeneous version: $a_n = 2a_{n-1}$, which has characteristic equation $x = 2$ and general solution $\alpha 2^n$.

Nonhomogeneous version: Let’s guess $\beta 3^n$. Plugging into the relation, we get $\beta 3^n =$
We divide both sides by $3^{n-1}$ to get $3\beta = 2\beta + 3$; hence $\beta = 3$. Thus $3^{n+1}$ is a specific solution to the original, nonhomogeneous, recurrence.

Putting them together, we find the general solution to the nonhomogeneous recurrence is $a_n = \alpha 2^n + 3^{n+1}$. We now consider the initial condition, $(n = 0) : 2 = a_0 = \alpha 2^0 + 3^1$. This has solution $\alpha = -1$, and so the specific solution is $a_n = 3^{n+1} - 2^n$.

**Example 6:** $a_0 = a_1 = 1, a_n = 2a_{n-1} - a_{n-2} + 5^n \ (n \geq 2)$

Homogeneous version: $a_n = 2a_{n-1} - a_{n-2}$, which has characteristic equation $x^2 - 2x + 1 = 0$. This has a double root of 1, hence has general solution $\alpha_1 1^n + \alpha_2 n 1^n = \alpha_1 + \alpha_2 n$.

Nonhomogeneous version: Let’s guess $\beta 5^n$. Plugging into the relation, we get $\beta 5^n = 2\beta 3^{n-1} - \beta 5^{n-2} + 5^n$. We divide both sides by $5^{n-2}$ to get $25\beta = 10\beta - \beta + 25$. This has solution $\beta = 25/16$, so a nonhomogeneous solution is $(25/16)5^n = 5^{n+2}/16$.

Putting them together, we find the general solution to the nonhomogeneous recurrence is $a_n = \alpha_1 + \alpha_2 n + 5^{n+2}/16$. Considering the initial conditions, $(n = 0) : 1 = a_0 = \alpha_1 + 25/16, \ (n = 1) : 1 = a_1 = \alpha_1 + \alpha_2 + 125/16$. This has solution $\alpha_1 = -9/16, \alpha_2 = -132/16$, and so the specific solution is $a_n = (-9 - 132n + 5^{n+2})/16$.

**Example 7:** $a_0 = 2, a_n = 3a_{n-1} - 4n \ (n \geq 1)$

Homogeneous version: $a_n = 3a_{n-1}$, which has characteristic equation $x = 3$ and general solution $\alpha 3^n$.

Nonhomogeneous version: We guess a solution of $\beta_1 n + \beta_0$. Plugging into the nonhomogeneous equation, we get $(\beta_1 n + \beta_0) = 3(\beta_1 (n - 1) + \beta_0) - 4n$. Simplifying, we get $0 = (2\beta_1 - 4)n + (-3\beta_1 + 2\beta_0)$. If a polynomial equals zero, then each coefficient must equal zero; hence $0 = 2\beta_1 - 4$ and $0 = -3\beta_1 + 2\beta_0$. We solve this system to get $\beta_1 = 2, \beta_0 = 3$. Hence $2n + 3$ is a solution to the nonhomogeneous recurrence.

Putting them together, we find the general solution to the nonhomogeneous recurrence is $a_n = \alpha 3^n + 2n + 3$. With our initial condition, we have $(n = 0) : 2 = a_0 = \alpha 3^0 + 3$, so $\alpha = -1$. So the specific solution is $a_n = -3^n + 2n + 3$.

**Example 8 (Tower of Hanoi):** We have three pegs and $n$ disks of different sizes. The disks all start on one peg arranged in order of size, and we must move them to another. We move one disk at a time, and may never put a larger disk onto a smaller. How many moves does it take?

Let $a_n$ represent the answer. We see that $a_1 = 1$. To move the biggest disk from peg 1 to peg 2, all the smaller disks must be in a single stack, on peg 3. Therefore, the solution must contain three steps: First, move the $n - 1$ smaller disks from peg 1 to peg 3, then move the largest disk form peg 1 to peg 2, then move the $n - 1$ smaller disks back onto the largest disk from peg 3 to peg 2. Hence, $a_n = a_{n-1} + 1 + a_{n-1} = 2a_{n-1} + 1$.

The homogeneous recurrence is again $a_n = 2a_{n-1}$ with general solution $\alpha 2^n$. To find a specific
solution to the nonhomogeneous recurrence, consider a constant (0-th degree) polynomial in $a$. Plugging into the nonhomogeneous equation, we get $\beta = 2\beta + 1$; we solve this to get $\beta = -1$. Hence the general solution to the nonhomogeneous relation is $a_n = \alpha 2^n - 1$. Our initial conditions tell us $1 = a_1 = \alpha 2^1 - 1$; hence $\alpha = 1$ and our specific solution is $a_n = 2^n - 1$.

Example 9 (Gambler’s ruin revisited): Consider the gambler of example 4. What is the expected number of games played until either the gambler or casino is ruined?

Let $a_n$ denote the desired answer (when the gambler starts with $\$n$). If the gambler wins, then the expected number of games is one more than the expected number of games, had the gambler started with $\$n + 1$. If the gambler loses, then the expected number of games is one more than the expected number of games, had the gambler started with $\$n - 1$. Hence we get the relation $a_n = p(a_{n+1} + 1) + q(a_{n-1} + 1)$ ($0 < n < m$). We have boundary conditions $0 = a_0 = a_m$, and may rewrite the relation as $pa_{n+1} = a_n - qa_{n-1} - 1$. The homogeneous recurrence has the familiar characteristic equation $px^2 - x + q = 0$; once again the problem splits into cases based on whether $q = p$.

$(p \neq q)$: The homogeneous general solution is $\alpha + \beta r_2^n$ (recall that $r_2 = q/p$). If we try to guess a 0-th degree polynomial solution to the nonhomogeneous recurrence, we will find no luck (try it and see). The reason is that all 0-th degree polynomials are already solutions of the homogeneous recurrence, and so none of them could ever solve the nonhomogeneous recurrence.

Instead let’s try a first-degree polynomial $c_1n + c_0$. We plug into the nonhomogeneous equation to get $p(c_1(n + 1) + c_0) = c_1n + c_0 - q(c_1(n - 1) + c_0) - 1$. We collect terms to get $n(pc_1 - c_1 + qc_1) + (pc_1 + pc_0 - c_0 - qc_1 + qc_0 + 1) = 0$. The first coefficient is zero already, and the second coefficient simplifies to $(p - q)c_1 + 1 = 0$; hence $c_1 = -1/(p - q)$, and we may as well take $c_0 = 0$ although the choice is arbitrary (in fact, we could have known this since all constants are part of the homogeneous solution). Therefore, the general nonhomogeneous solution is $a_n = \alpha + \beta r_2^n - n/(p - q)$. For the particular solution, we take $0 = a_0 = \alpha + \beta, 0 = a_m = \alpha + \beta r_2^m - m/(p - q)$. This has solution $\beta = \frac{m}{(1 - 2p)(1 - r_2)}; \alpha = -\beta$.

We plug these into the general solution, to find $a_n = \left(n - m \frac{1 - r_2^n}{1 - r_2^m}\right)/(1 - 2p)$.

$(p = q = 1/2)$: The homogeneous general solution is $\alpha + \beta n$. We won’t get very far trying low-degree polynomials, since they are all part of the homogeneous solution. So, let’s try $cn^2$. We plug into the nonhomogeneous equation to get $pc(n + 1)^2 = cn^2 - qc(n - 1)^2 - 1$. We rewrite to get $n^2(pc - c + qc) + n(2pc - 2qc) + (pc + qc + 1) = 0$. Since $p = q = 1/2$, the first two coefficients are zero already, and the last is zero when $c = -1$. Hence the general nonhomogeneous solution is $a_n = \alpha + \beta n - n^2$. For the specific solution, we take $0 = a_0 = \alpha, 0 = a_m = \alpha + \beta m - m^2$. This has solution $\alpha = 0, \beta = m$. Hence, the specific solution is $a_n = mn - n^2 = n(m - n)$.
Homework 5 Exercises

Solve problems 1-8 twice: once, using the methods of this supplement; then, again, using generating functions.

1. Solve the recurrence given by $a_0 = a_1 = 2, a_n = -2a_{n-1} - a_{n-2} \ (n \geq 2)$.
2. Solve the recurrence given by $a_0 = 0, a_1 = 1, a_n = 4a_{n-2} \ (n \geq 2)$.
3. Solve the recurrence given by $a_0 = 2, a_1 = -4, a_2 = 26, a_n = a_{n-1} + 8a_{n-2} - 12a_{n-3} \ (n \geq 3)$.
4. Solve the recurrence given by $a_0 = a_1 = a_2 = 0, a_n = 9a_{n-1} - 27a_{n-2} + 27a_{n-3} \ (n \geq 3)$.
5. Solve the recurrence given by $a_0 = 1, a_1 = 2, a_n = 4a_{n-1} - 5a_{n-2} \ (n \geq 2)$.
6. Solve the recurrence given by $a_0 = a_1 = 0, a_n = a_{n-1} + 2a_{n-2} + 3 \ (n \geq 2)$.
7. Solve the recurrence given by $a_0 = a_1 = 0, a_n = a_{n-1} + 2a_{n-2} + n \ (n \geq 2)$.
8. Solve the recurrence given by $a_0 = a_1 = 0, a_n = a_{n-1} + 2a_{n-2} + e^n \ (n \geq 2)$.
9. What is the maximum number of regions we can divide the plane into, using $n$ lines?
10. Let $a_n$ be the number of $n$-digit nonnegative integers in which no three consecutive digits are the same. Justify that $a_{n+2} = 9a_{n+1} + 9a_n$ (for certain $n$), then find $a_n$.
11. Let $a_n$ be the number of ways to color the squares of a $1 \times n$ chessboard using the colors red, white, and blue, so that no two red squares are adjacent.
12. Let $a_n$ be the number of ways to color the squares of a $1 \times n$ chessboard using the colors red, white, and blue, so that no red square is adjacent to a white square. Justify the relation $a_{n+2} = 2a_{n+1} + a_n$ (for certain $n$), and then find $a_n$.
13. Let $a_n$ be the number of ways to color the squares of a $1 \times n$ chessboard using the colors red, white, and blue, so that the specific sequence red-white-blue does not occur. Find a recurrence that this sequence satisfies. You need not solve the recurrence.
14. Codewords (strings) from the alphabet $\{0, 1, 2, 3\}$ are called legitimate if they have an even number of 0’s. How many legitimate codewords are there, of length $n$?