Notes on chapter 4 of Sieglemann's *Neural Networks and Analog Computation*.

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Lemma 4.1.2, stated on page 63

- The statement about the value of x_r is misleading. It suggests that there is a node value that will consist of a bunch of zeros, followed by the encoding string, followed by more zeros, but that's not what the algorithm in the proof provides. Rather, what you get is that node x_{16} contains zero during each step until the specified step (but see below about the count), and then in the specified step it contains the encoding string, and then after that it goes back to zero henceforth.

Note two off-by-one-ish errors in Lemma 4.1.2:

- The network needed in the proof has 17 nodes (numbered 0 through 16), not 16.
- The number of zero steps before the encoding appears is two less than what's stated. You can either change n to $n-1$, or change 5 to 3. (This becomes clear when you run the algorithm. Yes, I'm taking into account that the step numbering is 1-based.)

So the actual number of ticks at which zero appears in x_{16} before the circuit encoding appears is

$$2(n-1) + \sum_{i=1}^{n} l(C_i) + 5$$

or

$$2n + \sum_{i=1}^{n} l(C_i) + 3$$

where n is the number of 1's in u, and $l(C_i)$ is the length of the i th encoding (not including the preceding or following 8). So the desired circuit encoding appears at step

$$2n + \sum_{i=1}^{n} l(C_i) + 4$$

Circuit-retrieval algorithm

From page 65. Implemented in file siegelmann4.clj.

Miscellaneous preliminary notes:

This is the core of the proof of Lemma 4.1.2.

I'll refer to the step in which u appears as tick 1 or step 1. So steps are 1-based, while matrix and vector indexes will be 0-based.

All elements of the state vector (of length 17) start as zero.

I formulate the state update algorithm using matrices and vectors, in terms of Equation (2.2), p. 19:

$$x_i(t+1) = \sigma\left(\sum_{j=1}^{N} a_{ij}x_j(t) + \sum_{j=1}^{N} b_{ij}u_j(t) + c\right)$$

where $x_i(t)$ is the i th element of state vector x at time t. Or using matrices and vectors:

$$x(t+1) = \sigma(ax + bu + c)$$

where a is a 17x17 matrix, x, b, and c are column vectors of length 17, and u is a column vector of length 1. The preceding equation is implemented by `next-state`.

c-hat ("C" with a hat over it in the text), which encodes a series of Boolean circuits (pp. 61–62), is the col–9-to-row–10 weight.

How the algorithm works:

1. u **is added only on the first tick.** Not before, not after. That is, you can have zeros as inputs before that point, but when u shows up, it does so only for one tick. It's replaced with zero after the first tick. Nothing happens until u shows up.
2. So x_9 **is nonzero only on the first tick.** That causes c-hat to be placed into x_{10} on the second tick (since x_0 through x_8 are still zero). This is the *only* time that c-hat as a weight is used directly (since it's the only time that x_9 is nonzero). After that, information from c-hat shuttles around in the x_0 through x_8 nodes, and x_{10}. (Pieces of c-hat get into x_{10} not because of the c-hat weight on x_9, but because x_{10} is a linear combination of x_0 through x_8.)
3. x_{10} **and** x_0 **through** x_8 **implement the lambda-tilde shift operator, but they do a bit more** than that in the network. At each subsequent step, x_0 through x_8 will contain either:

   a. A number that contains the left-shift of the decimal part of what's left of c-hat. This will be in some in x_j for j in {0,2,4,6,8}. Specifically, this shifted portion of c-hat will be in the x_j such that j is the integer part of the shifted string–i.e. j is what used to be the first digit. The new value in this x_j will be the next value of x_{10}.

   b. 1 in x_i for $i < j$ (see a above). There is alwasy an even number of these 1's, so on the next tick, they will sum to zero in the the linear combination that produces x_{10}.

    c. 0 in x_i for $i > j$.

4. **x_{11} is used to build the possible output circuit encoding.** It reconstructs digits from c-hat using the 1's in x_0–x_7, and places them on the front of x_{11}:
    - 2 times the 4-part sum in x_{11} is the digit that was just stripped off in calculating x_j (see 3a above). This might not be obvious: the count of 1's below the newly shifted float (derived from c-hat) is equal to the digit that was shifted off. [You might think you could instead just sum all of the 1's. But you have to choose input nodes that will work every time, and then you'd accidentally add in the node with a shifted c-hat float in it. The trick to the algorithm here is based on the fact that the new piece of c-hat is always in an even-numbered node, so if you only use odd-numbered nodes, you're guaranteed to miss that node containing the shifted c-hat. Since there is always an even number of 1's below the shifted c-hat node, doubling the odd nodes gives you the same count as if you counted all of the 1's. (And the registers in x_0–x_8 above the c-hat float are zero.) So $2(x_1 + x_3 + x_5 + x_7)$ gives you the digit that was just shifted off.]
    - x_{11} is used to build an output encoding string. We will place a new digit on the front of a right-shifted x_{12}. This has the old version of the partially constructed circuit encoding. We right-shift using $(1/9)x_{12}$ in order to to make space for the newly reconstructed digit that will be pushed onto this string. This new digit is 2($x_1 + x_3 + x_5 + x_7$) [see preceding item]. This is an integer, so we need to right-shift it to put it into the output string: 1/9 times 2($x_1 + x_3 + x_5 + x_7$) right-shifts the integer into the first decimal place, after which it canb e added to $(1/9)x_{12}$.

    (This is why the encoding in c-hat has to be backwards: you're pulling digits off the stack that came from c-hat, and then pushing them onto the stack in x_{12} and x_{11}, so the order gets reversed.)
5. **Counting to find the desired circuit that's indicated by the number of 1's in u:**
    - We mentioned above that u is placed in x_9 to start the process, copying c-hat to x_10. u is also placed in x_{13} on tick 1. (At that point x_{14} and x_{15} are zero, so contribute nothing.) Again, u as a value coming from the input stream will never appear again after this tick.
    - This value is then copied to x_{14} or x_{15}, but not both:
        - If $x_7 = 0$ (i.e. the last digit shifted off the c-hat string is not 8), x_{13} is simply copied to x_{15}, which is then copied back to x_{13}, and so on. (Like vamping in music.) Meanwhile, x_{14} stays zero, since 2 is greater than a left-shifted u-string.
        - But when x_7 is 1 (i.e. when the last digit shifted off of the c-hat string is 8), x_{15} becomes zero (since u or any part of it is always < 1), and now x_{14} is in effect $\sigma(2x_{13} - 1)$. There the 1 simply strips off the 1 that is newly shifted into the integer position by $2\times$. (Remember, u consists of a series of 1's indicating how many circuits to count.)
        - The resulting value will then be copied back to x_{13}. This is how we increment the counter by stripping a digit from the u string when an 8 is encountered in c-hat. [Note that at the beginning, c-hat is copied to x_{10} in tick 2, is stripped in x_8 in tick 3, so it's in tick 4 that the first 1 is stripped from u, placing the new version x_{14}.]
    - The preceding assumed that some 1's remaine from u. When all that's left are zeros, x_{14} and x_{15}, and hence x_{13}, will be forced to zero.
6. **The relationship between counting through the 1's in u, and output encoding string construction:**

Although the x_{11} code always tries to go through the process of constructing an encoding string, shuttling partially constructed versions back and forth betweebn x_{11} and x_{12}, *this doesn't happen while there are still 1's left from u.*

That's because $2x_{13}$ is subtracted in the x_{11} formula. As long as there is at least a single 1 left from u, in x_{13}, $2x_{13}$ left-shifts that 1 into the integer place. Since the partially constructed output would always be < 1 (because of the $1/9$'s), x_{11} remains zero until all of the 1's are gone.

Note that it's the 8 *before* the encoding string that causes a 1 to be shifted. So if $u = 0.111$, the final 1 will be shifted off just as the network is starting to look at the third encoding. Since x_{13} will remain zero now, the encoding can now be copied, piece by piece and in reverse, into x_{11} and x_{12}.

7. **Putting the output on x_{16}:**

   Finally, all along, if there was a partially constructed output in x_{12}, it was copied to the formulat for x_{16}. However, since that formula contains -1, the output string, which is always < 1, is turned into zero by $sigma$. It's only when, now that a nonzero output string is in x_{12}, *and then* x_7 contains 1 because another 8 was found in the c-hat remains, that the -1 in the x_{16} formula is counteracted, and the now fully reconstructed encoding string will appear in x_{16}.

8. **Coda:**

   After the answer has been placed in x_{16} at step $2n + \sum_{i=1}^{n} l(C_i) + 4$, x_{16} goes back to zero because now x_7 is not 1, since the most recently removed digit is not 8.

   However, *the process continues*. As written, the algorithm doesn't stop. And since there are no more 1's left from u, new circuit encodings will periodically appear in x_{16}. Or rather, what happens is that new circuit encodings are concatenated onto the ones already seen so far, separated by 8's. It's pretty useless. (If you run the algorithm, you'll eventually get to states that are all zeros, but that's apparently just because you only included a finite number of circuits in c-hat, and they've run out.)

   Of course, it would be easy to stop the process after the first encoding is reported. This isn't a flaw in the proof.